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Ben Ma(马奔)[1,2,3], Si-Hang Wei(魏思航)[1,2,3], Ze-Sheng Chen(陈泽升)[1,2,3], Xiang-Jun Shang(尚向军)[1,2,3], Hai-Qiao Ni(倪海桥)[1,2,3], Zhi-Chuan Niu(牛智川)[1,2,3]

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Quantum frequency down-conversion of single photons at 1552 nm from single InAs quantum dot*

Ben Ma(马奔)[1,2,3], Si-Hang Wei(魏思航)[1,2,3], Ze-Sheng Chen(陈泽升)[1,2,3], Xiang-Jun Shang(尚向军)[1,2,3], Hai-Qiao Ni(倪海桥)[1,2,3], and Zhi-Chuan Niu(牛智川)[1,2,3,†]

[1] *State Key Laboratory of Superlattices and Microstructures, Institute of Semiconductors, Chinese Academy of Sciences, Beijing* 100083, *China*
[2] *College of Materials Science and Opto-Electronic Technology, University of Chinese Academy of Sciences, Beijing* 101418, *China*
[3] *Synergetic Innovation Center of Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei* 230026, *China*

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Near-infrared single photon sources in telecommunication bands, especially at 1550 nm, are required for long-distance quantum communication. Here a down-conversion quantum interface is implemented, where the single photons emitted from single InAs quantum dot at 864 nm is down converted to 1552 nm by using a fiber-coupled periodically poled lithium niobate (PPLN) waveguide and a 1.95 μmm pump laser, and the frequency conversion efficiency is ∼ 40%. The single-photon purity of quantum dot emission is preserved during the down-conversion process, i.e., $g^{(2)}(0)$, only 0.22 at 1552 nm. This present technique advances the III–V semiconductor quantum dots as a promising platform for long-distance quantum communication.

Keywords: quantum frequency down-conversion, quantum dot, telecommunication band, single photon

PACS: 78.67.Hc,81.07.Ta,73.21.La,42.65.Ky **DOI:** 10.1088/1674-1056/27/9/097802

1. Introduction

Long-distance quantum communication[1] has become increasingly important, which is essential for the improvement of many quantum technologies, such as quantum key distribution[2] and quantum internet.[3] Single photon sources with near-infrared wavelength at telecommunication bands is vital for efficient optical fiber communication.[4] However, traditional single layer InAs/GaAs quantum dots (QDs) emit single photons with wavelengths of 850–1000 nm,[5] which is hard to extend their wavelength to the telecommunication band, especially to 1550 nm. Although InAs/InP QDs can emit single photons in a 1550 nm wavelength range, it is difficult to combine them with a high-Q distributed Bragg reflector (DBR) cavity to realize high brightness single photon sources.[6,7] This optical frequency mismatch can be filled by a frequency conversion process[8] while preserving the photons' quantum state.[9] The optical quantum frequency conversion (QFC) has been performed using second-order nonlinearity with a periodically poled lithium niobate (PPLN) crystal, in which a photon of telecom wavelength was up-converted to a visible one.[10] This method can be used for efficient detection of photons in telecommunication bands.[11] On the other hand, quantum interfaces for frequency down-conversion from visible to telecommunication band have also been reported.[12–14]

In this letter, we implement a down-conversion quantum interface, where the single photons emitted from single InAs/GaAs quantum dot at 864 nm are down converted to 1552 nm by using a fiber-coupled PPLN waveguide and a 1.95 μm pump laser. The single-photon purity of the quantum dot emission is preserved during the down-conversion process.

2. Experimental methods

Single layer GaAs-based InAs QDs have demonstrated high-intensity single-photon emission in wavelength at 900–1000 nm. Furthermore, for some quantum memory applications,[15] single photon emission around 860 nm is necessary. Such short wavelength single photon sources can be realized by AlGaInAs QDs[16,17] which is a quaternary material and hard to control its component during growth. In this letter, InAs QDs with emission wavelength around 860 nm are realized on a GaAs/$Al_{0.3}$GaAs layer. Due to the strong Al bond strength, the surface migration of In atom is reduced, which results in smaller dots and short emission wavelengths.[17]

The samples were grown by solid source molecular beam epitaxy (MBE, VEECO Gen930 system) on semi-insulating (001) GaAs substrates. The structure of the test sample is shown in Fig. 1(a). After a 500 nm thick GaAs buffer layer growth at 580 °C, 20 nm $Al_{0.3}$GaAs was grown to decrease the migration length of the In atom. A thin layer of GaAs about 2 nm was introduced between the InAs and $Al_{0.3}$GaAs. The traditional subcritical indium deposition technique[18,19] cannot be used here. So we take the method of a gradient indium flux on the static substrate[20] and fix the growth condition of InAs (growth temperature: 540 °C, growth rate: 0.005 ml/s,indium deposition: 2.00 ml). The structure above QDs is symmetrical with the below.

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†Corresponding author. E-mail: zcniu@semi.ac.cn

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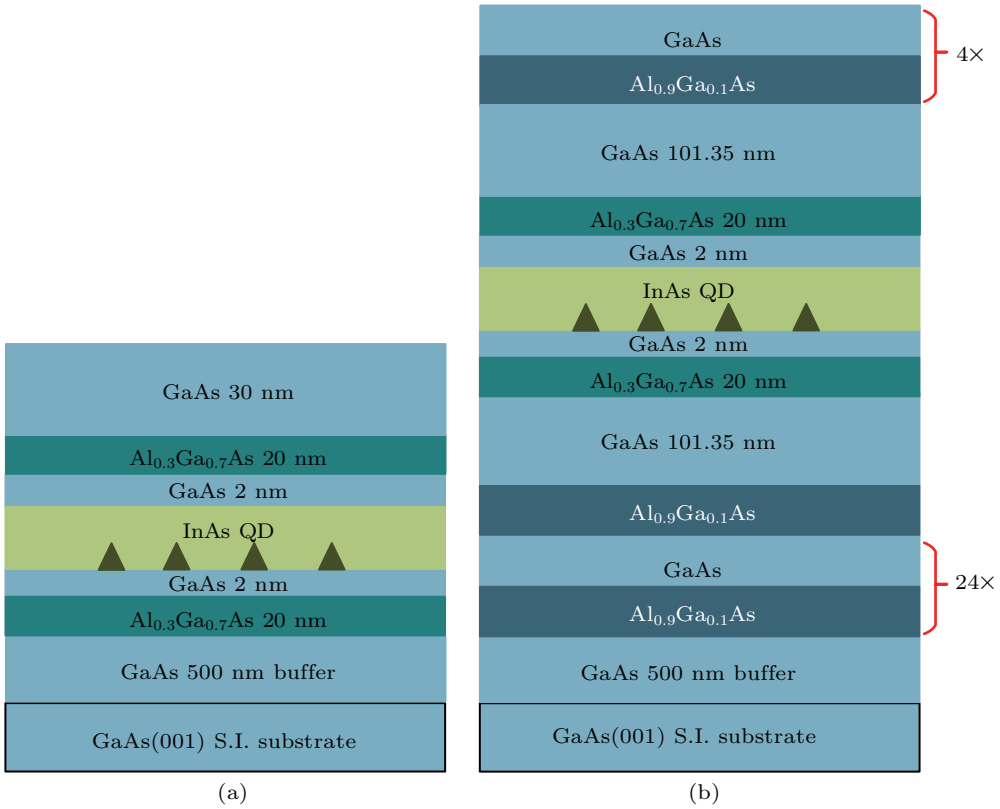


Fig. 1. (color online) Schematic structures of (a) the test sample and (b) the sample of QDs in a DBR cavity.

3. Results and discussion

3.1. μPL of short wavelength InAs quantum dot

Figure 2 shows the micro-photoluminescence (μPL) spectrum of the test sample at 77 K, where the wavelength covers a wide range of approximately 860–920 nm. Moreover, the wetting-layer emission of this test sample is located at ∼ 845 nm, which blue-shifts around 25 nm compared to that of the conventional InAs/GaAs QDs.[18] To enhance QD emission, we integrate the QDs into the DBR cavity.[21] As shown in Fig. 1(b), the structure consists of a DBR with 24 periods of $\lambda/4$ $Al_{0.9}Ga_{0.1}As$/GaAs as the bottom mirror, a 1λ thick cavity in the center, and 4 periods $Al_{0.9}Ga_{0.1}As$/GaAs DBR as the top mirror. The structure of the test sample (Fig. 1(a)) is inserted at the center of the 1λ planar cavity.

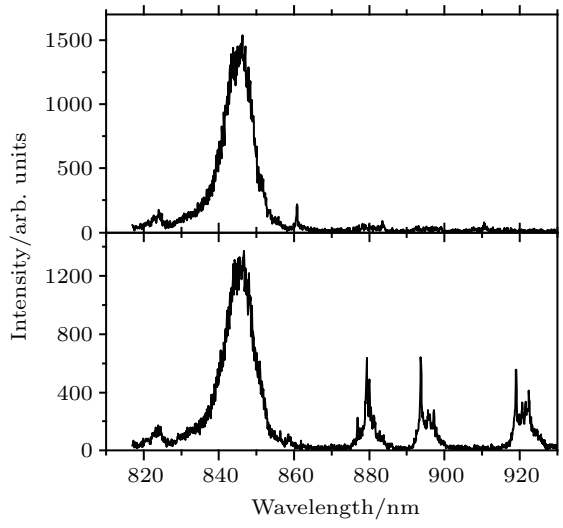


Fig. 2. μPL spectra of test sample at 77 K.

Figure 3 shows the experimental setup used for the generation and frequency conversion of single photons from a single InAs QD. One part of it consists of a confocal microscope setup for the collection light and investigation of the QD sample. This setup is combined with the frequency conversion stage including the PPLN crystal and a spectral filtering stage, which constitutes the second part of the setup.

3.2. Quantum frequency down-conversion

The quantum theory of frequency conversion using a second-order nonlinear optical interaction is shown in Ref. [12]. When the pump light at angular frequency ω_p is sufficiently strong, the quantum dynamics of a signal mode at angular frequency ω_s and a converted mode at angular frequency ω_c satisfies $\omega_c = \omega_s - \omega_p$.

We selected the QD emitting photon at 864 nm at 4 K as true single photon source. After passing through the long pass filter and beam splitter, the signal beam was coupled into a multimode fiber and sent into the PPLN crystal. A seed laser beam at 1950 nm was used as the pump light for QFC. After passing through the PPLN waveguide, the strong pump light is diminished by 1550 nm band-pass filters, and the converted light at 1552 nm is extracted, coupled into a 50/50 fiber beam splitter, and then sent into two superconducting single-photon detectors (SSPDs) for count rate and HBT measurement.

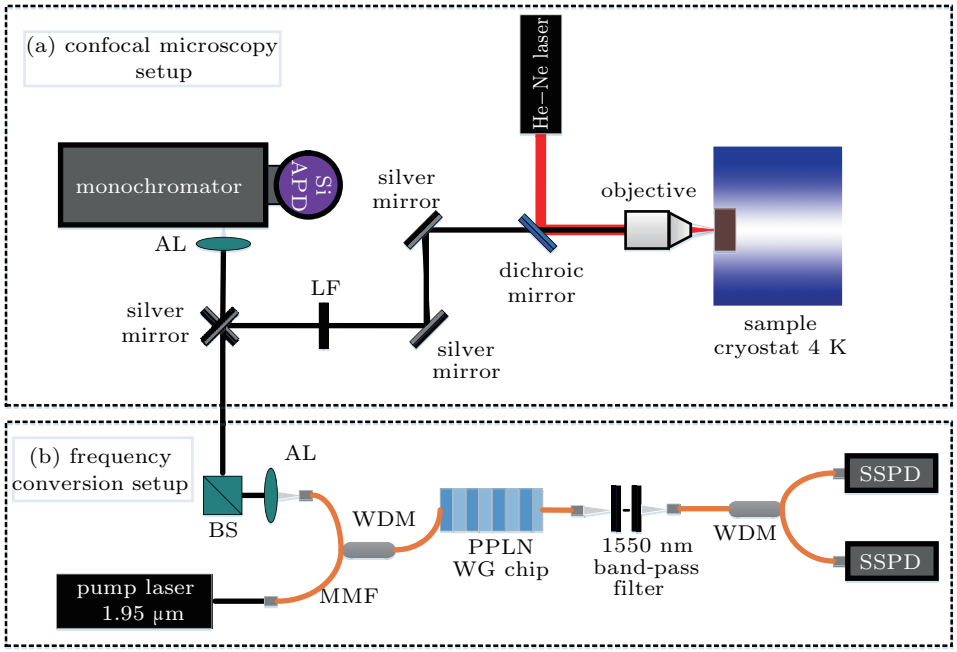


Fig. 3. (color online) Schematic of the combined experimental setup. (a) Confocal microscope for the investigation of the QD sample. (b) Frequency conversion setup. AL: aspheric lens, APD: avalanche photodiode, MMF: multimode fiber, LF: long pass filter, BS: beam splitter, SSPD: superconducting single-photon detector, WDM: wavelength division multiplex.

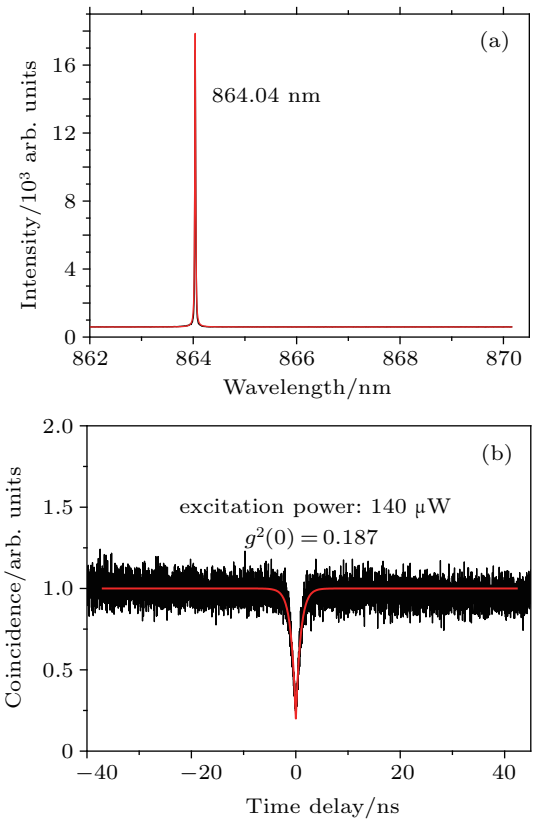


Fig. 4. (color online) Selected QD for frequency conversion experiment. (a) μPL spectra, wavelength at 864.04 nm at 4 K. (b) The $g^{(2)}(\tau)$ measurement of emission line in panel (a) under 140 μW cw excitation power, the dip to a value of $g^{(2)}(0) = 0.187$.

Figure 4(a) shows the filtrated micro-PL spectra of selected QD emitting photon at 864.04 nm at 4 K. Figure 4(b) shows the autocorrelation measurement of $g^{(2)}(\tau)$ for the QD, the dip to a value of $g^{(2)}(0) = 0.187$ under 140 μW cw excitation power. The measured nonzero $g^{(2)}(0)$ value is mainly due to the dark counts in the avalanche photodetectors (APD) and the recapture process.[22] So a true single photon emitter from a QD is presented for QFC.

As presented in Fig. 5(a), we use a laser at 864 nm to calibrate the wavelength of the converted signal which is at 1552.29 nm. The count rate of 1552.29 nm single photon stream on two SSPDs is shown in Fig. 5(b). The maximum count rate is 43 kHz when the detection efficiency of SSPD ($\sim 50\%$) is considered. To determine the signal-to-noise ratio (SNR) and conversion efficiency of our setup, we send a constant rate of single photons from the QD into the PPLN crystal with excitation power of 140 μW.

SNR given by

$$\mathrm{SNR} = \frac{N_{\mathrm{converted}} - N_{\mathrm{noise}}}{N_{\mathrm{noise}}}$$

is calculated in Fig. 5(b). We yield a maximum SNR of about 21 for 140 μW excitation power. Compared with the attenuated laser pulses, a much better SNR can be realized with quantum dots.[14]

Figure 6 shows conversion efficiency of the PPLN crystal under 140 μW cw excitation power. We measure the count rate at 1552.29 nm on two SSPDs for different pump power levels at 1950 nm between 0 and 500 mW. The conversion reaches the maximum value of 40% when the pump power of 1950 nm laser is 350 mW.

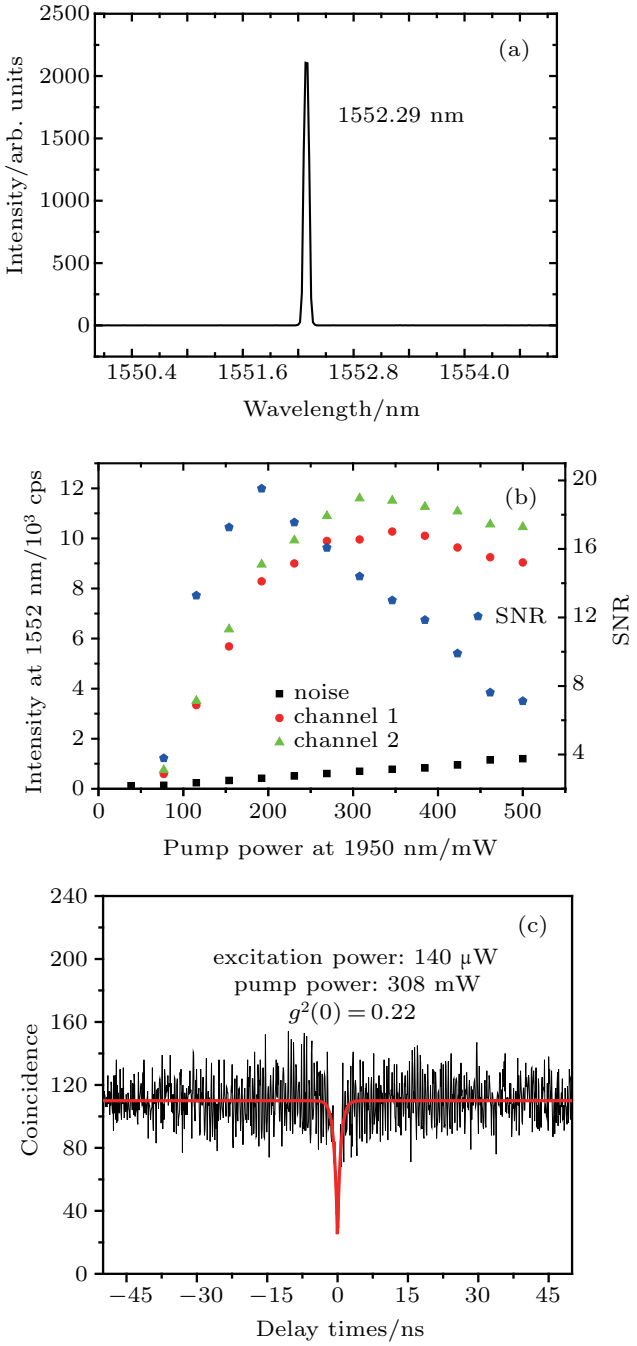


Fig. 5. (color online) (a) The wavelength of converted signal at 1552.29 nm calibrated by a laser at 864 nm. (b) The single-photon counting at 1552.29 nm using two SSPDs. The blue and red lines are count rates on different SSPDs and the black line is the noise background with excitation power of 140 μW. (c) The $g^{(2)}(\tau)$ measurement of the 1552.29 nm signal under 140 μW excitation power and 308 mW pump power.

It is crucial to test whether the anti-bunching behavior can be conserved or not during QFC. To this end, we measure the degree of second-order coherence $g^{(2)}(\tau)$ after the frequency conversion process. For the down-converted light at 1552.29 nm, we obtained $g^{(2)}(0) = 0.22$ at 140 μW excitation power and 308 mW pump power, as shown in Fig. 5(c). The observed anti-bunching again proves the conservation of the single photon character of the light after the QFC process. Compared with the attenuated laser pulses, high-purity of single photons can be realized with quantum dots.

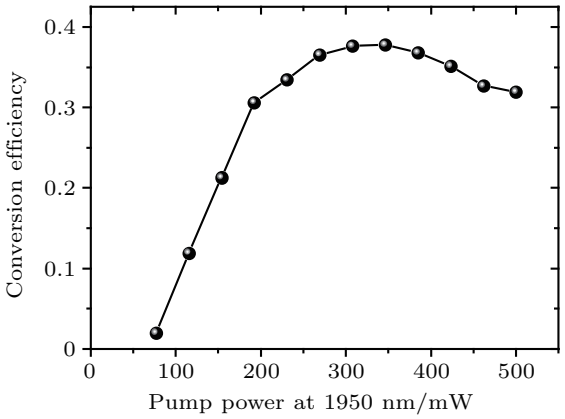


Fig. 6. (color online) Conversion efficiency of the PPLN crystal under 140 μW cw excitation power for different pump powers.

4. Conclusion

MBE growth of self-assembled quantum dots emitting photon at 860–900 nm is achieved by introducing GaAs/$Al_{0.3}$GaAs layer. Based on the QDs, frequency down-conversion of true single photon from single quantum dot at 864 nm to a telecommunication wavelength of 1552 nm is realized by using the PPLN crystal. The single-photon purity of the quantum dot emission is preserved during the down-conversion process. The second-order autocorrelation measurement yields $g^{(2)}(0) = 0.22$ of 1552 nm signal, demonstrating high-purity single-photon emission. The maximum count rate of 1552 nm single photon stream is 43 kHz. It has great scope for improvement based on the optimization of optical path efficiency. Such a quantum interface will be useful for long-distance quantum communication based on various photon emitters, such as color centers in diamond.[23]

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