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 (λ/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 x−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-
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.

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.

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. 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 corrugation corresponds well to SEM images, and reflects the SiO₂ 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.

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 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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References