Single- and entangled-photon emission from
strain tunable quantum dots devices

von der Fakultät für Naturwissenschaften der
Technischen Universität Chemnitz
genehmigte Dissertation zur Erlangung des akademischen Grades
doctor rerum naturalium
(Dr. rer. nat.)
vorgelegt von
M. Sc. Jiaxiang Zhang
geboren am 4. März 1984 in Anqing, China
eingereicht am 30. April 2015

Gutachter:
Prof. Dr. Oliver G. Schmidt
Prof. Dr. Armando Rastelli

Tag der Verteidigung: 21. August 2015
Dedicated to my wife Junwen Deng
Bibliographic record

Jiaxiang Zhang:
Single- and entangled-photon emission from strain-tunable quantum dots devices
Technische Universität Chemnitz, Fakultät für Naturwissenschaften, Dissertation, 2015, 105 Seiten.

Keywords:  Single-photon source, quantum dots, light-emitting diode, PMN-PT, excitation repetition rate, fidelity, nanomembrane, quantum tomography, entangled-light-emitting diode, Bell inequality, Peres criteria, light-hole, coherence time.

Abstract

On demand single-photon and entangled-photon sources are key building-blocks for many proposed photonic quantum technologies. For practical device applications, epitaxially grown quantum dots (QDs) are of increasing importance due to their bright photon emission with sharp line width. Particularly, they are solid-state systems and can be easily embedded within a light-emitting diode (LED) to achieve electrically driven sources. Therefore, one would expect a full-fledged optoelectronic quantum network that is running on macroscopically separated, QD-based single- and entangled-photon devices.

An all-electrically operated wavelength-tunable on demand single-photon source (SPS) is demonstrated first. The device consists of a LED in the form of self-assembled InGaAs QDs containing nanomembrane integrated onto a piezoelectric crystal. Triggered single photons are generated via injection of ultra-short electrical pulses into the diode, while their energy can be precisely tuned over a broad range of about 4.8 meV by varying the voltage applied to the piezoelectric crystal. High speed operation of this single-photon-emitting diode up to 0.8 GHz is demonstrated.

In the second part of this thesis, a fast strain-tunable entangled-light-emitting diode (ELED) is demonstrated. It has been shown that the fine structure splitting of the exciton can be effectively overcome by employing a specific anisotropic strain field. By injecting ultra-fast electrical pulses to the diode, electrically triggered entangled-photon emission with high degree of entanglement is successfully realized. A statistical investigation reveals that more than 30% of the QDs in the strain-tunable quantum LED emit polarization-entangled photon-pairs with entanglement-fidelities up to $f^+ = 0.83(5)$. Driven at the highest operation speed ever reported so far (400 MHz), the strain-tunable quantum LED emerges as unique devices for high-data rate entangled-photon applications.

In the end of this thesis, on demand and wavelength-tunable LH single-photon emission from strain engineered GaAs QDs is demonstrated. Fourier-transform spectroscopy is performed, from which the coherence time of the LH single-photon emission is studied. It is envisioned that this new type of LH exciton-based SPS can be applied to realize an all-semiconductor based quantum interface in the foreseeable distributed quantum networks.
# Contents

Abstract  

Acronyms  

## 1 Research motivation

1.1 Quantum information science  
1.1.1 Quantum technologies based on photons  
1.1.2 Single- and entangled-photon sources  
1.2 State-of-the-art  
1.2.1 QDs-based single-photon sources  
1.2.2 QDs-based entangled-photon sources  
1.3 Objective of this thesis  
1.3.1 Wavelength-tunable and triggered LED  
1.3.2 Fast strain-tunable entangled LED  
1.3.3 Light-hole single-photon emission  
1.4 Organization of this thesis  

## 2 Background, QD devices and optical apparatus

2.1 III-V group semiconductor QDs  
2.1.1 Quantum confinement  
2.1.2 Epitaxially-grown self-assembled QDs  
2.1.3 Multiexciton photon emission  
2.2 Band structure of strained semiconductor  
2.2.1 Introduction to $\mathbf{k} \cdot \mathbf{p}$ perturbation method  
2.2.2 $\mathbf{k} \cdot \mathbf{p}$ perturbation theory for strained semiconductors  
2.3 Strain-tunable QD devices  
2.3.1 Strain-tunable quantum LED  
2.3.2 GaAs QDs with LH ground states  
2.4 Overview of micro-PL/EL setup  

## 3 Wavelength-tunable and triggered quantum LED

3.1 Electrically pulsed injection to a quantum LED  
3.1.1 High frequency feed-through setup  
3.1.2 Injection of ultrafast electrical pulses to the QD LED  
3.2 Electrical control of the optical properties of QDs  
3.2.1 Lifetime reduction and “slow-pumping” effect  
3.2.2 Line width broadening
### Contents

3.3 Photon collection efficiency ........................................... 36
3.4 Wavelength-tunable and electrically triggered single-photon emission .... 37
3.4.1 Strain-induced energy shift of the photon emission .......... 38
3.4.2 Wavelength-tunable and triggered single-photon emission .. 38
3.5 High speed electrically triggered single-photon emission ........ 39

4 Triggered entangled-photon emission from strain-tunable quantum-LED 43
4.1 Entangled photon pairs from the cascade emission in QDs ........... 43
4.1.1 Cascade emission from anisotropic QDs ...................... 43
4.1.2 Origin of the fine structure splitting .......................... 45
4.2 Post-growth tuning of the fine structure splitting .................. 47
4.2.1 Review of the post-growth tuning methods .................... 47
4.2.2 Cancellation of the fine structure splitting with uniaxial strain .. 51
4.2.3 Experimental realization of zero fine structure splitting in the quan-
    tum LED .............................................................. 52
4.3 Quantitative characterization of two-photon polarization entanglement . 56
4.3.1 Two-photon polarization entanglement ....................... 56
4.3.2 Degree of the polarization correlation ....................... 58
4.3.3 Two-photon quantum tomography ............................. 60
4.3.4 Entanglement test parameters ............................... 64
4.4 High speed polarization entangled-photon generation ............... 65
4.4.1 400 MHz entangled-photon pairs generation ............... 65
4.5 Statistics measurement ............................................. 67

5 Single photons on-demand from light-hole excitons in GaAs QDs 71
5.1 Semiconductor-based quantum state transfer ........................ 71
5.2 Optical characterization of the LH Exciton photon emission ........ 74
5.2.1 Physical properties of the LH exciton ........................ 74
5.2.2 Experimental verification of photon emission from the LH excitons .. 75
5.2.3 PL spectrum of the LH exciton photon emission ............. 78
5.3 Wavelength-tunable and optically triggered LH single-photon emission .. 79
5.3.1 Wavelength-tunable LH photon emission ..................... 79
5.3.2 Optical triggered LH single-photon emission ............... 80
5.4 Coherence time of the LH single photons ........................ 81

6 Conclusions and outlook 85
6.1 Conclusion .............................................................. 85
6.2 Outlook ............................................................... 86

Bibliography ................................................................. 87
Appendix ....................................................................... 97
Acknowledgement ............................................................. 99
Publications and scientific presentations ............................... 101
Curriculum vitae .......................................................... 103
Selbständigkeitserklärung
## Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB</td>
<td>conduction band</td>
</tr>
<tr>
<td>VB</td>
<td>valence band</td>
</tr>
<tr>
<td>QD</td>
<td>quantum dot</td>
</tr>
<tr>
<td>MBE</td>
<td>molecular beam epitaxy</td>
</tr>
<tr>
<td>PL</td>
<td>photoluminescence</td>
</tr>
<tr>
<td>EL</td>
<td>electroluminescence</td>
</tr>
<tr>
<td>LED</td>
<td>light-emitting diode</td>
</tr>
<tr>
<td>SPS</td>
<td>single-photon source</td>
</tr>
<tr>
<td>HBT</td>
<td>Hanbury-Brown and Twiss</td>
</tr>
<tr>
<td>HH</td>
<td>heavy hole</td>
</tr>
<tr>
<td>LH</td>
<td>light hole</td>
</tr>
<tr>
<td>FSS</td>
<td>fine structure splitting</td>
</tr>
<tr>
<td>CCD</td>
<td>charge-coupled detector</td>
</tr>
<tr>
<td>ELED</td>
<td>entangled-light-emitting diode</td>
</tr>
<tr>
<td>ERR</td>
<td>excitation repetition rate</td>
</tr>
<tr>
<td>PB</td>
<td>Pikus-Bir</td>
</tr>
<tr>
<td>SPAD</td>
<td>single-photon counting avalanche detector</td>
</tr>
<tr>
<td>FWHM</td>
<td>full width and half maximum</td>
</tr>
<tr>
<td>PMN-PT</td>
<td>( [Pb(Mg_{1/3}Nb_{2/3})O_3]<em>{0.72}[PbTiO_3]</em>{0.28} )</td>
</tr>
<tr>
<td>SK</td>
<td>stranski-Krastanow</td>
</tr>
<tr>
<td>SEM</td>
<td>scanning electron microscopic</td>
</tr>
<tr>
<td>X</td>
<td>neutral exciton</td>
</tr>
<tr>
<td>XX</td>
<td>biexciton</td>
</tr>
<tr>
<td>SPE</td>
<td>single-photon emission</td>
</tr>
<tr>
<td>SPDC</td>
<td>Spontaneous parametric down conversion</td>
</tr>
<tr>
<td>NA</td>
<td>numerical aperture</td>
</tr>
<tr>
<td>qubit</td>
<td>quantum bit</td>
</tr>
<tr>
<td>QIP</td>
<td>quantum information processing</td>
</tr>
<tr>
<td>QKD</td>
<td>quantum key distribution</td>
</tr>
<tr>
<td>BSM</td>
<td>Bell-state measurement</td>
</tr>
<tr>
<td>TPI</td>
<td>Two-photon interference</td>
</tr>
</tbody>
</table>
1 Research motivation

1.1 Quantum information science

In the past decades, quantum information science has emerged and attracted intensive research interests in a broad range of applications, for example, quantum cryptography [1], quantum computation and scalable quantum network [2]. The driving factors behind this thriving development originate from its superior capability of offering an enhanced security to encode information and the extraordinary computation power. Specifically, quantum information science which employs quantum mechanics effects can be anticipated to address many challenging tasks which are beyond the ability of classical ones, for instance, prime factorization, database searching and so on [3].

To date, a variety of physical systems such as nuclear spins, Josephson junctions and electrons, etc. have been demonstrated to implement these quantum technologies. Arguably, the most suitable quantum systems so far are quantum states of light. The reason is two-fold [4, 5]. (i) Photons are in principle identical and they travel at the speed of light. They weakly interact with environment over long distances, which results in low noise and loss. (ii) The majority of quantum information applications require ‘flying’ quantum bits (qubits) as they can propagate from one node to another, and especially they can be manipulated by making only use of linear optics [6].

1.1.1 Quantum technologies based on photons

Photonic quantum technologies have offered a versatile testing ground for a variety of physical fundamentals of the quantum information science, for example, the first experimental demonstration of entangled-photon emission from calcium atom cascade in 1981 [7], in which Bell’s inequality was violated. Soon later in 1984, H. C. Bennett put forth a rigorous proposal of using polarized photons as qubits to implement the quantum cryptography [8]. This protocol is known as BB84 protocol, which has proven to be the most popular and successful prototype of the quantum cryptography until now. Thereafter, in 1995, P. Kwiat and co-workers made an important progress and experimentally demonstrated a new type of entangled-photon emission from a nonlinear crystal via spontaneous parametric down conversion (SPDC) [9]. The successful realization of the SPDC entangled-photon sources represented a remarkable achievement at that time and has boosted the development of the photonic quantum techniques. Noticeably, the invention of the SPDC entangled-photon sources has fostered experimental realizations of a plenty of quantum information processing (QIP) applications, including first experimental demonstration of quantum teleportation [10–13], quantum communication [14],...
quantum cryptography [15], and experimental one-way quantum computing [16] and so on.

Photons offer original and powerful degrees of freedom for processing information such as frequency, spatial mode and polarization. The most commonly used quantum states of photons are polarization states, which provide fundamental elements (referred to as qubits) on which the photonic quantum technologies rely. Similar to the qubits in atoms and ions, the qubit of a photon can be determined by the superposed polarization states, e.g., horizontal (H) and vertical (V) polarization states in rectilinear basis. In quantum mechanics framework, a qubit of a photon, $|\Psi\rangle_{1\text{bit}}$, can be defined as
\[
|\Psi\rangle_{1\text{bit}} = \alpha |H\rangle + \beta |V\rangle = \alpha |0\rangle + \beta |1\rangle,
\]
(1.1)
where logic bits $|0\rangle$ and $|1\rangle$ are represented by the physical polarization states $H$ and $V$ respectively. Moreover, by means of the polarization-entangled state of two photons, one could easily encode two bits of information [5]. Compared to the classical method of encoding two bits of information into two objects separately in a sophisticated way, quantum mechanics offers a simple and straightforward way to encode two bits of information. A general 2-qubits state can be written as:
\[
|\Psi\rangle_{2\text{bits}} = \alpha |HH\rangle + \beta |HV\rangle + \gamma |VH\rangle + \kappa |VV\rangle
= \alpha |00\rangle + \beta |01\rangle + \gamma |10\rangle + \kappa |11\rangle.
\]
(1.2)
A fascinating feature in such two bits quantum state is ‘entanglement’, in which the two bits are inseparable and correlated to each other even though they are separated light years apart.

![Figure 1.1: Sketch of QKD performed according to BB84 protocol.](image)

With the polarization qubits of photons, to date, many photonic quantum technologies have been successfully realized. Among them, quantum cryptography is one of the earliest examples, and there are several commercial quantum key distribution (QKD) systems
already. As it is one of the main motivations of developing feasible and practical single-photon sources (SPSs) in this thesis, herein, the photonic QKD is depicted in detail as follows.

According to Bennett and Brassard’s proposal [8], the QKD using single photons from the SPDC source, can be performed in the following way: the sender, say Alice, encodes information into the polarization states of individual photons using randomly chosen bases: HV and 45° basis (see Fig. 1.1). The H-polarized and 45°-polarized photons correspond to logic bit of “0”, while the V-polarized and -45°-polarized photons represent logic bit of “1”. Alice sends a photon sequence to a receiver, Bob. Bob measures the incoming photons using either the HV or 45° basis. Note this selection is also random. After his measurements, Alice and Bob communicate through a public channel to compare the bases they have used. Whenever they use the same bases, they get correlated results. On the other hand, when the bases are different, their results are not correlated. In the end, they keep the correlated results and discard uncorrelated ones so that a key is generated and shared at both sides secretly. Supposing the experimental error arising from the setup imperfections is negligible, the key produced in above process is absolute secure. Any intercepting from the eavesdropper will give a noise signal, which can be detected and identified experimentally. More information regarding the experimental realization of the QKD and the error analysis can be found in Ref. [17].

![Figure 1.2: Schematic of the polarization quantum teleportation.](image)

Figure 1.2: Schematic of the polarization quantum teleportation. The SPDC source provides a two-photon entangled state $|\Psi\rangle_{23} = \frac{1}{\sqrt{2}}(|H_2H_3\rangle + |V_2V_3\rangle)$. Alice performs a BSM measurement [18], so that the input state in path ‘1’ $|\Psi\rangle_1 = 1/\sqrt{2}(|H_1\rangle + |V_1\rangle)$ can be teleported to Bob in path ‘3’.

Another important photonic quantum operation is the quantum teleportation, by which the polarization states of a photon can be teleported from one node to another. The quantum teleportation plays a crucial role in achieving scalable QIP networks. Fig. 1.2 shows the importance of the polarization state teleportation demonstrated by D. Bouwmeester, et al. in 1997 [10]. In their proposal, Alice tends to teleport an unknown qubit $|\Psi\rangle_1 = 1/\sqrt{2}(|H_1\rangle + |V_1\rangle)$ to Bob. It can be accomplished by making use of an auxiliary entangled state $|\Psi\rangle_{23} = \frac{1}{\sqrt{2}}(|H_2H_3\rangle + |V_2V_3\rangle)$ provided by the SPDC source. Then the entire state is
the product state of the auxiliary state and the unknown state:

\[ |\Psi\rangle_{123} = |\Psi\rangle_1 |\Psi\rangle_23 = (|H_1\rangle + |V_1\rangle)(|H_2H_3\rangle + |V_2V_3\rangle)/2 \]
\[ = |\Psi_+\rangle_{12}(|H_3\rangle + |V_3\rangle)/\sqrt{2} + |\Psi_-\rangle_{12}(|H_3\rangle - |V_3\rangle)/\sqrt{2} \]
\[ + |\Phi_+\rangle_{12}(|V_3\rangle + |H_3\rangle)/\sqrt{2} + |\Phi_-\rangle_{12}(|V_3\rangle - |H_3\rangle)/\sqrt{2}, \]

(1.3)

\[ |\Psi_+\rangle, |\Psi_-\rangle, |\Phi_+\rangle \text{ and } |\Phi_-\rangle \text{ are maximally entangled Bell states:} \]

\[ |\Psi_+\rangle = \frac{1}{\sqrt{2}}(|H_1V_2\rangle + |V_1H_2\rangle), \]

(1.4a)

\[ |\Psi_-\rangle = \frac{1}{\sqrt{2}}(|H_1V_2\rangle - |V_1H_2\rangle), \]

(1.4b)

\[ |\Phi_+\rangle = \frac{1}{\sqrt{2}}(|H_1H_2\rangle + |V_1V_2\rangle), \]

(1.4c)

\[ |\Phi_-\rangle = \frac{1}{\sqrt{2}}(|H_1H_2\rangle - |V_1V_2\rangle). \]

(1.4d)

Thereafter, Alice carries out the Bell-state measurement [18] (BSM) on the product states. Note this measurement makes Eq.1.3 collapse to

\[ |\Psi_+\rangle_{12}(|H_3\rangle + |V_3\rangle)/\sqrt{2}, \]

so that Bob finally obtains the state \((|H_3\rangle + |V_3\rangle)/\sqrt{2}\) which is the same state as the polarization state of the unknown photon that Alice has.

Figure 1.3: A prototype of the quantum network from Ref. [19]. Top panel shows a segment of the quantum network with which entangled photons A-B and B-C can be swapped to A-C. The bottom panel is an envisaged quantum repeater by which two photons at distant nodes A, C can be correlated by N times BSM measurements at \(B_i (i = 1, 2, \ldots, N)\) channel.

The above photonic QKD and quantum teleportation serve as fundamental building blocks for realizing the envisioned scalable quantum network. Fig. 1.3 shows a sketch of the photonic quantum network [19]. The fundamental segments in this proposal are single-photon and entanglement-photon pairs. The single photons at each node, e. g., A
and C, can be connected by performing the BSM measurement at node B as shown in the top panel. At adjacent nodes, the BSM measurement is performed and it enables that the photon state at node A can be teleported to the remote node C. This process is called entanglement swapping (QS). Based on this QS, one is able to extend the entanglement to N distant nodes as shown in the bottom panel.

1.1.2 Single- and entangled-photon sources

The intriguing photonic quantum information applications mentioned above have spurred the development of versatile single- and entangled-photon sources. Many physical systems, involving SPDC sources [20], trapped atoms [21–25], ions [26–28], organic molecules [29, 30] and semiconductor quantum dots (QDs) [31–35], etc. have been successfully explored for this purpose. Nevertheless, they have different strengths and weaknesses when applied to the above quantum applications. Here a brief review about these quantum sources is given in order to motivate my work on semiconductor QD-based SPSs and entangled-photon sources.

*SPDC source*: Entangled-photon pairs can be generated by SPDC source made of solid-state nonlinear crystals. The SPDC process is achieved by impinging a high energy photon onto two nonlinear crystals aligned appropriately. When the conditions of the energy conservation and the phase matching are satisfied, two photons with lower energy which are entangled in a certain spatial range will be generated. Although the entangled-photon emission created in this parametric down conversion is bright, the probability of generating more than one photon at a time follows Poissonian statistics. If \( p \) is the probability to generate an entangled-photon pair in one pump pulse cycle, there is a probability of \( p^2 \) to generate two or more pairs of entangled-photon in the same pulse cycle. This unavoidably reduces the security once it is used in the above mentioned QKD application.

![Figure 1.4](image)

**Figure 1.4**: (a) Hanbury-Brown Twiss experimental setup and (b) Second-order correlation function \( g^{(2)}(\tau) \) as a function of delay time \( \tau = \tau_1 - \tau_2 \).

*Trapped atoms and ions*: Photons emitted from atoms are strictly “anti-bunched”, which means only one photon is generated at a time. Unlike the SPDC sources, single-photon emission from the atomic systems follows sub-Poissonian statistics, which was
revealed by H. J. Kimble, et al. in 1977 [36]. Experimentally, this anti-bunching property can be characterized by means of the second-order time correlation function $g^{(2)}(\tau)$ with a Hanbury-Brown and Twiss (HBT) setup as shown in Fig. 1.4. The second-order time correlation function between detector 1 and detector 2 is expressed by

$$g^{(2)}(\tau) = \frac{\langle a^+(t)a^+(t + \tau)a(t + \tau)a(t) \rangle}{\langle a^+(t)a(t) \rangle^2},$$

(1.5)

where $a^+$ and $a$ are photon creation and annihilation operators. Given a nonclassical photon number state $|n\rangle$:

$$g^{(2)}(\tau = 0) = \frac{\langle n|a^+a^+aa|n\rangle}{\langle n|a^+a|n\rangle^2} = 1 - \frac{1}{n}.$$  

(1.6)

Thus for nonclassical light emission: $g^{(2)}(0)\langle 1$, and for a single-photon source (n=1), e. g., two-level atomic systems: $g^{(2)}(0) = 0$ (see Fig. 1.4b)

Due to the absence of the inhomogeneous broadening, the spectral line width of the photon emission from atoms and ions is very sharp (typical line width $\sim 10$ MHz) and commonly lifetime-limited. Moreover, atoms can provide a broad range of spectrum for single-photon emission. Despite these advantages, atoms have very long lifetimes with typical values of 10$\sim$15 ns, which gives rise to a limitation of the photon emission rate. Additionally, most of the atomic systems are in vapor phase and they require very complicate trapping setups. This further constrains practical applications of the atomic systems in the quantum information processing.

**Organic molecules:** The strengths of organic molecules lie in their high natural abundance, which covers a broad wavelength of the single-photon emission from visible to near infrared. Not only working at cryogenic temperature, single molecules have proven to show excellent antibunching behavior at room temperature [37]. However, organic molecules are prone to photochemical processes, which leads to a severe change in the functionalities even though they are well-encapsulated from ambient environment. Furthermore, the most critical issue for the molecules is probably that there are no reports so far on entangled photon emission from molecules.

**Self-assembled QDs:** The antibunching behavior of the single-photon emission from self-assembled QDs was first reported in 2000 by P. Michler [31]. From then on, self-assembled QDs, especially III-V group direct-band gap In(Ga)As and GaAs QDs, have attracted intensive research interests. The main reasons are many-fold. (i) Self-assembled QDs grown via molecular beam epitaxy (MBE) have almost no defects and they have atom-like discrete electronic energy states. Thus they are capable of generating bright light emission with sharp line width. (ii) Particularly, self-assembled QDs are made of semiconductor materials and they can be easily embedded within a light-emitting diode (LED) structure in order to realize electrically driven SPSs. (iii) Self-assembled QDs can be easily integrated within photonic microcavities, which facilitates the realization of the future scalable “on-chip” QIP. (iv) The excitonic state has typical recombination time of about 1 ns, which results in an enhanced photon emission rate when compared to the others above. Although the most QDs-based single- and entangled-photon sources still need to work at cryogenic temperature in order to avoid phonon-induced effects, it seems this can be overcome by developing the III-Nitride compound semiconductor QDs so as
to achieve room temperature QD-based SPSs [38]. Making use of these strengths of self-assembled QDs, in this thesis I will dedicate my research to develop strain-tunable QDs-based single- and entangled-photon sources, which could not only provide fundamental research on quantum optical effects, but also fulfill the most of the demands in the future photonic quantum technologies.

1.2 State-of-the-art

1.2.1 QDs-based single-photon sources

It has been stated in the previous sections that most of the envisioned photonic quantum technologies strongly rely on two-photon interference (TPI), the central part in the above mentioned BSM measurement, between indistinguishable photons emitted from independent SPSs. Until now, the TPI has been realized successfully with a variety of quantum emitters such as atoms [39], trapped ions [40] and molecules [41]. This benefits from their intrinsically identical photon emission properties. For QD-based SPSs, an inhomogeneous spectral broadening of about 10 meV is commonly induced by the random distributions in shape and composition of QDs during the sample growth. This gives rise to the distinguishability of photons from the different QDs. To date this is the main obstacle to be overcome for realizing the TPI from the remote self-assembled QDs.

Many techniques including in-situ thermal annealing and temperature tuning [42–44], magnetic field [45] and electric field tuning [46] have been demonstrated in order to tune the self-assembled QDs to be identical. However, thermal annealing is an irreversible coarse tuning technique, while the magnetic field tuning requires complex and bulky setup which renders a practical implementation inconvenient. Although applying an electric field is a promising ‘tuning knob’ to tune the energy emission of QDs [47], the main drawback is the difficulty of combining it with electrical excitation at the same time. Recently, elastic strain fields induced by a piezoelectric crystal have been successfully employed as a reliable ‘tuning knob’ to control the optical properties of the QDs [48–53]. But until now wavelength-tunable triggered single-photon emission from quantum LEDs, which is crucial for a non-postselective TPI measurement with the remote QDs based SPSs [49], has not been demonstrated.

On the other hand, self-assembled QDs based SPSs are one of the promising candidates for photonic quantum interface applications. Firstly, QDs are excellent quantum emitters which can provide stable and bright single-photon emission and are compatible with standard semiconductor processing technologies. Secondly they can be simultaneously used as hosts for stationary qubits, i.e., electron and hole spins, which can be stored and manipulated locally [54]. Hence, self-assembled QDs can be used to build an all-semiconductor based quantum interface, from which the polarization state of single photons and the electron spin states can be coherently inter-converted [55]. By employing the large discrepancy between the g-factors of electrons and LHs confined in a semiconductor quantum well, Kosaka and co-workers recently demonstrated a coherent state transfer from classical light onto electron spins, which represents a breakthrough towards an all-semiconductor quantum interface application [56, 57]. However, the study is based on heavy-hole (HH) type, whereas the LH states are lower in energy. Rapid relaxation of holes from the LH
states to the HH states prevents formation of the LH exciton, and therefore results in a
difficulty of using this strategy to achieve the inverse electron-spin-to-photon interconversion.
In addition, a quantum well is a two-dimensional system and does not allow storage
and generation of single qubits. In this context, a QD with LH-GS appears very appeal-
ing, because it may allow for bidirectional interconversion between the states of single
stationary and flying qubits. To date, LH ground-state excitons have been realized in a
pyramidal GaAs/AlGaAs quantum dot-in-dot heterostructure [58], however, the studied
system shows broad LH emission spectra (> 2 meV) probably due to charged impurities.
This hampers their practical applications in the field of quantum information technologies.
Recently bright and sharp LH-exciton emission was reported from GaAs/AlGaAs QDs
with valence-band ground state of dominant LH character [59], but until now triggered
LH single-photon emission with tunable wavelength, which is critical for above-mentioned
quantum interface applications, has not been demonstrated.

1.2.2 QDs-based entangled-photon sources

Recent works have shown that the FSS can be suppressed or tuned to zero through appli-
cation of either a vertical electric field [60] or a strain-field-mediated vertical electric
field across the QDs containing LED [61, 62], but the main drawback for these strate-
gies is the difficulty of combining with electrical excitation and therefore it hampers the
realization of electrically driven ELED. Other techniques such as thermal annealing, and
in-plane magnetic field would be potentially compatible with the realization of ELEDs.
As stated in the last section, those techniques render a practical implementation incon-
venient. Recent theoretical works suggest (although not experimentally realized so far)
that the FSS can be effectively eliminated by using solely a single well-aligned uniaxial
strain field [63, 64]. Combining with electrical excitations and micro-/nano engineering
techniques, this can lead to a very compact quantum LED which will be arguably one of
the most practical entangled light sources to date. In this thesis a strain-tunable quantum
LED is demonstrated, from which a QDs diode is integrated onto a piezoelectric crystal in
order to apply an anisotropic in-plane strain fields to control the fine structure splitting.
With this device, a substantially enhanced probability of dots that tuned to have FSS of
zero value is achieved and thereby electrically triggered entangled-photon emitters with
a high dots yield is realized.

1.3 Objective of this thesis

This thesis will be focused on demonstrating the following objectives:

1.3.1 Wavelength-tunable and triggered LED

A nanomembrane-based, high speed and electrically triggered single-photon emission from
a wavelength tunable quantum LED is about to be demonstrated. The device is based
on InGaAs QD-containing $n$-$i$-$p$ nanomembranes integrated onto a piezoelectric crystal.
Triggered single-photon emission is realized by applying sub-nanosecond electrical pulses
to excite the In(Ga)As QDs. The wavelength tuning is achieved by applying a variable external strain field to the QDs using the piezoelectric crystal. The second-order autocorrelation \([g^{(2)}(\tau)]\) measurements are carried out with a HBT setup to illustrate the triggered single-photon emission from this electrically operated, wavelength tunable single-photon-emitting diode. Together with a demonstration of the high speed operation up to 800 MHz, these results hold strong promise towards the non-postselective TPI measurements with two remote electrically driven SPSs.

1.3.2 Fast strain-tunable entangled LED

A fast strain-tunable ELED is demonstrated. A highly anisotropic piezoelectric crystal is employed for the first time in this study. Rather than using biaxial piezoelectric crystal, the specific piezoactuator can be used to control the fine structure splitting of exciton photon emission effectively. With this device, a high-degree fidelity of entangled-photon pairs is achieved. In addition, the device shown here facilitates fast electrical pulses excitation with repetition rate up to 400 MHz, which is so far the highest excitation repetition rate reported. Most importantly, by employing this technique, it is possible to tune numerous dots to be entangled-photon quantum emitters.

1.3.3 Light-hole single-photon emission

On-demand wavelength-tunable LH single-photon emission from tensile-strained GaAs QDs is demonstrated. Firstly the typical photon emission from a LH neutral exciton, which is characterized by three orthogonally polarized emission lines, is presented. Then triggered LH single-photon emission via second-order time correlation measurements is measured. It is also shown that the emission wavelength of LH single photons can be dynamically and precisely tuned in a wide range by means of an externally-induced strain field. Moreover, the coherence time of the LH single photons is investigated via a single-photon interference with a Michelson interferometer.

1.4 Organization of this thesis

In order to clarify the achievements, the thesis is organized in the following way:

**Chapter 2**: Theoretic background on QDs and on the effect of strain on the electronic structure of QDs, strain-engineering band structure of QD is introduced. Then a detailed description of the strain-tunable devices, including strain-tunable quantum-LED and strain-engineered GaAs QDs, is specifically presented. In addition, an overview of the experiment setup is also provided.

**Chapter 3**: Wavelength-tunable and ultra-fast electrically-triggered single-photon emission based on the strain-tunable quantum-LED is demonstrated. Experimental details, including ultra-fast electrical pulse feed-through, lifetime tuning via diode bias voltage, etc. are provided. Wavelength-tunable and ultra-fast electrically-triggered single-photon emission are achieved simultaneously in one single device.
Chapter 4: By modifying the strain configuration provided from the piezoelectric crystal, it is found that the strain-tunable diode owns strong capability to control the fine structure splitting. In this chapter, a concrete introduction of the polarization-entangled two-photon emission from the QD biexciton cascade is given. Both theoretic and experimental aspects of the two-photon polarization entanglement are provided in this chapter.

Chapter 5: In this chapter, the physical origin of the LH emission from the prestressed GaAs QDs is introduced, and followed by presenting the experimental systematic characterization of such LH photon emission. The quantum nature of the LH single-photon emission is thereafter clarified via $g^{(2)}(\tau)$ measurements. In the end, measurements of the first-order time correlation function $g^{(1)}(\tau)$ to this LH single-photon emission is presented by employing a Michelson interferometer.

Chapter 6: A brief conclusion of this thesis, together with an outlook for future perspective is given in this chapter.
2 Background, QD devices and optical apparatus

In the last decades, self-assembled QDs grown by epitaxy techniques such as molecular beam epitaxy (MBE) have become a topic of extensive research not only for the fundamental understanding of fascinating physics of the zero-dimensional systems, but also for their applications in electronic and optical devices for quantum information processing. In this chapter, a brief introduction to III-V Group semiconductor QDs is given. This includes quantum confinement, multi-excitonic transition and energy band theory of strained semiconductors. Description of the strain-tunable QD-based devices, involving nanomembrane-based single/entangled-photon quantum LED, strain-tunable LH SPSs will be given in great detail. In the end, explicit illustration of the experiment methods and the optical setup for common PL characterization and sing-/entangled-photon emission measurements are introduced.

2.1 III-V group semiconductor QDs

2.1.1 Quantum confinement

Well-established theory points out that if the size of a semiconductor material is reduced to values as comparable to the de Broglie wavelength of the electron wave, its electronic and optical properties will deviate substantially from its bulk. Let us consider InAs as an example, the de Broglie wavelength of electron wave at room temperature \( T=300K \) is given by

\[
\lambda_{\text{BulkInAs}} = \frac{\hbar}{\sqrt{2kT_Bm^*}} \approx 40 \text{ nm},
\]

where \( m^* \) is the effective mass of the electron: \( m^* = 0.025m_0 \) (\( m_0 \) is mass of the free electron); \( T_B \) is Boltzmann constant. Therefore, one could expect that a size confinement phenomenon becomes apparent for InAs having structures of a few tens nanometers size. This effect is commonly known as quantum confinement effect. Remarkably, the quantum confinement effect results in quantization of the electronic energy states in nanocrystals and makes electrons and holes become localized. Accordingly, carrier energies (i.e. electrons and holes) are no longer quasi-continuous but discrete.

Semiconductor QDs are tiny domains surrounded by another semiconductor material with higher energy band-gap. In this scenario, electrons and holes confined in the nanometric domains are subject to a space-dependent potential, which is analogous to a particle
in a 3D box. As the confining dimension decreases and reaches scale of the de Broglie wavelength of the electron, the electrons and the holes are squeezed in the nanostructures due to the quantum confinement effect. An electron and a hole confined in the same region of space bond due to Coulomb attraction and form a quasi-particle called ‘exciton’, which plays a core role in the optical properties of the QD.

Similar to the situation encountered in a Hydrogen atom, the exciton can be characterized by a Bohr radius, which depends on the material parameters:

\[
a_B = \frac{\varepsilon}{m^*} \cdot \frac{4\pi\varepsilon_0\hbar^2}{e^2} = \frac{a_0 \varepsilon}{m^*/m_e},
\]

in which \(a_0 = 4\pi\varepsilon_0\hbar^2/m_e e^2\) is Bohr radius, \(m^*\) is the reduced effective mass of the exciton and is defined by \(1/m^* = 1/m_e + 1/m_h\). Depending on the exciton Bohr radius, one can categorize two different quantum confinement regimes: strong confinement when the size of the semiconductor is smaller than the exciton Bohr radius, and weak confinement regime when the size of the semiconductor is larger than the exciton Bohr radius.

The change in optical properties for a semiconductor structure with the strong quantum confinement is manifested in its density of states (DOS), which is defined as number of states per carrier per energy interval. As one goes from bulk material in which there is no quantum confinement, to a system in which the carriers are allowed to move in two dimensions (quantum well, QW), one dimension (quantum wire, QWR) or in quasi-zero dimensions (QD), the DOS changes as shown in Fig. 2.1. In the case of QDs the DOS is simply given by a series of \(\delta\)-like peaks, which are similar to the discrete levels in an atomic system, in this sense, QDs are also referred to as “artificial atoms”. In reality, the \(\delta\)-like peaks has finite width. This is caused by underlying homogeneous and inhomogeneous
broadening mechanisms. In contrast, in other cases, i.e., 3D bulk, 2D QW and 2D QWR, the DOS is continuous in certain direction, which implies not all three directions are quantized and thus the motion of the electron (hole) is classical.

2.1.2 Epitaxially-grown self-assembled QDs

Quantum dots can be fabricated using different processes [65]. Nowadays, one of the mostly studied optical active QDs is InAs/GaAs QD.

Epitaxy growth of InAs/GaAs QDs via MBE starts with depositing a single crystalline InAs material on a GaAs substrate (see Fig. 2.2). The substrate material has larger band gap, but it has smaller lattice constant \((a_{GaAs} = 0.56 \text{ nm})\) than the deposited InAs material \((a_{InAs} = 0.605 \text{ nm})\). In most cases, the GaAs substrate is [001]-orientated, and the active material InAs is provided by thermal evaporation of indium and arsenic elements from hot crucibles. Thereafter, as more and more InAs material is accumulated on the GaAs substrate, a thin film known as wetting layer is firstly formed. Further deposition of the active InAs material results in a high accumulated strain energy in the wetting layer. Once the thickness of this layer exceeds a certain value, the accumulated strain energy will drive the formation of three-dimensional islands on top of the flat film as shown in Fig. 2.2c. Finally, in order to provide well-defined quantum confinement in three dimensions, a capping layer with larger band gap must be deposited (see Fig. 2.2d).
2 Background, QD devices and optical apparatus

Figure 2.3: (a) Atomic Force Microscopic (AFM) images of a few InAs islands on GaAs substrate in area of $2 \times 2 \mu m^2$ and (b) Cross sectional Transmission Electron Microscopic (TEM) image of a single InAs QD after capping with GaAs top barrier.

Fig. 2.3 shows AFM and TEM images of InAs three-dimensional islands and a single InAs QD grown by MBE in S-K mode. The large scale AFM characterization in an area of $2 \times 2 \mu m^2$ shows the InAs islands with a density of about $2.5 \times 10^7/cm^2$. The morphology of a single InAs QD is clearly seen in the right panel TEM image, the lateral size of the InAs QD is about 40 nm, while the height is less than 10 nm. Obviously, there is an ambiguous border between the InAs island and the GaAs matrix which is ascribed to the intermixing of indium and gallium. In this respect, the QDs are made of an InGaAs alloy rather than of pure InAs.

Figure 2.4: AFM images of InAs/GaAs QDs. It shows a density variation from the center to the edge of a 2-inch [001]-oriented GaAs wafer.

Noticeably, by controlling the growth conditions, e. g., temperature, one is able to control the density of the dots, which is later proven to be very helpful in optical addressing a single QD. Fig. 2.4 shows the dot density variation on a 2-inch [001]-oriented GaAs wafer arising from the gradient of $\sim 10^\circ$ temperature and partially different amount of deposited materials across the wafer. The dot density tends to decrease from the central to the edge, and especially in some areas the dot density can be well-controlled so that the spatial distance between each of them exceeds 1 $\mu$m. Such control on dot density facilitates the later micro-photoluminescence (µ-PL) measurements, from which one can address a single QD optically through a powerful microscope objective [66].
2.1.3 Multiexciton photon emission

Benefiting from the three-dimensional quantum confinement, the epitaxially-grown QDs have atom-like electronic energy states. Photonexcited electrons and holes confined in the QD can occupy different charge configurations, which lead to rich multiexcitonic emission spectra. Fig. 2.5a shows a diagram of the electronic energy states in a single In(Ga)As QD in GaAs matrix. Since the bulk GaAs and the wetting layer are 3D bulk material and 2D QW respectively, their electronic states are in the form of continuum states. In the dot, as a result of the quantum confinement, the electronic states in CB and VB are discrete. Given the light effective mass for electron, its energy states in the CB are well separated and denoted by \( \{e_0,e_1,\ldots,e_n\} \). The number of confined holes in the VB have large effective mass and thus the confined hole states in the VB are denser. They can be expressed by \( \{h_0,h_1,\ldots,h_n\} \). Note \( e_0 \) and \( h_0 \) are confined electron ground-state and confined hole ground-state respectively [67].

Figure 2.5: (a) Schematic illustration of electron (black circle) and hole (empty circle) relaxation in self-assembled In(Ga)As/GaAs QD. (b) Example of PL spectrum of a QD showing the emission of different excitonic states, neutral exciton (X), biexciton (XX) and charged exciton (X\(^{-}\)), from a single In(Ga)As QD.

Because of the relatively large energy separation between levels in the CB (40 ~ 60 meV), the excitonic emission involving an electron in a specific level give rise to “shells” consisting of different lines. Each line corresponds to a specific charge configuration in the QD, as illustrated for the S-shell emission of a QD in Fig. 2.5b.

Relaxations of the photo-excited electrons and holes follow a complicated dynamics. After non-resonant optical excitation, an electron and a hole will be firstly created in the GaAs barrier, and then they will relax to their ground-states respectively through a series of fast decay processes. These processes consist of barrier-to-wetting layer (WL), WL-to-QD and intrashell relaxation within the QD. Noticeably, the hole relaxation in the QD, from its lowest-energy confined hole state \( h_n \) to highest-energy confined hole state \( h_0 \), occurs within sub-picosecond times. Finally, a confined exciton, consisting of an electron and hole, is formed. Recombination of the neutral exciton gives a sharp exciton emission as shown in Fig. 2.5b. According to Pauli exclusion principle as well as angular momentum conservation, the electron and hole constructing the optically active
neutral exciton has spin number of $S_{e,z} = 1/2$ and $J_{h,z} = -3/2$ or $S_{e,z} = -1/2$ and $J_{h,z} = 3/2$. The total spin number of exciton is 1 so that it induces an unavoidable spin-exchange interaction, which results in a doublet energy structure of exciton photon emission. The exciton spin-exchange interaction will be discussed in more detail later. Further, increasing pump power will create more confined electrons and holes in the QD so as to form sophisticated charge configurations, e.g., two confined electrons and one hole form a negative charge exciton ($X^-$), while two confined elections and two holes form a biexciton (XX). In contrast to the neutral exciton X, the total spin number of XX is zero, so that there is no spin-exchange interaction expected for biexciton.

2.2 Band structure of strained semiconductor

The electronic band structures of semiconductor, e.g., GaAs in my studies, play an important role in understanding the optical properties of semiconductor, such as photon absorption and emission. Especially for optical devices, most semiconductors have direct band gaps, and many physical properties near the band edge are of great interest. In this section, the general properties of the band-structure of strained semiconductors are discussed, which provides an essential theoretical background for comprehensively understanding the most optical phenomenon in the optically strain-tunable QD devices.

2.2.1 Introduction to $k \cdot p$ perturbation method

The optical properties of a semiconductor can be explained by employing the $k \cdot p$ perturbation method [68]. For an electron in a periodic potential $V(r)$

$$V(r) = V(r + \mathbf{R}), \quad (2.2)$$

the electron wavefunction can be obtained from the Schrödinger equation

$$H_0 \Psi(r) = \left(-\frac{\hbar^2}{2m_0} \nabla^2 + V(r)\right) \Psi(r) = E \Psi(r). \quad (2.3)$$

where $\mathbf{R} = n_1 \mathbf{a}_1 + n_2 \mathbf{a}_2 + n_3 \mathbf{a}_3$, and $\mathbf{a}_1$, $\mathbf{a}_2$ and $\mathbf{a}_3$ are lattice vector and $n_1$, $n_2$ and $n_3$ are integer numbers. According to the Bloch theorem, the general solution of Eq. 2.3 $\Psi_{nk}(r)$:

$$\Psi_{nk}(r) = e^{ikr}u_{nk}(r), \quad (2.4)$$

where $u_{nk}(r)$ is a periodic function $u_{nk}(r) = u_{nk}(r + \mathbf{R})$. Substitute the above function to Eq. 2.3 and write the Schrödinger equation in terms of $\Psi_{nk}(r)$,

$$\left[\frac{p^2}{2m_0} + \frac{\hbar}{m_0} \mathbf{k} \cdot \mathbf{p} + V(r)\right] \Psi_{nk}(r) = E \Psi_{nk}(r). \quad (2.5)$$

Supposing $k \approx 0$, then the term $\hbar/m_0 k \cdot p$ in Eq. 2.5 can be safely treated as a perturbation. By means of general quantum mechanical perturbation theory, one can find the energy
bands, as well as the wavefunction.

The above k·p model excludes the impact from spin-orbit interaction. In some cases, this effect plays a minor role in the optical properties of semiconductors. In this respect, it is desirable to improve this k·p model so that the spin-orbit interaction is also taken into account. The spin-orbit coupling Hamiltonian has a form

\[ H_{so} = \frac{\hbar}{4m_0c^2} \sigma \times \nabla V(r). \]  

(2.6)

Thus, the entire perturbation Hamiltonian in k·p method can be written as

\[ H = H_0 + H' = H_0 + p + \frac{\hbar}{4m_0c^2} \sigma \times \nabla V(r) \]  

(2.7)

As shown in Fig. 2.5a, the behavior of confined electrons and holes are mainly determined by two valence bands and one conduction band, while the impact from other bands which are energetically well separated from the above electron and hole ground states can be safely neglected. In an ideal semiconductor GaAs, the conduction band can be expressed by \(|S_e = 1/2\rangle\) and the projections on z-axis \(|S_{e,z} = \pm 1/2\rangle\). As for the two valence bands, they contain two energetically degenerate heavy-hole (HH) bands and light-hole (LH) bands with a total angular momentum \(J_h = 3/2\). The definition of HH and LH bands stem from the difference in their effective masses: \(m_{LH}^* = 0.082m_0\) for HH bands and \(m_{HH}^* = 0.51m_0\) for LH bands. The projection of the total angular momentum for LH on z-axis is \(|j_{h,z} = \pm 1/2\rangle\), and for HH \(|j_{h,z} = \pm 3/2\rangle\). The third valence band, caused by spin orbit interaction, plays a minor role in the analysis. This valence band is usually hundreds of meV lower than the HH and LH bands and its total angular momentum \(J_h = 1/2\).

By using the wavefunctions of these six valence bands as basis functions and employing
Eq. 2.7, one can write the whole Hamiltonian in matrix representation:

\[
H = \begin{bmatrix}
  P + Q & -S & R & 0 & -S/\sqrt{2} & \sqrt{2} \\
  -S^+ & P - Q & 0 & R & -\sqrt{2}Q & \sqrt{3/2}S \\
  R^+ & 0 & p - Q & S & \sqrt{3/2}S^+ & \sqrt{2}Q \\
  0 & R^+ & S^+ & P + Q & -\sqrt{2}R^+ & -S^+/\sqrt{2} \\
  -S^+/\sqrt{2} & -\sqrt{3/2}Q^+ & \sqrt{3/2}S & -\sqrt{2}R & P + \delta & 0 \\
  \sqrt{2}R^+ & \sqrt{3/2}S^+ & \sqrt{2}Q^+ & -S/\sqrt{2} & 0 & P + Q
\end{bmatrix}
\begin{bmatrix}
  |3/2, 3/2\rangle \\
  |3/2, 1/2\rangle \\
  |3/2, -1/2\rangle \\
  |3/2, -3/2\rangle' \\
  |1/2, 1/2\rangle \\
  |1/2, -1/2\rangle
\end{bmatrix}
\]  

(2.8)

where \( P, Q, R \) and \( S \) are given by:

\[
P = \frac{\hbar^2 \gamma_1}{2m_0} (k_x^2 + k_y^2 + k_z^2)
\]

\[
Q = \frac{\hbar^2 \gamma_2}{2m_0} (k_x^2 + k_y^2 - 2k_z^2)
\]

\[
R = \frac{\hbar^2 \gamma_3}{2m_0} [-\sqrt{3}\gamma_2 (k_x^2 - k_y^2) + i 2 \sqrt{3} \gamma_3 k_x k_y]
\]

\[
S = \frac{\hbar^2 \gamma_3}{2m_0} \sqrt{3} (k_x - ik_y) k_z
\]

(2.9)

In Eq. 2.8, the superscript “+” is Hermitian conjugate, while \( \gamma_{1,2,3} \) are the Luttinger parameters, which describe the valence band curvatures. In the absence of strain and magnetic filed, Luttinger-Kohn Hamiltonian can be used effectively to calculate the band structure of semiconductors.

### 2.2.2 \( \mathbf{k} \cdot \mathbf{p} \) perturbation theory for strained semiconductors

Once the semiconductor is subjected to a uniform deformation due to an internal or external stress, its band structures of semiconductor will be subsequently modified. This is a case in my studies for most QD samples, which are grown via strain engineering. In this section, a theoretic background on the strained semiconductor is introduced.

A Hamiltonian incorporating the effects of strain was successfully developed by Pikus and Bir in the 1960s [69, 70]. Under certain strain fields, the lattice of the semiconductor changes but the periodicity remains as shown in Fig. 2.7. In order to incorporate the strain effect in the Hamiltonian, the volume change in presence of the strain field is considered firstly. The unit vector \( \mathbf{r}' \) of the deformed crystal lattice can be correlated to the unit vector \( \mathbf{r} \) in the following way:

\[
x' = (1 + \varepsilon_{xx})x + \varepsilon_{xy}y + \varepsilon_{xz}z
\]

\[
y' = \varepsilon_{yx}x + (1 + \varepsilon_{yy})y + \varepsilon_{yz}z
\]

\[
z' = \varepsilon_{zx}x + \varepsilon_{zy}y + (1 + \varepsilon_{zz})z,
\]

(2.10)

where \( \varepsilon_{ij} \) is strain tensor. With these equations, the volume change before and after the
deformation of the lattice can be obtained by

\[
\frac{\delta V}{V} = \frac{(V' - V)}{V} = 1 + \mathbf{x}' \cdot \mathbf{y}' \times \mathbf{z}' - \mathbf{x} \cdot \mathbf{y} \times \mathbf{z} = 1 + \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}. \tag{2.11}
\]

By using the Bloch theorem \( \Psi_{nk}(\mathbf{r}') = e^{ik\mathbf{r}} u_{nk}(\mathbf{r}') \), the Schrödinger equation is rewritten as

\[
[H_0 + V_n(\mathbf{r})] \Psi_{nk}(\mathbf{r}) = e^{ik\mathbf{r}} u_{nk}(\mathbf{r}) = E_n(k \approx 0) \Psi_{nk}(\mathbf{r}) = e^{ik\mathbf{r}} u_{nk}(\mathbf{r}). \tag{2.12}
\]

When the above mentioned 6 valence bands are used as basis functions, one could derive the strain-included Hamiltonian in the matrix form

\[
H = H_{LK} + H_\varepsilon = \begin{bmatrix}
P + Q & -S & R & 0 & -S/\sqrt{2} & \sqrt{2} \\
-S^+ & P - Q & 0 & R & -\sqrt{2}Q & \sqrt{3/2}S \\
R^+ & 0 & p - Q & S & \sqrt{3/2}S^+ & \sqrt{2}Q \\
0 & R^+ & S^+ & P + Q & -\sqrt{2}R^+ & -S^+ / \sqrt{2} \\
-S^+/\sqrt{2} & -\sqrt{2}Q^+ & \sqrt{3/2}S & -\sqrt{2}R & P + \delta & 0 \\
\sqrt{2}R^+ & \sqrt{3/2}S^+ & \sqrt{2}Q^+ & -S/\sqrt{2} & 0 & P + Q
\end{bmatrix} \tag{2.13}
\]

where

\[
\begin{align*}
P &= P_k + P_\varepsilon \\
R &= R_k + R_\varepsilon \\
Q &= Q_k + Q_\varepsilon \\
S &= S_k + S_\varepsilon \\
P_\varepsilon &= -a_\varepsilon (\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}) \\
Q_\varepsilon &= -b_\varepsilon (\varepsilon_{xx} + \varepsilon_{yy} - 2\varepsilon_{zz}) \\
R_\varepsilon &= \sqrt{2}b(\varepsilon_{xx} - \varepsilon_{yy}) - id\varepsilon_{xy} \\
S_\varepsilon &= -d(\varepsilon_{xx} - i\varepsilon_{yz})
\end{align*} \tag{2.14}
\]

in which \( a_\varepsilon, b \) and \( d \) are deformation potentials of the semiconductor. The above Hamiltonian is also called Pikus-Bir Hamiltonian.

### 2.3 Strain-tunable QD devices

The samples, studied in this thesis, include two types of strain-tunable QDs devices: i) strain-tunable quantum-LED incorporating In(Ga)As QDs, which is used to develop
a versatile electrically-triggered single-/entangled-light-emitting diode; ii) strain-tunable GaAs QDs devices with a purpose to demonstrate an optically-triggered LH single-photon emission. Detailed descriptions, including the sample growth and processing of these strain-tunable QD devices, are given in this section.

### 2.3.1 Strain-tunable quantum LED

The strain-tunable QDs-containing LED is grown with a solid-source MBE. It contains a single layer of low density In(Ga)As QDs embedded within a p-i-n junction. Fig. 2.8a shows an as-growth structure. The whole sample was grown on a 2-inch semi-insulating [001]-oriented GaAs substrate. The dots were buried in the middle of a 150 nm-thick undoped GaAs layer, which was sandwiched between a 96 nm-thick p-type GaAs layer and a 178 nm-thick n-GaAs layer. The p-type GaAs contact layer was formed by doping Carbon with a density of $5 \times 10^{18} \text{cm}^{-3}$, and the n-type GaAs contact layer was formed by doping Silicon with a density of $5 \times 10^{18} \text{cm}^{-3}$. In particular, a heavily delta n-doped GaAs layer was made on the bottom of the normally n-doped GaAs layer, which was designed specifically for the bonding with an aluminum wire in order to form n-GaAs ohmic contact in subsequent device processing. The entire n-i-p LED structure was laid on a 100 nm-thick Al$_{0.75}$Ga$_{0.25}$As sacrificial layer.

Based on the doping density in p- and n-type GaAs, by solving the 1D Poisson-Boltzmann equation via finite differences, one is able to estimate the band diagram of such QDs-containing p-i-n junction as shown in Fig. 2.8b. The potential difference between n-GaAs and p-GaAs region defines the diode built-in potential, and it is found to be

$$V_b = \frac{E_n - E_p}{e} = \frac{1.46 \text{ eV} - (-0.06 \text{ eV})}{e} = 1.52 \text{ V}.$$  

(2.15)

In addition, the presence of a δ-like band for QD verifies the successful integration of QDs layer into such p-i-n junction.

In order to process the strain-tunable quantum-LED, the following standard photolithography and chemical wetting etching technique were used. First of all, photolithography was used to define 120 × 160 µm$^2$ mesa structures with AZ5214 negative photo-resist as shown in Fig. 2.9a. Secondly a 3 nm-thick Chromium and 100 nm-thick gold were deposited, and followed by a lift-off process. Then using this gold as etching masks, the sample was etched in a mixture solution of H$_2$SO$_4$ : H$_2$O$_2$ : H$_2$O with a well-calibrated volume ratio of 1:8:200 for 6 min. Finally, to detach the QDs-containing quantum-LED nanomembrane, diluted HF (~25%) was used to etch away the 100 nm-thick Al$_{0.75}$Ga$_{0.25}$As sacrificial layer. After these processing, the nanomembranes are now free-standing and transferable. Strain-tuning of the optical properties of QDs is achieved by transferring the nanomembrane onto a piezoelectric crystal. Here the piezoelectric crystal, gold-coated PMN-PT is used as it can provide external strain field up to 0.4% when applying a moderate electric field [71]. Compared to nowadays more commercialized piezoelectric product PZT, the PMN-PT used in this thesis displays larger piezoelectric constants, enabling larger strain fields for the same applied electric field. [50, 51, 53, 62, 72, 73].

Gold-gold thermo-compression bonding technique was used to transfer the nanomembranes onto the flat surface of the PMN-PT crystal. In order to strengthen the bonding
2.3 Strain-tunable QD devices

<table>
<thead>
<tr>
<th>Layer Description</th>
<th>Electrical Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 mm [001]-oriented GaAs substrate</td>
<td></td>
</tr>
<tr>
<td>200 nm GaAs buffer layer</td>
<td></td>
</tr>
<tr>
<td>100 nm AlGaAs buffer layer</td>
<td></td>
</tr>
<tr>
<td>0.75 0.25 180 nm GaAs layer ($n = 5 \times 10^{18}$)</td>
<td></td>
</tr>
<tr>
<td>150 nm GaAs layer</td>
<td></td>
</tr>
<tr>
<td>180 nm GaAs layer ($n = 5 \times 10^{18}$)</td>
<td></td>
</tr>
<tr>
<td>100 nm Al$<em>{0.75}$Ga$</em>{0.25}$As buffer layer</td>
<td></td>
</tr>
<tr>
<td>200 nm GaAs buffer layer</td>
<td></td>
</tr>
<tr>
<td>0.5 mm [001]-oriented GaAs substrate</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2.8: (a) As-grown quantum-LED structure, in which low density In(Ga)As QDs layer is sandwiched inside a $p$-$i$-$n$ diode. (b) Band diagram of the $p$-$i$-$n$ junction ($T = 300$ K), together with In(Ga)As QDs Layer.

between nanomembrane and the piezoelectric crystal, a suitable force and temperature were applied during the transfer process. The bonded gold layer on the bottom formed the $p$-contact, while the $n$-contact was made by bonding a 25 µm-thick aluminum wire via a wedge bonder on the top of the nanomembrane [62, 66, 74].

Figure 2.9: (a)∼(d) Standard photo-lithography and chemical etching are used to detach In(Ga)As QDs-containing nanomembrane from intentionally grown 100 nm-thick Al$_{0.75}$Ga$_{0.25}$As sacrificial layer. (e) Sketch of the strain-tunable quantum-LED obtained by transferring the detached In(Ga)As QDs-containing diode nanomembrane onto a piezoelectric crystal, PMN-PT(28%).

Fig. 2.10 plots microscopic images of the real strain-tunable quantum-LED devices. Direct bonding is made and connected to the outside electronics in order to pump the QDs in diode either using DC current or ultra fast current pulses. Current vs. voltage characteristic (I-V) of one of the diodes was measured at room temperature (see Fig. 2.10b), a negative (positive) voltage $V_d(<0)$ corresponding to a forward (reverse) bias is applied to the diode. It is clearly seen that the current has a jump at about $V_d = -0.8 \sim -1.0$ V, which reflects an open voltage for the diode. In addition, there was no measurable leakage.
current as the reverse bias was applied up to 1.0 V, which clarifies an unambiguous $p$-$i$-$n$ diode behavior.

### 2.3.2 GaAs QDs with LH ground states

In order to enable switching LH bands over HH bands in three-dimensionally III-V group self-assembled QDs, sufficient biaxial tensile strain filed must be applied. When no strain is applied to the material, HH and LH bands are energetic degenerate as shown in Fig. 2.11. By applying a biaxial strain field, energy bands of the III-V group semiconductors will be dramatically changed: tensile (compressive) strain induces shrinkage (expansion) of the band-gap, and in the meanwhile enables the LH (HH) bands become the topmost hole states [75, 76].

![Figure 2.11: Schematic illustration of electron energy band under biaxial compressive and tensile strain for III-V group semiconductor materials.](image)

Regardless of this simple routine for obtaining LH ground states in self-assembled QDs, so far it has rarely been studied and experimentally demonstrated. This is because most of the self-assembled QDs are under compressive strain. For example, for InAs QDs grown on GaAs substrate via the S-K mode the lattice constant of InAs ($a_{InAs} = 0.606$ nm) is much larger than that of GaAs ($a_{GaAs} = 0.565$ nm). Hence, a large compressive strain...
rather than tensile stain will be accumulated in the course of QDs formation. Therefore, in InAs/GaAs QD system, the compression is too large to be overcome by either using in-situ or post-growth tuning technologies. In this context, it is extremely difficult to use InAs/GaAs QD system for realizing exciton with LH ground states.

In this context, GaAs QDs within AlGaAs or AlAs matrix appears instead very promising. They have almost same lattice constants, hence such QD systems are generally strain-free and it could be used to realize LH ground states. The first result of three-dimensionally confined QDs heterostructure with LH ground state was reported by V. Troncale et al. [58] By tailoring the confinement potential shape of pyramidal GaAs/AlGaAs quantum dot-in-dot heterostructure, they can enable a change of the ground confined hole state from HH like to LH like. In their studies, LH photon emission was verified by side-view polarization resolved PL measurements. Though, the studied QDs system shows broad LH emission spectra (>2 meV) due to charged impurities. This hampers their practical applications in the field of quantum information technologies. Very recently, a breakthrough has been made by Y. Huo et al. in our group [59], who demonstrated a sharp and bright LH-exciton emission from GaAs/AlGaAs QDs with valence-band ground state of dominant LH character. Based on this new type QD system, it is possible to demonstrate wavelength-tunable and triggered LH single-photon emission.

### Experimental realization of QDs with LH ground states

By applying an elastic tensile stress to an initially unstrained GaAs QD grown via droplet etching technique, the ground state in the valence band becomes of LH character [59], which ensures the demonstration of the LH single-photon emission to be revealed in this thesis.

The basic idea to reach this goal is to embed a GaAs QDs heterostructure into two prestressed InAlGaAs layers [59]. Figure 1a shows the as-grown sample structure fabricated by MBE. It includes a 140-nm-thick QD-containing nanomembrane on top of a 100-nm-thick Al$_{0.75}$Ga$_{0.25}$As sacrificial layer. In situ Ga droplet etching was used to create GaAs QDs within Al$_x$Ga$_{1-x}$As barriers (dot density $\langle 10^8 \text{ cm}^{-2} \rangle$). In particular, the sample structure was designed in such a way that the GaAs/Al$_x$Ga$_{1-x}$As QD layer is sandwiched between a pair of 20-nm-thick In$_{0.2}$Al$_{0.4}$Ga$_{0.4}$As stressor layers. In order to grow such heterostructure, the following growth protocol is employed: first remove surface oxide of the [001]-oriented 2-inch GaAs wafer, followed by growing a 200 nm-thick GaAs buffer layer at 600°C, and by the deposition of a 100 nm-thick Al$_{0.75}$Ga$_{0.25}$As sacrificial layer. Afterwards, the growth temperature was decreased to 430°C and 20 nm-thick In$_{0.2}$Al$_{0.4}$Ga$_{0.4}$As, serving as a bottom stressor layer, was grown at equivalent rates of 0.4(Ga), 0.2(In) and 0.4 (Al) ML/s. Then 2 nm Al$_{0.44}$Ga$_{0.56}$As were grown to cap the stressor layer. Later the temperature was raised to 515 °C and a 35 nm-thick GaAs layer was grown. In order to etch nanoholes on the GaAs surface, droplets composed of 11.4 ML excess Ga were deposited at an equivalent growth rate of 0.15 ML/s with Ga supplied continuously and the As shutter being opened (3.5s) and closed (0.5s) periodically for 19 rounds. Then the surface was annealed under As flux for 5 min which enabled the etching of the Ga droplets on the surface so that holes in nanometer scale were fabricated. After the holes formed, 7 nm Al$_{0.44}$Ga$_{0.56}$As acting as a bottom barrier for the QDs were grown over the nanohole templates, followed by 2.15 nm GaAs and 2 min growth interruption to allow the diffusion.
of GaAs into the nanoholes to form GaAs QDs. The QDs were then capped with 25 nm Al_{0.37}Ga_{0.63}As. Following this, 10 nm-thick graded Al_xGa_{(1-x)}As (x = 0.37 ∼ 0.44) was grown to enhance the collection of excited carriers into the QD region. Subsequently, a 10 nm-thick GaAs layer was grown to recover a smooth surface. Again, the temperature was decreased to 430 °C for the growth of a 20 nm-thick top In_{0.2}Al_{0.4}Ga_{0.4}As stress-layer. Noticeably, the QDs were intentionally grown to have an asymmetric shape so that the optical axis of the QDs is tilted away from the [001] crystal axis by about 6°. Therefore, all three orthogonal bright excitonic emission lines are accessible with an objective placed normal to the sample surface (//z). This will be extensively discussed in later morphology and optical light extraction efficiency analysis. Alternatively, replacing the bottom GaAs layer beneath AlGaAs bottom barrier with Al_{0.4}Ga_{0.6}As, it is also possible to grow symmetric shaped ally QDs.

**Structural and morphology analysis**

In order to closely look at the shape or morphology of the grown QDs, atomic force microscopic (AFM) measurements were carried out on both symmetric and asymmetric QDs as show in Fig. 2.13. Thanks to the limited intermixing between GaAs and AlGaAs, the QDs have nearly the same shape as the nanoholes they filled. The shape of the QDs can be determined by measuring AFM images of the nanoholes etched with the same growth parameters as those in the aforementioned sample. Fig. 2.13a shows representative AFM images for nanoholes directly created on AlGaAs layer, while Fig. 2.13c represents AFM images of nanoholes on GaAs substrate. The shape of AlGaAs nanoholes are almost
2.3 Strain-tunable QD devices

Figure 2.13: (a) and (c) Representative AFM images of symmetric and asymmetric AlGaAs nanoholes in which GaAs QDs were formed. (b) and (d) Linescans of the AFM images along [110] and [1-10] crystal directions. Figure courtesy of Y.H. Huo.

The symmetric, while GaAs nanoholes have large shape anisotropy. More information for the as-grown sample is obtained in the line scans of the AFM images as shown in Fig. 2.13b and d. It is clearly seen that both types of nanoholes have a height of about 15 nm and lateral size of about 70 nm.

Figure 2.14: (a) Representative AFM image of the nanoholes etched on GaAs surface and overgrown with AlGaAs. Note that the elongated mounds along [1-10] crystal direction in the image are due to buried QDs which can be used for optical characterization. (b) to (e) Line scans of 4 QDs along the [110] crystal direction marked in the AFM image. The linear fits to the left and right edge enable the quantification of the orientation of the nanoholes (QD) axes relative to the growth direction, z, which is denoted as $\theta$.

Further characterization of the asymmetric QDs is provided in Fig. 2.14 and it shows many nanoholes in a $5 \times 5 \mu m^2$ area. Line scans along the [110] direction (elongation direction) was used to quantify the orientation of QDs. 4 dots are randomly selected
from the AFM image to evaluate the tilt of QDs axes away from the $z$ direction. From Fig. 2.14b to e, the tilt angle ($\theta$) between the orientation of QDs and growth direction ($z$) are found to be $5^\circ$, $5.8^\circ$, $6.1^\circ$ and $5.4^\circ$ respectively, which indicate that the axes of QDs used in my work deviate from their crystal directions [77].

2.4 Overview of micro-PL/EL setup

The experimental setup used for optical measurements is sketched in Fig. 2.15. It provides a versatile platform to perform a variety of optical experiments:

- **Optical and electrical excitation**
  The setup includes a number of optical and electrical pumping sources, including Ti:Sapphire femtosecond mode-lock laser, a $Nd:YVO_4$ continuous-wave (CW) laser and ultra-fast electrical pulse generator. For optical excitation, the Ti:Sapphire mode-locked laser can deliver extremely short optical pulses with 120-fs-long pulse duration, repetition rate of 76 MHz and tunable wavelength ranging from 720 $\sim$ 980 nm. This can be used to perform time-resolved PL measurements, i.e., for determining lifetime. Alternatively, the $Nd:YVO_4$ CW laser can provide steady and wavelength-fixed (532 nm) pumping source. These two lasers meet most of the needs in my work in optical measurements. Especially, an ultrafast pulse generator was employed to excite the QDs embedded inside diode via a homemade high-frequency feed-through. Regarding the details of electrically-pulse driven QDs, an explicit description will be given in the next chapter.

- **Polarization-resolved PL measurements**
  Secondly, by inserting a combination of a half-wave plate and a polarizer (H1 and P1 respectively in Fig. 2.15) in the optical path, one is able to perform polarization resolved measurements. This can be effectively used to resolve the fine structure splitting (FSS) of photon emission from neutral excitons of QDs.

- **Michelson interferometer: $g^{(1)}(\tau)$ measurement**
  The first-order time correlation function of photon emission from QDs can be measured. By controlling the flip mirror (FM1), the PL/EL can be sent to the Michelson interferometer, which consists of a 50:50 beam splitter (BS3) and two retro-reflectors (R1 and R2). The interference signal is then directed to the spectrometer (S1), so that the first-order time correlation known as $g^{(1)}(\tau)$ function can be measured. This can be effectively used to measure the coherence time of PL/EL.

- **Co-and cross-polarization correlation measurements**
  Most importantly, the system is specifically designed for measuring co-and cross-polarization time correlation. The PL/EL is guided to the 50:50 beam splitter (BS1), and then it will be split into two paths. Each of them is sent to a high-resolution spectrometer with 750 mm long focus-length in order to pick up the wavelength of interest. After each spectrometer, there is Hanbury-Brown Twiss (HBT) setup which is composed of a polarization beam splitter and two high efficiency avalanche single-photon detecting diode (APD). The correlation is accomplished by sending the electronic signal from APDs to a time correlation modulator.
Figure 2.15: Schematic of the versatile micro-PL/EL experimental setup.
3 Wavelength-tunable and triggered quantum LED

An all electrically operated quantum LED device is demonstrated in this chapter. The device can be excited with sub-nanosecond electrical pulses to achieve fast electrically-triggered single-photon emission. By processing the quantum LED in the form of nanomembrane and integrating it onto a piezoelectric crystal, a broad wavelength tuning to the single-photon emission is realized. In this chapter, a technique of injecting the sub-nanosecond electrical pulses will be introduced first. Then, a series of experiments, including control of the time uncertainty of single-photon emission event and time varying quantum stark shift, are carried out under electrically pulsed excitation. Aside from these, a strain-tunable quantum LED which allows for both electrically pulsed excitation and wavelength tuning is successfully prepared, and accordingly wavelength-tunable and triggered single-photon emission from such device is achieved. In addition, the device demonstrated here is also able to emit single photons at an ultra fast speed when it operated under the lifetime reduced mode.

3.1 Electrically pulsed injection to a quantum LED

3.1.1 High frequency feed-through setup

Electrically pulsed excitation to a single QD inside a quantum LED can be accomplished by injecting charge carriers within the recombination time of the exciton (typically, \( \sim 1 \) ns) \([4, 78]\). In order to achieve this goal, sub-nanosecond electrical pulses and related apparatus are needed.

A new home-made high frequency feed-through is designed and fabricated to meet the above requirements. As shown in Fig. 3.1, this home-made high frequency feed-through is composed of two SMA connectors, an elongated tube and a movable top flange. This simple home-made feed-through holds many features. Firstly, the two SMA connectors are specially designed for the purpose of high frequency microwave signal. It can be reliably used for transferring the microwave signal with a broad bandwidth from DC to 18 GHz. Secondly, they are sealed tightly inside with ceramic materials and are compatible with a high vacuum environment. As for the elongated tube, it is particularly designed to eliminate the temperature gradient from the outside room temperature environment to the inner cryogenic environment, so that the heating effects can be effectively avoided.
It is noticeable that in this setup, a semi-rigid coaxial cable with extremely low thermal conductivity is used, which further reduces the thermal effect arising from the electronic connections.

![Figure 3.1](image_url)

**Figure 3.1**: High frequency electrical feed-through. It consists of (a) two high frequency connectors, an elongated tube and a movable top flange. (b) Zoomed SMA connectors which can support electrical pulses feed-through from DC to 18 GHz.

The reliability of such home-made high frequency feed-through is tested in the following procedure. An ultrafast pulse generator is connected to the input of the feed-through, and its output is terminated with a broadband oscilloscope (see Fig. 3.2). In the measurement, to satisfy the impedance matching condition, all the electronics are set to 50 Ω impedance. The input pulse from the pulse generator is kept at 50 mV while its pulse duration is varied from 1 ns to 300 ps. The output pulses at the end of the feed-through are measured by the oscilloscope and the results are shown in Fig. 3.2c. Compared with the input pulses, the following changes for the output pulses are observed: for the slow input pulse with 1 ns duration time, there is no observable pulse width broadening but a reduced amplitude of 35 mV, whereas, for fast input pulses, i.e., 500 ps and 300 ps, also a broadening in the peak width is observed.

These observations can be ascribed to the limited bandwidth of the setup and the imperfect electronic connections. The former induces not only the reduction of the pulse amplitude, but also the broadening of the peak width. While the later has strong impact on the feed through as it causes a parasite resistance to the whole electronics and results in reflections to the signal. Subsequently, the amplitude of the input pulses is induced.

### 3.1.2 Injection of ultrafast electrical pulses to the QD LED

By replacing the oscilloscope in Fig. 3.2a with a quantum LED, it is possible to perform electrically pulsed excitation of the QDs. Note that the impedance of the diode $R$ changes as the applied voltage $V_d$ is varied, and it can be determined by $R = \delta V_d/\delta I_d$. 
where $I_d$ is the flowing current. In order to enhance the injection efficiency, an impedance matching network is therefore required between the diode and the external electronics.

A capacitor $C_m = 1nF$ and a resistor $R_m = 50 \Omega$ are chosen to comprise such impedance matching network [79, 80], which is placed in parallel with the diode as shown in Fig. 3.3a. Moreover, in order to maximize the pulse injection efficiency, a DC voltage $V_d$ is superposed to the pulse stream with an amplitude of $V_{pp}$ (see Fig. 3.3b). Upon application of the bias to the $p$-i-$n$ junction, the DC voltage is going to drop across the depletion region and as a result the impedance of the diode can be subsequently changed. As a negative $V_{dc}$ is applied, the impedance of the diode is changed. As a consequence, the injection efficiency of the electrical pulses can be substantially optimized.

![Figure 3.2](image)

**Figure 3.2:** (a) Schematic illustration of the experiment setup, in which fast electronics including a broadband oscilloscope and a ultrafast pulse generator are connected. (b) Sketch of the input pulses from the pulse generator. It has a fixed amplitude at 50 mV, and its pulse duration is varied from 1 ns to 300 ps. (c) The output pulses was measured by the oscilloscope at the end of the high frequency feed-through.

Experimentally, the electrical pulse stream and the DC bias are superposed by a broad bandwidth bias Tee. Then the entire signal is sent to the diode via the above homemade feed-through, and the QDs embedded within the diode are expected to be excited. Fig. 3.3c shows the typical spectra of the EL from a single QD under electrically pulsed excitation. The electrical pulses have nominal peak width of 300 ps, -0.7 V amplitude and ERR of 80 MHz. The multie exciton emission, including neutral exciton $X$, biexciton $XX$ and charge exciton $X^*$ in these spectra, are identified by employing the polarization-resolved measurement. It is worth noticing that all the spectra are recorded with the DC bias below the EL threshold voltage (about -1.8 V) of the diode. As $V_d$ is increased and $V_{pp}$ is kept constant, the excitation of neutral exciton $X$ become stronger. This is partially ascribed to the reduced impedance mismatch between the device and the 50 $\Omega$ pulse generator as $V_d$ is close to the threshold voltage. Generally, this excitation regime below the threshold voltage of the diode is called weak pulsed excitation in that it can induce an additional decay channel to the exciton recombination and thus increase the
spontaneous rate \[\text{[81, 82]}\]. The details of the weak excitation regime will be discussed in the next section.

Figure 3.3: (a) Sketch of the strain-tunable quantum LED structure under electrically pulsed excitation. A RC circuit made of a 1 nF capacitor and a 50 Ω resistor is intentionally connected to the diode in parallel. The arrow shows the region where the EL is extracted. (b) Electrically pulsed excitation scheme, in which a DC bias \(V_{dc}\) and the ultrafast electrical pulses are superposed. (c) Typical spectra of a single QD emission from the LED under electrical pulsed excitation. The input pulses have nominal 300 ps width and amplitude of -0.7 V. (d) Time-resolved PL measurements at different pulse duration.

Kessler et al. found out that, for electrically pulsed excitation of QDs in an LED structure, in the case of the weak excitation regime, the exciton emission increases during the excitation electric pulse, and reaches its maximum directly after the pulse has ended, followed by a typical excitonic decay behavior \[\text{[83]}\]. With this argument, the electrical injection speed can be estimated experimentally. To ensure that the diode operated under the weak excitation regime, a fixed DC voltage bias of -1.7 V, electrical pulses with constant pulse amplitude of -0.7 V, but different pulse widths of 300 ps and 1000 ps, were applied to the diode. Then time-resolved EL measurements are performed and the results are plotted in Fig. 3.3d. It is found that for the 300 ps-long pulse, the rise time is \(\sim 700\) ps, which is different from the nominal time of 300 ps and this is probably due to the imperfect impedance matching. In contrast, for the 1000 ps pulse, the rise time is approximate 1000 ps. From such experiment, an injection time of about 700 ps provides an upper limit of the injection speed for the device. This can be further improved by optimizing the device design and the external electronic connections.
3.2 Electrical control of the optical properties of QDs

Electrically pulsed excitation to a single QD in the LED structure has significant impacts on the photon emission, which include lifetime reduction, line width broadening, etc. Such phenomena are discussed in this section.

3.2.1 Lifetime reduction and “slow-pumping” effect

The lifetime of the single-photon emission can be controlled by varying the DC bias in the electrically pulsed excitation regime [81, 82, 84]. Fig. 3.3b shows the electrical excitation scheme in which the ultrafast electric voltage pulses $V_{pp}$ are superposed with the DC bias $V_d$ via a high frequency bias tee. In the experiment, the DC bias is intentionally chosen below the EL threshold of about -1.8 V to enhance the band bending [81]. Representative EL spectra from an In(Ga)As QD under pulsed excitation are shown in Fig. 3.4a, and the emission lines are assigned to the neutral (X) and charged exciton (X*) according to the polarization-resolved EL measurements. The extra line at higher energy is probably from a nearby QD.

![Figure 3.4](image)

Figure 3.4: (a) EL Spectra from InAs QD excited by electric pulses with 80 MHz repetition rate, nominal 300-ps-long pulse width and a fixed $V_{pp}$ of -0.7 V. (b) Time-resolved EL of the neutral exciton X measured at different DC bias $V_d$. (C) Measured exciton decay time ($\tau_{meas}$) and estimated tunneling time ($\tau_{tunneling}$).

To investigate the DC voltage-dependent lifetime of the QD emission, time-resolved EL measurements were performed on the X line and the results are shown in Fig. 3.4b. The pulse amplitude $V_{pp}$ is fixed at -0.7 V while the DC bias $V_d$ is systematically varied. The lifetime of the X is reduced from 950 ps to 540 ps as $V_d$ is decreased from -1.8 V to -1.65 V. The change in lifetime is mainly ascribed to charges tunneling out of the QD [81, 82, 84]. This quantum tunneling effect introduces an additional fast, non-radiative decay channel to the bright X emission of the QD. This implies that a reduced time jitter of the single
Figure 3.5: Slow-pumping effect. In the strong excitation regime, the emission of the X line is close to the saturation or in saturation with constant pulse width of 300 ps, but at different $V_d$. Photon emission can be achieved at a lower DC bias (here, -1.65 V) due to the stronger band bending.

The tunneling time of carriers in the QD can be estimated from the relation $1/\tau_{\text{meas}} = 1/\tau_{\text{radiative}} + 1/\tau_{\text{tunneling}}$, where $\tau_{\text{meas}}$, $\tau_{\text{radiative}}$ and $\tau_{\text{tunneling}}$ are measured lifetime (see Fig. 3.4b), radiative lifetime and non-radiative tunneling time, respectively. The radiative lifetime is obtained from the QDs in undoped structures [82] and a mean radiative lifetime of about 1.3 ns is recorded. Therefore, the tunneling time is estimated according to the above relation. It is found that the tunneling time decreases from 3.52 ns to 0.92 ns when the DC bias in magnitude decreases from -1.8 V to -1.65 V [66] (see Fig. 3.4c).

In addition, it is worth noticing that the rise time increases when the DC bias increases in magnitude as shown in Fig. 3.4b and Fig. 3.5. This “slow-pumping” effect is mainly ascribed to the population of higher occupied excitonic states which occurs for the excitation powers close to the saturation or in saturation of the QD emission. In contrast to the weak pulsed excitation regime as demonstrated above, a strong pulsed excitation regime is enabled when $V_d$ from -1.75 V to -1.95 V is applied. As shown in the inset of Fig. 3.5, the photon emission of the X line is close to or even in the saturation at those biases. The rise time is found to be increased from 800 ps to 1 ns as the magnitude of the DC bias is increased, which confirms the above explanation.

### 3.2.2 Line width broadening

Apart from the reduced lifetime effect, fast electrical pulses can cause a broadening to the line width of the photon emission. A narrowing of the exciton (X) emission line in Fig. 3.4 is observed from $118 \pm 4 \mu eV$ to $83 \pm 5.6 \mu eV$ as DC voltage is varied from -1.65
3.2 Electrical control of the optical properties of QDs

to -1.80 V (see Fig. 3.6). The polarization-dependent measurements reveal that the line width broadening is ascribed to the combined effects of the fine structure splitting and the time-varying Stark effect.

Figure 3.6: (a) Line width change of the X emission line as the DC voltage is varied from -1.65 to -1.80 V (b) Redshift of the effective emission peaks of the fine-structure-split X emission line.

Figure 3.7: Polarization-dependent measurements of the X emission at different DC voltage: (a) -1.65 V, (b) -1.7 V, (c) -1.75 V and (d) -1.8 V under electrical pulsed excitation with 80 MHz ERR, 300 ps-long width and fixed pulse amplitude $V_{pp} = -0.7$ V

In order to investigate the line width broadening mechanism, a double-stage spectrometer with spectral resolution down to 10 $\mu$eV was used. Spectra of polarization-dependent measurements were performed and the results are shown in Fig. 3.7. A FSS of $\sim 65$ eV is clearly observed for the X emission line. In addition, at low excitation power, e. g., -1.65 V, each component has a low energy shoulder, which disappears for $V_d$ of -1.80 V, the shoulder disappears. The above results are ascribed to the time-varying stark [82, 85]: each linearly-polarized component of the FSS consists of two Lorentz-shape lines with the same polarizations, in which the high energy component corresponds to the photons emitted during the excitation pulse, while the low energy component corresponds to the
photons emitted between two neighboring pulses. When the excitation power is increased, excitation of the higher occupied excitonic states occurs during the pulse leading to the prohibition of the high energy component emission. This directly gives rise to a slight red-shift of the effective peak position when raising the DC bias as shown in Fig. 3.6b, which is consistent with the observations in Ref. [82].

### 3.3 Photon collection efficiency

In this section, another important property of the quantum-LED is presented, that is, the improved photon collection efficiency. Generally, the collection efficiency of the photon flux, emitted from InAs QDs in GaAs matrix to free space, is determined by the total internal reflection at the GaAs/air interface and the numerical aperture of the optics. It has been well-known that this collection efficiency is given by the following analytical formula:

\[
\eta = \left[1 - \left(\frac{n_{GaAs} - 1}{n_{GaAs} + 1}\right)^2\right] \times \left(\frac{1}{2} - \frac{3}{8} \cdot \cos\left(\sin^{-1}\left(\frac{NA}{n_{GaAs}}\right)\right) - \frac{1}{8} \cdot \cos^3\left(\sin^{-1}\left(\frac{NA}{n_{GaAs}}\right)\right)\right),
\]

(3.1)

where \(n_{GaAs}\) is the refractive index of GaAs. When the light emission is centered at 880 nm, it can be calculated that the collection efficiency by a microscopic objective with NA of 0.42 is 0.37%. For the quantum LED presented above, the photon collection efficiency is enhanced by employing a well-designed gold-semiconductor-air planar cavity. In this planar structure, the QDs layer was placed at \(\lambda_m\) from the top GaAs/air interface and the total thickness was 1.67\(\lambda_m\) (\(\lambda_m\) was the center cavity mode wavelength in GaAs matrix). All of these parameters were chosen to satisfy the standing wave condition as the QD layer was placed at the antinode of the electric field so that the photon extraction efficiency was optimized. The theoretical background of this planar cavity is presented in Ref. [86] and Ref. [62]. Here a theoretical simulation of this gold-semiconductor-air planar cavity is performed by using the free electromagnetic wave simulation package CAMFR (http://camfr.sourceforge.net/). The InAs quantum emitter is replaced with an electric dipole parallel with the surface. The wavelength in the simulation is set to 885 nm close to the emission of the X line. The collection efficiency is defined as the integrated power into the NA of the objective divided by integrated power at all angles.

Fig. 3.8 shows the simulation results of the photon collection efficiency as a function of NA. The overall collection efficiency of 5.3% is found when the NA of 0.42 is chosen, which gives \(\sim\)14-fold enhancement with respect to the semiconductor-air interface. Experimentally, the cavity mode of this planar cavity was characterized by performing an reflectivity measurements at 5K and 300K. The results are shown in Fig. 3.8, from which the cavity modes are clearly identified. The temperature-dependent cavity mode is due to the changes of the refractive index and the thickness of the GaAs at different temperature.

In order to experimentally estimate the photon collection efficiency into the optical setup, the method presented in Ref. [87] was used. First of all, the system detection efficiency was calibrated with a tunable Ti:Sapphire laser. The wavelength of the laser was set to the X line as shown in Fig. 3.4a. The laser was focused on the gold layer a
Figure 3.8: (a) Theoretical calculation of photon collection efficiency as a function of NA=sinθ (θ is the angle into NA). The inset is the simulation model. (b) Reflectivity measurements of the planar cavity at 5K and 300K respectively. (c) Laser power-dependent measurement of the peak intensity of the X line on CCD.

few tens of micrometers away from the nanomembrane. The power of the laser before the objective was measured (around 2.2 nW). Next, the integrated counts of the reflected laser (NL_{SPAD}) on SPAD were recorded in the well-aligned system. An appropriate neutral density filter, with transmission t, was employed in order to obtain the counts on a SPAD comparable with the saturation counts of the X line. Therefore, the system detection efficiency was estimated from the relation ε = (NL_{SPAD})/N_{laser}, where N_{laser} is given by P_{laser}/hω. For the setup, ε = 1.09 × 10^{-2}. Secondly, the photon collection into the first lens in the optical setup was estimated. The pulsed Ti:Sapphire laser with 220 fs pulse duration and repetition rate f=76.1 MHz was used to excite the QD which was biased at the EL threshold of -1.9 V. The power of the laser was carefully modified to ensure the X emission was saturated so that at most one photon was generated in each pulse cycle. Fig. 3.8c shows laser power-dependent peaks counts of the X on CCD. At saturation, the spectrally integrated counts (NX_{SPAD}) on high efficiency SPAD was recorded to estimate the photon collection efficiency, which was given by the relation η =NX_{SPAD}/(fη). In the experiment, η ~4.8% was found, which was consistent with the theoretical calculation.

3.4 Wavelength-tunable and electrically triggered single-photon emission

In this section, the wavelength-tunable and electrically triggered single-photon emission from the quantum-LED is demonstrated. The capability of tuning the energy of the photon emission through in-plane biaxial strain field is presented first. Then, combining with fast electrical pulse excitation, deterministic single-photon emission is realized as demonstrated by the second-order time correlation measurements.
3.4.1 Strain-induced energy shift of the photon emission

As stated in the previous chapter, the challenge of using self-assembled QDs as independent SPSs to realize quantum interference is to find out a reliable method to tune the emission energy of photons. In the strain-tunable quantum LED presented in this work, this has been achieved by applying an electric field $F_p$ to the PMN-PT crystal through which a variable strain fields can be imposed onto the QDs. The application of $F_p$ to the PMN-PT leads to an in-plane strain field, $\varepsilon_\parallel$, in the nanomembrane. An in-plane tensile strain ($\varepsilon_\parallel > 0$) is obtained when a negative electric field ($F_p < 0$) is applied, and vice versa.

![Figure 3.9: Tunable X emission under in-plane biaxial strain field, $\varepsilon_\parallel$. Large compressive ($\varepsilon_\parallel < 0$) or tensile strain ($\varepsilon_\parallel > 0$) can be obtained by applying different electric fields to the PMN-PT along the $z$ direction. The QD is under pulsed electric excitation at 80 MHz ERR, 300 ps pulse width and $V_{pp} = -0.7$ V, $V_d = -1.7$ V.](image)

Fig. 3.9 shows the EL spectra from a single In(Ga)As QD in the diode under pulsed operation. Here the applied DC voltage, $V_{ds}$, is -1.7 V, and the electric pulse has an ERR of 80 MHz, a nominal 300 ps pulse duration and an amplitude ($V_{pp}$) of -0.7 V. Both precise blue- and red-shift tuning are observed when compressive and tensile stresses are applied to the QD, respectively, which is consistent with previous observations [53, 72]. For the neutral exciton X, a total energy shift of approximate 4.8 meV has been achieved when $F_p$ is changed from -10 to 20 kV/cm.

3.4.2 Wavelength-tunable and triggered single-photon emission

To demonstrate the wavelength-tunable single-photon emission, the second-order autocorrelation measurement $G^{(2)}(\tau)$ was performed for X as $F_p$ is varied from -10 to 20 kV/cm and the results are shown in Fig. 3.10a - c. The emission energy of X at $F_p = 0$ kV/cm, $E_0$
3.5 High speed electrically triggered single-photon emission

$= 1.3982$ meV is defined as zero-point, while the tuned energy $E_p$ at different $F_p$ is defined relative to the zero-point by $\Delta E = E_p - E_0$. At $\Delta E = 0$ meV, the non-normalized photon autocorrelation result is shown in Fig. 3.10b. The periodic autocorrelation peaks together with the absent peak at zero time-delay provide an unambiguous evidence of the triggered single-photon emission. The time separation between neighboring peaks is 5 ns, which coincides with the repetition rate of 200 MHz. The normalized value of $g^{(2)}(0)$ provides a multi-photon emission probability of $0.14 \pm 0.2$. This finite probability probably originates from the contributions of the background and the dark counts of the SPADs [88].

We also measured the photon autocorrelation when the emission energy of the X line is tuned to different values by the strain field, and the results are shown in Fig. 3.10a ~ d for $\Delta E = -1.6$ meV and 3.2 meV, respectively. By comparing the $g^{(2)}(\tau = 0)$ at different X emission energies, we do not observe significant changes. This finding, together with the demonstrated capability of achieving energy tuning with $\mu$eV precision, proves that the technology provides a stable and precise tuning method to the photon emission from a triggered QD-based SPS.

Figure 3.10: Autocorrelation measurements demonstrating electrically triggered single-photon emission from X emission line. The QD is excited by the DC bias $V_{dc} = -1.7$ V, 200 MHz ERR, 300 ps pulse width and $V_{pp} = -0.7$ V. The single-photon emission characteristic of the QD, which is signaled by the suppression of the zero-delay peaks, is well maintained even when the emission energy is tuned in a broad range of about 4.8 meV by the strain field.

3.5 High speed electrically triggered single-photon emission

The quantum tunneling effect at the lower DC bias can be used to significantly reduce the X lifetime which determines the time uncertainty of the single-photon emission event in each pulse cycle, which actually results in a low time jitter mode of the single-photon emission. Most importantly, such low time jitter mode has a strong impact on the single-photon emission rate. Bennett and co-workers have studied this low timing jitter effect in order to improve the single-photon emission rate [81], and they pointed out the long lifetime can cause an overlapping of the neighboring peaks in the second-order time autocorrelation measurements and thus limit the maximum excitation frequency. Alternatively, the overlapping causes a crosstalk between the early emitted photons and later
photons, which predominantly increase multi-photon emission probability. Based on this consideration, it is desirable to make the quantum-LED work at lower time jitter mode in order to avoid this cross-talk effect.

Figure 3.11: Modeling of $g^{(2)}(\tau)$ under high frequency electrical pulses excitation.

In order to clarify the effect of the low time jitter on the single-photon emission rate, a theoretical simulation is performed utilizing the following physical model [89, 90]:

$$G^{(2)}(\tau) = B + \sum_n a_n \exp(-|\tau - \frac{n}{f}|/\tau_{\text{lifetime}}),$$

(3.2)

where $B$ is the background, which is ascribed to the emission of sample rather than QDs, $f$ is the ERR of the electrical pulse stream and $\tau_{\text{lifetime}}$ is the recombination lifetime of the studied excitonic emission, i.e. X, XX and $X^-$ etc. Suppose that the single photons emitted from a self-assembled QD has lifetime of about 1 ns, then the simulated second-order correlations (normalized) at different ERR are given in Fig. 3.11. From the bottom panel to the top panel, the neighboring peaks in the autocorrelations overlaps dramatically as the excitation frequency increases from $f = 100$ to $800$ MHz.

Theoretically, the peak width in the $g^{(2)}(\tau)$ function is determined by the lifetime and is found to be 2 times longer than the lifetime. Thus, the peak width will be 2 ns if a lifetime is 1 ns. Compared with the temporal distance of 10 ns for autocorrelation peaks in the simulated $g^{(2)}(\tau)$ function at 100 MHz, the much larger temporal distance prevents the correlation peaks from overlapping. Though, as the ERR is increased from 400 MHz to 800 MHz, the temporal distance is subsequently deceased from 2.5 ns to 1.25 ns. At these excitation frequencies, the temporal separation is close and even less than peak width. As a consequence, the overlap of neighboring peaks in the $g^{(2)}(\tau)$ function become more pronounced. It is noticeable that such overlap gives rise to indistinguishable autocorrelation events in the $g^{(2)}(\tau)$ function and it results in a crosstalk for the successively emitted single photons. Hence, for the assumption of 1 ns lifetime, it would
be necessary to operate the source at excitation frequency below 500 MHz in order to distinguish individual peaks.

Driving the quantum-LED with a low DC bias $V_{dc}$, the lifetime can be drastically reduced, and therefore a higher ERR would be expected. However, a low $V_{dc}$ induces a large band bending for the diode, which can result in a reduction of electron-hole recombination efficiency known as inner quantum efficiency, $\eta_{int}$. Theoretically, $\eta_{int}$ is defined as $\eta_{int} = \tau_{r}^{-1}/(\tau_{r}^{-1} + \tau_{nr}^{-1})$. $\tau_{r}$ is the measured lifetime as shown in Fig. 3.4c and $\tau_{nr}$ is the non-radiative decay time. In the quantum LED studied here, the non-radiative recombination process is mainly dominated by the quantum tunneling effects as described above. According to the experimental measurement, at $V_{dc} = -1.8V$, the lifetime $\tau_{r}$ and the tunneling time $\tau_{nr}$ are 950 ns and 3.6 ns respectively, so the $\eta_{int}$ is found to be 80%. While at -1.65 V, the lifetime is shortened to be 540 ps and tunneling is correspondingly decreased to 900 ps. With these values, $\eta_{int}$ is 62%. In this context, the low time jitter and quantum efficiency are trade-off in the design of high speed quantum LED.

![Figure 3.12: Autocorrelation measurements of the neutral exciton X0 at different ERR of (a) 400 MHz (b) 600 MHz and (c) 800 MHz. The diode is excited at fixed DC bias of -1.7 V. The pronounced anti-bunching dip at zero time-delay provides the evidence of the single-photon emission up to 800 MHz](image)

Based on the above considerations, a DC bias of -1.7 V is chosen to drive the QD LED, and the electrical pulses have amplitude of -0.7 V, and duration of 300 ps. Note that at $V_{dc} = -1.7 V$, the lifetime of the single-photon emission is found to be 667 ps with which the quantum LED is able to work reliably below 800 MHz. However, the whole time jitter includes not only the decay process of 667 ps, it also includes the rise time of 700 ps. Thus the total time jitter is about 1.3 ns, which implies that, practically, the maximum ERR can only reach about 400 MHz instead of 800 MHz. The experimental demonstration of the high speed single-photon emission is illustrated in Fig. 3.12a ~ c. They show correlation measurements at different ERR from 400 to 80 MHz. The vanishing peaks for these correlations are unambiguous signs of the single-photon emission, and the periodic histograms are raised due to the deterministic single-photon emission. Obviously, due to the timing jitter, the neighboring histograms slightly merge at 400 MHz because the comparable total timing jitter of about 1.3 ns and temporal distance of 2.5 ns. However, the histograms merge more significant when the ERR is increased to 600 MHz and 800 MHz.
MHz.

In summary, an all-electrically driven single-photon-emitting diode has been demonstrated, which allows for the generation of triggered, wavelength-tunable single photons. This device is based on a QDs-containing LED nanomembrane integrated onto a 300 μm-thick PMN-PT piezoelectric crystal. The energy of the QD emission lines can be precisely and stably tuned over a broad range by varying the voltage applied to the PMN-PT. We show that the triggered single-photon-emitting characteristic of this diode is well maintained during the strain-controlled wavelength tuning. Together with the ability of shortening the exciton decay-time by band-bending at low DC voltages, which can increase the ERR up to 800 MHz, the device demonstrated here represents a promising way to achieve indistinguishable single-photon emission from two remote single-photon-emission diodes at high repetition rates.
4 Triggered entangled-photon emission from strain-tunable quantum-LED

The strain field can not only be used to tune the energy of single photons emitted from QDs, it can also be employed to control the exciton spin splitting so as to achieve entangled-photon emission. In this chapter, the main results of generating entangled-photon pairs from the strain-tunable quantum-LED will be demonstrated. The relevant theoretical background of the polarization-entangled photons emitted from the self-assembled QDs via biexciton cascade will be presented first. Experimental techniques for measuring the two-photon polarization entanglement are also introduced. High degree of the polarization-entangled photons emitted from the strain-tunable quantum-LED is explicitly measured under both DC and ultrafast electrical pulsed excitation. In addition, relevant techniques of performing two-photon quantum tomography measurements are explicitly depicted, which allow the polarization entanglement from the QD biexciton cascade emission is completely characterized.

4.1 Entangled photon pairs from the cascade emission in QDs

Analogous to the cascade emission occurring in alkali atoms, e.g., rubidium atoms [91, 92], self-assembled QDs possess a radiative cascade involving biexciton-to-exciton-to-ground state. The method of using this cascade emission from the QD to generate polarization-entangled photon pairs was proposed by Oliver Benson and co-workers in 2000 [93]. After regularly injecting electrons and holes into a semiconductor QD within a diode structure, two electrons and two holes are injected into the QD and form a quasi-particle so called biexciton. Thereafter, the biexciton relaxes radiatively through the sequential recombination of two electron-hole pairs by emitting two polarization-entangled photons.

4.1.1 Cascade emission from anisotropic QDs

The biexciton is composed of two electrons and two holes with opposite spin up and down states as shown in Fig. 4.1. The electrons occupy the lowest-energy confined electron state
in the CB and they have spin number $s_{e,z} = 1/2$ and $s_{e,z} = -1/2$. The two holes occupy the highest-energy confined hole states in the VB and they have spin number $j_{h,z} = 3/2$ and $j_{h,z} = -3/2$. In the commonly studied QDs systems, the highest-energy hole states are predominantly governed by HH character, while the LH states with spin states of $j_{h,z} = \pm 1/2$ are energetically lower than the HH states.

![Figure 4.1: Schematic illustration of the biexciton cascade emission in the semiconductor QD. The biexciton state consists of two electrons and holes with opposite spin states. The intermediate excitonic states occupied by one electro-hole pair are energetically degenerate for an ideal QD without broken symmetry. Because of angular momentum conservation, the relaxation of the biexciton cascade follows two decay channels: one produces an R-polarized biexciton photon and a L-polarized exciton photon, and the other one produces a L-polarized biexciton photon and an R-polarized exciton photon.](image)

When the biexciton cascade occurs, first of all, an electron-hole pair will recombine and generate a biexciton photon (XX). According to the angular momentum conservation, the biexciton photon has two possible polarizations: if the biexciton recombination takes place between the electron $s_{e,z} = 1/2$ and the hole $j_{h,z} = -3/2$, the biexciton photon with left-hand polarization (L) will be generated. Alternatively, if the biexciton photon stems from the recombination between the $s_{e,z} = -1/2$ electron and the $j_{h,z} = 3/2$ HH, then the biexciton photon with right-hand polarization (R) will be generated. The remaining electron and hole form a neutral exciton with total spin state $j_z = 1$ and $j_z = -1$ ($j_z = s_{e,z} + j_{h,z}$). As a consequence, after the biexciton photon emission the state of the whole system is given by

$$|\Psi\rangle = (L_{XX}|R_X\rangle + R_{XX}|L_X\rangle)/\sqrt{2}. \quad (4.1)$$

Thereafter, the neutral exciton relaxes to the ground state $|0\rangle$ through two possible decay channels: if the exciton relaxes from $|R_X\rangle$ to $|0\rangle$, an exciton photon with R circular polarization is emitted; if the exciton relaxes from $|L_X\rangle$ to $|0\rangle$, an exciton photon with L polarization is emitted. Therefore, after the biexciton cascade emission, two photons (biexciton XX and exciton X) with two possible circular polarizations will be generated.
and state of the two photons can be expressed by

$$|\Psi^+\rangle = (L_{XX}R_X + R_{XX}L_X)/\sqrt{2}. \quad (4.2)$$

If there is no way to distinguish which path the biexciton cascade emission follows, then the generated two photons are polarization entangled and the entanglement state is generally written as in Eq. 4.2.

![Figure 4.2: (a) Observation of the FSS in the polarization-resolved PL measurement from a single In(Ga)As/GaAs QD, in which two linearly polarized exciton emission lines are resolved. (b) The biexciton cascade emission follows two possible decay paths. One gives a H-polarized biexciton photon and a H-polarized exciton photon, while the alternative one gives a V-polarized biexciton photon and a V-polarized exciton photon. Removal of the degeneracy of the intermediate excitonic states due to the broken symmetry makes the two decay paths distinguishable.]

The above statement about the biexciton cascade emission, producing two-photon entanglement, is only valid for an ideal QD without any broken structural symmetry. In realistic QDs, the symmetry of the QD is reduced to $C_{2v}$ or $C_1$ arising from the structural anisotropy and composition fluctuations [64]. This unavoidable effect results in the removal of the degeneracy of the excitonic states so that two bright exciton states will be formed. Optically, these two exciton states will be mapped into two linearly polarized exciton emission lines, horizontal polarization (H) and vertical polarization (V). The energetic separation between these two states defines the FSS ($s$). The presence of the FSS induces distinguishable decay paths in the biexciton cascade emission and hence prevents generation of the entangled photon pairs. Therefore, the key to generate the entangled photon pairs from a QD is the reduction of the FSS to zero. (see Fig. 4.2).

4.1.2 Origin of the fine structure splitting

The existence of the FSS in semiconductor QDs was firstly discovered by D. Gammon et al., in 1996 [94]. Their studies are based on interface fluctuations of GaAs/AlGaAs QWs, for which elongation of the in-plane confinement potential lifts the degeneracy of exciton
states and FSS as large as $20 \sim 50$ µeV were found. Since then, the FSS has been observed in diverse QDs systems, including III-V group QDs such as In(Ga)As/GaAs [95–97], GaAs/AlAs [98–100]; and II-VI QDs such as CdSe/ZnSe [101–103], etc.

The physical origin of the FSS in three-dimensionally confined QDs systems has been intensively studied. As stated shortly in the previous section, the underlying mechanism of the FSS is the broken structural symmetry, which induces a spin-exchange interaction [45, 104, 105]. An ideal QD without any broken symmetry possesses $D_{2d}$ symmetry as shown in the left panel of Fig. 4.3. Structural anisotropies result in an elongation of the QD along one crystal direction ([110] or [1-10]), so that the symmetry of the QD is reduced to $C_{2v}$ or $C_{1}$. Theoretically, the spin-exchange interaction for the exciton can be written as

$$H_{ex} = - \sum_{i=x,y,z} (a_{i} j_{h,i} + b_{i} j_{h,i}^{3} s_{e,i}),$$

(4.3)

where $a_{i}$ and $b_{i}$ are deformation potentials, and $j_{h,i}$ and $s_{e,i}$ are spin states of the HH and the electron respectively. In the single-particle picture, the exciton is composed of a heavy hole with $J_{h} = 3/2$, $J_{h,z} = \pm 3/2$ and an electron with $s_{e} = 1/2$, $s_{e,z} = \pm 1/2$. In the total angular momentum representation, these four single-particle states construct four excitonic states $J_{z} = j_{h,z} + s_{e,z} = \pm 1$ and $\pm 2$. $|J_{z}| = 2$ are optically inactive states as they cannot couple to any light field so that the exciton with spin number of $|J_{z}| = 2$ is called “dark exciton”. $|J_{z}| = 1$ is optically active state and it can be coupled to light field so that it is called “bright exciton”. From the spin-exchange interaction Hamiltonian in Eq. 4.3, the exciton Hamiltonian can be written in the matrix representation by using the
exciton states $| +1 \rangle, | -1 \rangle, | +2 \rangle, | -2 \rangle$ as basis functions [45].

$$
H_{ex} = \frac{1}{2} \times \begin{bmatrix}
1.5(a_z + 2.25b_z) & 0.75(b_x - b_y) & 0 & 0 \\
0.75(b_x - b_y) & 1.5(a_z + 2.25b_z) & 0 & 0 \\
0 & 0 & -1.5(a_z + 2.25b_z) & 0.75(b_x + b_y) \\
0 & 0 & -0.75(b_x + b_y) & -1.5(a_z + 2.25b_z)
\end{bmatrix}.
$$

According to Eq. 4.4, if $b_x = b_y$, one finds $\sigma_1 = 0$. This corresponds to the QD having $D_{2d}$ or even higher symmetry. In this scenario, degenerate bright exciton states can be easily deduced: both $| +1 \rangle$ and $| -1 \rangle$ excitonic states have the same energy $\sigma_0$. In contrast, when the QD system is prone to a structural imperfection and the symmetry is lowered to $C_{2v}$ or $C_1$, the degeneracy of the exciton states is removed. As a result, two hybridized bright excitonic states are formed and can be written in terms of the superposition of $| +1 \rangle$ and $| -1 \rangle$:

$$
| \chi_1 \rangle = (| +1 \rangle + | -1 \rangle)/\sqrt{2} \quad (4.5)
$$
$$
| \chi_2 \rangle = (| +1 \rangle - | -1 \rangle)/\sqrt{2}, \quad (4.6)
$$

where $| \chi_1 \rangle$ and $| \chi_2 \rangle$ are symmetric and asymmetric superposition states and they will be mapped into the linearly polarized light fields along [110] and [1-10]. In addition, the energetic difference which gives the FSS is $S = | E_{+1} - E_{-1} | = \sigma_1 = 0.75(b_x - b_y)$. Thus the amplitude of the FSS is determined by the difference of the two in-plane confined potential, $b_x$ and $b_y$. Therefore, in order to eliminate the FSS in a QD for generating the entangled-photon emission, external post-growth tuning techniques that required to restore the symmetry of the dot is strongly demanded.

### 4.2 Post-growth tuning of the fine structure splitting

In the last section, it is shown that the spin splitting of the intermediate exciton states play a central role in generating polarization-entangled photon emission from the QD cascade emission. Although a new type of In(Ga)As QDs grown along [111] crystallographic axis have been proposed to have extremely small FSS [106], self-assembled QDs grown along [001] still dominate the applications in the quantum communication [60, 107, 108]. Hence, various techniques have been tested so far in order to suppress or tune the FSS to zero for QDs systems. Herein, a brief review of the most commonly used tuning techniques is given such as thermal annealing [109–112], in-plane magnetic field tuning [113, 114], electrical field and strain-field tuning.

#### 4.2.1 Review of the post-growth tuning methods
(1) Thermal annealing

The FSS of the self-assembled QDs can be effectively reduced through thermal annealing. The impact of the thermal annealing on the FSS were explicitly studied by R. J. Young and co-workers in Ref. [111]. In this study, the change of the FSS is evidenced by measuring a number of In(Ga)As QDs with different annealing conditions as shown in Fig. 4.4. All the sample used were grown by solid-source MBE. Among them, one sample was not annealed and used as reference. It is clearly seen that the distribution of the FSS for non-annealed QDs is entirely random because their the excitonic emission energies cover a range from 1.34 to 1.41 eV, and the FSS ranges from 80 to -30 µeV. When the In(Ga)As/GaAs QDs systems were annealed at different temperatures and different time, the distribution of the FSS shows a certain correlation with the exciton binding energy. The FSS tends to decrease monotonically with increasing exciton recombination energy. This behavior is ascribed to the reduction of the exciton confinement as the thermal annealing results in an intermixing of Ga and In. This intermixing effect induces an extension of the dimensions of the QD and makes the exciton wavefunction expand towards the wetting layer, which reduces the long-range spin-exchange interaction and hence reduces the FSS. It is also noticeable that the average FSS can be possibly tuned to zero when the dots are annealed at 750° for 10 min. Based on this technique, the entangled-photon emission from In(Ga)As QDs had been demonstrated (see Ref. [115, 116]).

(2) Magnetic field

It is also possible to employ magnetic fields to tune the FSS, which was firstly demonstrated by R. M. Stevenson, et al. [114] An in-plane magnetic field can mix the bright and dark exciton states, causing a different energy shift for the two bright excitonic states and a change in their splitting.

Specifically, by applying an in-plane magnetic field ($B_x$, perpendicular to the QD growth
Figure 4.5: Top panel represents two orthogonally linear polarization emissions of exciton at $B_x = 0$ for three different QD systems: InAs QDs in GaAs barrier with $S_0$, InAs dots within $Al_{0.33}Ga_{0.67}As$ barrier with large $S_0$ and InAs dots in GaAs barrier with small $S_0$. The bottom panel shows the change of FSS as function of $B_x$.

direction of [001]), the behavior of the FSS is given by

$$s(B_x) = s_0 + K_1 B_x^2 + k_2 B_x^4,$$

(4.7)

$$K_1 = \frac{\mu^2 D_0}{D_0(1 - S_0^2/4D_0^2)} [g_{e,x}g_{h,x} - \frac{S_0^2}{4D_0^2}(g_{e,x}^2 + g_{h,x}^2)],$$

(4.8)

where $s_0$ and $D_0$ are the FSS and the energetic separation of the bright exciton from the dark exciton at $B_x = 0$. $g_{e,x}$ and $g_{h,x}$ are g-factors of the electron and the hole. In Eq. 4.7, the third term can be neglected safely. Thus the behavior of the FSS change is mainly governed by $K_1$, which is determined by parameters of the microscopic QDs structure. Such effect is verified in the experimental measurements on three different QDs systems, including InAs QDs in GaAs barrier with typical $S_0$, InAs dots within $Al_{0.33}Ga_{0.67}As$ barrier with large $s_0$ and InAs dots in GaAs barrier with small $s_0$. The FSS as function of $B_x$ is shown in Fig. 4.5. The $K$ was found to be different for these three QDs systems. It was estimated that the $K$ is about $2.5\pm1.8 \, \mu eV T^{-2}$ for dot systems with GaAs barrier, while $K$ is approximately estimated to be $-1.67\pm0.94 \, \mu eV T^{-2}$ for dots in $Al_{0.33}Ga_{0.67}As$ barrier. So far, the entangled-photon emission has been demonstrated with InAs/GaAs based on in-plane magnetic field tuning technique (see Ref. [114]).

(3) Vertical electric field

Electric field has emerged as powerful technique to tune FSS since 2002 [117]. An in-plane electric field was firstly proposed to compensate the QDs shape anisotropy so as to tune the FSS to zero. In spite of some success, it turned out to be difficult to apply well-defined lateral electrical fields to QDs. Later, vertical-electric-field was found to be a
promising technique to cancel the FSS [60, 107, 118]. Here the discussion is only focused on the vertical electric field tuning, while more details of the in-plane electric field tuning technique to the FSS can be found in Refs. [118–122].

\[
\text{Figure 4.6: (a) Vertical-electric-field induced anti-crossing of bright exciton levels. (b) Rotation of the polarization direction of the low-energy component of the bright exciton emission lines.}
\]

Simply, the dot can be thought as a point dipole and the impact of the vertical electric field is expressed by

\[
E = E_0 - pF + \beta F^2, \quad (4.9)
\]

where \(E_0\) is the energy of the exciton, \(p\) is its permanent dipole moment along the dot growth direction (\(z\) axis), \(\beta\) its polarizability and \(F\) is the applied vertical electric field. A. J. Bennett have studied extensively the influence of the vertical-electric-field \(F\) on the FSS and the exciton polarization, \(\theta\) [60]. As shown in Fig. 4.6, the FSS undergoes an anti-crossing behavior and \(\theta\) is changed by 90° as the vertical electric field is applied. The change rate of the FSS induced by the vertical electric field can be quantified \(\Delta s = |p_1 - p_2| \times F\), where \(p_1\) and \(p_2\) are the dipole moment along [110] and [1-10] respectively, which are determined by the anisotropic quantum confinements of the dot.

(4) Biaxial strain tuning

Strain field is another promising external perturbation that employed to control the FSS of the self-assembled QDs [48, 50, 51, 72, 123, 124]. The strain field was first introduced by S. Seidl and co-workers [48, 123]. In their study, a thin (~ 0.5 mm) GaAs substrate with InAs QDs was glued onto a PZT piezoelectric actuator. When a electric field was applied on the actuator, an uniaxial stress is imposed to the QDs. As a consequence, the FSS has been observed to undergo pronounced change. However, due to the very thick substrate, the maximum achievable strain on QDs is limited to about 20 MPa and therefore they didn’t manage successfully to tune the FSS to zero. This technique is later improved by F. Ding et al. [50] who processed the QD-containing GaAs substrate into ultra-thin films with hundreds of nanometer. In addition, a new type of piezoelectric actuator \([Pb(Mg_{1/3}Nb_{2/3})O_3]_{0.28}[PbTiO_3]_{0.72}\) (PMN-PT 28%), was adopted, and a large strain field can be applied. Moreover, the energy shift of about
4.2 Post-growth tuning of the fine structure splitting

10 meV for the QD emission was realized. Compared with the previous method, such new route fosters a robust platform for further research of using strain field to tune the FSS [53, 66, 72, 73, 124].

With the QDs-containing nanomembrane stuck on the PMN-PT actuator, J. Plumhof and co-workers conducted an experiment [72], in which large change in FSS was observed as the voltage is applied on the piezoeactuator. The FSS was tuned to a minimum value of about 5 µeV. Aside from the FSS change, an angle representing the orientation of excitonic eigenstate was also measured. The orientation of the excitonic eigenstates would not change much when the applied electric field \( F_p \) less than 10 kV/cm, after this value, the angle changes rapidly. This behavior implies that the symmetry of the dot can be effectively recovered by making use of the external biaxial strain field. However, to date it has not been managed to tune the FSS to zero. Therefore, polarization-entangled photon emission from this kind of strain-tunable QD devices has not been demonstrated yet.

4.2.2 Cancellation of the fine structure splitting with uniaxial strain

Theoretically, the FSS in QDs can be tuned to zero only if an uniaxial strain is applied along the optical axis of the dot, which was predicted by R. Singh [125] and M. Gong [64].

![Figure 4.7](image.png)

Figure 4.7: (a) FSS change under [110] uniaxial (black square) strain or [100] uniaxial strain (red circles) and the phase, representing orientation of the hybridized excitonic state with respect to [110] direction, are shown in (b). The jump of phase is a critical sign of tuning the FSS to zero.

When an uniaxial strain \( P \) is applied to a pure lens shaped InAs QD, the strain-incorporated Hamiltonian with basis functions of the two bright exciton states \(|+1\rangle \) and \(|-1\rangle \) can be written as [64]

\[
H(p) = H_2 + V_1 + V_s(n)p = \begin{pmatrix} E_0 + \delta + \alpha_3 p & \kappa + \beta p \\ \kappa + \beta p & E_0 - \delta + \alpha_4 p \end{pmatrix},
\]

(4.10)
where $H_{2v}$ is the Hamiltonian of an idea QD with $C_{2v}$ symmetry and $V_1$ is a deform potential which makes the dot symmetry low to $C_1$. While $V_5(n)p$ is the uniaxial incorporated item. After diagonalizing the Hamiltonian, the FSS $s$ and the reluctant orientation angle of the hybridized eigenvector, $\theta$, are immediately solved:

$$E_{+, -} = E_0 + \frac{p\gamma \pm \sqrt{4(\beta p + \kappa)^2 + (\alpha p + 2\delta)^2}}{2}$$

(4.11)

$$\tan(\theta_\pm) = -\frac{2\delta - p\alpha \mp \sqrt{4(\beta p + \kappa)^2 + (\alpha p + 2\delta)^2}}{2(\beta p + \kappa)}.$$ 

(4.12)

The FSS $s$ can be found from Eq. 4.11, $|s| = |E_+ - E_+| = \sqrt{4(\beta p + \kappa)^2 + (\alpha p + 2\delta)^2}$, where the parameters $\alpha = \langle i|V_s(n)|i\rangle (i = 1or -1)$, $\beta = \langle +1|V_s(n)| -1 \rangle$, and they are determined by the strain configuration with respect to the optical axis of the QD. For an uniaxial strain filed which is applied along [110] ([1-10]) direction, $\beta = 0$; and if this strain is applied along [100] ([010]), then $\alpha = 0$. In addition, $\kappa$ and $\delta$ are QD structure-related parameters and are determined by the QD nanostructure.

### 4.2.3 Experimental realization of zero fine structure splitting in the quantum LED

Recent works have shown that the FSS can be suppressed or tuned to zero through application of either a vertical electric field [60] or a strain-field-mediated vertical electric field across the QDs containing LED [53, 61], but the main drawback for these strategies is the difficulty of combining it with electrical excitation and therefore it hampers the realization of electrically driven ELED. Other techniques such as thermal annealing [44] and in-plane magnetic field [45] would be potentially compatible with the realization of ELEDs, but the thermal annealing is an irreversible coarse tuning technique, while the magnetic field tuning requires complex and bulky setup which renders a practical implementation inconvenient. The theoretical works (presented in the last section) suggest that the FSS can be effectively eliminated by using solely well-controlled strain field [63, 64]. Using piezoelectric-induced strains to engineer the properties of ELEDs would be highly desirable because this fully electrically-controlled tuning knob would allow the problems related to the FSS in ELEDs to be overcome. Here a quantum device, consisting of a standard QDs-containing LED integrated onto the piezoelectric actuator, is demonstrated. The device presented in this work features a giant piezo-electric response and capable of delivering well-defined anisotropic strain fields. With this novel device, the following results will be demonstrated: (i) the FSS of QDs therein embedded can be tuned effectively with the elastic strain fields without affecting the electrical injection of the ELEDs; (ii) more than 30% of the QDs are tuned be suitable for the generation of entangled photon pairs (more than an order of magnitude more than in previous devices 5) and (iii) the highest operation speed ever reported so far for an entangled-photon source (400 MHz). This unique set of properties paves the way towards the real exploitation of ELEDs in high data-rate entangled-photon applications involving a large numbers of quantum emitters.

The strain-tunable ELED studied in this work is schematically shown in Fig. 4.8, in which a 440 nm-thick n-i-p nanomembrane containing InGaAs QDs are integrated onto a
4.2 Post-growth tuning of the fine structure splitting

In this section, the post-growth tuning of the fine structure splitting is discussed. Specifically, the tuning of the fine structure splitting in n-type GaAs, p-type GaAs, and In(Ga)As dots is considered. PMN-PT (28%) is used as the actuator to apply strain. The figure shows a sketch of the strain-tunable entangled-light-emitting diode and strain tuning of the electroluminescence.

Figure 4.8: Sketch of the strain-tunable entangled-light-emitting diode and strain tuning of the electroluminescence. (a) Detailed schematic of the diode structure. (b) Electroluminescence from a single quantum dot versus electric field $F_p$ applied on the PMN-PT actuator.

The detailed fabrication process is described elsewhere [62, 66]. The PMN-PT actuator used here has pseudo-cubic cut directions [100], [0-11] and [011], denoted by $x$, $y$, $z$ axes respectively. When the PMN-PT is poled along $z$ axis, anisotropic in-plane strain fields, $\epsilon_{xx}$ along $x$ axis and $\epsilon_{yy}$ along $y$ axis with opposite sign, can be obtained. Accounting for the relevant piezoelectric coefficients $d_{31} \simeq +420$ pC/N along [100] direction and $d_{32} \simeq -1140$ pC/N along [1-10], this in-plane strain anisotropy can be roughly estimated to be $\epsilon_{xx} \approx -0.37 \epsilon_{yy}$. With this specific anisotropic in-plane strain fields, an equivalent effect of uniaxial strain applied along only one of the principle axes is expected. This is because a compressive (tensile) strain along one axis can be always treated as an equivalent tensile (compressive) strain along the perpendicular axis [64]. Such anisotropic strain fields, which have received little attention so far, has proved to be vital in this work.

Beside the strain fields, electrical contacts are arranged in such way that electrical fields can be independently applied across the ELED and the PMN-PT actuator. By biasing the diode and applying a variable electric field ($F_p$) to the PMN-PT simultaneously, energy-tunable electroluminescence (EL) from a single QD is produced, as shown in Fig. 4.8b. According to the power and polarization-resolved measurements the observed EL lines are ascribed to exciton, biexciton and charged exciton emission, respectively. As the magnitude of $F_p$ is varied, all the emission lines shift in energy. The shift is expected...
to be mostly proportional to the opposite of the variation of the volumetric strain at
the QD position, which can be estimated as $\epsilon_{\text{tot}} = (1 - 0.37)\epsilon_{yy} \times (S_{11} + S_{12})/(S_{11} + S_{12}) \approx 0.33\epsilon_{yy} \approx 0.33d_{32}F_p$ (with $S$ the compliance coefficients of the host material).

Since $\epsilon_{\text{tot}}$ has the same sign as $d_{32}$, which has a relatively large magnitude and is negative, we expect a positive $F_p$ to induce a compressive strain which results in a blue shift of the EL, while a negative $F_p$ induces a tensile strain, which results in a red shift. Note that a total energy shift of about 2.5 meV is achieved as the $F_p$ is varied from $-6.7$ to $20$ $kV \cdot cm^{-1}$.

Figure 4.9: (a) Polarization-resolved spectrum of EL from the strain entangled-light-emitting diode. The diode is bias with a appropriate DC voltage $V_d = -2.0V$ so that multiexciton emission can be excited. (b) Wave-like behavior of energy-dependent exciton $X$, biexciton $XX$ and charged exciton $X^-$. By inserting a half-wave plate and a linear polarizer in the optical path after the objective, a polarization-resolved spectrum from the diode is acquired as shown in Fig. 4.9a. The diode is under a DC power excitation. The polarization-resolved spectrum is dominated by three bright lines which are assigned to be exciton $X$, biexciton $XX$ and charged exciton $X^-$. The wave-like behavior of the $XX$ and $X$ gives an unambiguous sign of the presence of the FSS. In the fit, amplitude of the sine waveform function gives the FSS and the phase is represented by the angle of high (low) energy component with respect to the polarizer orientation. By comparing with the phase of the higher component for the $X$ and $XX$, they have $90^\circ$ difference. While for the negative charge exciton $X^-$, the position of the line keeps constant, which reflects that $X^-$ has single line with circular polarization. It is worth mentioning that, by fitting $XX$ and $X$ together, one can get their relative energy difference which is exactly 2 times larger than the FSS. By means of this technique, the resolution of the measurements can be up to $\sim 0.5 \mu eV$.

In order to control the FSS of the dots embedded in the quantum LED, the crystal axes [1-10] and [110] of the GaAs nanomembrane were carefully aligned along the $x$ and $y$ axes of the PMN-PT actuator, respectively (see Fig. 4.8). Representative plots of the FSS of different QDs as a function of $F_p$ are shown in Fig. 4.10a. Although the emission energy shift is only about 2.5 meV as $F_p$ is varied from $-6.7$ to $28$ $kV \cdot cm^{-1}$, which is a consequence of the strong strain anisotropy (and thus relatively small $\epsilon_{\text{tot}}$), the FSS is tuned over a broad range from $30 \sim 0 \mu eV$. In addition to this drastic change in FSS, the rotations of the polarization angle $\theta$ is also observed, i.e., the polarization direction of the high-energy
4.2 Post-growth tuning of the fine structure splitting

Figure 4.10: (a) FSS change as a function of the piezo-voltage $V_p$. (b) Phase change of the higher energy component as $V_p$ varied from -6.7 to 28 kV/cm$^{-1}$, and the insets show sketches of biexciton cascade and orientation of the exciton polarization. (c), (d), (e), (f), (g), initial FSS $s_0$ and exciton polarization $\theta_0$ corresponding to the studied five dots at $F_p = 0$ kV/cm$^{-1}$. In the polar plot 0 degree indicates the [1-10] crystal axis and 90 degree indicates the [110] crystal axis.

line of the exciton with respect to the [110] direction of the GaAs nanomembrane (see Fig. 4.10b). At the largest available tensile (compressive) strain, $\theta$ for all dots tends to be directed along the [1-10] ([110]) direction. Furthermore, note that the above tuning behavior is mainly determined by the dot principal axis with respect to the fixed direction of the strain. Experimentally the dot principal axis can be obtained by simply inspecting the initial exciton polarization angle $\theta_0$ at $F_p = 0$ kV/cm$^{-1}$ [72], which was extracted from $\Delta E = |E(\theta, F_p) - E_{\text{min}}(\theta, F_p)|$ as a function of $\theta$, where $E_{\text{min}}$ is the minimum energy of $E(\theta, F_p = 0)$. Fig. 4.10c∼g show the dependence of $\Delta E$ on $\theta$ for the five dots. The initial FSS $s_0$ and $\theta_0$ are represented by the magnitude and orientation of the lobes in each polar plot. For the dot A and B, $\theta_0$ are $102.0 \pm 0.4^0$ and $92.7 \pm 0.2^0$, suggesting positive deviations of the dot axis from the $x$ axis. Consequently, as $F_p$ is increased, the polarization angle rotate counterclockwise and the FSS experiences a finite lower bound $s_{\text{min}} = 7.2 \pm 0.2 \mu\text{eV}$ and $2.2 \pm 0.1 \mu\text{eV}$ (the green and wine curves in Fig. 4.10a and 4.10b). For dot C, $\theta_0$ is found to be $86.1 \pm 0.4^0$, which suggests a negative deviation from the $x$ axis. Thus a counter-clockwise rotation of $\theta$ over $F_p$ is observed, together with a $s_{\text{min}} = 4.2 \pm 0.2 \mu\text{eV}$ (the purple curve). For the dots D and E, $\theta_0$ is found to be $90.4 \pm 0.3^0$ and $90.6 \pm 0.3^0$ respectively, which indicate exact alignment of the dot and strain principal axes. The polarization angles for both dots rotate clockwise as the strain is varied, and this implies that the dot axes are oriented at angles slightly less than $90^0$. It should be noted that this difference from the observed values (larger than $90^0$) is ascribed to the limited alignment precision of the polarizer (within a few degrees) [53]. Most importantly, owing to this exact alignment between the dot strain axes for dot D and E, their FSS can be reduced well below 1 $\mu\text{eV}$ and $s_{\text{min}}$ is found to be $0.3 \pm 0.25 \mu\text{eV}$ and $0.6 \pm 0.2 \mu\text{eV}$ respectively. By simply treating the anisotropic strain as an effective uniaxial strain [64], the behavior of
s and \( \theta \) are well fitted (solid lines in Fig. 4.10a and 4.10b). The minimum reachable FSS value, following the form \( s_{\text{min}} = s_0 \sin(2\theta) \), is determined only by \( s_0 \) and \( \theta_0 \). The \( s_{\text{min}} \) predicted before varying the strain fields are: 8.18\( \pm \)0.2 \( \mu \)eV, 2.34\( \pm \)0.2 \( \mu \)eV, 3.3\( \pm \)0.2 \( \mu \)eV, 0.24\( \pm \)0.3 \( \mu \)eV and 0.76\( \pm \)0.1 \( \mu \)eV for dot A, B, C, D, E, which show excellent agreement with our experimental data. From the above experimental observations and theoretical analysis, it is clearly seen that, in order to cancel the FSS with our external strain fields, the polarization angle at zero applied stress should be as close as possible to the strain principal axes.

The data shown above prove that the same tuning effect has been achieved as that of the vertical electric field [53, 60]. Both of them restore the degeneracy of the two bright exciton states by deforming the QD confinement potentials along [110] and [1-10] crystal axes. However, the vertical strain field induces deformations along the two axes with almost same rates, which is due to the fact that the dipole moments of the two exciton eigenstates for In(Ga)As-GaAs QDs differ by only a few percents. This gives rise to a poor FSS tuning rate of about \(-0.285\pm0.019 \mu eV/cm\) [60]. Therefore, an extremely large electric field is necessarily required to achieve a giant stark shift (> 20 meV) in order to access the minimum FSS experimentally [53, 60, 61]. In contrast to the vertical electric field, the anisotropic strain tuning technique presented here could facilitate such deformation restoration process as it causes opposite deformation trends along [110] and [1-10] crystal axes, which results in a much more efficient tuning rate of FSS in the experiment (typically 1.1~2.0\( \mu \)eV/cm).

### 4.3 Quantitative characterization of two-photon polarization entanglement

It has been already shown that the FSS in the strain-tunable quantum-LED device can be effectively controlled and tuned to be almost zero value. The ability to tune the FSS to zero in the strain-tunable quantum LED allows for electrically triggered generation of the polarization-entangled photon pairs without any post filtering techniques [126, 127].

#### 4.3.1 Two-photon polarization entanglement

Fig. 2.15 shows the experimental setup for measuring the two-photon polarization entanglement. The device was loaded in the helium flow cryostat and it was cooled to 5 K. Meanwhile, the high frequency feed-through are used, which can enable injection of the ultra-fast electrical voltage pulses in order to achieve electrically triggered entangled-photon pairs emission, and more details about this high frequency electrical pulse injection can be referred in the chapter 4.

In the optical measurements, the EL from QDs is extracted and collected by a 50\( \times \) objective with NA=0.42. Then the EL is sent to a 50:50 beam splitter (BS1) and divided into two paths. Each of the paths is directed to a spectrometer in order to pick up the XX and X respectively. After each spectrometer, there is a HBT setup, consisting
of a polarization beam splitter (PBS1 and PBS2 in Fig. 2.15) and two high efficiency
APDs. The four APDs, used for detecting different polarization projection states of XX
(APD3 and APD4) and X (APD1 and APD2), are connected to four channels of a time
correlator (HydraHarp-400, Picoquant, GbmH). Each of the four channels acquires photon
registration event with time-tag information independently.

Table 4.1: Angles set for projection states of XX and X

<table>
<thead>
<tr>
<th>Mode of XX</th>
<th>$q_1$</th>
<th>$h_1$</th>
<th>Mode of X</th>
<th>$q_1$</th>
<th>$h_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>0°</td>
<td>0°</td>
<td>V</td>
<td>0°</td>
<td>0°</td>
</tr>
<tr>
<td>H</td>
<td>0°</td>
<td>45°</td>
<td>H</td>
<td>0°</td>
<td>45°</td>
</tr>
<tr>
<td>D</td>
<td>45°</td>
<td>22.5°</td>
<td>D</td>
<td>45°</td>
<td>22.5°</td>
</tr>
<tr>
<td>A</td>
<td>45°</td>
<td>22.5°</td>
<td>A</td>
<td>45°</td>
<td>22.5°</td>
</tr>
<tr>
<td>R</td>
<td>0°</td>
<td>22.5°</td>
<td>R</td>
<td>0°</td>
<td>22.5°</td>
</tr>
<tr>
<td>L</td>
<td>90°</td>
<td>22.5°</td>
<td>L</td>
<td>90°</td>
<td>22.5°</td>
</tr>
</tbody>
</table>

The polarization entanglement state produced in the biexciton cascade has different
form depending on the given basis: rectilinear (HV), diagonal (DA) and circular basis
(LR). The H (V) is denoted as horizontally (vertically) linear polarization with respect to
the optical table, and D(A) present a linear polarization rotated by 45° with respect to
HV base, and is termed by diagonal (anti-diagonal) polarization. Note that the DA and
RL basis can be expressed in terms of the HV basis:

$$D = \frac{1}{\sqrt{2}} (H + V)$$

$$A = \frac{1}{\sqrt{2}} (H - V)$$

$$L = \frac{1}{\sqrt{2}} (H + iV)$$

$$R = \frac{1}{\sqrt{2}} (H - iV)$$

In these three different bases, the polarization entanglement state can be written
as

$$|\Psi_{HV}^{+}\rangle = \frac{1}{\sqrt{2}}(|H_{XX}H_X\rangle + |V_{XX}V_X\rangle),$$

$$|\Psi_{DA}^{+}\rangle = \frac{1}{\sqrt{2}}(|D_{XX}D_X\rangle + |A_{XX}A_X\rangle),$$

$$|\Psi_{RL}^{+}\rangle = \frac{1}{\sqrt{2}}(|R_{XX}L_X\rangle + |L_{XX}R_X\rangle).$$

With these different forms of entanglement state, one can expect a strong polarization
correlation between the co-polarized XX and X photons in the HV and DA bases, and anti-
correlation in the RL basis. This theoretical prediction provides an experimental route
to characterize the two-photon polarization entanglement: characterize the second-order
polarization correlation in different bases.

In order to measure the polarization correlation of the XX and X photon pairs, the
different projection states in given basis is needed to prepared. This can be accomplished
by inserting a quarter-wave plate ($q_1$ and $q_2$) and a half-wave plate ($h_1$ and $h_2$) in the
optical path. With this experimental arrangement as shown in Fig. 2.15, the angles of the
fast axes of the wave-plates can be set arbitrarily, which allows the V (or H) projection
state to be rotated into any polarization state[128].
By using the Jones matrix method, the polarization states of the light could be depicted by a matrix, for instance, the vertically-polarized photon $V$ and horizontally-polarized photon $H$ can be expressed by

$$V = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \quad H = \begin{bmatrix} 1 \\ 0 \end{bmatrix}. $$

Similarly, the optical component can also be expressed with the Jones matrix convention. For example, the quarter and half wave plates with fast axis at angle $q_i$ and $h_i$ ($i = 1, 2$) with respect to the vertical axis are expressed by the $2 \times 2$ matrices

$$T_{Q}(q_i) = \frac{1}{\sqrt{2}} \begin{bmatrix} i - \cos(2q_i) & \sin(2q_i) \\ \sin(2q_i) & i + \cos(2q_i) \end{bmatrix}, \quad T_{H}(h_i) = \frac{1}{\sqrt{2}} \begin{bmatrix} \cos(2h_i) & -\sin(2h_i) \\ -\sin(2h_i) & -\cos(2h_i) \end{bmatrix}. $$

(4.16)

By using these simple conventions, the projection states of the $V$-polarized photon before the quarter and half wave plates can be conveniently obtained

$$|\Psi_{\text{proj}}(q_i, h_i)\rangle = T_{Q}(q_i) \cdot T_{H}(h_i) \cdot \begin{bmatrix} 0 \\ 1 \end{bmatrix}. $$

(4.17)

According to Eq. 4.16 and Eq. 4.17, the projection states of D, A, R, L can be obtained by setting $q_i$ and $h_i$ to the angles shown in the TABLE 4.1.

With these settings, the polarization correlation of the biexciton and exciton can be evaluated, and thereby the entanglement can be quantified.

### 4.3.2 Degree of the polarization correlation

To access the polarization properties of the XX-X photon pair, co- and cross-polarization correlations are measured in a given basis, so that the degree of the polarization correlation ($C$) can be measured

$$C_{\text{basis}} = \frac{g^{(2)}_{XX,X} - g^{(2)}_{XX,X}}{g^{(2)}_{XX,X} + g^{(2)}_{XX,X}}, $$

(4.18)

where $g^{(2)}_{XX,X}$ and $g^{(2)}_{XX,X}$ are normalized co- and cross-polarization correlations which can be measured by making use of the setup shown in Fig. 2.15. Experimental test $C_{\text{basis}} = 0, 1$ and -1 indicate non-correlation, maximum correlation and maximum anti-correlation between the XX and X photons. For an ideal two-photon polarization entangled state, the degree of the polarization correlation in the HV, DA and RL basis will be 1, 1 and -1 respectively. Correspondingly, the entanglement fidelity ($f^+$), representing a physical overlap of the measured state and the maximally-entangled state, $|\Psi^+\rangle$, can be calculated [60, 129–131]

$$f^+ = (1 + C_{HV} + C_{DA} - C_{RL})/4. $$

(4.19)

From Eq. 4.19, for an ideal entangled-photon source, the above experimental test gives $f^+ = 1$, while for a source possessing only classical polarization correlations, $f^+ = 0.5$. The value of 0.5 is referred to as a ‘classical-limit’. 
Fig. 4.11 shows the experimental results of the two-photon polarization correlations for the dot which was tuned to have (a) very large FSS and (b) almost zero FSS with the external strain fields. When the FSS was tuned to be $11\mu eV$, the dot only shows strong polarization correlation in the HV basis, and no significant correlation is observed in the DA and RL bases (see Fig. 4.11a). These behaviors indicate that the XX and X photons only show classical radiative cascade emission. Furthermore, the degree of the polarization correlation in the three bases are found to be $C_{HV} = 0.65$, $C_{DA} = 0.1$ and $C_{RL} = -0.1$, and the fidelity is $f^+ = 0.46 < 0.5$. Apparently, the dot with large finite FSS has no entangled-photon pair emission, which is consistent with the previous statements.

Once the FSS was tuned to be close zero, significantly, pronounced correlations appear in both DA and RL bases. Fig. 4.11b shows strong correlations in the rectilinear and diagonal bases at zero FSS. The degree of these correlations are found to be $C_{HV} = 0.70$, $C_{DA} = 0.64$. While in RL basis, a remarkable anti-correlation is measured and the degree of the polarization correlation is found to be $C_{RL} = -0.62$. Subsequently, the fidelity is found

$$f^+ (|s| = 0) = \frac{1 + C_{HV} + C_{DA} - C_{RL}}{4} = \frac{1 + 0.7 + 0.64 + 0.62}{4} = 0.74.$$ 

The fidelity is calculated at $\tau = 0$ and is found to be upper than 0.5 without any background subtraction, which proves that entangled photons has been electrically generated from the strain-tunable quantum LED device.
4.3.3 Two-photon quantum tomography

In contrast to calculating the degree of the polarization correlation, one could employ another way to characterize two-photon state entanglement: density matrix representation. The density matrix is widely employed in quantum information processing field in that it is an outstanding method to be used to distinguish entanglement state from pure state and mixed state.

Considering the anticipated entanglement state from the biexciton cascade is one of the four Bell states (see Eq. 4.13), its density matrix expanded in the HV basis is

\[
\hat{\rho} = \frac{1}{2} (|\Psi^+\rangle \langle \Psi^+| + |H_{xx}H_x\rangle \langle H_{xx}H_x| + |V_{xx}V_x\rangle \langle V_{xx}V_x|) 
\]

\[
= \begin{pmatrix}
\frac{1}{2} & 0 & 0 & 0 & \frac{1}{2} \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
\frac{1}{2} & 0 & 0 & 0 & \frac{1}{2}
\end{pmatrix},
\]

(4.20)

in which the strong outer diagonal elements demonstrate a high probability that the XX-X photon pair has the same linear polarization states. The inner diagonal elements represent a probability of the XX-X photon pair having opposite polarization, i.e. \(H_{xx}\) and \(V_{xx}\) and \(H_x\). Particularly, the outer off-diagonal elements, representing a superposition of the two photon wavefunction, is a signature of entanglement. For classical light, these elements should be zero, while for two-photon entanglement state, especially for the maximally entangled Bell state, they will be 0.5. In this sense, the density matrix \(\hat{\rho}\) provides a comprehensive method to evidence whether the entanglement appears between the XX and X photon. Hence, it is highly desirable to construct density matrix in my thesis in order to fully characterize the entanglement properties.

In order to uniquely determine the density matrix for the XX and X entangled-photon pair in the measurement, at least 16 polarization correlation measurements are required as there are 16 unknown variables in the density matrix \(\hat{\rho}\). Following the procedure presented in Ref [128], 16 polarization correlation measurements were carried out so that the coincidence counts \(n_1, n_2, ..., n_{16}\) are obtained. Then the following formula is used to calculate the density matrix

\[
\hat{\rho} = (\sum_{\nu=1}^{16} \hat{M}_{\nu} n_\nu) / (\sum_{\nu=1}^{4} n_\nu).
\]

(4.21)

Fig. 4.12 plots 16 co- and cross-polarization correlations of the XX and X photon pairs emitted from the strain-tunable LED. The dot is driven by a fast electrical pulse stream with repetition rate of \(f = 185 MHz\), amplitude of \(V_{pp} = -8.0 V\) and pulse duration of 300 ps. The DC bias is \(V_d = -1.65V\). Similar to the pure DC power excitation case, in the rectilinear and diagonal basis, co-polarized two photons show strong positive correlation at zero-time delay. The opposite behavior is seen clearly in the circular basis: cross-polarized two photons show positive correlation. This indicates that under such electrical pulses excitation the XX and X are polarization-entangled. Remarkably, apart
Figure 4.12: Tomographic measurements of the co- and cross-polarization correlations of the exciton X and the biexciton XX in given bases. The dot in the strain-tunable LED has almost zero FSS (∼ 0.6µeV), and it is driven by electrical pulses.

from the center peak, all other peaks are periodic and the temporal distance are well separated by 5.4 ns, which is consistent with the electrical pulse excitation repetition rate.

In order to construct the density matrix $\hat{\rho}$, a temporal window of 3 ns centered around the zero-time delay is applied to extract integration coincidence counts $n_1, n_2, ..., n_{16}$. These coincidence counts are then used to calculate the density matrix of the XX and X photon pairs. Applying Eq. 4.21 $\hat{\rho}$ is found to be

$$
\hat{\rho} = \begin{pmatrix}
0.451 + 0.0i & -0.026 - 0.074i & -0.0839 - 0.055i & 0.338 - 0.072i \\
-0.026 + 0.0745i & 0.084 + 0.0i & 0.188 - 0.073i & -0.031 + 0.0249i \\
-0.083 + 0.055i & 0.188 + 0.073i & 0.107 + 0.0i & 0.013 - 0.073i \\
0.338 + 0.072i & -0.031 - 0.025i & 0.013 + 0.0739i & 0.358 + 0.0i
\end{pmatrix}.
$$

This density matrix can be graphically shown in Fig. 4.13, in which the “strong” diagonal components in real part of density matrix demonstrate the high probability of the two photons with same polarizations, whereas the suppressed inner diagonal components...
4 Triggered entangled-photon emission from strain-tunable quantum-LED

Figure 4.13: Color encoded real (left panel) and imaginary components of the density matrix extracted from the above tomographic measurements. It is worth noticing that the residual elements are not zero. The contribution of these non-zero elements could probably be from many factors: background light from environment or sample; secondly, scattering of the exciton spin states \([132]\) and uncorrelated photons in such large integration window of 3 ns. Noticeably, the lifetime of the X and XX are found to be about 1.0 ns and 400 ps respectively, which implies that each emission cycle of the photon pair occurs in the range of 1.4 ns. Hence, a smaller time window should be chosen so that the coincidence counts from the same cascade should be taken.

Figure 4.14: Color encoded real (left panel) and imaginary components of the density matrix extracted from the above tomographic measurements with 1.5 ns temporal window.

Fig. 4.14 shows the density matrix \(\hat{\rho}\) constructed by using 1.5 ns time integration window. It is seen that the four components on corners are slightly improved, which could be likely arising from the exclusion of the uncorrelated photons from the different cascade cycle. However, the residual components remains at similar value even though the integration window is reduced and further some components in the density matrix are found to be negative. This violates the important property of a physical density matrix, i.e., positivity. Thus in order to avoid this problem, A numerical method, termed
4.3 Quantitative characterization of two-photon polarization entanglement

Maximum Likelihood Estimation (MLE), can be employed to construct a more precise density matrix which can fulfill the most conditions such as normalization, Hermiticity and positivity.

The route of using the MLE method is as follows: (i) generate a “physical” density matrix \( \hat{\rho}_p(t_1, ..., t_{16}) \) with 16 real variables \( t_1, ..., t_{16} \). (ii) find a suitable “likelihood” function which contains the 16 \( t_i \) (\( i = 1, ..., 16 \)) parameters and 16 experimental coincidence counts \( n_i \) (\( i = 1, ..., 16 \)) which is able to quantify how good the density matrix is in relation to the experimental data. This “likelihood” function can be denoted as \( L(t_1, ..., t_{16}; n_1, ..., n_{16}) \). (iii) Thereafter, use standard numerical optimization techniques to find an optimized set of \( t_i^{opt} \) at which the “likelihood” function have maximum value. As a consequence, the optimized density matrix \( \hat{\rho}(t_1^{opt}, ..., t_{16}^{opt}) \) will represent the best density matrix closest to the real one.

Generally, the “likelihood” function has following form

\[
L(t_1, ..., t_{16}; n_1, ..., n_{16}) = \sum_{\nu} \frac{[N < \psi_{\nu} | \hat{\rho}_p(t_1, ..., t_{16}) | \psi_{\nu} > - n_{\nu}]^2}{2N < \psi_{\nu} | \hat{\rho}_p(t_1, ..., t_{16}) | \psi_{\nu} >},
\]

(4.22)

where \( < \psi_{\nu} | \hat{\rho}_p(t_1, ..., t_{16}) | \psi_{\nu} > \) is expected coincidence count in the given state \( | \psi_{\nu} > \). The core operation of the MLE is to optimize such likelihood function in terms of the variables \( t_1, ..., t_{16} \). Applying the MLE method, the density matrix is constructed and it is shown in Fig. 4.15.

**Figure 4.15**: Color encoded real density matrix constructed by using numerical MLE method. **(a)** Real and imaginary components of the density matrix for 3 ns temporal window. **(b)** Density matrix for 1.5 ns temporal window.

From the density matrix constructed by using the MLE method, the residual components are well suppressed and have an average value of about 0.025, which could
probably from the dark counts of the detectors. Furthermore, two significant components appear in the imaginary part, which indicates a phase in the entanglement state.

### 4.3.4 Entanglement test parameters

In order to fully characterize the entanglement from the density matrix, a number of measures have been proposed to quantify the entanglement of the XX and X photons [133].

**Fidelity**  As stated before, the fidelity is a measure of a state overlapping to the ideal entanglement state and it is defined as

\[
    f^+ = \left( \text{Tr} \sqrt{\hat{\rho}_i \hat{\rho}_m \sqrt{\hat{\rho}_i}} \right)^2.
\]

where \( \hat{\rho}_i \) and \( \hat{\rho}_m \) are the density matrix for the ideal entanglement state and the experimentally measured state. The formula can be simplified as

\[
    f^+ = | \langle \Psi_i | \Psi_m \rangle |^2.
\]

**Concurrence** Concurrence is measure of the non-classical properties of a quantum state. For two-photon entanglement state, concurrence is defined as follows: first consider the non-Hermitian matrix \( \hat{R} = \hat{\rho} \hat{\sum} \hat{\rho}^T \hat{\sum} \) in which \( \hat{\rho}^T \) is the transpose matrices of density matrix \( \hat{\rho} \), and \( \hat{\sum} \) is defined

\[
    \hat{\sum} = \begin{pmatrix}
    0 & 0 & 0 & -1 \\
    0 & 0 & 1 & 0 \\
    0 & 1 & 0 & 0 \\
    -1 & 0 & 0 & 0
    \end{pmatrix}.
\]

Secondly, solve \( \hat{R} \) to get all the eigenvalues and sorted them in a increasing order: \( r_1, r_2, r_3 \) and \( r_4 \). Finally, the concurrence is defined as

\[
    C = \max\{0, \sqrt{r_4} - \sqrt{r_3} - \sqrt{r_2} - \sqrt{r_1}\}.
\]

**Tangle** Tangle represents an almost similar physical meaning as the concurrence, and it is

\[
    T = C^2.
\]

**Entanglement of formation** Entanglement of formation stands for the number of maximally entangled-photon pairs over the total generated photon pairs. It is given by

\[
    E_F = h\left(1 + \frac{1 - C^2}{2}\right),
\]

where the function \( h(x) \) has the form: \( h(x) = -x \log_2 x - (1-x) \log_2 (1-x) \).

**Entropy (S) and Linear Entropy (S_L)** Both of them quantify a degree of mixture in measured quantum state. They are given by [134]

\[
    S = -\text{Tr}\{\hat{\rho} \log_2 (\hat{\rho})\} = - \sum_i \lambda_i \log_2 \lambda_i
\]

\[
    S_L = \frac{4}{3} (1 - \text{Tr}\{\hat{\rho}\}) = \frac{4}{3} (1 - \sum_i \lambda_i^2)
\]
4.4 High speed polarization entangled-photon generation

Table 4.2: Quantitative measures of density matrix \( \rho \) performed on the dot embedded in a diode with almost zero FSS, which is tuned by external strain field.

<table>
<thead>
<tr>
<th>Test Description</th>
<th>Test Limit</th>
<th>Test Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>((HH + VV)/\sqrt{2}) projection</td>
<td>&gt; 0.5</td>
<td>0.74</td>
</tr>
<tr>
<td>Concurrence</td>
<td>&gt; 0</td>
<td>0.638</td>
</tr>
<tr>
<td>Tangle</td>
<td>&gt; 0</td>
<td>0.407</td>
</tr>
<tr>
<td>Entanglement of formation</td>
<td>&gt; 0</td>
<td>0.515</td>
</tr>
<tr>
<td>Largest eigenvalue</td>
<td>&gt; 0.5</td>
<td>0.82</td>
</tr>
<tr>
<td>Eigenvector</td>
<td>((</td>
<td>HH\rangle +</td>
</tr>
<tr>
<td>Peres [135]</td>
<td>&lt; 0</td>
<td>-0.32</td>
</tr>
</tbody>
</table>

in which \( \lambda_i \) is the \( i \)th eigenvalue of the density matrix \( \hat{\rho} \).

Based on the density matrix acquired in Fig. 4.15, the above tests are extracted and shown in TABLE 4.2. All these tests in each case exceed the classical limit, proving that the quantum state obtained in our experiment is highly entangled.

Peres criterion tells that if a density matrix is in-separable, and it is a necessary and sufficient condition to be satisfied for actual entangled state: the matrix must have at least one negative eigenvalue. Remarkably, Peres criterion gives a much more strict judgment for entanglement state than others.

4.4 High speed polarization entangled-photon generation

In particular, the device demonstrated here is capable of emitting high-speed entangled-photon pairs once high-frequency electrical pulses are applied. Analogous to the demonstration of high-speed single-photon emission in last chapter, it is of great importance to realize high-speed entangled photons as one can boost the speed of future quantum information processing. In this section, the feasibility of high-speed emission of entangled-photon pairs from the strain-tunable ELED is realized.

4.4.1 400 MHz entangled-photon pairs generation

Fig. 4.16 shows polarization correlation in the H-V, D-A and R-L bases. The dot is excited with a DC bias \( V_d = -1.6V \) superimposed with a fast electrical pulses which has amplitude of -0.6V, pulse duration of 300 ps. The ERR was set to 400 MHz. From time resolved polarization correlations, it can be found that apart from the peak at zero-delay time, they are separated in time by 2.5 ns, which is consistent with the ERR of 400 MHz. As clearly shown from Fig. 4.16(a) to (f), correlations for photon pair owning the same polarizations shows positive correlation in rectilinear and diagonal bases, while anti-correlation in circular basis. This suggests that the photon pairs are polarization-entangled even
4 Triggered entangled-photon emission from strain-tunable quantum-LED

Figure 4.16: Co- and cross-polarization correlations between XX and X under pulsed electrical excitation measured in the rectilinear, diagonal and circular bases with a time resolution of 0.125 ns. Correlations measured for photons of the same polarizations are shown in blue. Significantly, in circular basis, the photon pair with orthogonal polarizations are positive correlated. This provides a signature of entanglement.

Note that the fidelity at 400 MHz is smaller than the fidelity at 185 MHz reported above. This is likely ascribed to the contribution of a small amount of uncorrelated photon pairs due to the time-dependent re-excitation process, finite FSS and the background emission \cite{129, 131, 136}. By applying a well-defined temporal gate centered at zero delay time in polarization correlations, such time-dependent processes can be effectively excluded. The red curves in Fig. 4.17 show the enhanced degree of correlation when a temporal gate of 0.8 ns is applied, in which the degree of correlation increases obviously: $C_{HV} = 0.67 \pm 0.06$, $C_{DA} = 0.63 \pm 0.04$ and $C_{RL} = -0.78 \pm 0.07$. These give $f^+ = 0.77 \pm 0.03$. Remarkably, the degree of correlation and entanglement fidelity can be significantly improved by further shortening the temporal gate. With the narrowest available gate width of 0.1 ns applied, the degrees of correlation are substantially improved: $C_{HV} = 0.74 \pm 0.12$, $C_{DA} = 0.74 \pm 0.09$ and $C_{RL} = -0.84 \pm 0.12$, which defines the highest fidelity of 0.83 $\pm$ 0.05. In addition, it is also possible to determine the Bell parameters $S_{RD}$, $S_{RC}$ and $S_{DC}$ with the degrees of correlation obtained at 0.1 ns gate width, and we find that $S_{RD} = 2.09 \pm 0.15$, $S_{RC} = 2.23 \pm 0.17$ and $S_{DC} = 2.23 \pm 0.15$. All of the three Bell parameters have violated the Bell’s inequality, which proves that the strain-tunable ELED can be reliably used for advanced quantum information applications.
such as quantum relay.

Figure 4.17: Polarization correlation results from electrically pulsed injection into the LED at repetition rate of 400 MHz. Degree of correlation C in given basis, in which correlation in HV and DA bases (C > 0) and anti-correlation (C < 0) in RL basis are obtained without temporal gate (left panel) and with a temporal gate width of 0.8 ns (right panel).

Fig. 4.18 shows fidelity and Bell’s parameters as a function of temporal gate width, which is applied on the co- and cross-polarization correlations at the excitation repetition rate of 400 MHz as shown in Fig. 4.16. By narrowing the gate width from 2.0 to 0.1 ns, the fidelity increases drastically from $0.66 \pm 0.02$ to $0.83 \pm 0.05$. In the experiments, it is clearly seen that all the three Bell parameters increase rapidly as the gate width decreases. Moreover, $S_{RD}$ is found smaller than $S_{RC}$ and $S_{DC}$ and this is because the highest degree of correlation is obtained in circular basis for most cases [61, 129]. C. L. Salter et al., pointed out that, for actual entangled state, $S_{RD}$ is not necessarily optimized to test Bell’s inequality. Based on this consideration, only the $S_{RC}$ and $S_{DC}$ Bell parameters are considered. It is found from the above plot that $S_{RC}$ and $S_{DC}$ become greater than 2 as the gate width is narrowed down to 0.8 ns, which are indicators of violation of Bell’s inequality on the corresponding plane of the Poincâtre sphere. Particularly, as the gate width of 0.1 ns is applied, all the three Bell parameters have shown violation of Bell’s inequality by at least 1 standard deviation.

4.5 Statistics measurement

The final important feature of the device worth mentioning is a high yield of dots allowing for entangled light sources. Table 4.3 summarizes entanglement results for the other three dots, which were characterized in terms of fidelity. The high fidelities, exceeding the classical limit of 0.5, suggest all these dots have been successfully tuned to be ‘good’ entangled light sources via the external strain field. It is however time-consuming to
perform polarization correlation spectroscopy on a large number of dots. For an estimation purpose, a FSS-dependent entanglement fidelity $f^+$ for a single strain-tuned QD was measured (see Fig. 4.19). It is clearly shown that a Lorentzian function fits the data excellently and the entanglement fidelity $f^+$ exceeds the classical limit of 0.5 as the FSS was tuned to below $\sim 3 \, \mu eV$. Considering a roughly constant QD lifetime of about 1.3 ns in the device [66], a FSS of $\sim 3 \, \mu eV$ provides an upper limit for observing the entanglement in the sample. This value is consistent with the previous reports on InGaAs QDs and thus indicates a tolerance of entanglement to small fluctuations in the FSS [114, 129, 132]. Furthermore, a statistics measurement on $s_{\text{min}}$ for the dots was carried out, from which 82 dots were randomly selected and studied. The statistics reveals that 27 dots (32.9%) can be well tuned below $3 \, \mu eV$ via the anisotropic strain field, and noticeably 9 out of them (11%) can be tuned well below 1 $\mu eV$. Therefore the probability of selecting suitable dots for high-degree entanglement is very high in the strain tunable ELED. These results are significant improvements to those in traditional QD systems grown on [001] GaAs substrate, and are comparable to the result (15% of all dots) in the pyramid QD arrays on [111] GaAs substrate [106], where, however, the electrical injection has not been realized yet.

In conclusion, an electrically triggered strain-tunable ELED is demonstrated, in which a versatile strain ‘tuning-knob’ is integrated to control the FSS of the dots embedded within the $p-i-n$ diode. A substantially enhanced yield of dots, allowing for polarization entangled-photon emission, has been achieved through application of the specific

![Figure 4.18: (a) Fidelity as a function of the temporal gate width. (b) Bell parameters $S_{RD}$, $S_{RC}$ and $S_{RD}$ as a function of the gate width.](image)

Table 4.3: Summary of entanglement results for other three dots

<table>
<thead>
<tr>
<th>dots</th>
<th>X (eV)</th>
<th>XX (eV)</th>
<th>$V_d$ (V)</th>
<th>$S_{\text{min}}$ (µeV)</th>
<th>$f^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.4127</td>
<td>1.4122</td>
<td>-1.75</td>
<td>0.30±0.25</td>
<td>0.72±0.03</td>
</tr>
<tr>
<td>2</td>
<td>1.4013</td>
<td>1.4000</td>
<td>-1.98</td>
<td>0.20±0.30</td>
<td>0.75±0.02</td>
</tr>
<tr>
<td>3</td>
<td>1.4000</td>
<td>1.3993</td>
<td>-2.05</td>
<td>0.60±0.20</td>
<td>0.71±0.02</td>
</tr>
</tbody>
</table>
Figure 4.19: (a) $s_{\min}$ as function of exciton energy $E_x$. (b) Fidelity as function of the tuned FSS of a single strain-tuned QD. (c) A statistical histogram of the distribution of $s_{\min}$ (red) and their initial FSS $s_0$ (black).

anisotropic in-plane strain filed. This is the major improvement to the only demonstrated ELED by C. L. Salter, et al. [129], where only $\sim 1\%$ of dots, showing naturally small FSS, can be used as polarization entangled light sources. With this device, fast electrically trigged entangled-photon emission with the highest excitation repetition rate of 400 MHz has been realized. The device demonstrated here suggests an attractive route towards the fabrication of ultra-compact all-electrically operated ‘on-demand’ sources of polarization-entangled photon pairs, which can be further exploited in practical large-scale quantum communication and quantum computation.
5 Single photons on-demand from light-hole excitons in GaAs QDs

In this chapter, a novel triggered SPS based on light-hole excitonic transitions in strain-engineered QDs is demonstrated. Such new type of SPS would facilitate realization of an all-semiconductor quantum interface, which can play a key role in future quantum network application. In this work, the concept of quantum state transfer will be firstly introduced, and then followed by a depiction of a semiconductor quantum interface. Thereafter, a novel droplet GaAs QD with confined LH-ground-state is introduced. In the end, experimental realization of wavelength-tunable and deterministic LH single-photon emission from these QDs are demonstrated.

5.1 Semiconductor-based quantum state transfer

Photon-mediated quantum state transfer has attracted considerable attention recently. It provides an indispensable building block for realizing a quantum interface for coherent interconversion of one physical form of quantum bit (qubit) to another, which plays a key role in establishing a scalable quantum network. In many envisioned schemes, this quantum interface can be realized by using atom or ion systems as they can provide suitable stationary atomic qubit, for instance, a two-level state [137, 138]. Fig. 5.1 shows an example of such atomic state transfer based on $^{40}Ga^+$ ions confined in a linear Paul trap. In order to implement the state transfer, the following procedures are taken. Degeneracy of the $^2S_{1/2}$ state is firstly removed to create an electronic superposition state between $|S\rangle = |^2S_{1/2}, m_j = 1/2\rangle$ and $|S'\rangle = |^2S_{1/2}, m_j = -1/2\rangle$. Then, photon excitation results in the state transfer from atomic states to the polarization states of the emitted photon. The entire state transfer procedure can be formalized as follows[138]:

$$(cos\alpha|S\rangle + e^{i\theta}sin\alpha|S'\rangle) \otimes |0\rangle \implies |D\rangle \otimes (cos\alpha|H\rangle + e^{i\theta}sin\alpha|V\rangle) \quad (5.1)$$

Particularly, the experimental realization of such coherent state transfer between stationary qubit and flying qubit provides an intriguing route to implement the foreseeable scalable quantum communication. However, most atomic systems are in vapor phase.
and require complex trapping setup, which makes the atomic systems cumbersome to be applied in real quantum networks.

This drawback can be overcome by employing semiconductors as the state transferring media. The idea was proposed by R. Vrijen and E. Yablonovitch in 2000 [55] and it relies on the angular momentum conservation. A right-handed circularly polarized light, owning angular momentum \( m_j = 1 \), could be coupled with an electron with \( m_{e,z} = -1/2 \) in the CB and a hole with \( m_{h,z} = -3/2 \) in the VB, while a left-handed circularly polarized light \( (m_j = -1) \) could be coupled with an electron with \( m_{e,z} = 1/2 \) and a hole with \( m_{h,z} = 3/2 \).

Hence, a superposition of the polarization states will create

\[
\alpha |+1> + \beta |-1> \rightarrow \alpha |m_{e,z} = -1/2, m_{h,z} = -3/2 > + \\
\beta |m_{e,z} = 1/2, m_{h,z} = 3/2 > .
\]

Actually, Eq. 5.2 represents a state transfer from the polarization states of light onto the entangled state of an electron and a heavy-hole. But this state transfer is undesirable as the polarization states couple to both the electron and the hole. Therefore, one would have to maintain the coherence of both electron and hole in quantum information processing. This is an extremely challenging task as this electron-hole entangled state is prone to collapse due to the interaction with the rest of system. Recent experimental works suggest that, by using a semiconductor material with LH ground-state, such state transfer could be manipulated practically. If a semiconductor e. g., GaAs, is subject to a sufficient tensile strain, LH bands in the VB will be lifted up over the HH bands and become the topmost band. Accounting for the small \( g_e \) and larger \( g_{lh} \), one could expect a giant energetic separation between the two hole states \( m_{h,z} = 1/2, m_{h,z} = -1/2 \) and negligible Zeeman splitting between two electron states \( m_{e,z} = 1/2, m_{e,z} = -1/2 \) as shown in Fig. 5.2.

Considering the envelop function of the topmost LH ground-state

\[
|\Psi >_{lh} = |m_{h,z} = 1/2 > = \alpha |m_l = 0, m_s = 1/2 > + \beta |m_l = 1, m_s = -1/2 > ,
\]

the interaction of the semiconductor with external light field is mainly determined by the spatial part. A light with polarization perpendicular to the growth direction will change
5.1 Semiconductor-based quantum state transfer

![Figure 5.2: Sketch of coherent quantum state transfer from a superposition of linear polarization states of light to semiconductor with LH ground hole state.](image)

The left shows a Bloch sphere representing a superposition of polarization state $\alpha|\hsup{1/2}{x}\rangle + \beta|\hsup{1/2}{z}\rangle$. The right shows removal of degeneracy of LH and electron states, and their Zeeman splits are determined by $g$-factors.

magnetic quantum number $m_l$ and thus its polarization state can be transferred to electron spin state of $m_s = -1/2$, while a light with polarization parallel to the growth direction cannot change $m_l$, and it will be mapped onto the electron spin state $m_s = 1/2$. As a result, a superposition of these two orthogonally linear polarizations can be subsequently transferred to the electron spin states coherently:

$$\alpha|\hsup{1/2}{x}\rangle + \beta|\hsup{1/2}{z}\rangle \rightarrow |m_{h,z} = 1/2\rangle \otimes (\alpha|m_s = 1/2\rangle + \beta|m_s = -1/2\rangle). \quad (5.4)$$

Apparently, the prerequisite of using the above envisioned scheme to implement the quantum state transfer, is to prepare suited semiconductor with LH ground-state. Recently a break-through was made by Kosaka and co-workers [56]. In their studies, by employing large discrepancy between the $g$-factors of electrons and LHs confined in a semiconductor quantum well, they demonstrated a coherent state transfer from classical light onto electron spins. This represents a remarkable progress towards an all-semiconductor quantum interface application. However, the study is based on a conventional semiconductor quantum well with valence-band ground states of dominated HH type, whereas the LH states are lower in energy. Rapid relaxation of the LH states to the HH states thus prevents using this strategy to achieve the inverse electron-spin-to-photon interconversion. In addition, a quantum well is a two-dimensional system and does not allow storage and generation of single qubits. In this context, a QD with LH ground states appears very promising, because it may allow for bidirectional interconversion between the states of single stationary and flying qubits.

So far, LH ground-state excitons have been realized in pyramidal GaAs/AlGaAs quantum dot-in-dot heterostructure [58], however, the studied QD system is prone to broad LH emission spectra due to charged impurities. This hampers their practical applications in the field of quantum communications. The recent demonstration of droplet GaAs/AlAs QDs with LH ground-state exciton has proved to possess bright LH photon emission with narrow line width [59], but until now triggered LH single-photon emission, wavelength-tunable, which is critical for above quantum interface application has not been demonstrated yet.

In the next, a novel design of QD heterostructure with LH ground states will be
introduced, and their fundamental optical properties are depicted in the $k \cdot p$ framework [59]. Experimental verification of LH photon emission from symmetric and asymmetric QDs via polarization-resolved, excitation power-dependent and polarization cross-correlation measurements, is performed. In the end, wavelength-tunable and triggered LH single-photon emission from such novel quantum dot with LH ground states is realized.

5.2 Optical characterization of the LH Exciton photon emission

As introduced in the previous section already about the sample of GaAs QDs with LH ground-states (see Fig. 2.12), after removal of the sacrificial layer in diluted HF solution (concentration of 25%), the compressed stressor layers expand and induce an in-plane ($xy$ plane) biaxial tension of about 0.4% to the GaAs QDs. This feature results in the switching of the hole GS from a dominant HH character to a dominant LH character (see more in Ref. [59]). Thereafter, the free-standing QDs nanomembranes were transferred onto a 200-$\mu$m-thick piezoelectric crystal PMN-PT via Au-to-Au thermo-compressive bonding as illustrated in Fig. 2.12. When an electric field $F_p (//z)$ is applied, an in-plane biaxial strain field from the PMN-PT actuator will act on the QDs nanomembranes. This allows for a precise tuning of the emission wavelength of single photons emitted from the LH excitons.

5.2.1 Physical properties of the LH exciton

A pure LH exciton in three-dimensionally confined QDs consists an electron and a LH with single-particle spin states $|S_e, S_{e,z} > = |1/2, \pm 1/2 >$ and $J_{lh}, J_{lh,z} > = |1/2, \pm 1/2 >$ (see Fig. 2.12). In total spin angular momentum representation $J_z = J_{lh,z} + S_{e,z}$, these single-particle states give rise to four LH exciton states $| + 1 > = | + 1/2, +1/2 >$, $| + 0 > = | + 1/2, -1/2 >$, $| - 0 > = | - 1/2, +1/2 >$ and $| - 1 > = | - 1/2, -1/2 >$. The presence of spin exchange interaction (see Eq. 4.3) leads to four LH excitonic eigenstates, which are denoted as

$$|B_1 > = \frac{1}{\sqrt{2}}(| - 1 > - | + 1 >),$$

$$|B_2 > = \frac{1}{\sqrt{2}}(| - 1 > + | + 1 >),$$

$$|B_3 > = \frac{1}{\sqrt{2}}(| - 0 > + | 0 >),$$

$$|D_1 > = \frac{1}{\sqrt{2}}(| - 0 > - | 0 >).$$

In order to correlate the polarization of the LH emission to the above LH exciton eigenstates and obtain the transition strength, optical transition dipole moments between the electron state $|e >$ and the LH state $|lh >$ are found to be

$$f_{e-lh} = < e | \varepsilon \cdot p | lh >,$$
5.2 Optical characterization of the LH Exciton photon emission

where ε is electric field vector of light and p is the LH exciton dipole moment. Accordingly, the transition strength of above four eigenstates can be found

\[ f_1 = \langle e | \varepsilon \cdot p | B_1 \rangle = \frac{\varepsilon_x}{\sqrt{3}} \Pi \] (5.6a)

\[ f_2 = \langle e | \varepsilon \cdot p | B_2 \rangle = -i \frac{\varepsilon_y}{\sqrt{3}} \Pi \] (5.6b)

\[ f_3 = \langle e | \varepsilon \cdot p | B_3 \rangle = \frac{2\varepsilon_z}{\sqrt{3}} \Pi \] (5.6c)

\[ f_4 = \langle e | \varepsilon \cdot p | D_1 \rangle = 0, \] (5.6d)

where \( \Pi = \langle s | p_x | x \rangle = \langle s | p_x | y \rangle = \langle s | p_z | z \rangle \) [139], they can be obtained by expressing \(|J, J_z\rangle\) in a combination of eigenfunctions of orbital angular momentum and spin state.

From above derivation, it is found that the eigenstates \(|B_1\rangle, |B_2\rangle, |B_3\rangle\) are optically allowed bright exciton states, while \(|D_1\rangle\) has 0 transition strength hence it is an optically forbidden dark state. Moreover, the transition strength, corresponding to the three bright LH excitonic eigenstates, are oriented along \(x, y, z\) direction respectively. Additionally, amplitude of the \(z\)-oriented (or along [001] growth direction) transition strength is 2 times larger than others, which implies the light emission along \(z\) axis is 4 time than other two directions.

Provided that the energetic differences (referred to as FSS) are large, the bright eigenstates can be thought as electric dipoles aligned along the [110], [1-10] and [001] crystallographic axis, respectively [60]. These states will be mapped onto the linear polarizations of emitted photons in optical measurements. Specifically, the \(|B_1\rangle\) and \(|B_2\rangle\) eigenstates can couple to the in-plane linearly polarized light, and the corresponding emission lines are denoted here as \(I_1\) and \(I_2\), while the \(|B_3\rangle\) eigenstate can only couple to out-of-plane (/\(z\)) linearly polarized light, denoted as \(I_3\).

5.2.2 Experimental verification of photon emission from the LH excitons

Before presenting experimental results, the extraction efficiency of LH photon emission from both type of symmetric and asymmetric tensile-stressed GaAs QDs is firstly determined. As stated already, the relevant three orthogonally polarized emissions from light-hole (LH) exciton, corresponding to \(|B_1\rangle, |B_2\rangle, |B_3\rangle\), can be thought as three dipole moments aligned along [110], [1-10] and [001] crystal axis, respectively. For type I QDs, the shape is symmetric and hence their dipole moments overlay these crystal axis (suppose \(x, z, y\) axis in cardinal coordinates). While for type II asymmetric QDs, the three dipole moments are titled slightly away from the crystal directions, and therefore their polarization directions are not exactly along the defined crystal directions.

The photon collection efficiency is firstly considered for \(|B_1\rangle, |B_2\rangle, \) dipole moments, which overlay [110], [1-10] and [001] crystal direction. Provided that these dipoles are embedded inside an air/GaAs/air planar cavity as in the QDs-containing nanomembrane after releasing from substrate. Therefore, for the in-plane orientated dipole \(|B_1\rangle, |B_2\rangle, \) a lens with NA of 0.42, placed along \(z\) direction can collect the photons in an angle of
Single photons on-demand from light-hole excitons in GaAs QDs

Figure 5.3: (a) Statistics of the tilt angle for the asymmetric QDs with respect to the growth direction extracted from the AFM data. The Gaussian fit gives the mean angle $\theta_0$ is about 6°. (b) Orientation of the dipoles $B_1$ and $B_3$ (solid lines) for the asymmetric GaAs QDs with respect to $B_x$ and $B_z$ in a symmetric QDs.

$$\sin^{-1}(NA/n_{GaAs})$$ with efficiency $\eta$ [88, 140]

$$\eta = [1 - (n_{GaAs} - 1)(n_{GaAs} + 1)]^2 \times (2 - \frac{1}{2} \cdot \cos(\sin^{-1}\left(\frac{NA}{n_{GaAs}}\right))) - \frac{1}{8} \cdot \cos^3(\sin^{-1}\left(\frac{NA}{n_{GaAs}}\right)),$$ (5.7)

$n_{GaAs}$ is the refractive index of GaAs at 790 nm, $n_{GaAs} = 3.5$. Based on above simple model, one can estimate the photon collection efficiency for $B_x$, $B_y$ and $B_z$ is 0.37%, 0.37% and 0, respectively. This implies for type I symmetric QDs, the third LH emission can not be collected by the top-placed objective and it can be only accessible by a cleaved-edge objective along $x$ (or $y$) axis [58, 59].

While for type II QDs, the axes of such QDs are slightly tilted away from the crystal directions because of the special growth protocol, so that the potential profiles of the confined excitons are also tilted. Thus the polarization directions of the dipole moments in the sample are not exactly along the defined crystal directions. For simplicity the tilt angle $\theta$ is evaluated from the AFM image (see Fig. 2.14 and statistics in Fig. 5.3). As the dipole directions in the dots are tilted, polarization directions of $B_1$ and $B_3$ are rotated by about 6° with respect to the growth direction, $z$, which is given by the statistical characterization of 30 QDs (see Fig. 5.3a). It should be pointed out that $B_2$ is equivalent with $B_1$ which is not shown. To simplify the analysis, only $B_1$ is considered. In Fig. 5.3b (solid lines), the projections of $B_3$ and $B_1$ on [110] axis are indicated with red and blue dash line. These non-zero projections ensure that the photons emitted from both dipoles of $B_1$ and $B_3$ can be collected by the lens placed along $z$ direction.

Alternatively, the tilted dipole corresponding to $B_1$ and $B_3$ can be confirmed in PL measurements. Before the LH QDs-containing nanomembrane was transferred onto the PMN-PT substrate, the polarization resolved PL spectroscopy from the cleave-edge of the nanomembrane along $x$ axis were measured as shown in Fig. 5.4. In order to determine the dipole orientations, the optical axis of the polarizer and half-wave plate are carefully aligned along the crystallographic direction [110] (y axis in Fig. 5.4b). A typical
Figure 5.4: (a) Polarization resolved spectrum of a single QD from the cleave-edge of the LH QDs-containing nanomembrane. (b) Configuration for collecting the PL along x axis and the optical axes of the polarizer and the half-wave plate are aligned along [110] axis (not shown). (c) The intensity polar diagrams for the LE and HE components shown in (a), which corresponds to the in-plane dipole $B_1$ and out-of-plane $B_3$ dipole respectively. (d) Tilt angles of $B_1$ and $B_3$ dipoles with respect to [110] direction for 6 studied dots. The average difference between the orientations of $B_1$ and $B_3$ dipoles is denoted as $\delta$.

polarization resolved spectrum of a single QD from the cleave-edge of the nanomembrane is shown in Fig. 5.4, from which two linear polarized emission are observed. Based on the previous discussions, these two linear polarized emissions are ascribed to the emission of the in-plane dipole $B_1$ and out-of-plane $B_3$, respectively; and the in-plane polarized emission $B_1$ contributes the low energy (LE) component, while the out-of-plane polarized emission $B_3$ contributes the high energy (HE) component. By plotting the intensity polar diagram for these two dipoles, their orientation with respect to the crystallographic axis [110] or [001] can be subsequently determined. As shown in Fig. 5.4c, the tilt angle with respect to the [110] for the in-plane dipole $B_1$ and out-of-plane $B_3$ dipoles can be extracted: $\varphi(B_1) = 170.8^\circ$ and $\varphi(B_3) = 76.6^\circ$. This reflects that the $B_1$ dipole is tilted by $9.2^\circ$ away from the [110] direction and the $B_3$ dipole is $13.4^\circ$ away from the [001] axis (z axis). In this measurement, 6 dots are measured and their tilt angles for $B_1$ and $B_3$ dipoles are summarized in Fig. 5.4d. As a result, the average tilt angles for these two dipoles are found $\varphi(B_1) = 172.2^\circ$ and $\varphi(B_3) = 80.6^\circ$. Then we can find that the orientation of $B_1$ dipole is tilted by $7.8^\circ$ with respect to the [110] axis, and $B_3$ dipole is tilted by $9.4^\circ$ with respect to the [001] axis. It is noticeable that this result is in agreement with
5 Single photons on-demand from light-hole excitons in GaAs QDs

the above estimation from the AFM image.

5.2.3 PL spectrum of the LH exciton photon emission

LH photon emission from type I symmetric QDs

Figure 5.5: Top (∥z) and side (⊥z) PL collection for verifying LH photon emission from type I QDs. Top panel shows PL spectrum collected normal to the sample surface. Two sharp emission lines, corresponding to in-plane LH exciton photon emission, have FWHM of about 30 µeV. Lower panel shows a spectrum taken from the same QD with a side collection PL setup (⊥z). Figure courtesy of Y.H. Huo in Ref. [59].

Fig. 5.5 plots spectra taken from the same QD by top and side collection PL setup. The upper panel shows two bright and narrow emission lines and they are separated by a small value in energy. Indeed these two lines are contributed to light emission stemming from $B_1$ and $B_2$ dipole moment. The ultra small energetic separation is due to high symmetry of the dot shape and it’s actually referred to as in-plane FSS (FSS$_{in}$). In bottom panel, a spectrum collected by a side PL setup is shown. It contains three peaks resolved in polarization mapping, in which low energy components are from in-plane polarization emission lines, and additional higher energy component can be ascribed to emission from the third dipole moment of the LH exciton, $B_3$. In contrast to density of in-plane emission lines, this out-of-plane emission line has higher intensity and this is expected from the transition strength in Eq. 5.6c and Eq. 5.6b.

LH photon emission from type II asymmetric QDs

Representative polarization-resolved spectra of the LH photon emission from type II asymmetric QDs are shown in Fig. 5.6a. The plot clearly shows three linearly polarized emission
lines, which are attributed to $I_1$, $I_2$ and $I_3$ respectively. $I_3$ becomes the dominant spectral feature when PL is collected from the sample side, indicating that this line is mostly polarized along the growth direction. To further characterize the LH exciton emission, the excitation power-dependent measurement were performed and the results are plotted in Fig. 5.6b. The power law, $I \propto P^\alpha$ is used to fit the experimental data and exponents of the power-law $\alpha$, corresponding to the $[I_1 + I_2]$ and $I_3$ are estimated to be $1.08 \pm 0.02$ and $1.17 \pm 0.02$. Such linear dependences on the excitation power support the assumption that all the three emission lines stem from the neutral excitonic transitions. Further, cross-correlation measurements between each of the three emission lines were carried out. In Fig. 5.6c, the upper panel shows the cross-correlation between the two in-plane polarized emission lines, $I_1$ and $I_2$, and the lower panel is the cross-correlation between the in-plane and the out-of-plane polarized emission lines, $I_1$ and $I_3$. Pronounced symmetric anti-bunching dips at zero-time delay for both correlations $g^{(2)}(0) = 0.33$ and $0.23$ are found, which suggest that these emission lines are from different recombination channels of the same neutral exciton state in the studied QD. With these results, sufficient evidence of single photon emission from a LH neutral exciton with three emission lines is undoubtedly provided.

### 5.3 Wavelength-tunable and optically triggered LH single-photon emission

#### 5.3.1 Wavelength-tunable LH photon emission

Interfacing remote nodes in a quantum network requires the initialization of qubits in the same state and the communication between nodes via indistinguishable single photons [47]. Unlike natural atoms or ions, the inhomogeneous spectral broadening of self-assembled QDs is a big challenge for the realization of this scheme. In Fig. 5.5 and
Fig. 5.6, the preparation of excitons with LH ground state in a semiconductor QD have studied, which can be used for the coherent state transfer from photon qubit to electron qubit, as already shown by Kosaka et al. with a quantum well [56]. The basic ingredient for this scheme is a substantially larger in-plane g-factor for the LH state compared to the electron, which is the case for the QDs studied here [B. J. Witek et al. (in preparation)]. Now, one of the most important elements for a LH-based reversible quantum interface is a ‘tuning knob’ for the ground state energy levels of different QDs, which facilitates the direct state transfer from the photon qubit emitted by one QD to the electron qubit in another QD. Such a tunability is demonstrated with the LH QDs in Fig. 5.7. An electric field $F_p$ was applied to the PMN-PT actuator to generate an in-plane strain field on the QDs and a series of PL spectra from the dot A were recorded as a function of $F_p$. Compared to the emission wavelength at $F_p = 0$ kV/cm, the LH single-photon emission can be blue-shifted (red-shifted) when a positive (negative) electric field is applied [50, 62, 66, 72]. The total wavelength was tuned by about 5 nm (10 meV in energy) as $F_p$ varied from -20 to 50 kV/cm. In the meantime, autocorrelation measurements were carried out for the wavelength-shifted LH emission. At $F_p = -20$ and 50 kV/cm, it is observed that the wavelength of the in-plane polarized LH exciton emission is shifted to 1.5615 eV (794.11 nm) and 1.5715 eV (789.16 nm), respectively.

![Figure 5.7](image_url)

Figure 5.7: Wavelength tuning of the LH single-photon emission as a function of $F_p$ from -40 to 50 kV/cm. A positive (negative) electric field corresponds to a compressive (tensile) strain field.

### 5.3.2 Optical triggered LH single-photon emission

Of most interest is the pulsed optical operation of the above device. This allows controlling the time of generation of excitons, and thereby realizing triggered LH single-photon emission. In order to achieve this, the diode laser was used to drive the QDs and meanwhile the second-order time correlation function was measured under pulsed excitation. Fig. 5.8b shows the unnormalized autocorrelation function of the in-plane polarized exciton emission at $F_p = 0$ kV/cm. The quantum nature of LH photon emission is revealed by...
the significantly suppressed peak at zero-time delay. The normalized correlation function for this peak shows $g^{(2)}(0) = 0.20 \pm 0.12$. This finite value represents a multiphoton emission probability that likely arises from the weak background emission from the sample rather than the QD. In addition to the vanishing peak at zero-time delay, periodic peaks in the autocorrelation measurement are also observed. This provides an unambiguous signature of a triggered LH single-photon emission.

The autocorrelation results at the other two tuned wavelengths (794.11 nm at $F_p = -20$ kV/cm and 789.16 nm at $F_p = 50$ kV/cm) are shown in Fig. 5.8a and 5.8c, from which $g^{(2)}(0) = 0.22 \pm 0.10$ and $0.18 \pm 0.08$ are found. These results indicate that the optical properties of the LH SPS can be accurately tuned, and stable single-photon emission during the tuning process is preserved.

### 5.4 Coherence time of the LH single photons

One of the important parameters for single-photon qubits is a long coherence time, as this not only determines the maximum number of possible qubit operations, but also the efficiency of the coupling between independent quantum systems [2, 141]. In this work, the coherence time of the triggered LH single-photon emission was studied by a Michelson interferometer inserted in the PL optical path. The interferometer consists of two arms. One arm is equipped with a fixed retroreflector, and the other one is equipped with a retroreflector, which is translated by the combination of a mechanical translation stage and a piezodriven stage (see Fig. 5.9a). The interference signal was acquired by the spectrometer and the integrated interference intensity as a function of the optical path difference $\Delta L$ was recorded [142–144]. The results for a typical LH QD (dot B) are shown in Fig.5.9. Figure 5.9b shows interference fringe visibility of the in-plane polarized LH photon emission lines from dot B (green rectangular area is the integration window of 0.12 nm). The visibility is defined as $V = (I_{\text{max}} - I_{\text{min}})/(I_{\text{max}} + I_{\text{min}})$, where $I_{\text{max}}$ and $I_{\text{min}}$ are the maximum and minimum integrated peak intensities from the interference fringes. It is clearly seen that the visibility is as high as 95% at $\Delta L = 0$ mm, see the left inset in Fig. 5.9b and decreases with increasing $\Delta L$. When $\Delta L = 15$ mm, the interference
fringes become extremely weak and the visibility drops to about 9% (see the right inset of Fig. 5.9b). After acquiring the visibilities at different positions defined by the mechanical stage, a coherence length (or coherence time) is extracted by fitting the curve with a single exponential function $V(\tau) = c \exp(-\tau/T_2)$, where the coherence time $T_2$ is found to be $34 \pm 2.3$ ps. From the inverse Fourier transform, a homogeneous line width of about 32 $\mu$eV is deduced. It is noticeable that the coherence time reported here for the LH single-photon emission is comparable to that of HH single-photon emission from GaAs QDs grown by the similar droplet method [144]. Time-resolved PL measurements were used to determine the lifetime $T_1$ for the LH single-photon emission, see open symbols in Fig. 5.9c. By fitting the decay curves with a single exponential decay function, a lifetime of 636 ps for in-plane polarized and 670 ps for out-of-plane polarized emission lines were extracted. The similar radiative decay times for both polarized emission lines of the LH photon emission further support their common origin as discussed above. The large difference between $T_1$ and $T_2$ implies that a strong dephasing process occurs in the sample. This is ascribed to the non-resonant excitation, which leads to the creation of free charge carriers in the vicinity of the QD interacting with carriers confined in the QD [143, 145]. Recent studies have shown that such dephasing processes can be substantially suppressed under resonant excitation conditions and thereby the coherence time can be drastically enhanced [141, 146].

In summary, a novel triggered and wavelength-tunable LH single-photon source has been demonstrated, which is based on well-designed tensile-strained GaAs QDs. The LH photon emission, characterized by three linearly polarized emission lines, is explicitly verified in a series of PL measurements, including polarization-resolved, power-dependent, and photon-correlation measurements. The triggered single-photon emission from the LH neutral exciton is manifested in the second-order time autocorrelation measurements. By in-
Integrating the LH QD-containing nanomembrane onto a PMN-PT actuator, a broad wavelength tuning for the triggered LH single-photon emission has been successfully achieved. The observed low multiphoton emission probabilities $g^{(2)}(0)$ values imply that the energy tuning by the externally induced strain fields does not deteriorate the emission properties. In addition, the coherence time of the LH single-photon emission has been studied by Michelson interferometry for the first time, and a coherence time of about 34 ps for the LH exciton is found. Further improvements, including growth optimization and resonant excitation, are necessary to improve the coherence of LH single photons from such QDs. It can be predicted that, combining with an external magnetic field in the Voigt geometry, the demonstrated triggered LH SPS opens up a possibility to realize an all-semiconductor two-way quantum interface between single photons and spin qubits.
6 Conclusions and outlook

6.1 Conclusion

SPSs and entangled-photon sources play are central parts in photonic quantum information processing. In this thesis, strain-tunable QD-based single- and entangled-photon sources have been successfully demonstrated, which would provide flexible and robust non-classical light sources for future quantum information applications.

In the first part of this thesis, an all-electrically driven single-photon-emitting diode has been demonstrated, which allows for the generation of triggered, wavelength-tunable single photons. This device is based on a QD-containing LED nanomembrane integrated onto a 300 μm-thick PMN-PT piezoelectric crystal. The energy of QD emission lines can be precisely and stably tuned over a broad range by varying the voltage applied to the PMN-PT. It is shown that the triggered single-photon-emitting characteristic of this diode is well maintained during the strain-controlled wavelength tuning. Together with the ability of shortening the exciton decay time by band-bending at low DC voltages, which can increase the ERR up to 0.8 GHz, the device realized in the thesis represents a promising way to achieve indistinguishable single-photon emission from two remote single-photon-emitting diodes at high repetition rates.

In the second part, fast on-demand entangled-photon emission from the strain-tunable quantum-LED was demonstrated. The generation of a high degree of entangled-photon emission from the diode has been shown. Under both d.c. and pulsed current injection, the two-photon polarization entanglement was characterized through measuring the degree of polarization-correlation and constructing the quantum tomography, from which fidelity of the entanglement was found to be about 0.83. In addition, the diode could be engineered to emit high frequency entangled-photon pairs of up to 400 MHz. Noticeably, this value is the highest ERR that so far ever reported. In particular, the biggest breakthrough is, by using the strain-tuning technique, that we have achieved a substantial high yield of applicable dots (about 32.9% ), which may allow for polarization-entangled quantum emitter on a single nanomembrane diode. With this strain-tunable quantum-LED, one can envisage to apply it in future entanglement swapping and quantum repeater applications.

Thirdly, a novel triggered and wavelength-tunable LH single-photon source based on well-designed tensile-strained GaAs QDs is successfully realized. The LH photon emission, characterized by three linearly polarized emission lines, is explicitly verified through polarization-resolved, power-dependent and photon-correlation measurements. The triggered single-photon emission from the LH neutral exciton is manifested in the second-order
time autocorrelation measurements. By integrating the LH QDs-containing nanomembrane onto the PMN-PT actuator, a broad wavelength tuning for the triggered LH single-photon emission was achieved. The observed low multi-photon emission probabilities \( g^{(2)}(0) \) values imply that the energy tuning by the externally-induced strain fields does not deteriorate the emission properties. In addition, the coherence time of the LH single-photon emission has been studied by Michelson interferometry for the first time, and a coherence time of about 34 ps for the LH exciton is found. Further improvements, including growth optimization and resonant excitation, are necessary to improve the coherence of LH single photons from such QDs. By combining with an external magnetic field in the Voigt geometry, the demonstrated triggered LH SPS opens up a possibility to realize an all-semiconductor two-way quantum interface between single photons and spin qubits.

### 6.2 Outlook

In this thesis, a versatile single- and entangled-photon sources has been realized, which can be envisaged as potential candidates for quantum information processing. Most importantly, the QDs-based devices reported here can satisfy the most requirements in the “wish list” of an idea single-photon emitter, i.e., electrically driving, triggering, wavelength tuning, high excitation repetition rate, etc. However, some other features, which are not available in the device right now, are also required. Here we list these requirements as our future directions:

1. The collection efficiency of the single and entangled photons from the strain-tunable quantum-LED must be increased in the future. This can be accomplished by integrating the diode with some photonic microcavities, for instance, micropillars and photonic crystals.

2. The issue of the low operation temperature must be solved. At present, most of QDs devices have to be cooled down to liquid-helium temperature (\( \sim 4K \)) in order to avoid phonon effects.

3. There is a strong demand of the single and entangled photon emission with telecoms wavelength, as it can be compatible with the current fiber communication network.

4. The research of LH single-photon emission is still in infancy, and further intensive investigations are required.
Bibliography


Appendix

The $\hat{M}$ matrices, used in Eq. 4.21 are as follows:

$$\hat{M}_1 = \frac{1}{2} \begin{pmatrix} 2 & -(1+i) & -i & 1 \\ -(1+i) & 0 & -(1+i) & 0 \\ -i & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix} , \quad \hat{M}_2 = \frac{1}{2} \begin{pmatrix} 0 & -1 & 0 & 1 \\ -(1+i) & 2 & i & -(1+i) \\ 0 & -i & 0 & 0 \\ 1 & -(1-i) & 0 & 0 \end{pmatrix}$$

$$\hat{M}_3 = \frac{1}{2} \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & i & -(1+i) \\ 0 & -i & 0 & -(1-i) \\ 1 & -(1-i) & -(1+i) & 2 \end{pmatrix} , \quad \hat{M}_4 = \frac{1}{2} \begin{pmatrix} 0 & 0 & -(1+i) & 1 \\ 0 & 0 & i & 0 \\ -(1-i) & -i & 2 & -(1-i) \\ 0 & 1 & -(1+i) & 0 \end{pmatrix}$$

$$\hat{M}_5 = \frac{1}{2} \begin{pmatrix} 0 & 0 & 2i & -(1+i) \\ 0 & 2i & -(1+i) & 0 \\ 0 & 0 & 0 & 0 \\ -(1-i) & 0 & 0 & 0 \end{pmatrix} , \quad \hat{M}_6 = \frac{1}{2} \begin{pmatrix} 0 & 0 & 0 & -(1+i) \\ 0 & 0 & 2 & -(1+i) \\ 0 & 0 & 0 & 0 \\ -(1-i) & -2i & 0 & 0 \end{pmatrix}$$

$$\hat{M}_7 = \frac{1}{2} \begin{pmatrix} 0 & 0 & 0 & -(1+i) \\ 0 & 0 & -(1+i) & 2 \\ -(1-i) & 2 & 0 & 0 \end{pmatrix} , \quad \hat{M}_8 = \frac{1}{2} \begin{pmatrix} 0 & 0 & 0 & -(1+i) \\ 0 & 0 & 2 & -(1+i) \\ 2 & -(1+i) & 0 & 0 \\ -(1-i) & 0 & 0 & 0 \end{pmatrix}$$

$$\hat{M}_9 = \begin{pmatrix} 0 & 0 & 0 & i \\ 0 & 0 & -i & 0 \\ 0 & i & 0 & 0 \\ -i & 0 & 0 & 0 \end{pmatrix} , \quad \hat{M}_{10} = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix}$$
\[ \hat{M}_{11} = \begin{pmatrix} 0 & 0 & 0 & i \\ 0 & 0 & i & 0 \\ 0 & -i & 0 & 0 \\ i & 0 & 0 & 0 \end{pmatrix} , \quad \hat{M}_{12} = \frac{1}{2} \begin{pmatrix} 0 & 2 & 0 & -(1 + i) \\ 2 & 0 & -(1 + i) & 0 \\ 0 & -(1 - i) & 0 & 0 \\ -(1 - i) & 0 & 0 & 0 \end{pmatrix} \]

\[ \hat{M}_{13} = \frac{1}{2} \begin{pmatrix} 0 & 0 & 0 & -(1 + i) \\ 0 & 0 & -(1 + i) & 0 \\ -(1 - i) & 0 & 0 & 2 \\ -(1 - i) & 0 & 2 & 0 \end{pmatrix} , \quad \hat{M}_{14} = \frac{1}{2} \begin{pmatrix} 0 & 0 & 0 & -(1 - i) \\ 0 & 0 & (1 - i) & 0 \\ 0 & (1 + i) & 0 & -2i \\ -(1 + i) & 0 & 2i & 0 \end{pmatrix} \]

\[ \hat{M}_{15} = \frac{1}{2} \begin{pmatrix} 0 & -2i & 0 & -(1 - i) \\ -2i & 0 & -(1 - i) & 0 \\ 0 & -(1 - i) & 0 & 0 \\ -(1 + i) & 0 & 0 & 0 \end{pmatrix} , \quad \hat{M}_{16} = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & -1 \end{pmatrix} \]
Acknowledgments

The PhD thesis was conducted under Prof. Dr. Oliver G. Schmidt’s supervision in Institute for Integrative Nanosciences (IIN) at IFW-Dresden and Technische Universität Chemnitz. I would like to express my deep gratitude for his devoted guidance in the research and providing me all the necessary facilities.

I would like to place on record my sincere thanks to Prof. Dr. Armando Rastelli for his great supervision, advices and supports in my research, for instructive discussions on building experimental setup and conducting experiments, and for creating a working atmosphere in the group.

I also place on record, my sense of gratitude to Dr. Fei Ding for the help and supports in my last two years of the research. I am grateful to him for the fruitful discussions and for working together as a team.

I would like to express my thanks to Dr. Rinaldo Trotta for his faithful introduction of using various experimental facilities, for many helpful discussions on finding solutions when encountering problems during the experiment.

Many thanks to Dr. Yongheng Huo and Eugenio Zallo for their generous supply of the samples which are used in most of experiments of this thesis.

I am also thankful to Barbara Eichler, Ronny Engelhard, Dr. Stefan Harazim, Dr. Stefan Baumack, Martin Bauer for their great technique supports.

Furthermore, I would like to thank my IIN colleagues, friends and external collaborators: Dr. Santosh Kumar, Dr. Plumhoff Johannes, Yan Chen, Keil Robert, Dr. Denys Makarov, Michael Zopf, Dr. Chongyun Jiang, Bianca Höfer, Madani Abbas, Robert Streubel, Shilong Li, Daniil Karnaushenko, Martin Kopte, Wildmann Johannes (JKU, Austria), Tristan Braun (Universität Würzburg, Germany). Special thank Dr. Luyang Han, Dr. Peixuan Chen and Stefan Böttner, for the nice discussions and helpful assistance in my experiments.

The financial support from China Scholarship Council (CSC, No. 2010601008) is gratefully acknowledged. Many thanks to my previous supervisors Prof. Dr. Xiaoyong Hu and Pro. Dr. Qihuang Gong at Peking University (Beijing, China) for their faithful guidance in my master studies, which influences me a lot about the way of thinking during scientific activities.

Finally, I want to thank my wife Junwen Deng, for your deep love, help and encouragement, your endless patience and ability to back up my research.
Publications and scientific presentations

Publications


Scientific Presentations


• DPG Spring meeting 2013. Talk, A Wavelength Tunable Quantum Light-emitting Diode (QLED). Hanover, Germany. March 18\textsuperscript{nd}-22\textsuperscript{nd}, 2013.


• IIN PhD student Seminar, Talk, Strain-tunable devices: from fundamental studies to technological applications. Dresden, Germany. May 3\textsuperscript{rd}, 2012.
PERSONAL INFORMATION

Birth of Place
Anhui, China
Date of Birth
04 March, 1984
Nationality
China

EDUCATION BACKGROUND

TU Chemnitz
PhD candidate
2011 ~ present
Chemitz, Germany
Peking University
MSc
2007 ~ 2010
Beijing, China
CUST, Changchun
BSc
2003 ~ 2007
Changchun, China

RESEARCH EXPERIENCE

IFW Dresden
02.2011 ~ Present

- Designed an ultra-fast electric pulses feed-through which allows for high vacuum and cryogenic environment. The setup was successfully used to send > 10 GHz broadband electric pulses to excite self-assembled QD so as to obtain ‘on-demand’ electrically driven single-photon source
- Processing strain-tunable LED device containing self-assembled QDs which is mainly used to prepare broad energy controllable (4 ~ 15 meV) electrically-driven non-classical photons source
- Build experimental setup for measuring polarization-entangled photon emission from quantum LED

Peking University
09.2007 ~ 07.2010

- Built computer-controlled optical pump-probe time-resolved setup including: 120 fs laser (Mira 900) laser, > 2 ns delay time and spectral analysis system and applied the system to research the dynamics of all-optical switch based on 2D photonic crystal slab.
- Theoreticaly design and experimentally fabricate 2D photonic crystal slab by using polymer materials.

HOBBIES

Handwriting
Fishing
Programming
Selbständigkeitserklärung


Die Dissertation wurde in dieser oder ähnlicher Form an keiner anderen Stelle zum Zwecke eines Promotionsverfahrens eingereicht. Es wurde von mir bisher kein Promotionsverfahren an anderer Stelle beantragt.

Dresden, 21. August 2015

(Jiaxiang Zhang)