Position controlled nanowires for infrared single photon emission

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We report the experimental demonstration of single-photon and cascaded photon pair emission in the infrared, originating from a single InAsP quantum dot embedded in a standing InP nanowire. A regular array of nanowires is fabricated by epitaxial growth on an electron-beam patterned substrate. Photoluminescence spectra taken on single quantum dots show narrow emission lines. Superconducting single photon detectors, which have a higher sensitivity than avalanche photodiodes in the infrared, enable us to measure auto and cross correlations. Clear antibunching is observed [g^{(2)}(0)=0.12] and we show a biexciton–exciton cascade, which can be used to create entangled photon pairs. © 2010 American Institute of Physics. [doi:10.1063/1.3506499]

Semiconductor quantum dot (QD) structures are attractive candidates for solid-state single photon and/or entangled-photons pair generation.¹–³ Nanowire QDs (NW-QDs) are promising candidates for such sources because of the controllability of doping, shape, and material freedom.¹,² Fine structure splitting is predicted to be absent, which makes NW-QDs ideal for the creation of entangled photon pairs.⁴ Single photon emission from a NW-QD has been shown at wavelengths shorter than 1000 nm.⁵ However, a single photon NW-QD emitter at telecommunication wavelengths is not needed, preventing diffusion of the metal into the NW. A polarisation and associated exchange interaction⁹ is not observed in polarization dependent measurements, within our setup resolution of less than 5 μeV. An additional line, labeled XX₀, can be seen at 1211.3 nm and we show a biexciton–exciton cascade, which can be used to create entangled photon pairs.

NW-QD PL spectroscopy is performed by micro-PL measurements. The sample is cooled to 5 K. The NW-QDs are excited with a continuous wave Ti:sapphire laser tuned at a wavelength of 920 nm, at a power of ~3 kW/cm² directed along the NW growth direction and focused with an aspheric lens (numerical aperture=0.5). The NW-QD emission collected by the same aspheric lens is dispersed by a double grating spectrometer (f=1.0 m) and detected with a cooled InGaAs photodiode array. An exposure time of 1 s yields a spectrum with a high signal-to-noise ratio. A typical spectrum is shown in Fig. 1(c). We identify an intense peak centered at 1211.6 nm (1.0254 eV) with a line width of 46 μeV full width at half maximum and we name it X₀ (neutral exciton), for reasons which will appear later. As expected, the fine structure splitting normally induced by QD lateral anisotropy and associated exchange interaction⁹ is not observed in polarization dependent measurements, within our setup resolution of less than 5 μeV. An additional line, labeled XX₀ (neutral biexciton), can be seen at 1211.3 nm (1.02328 eV).

Arrays of InAsP QDs embedded in InP NWs are synthesized by selective area metal organic vapor phase epitaxy (SA-MOVPE).⁸ A metal catalyst is usually used (i.e., Au) to grow NW structures, however with SA-MOVPE a catalyst is not needed, preventing diffusion of the metal into the NW. A (111) InP wafer is covered by 30 nm of SiO₂. By electron beam lithography and wet-etching, 40–60 nm diameter openings are created to form NW nucleation-sites. At a growth rate of 3 nm/s, a 1 μm long segment of InP is grown by adding trimethylindium and tertiarybutylphosphine (TBP) to the MOVPE reactor at 640 °C. Subsequently the temperature is lowered to 580 °C and arsine (AsH₃) is added to the reactor (V/III ratio 340, partial pressure TBP:AsH₃:1) to grow 8 to 10 nm InAsP to form the QDs. The QDs are embedded in an InP shell, grown at 580 °C. To finalize the NW, a second 1 μm segment of InP is grown at 640 °C. A scanning electron microscope image of the array is shown in Fig. 1(a). A schematic of an individual NW is shown in Fig. 1(b).
The solid line is a fit with a monoexponential decay, which gives a lifetime of 2.8 ns and 0.87 ns, respectively. The long lifetime indicates absence of fast nonradiative processes, revealing the high quality of NW-QDs. We note that the ratio of the lifetime is $\tau_{X^0}/\tau_{XX^0} = 3.2$, which indicates a larger dot. We also note the appearance of cascaded emission of $XX^0$ and $X^0$, which we will prove with a cross correlation measurement.

Single photon emission is demonstrated with a Hanbury Brown–Twiss (HBT) experiment [see Fig. 2(a)]. The NW-QD is excited with continuous wave He–Ne laser at 633 nm at a power of $\sim 150$ kW/cm², close to saturation power. In each arm of the beam splitter (BS) the emission is filtered with a 0.5 nm wide band pass filter (BPF) to select the $X^0$ line and sent to an SSPD, chosen for their sensitivity at the wavelength of interest. A detailed description of our SSPDs is given in Refs. 11–13. The detectors are operated at 4.2 K and current biased near the critical current ($I_c$). The following characteristics are observed: for detector 1, at $0.85-I_c$, the dark count rate is 70 counts per second, together with 4% efficiency at a wavelength of 1.3 $\mu$m. Detector 2 is operated at $0.82-I_c$, where it shows 40 dark counts per second and an efficiency of 3%. The second order correlation function of the output of the two detectors is measured with a time to amplitude converter (TAC). A histogram of the coincidence counts with time bins of 200 ps and an integration time of 30 min is shown in Fig. 2(b). The dip at zero time delay indicates the emission of nonclassical light. The data is fitted through a second-order correlation function $g^{(2)}(\tau) = 1 - \rho^2$, with $\rho$ the signal to noise ratio. Here a value of $g^{(2)}(0) = 0.12$ is obtained with $p = 0.97$. From the monoeponential decay of the fit the time constant of this measurement can be extracted, which is $t = 1.51$ ns. Measurements with different $I_c$ would allow to extract $t_c$, which can be compared to the streak camera measurement.

With cross correlation experiments a biexciton–exciton cascade can be identified. In the inset of Fig. 3 a schematic of the biexciton–exciton cascade is shown. Upon excitation with rate $r_{11}$ and $r_{12}$, the dot is filled with two electron-hole pairs ($XX^0$), neglecting resident charges. At a rate $r_{13}$ one electron-hole pair recombines, leaving the $X^0$ behind, which

![FIG. 1.](image1)  
![FIG. 2.](image2)  
![FIG. 3.](image3)
properties of NWs, an electrically controlled source 16 is now within reach.

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