Chapter 9

Conclusions and Future Outlook

In this concluding chapter, we briefly summarize some of the remaining challenges to accessing the strong coupling regime in our experiments. Addressing these challenges is an on-going effort, and is essentially the primary focus of my current research.

Semiconductor microcavity-QD vacuum Rabi splitting has been demonstrated in the experiments of three groups in late 2004 [70, 71, 72]. The procedure in these experiments is as follows: 1) the sample is cooled within a liquid He cryostat, in order to reduce non-radiative dephasing in the QDs, 2) the sample is incoherently pumped at energies above the bandgap of the dominant material in the microcavity (e.g., 870 nm for GaAs), in order to efficiently generate carriers that can fill the QDs, and 3) spontaneous emission from the device is collected through free-space optics and dispersed by a spectrometer onto a linear array of detectors (typically a CCD for measurements below 1 μm, or an InGaAs detector array for wavelengths above 1 μm). The primary technical hurdles in such experiments are creating a sufficiently high-Q cavity to be within the strong coupling regime, and achieving spectral and spatial alignment of a single QD with the cavity mode. In addition, efficient collection of emitted light can be difficult, and is particularly necessary for work at longer wavelengths (> 1 μm), where the InGaAs detector dark count rates are significantly greater than those of Si detectors used at shorter wavelengths [164].

We are interested in being able to observe vacuum Rabi splitting within the spontaneous emission spectrum of incoherently pumped devices, but beyond this, our goal is to use the fiber taper to provide efficient near-resonant pumping. Initial experiments will examine the spectral response of a coupled microcavity-QD system as a function of the frequency of a weak probe beam, providing a slightly different measurement of vacuum Rabi splitting than has been accomplished in refs. [70, 71, 72]. Such fiber-taper-based measurements have been discussed in detail in the context of microdisk cavities in chapter 8. Beyond vacuum Rabi splitting, further experiments will explore

phenomena like switching or other nonlinear optical effects in a strongly coupled microcavity-QD system. In such measurements, the fiber taper (or some other form of efficient input-output coupling) is basically a necessity.

Incorporating the fiber taper within a liquid He cryostat is thus a critically important step, and one that is specific to the experiments we wish to conduct. As mentioned in the preface to this thesis, our initial hope was to create fiber-pigtailed devices using the taper mounting technique developed by Paul Barclay for use in ultra-high-vacuum chambers and atomic physics experiments [80]. Our attempts at using such structures were unsuccessful, due to the mechanical failure of the epoxy joints (used to affix the taper onto the microcavity chip) at low temperatures. On the positive side, the fiber taper itself showed no degradation (in terms of its transmission properties, for example) at low temperatures. Current efforts are focused on utilizing low-temperature-compatible micropositioners to actively position the taper with respect to the cavity in the same way we do so at room temperature.

The other principal technical challenges that we face are common to the field as a whole, rather than our specific experiments. As mentioned above, foremost amongst these is achieving spectral and spatial alignment of a single QD with the cavity mode. Let us first consider spectral alignment. Unlike atomic systems, for which the transition wavelength of interest is known (e.g., 852.3 nm for the Cs D2 transition) and as a result, so is the desired cavity mode resonance wavelength, there is typically a non-uniform size distribution of QDs within a sample. For example, the inhomogeneous linewidth of the QD exciton ground state transition in our samples is $\sim$50 nm. Devices are then fabricated to have cavity mode resonances lying within this inhomogeneous QD spectrum, and precise spectral alignment is achieved through some tuning mechanism of the cavity mode and/or the QD exciton line. This is sometimes accomplished through temperature tuning [187], where the differing tuning rates of the QD exciton line and the cavity mode can be exploited to tune the two into resonance. There are significant limitations here, however; in ref. [187], for example, the InAs quantum dot shifts by $\sim$1 nm when the sample temperature is changed between $\sim$4 K and 40 K, while the cavity mode shifts by less than one-quarter of this. The tuning range is limited by the maximum sample temperature at which QD non-radiative dephasing is acceptable; even at 20 K, non-radiative dephasing can be significant [142]. If the QD exciton and cavity mode are more widely separated than what can be compensated for through temperature tuning, the cavity geometry can be slightly modified, through etching away a thin layer of material to blue-shift the resonances, for example [188, 48]. One drawback of this method is that it has to be done outside

of the cryostat, and therefore lacks the flexibility and of an *in situ* tuning mechanism. Red shifting of the cavity modes can be accomplished through deposition of a thin dielectric layer by a process such as PECVD (again, not an *in situ* process), or through condensation (of an introduced gas such as Xenon, for example) on the sample surface within the cryostat [189, 190].

Spatial alignment of the QD with the cavity mode is typically achieved by playing the percentages, rather than any sort of active positioning technique. For example, the material we use in our experiments typically has a QD areal density of around 100-300 μm^{-2}. For a microcavity mode with an area of 1 μm^2 (e.g., a standing wave mode in a 2 μm diameter microdisk), this means that 100-300 QDs are expected to be spatially located within the cavity mode. By choosing cavity modes that are located within the long wavelength tail end of the QD spectrum, a small number of these QDs (ideally one) will be within temperature tuning range of the cavity mode. Of course, just because a single QD is on-resonance with the cavity mode and is spatially located within it does not mean the coupling is optimal. Optimal coupling is achieved if the electric dipole vector is aligned parallel to the cavity field, and if the QD is located at a field maximum. For cavity geometries like photonic crystals and microdisks, the field is highly oscillatory in-plane, so that relatively small displacements ($\sim$200 nm) of the QD with respect to the position of the field maximum can cause the observed coupling strength g to be significantly smaller than the maximum achievable coupling strength g_0. As our experiments (and the vast majority of the experiments within the field) stand, we have no way to account for this other than to create a number of devices and hope to have some number of those devices exhibit sufficiently good QD positioning for strong coupling to be obtained. A more deterministic approach for achieving QD-cavity alignment is really contingent upon continued progress in the growth of QDs. There has recently been some exciting progress in this area by the group at the University of California at Santa Barbara [158]. In this work, very dilute samples of QDs (QD density $\sim$0.01 μm^{-2}) are grown, so that at most one QD will be located within the cavity mode. Furthermore, above each QD, a stack of five red-shifted QDs was grown all the way up to the sample surface, so that the in-plane position of the QDs within the sample could be ascertained by imaging the material (with an SEM, for example). Alignment features are then fabricated on the sample surface, and PC cavities are aligned to these features in such a way so that the a single QD is appropriately positioned within each of the cavities. For future demonstrations, it will be of great use if the QD positions can not only be identified, but specified, within a regular 2D matrix, for example. This will ultimately be necessary for applications involving the integration of multiple QD-cavity systems, such as in quantum networks [141]. This topic is of interest to a number of

other important applications (such as lasers), and as such, ordered quantum dot growth is an active area of research. Techniques under consideration include growth on patterned substrates [191, 192], where recent work [193] has shown great promise, with the QDs in a hexagonal array (spacing of 5 μm) displaying an inhomogeneous spectral width of 7.6 meV and a homogeneous spectral width of 140 μeV.