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Characterization of Heterojunction Laser Diodes by Near Field Optical Scanning Microscopy: Layer Composition and Mode Structure Analysis

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We report mode structure and semiconductor layer composition analysis of strained (In,Ga)As quantum well lasers using the super-resolution capabilities of near field scanning optical microscopy (NSOM). Submicron collection mode imaging of the emission mode structure easily identifies high order transverse modes as well as mode leakage into the substrate. Using the tip as a localized, tunable source of photons, near field optical beam induced current (NOBIC) measurements reveals the compositional profile of the layer structure. The active region is very sensitive to the excitation wavelength due to the effect of a changing optical absorption in near field coupling to a thin ($d \sim \lambda/10$) layer.

Near field scanning optical microscopy and spectroscopy (NSOM) is a recent technique [1,2], where a tapered optical fiber probe is placed within a fraction of a wavelength of a sample and scanned over the surface [3]. The tapered single-mode optical fiber provides a tiny aperture through which the light is coupled. Because both the tip-to-sample separation and the tip aperture are a small fraction of the wavelength, the spatial resolution is slightly less than tip diameter ($a \sim 50$nm). This yields resolutions as high as $\sim \lambda/40$, or $\sim$ 15nm for visible wavelengths. Spectroscopic information is obtained by coupling the collected signal to a grating spectrometer. High resolution chacterization of materials and devices can also be performed by optical beam induced current measurements where the tip provides the excitation [4].

Simultaneous shear-force provides an independent measure of the surface topography to maintain a fixed proximity ($\sim$ 5nm) between tip and sample [5,6]. The fiber tip is dithered (vibrated) at its mechanical resonant frequency and an independent optical beam monitors the amplitude of the vibration in transmission. Any tip-surface interaction quenches the resonance and shifts the resonant frequency, providing a height measurement with sub-nanometer resolution. The shear-force topography is used to reference optical imaging techniques with the physical device structure.

Figure 1 displays a schematic diagram of the experimental setup. The laser diode sample is mounted facet up on a piezo-electric tube and scanned in the $\hat{x} - \hat{y}$ plane beneath the probe tip. In collection mode operation, the laser diode is driven with a pulse generator and the emission collected in the near field by the tip and transmitted to a detector. In NOBIC mode, a tunable Ar^+ pumped Ti:Sapphire laser provides excitation through the tip for the biased diode and the photo-induced current is monitored by a current amplifier. Reflection mode imaging is performed by exciting with the tip and collecting with co-axial mounted optics in the far-field. Simultaneous shear-force topography is used to control the tip height $z \sim 10$nm in all modes.

We studied a strained (In,Ga)As graded-index separate confinement heterojunction (GRINSCH) laser grown on the (112) surface of n^+-GaAs. These devices are important for second harmonic generation in a single planar device structure [7]. The structure consists of a single 80Å $\mathrm{In_{0.2}Ga_{0.8}As}$ quantum well sandwiched in a symmetrical waveguide of 400Å GaAs, 0.2μm graded $\mathrm{Al_{0.2\rightarrow0.6}Ga_{0.8\rightarrow0.4}As}$ and 1.5μm $\mathrm{Al_{0.6}Ga_{0.4}As}$ cladding layers. Broad area (width=25μm) metal stripe lasers were fabricated using standard litho-

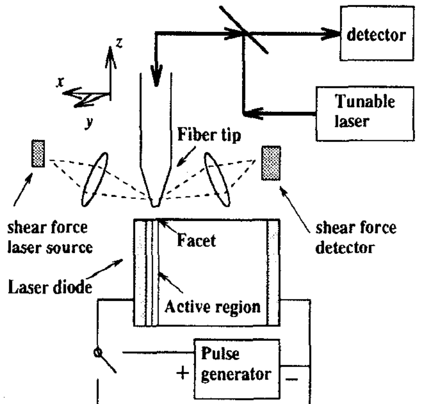

Fig. 1. Block diagram of the measurement for laser diode emission mode profiling and near field optical beam induced current (NOBIC) compositional analysis. Simply changing connections, all optical diagnostic techniques are performed on the same section of the device. The lenses to the side of the fiber tip provide the shear-force signal for topology.

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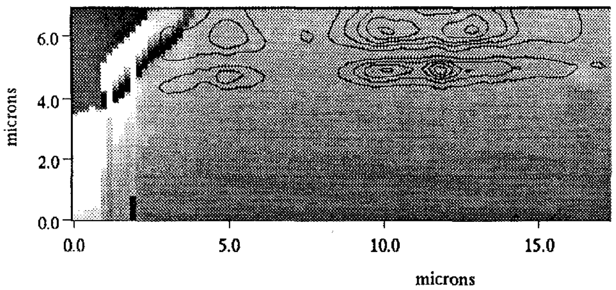

Fig. 2. Shear force and mode profile of a section of the 25 μm device mesa. The contour plots showing the light intensity distribution are superimposed upon the topographic shear-force image.

graphic techniques. The cavity was formed by cleaves parallel to the $(\bar{1}10)$ surfaces.

Figure 2 shows a large scale collection mode and shear force image of the laser structure at $I = 120$mA pulsed current excitation [8]. The contour lines indicate the light emission intensity and the grey scale the surface topology. At the upper left a piece of overhanging metal contact is visible. Along the width of the stripe, forth order transverse modes are apparent. Along the growth direction, two emission peaks are observed. We believe the topmost is due to the active layer lasing, while the lower is a result of mode leakage into the n-GaAs substrate, suggesting poor mode confinement.

For high resolution analysis of the semiconductor layer structure, NOBIC and mode emission measurements on $2 \times 5\mu$m sections of the device facet were made. The top panel of Figure 3 shows the relevant layer structure of the diode as a function of distance from the top surface constructed from the growth parameters, topography, and reflectivity measurements. Figure 3(a) displays a line cut in the growth direction of mode emission from the laser at $I = 250$mA current bias. The left most peak is from the active region and the right from mode leakage into the substrate. This interpretation is confirmed by the NOBIC results in Fig. 3(b). Here, four different wavelength excitations of the device yield the presented photocurrent versus position in the growth direction. The most remarkable feature is the strong increase in photocurrent at the active region for increasing incident photon energy. We believe this is caused by the increase in light absorption for decreasing penetration depths when a localized, divergent source is in close proximity to a narrow layer. Because the substrate is wide, most of the light is already absorbed, and decreasing the absorption depth provides only a modest increase in signal. The peak in the NOBIC in the substrate region is a reflection of the $\sim 1\mu$m diffusion length in this neutral region.

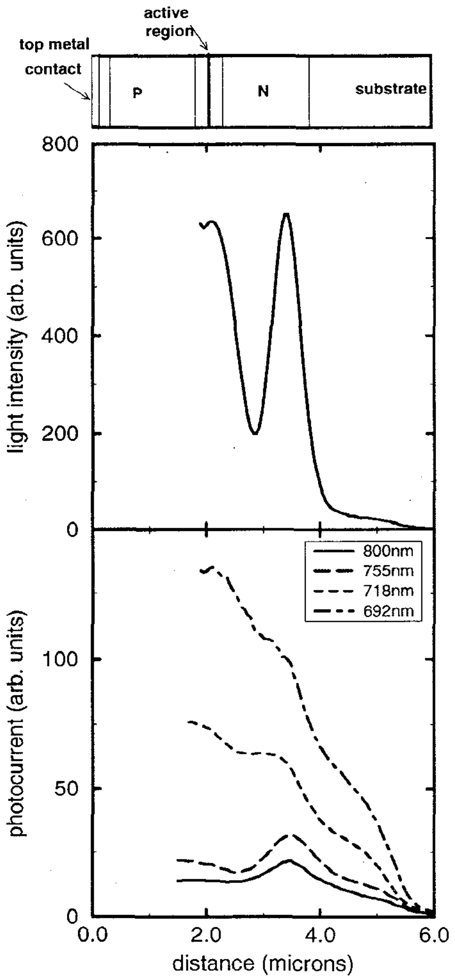

Fig. 3. Comparison of the data obtained by NOBIC and mode profiling. (a) The emission profile at 250mA pulsed current excitation. (b) The NOBIC measurements for a variety of excitation wavelengths as indicated. The scans are begun quite close to the active region due to the hindrance of overhanging metal layers.

In conclusion, we demonstrate that the super-resolution imaging capability of NSOM is a valuable diagnostic and analytical tool for optoelectronic devices. The devices we have investigated are the early prototypes of lasers grown on (112) GaAs surfaces. The diagnostic result of mode leakage, etc. will enable rapid development and optimization of these and other devices. The NOBIC results, believed to be the first demonstration of the technique, hold great potential since they demonstrate the ability to correlate layer composition directly with optical properties.

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