Near-field scanning optical microscopy studies of V-grooved quantum wire lasers

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Detailed near-field scanning optical microscopy studies of GaAs/AlGaAs V-grooved quantum wire lasers at room temperature were performed. We measured the spectrally resolved near-field intensity distributions, emitted from the complex epitaxially grown optical waveguide in the V groove with a spatial resolution of $\sim 0.1 \mu m$. Distinct regions emitting at different wavelengths were identified, and a heart shaped modal distribution of less than 0.5 $\mu m$ in diameter was measured and well matched the calculated light distribution of this structure. © 1998 American Institute of Physics. [S0003-6951(98)02438-3]

Low dimensional quantum wire (QWR) and quantum dot (QD) semiconductor lasers have been predicted to show a static and dynamic performance superior to that of conventional quantum well (QW) devices. However, the successful realization of such quantum confined structures requires configurations which are considerably more complex than those employed in QW lasers. In particular, the extremely small active volume associated with the nanometer-sized QWRs and QDs necessitate the utilization of very tight optical confinement in order to achieve useful modal gains. Furthermore, the optimization of carrier injection into the wires or dots often results in structure designs involving complex barrier structures including regions of intermediate dimensionalities (e.g., QWs in the case of QWR active regions, QWs and QWRs for QD devices). This leads to laser configurations exhibiting a rich structure on a scale of $\sim 100$ nm. The investigation of the properties of such optical nanostructures, which is important for the device optimization, calls for the application of novel characterization techniques capable of spatial resolution on a corresponding scale.

A useful model system for such low dimensional lasers is the V-groove QWR laser which exhibits particularly tight, V-shaped channel waveguides and a variety of QW structures in the QWR barriers. Optical measurements of the optical modes of these lasers, using far-field optics, have shown mode diameters of $\sim 1 \mu m$. However, model calculations of these structures predict mode diameters on the order of 0.5 $\mu m$, beyond the spatial resolution of the far-field techniques.

In this letter, we report the use of near-field scanning optical microscopy (NSOM) with subwavelength optical resolution to investigate the complex near-field emission properties of GaAs/AlGaAs V-grooved QWR lasers, at room temperature. Several studies of semiconductor lasers and quantum structures by NSOM were reported before. Our results provide an important diagnostic tool for correlating the laser properties with the geometry of the structure. The addition of high spectral resolution allows us to discriminate between different emitting regions in order to analyze the QWR laser in detail. Furthermore, NSOM measurements enable the imaging of the waveguide mode which exhibits details on the order of 0.1 $\mu m$ (half the wavelength in the material). It is impossible to extract such details from far-field measurements which are limited by the Rayleigh criterion to $\sim 0.8\lambda=0.65 \mu m$ details at the best.

The experimental setup is shown in Fig. 1. The QWR lasers were operated with a pulsed electrical drive at room temperature while their facets were scanned using a collection mode NSOM system, attached to an upright optical microscope. Imaging at subwavelength resolution was accomplished by a cantilevered optical fiber tip with a subwavelength aperture, which raster scanned the sample facet. The near-field light emitted from the sample was collected through the tip and detected by a sensitive silicon avalanche photodiode (APD) to generate an optical image. A monochromator was placed in front of the APD to resolve the spectral content of the images. During scanning, the tip was in contact with the sample facet, using a normal-force feedback control. Far-field data were collected simultaneously.

![FIG. 1. The experimental arrangement.](image-url)
from the second facet of the scanned laser through an objective lens. To validate that there are no measurement errors due to the potential modification of the laser boundary conditions by the metal coated tip, the far-field laser emission with/without the tip presence were compared—resulting in no measurable difference in the lasing intensity, spectrum, or noise.

The QWR lasers investigated here were grown by a low pressure organometallic chemical vapor deposition on (100)GaAs substrates grooved along the [01-1]. Two V-groove QWR laser structures were studied. The first (Fig. 2) incorporated a single, 10 nm thick, crescent shaped GaAs QWR located at the center of a 400 nm thick Al0.25Ga0.75As waveguide layer cladded by Zn- and Si-doped Al0.53Ga0.47As layers. The waveguide layers were nominally undoped. The second structure had three 10 nm thick GaAs QWRs separated by 40 nm undoped Al0.25Ga0.75As barriers, sandwiched between two undoped, 156 nm thick Al0.25Ga0.75As waveguide layers which, in turn, were cladded between Zn- and Si-doped Al0.53Ga0.45As layers. Both structures were grown at 700 °C. In both structures, the growth in the V groove resulted in a V-shaped optical waveguide providing tight two-dimensional (2D) waveguiding near the center of the groove. Current confinement to the center of the V-shaped waveguide, where the wires reside, was achieved using the self-aligned proton implantation technique.6

In the various room temperature experiments the QWR laser was pulsed at different currents and with different pulse widths. The drive current amplitudes spanned from well below threshold to twice the threshold current for some scans. The pulse width was varied between 70 and 750 ns and the repetition rate was 10 kHz.

In the first experiment (single QWR devices), we employed the NSOM system in a dual mode, simultaneously providing images of surface topography by a contact mode normal force atomic force microscope (AFM) and light intensity distributions using the NSOM data [Figs. 3(a) and 3(b)]. This simultaneous imaging allows, with additional calibration, the accurate placement of the mode relative to the geometrical center of the waveguide and the QWR. This placement is based on the high correlation between the two images, taking into account a constant shift and different resolutions. We measured a modal displacement on the order of 100 nm towards the p side—as also predicted by the cal-

FIG. 2. (a) TEM photograph showing the 2D optical waveguide region with the wire and wells structures. (b) Schematics of the explored emission sources and waveguide structures in the device (not to scale). The square denotes the region corresponding to the transmission electron microscope (TEM) photo.

FIG. 3. NSOM images of the V-grooved single QWR laser: (a) 3×3 μm AFM (b) the associated simultaneous 3×3 μm² NSOM image (150 mA, 70 ns), (c)–(f) 2×2 μm² spectrally unresolved NSOM images for different currents (70 ns pulse width). The color scale from dark blue through green, red to orange–yellow corresponding to a low–high intensity range.

FIG. 4. The fundamental heart shaped mode of a three QWR laser: (a) NSOM image (73 mA, 70 ns, Ith = 70 mA). Color scale as in Fig. 3(b) BPM calculations result. Intensity is increasing towards the center—each line denotes a 10% of intensity change.

rated by 40 nm undoped Al0.25Ga0.75As barriers, sandwiched between two undoped, 156 nm thick Al0.25Ga0.75As waveguide layers which, in turn, were cladded between Zn- and Si-doped Al0.53Ga0.45As layers. Both structures were grown at 700 °C. In both structures, the growth in the V groove resulted in a V-shaped optical waveguide providing tight two-dimensional (2D) waveguiding near the center of the groove. Current confinement to the center of the V-shaped waveguide, where the wires reside, was achieved using the self-aligned proton implantation technique.6

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culations. More accurate results can be obtained by using a smaller diameter tip and in situ calibration. The accuracy of this placement is a crucial parameter in improving the design of these lasers by optimizing the overlap of the mode and the QWR gain medium.

Figures 3(c)–3(f) show additional images of the QWR laser emission for different drive currents ranging in intensity from 0.22Ith to 1.3Ith. Images recorded at a scanning range of 2×2 μm² with a resolution of 128×128 are shown. The intensity pattern exhibited an overall drift of ~0.28 μm towards the substrate side as the injection current was increased, with the most pronounced shift experienced near the lasing threshold. This effect may be explained by the spontaneous emission pattern following the cold waveguide mode—shifted towards the p side as was discussed above, while after lasing—the better overlap with the gain medium pulled the mode to the center.

Exact details of the optical modes cannot be determined from the images shown in Fig. 3 since they are not spectrally resolved. The addition of spectral filtering using a monochromator enabled the proper study of the evolution of the optical mode as a function of the drive current. The fundamental lasing mode was obtained by imaging the three QWR laser at 816 nm and is shown in Fig. 4(a). This mode is heart shaped, as also predicted by the calculations described below, with a full width at half maximum (FWHM) of 0.47 μm. For the single QWR laser (Fig. 5) the recorded lasing pattern [Fig. 5(a)] at 805 nm, consisted of a combination of the first order and a higher order mode of the V-shaped waveguide. The higher order mode was resolved by imaging [Fig. 5(b)] at 805.8 nm. This high order mode has a vanishing overlap with the QWR and thus is supported mainly by the QWs at the sloped barriers. The high spatial resolution enabled us to locate the tip on the center of the waveguide and measure the local spectrum as well as the light-current characteristics at a specific wavelength. The results are shown in Fig. 5(c).

The near-field intensity distribution of the V-groove passive waveguide was calculated using both the split-step beam propagation method with transparent boundary conditions as well as the finite difference in the time domain method. The waveguide geometrical parameters for the calculations were taken from a transmission electron microscope photograph and the wavelength was 800 nm. An initial Gaussian intensity distribution at the geometrical center of the waveguide was employed and the results are shown in Fig. 4(b). The fundamental mode of this structure is characterized by a heart shaped field pattern with a FWHM of 0.47 μm and a center of mass shifted by 150 nm p-wards relative to the waveguide geometrical center. A good agreement with the measured pattern, [shown in Fig. 4(a)] was obtained. The calculations did not yield higher order modes confined to the 2D region of the passive waveguide at the lasing wavelength. Thus the experimentally observed “higher order mode” pattern of Fig. 5(b) might be supported by additional effects such as thermal lensing and structural imperfections at the sloped side walls.

The combined spatial and spectral resolutions offered by the NSOM system enabled us to separate the various emitting regions of the structure. For example, the optical mode is fed by both the quantum wire and the tails of the sloped quantum well. However, these two have different band gaps so that the emitted wavelengths differ. By determining the emission wavelength of the sloped quantum well in a separate experiment and comparing it with the emission from the waveguide mode, we find that for the specific single QWR device that we tested, the emission was probably primarily due to the gain of the sloped quantum well. This is a result of the reduced filling factor of this single wire structure. We should note that operation of single QWR V-grooved devices can be achieved with thicker wires and tighter V-shaped waveguides, which enhance the optical confinement factor. For the three QWRs device, we found a clear spectral distinction between the side QW and the emission recorded from the waveguide, which indicates that for this sample, the emission of the heart shaped mode results from the QWR gain.

In this letter we have addressed two main issues. First, we demonstrated the power of a new methodology for characterizing quantum wire lasers as one example of the important class of quantum size active devices. We were able to place the light emission source with respect to the geometric structure that is simultaneously imaged with AFM with an accuracy of 100±50 nm while at the same time spectrally resolving it with less than 1 nm resolution. Second, we have studied the details of the optical model of V-grooved QWR lasers and demonstrated the relation between emitted wavelengths and the region from which the emission originates. We measured a heart shaped emission mode with spatial details of less than 0.1 μm and compared it to the calculated mode obtained by theoretical modeling. Furthermore, we were able to discriminate between the wells and wire contribution to the lasing of the devices.

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