

On-demand Single Photons from Individual Epitaxial Quantum Dots

Richard P. Mirin and Martin J. Stevens

Optoelectronics Division, National Institute of Standards and Technology, 325 Broadway,
Boulder, CO 80305

We will describe our group's efforts to use epitaxial InGaAs/GaAs quantum dots as sources of on-demand single photons and indistinguishable single photons. We have demonstrated second order intensity correlation measurements, $g^{(2)}(\tau)$, with $g^{(2)}(0)$ as low as 0.09 at 5 K. $g^{(2)}(0) < 0.5$ is demonstrated at temperatures up to 120 K, and nonclassical light is seen to 135 K. We will describe our progress towards microcavity-enhanced emission from single quantum dots, which is necessary for indistinguishable photon emission in this system.

Self-assembled, epitaxial quantum dots (QDs) are one of the most promising systems for practical sources of on-demand single photons, indistinguishable single photons, and entangled photon pairs. These QDs are available over a wide wavelength range (~ 600 -1300 nm), exhibit excellent photostability (no blinking or photobleaching), have a short spontaneous emission lifetime (< 1 ns), and are easily incorporated in microcavities (needed for enhanced spontaneous emission and indistinguishability). The main drawback to these QDs is the need for cryogenic cooling.

Our QDs are grown using molecular beam epitaxy (MBE) and the Stranski-Krastanow transition of a highly strained epitaxial layer. We grow a low areal density (1 - $10 \mu\text{m}^{-2}$) by carefully controlling the MBE growth conditions and the amount of deposited material. Our dots are formed using InGaAs on GaAs. Variable size mesas (from about 2 - $10 \mu\text{m}$ in diameter) are wet etched to isolate various numbers of QDs. Our experimental apparatus for measuring single photon emission utilizes a liquid-nitrogen cooled CCD camera for acquiring the single QD emission spectrum and a Hanbury Brown-Twiss interferometer (HBTI), both on the output ports of a grating monochromator. Silicon avalanche photodiodes (APDs) are used as photon counting detectors in the HBTI. Continuous wave (532 nm) and pulsed (tunable Ti:Sapphire) lasers are available for exciting the QD.

Figure 1 (a) shows the temperature-dependent photoluminescence spectra from a single InGaAs QD. At low temperatures, the radiative efficiency of the QDs is very high, and only a weak excitation is required. Sharp emission lines are measured in the optical emission spectrum at low temperatures, but the lines broaden as the temperature is increased and the radiative efficiency decreases, requiring higher excitation intensity. Figure 1 (b) shows the corresponding HBTI measurements acquired by spectrally filtering the narrowest emission line. For the higher temperatures, only a fraction of the emission line is utilized. Photon antibunching corresponding to single emitter operation is observed up to a temperature of 120 K.

We are also pursuing sources of *indistinguishable* single photons by placing our QDs in microcavities. Indistinguishable single photons are an important building block for making other interesting quantum states of light, such as entangled photon pairs and NOON states, that are useful for applications such as quantum measurements and linear optical quantum computing. The microcavities consist of GaAs/AlAs distributed Bragg reflectors sandwiched around a 1λ GaAs cavity spacer that has a layer of InGaAs QDs embedded at the center. We use reactive ion etching to form small diameter pillars in order to decrease the mode volume.

Figure 2 shows an example of temperature tuning a QD emission line and the cavity resonance. As the detuning decreases, the spontaneous emission lifetime decreases as well due

to the Purcell effect. The QD emission is nearly on resonance (spectral detuning of 0.008 nm) at the lowest temperature of 4.0 K, and a spontaneous emission lifetime of about 400 ps is measured. As the temperature is increased, the cavity resonance and the QD emission wavelength both shift, but at different rates. At a temperature of 47.0 K, the QD emission is detuned from the cavity resonance by 1.118 nm, and the spontaneous emission lifetime has increased to 640 ps. The Purcell enhancement is a modest 1.6 for this particular micropillar. We will discuss our efforts at improving this figure of merit by decreasing the pillar size, which requires improved dry etching over this initial effort. We will also discuss our measurements of the indistinguishability of these single photons by comparison of Hong-Ou-Mandel interferometry, Michelson interferometry, and time-resolved photoluminescence.

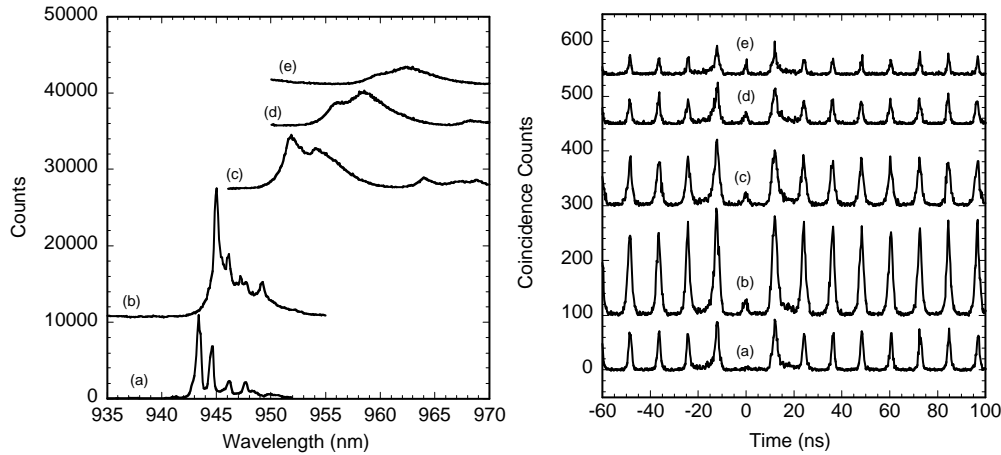


Figure 1: (a) The temperature and the average pump excitation intensity are (a) 5.0 K, 1.8 W/cm², (b) 50.0 K, 5.3 W/cm², (c) 100.0 K, 16.2 W/cm², (d) 120.0 K, 57.3 W/cm², and (e) 135.0 K, 84.3 W/cm². The spectra are vertically offset for clarity. (b) The temperatures and average pump laser intensity for each trace are as indicated in Figure 1 (a). The values of the second order intensity correlation, $g^{(2)}(0)$ are (a) 0.087 ± 0.009 , (b) 0.177 ± 0.013 , (c) 0.260 ± 0.024 , (d) 0.471 ± 0.067 , and (e) 0.667 ± 0.063 .

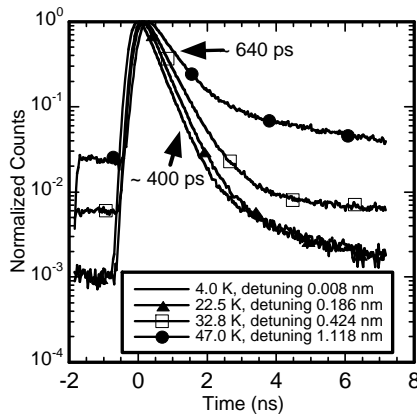


Figure 2: The QD emission line is temperature-tuned around the cavity resonance. On-resonance emission shows a faster spontaneous emission lifetime due to the Purcell effect.