Semiconductor quantum dots (QDs) have drawn significant recent interest due to their potential to create novel optoelectronic devices such as those that can generate single photons on demand. Methods to optically interrogate single QDs include physical isolation via microfabricated mesa and diffraction-limited confocal optical microscopy. Despite the technical challenges involved in developing tools for use at cryogenic temperatures (a prerequisite for most single QD studies), solid immersion lenses have been implemented to improve the efficiency of light collection, while near-field scanning optical microscopy (NSOM) has been used to achieve sub-100 nm spatial resolution. In this paper, we examine the use of optical fiber taper waveguides as a near-field optic for performing single QD spectroscopy. These micron-scale silica waveguides have been used in many studies of optical microcavities, beginning as an efficient coupler to silica microspheres. More recently, we have shown that they can effectively probe the spatial and spectral properties of small mode volume ($V_{\text{eff}}$), high refractive index semiconductor cavities such as planar photonic crystals and microdisks. Other researchers have proposed and realized their use as a collection tool for spontaneous emission from atomic vapor. Here, we show that a fiber taper may be used to channel emission from single self-assembled QDs embedded in a semiconductor slab directly into a standard single-mode fiber with high efficiency ($\sim 0.1\%$), and to provide sub-micron spatial resolution of QDs, either through taper positioning or resonant pumping of the optical modes of etched microdisk structures.

The QDs we study consist of a single layer of InAs QDs embedded in an In$_{0.15}$Ga$_{0.85}$As quantum well, a so-called dot-in-a-well (DWELL) structure. The DWELL layer is grown in the center of a GaAs waveguide (total waveguide thickness of 256 nm), which sits atop a 1.5 μm thick Al$_{0.3}$Ga$_{0.7}$As buffer layer. The resulting peak of the ground state emission of the ensemble of QDs is located at $\lambda = 1.35$ μm at room temperature. To limit the number of optically pumped QDs, microdisk cavities of diameter $D = 2$ μm were fabricated using electron beam lithography and a series of dry and wet etching steps. Although the QDs physically reside in a microcavity, they are non-resonant with the cavity whispering gallery modes (WGMs). In other words, our primary interest here is general single QD spectroscopy through the fiber taper, without enhancement through interaction with the high quality factor ($Q$) microdisk WGMs. The samples were mounted in a continuous-flow liquid He cryostat that has been modified to allow sample probing with optical fiber tapers while being held at cryogenic temperatures ($T \sim 14$ K), as described in detail in ref. [13]. The cryostat is part of a microphotoluminescence setup that provides any combination of free-space and fiber taper pumping and collection; see Fig. 1(a) for details.

The inset of Fig. 1(b) shows the emission spectrum from an ensemble of QDs in one of the microdisks. Here, the device is optically pumped through an objective lens at normal incidence (free-space pumping), with a spot size of 3 μm and wavelength $\lambda_p = 830$ nm. Clearly present are the ground and excited states ($s$ and $p$ shells) of the ensemble of QDs which, based on the estimated QD density of 300-500 $\mu$m$^{-2}$, consists of $\sim 1000$ QDs. To study isolated emission lines from single QDs, we focus on the long-wavelength tail end of the QD distribution ($\lambda = 1290-1310$ nm). In this range, isolated emission lines from a single QD are seen for a fraction (10%) of the interrogated devices. A typical spectrum as collected through the pump lens (free-space collection) from one such device is shown in the top panel of Fig. 1(b). Under identical pumping conditions, the signal collected through a fiber taper waveguide positioned on top of, and in contact with, the microdisk is shown in the bottom panel of Fig. 1(b). The taper is a single mode optical fiber that has been heated and stretched down to a minimum radius of $a = 650$ nm, and is installed in the customized liquid He cryostat as detailed in ref. [13]. The most stark difference between the free-space and fiber taper collected spectra is the $25 \times$ increase in fiber taper collected power. Similar improvement in collection efficiency was measured over all the QDs studied in this work.

Before further studying the fiber taper as a collection optic, we attempt to identify the different QD lines of Fig. 1(b). Of particular benefit in this assignment is the recent work of Cade, et al. [14], who study a DWELL material very similar to that investigated here. In Fig. 2(a), we show taper-collected emission spectra as a function of pump power (free-space, $\lambda_p = 830$ nm) for a fixed taper position. Emission is first seen for incident powers of a few nW (estimated absorbed pow-

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**Single quantum dot spectroscopy using a fiber taper waveguide near-field optic**

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Photoluminescence spectroscopy of single InAs quantum dots at cryogenic temperatures ($\sim 14$ K) is performed using a micron-scale optical fiber taper waveguide as a near-field optic. The measured collection efficiency of quantum dot spontaneous emission into the fundamental guided mode of the fiber taper is estimated at 0.1%, and spatially-resolved measurements with $\sim 600$ nm resolution are obtained by varying the taper position with respect to the sample and using the fiber taper for both the pump and collection channels.

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ers of tens of pW), with excitonic lines centered at 1291.95 nm, 1300.97 nm, 1301.81 nm, and 1307.75 nm. As we discuss later, spatially-resolved measurements clearly indicate that the shortest wavelength emission line is unrelated to the latter three, which we identify as the polarization-split exciton lines ($X_{\pm}$ and $X_0$)\cite{14,15} and the negatively charged exciton line ($X^-$). As the pump power is increased, additional emission lines appear, including the positively charged exciton ($X^+$) at 1299.87 nm and the bi-exciton ($2X$) line at 1305.11 nm. The $X^+-X$, $X^+-X$, and $2X-X$ splitting values of 4.6, -1.1, and 2.8 meV match reasonably well with the 5.6, -1.1, and 3.1 meV values measured in Ref. \cite{14}, although the fine structure splitting in the $X$ line is significantly larger (600 vs. 300 µeV) for this QD. In Fig. 2(b), we plot the emission level in each QD state against pump power. Below saturation, the emission lines all scale nearly linearly with pump power, except for the 2X line which scales superlinearly, although more slowly than expected ($n = 1.54$ as opposed to 2). Previous studies of 1.2-1.3 µm QDs have also measured a sub-quadratic pump-power-dependence for the 2X line\cite{14,16}, although usually in conjunction with a sub-linear dependence of the $X$ line. Finally, the temperature (T) dependence of the $X$ lines is shown in Fig. 2(c), where significant broadening is seen for T > 50 K. Below this temperature we measure linewidths of 0.1-0.15 nm, roughly corresponding to the spectral resolution of our system (0.1 nm = 75 µeV).

A rough estimate of the absolute collection efficiency of the fiber taper is derived by considering the saturated photon count rates for the $X$ lines in Fig. 2(b). The measured saturated photon count rate into the $X_0$ line is $1.5 \times 10^5$ counts per second (cps), which after considering the spectrometer grating efficiency (60%), the detector array quantum efficiency (85%), and including the light in the backwards fiber channel, corresponds to a count rate of $5.9 \times 10^5$ cps. Taking into account the transmission efficiency of the fiber taper ($\sqrt{0.64}$ for a QD centrally located along the tapered region of the fiber), the taper-collected photon count rate rises to $7.4 \times 10^5$ cps. Neglecting possible suppression or enhancement of radiation due to the presence of the microdisk (a good approximation for QDs located above the disk’s central pedestal), the saturated photon emission rate for InAs QDs is $5-10 \times 10^8$ cps (photon lifetime $\tau = 1-2$ ns). This yields an approximate fiber taper collection efficiency of $\eta_t = 0.1\%$. It is important to note that this efficiency is for non-resonant collection, and does not correspond to that attainable for QDs resonant with a high-$Q$ microdisk WGM, which one would expect to be much higher due to the Purcell-enhanced emission into a localized cavity mode and the efficient taper-WGM coupling\cite{89,86}.

Obtaining a theoretical value for the non-resonant fiber taper collection efficiency is hindered by the complex geometry in which the QD is embedded; however, a coarse estimate can be made by comparison to refs. \cite{80,89}. In these works, a spontaneous emission collection efficiency of 20-50% is estimated for a dipole emitter on the surface of a silica fiber taper of ra-
Spatial selection of QDs may also be realized by resonantly pumping a microdisk WGM. This excites QDs located in a 250 nm thick annulus at the microdisk perimeter, where the pump beam resides, and efficient taper-WGM coupling allows for an accurate estimate of the absorbed pump power. The QDs located at the disk periphery are of course those that are of interest for cavity QED studies involving high-\(Q\) ultrasmall \(V_{eff}\) WGMs. Figure 3(d) shows a transmission scan of a pump-band WGM with a coupling depth of 60% and \(\lambda\sim 1000\) (limited by DWELL absorption). By pumping on resonance at \(\lambda_p = 974.5\) nm, we reduce the power needed to achieve a given signal by 2-3 orders of magnitude relative to non-resonant pumping. The bottom scan of Fig. 3(c) shows the emission spectrum when we pump on resonance with 690 pW of power at the taper input (corresponding to 330 pW of dropped/absorbed power). Emission from the centrally located QD (top scan of Fig. 3(c)) is no longer present, and has been replaced by a pronounced emission peak at \(\lambda = 1291.95\) nm, corresponding to the X' line, confirming that this emission is likely due to a QD located in the disk periphery. Another difference in comparison to the non-resonant pumping spectrum is the presence of several broad emission peaks. These peaks are due to emission into relatively low-\(Q\), higher-radial-order WGMs of the microdisk, as confirmed by fiber-taper-based transmission spectroscopy of the cavity with a tunable laser. The source of such background emission into detuned cavity modes is not well understood, but has been observed to occur for even large detunings of 10-20 nm. In this case, it is likely that the preferential excitation of QDs that reside in the microdisk perimeter, even those that have exciton lines which are significantly detuned spectrally, results in enhanced emission into the microdisk WGMs.

In summary, we have shown that a micron-scale optical fiber taper waveguide, previously demonstrated to be an effective tool for characterization of semiconductor microcavities, can also be used to study single semiconductor quantum dots. As a near-field collection optic, the fiber taper is shown to channel quantum dot light emission directly into a single mode fiber with a high efficiency of 0.1%, and to provide a sub-micron spatial resolution of QDs. The ability to effectively investigate both microcavities and quantum dots suggests that these fiber tapers can serve as a very versatile tool for studying microphotonic structures, and in particular, for investigations of chip-based cavity QED.
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