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Low temperature near field spectroscopy and microscopy

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Abstract

A low temperature near field scanning optical microscope has been constructed. Images of InGaAs quantum wires have been obtained at 4.2 K with a resolution < 100 nm ($\lambda/8$). Low temperature spectroscopy and images of 270 nm GaAs quantum dots show vertical dependence in both intensity and spectral shape in collection mode operation. The microscope is designed for use in high magnetic fields and top loads into a 1.2 inch cryostat. A pulled optical fiber [1] tip is mounted in a simple and novel lens collection scheme for reflection mode NSOM. Additional side mounted fibers with focusing GRIN lenses are used for detecting the fiber tip resonance, providing independent shear force microscopy.

1. Introduction

For more than ten years, spectroscopists have been investigating microstructures where the energy separation between quantum confined states is large enough to effectively reduce the system dimensionality. With a few notable exceptions [2] all such studies have examined arrays of microstructures, inferring the physics of individual devices from spectra obtained by studying an ensemble. In an effort to directly examine single microstructures, we have constructed a low temperature near field scanning optical microscope for operation in a high magnetic field. We discuss the design and operation, presenting images from quantum wires and dots, as well as low temperature near field spectra of quantum dots.

2. Design

Fig. 1 shows a schematic of the bottom of the NSOM. A 2.0 inch long, 0.25 inch diameter, four quadrant piezo tube is used to provide the large $\hat{x}$–$\hat{y}$ scan range. At the base, a macor piece with integral secondary collection microlens and 200 μm collection fiber is used to mount a 0.125 inch diameter piezo tube for dithering the tip. The fiber tip is installed through a 0.013 inch hole in the primary collection microlens affixed to the end of the smaller piezo tube. The image of the 200 μm collection fiber is focused at the fiber tip, typically 0.080 inch from the primary collection microlens face.

Reflection geometry illumination mode operation is obtained by illuminating the sample through the fiber tip, and collecting the reflected and emitted light back up through the microlens assembly into the 200 μm collection fiber. Collec-

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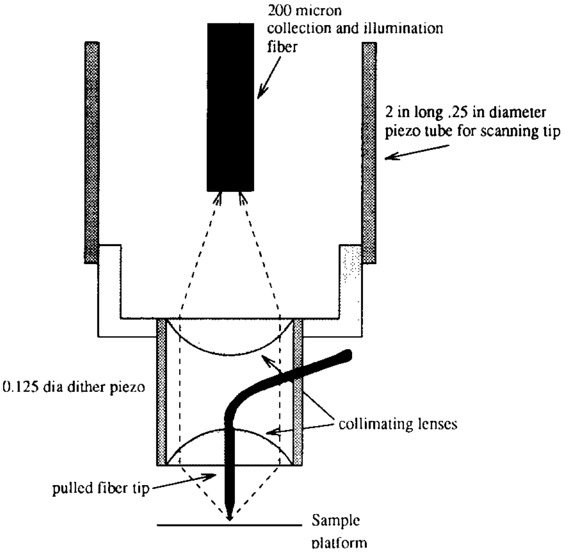

Fig. 1. Schematic diagram of the bottom section of the low temperature near field scanning optical microscope. Refer to the text for details.

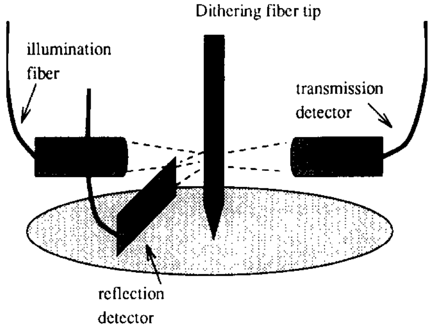

Fig. 2. Schematic diagram of the shear force detection mechanism. An input fiber focuses 1.3 μm laser light onto the tip end, and both reflection and transmission signals are collected.

tion mode operation is the reverse: The 200 μm fiber is used to illuminate a broad area of the sample, with the fiber tip collecting the light in near field at the sample surface. Finally, a 100 μm fiber and GRIN lens is mounted in the center of the sample stage for transmission operation.

Coarse vertical approach is provided by a differential screw driving a piston ground to close tolerance with a matching cylinder. The differential screw can be decoupled by means of a pair of forks, one attached to the differential screw, and the other fed through a long rod at atmosphere at the top of the cryostat. In typical operation, a tip to sample separation at room temperature of 80 μm (a single turn on the differential screw) changes less than 10% at low temperature. The sample is mounted on a 0.5 inch diameter piezo which can be used to position the sample using the standard inertial motion, or slip stick technique.

Independent knowledge of the sample topography is important for NSOM operation, especially with microstructured samples. We have constructed a shear force detection apparatus which employs three additional fiber and lens mounts, displayed in Fig. 2. A 100 μm fiber with attached GRIN lens focuses a 1.310 μm laser from a laser diode onto the tip. A fiber and GRIN lens pair is mounted directly opposite, collecting the shear force signal in transmission, while another pair is mounted at 90° to collect in reflection. Our best shear force data is generally collected in transmission. Fig. 3 shows a resonance frequency scan using the transmission configuration.

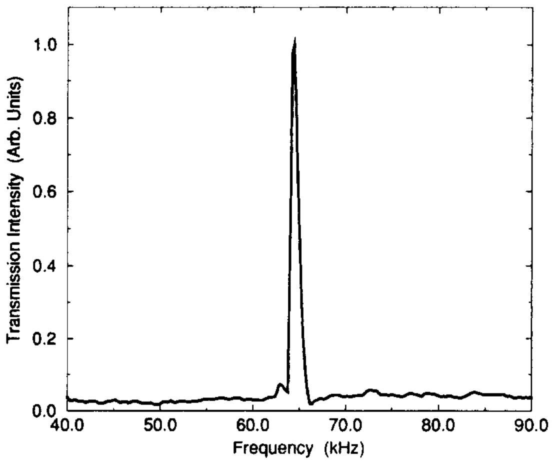

Fig. 3. Typical shear force resonance signal as a function of frequency using 1.3 μm laser light and collecting with the transmission GRIN lens and fiber assembly.

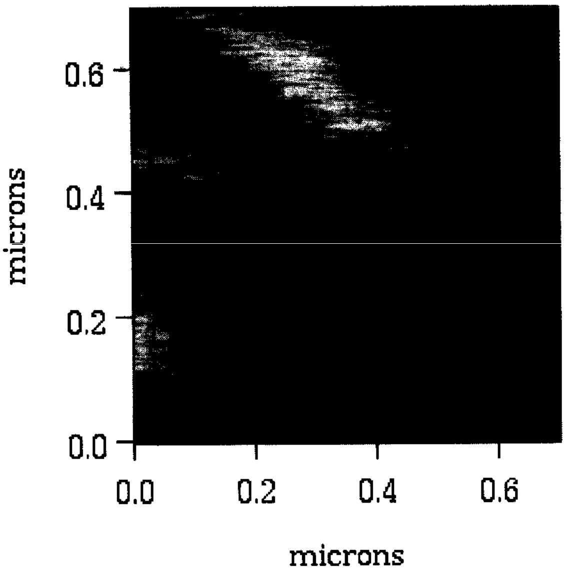

Fig. 4. Room temperature near field optical image of 90 nm wide Au wires evaporated on a GaAs substrate taken in illumination mode.

3. Microscopy

Room temperature operation in near field was tested by imaging a series of Au wires, 92 nm in width on 90 nm spacings evaporated onto GaAs. Fig. 4 shows a near field image taken in reflection at constant height with 780 nm light in illumination mode operation. For low temperature operation, the microscope is placed in a can immersed in helium at 4.2 K. To prevent dielectric breakdown, the can is back-filled with ~ 1.5 atm of gas, cooling the microscope and sample stage to 4.2 K. A low temperature (4.2 K) image of V-groove InGaAs quantum wires is shown in Fig. 5. The rough surface corrigation corresponds well to SEM images, and reflects the SiO_2 mask used to etch the V-groove regions for regrowth. In this image, the tip size was approximately 200 nm, as measured by SEM. A final image, of GaAs quantum dots, is presented in Fig. 6. This image is also taken in illumination mode, and dots of nominal size 270 nm diameter are clearly resolved. The sample is made by electron beam lithography, with the dots formed by etching the surrounding material.

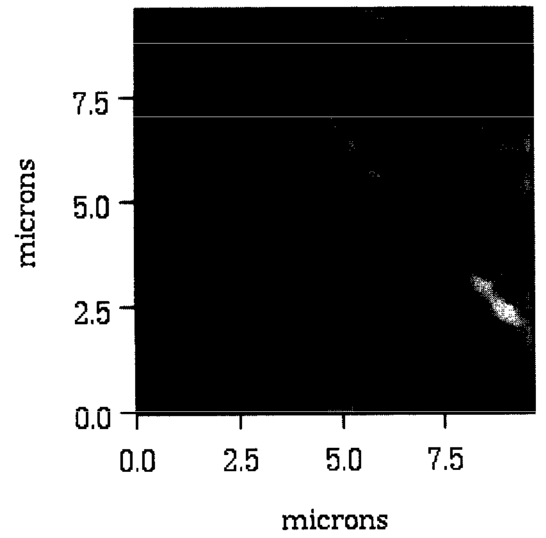

Fig. 5. Low temperature (4.2 K) near field image of InGaAs V-groove quantum wires taken in illumination mode. The reflected laser light is used to form the image. The surface roughness has been imaged by SEM, and is due to the SiO_2 mask used to selectively etch the V-groove prior to regrowth.

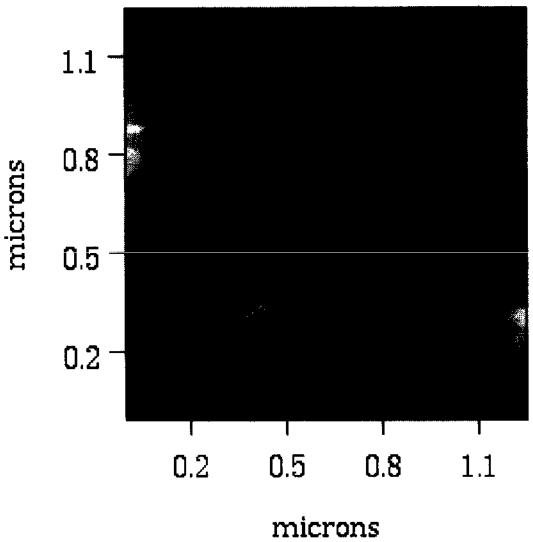

Fig. 6. Low temperature (4.2 K) near field image of GaAs quantum dots taken in illumination mode. The reflected laser light is used to form the image.

4. Spectroscopy

Initial spectroscopic scans of the GaAs quantum dots in collection mode showed an increase

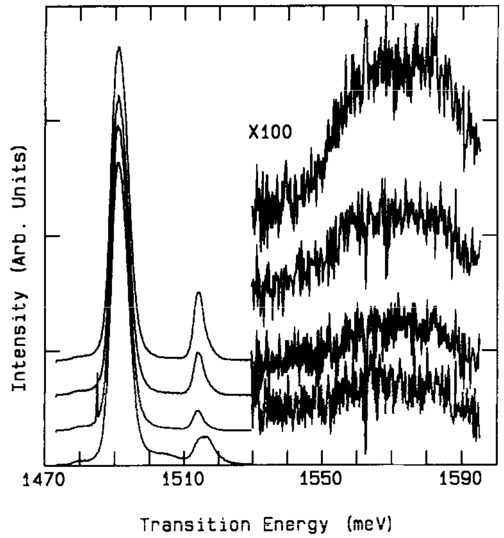

Fig. 7. Near field collection mode spectra of the GaAs 270 nm quantum dots. The laser excitation wavelength was 710 nm. The set of four spectra represents the changes in emission as a function of tip to sample separation, all in the near field. The topmost is taken at 50 nm, the second at ~ 5 nm, the third just touching the sample, and the bottommost spectrum is lightly pressing the tip into the sample. Note the strain induced energy shift and peak broadening of the GaAs free exciton at 1515 meV. Note also that the dot emission is a factor of ~ 100 less than the bulk impurity bound-exciton emission.

in signal intensity of approximately a factor of two as the tip approached the sample and entered into the near field regime. The quantum dots consisted of a series of five modulation doped quantum wells of ~ 8 nm width, with carrier densities of order 10^{12} cm^{-2}. Emission from the wells in an unpatterned test sample in far field spectra was dominated by an emission band 35 meV broad with a peak near 1560 meV and a high energy shoulder near 1585 meV. 710 nm laser light from a Ti : sapphire laser was focused by the collection optics onto an ~ 200 μm spot surrounding the tip, with power densities of ~ 80 W/cm^{-2}. Fig. 7 displays a series of four spectra taken in collection mode as a function of height which are offset for clarity. The topmost trace is taken in the near field 50 nm above the dots, the second at ~ 5 nm, the third just touching the sample, and the bottommost spectrum is pressing the tip into the sample. The dot emission is typically a factor of 100 less than the GaAs impurity and free exciton peaks, and extinguishes as the tip touches the sample. The dot emission is broad due to the high carrier density in the quantum wells. It is interesting to note that as the tip is pushed slightly into the sample, the GaAs free exciton emission at 1515 meV displays a broadening and shift to higher energy. We believe this is due to local strain induced by the fiber tip. The large impurity feature is likely due to states relatively deep into the substrate, and is thus unaffected by the minor tip to sample separations displayed. We note that the emission associated with these localized impurities is much weaker in far field spectra, relative to the free exciton, presumably due to the higher mode density at large wavevectors in both the localized impurity emission and the evanescent field of the tip.

In conclusion, we have observed changes in the dot emission as a function of both vertical and lateral position, and are currently working to obtain clear enough optical or shear force images to correlate the spectra to an individual quantum dot.

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