

Numerical Aperture Increasing Lens Microscopy for High Resolution and High Collection Efficiency Spectroscopy of Single Quantum Dots

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Abstract: The Numerical Aperture Increasing Lens (NAIL) technique is applied to imaging and spectroscopy of single InGaAs quantum dots (QDs). Using NAIL, we demonstrate a resolution of 350 nm ($\sim\lambda/3$) and a six-fold collection efficiency increase.

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Solid Immersion Lens (SIL) microscopy techniques have previously been applied to spectroscopy [1] and imaging of single quantum dots (QDs). SIL techniques require the QD emitter to ideally be situated at the interface between air and the epitaxial side of the semiconductor substrate. By immersing the optical near-field of the emitter in a higher index medium (the SIL), both the optical resolution and collection efficiency of a confocal μ PLE system are enhanced. However, it is deleterious to have the SIL-semiconductor interface near the QDs, i.e., in the focal plane of the microscope. Furthermore, the QDs are often buried at a distance from the epi-surface rendering the conventional SIL techniques unfeasible. Recent experimental studies have shown that buried QDs emit light more efficiently than QDs situated near the semiconductor-air interface [2] even when conventional microscopy with light collection through the planar interface is utilized. In contrast to conventional Solid Immersion Lens (SIL) microscopy, NAIL subsurface microscopy allows one to study QDs buried far below the semiconductor-air interface. We apply the subsurface Numerical Aperture Increasing Lens (NAIL) technique [3] to low temperature imaging and spectroscopy of single, self-assembled InGaAs QDs on GaAs substrates (see figure 1).

Figure 1(a) provides an illustration of our fiber-coupled, low temperature confocal microscope. The objective external to the cryostat has a numerical aperture of .12 and acts to both focus the laser excitation and collect the PL. Figure 1(b) illustrates the details of the sample-NAIL assembly. Most notably, the interface between the lens and the substrate is moved far away from the microscope focal plane. The location of the NAIL focal plane reduces artifacts due to interface imperfection in the QD image. At the same time, inclusion of a NAIL increases the overall numerical aperture of the confocal microscope. Figure 2 shows a typical image of a single QD taken with our system. The inset of the figure is a linecut of the QD image. Using the Houston Criterion it is possible to calculate an optical resolution of 350 nm for the NAIL confocal microscope which corresponds roughly to a

resolution of $\sim \lambda/3$. The 350 nm resolution of our system allows us to perform PLE measurements on single QDs. Figure 2 displays a typical QD spectrum taken at 8K.

Not only does the NAIL technique increase the optical resolution of the confocal microscope, but, it also increases the microscope's collection efficiency. By altering the geometry of the semiconductor-air interface, it is possible to collect photons into the system that would have otherwise been reflected by the planar interface. We have measured a six-fold increase in collection efficiency for our system when employing a GaAs NAIL. Earlier results [2], in which photons were collected from QDs buried below a planar semiconductor-air interface, have shown a continuous increase in QD emission intensity, without saturation, as a function of depth below the semiconductor-air interface to depths of 50 nm. We are now trying to take advantage of the previous results in applications where high signal-to-noise ratio is beneficial. Specifically, we are building a Hanbury-Brown Twiss (HBT) interferometer to do both auto-correlation and cross-correlation measurements on lines in QD spectra.

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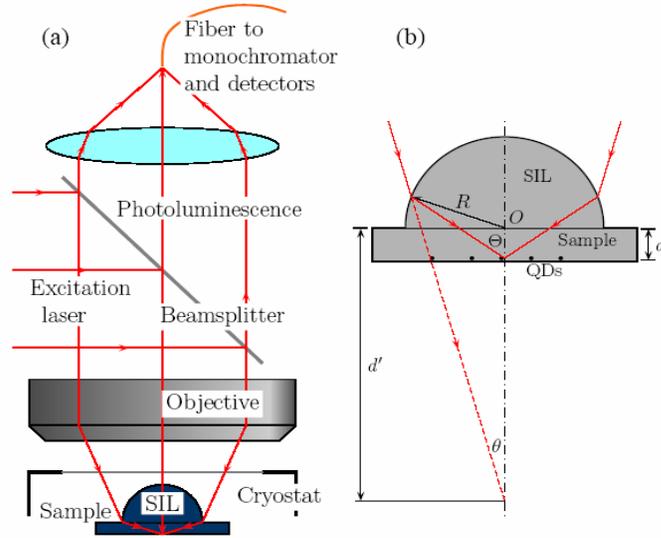


FIG. 1: The optical setup of the experiment. (a) Overview of optical layout. NAAIL-sample assembly is placed inside a microscopic cryostat, which moves in X and Y directions during a 2D scan. (b) Optics of the NAAIL-sample assembly. The hemispherical SIL is placed on the back side of the sample, whose thickness d satisfies $d = R/n$ for stigmatic imaging.

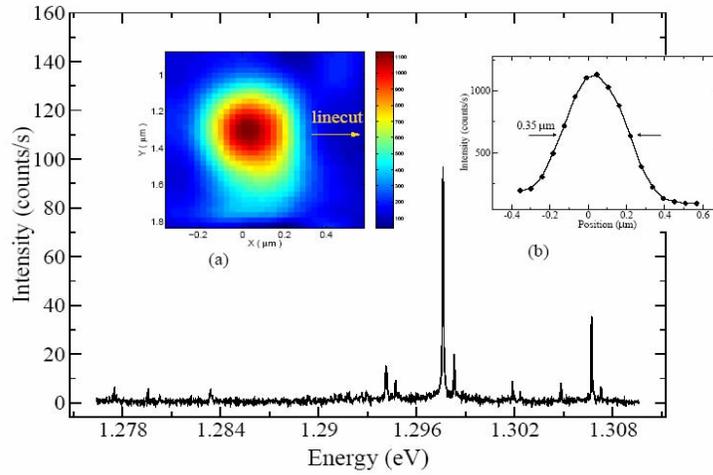


FIG. 2: Measurement of the spatial resolution of the optical system and a typical PL spectrum of the QD taken with our microscope. Excitation laser energy: 1.476 eV. Temperature: 8 K. Inset (a), 2D spatial distribution of the intensity of a sharp QD PL line. Inset (b), the linecut along X direction as marked by the arrow in Inset (a).