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"Plug and play" single-photon sources

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The authors report a "plug and play" source of single photons, with full integration to a single-mode optical fiber. One end of the fiber is attached to the top of an InGaAs/GaAs quantum dot wafer. The other end is connected via a wavelength-division multiplexing system to two separate fibers: one for carrying excitation light and the other for emitted light. A Hanbury-Brown and Twiss [Nature (London) **77**, 27 (1956)] measurement was performed on the emission from single excitons recombining in the quantum dots. A second-order correlation function at zero time delay of approximately 0.01 indicates a nearly ideal source of single photons. The maximum variation of peak position over 24 days is less than 0.1 nm. © *2007 American Institute of Physics*.
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Quantum key distribution is a central aspect of implementing quantum cryptography, which has recently been under intense investigation. Distribution has been demonstrated via optical fiber over a distance of more than 100 km,[1–3] in addition to impressive demonstrations of free-space distribution.[4–6] Most photon sources coupled to optical fibers in use for quantum cryptography are based on highly attenuated lasers, in which the average photon number per pulse is significantly less than one. The number of photons in these pulses is described by Poissonian statistics, so there is a possibility that there are multiple photons in one pulse. Sources of *single* photons are desirable for implementation of real quantum communication and quantum computation based on linear optics.[7,8] Therefore, sources with optical fiber integration and with genuine single-photon character are in demand for these applications.

To obtain single-photon emission, individual quantized systems are under intensive investigation.[9–16] Semiconductor quantum dots, pumped either optically or electrically, appear very promising, despite the requirement of operation at cryogenic temperatures. Most experiments are performed using confocal microscopy systems collecting light with an objective of large magnification (100×) and large numerical aperture (⩾0.5). The area from which light is coupled into the external system can then be less than 1 μm in diameter. This place constraints on the stability of the cryogenic optical system. In general, a simple approach based on a coldfinger offers only short-term stability. Much improved performance has been obtained by the use of large titanium-based confocal microscopes[17] which offer stability over many weeks, but which are costly and bulky. Attaching an optical fiber to a quantum dot wafer is one of the methods available that avoids these problems.[18–20] In this letter, we report a stable "plug and play" single-photon source from InGaAs quantum dots with optical fiber integration.

Phillips *et al.*[20,18] have demonstrated microphotoluminescence of interfacial quantum dots and self-assembled quantum dots by exciting the sample and collecting the emitted light via a single-mode optical fiber. The fiber is attached to the sample surface or mounted on the side via a *V* groove using an optical adhesive cured with ultraviolet light. To obtain single-photon emission, it is desirable that only one quantum dot is being excited by the fiber. Since the mode field size of a single-mode fiber is usually around 5 μm in diameter, the quantum dot density needs to be very low (less than 0.1 dot/μm^2 in this work). However, low dot density leads to a low probability of obtaining a quantum dot coupled to the optical fiber mode. To avoid this problem, we used a bundle of optical fibers (around 600) bound together at one end and polished, as shown in Fig. 1. The polished end of the fiber bundle is mounted to the sample holder (the inset in Fig. 1) without optical adhesive. All fibers in the other end were free and could be connected to a wavelength-division multiplexing (WDM) device with two separate output fibers. One of these two fibers carries the excitation light and the other carries the emitted light. The WDM acts as a dichroic beam splitter and has a special coating which pre-

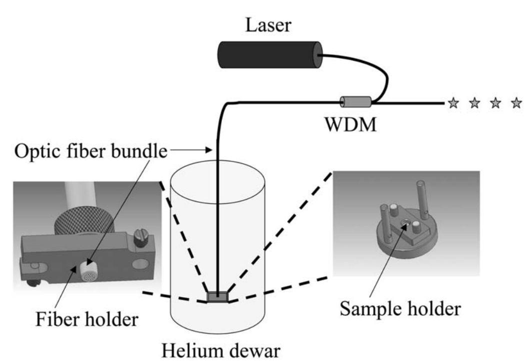

FIG. 1. Sketch of the single-photon source with integrated optical fiber A 5×5 mm^2 wafer was mounted onto the sample holder (right inset) with fibers attached directly on the top surface by the fiber holder (left inset).

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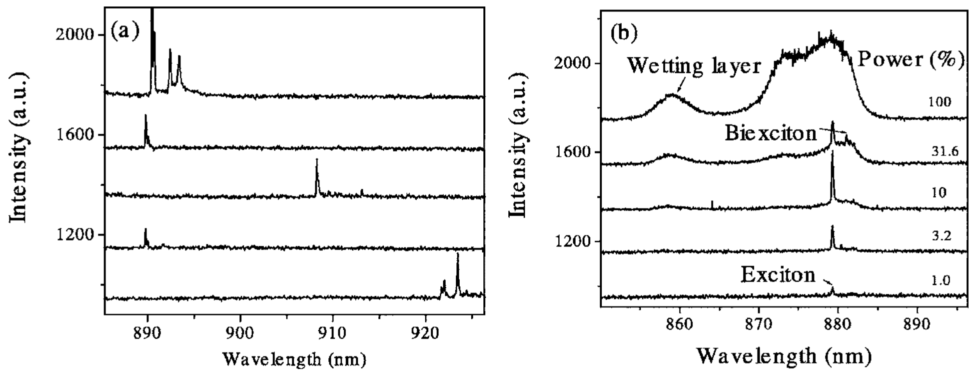

FIG. 2. (a) Photoluminescence spectra of single quantum dots from different optical fibers in a single fiber bundle. (b) Photoluminescence spectra of a single quantum dot, as a function of excitation power. [In both (a) and (b) spectra are shifted vertically for clarity.]

vents excitation light being reflected in the the output fiber carrying the emitted signal.

The sample holder was dipped into liquid helium at 4.2 K in an ordinary storage Dewar. The quantum dots were excited with a HeNe laser. The photoluminescence (PL) spectrum from the fiber was measured using a 0.55 m spectrometer and a cooled charge-coupled device camera. To obtain the PL emission only from the quantum dots, bandpass filters need to be used to block the emission from the wetting layer. Since there is no commercialized tunable bandpass fiber-optic filter for this wavelength range, the emitted light from the fiber is coupled to a measurement fiber via free space which permits insertion of bandpass interference filters. Correlation measurements of the photoluminescence were performed using a Hanbury-Brown and Twiss setup[21] with a 50/50 fiber splitter and two single-photon-counting avalanche photodiodes (APDs). The two APDs were connected to start and stop inputs of a time-to-amplitude converter, whose output was stored in a time-correlated photon-counting card. The resulting histograms show a large number of photon pairs with arrival time separations of $\tau = t_{\text{start}} - t_{\text{stop}}$. The histograms are equivalent to the second-order correlation function $g^{(2)}(\tau)$ when τ is much shorter than the average time between detected photons.

Figure 2(a) shows the PL spectra from different fibers in the same bundle. Sharp peaks can be clearly observed from single quantum dots due to exciton recombination. With different excitation powers, biexciton recombination can be observed from certain dots at the low energy side of the exciton as expected.[15] Figure 2(b) shows exciton and biexciton emissions from a single quantum dot with different excitation powers. At low excitation power, only the single peak from exciton recombination is observed around 879.3 nm. With increasing excitation power, a peak around 881 nm appears which comes from biexciton recombination. At high excitation powers the discrete emission from the quantum dot states is contaminated by an unresolved background, which appears to be associated with the wetting layer. This sets an upper limit on excitation power consistent with observing single-photon-mode occupation.

We have observed a lower PL intensity from a typical dot in the fiber-coupled system than in conventional micro-PL on the same wafer. This can be explained on the basis of simple optics: loss at the dielectric interface and the large difference in numerical aperture (0.12 for the fiber and 0.5 for the objective) together lead to approximately a factor of 10 reduction in expected signal using the fiber method. The intensity collected from fibers is approximately three times lower in practice.

Since the wetting layer recombination of the wafer is very close to the quantum dots of interest, interference bandpass filters are essential to control the spectral content of light passed to the Hanbury-Brown and Twiss correlation measurement. The behavior of the filter is sensitive to its angle relative to the beam, as illustrated in Fig. 3(a) which shows two different PL spectra with the filter at different angles. The bottom trace shows an optimal filter position at which only a single quantum dot emission can be observed. With a slight change of the filter angle, the emission from the wetting layer can be detected, as shown in the top trace in Fig. 3(a). We have performed measurements of the second-order correlation function $g^{(2)}(\tau)$ under the conditions corresponding to these two spectra, as shown in Fig. 3(b). Clear antibunching at $\tau=0$ can be observed in both cases, which shows that the simultaneous emission of two photons is largely suppressed. Although the height of the wetting layer peak is much lower than that of the quantum dot in the top trace, it contributes more in overall intensity since it is much broader than the quantum dot peak. Therefore, the dip in $g^{(2)}(2)$ is shallower when emission from the wetting layer is included, as shown in the top trace of Fig. 3(b). The values of $g^{(2)}(0)$ are 0.46 ± 0.15 and 0.14 ± 0.15 for the two cases with dark counts. The correlation function can be corrected with $g^{(2)}(\tau) = 1 + (g_b^{(2)}(\tau) - 1)/\rho^2$, where $\rho = S/(S+B)$ is the ra-

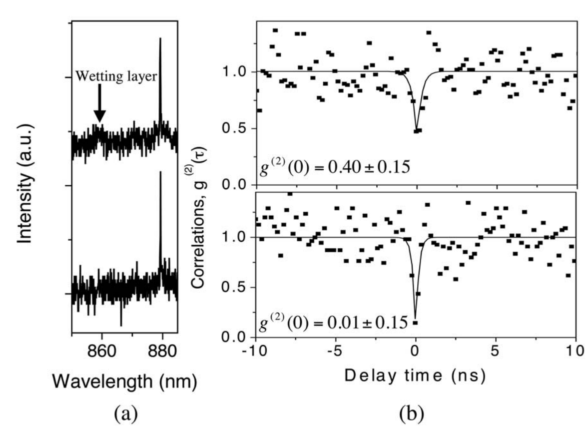

FIG. 3. (a) Photoluminescence spectrum of a single quantum dot is shown for each of two angular positions of the interference filter; in the lower spectrum the filter has eliminated the contribution from the wetting layer. (b) Second-order correlation function $g^{(2)}(\tau)$ measured (solid squares) and fitted (line) of the PL spectra corresponding to (a) with dark counts. The results of $g^{(2)}(0)$ inset are corrected values without dark counts.

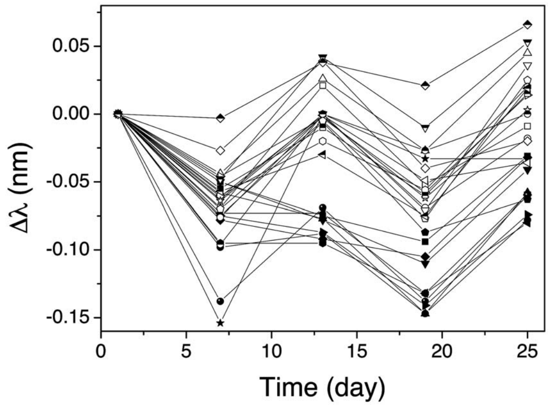

FIG. 4. Change in emission wavelength measured over a 24 day period is plotted for 27 quantum dots from different optical fibers.

tio of signal S to total counts, including dark count B.[22] The corrected results of these two cases are 0.40 ± 0.15 and 0.01 ± 0.15 with ρ at 0.95 and 0.93, respectively. A $g^{(2)}(0)$ equal to 0.01 indicates that the probability of generating more than one photon in a resolved time channel is reduced 100 times.

To confirm the stability, we measured 27 quantum dots from different optical fibers in the same bundle over 24 days under the same conditions. Figure 4 shows the variation in the measured wavelength of the transition from those quantum dots as a function of time, expressed as the offset from the initial measured wavelength. The variation between successive measurements is partly attributable to variation in the optical alignment, but there is also the possibility that there is a contribution which can be ascribed to random Stark shifts arising from carrier trapping following optical excitation.[23] Any variation in peak width is below our resolution. Variation in intensity appears to be explained entirely by different alignment conditions from day to day. These measurements indicate that the fiber-based system is stable and reproducible on the time scale of weeks, and we have no evidence to suggest degradation over a substantially longer period.

With increasing excitation power, the dip in $g^{(2)}(0)$ becomes shallower and shallower, and finally disappears (indicating Poissonian statistics). This is due to the increased biexciton recombination and unresolved background emission.[15,16] Usually, one can fit the histogram with $g^{(2)}(\tau) = 1 - a \exp(-\tau/b)$, where $1-a$ and b are $g^{(2)}(0)$ and the recombination lifetime, respectively, if the life time is longer than the resolution of the system. However, with increasing excitation power, the light fed into the correlation measurement includes both exciton and biexciton recombinations which have different lifetimes. Therefore, the width of dip is no longer correctly indicating the spontaneous lifetime. We fitted our data with an excitation power low enough when only a single exciton line is observed, as the case in Fig. 3(a). The line of the lower traces in Fig. 3(b) shows the fitting results. The lifetime around 200 ps in this case is smaller than that of normal dots (usually $\sim$1 ns),[15,16,24,25] this might be due to the fact that the exciton energy of this dot is high.[26]

In summary, we have demonstrated a plug and play source of single photons using optically excited quantum dots coupled to single-mode optical fiber. Single quantum dot emission has been observed with a high stability both in intensity and energy. Background emission from the wetting layer gives a lower bound of $g^{(2)}(0) \approx 0.40 \pm 0.15$. Excluding this background by means of an interference filter reduces the probability of detecting more than one photon 100-fold, which indicates a nearly ideal single-photon source. The system is totally compatible with quantum dots at optical communication wavelengths. Devices with quantum dots embedded in distributed Bragg reflectors and photonic crystals are under investigating to improve efficiency. We believe that the stability and versatility of this single-photon source system are very promising for applications in implementation of fiber-based quantum communication and linear optical quantum computation.

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