SPECTROSCOPY OF INDIVIDUAL QUANTUM STRUCTURES WITH LOW-TEMPERATURE NEAR FIELD OPTICAL MICROSCOPY

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A low temperature Near Field Scanning Optical Microscope (NSOM) has been built and operated to study the optical properties of individual quantum structures. Near field spectroscopy of modulation doped quantum dots is performed and spectra of a single dot is obtained. Spectral maps of 100nm quantum wires resolve a well defined region where emission from the n=2 quantum confined state is enhanced. This effect is attributed to local strain in the sample.

Optical studies of quantum confined structures in semiconductors generally probe an array of devices resulting in optical spectra which represents a statistical averaging over the array. It is of scientific importance to develop techniques for studying individual structures to examine their characteristic properties as well as the variations of properties among different structures in an array. With the rapid development of Near Field Scanning Optical Microscopy (NSOM) over the past few years it is now possible to perform microscopy and spectroscopy with resolution far greater than the diffraction limit at visible and near-IR wavelengths [1]. A near field probe is a sub-wavelength aperture that is positioned just above the sample at a height much less than the wavelength. By scanning the probe above the sample and collecting the reflected/transmitted light at each point, images with resolution of the order of the size of the probe can be generated. The sub-wavelength aperture is formed by heating and pulling a single mode optical fiber whose tip size can be controlled between 50-200 nm. The fiber tip is then placed in a scanning probe microscope modified with ancillary optics. In order to obtain independent topographical information shear force microscopy is performed simultaneously. The fiber tip is dithered at its mechanical resonance and its amplitude is monitored. As the tip approaches the sample any interaction between the two (such as van der Waals and friction) dampens the resonance and an approach curve is obtained.

The schematics of the low temperature NSOM are shown in fig. 1. In illumination mode excitation laser light is coupled to the tip and reflected light and photoluminescence (PL) from the sample is collimated and focused into a 200 micron fiber by a pair of lenses mounted coaxially above the tip. The tip is mounted through a central hole drilled in the primary lens. In collection mode a 200 micron area of the sample under the tip is illuminated from the far field and the tip collects locally emitted light. The coarse approach is performed by a vertical piezo-electric inertial walker

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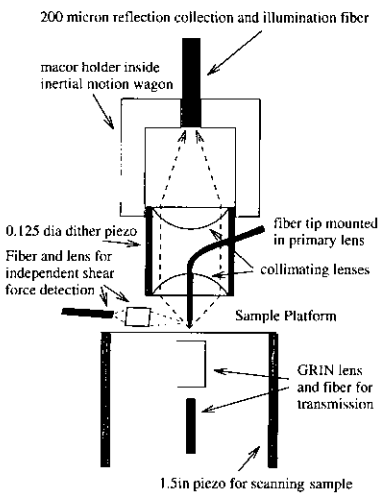

Fig. 1. Schematic diagram of low-temperature NSOM. The dither piezo and primary and secondary collection lenses are mounted to the wagon (not shown). The tip is mounted through a central hole in the primary collection lens. During optical or spectral image formation only the sample is scanned, preventing the collection efficiency of the tip and lenses from varying. For coarse approach the upper section moves vertically up and down by slip-stick motion of the wagon on two sapphire rods (also not shown).

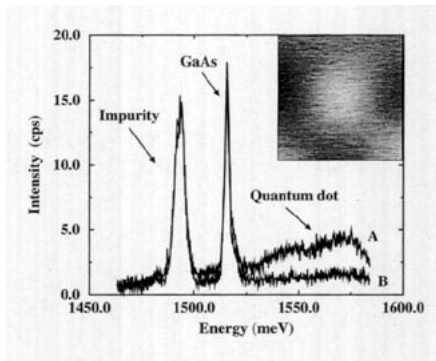

Fig. 2. Low-temperature spectra of a single dot taken in the near field (A) on top of and (B) off to the side. The dot consists of 10 modulation doped quantum wells. The inset shows an optical image of the dot in a $0.5 \times 0.5\mu$m scan.

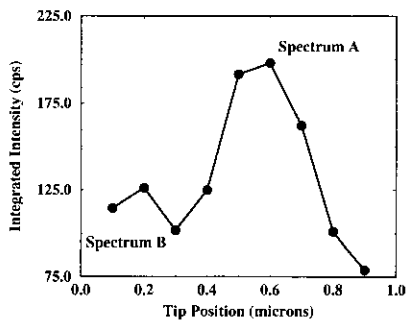

Fig. 3. The integrated energy region about the dot emission as a function of position across the dot. The width corresponds well to the lithographic width of 270 nm defined by dry etching.

designed by Renner [2]. The tip and collection lens assembly are mounted on a wagon that moves along two parallel sapphire rods. The rods are rigidly connected to a piezo-tube which drives the wagon with step sizes as fine as 7 nm over a 1 mm range at low temperature. Shear force is performed by a small piezoelectric tube which vibrates the tip at its mechanical resonance. Laser light of 1300 nm is focused onto the tip via a coherent fiber bundle. The use of the fiber bundle allows for remote control of the laser spot on the tip in case of misalignments caused by the cool-down process. A 600 micron fiber collects the transmitted laser light and a detector and lock-in amplifier is used to measure the amplitude signal at resonance. The sample is mounted on a 1.5 in. long piezo tube which allows for a scan range of 10 micron at 4 K.

The inset of Fig. 2 is a NSOM image of a 270 nm quantum dot dry etched in a multiple quantum well sample. The structure consists of ten modulation doped, 80Å wide quantum wells with high carrier density ($n_s \sim 7 \times 10^{11}\text{cm}^{-2}$). Near field spectra of these dots was obtained in collection mode; fig. 2 shows spectrum taken on top of the dot (A) and spectrum over the etched region (B). Two bulk features (GaAs bulk exciton and impurity emissions) are present in both spectra whereas only spectrum A shows the dot emission at higher energies. Fig. 3 displays the integrated PL intensity over the energy range of the dot's emission as a function of position in a spectral line scan across the dot. The spectral width corresponds well with the lithographic width and sharp drop of PL intensity at the edges is evident. The spectral shape of the emission from an individual dot in near field is similar to that of far field. We attribute this to broadening to the heavily doped dots [3], as well as the inhomogeneous broadening due to the presence of 10 multiple quantum wells. Also, confinement effects are typically pronounced only for much smaller dots (~60 nm).

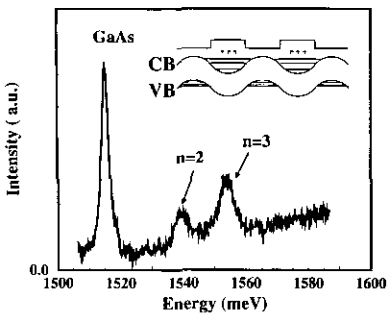

Fig. 4. Far field spectrum of 1000Å quantum wires. The quantum confined states are spectrally resolved in these structures. A schematic of the modulation of conduction and valence bands due to shallow etching is shown in the inset.

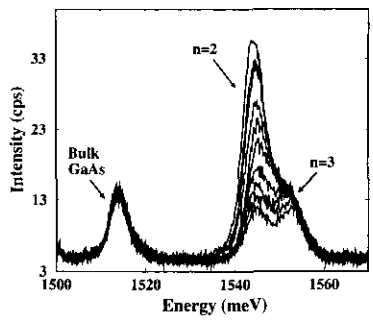

Fig. 5. Near field collection mode emission spectra of quantum wires show a pronounced position dependence of n=2 peak. Each spectrum was taken at intervals of 100 nm in a line across the region shown in fig. 6.

In order to study the effect of confinement in individual structures we studied a series of 100 nm quantum wires shallow etched in a modulation doped GaAs-AlGaAs single quantum well. These structures are lateral superlattices and the shallow etch results in a modulation of conduction and valence band as shown schematically in the inset of fig. 4. It is important to note that the electron and hole wavefunctions are spatially separated in this structure. A far field PL spectrum is shown in fig. 4, displaying spectrally resolved emission from the different laterally confined states. There is no emission from the ground state due to absence of overlap between e-h wavefunctions; the n=2 has a moderate overlap and n=3 is quasi-bound with a much larger overlap. The near field spectra exhibit a striking position dependence of n=2 emission as shown in fig. 5. The spectrum taken at each point is fitted to generate individual intensity and peak position spectral maps of the two transitions. Fig. 6 is a spectral intensity map of the n=2 state and shows a localized region of bright intensity with spatial extent of $\sim 0.5\mu$m. In contrast, the spectral intensity map of n=3 lacks any significant position dependence. The contours in fig. 6 depict the spectral peak position of the n=2 emission, showing a direct correlation of the large intensity with a slight ($\sim$ 1.5meV) reduction in emission energy. The increase in n=2 emission means a greater overlap of electron and hole wavefunctions, which implies a modification of the wire potential. Since the wavefunctions have a greater effective width, the energy will be lowered with respect to the band edge which is consistent with the observed red shift. We tentatively attribute the reduction in wire confinement potential to a local strain, distributed non-uniformly due to the sample corrugation. This picture is not inconsistent with the lack of variation in n=3 emission, since this state is already quasi-bound.

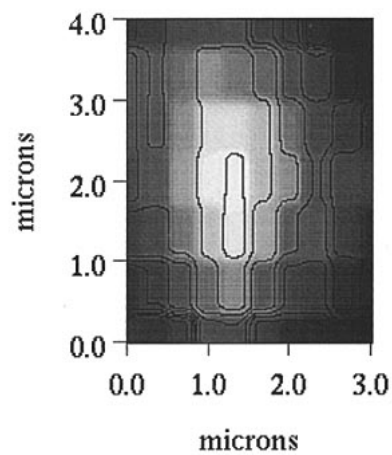

Fig. 6. Spectral map of n=2 emission as a function of position. Bright regions correspond to increase in peak optical emission (see fig. 5). The spectrum at each point was fitted with combined Lorentzians for n=2 and n=3. The contours display the shift in peak energy and are separated by 0.3 meV. The innermost contours represent a red shift of 1.5 meV from the outer regions. Note that the increase in emission intensity is strongly correlated with the red shift in peak position. The n=3 spectral map shows a factor of 10 less intensity variation, but displays a similar red shift. In imaging the surface individual wires were not resolved and thus the orientation of wires is unknown.

In summary, we have demonstrated the ability of near field spectroscopy to probe the optical properties of single quantum structures. Spectral maps with resolutions greater than the diffraction limit have been obtained. Near field microscopy and spectroscopy provide great potential in extending experimental studies of quantum structures beyond traditional optical techniques.

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