

# Optical spectroscopy of a GaAs/AlGaAs quantum wire structure using near-field scanning optical microscopy

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We report the first spectroscopic study using a low temperature near-field scanning optical microscope. We have studied an array of GaAs/AlGaAs cleaved edge overgrowth quantum wires. The three luminescence peaks originate from different structures in the sample: The (001)-oriented multiple quantum wells, the (110)-oriented single quantum well, and the quantum wires. The linewidth of the quantum wire emission is related to roughness in the (110)-oriented single quantum well. Quenching of the multiple quantum wells and single quantum well emission near the quantum wires is attributed to diffusion of photoexcited carriers into the wires.

Optical spectroscopy is an important tool in the characterization of mesoscopic semiconductor systems. One would like to be able to conduct spectroscopic experiments on single mesoscopic devices; however, the spatial resolution of diffraction limited optics usually limits the spectroscopist to studying several devices simultaneously. It is therefore useful to be able to conduct spectroscopic experiments with spatial resolution better than the diffraction limit. The invention of the aluminum coated, tapered fiber probe,<sup>1</sup> and the subsequent developments in near-field scanning optical microscopy (NSOM)<sup>2</sup> have enabled us to build a low temperature near-field scanning optical microscope for use in spectroscopic studies. We present the results of a study conducted in our low temperature apparatus on an array of cleaved edge overgrowth quantum wires. To the best of our knowledge this is the first use of NSOM for spectroscopic characterization.

NSOM is a scanned probe technique that achieves spatial resolution by funneling light through a small aperture in the end of a sharp and otherwise opaque probe. A detailed description of the experimental apparatus, depicted in Fig. 1, has been given elsewhere.<sup>3</sup> The fiber probe used in this experiment is made of single mode optical fiber with a cutoff wavelength of 850 nm. The aperture at the end of the probe has a diameter of 0.25  $\mu\text{m}$  as measured after the experiment using a scanning electron microscope. All data are obtained with the sample and probe immersed in 1.5 K superfluid liquid helium. We use a Ti:sapphire laser for the optical pump. Luminescence is dispersed in a 0.6 m triple spectrometer and detected with a liquid-nitrogen cooled silicon charge coupled device detector. NSOM can be done in the collection mode (i.e., photoexcite from the far field and collect luminescence locally using the fiber probe) or in the excitation mode (i.e., photoexcite locally with the probe and collect the luminescence in the far field). Results for both configurations are presented.

The sample is an array of GaAs/AlGaAs, cleaved edge overgrowth, quantum wires. The cleaved edge overgrowth method is described elsewhere.<sup>4</sup> Our sample is nominally identical to the recently reported quantum wire laser.<sup>5</sup> Figure 2 depicts the sample from the perspective of the fiber probe. In the (001) orientation are grown a 1  $\mu\text{m}$   $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$

buffer, multiple quantum wells (MQW) consisting of 22 periods of 70  $\text{\AA}$  GaAs quantum wells and 380  $\text{\AA}$   $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$  barriers, a 3  $\mu\text{m}$   $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$  buffer, and a 100  $\text{\AA}$  GaAs cap. The sample is then cleaved *in situ* along the (110) direction on which are grown a single 70  $\text{\AA}$  GaAs quantum well (SQW), a 70  $\text{\AA}$   $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$  barrier, a 0.167  $\mu\text{m}$   $\text{Al}_{0.1}\text{Ga}_{0.9}\text{As}$  cladding layer, a 1  $\mu\text{m}$   $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$  buffer, and a 100  $\text{\AA}$  GaAs cap. At the intersections of the GaAs MQW and the SQW are formed quantum wires. In our experiment the wires run coaxially with the direction of propagation of light from the fiber probe (i.e., the wires are viewed in cross section).

In collection mode the sample is photoexcited with a far-field optical pump and the resulting luminescence is collected locally with the fiber probe. For the optical pump we use 3 mW of 750 nm photons focused to a 30- $\mu\text{m}$ -diam spot. The photoluminescence spectrum shown in Fig. 3(a) is obtained by positioning the tip 1.0  $\mu\text{m}$  above the sample and

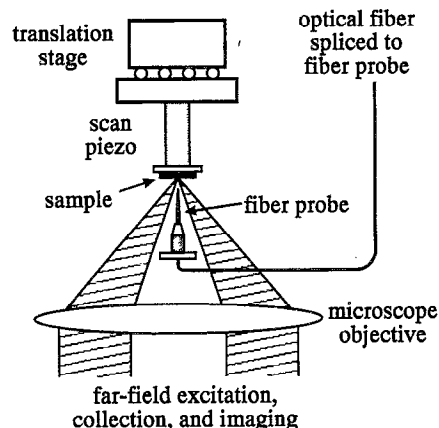


FIG. 1. A schematic of the experimental apparatus. The sample is mounted on the end of a piezoelectric scan tube, which is capable of three degrees of motion. The scan tube is mounted on a mechanical translation stage which allows course positioning of the sample. The fiber probe is mounted on a platform which can be moved vertically. The fiber probe is spliced to a single mode optical fiber for access to external spectroscopic equipment. The microscopic objective is used both for excitation/collection of far-field photons during spectroscopic experiments and for far-field imaging of the sample.

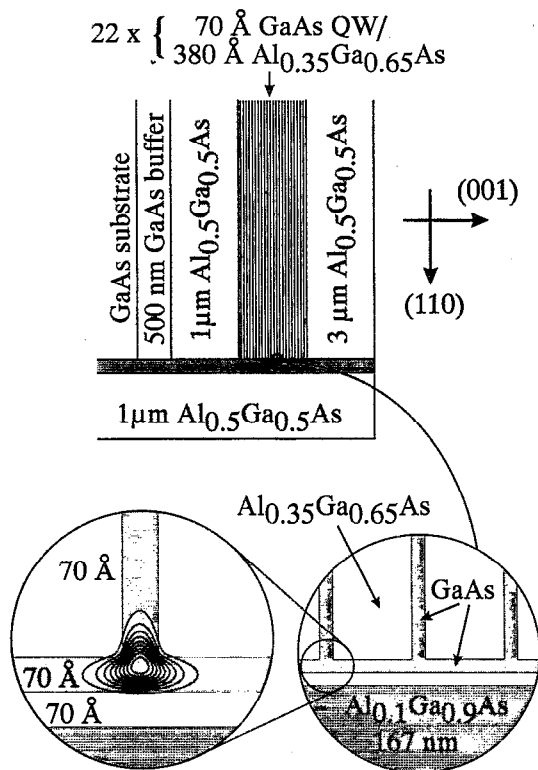


FIG. 2. A schematic showing the quantum wire sample as presented to the probe. In the inserts are shown the intersection of the (001)-oriented MQW and the (110) SQW and a contour plot representative of the quantum wire wave function.

typifies far-field spectra. The images in Figs. 3(b)–3(d) are obtained by monitoring the emission intensity of the low, middle, and high energy peaks, respectively, while scanning the probe over the surface at a height of 1000 Å. The images are  $2.0 \mu\text{m} \times 2.0 \mu\text{m}$  with a pixel size of  $0.1 \mu\text{m}$ . Signal levels are of order  $10^4$  photons/s. Superposed on each image is a schematic indicating the orientation of the sample. This sequence of images clearly identifies each of the peaks: (1) the low energy peak as emission from the wires; (2) the middle energy peak as emission from the SQW; and (3) the high energy peak as emission from the MQW. We are unable to resolve individual wires, which is expected since the wires are spaced by  $450 \text{ \AA}$  and the probe aperture is  $0.25 \mu\text{m}$ .

Though the SQW and the MQW were designed to be of identical thickness, the 12 meV shift between the emission peaks indicates that they differ in thickness by three monolayers.<sup>6</sup> The linewidth of the quantum wire emission [full width at half-maximum (FWHM)=8 meV] is much broader than the line width of the MQW emission (FWHM=3 meV) but nearly identical to the line width of the SQW emission. We conclude that the quantum wire emission spectrum is dominated by the properties of the SQW. The linewidth of the SQW indicates two monolayers of micro-roughness in the well width. Note that growth in the (110) orientation is not as well refined a process as is growth in (001) and roughening of this quantum well is not particularly surprising.

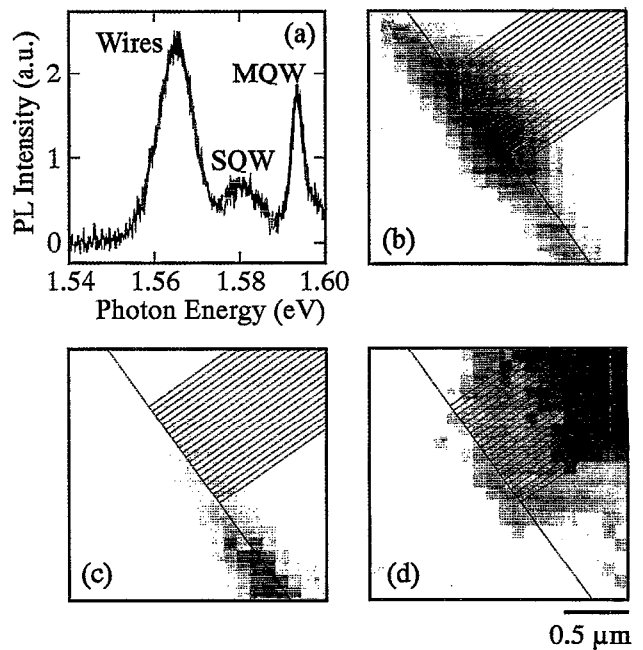


FIG. 3. In (a) is a spectrum typical of the far-field luminescence. In (b)–(d) are collection mode images obtained by monitoring the emission intensity of the low, middle, and high energy peaks, respectively. (a) A schematic indicating the orientation of the sample is overlaid on each image.

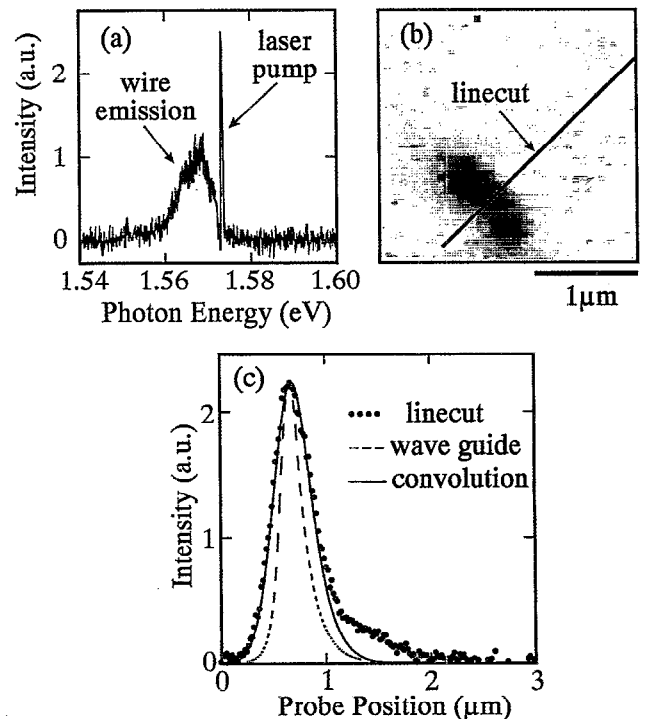


FIG. 4. Shown in (a) is the spectrum obtained in emission mode with the optical pump resonantly exciting the quantum wires. The image obtained using this technique is shown in (b). The linecut, shown as dots in (c), is compared with a calculation of the waveguide mode, shown as the dashed line. The solid line is the convolution of the waveguide mode with a  $0.25\text{-}\mu\text{m}$ -diam Gaussian line shape meant to approximate the instrument function of the aperture.

The luminescence from both the MQW and the SQW quenches near the wires. We interpret this as diffusion of carriers from the quantum wells into the quantum wires. The luminescence quenches on a length scale of order  $0.5 \mu\text{m}$  in the SQW and  $0.7 \mu\text{m}$  in the MQW. We interpret this as a measure of the diffusion length of the photoexcited carriers. Note that the emission intensity of the SQW is not symmetric about the wires (i.e., there is almost no emission from the side nearest the substrate). However, the SQW structure is asymmetric: On the substrate side of the wires the SQW is only  $1 \mu\text{m}$  long while on the surface side of the wires the SQW extends for  $3 \mu\text{m}$ . We interpret the quenching of the SQW emission on the substrate side of the wires as diffusion of carriers from the SQW into the GaAs buffer layer. This is consistent with the  $0.5 \mu\text{m}$  diffusion length observed in Fig. 3(c).

The argument for carrier diffusion is strengthened by comparing the emission intensity of the quantum wires to that of the MQW. The wire emission is six times more intense than the MQW emission. This can be understood using a geometric argument. The area of MQW under the tip is roughly the area of the probe aperture,  $\pi(1250)^2 \text{ \AA}^2$ , while the area of the wires sampled by the probe is  $70 \text{ \AA} \times 2500 \text{ \AA}$ . From the ratio of these cross sections one expects the MQW emission to be 28 times more intense than the wire emission. Carrier diffusion from the MQW into the wires increases the emission intensity of the wires linearly with diffusion length. Considering the  $70 \text{ \AA}$  well to be a unit of length, one needs diffusion from  $28 \times 6 = 168$  units to account for the intensity of the wire emission. This amounts to a diffusion from  $168 \times 70 \text{ \AA} = 1.2 \mu\text{m}$ . Within a factor of 2 this is consistent with the  $0.7 \mu\text{m}$  diffusion length observed in Fig. 2(d). This analysis strongly supports the notion that carriers are funneled from the MQW system into the quantum wires where they equilibrate and then radiate.

In excitation mode the fiber probe is used to locally photoexcite the sample and the resulting luminescence is collected with the far-field optics. This technique is similar to cathodoluminescence with the important advantage that one can tune the energy of the excitation source to be resonant with a particular absorption feature. We demonstrate this technique by resonantly pumping the wires. The spectrum shown in Fig. 4(a) shows both the optical pump ( $\lambda = 788.1 \text{ nm}$ ) and the resulting quantum wire emission. For optical excitation we directed  $0.5 \text{ mW}$  to the fiber probe and measured single levels of order  $10^4$  photons/s. The optical pump is lower in energy than both the SQW and MQW luminescence and is therefore not absorbed by these features. The image obtained by this technique is shown in Fig. 4(b). This image is  $2.5 \mu\text{m} \times 2.5 \mu\text{m}$  with a pixel size of  $625 \text{ \AA}$ . We have studied the width of this absorption profile by taking a detailed linecut along the path indicated in Fig. 4(b). The resulting profile, shown in Fig. 4(c), exhibits an asymmetric line shape with a FWHM of  $0.4 \mu\text{m}$ . We argue in the follow-

ing paragraph that both the linewidth and the asymmetry are due to absorption occurring at depth of order the aperture diameter.

Scanned probe microscopies are ideally used to study surfaces; however, one has to consider effects due to the bulk material. This is especially true for NSOM since the near-field spot diverges rapidly. The orientation of this experiment is such that the direction of propagation of light from the probe is coaxial with the wires, which are enclosed in a waveguide. After the growth of the SQW on the (110) face there is grown a  $0.167\text{-}\mu\text{m}$ -thick cladding layer of  $\text{Al}_{0.1}\text{Ga}_{0.9}\text{As}$ . The waveguide formed by this cladding layer and the MQW is asymmetric, with a sharp edge on the side nearest the cladding. A calculation of the fundamental mode of this waveguide is shown as the dashed line in Fig. 4(c). The solid line is the convolution of this mode with a Gaussian line shape of width  $0.25 \mu\text{m}$ . We assume that this line shape adequately approximates the instrument function of the fiber probe and that the convolution is representative of the actual measurement. Had the experiment only been sensitive to absorption within a few hundred angstroms of the surface the waveguide would not be relevant. Since the waveguide is relevant, both in determining the width and the asymmetry, one reasons that there is a significant absorption from within the sample. That the width of the instrument function is close to the aperture diameter of the probe puts an upper limit on the relevant depth. If it is assumed that the light diverges from the probe roughly like an  $f/1$  optic, only absorption at a depth of order the aperture diameter contributes to the observed line width.

In conclusion, we report the first use of a low temperature ( $T = 1.5 \text{ K}$ ) near-field scanning optical microscope and demonstrate that NSOM can be used for spectroscopic application. We study an array of GaAs/AlGaAs cleaved edge overgrowth quantum wires. The luminescence peaks originate from three structures in the sample: The (001)-oriented MQW, the (110)-oriented SQW, and the quantum wires. The linewidth of the quantum wire emission is shown to be related to roughness in the SQW. The quenching of MQW and SQW emission near the quantum wires is due to diffusion of photoexcited carriers from the MQW and SQW into the quantum wires.

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<sup>6</sup>We calculate that a monolayer fluctuation in the well width of a  $70 \text{ \AA}$  quantum well will result in a shift in the luminescence peak position of order  $4 \text{ meV}$ .