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## Spectroscopic Imaging in a Narrow GaAs Quantum Well

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Spectroscopic images from a narrow GaAs/AlGaAs quantum well obtained with a microscope based on a solid immersion lens are presented. We show that the luminescing excitons are localized in quantum dot-like states but that they share a common excitation resonance. Excitation images obtained at this energy are extended in the plane of the quantum well. With increasing pump power density the exciton intensities saturate and biexciton lines are observed. Further increasing the pump power leads to the growth of a broad spectral feature that is ascribed to an electron-hole plasma.

**Introduction** Quantum wells formed out of GaAs and AlGaAs have provided an enormously productive research medium for optical studies of one-dimensional quantum confinement effects in semiconductor materials. Early research demonstrated that lateral interface structures could lead also to localization in all three dimensions [1]. In recent years high spatial resolution techniques have shown in detail that these systems provide highly useful model quantum dot (QD) systems that can be studied in the limit of single quantum dot spectroscopy. Here we show examples of spectroscopic imaging studies that provide new insight into these natural quantum dot systems. In particular we give experimental examples of how localized and delocalized behavior can coexist in the same narrow quantum well sample.

**Photoluminescence Spectroscopic Imaging** Optical spectra obtained from single quantum dots using microscopic [2, 3] and even submicroscopic techniques based on near-field microscopes [4] or shadow masks [5, 6] have led to new opportunities to explore the physics of quantum dots. Recently we have constructed a novel microscope for photoluminescence (PL) spectroscopy based on a solid immersion lens that while retaining the capability for ultra high spatial resolution spectroscopy of the shadow mask technique also has imaging capabilities with near unity throughput [7, 8]. Combining this microscope with a triple monochromator and a tunable Ti:sapphire laser, excitation spectroscopy on single quantum dots has been performed. By tuning the laser in frequency to a strong resonance of an individual QD and recording the entire PL spectrum while scanning the sample in real space, a spectral data cube is obtained (Fig. 1). Local PL spectra can be obtained from the data cube as line cuts in the vertical direction. One such example is displayed in Fig. 1, where a very sharp line is shown. We

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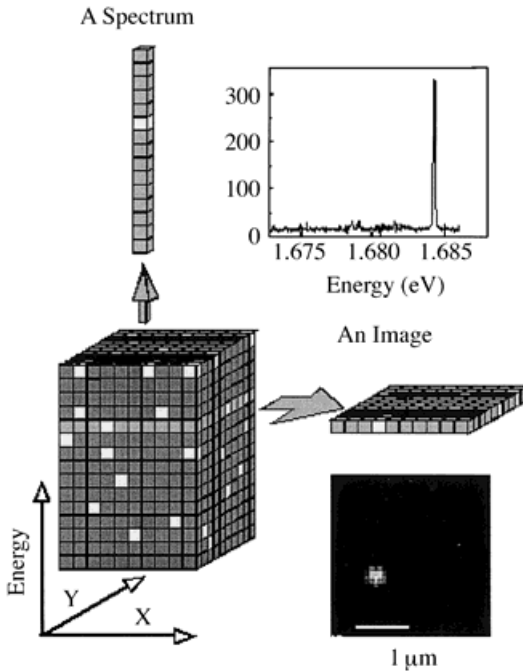
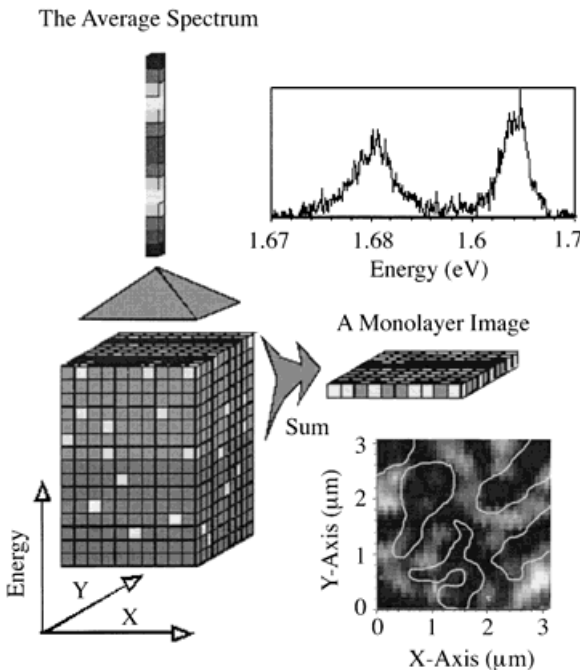


Fig. 1. A spectral cube in which the PL spectrum for each  $(x,y)$  position is schematically displayed. A single column gives a spectrum at a particular  $(x,y)$  position, while a slice through the energy of a given QD emitter gives its image. Examples are shown. In this case the laser energy is fixed in energy as shown but is scanned with the detected spot

spectral cube consists of a much larger but still localized set of QD emissions from both the upper and lower monolayers (Fig. 2). Besides studying individual dots and their sharp-



also obtain the image of the dot that emits this line by taking a slice of the cube at the peak energy of the sharp emission line. From the image shown, it is clear from this data that the PL arises from a localized region, its size limited by the resolution of the microscope. In most cases, PL originates from isolated, dot-like regions within the quantum well.

When the laser energy is tuned above the upper monolayer the spectral cube consists of a much larger but still localized set of QD emissions from both the upper and lower monolayers (Fig. 2). Besides studying individual dots and their sharp-line emissions, we can also gain some insight in the structure of the quantum well sample from the statistics of the dots. For instance, a composite spectrum is obtained from this data cube by adding all the vertical columns together, which resembles a typi-

Fig. 2. Integration over all the columns provides the ensemble spectrum. Alternatively, integrating over PL energy within either the upper or lower monolayer leads to composite images of the luminescing QDs within either the upper or lower monolayer. Contours are superimposed to show the boundary of the monolayer regions

cal large area far field PL spectrum that shows the monolayer splitting that exists in high quality wells. Alternatively, composite images of either the lower or upper monolayer are obtained by projecting the appropriate energy region of the cube onto a plane perpendicular to the energy axis. We find that the PL in the upper and lower monolayers is emitted largely from spatial regions that are anticorrelated, which is consistent with the concept of monolayers. – According to previous studies [5 to 7], these QDs, about 40 nm in diameter, have a packing density around 20 dots/ $\mu\text{m}^2$ , which indicates that the emission comes from a relatively small fraction of the sample and most of the sample does not emit light.

**Photoluminescence Excitation Imaging** Interestingly, the photoluminescence excitation (PLE) spectra of most of the QDs examined in the lower monolayer had a common spectral line whose energy lies between the two monolayers. To explore the nature of this common excitation resonance, we performed a novel PLE imaging experiment [7]. The detection was fixed in energy and centered spatially to a single QD emission while the laser excitation spot was scanned spatially with laser frequency fixed to various PLE resonances. Although the PLE resonances normally were localized on the same spot as the QD PL emission within the resolution of the microscope, the common line demonstrated an extended image (Fig. 3). We conclude that this common PLE resonance arises from absorption in regions of the quantum well around the QD potential depression that are two-dimensional. The PLE process is determined by the creation of the somewhat extended exciton that then decays to the QD exciton ground state through various processes. This explains why most of the region in the quantum well

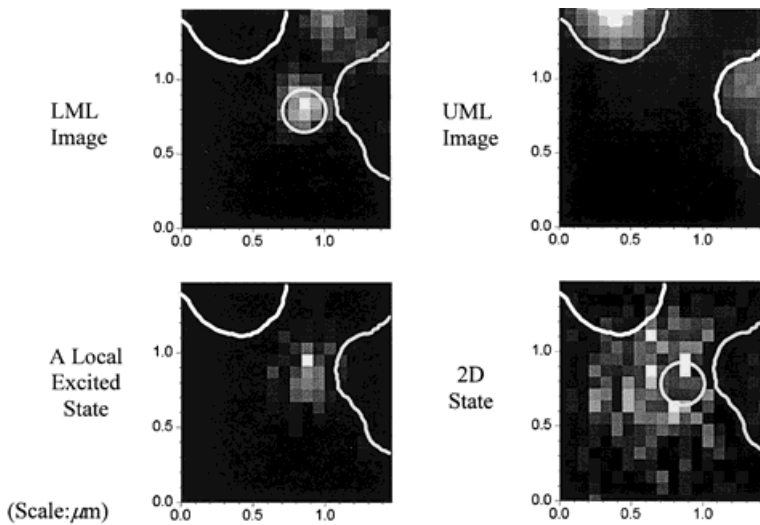


Fig. 3. Top: Composite images of the luminescing QDs in the lower (left panel) and upper (right panel) monolayer spectral regions. Bottom: PL excitation images obtained by fixing the detection in position and energy on the QD circled in the upper left-hand panel. The laser energy is fixed at an excitation resonance for this QD and its position is scanned. The bottom left-hand image shows a localized excited state while the bottom right-hand image shows the extended resonance discussed in the text and in Ref. [7]

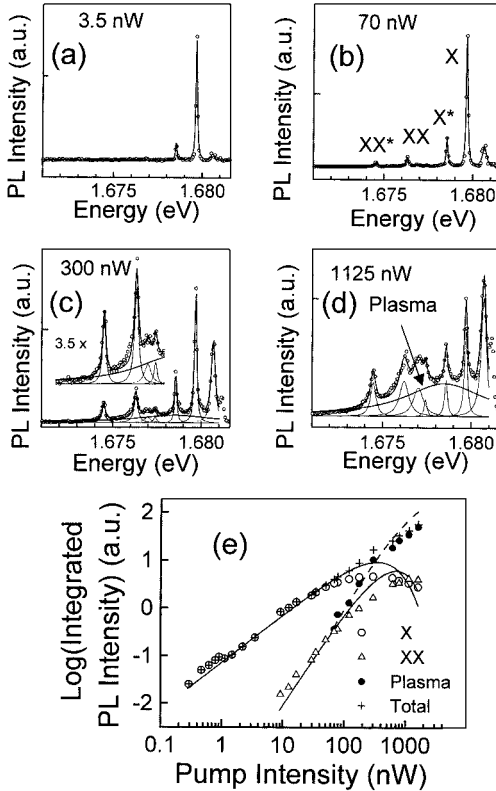


Fig. 4. The power dependence of the PL at a fixed  $(x,y)$  position. Two exciton lines that are within the field of view of the probe spot but independent are labeled by X and X\*. Biexciton lines are labeled XX and XX\*. In (e) is shown the dependence of the integrated PL intensity on pump intensity for X, XX and the broad spectral feature. This feature is identified as an electron–hole plasma

does not emit light. The shape and size of this extended image depends both on the topography of the demarcation lines between the upper and lower monolayer and the presence of nearby lower monolayer dots, which act as same absorption centers.

**Exciton Saturation and Biexcitons** With increasing laser power density the spectra change dramatically (Fig. 4). The

sharp-line QD exciton emission saturates and then decreases in intensity. Simultaneously in many cases new spectral lines arise at energies lower by 3 to 4 meV. As previously discussed [3] these new lines arise from recombination from biexciton states. Their intensities can be described within a random capture model, whose fitting results are shown in Fig. 4e. The center of the PL images associated with these biexciton lines is within half a single pixel (about 40 nm) of the center of the PL images associated with the corresponding exciton spectral line. Such identification reaffirmed the picture that a biexciton originates from the same dot its single exciton counterpart resides.

**Plasma** When the laser power density is increased further, the biexciton lines also saturate and a broad spectra continuum grows. The total emission intensity of the exciton, biexciton and the broad spectral line grows nearly linearly with pump power density. We ascribe this broad spectral continuum to emission from an electron–hole plasma. We found that the spectral width of this feature as a function of power density can be self-consistently described in terms of recombination within a 2D Fermi sea of electrons and holes. This analysis will be presented elsewhere [9]. From the study of the plasma density as a function of pump intensity, we found that although the plasma originates from individual disc-shaped dots, it grows out of the boundary of the dots and becomes extended inside the quantum well at high pump intensities.

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