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A semiconductor quantum light emitting diode for the standard telecom window around 1550 nm

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Abstract

Semiconductor sources of pure single photons and entangled photon pairs are an essential building block to implement quantum technologies over optical networks, such as communication secured by the laws of physics. Previous implementations based on gallium arsenide quantum dot devices have shown great promise in these areas. However, they typically emit light in the wavelength region between 900 nm 1350 nm, and are not compatible with the low-loss fiber telecom window around 1550 nm. Here, we develop indium phosphide based quantum dot devices to demonstrate the first LED emitting single photons around 1550 nm, as well as entangled light with fidelity of 0.87± 0.04 sufficient for the application of error correction protocols. Our quantum photon source can be directly integrated with existing long distance quantum communication and cryptography systems, and provides a new material platform for developing quantum network hardware.

1. Introduction

Entangled photon sources are a versatile basic building block for a variety of quantum network technologies. For example, they can be used in extending the range of quantum cryptography systems using the principle of teleportation [1]. While photon sources based on non-linear processes have shown considerable success in such applications even operating at the preferred wavelength of 1550 nm, their photon number statistics is Poissonian. As such, they are unsuitable for the simplest and most efficient security protocols. On the other hand, standard quantum dot LEDs based on GaAs can produce the signatures of quantum light [2], but do not operate the 1550 nm spectral region.

Here, we develop indium phosphide (InP) based semiconductor devices, which can readily reach the 1550-nm window in applications such as quantum dot lasers. The challenge here is to provide optoelectronic access to individual dots producing light with quantum signatures, i. e. single or entangled photons.

2. Device Fabrication

The key steps in fabricating our device are outlined in the schematic drawing in Fig. 1. Growth is started with an n-doped Bragg mirror consisting of 20 InP/AlInGaAs (Aluminium Indium Gallium Arsenide) pairs. This is followed by a layer of intrinsic InP upon which metallic In droplets are deposited (step I). They are crystallized under AsH_3 flow (step II), and overgrown with a further layer of intrinsic InP. A top mirror consisting of 3 pairs of p-doped InP/AlInGaAs finishes the 2-lambda cavity (step III). To enable optoelectronic operation of the device, mesas are wet-etched to the n-doped layer. Subsequently, the p-doped and n-doped layers are contacted using CrAu and a NiGeAu alloy, respectively (step IV).

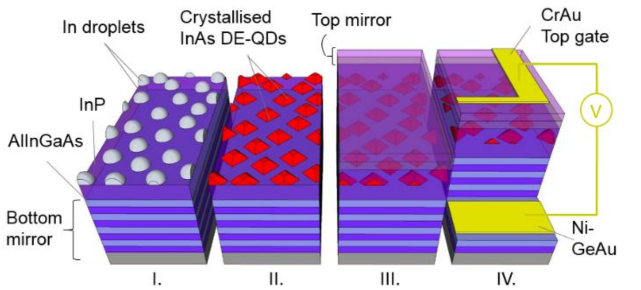

Fig. 1 Schematic of the device and its fabrication. See text for a detailed description.

This protocol results in ultra-low density quantum dots with cavity enhanced emission, which is excited when a DC bias voltage larger than 1.5 V is applied.

3. Experiments

We can identify individual quantum dots as bright spots on a camera image, as shown in Fig. 1 (a), where the black region is the electronic top contact to the device. To analyze the quantum dot light, we collect emission using a confocal microscope and guide it via optical fibers either to a spectrometer or to a polarization sensitive detection setup based on superconducting single photon detectors.

A spectrum of a single quantum dot consisting of bright, sharp, well isolated lines is shown in Fig. 1 (b). The exciton (X) and biexciton (XX) transitions, upon which entangled light generation is based, can be identified by observing their transition energy as a function of the detected linear polarization angle. Their finite fine structure splitting S (17.7±0.02 μeV for this dot) will lead to typical anticorrelated oscillations. After identification, the X and XX transitions are spectrally isolated using a grating.

The quantum dots can generate entangled photons using the biexciton cascade mechanism [Ref], which is schematically shown in the inset to Fig. 1 (a). When the dot is initially occupied by two electron-hole pairs, the two routes for electron-hole pair recombination result in the emission of the superposition state $\left(|L_{XX}R_X\rangle + e^{iS\tau/\hbar}|R_{XX}L_X\rangle\right)/\sqrt{2}$ [3], which is a maximally polarisation entangled state. Here, L and R denote left-hand and right-hand circularly polarised light, respectively, and τ is the time spent in the exciton state before the second recombination. This results in characteristic correlations between the XX and subsequent X emission polarisation, which can be measured to reveal the signatures of entanglement.

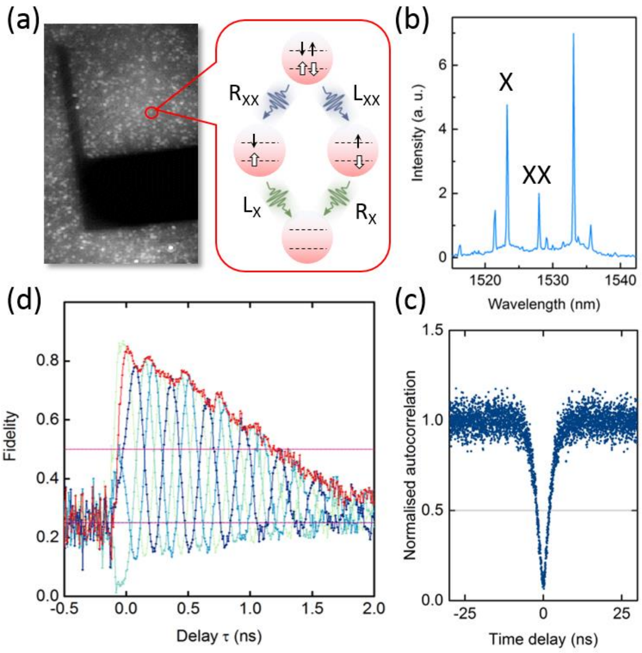

Fig. 2 (a) Camera image of the device. The sketch shows the mechanism used to generate entangled photons, with electron and hole spins given by black and white arrows, respectively. (b) Spectrum of the quantum dot circled in (a) at a temperature of 44 K. (c) Entanglement fidelity to four maximally entangled states with phases $iS\tau/\hbar$ = 0, π/2, π, and 3π/2 (light to dark blue curves), as well as to an evolving state (red curve). Pink and purple lines give the classical limit and uncorrelated values for coincidences, respectively. (d) Autocorrelation measurement of the X transition, confirming that the device acts as an optoelectronic single photon source.

4. Results

Single photon emission

To determine the quantum nature of the observed transitions, we performed intensity autocorrelation ($g^{(2)}$) measurements, as shown in Fig. 1 (c) for the exciton transition of the dot in Fig. 1 (a). At zero delay, a dip extending well below 0.5 is observed, with the measured $g^{(2)}(0)$=0.11±0.02. This proves emission from a true single photon source. The value does not include corrections due to dark and background counts or detector jitter and therefore gives an upper bound to multiphoton emission from our device. Even without further optimization, it is suppressed by almost a factor 10 compared to a Poissonian photon source.

Entangled photon generation

To prove that emission from our device is entangled, and to determine the fidelity to an evolving Bell state, we performed polarization correlation measurements in five different polarization bases. In each case, events where XX and X photons were co-polarized where contrasted with those where they were cross-polarized, by dividing the difference between orthogonal coincidences by their sum. From this, the fidelity to the expected ideal evolving Bell state was calculated [4]. As shown in Fig. 2 (c), the fidelity exceeds the classical limit of 0.5 for all calculated phases during the first nanosecond of delay between the XX and X photons, which is a clear proof of entanglement. For longer delays, the emission eventually drops to the uncorrelated uncorrelated value of 0.25 as emission from separate excitation cycles begins to dominate. In our experiments, entangled emission could be observed for temperatures up to 93 K, which is the highest operating temperature observed so far for an entangled photon source.

3. Conclusions

In summary, we have shown the first electrically driven semiconductor device capable of non-Poissonian emission in the coveted 1550-nm window [4]. We have shown that our device acts as a true single photon source, and we have observed the unambiguous signatures of entangled photon emission. In practical terms, our device is compatible with standard industry fabrication techniques, and is made of use of materials dominant in 1550 nm photon detectors. Its electrical operation further makes it suitable for miniaturization and on-chip integration. We therefore expect that devices based on our technology will have a significant impact on the development of quantum network technology.

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