Near-Field Optical Studies of Semiconductor Heterostructures and Laser Diodes

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Abstract—Near-field optical microscopy and spectroscopy is emerging as a powerful tool for the investigation of semiconductor structures. Tunable excitation combined with sub-wavelength resolution is providing an unprecedented level of detail on the optical properties of semiconductor structures. Recent near-field optical studies have addressed issues of laser diode mode profiling, minority carrier transport, near-field photocurrent response of quantum-well structures and laser diodes, imaging of local waveguide properties, and location and studies of dislocations in semiconductor thin films. We present results on the intrinsic resolution limitations of near-field photoconductivity in quantum-well heterostructures and demonstrate that the resolution depends strongly on the amount of evanescent and propagating field components in the semiconductor. Spectroscopic mode-profiling of high-power laser diode emission details the spatial dependence of multiple spectral modes. This paper presents an overview of NSOM techniques for semiconductor systems, its limitations, and present status.

I. INTRODUCTION

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 given approximately by the tip diameter. This can yield resolutions as high as $\lambda/40$, or $\lambda/15$ nm for visible wavelengths [2]. High-resolution characterization of materials and devices is performed both by collecting emitted radiation in the nearfield [4]–[6] and by exciting local photocconductivity in the semiconductor with radiation from the tip [5], [7]–[9]. Using wavelength tunable excitation sources, near-field optical beam induced current (NOBIC), or near-field photocurrent (NPC) measurements provide information on the compositional and electronic structure of the semiconductor samples. NSOM can also be used to examine the evanescent fields of waveguides [10] and couplers [11], and local heating in active devices [6].

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II. EXPERIMENTAL METHODS OF NSOM FOR SEMICONDUCTOR STRUCTURES

Near-field scanning optical microscopes are comprised of a piezo-electric scanning stage for sub-nanometer positioning of the sample under study and a sub-wavelength aperture to either collect the emitted optical radiation in the near-field or provide a local, tunable excitation source for current induced measurements. A typical experimental configuration is displayed in Fig. 1. The sample is mounted facet up on a piezo-electric tube and scanned in the $x$–$y$ plane beneath the probe tip. For collection mode imaging, the radiation coupled into the tip in the near-field is sent to a detector or spectrometer (path illustrated in solid lines) [4], [5], [8]. Reflection mode imaging is performed by exciting with the tip and collecting with co-axial mounted optics in the far-field, which can be accomplished by staging the NSOM beneath conventional microscopes. For near-field photocconductivity and NOBIC, a tunable laser provides excitation through the tip, and the resulting photo-induced current is monitored by a current amplifier (path illustrated by dashed lines).

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Simultaneous shear-force measurements provide an independent measure of the surface topography to maintain a fixed proximity (~10 nm) between tip and sample [12], [13]. The fiber tip is dithered (vibrated) at its mechanical resonant frequency with a small piezo and an independent optical beam monitors the amplitude of the vibration in transmission. Any tip-surface interaction quenches the resonance, providing a height measurement with nanometer resolution. The shear-force topography is used to reference various optical imaging techniques with the physical device structure, as well as provide information on surface defects [7] and thermal expansion of operating devices [6]. In addition to the optical detection method for shear-force, several recent techniques have been developed for nonoptical sensing of the damping of the fiber tip motion near the surface. Capacitance between the tip and a nearby external sensor [14], impedance changes in the dither piezo itself, and mounting the tip on a quartz tuning-fork detector [16] are all providing electrical, nonoptical shear-force detection techniques. An excellent review of single-mode fiber tip preparation for NSOM is given by Valaskovic et al. [17].

The optical detection of tip motion has the advantages of simple, though costly setup, intuitive operation, good signal-to-noise, and large dynamic range. It also provides an accurate way to find the sample surface, since the shear-force signal quenches completely when the tip is in contact with the surface. However, this optical technique may pose a significant difficulty, especially for a NSOM system designed to study various semiconductors, due to possible undesirable interaction of the optical excitation for shear-force detection with the devices and materials under test. A nonoptical technique, therefore, is desirable which may also have added advantages of lower cost and complexity. The nonoptical technique of mounting the tip on a commercial watch crystal quartz tuning fork [16] utilizes the quartz tuning fork as the shear-force detector. This technique has the advantages of good signal-to-noise, and a simple, inexpensive and compact implementation. Additionally, since the resonant frequency is that of the tuning fork, large frequency scans to find the mechanical resonance of the tip become unnecessary. The chief disadvantage of the tuning fork method is that the signal does not fully quench at the surface, since presumably one leg of the fork continues to oscillate, making it difficult to predict from the damping the exact position of the surface. The method of monitoring the impedance change in the dither [15] piezo is the simplest method, but generally does not provide as high a signal-to-noise ratio. Besides, the optimal resonant frequency can be different from the one used in optical detection, and can be difficult to find. Finally, the technique of measuring the changes in capacitance between the probe tip and an external sensor can provide extremely high accuracy [14], at the expense of having to independently position a capacitance sensor within ≤100 nm of the fiber tip. These nonoptical techniques are all new, and the best ones will likely emerge from the group. Our work is done with both the optical sensing method and the quartz tuning fork nonoptical method.

### III. APPLICATION OF NSOM TECHNIQUES TO SEMICONDUCTORS

The goal of NSOM studies on semiconductor structures is to locally probe physical properties which emit or absorb optical radiation. The combined capability of collection and reflection mode NSOM and NOBIC measurements on the same structure can yield information on composition, defects, mode structure in emission, carrier diffusion, local scattering, and a host of other properties. Central to the NSOM technique are the issues affecting resolution. Unlike studies of single molecules [18]–[20], thin metallic films examined in reflection and transmission [2], [3] and Faraday-effect NSOM [21]–[23], characterization of NSOM in semiconductor samples is complicated due to the diffusion of photoexcited carriers and the small absorption coefficient resulting in long penetration depths. These lengths often exceed the tip diameter, fundamentally affecting NSOM resolution of semiconductors.

Photoluminescence spectroscopy using the sub-wavelength aperture as either the source of laser excitation (illumination mode) or the collector of emitted light (collection mode) have different resolution characteristics. Low-temperature collection mode spectroscopy on quantum wells and wires [24] has shown that while photoexcited carriers can diffuse several microns [25], [26], collection of the light emitted due to local electron-hole recombination has resolution determined largely by the tip aperture. We have recently examined GaN epilayers grown on GaAs[001] in both collection and illumination modes at low temperatures [27] and while collection mode imaging has a resolution of ~150 nm, illumination mode spectra show a factor of 5 or more degradation.

Room temperature collection mode NSOM has been used to examine primarily photoluminescent or lasing structures, since the reduction in quantum efficiency and broadening in spectral width make room temperature PL studies of semiconductors impractical. Buratto [6] has shown that the collection
mode image reflects local, near-surface electro-luminescence as well as the mode structure of the waveguide.

The factors limiting resolution in near-field photoconductivity fall into two broad areas: First, the size of the sample volume beneath the tip that absorbs the incident radiation and the resulting spatial distribution of photo-generated carriers; and second, the transport of those carriers following their creation to contacts in the sample. Kolb et al. examined the photoconductive response of a p-n junction [28] by scanning the tip along the growth direction perpendicular to a cleaved facet. They found that the resolution was effectively limited by the diffusion length of the minority carriers. A confirmation was the asymmetry in photoconductive response between the p and n due to the differences in minority carrier diffusion lengths. Use of heterojunctions can eliminate the limitation due to diffusion, as illustrated by placing a larger band-gap AlGaAs layer in the depletion region [28]. Near-field photoconductivity of laser diodes has also indicated the dominance of minority carrier diffusion lengths in NPC resolution [6]. In these studies, the length scales of both the intrinsic or depletion regions as well as the penetration depth of the exciting radiation were of the same order as the minority carrier diffusion lengths. Because of these factors the location of the p-n junction and carrier diffusion dominate the resolution process. Further, neither study examined samples with two closely spaced regions of identical composition to fully address the resolution issue.

A. NOBIC Resolution Studies in Heterojunctions

To study the resolution capability of NOBIC, we have designed and fabricated semiconductor structures consisting of three sets of GaAs QW pairs surrounded by Al0.35Ga0.65As barriers placed in the depletion region of a p-i-n diode. The layers were grown by Molecular Beam Epitaxy (MBE) on n-type GaAs substrates and fabricated by standard photolithographic techniques. The device structure is shown in Fig. 2 and from the substrate up consists of a heavily doped n-type GaAs contact region, followed by n-type (0.2 \( \mu \)m, \( n = 2 \times 10^{18} \text{ cm}^{-3} \)) and unintentionally doped (estimated at \( p \sim 10^{16} \text{ cm}^{-3} \), total thickness of 1.9 \( \mu \)m) Al0.35Ga0.65As regions. Three pairs of 30-nm-thick GaAs quantum wells (QW) were placed in this Al0.35Ga0.65As i-region. The spacing between the QW’s is varied from 300–500 nm and the pairs are separated by 500 nm. Then, a 0.2-\( \mu \)m-thick p-type Al0.35Ga0.65As is grown and the structure is capped by a heavily doped p-type GaAs contact region. The purpose of the Al0.35Ga0.65As barrier regions around the GaAs quantum wells is to provide a wavelength window roughly from 700–850 nm in which only the GaAs QW’s absorb the incident radiation. This allows for the study of wavelength dependent NOBIC. Additionally, the p and n Al0.35Ga0.65As regions provide diffusion barriers for the carriers generated in the neutral GaAs regions, namely the p-GaAs cap layer and the substrate.

Mesa photodiodes were fabricated by forming ohmic contacts on the n-type substrate and the p-type GaAs cap. The devices were cleaved to reveal the vertical structure. Coupling laser radiation into the tip and scanning in the near-field across the exposed facet produces a photocurrent response used to generate two dimensional NOBIC images. These two dimensional images are uniform in the direction parallel to the substrate so only line scans in the growth direction will be displayed and discussed. Note also that the QW structures are semi-infinite in extent in the z direction.

Fig. 2 shows a NOBIC line scan at \( \lambda = 700 \text{ nm} \) in the epilaxial growth direction and its correlation to the layer structure. The QW’s separated by 300 nm are clearly resolved. At tip heights above the sample in excess of \( \sim 500 \text{ nm} \) these two GaAs wells were unresolved. In this experiment, we were unable to resolve more closely spaced QW pairs due to the relatively large tip diameter (\( \sim 130 \text{ nm} \)), and lack of full depletion caused by a high p-type background in the unintentionally doped region resulting in a p-\( \pi \)-n structure. The high background is also evident as a high reverse leakage current in these diodes prohibiting the use of a large reverse bias. The electric field profile in the depletion region is evident from the overall decrease in photocurrent as the excitation tip moves away from the n-\( \pi \) junction. This limits the collection efficiency of the photo-generated carriers, as well as the image resolution.

The near-field profile from a sub-wavelength fiber-tip aperture has both evanescent and propagating field components. The evanescent modes, which comprise the majority of the total intensity, decay rapidly in free space, on length scales less than the aperture diameter [18], [28], [29]. When the tip is scanned in close proximity to a semiconductor surface, one might expect super-resolution imaging capability due to the decay of the evanescent fields regardless of the absorption coefficient. In this case, a wavelength dependence of the

Fig 2. Schematic of device structure for NOBIC resolution experiments. From the substrate up the sample consists of a heavily doped n-type GaAs contact region, followed by n-type (0.2 \( \mu \)m) and unintentionally doped (estimated at \( p \sim 10^{16} \) cm\(^{-3}\), total thickness of 1.9 \( \mu \)m) Al\(_{0.35}\)Ga\(_{0.65}\)As regions. Three pairs of 30 nm thick GaAs quantum wells (QW) were placed in this Al\(_{0.35}\)Ga\(_{0.65}\)As i-region. The spacing between the QW’s is varied from 300-500 nm and the pairs are separated by 500 nm. Then, a 0.2-\( \mu \)m-thick p-type Al\(_{0.35}\)Ga\(_{0.65}\)As is grown and the structure is capped by a heavily doped p-type GaAs contact region.
NOBIC resolution would not be observed. However, since the semiconductor is a much denser medium ($n \sim 3.5$ for GaAs) than the silica ($n \sim 1.5$) fiber-tip and surrounding air, the evanescent modes from the tip may be coupled into propagating modes in the semiconductor. The field profile for these propagating modes is thus governed by the bulk absorption characteristics of the medium. In this case, the penetration depth in the GaAs QW's determines the maximum resolving power for NOBIC imaging of semi-infinite structures.

By using different aperture diameters, and thereby varying the size of the wavevector of the evanescent component of the emanating fields, we have been able to observe both these regimes. NOBIC scans across the QW structures were performed as a function of excitation wavelength with both 130 nm and 100 nm diameter tips. The results are shown in Fig. 4 for excitation wavelengths ranging from 700–855 nm in successive scans across the 300 nm separated QW's. Fig. 4(a) shows that for a relatively large 130 nm tip aperture, the highest resolution is obtained with the shortest wavelength. By $\lambda = 775$ nm the two QW's are not resolved. From 700–855 nm the absorption coefficient in bulk GaAs decreases from $\sim 4 \times 10^5$ to $1 \times 10^2$ cm$^{-1}$ with increasing wavelength, corresponding to optical penetration depths from 250 nm at $\lambda = 700$ nm to 1 $\mu$m at $\lambda = 855$ nm. Thus, shorter wavelengths and shallower penetration depths mean that a larger part of the optical field is absorbed in the QW directly under the tip. Conversely, longer wavelengths allow for deeper penetration of the optical field into the semi-infinite 2-D structure, and a significant amount of the diverging beam is absorbed in the neighboring QW, resulting in reduced NOBIC resolution.

Wavelengths shorter than 700 nm would not lead to higher resolution, since the AIGaAs barriers would no longer be transparent, destroying the NOBIC contrast mechanism.

Fig. 4(b) shows similar line scans for a 100 nm aperture tip as a function of wavelength. Instead of a loss of resolution for longer wavelength excitation, the smaller aperture maintains the same resolution even at longer wavelengths where the optical absorption depth is large ($1/\alpha \sim 1 \mu$m). At 100 nm, the tip aperture is smaller than half the wavelength in GaAs ($\lambda/2\alpha$, $n = 3.5$) for the entire 700–855 nm range. We interpret the data as indicating that a large part of the optical field causing photoexcitation remains evanescent in the GaAs. In this case, the resolution is independent of the excitation wavelength. In contrast, the 130 nm tip is larger than $\lambda/2\alpha$ for the entire wavelength range which results in strong coupling into propagating modes as indicated by the wavelength dependent resolution capability.

In Fig. 4(b) the full-width-at-half-maximum (FWHM) of the photocurrent signal is $\sim 350$ nm which is significantly larger than the tip size. This relatively large width is due to surface depletion at the GaAs-air interface which effectively introducing a spacer layer between the tip and optically active semiconductor region for the rapidly diverging optical field. The surface depletion also partially accounts for the reduced photocurrent when the excitation is away from the junction. Thus to obtain evanescent field-coupled near-field resolution in semi-infinite semiconductor structures, the aperture size should be chosen according to the refractive index ($n$) of the material and the excitation wavelength used: $a \leq \lambda/2n$.

When the excitation energy is increased above the barrier energy, carriers are photo-induced across the entire depletion region. Thus at short wavelengths, the contrast mechanism...
is due to simple changes in the reflectivity, since all the transmitted radiation is absorbed. Scans taken at 633 and 514 nm show a decrease in photocurrent in the GaAs QW regions versus the AlGaAs barriers, due to the slight difference in surface reflectivity. Fig. 5 displays a comparison of the photoinduced current at excitation wavelengths of 514 and 700 nm. The left hand peak in the photo-response at 514 nm is due to the high field at the n-p junction, but a clear peak is seen in the AlGaAs barrier region between the two GaAs wells to the right. The calculated reflectivity for GaAs is 30.9% and for Al_{0.35}Ga_{0.65}As is 28.5% leading to a transmission (and absorption) difference of just 3%, hence, the relatively small peak in the AlGaAs region at 514 nm. Also note that the 514 nm data displays a significant reduction in reflectivity in the depletion region to the right of the second GaAs QW, which we believe is due to the weaker transverse electric field away from the junction, combined with a surface depletion layer that is likely larger than the short optical penetration depth. A confirming set of data is displayed in Fig. 6, where we have measured high power, strained (In,Ga)As graded-index separate confinement heterojunction (GRINSCH) laser diodes in NOBIC. For this laser structure the active region is InGaAs and the Al mole fraction in the AlGaAs barriers is graded up from ~15%. A slight decrease (~10%) in the FWHM of the NOBIC line scan is observed as the excitation wavelength is varied from 855–800 nm. When the wavelength is decreased below 755 nm, the InGaAs active region becomes a local minimum, the surrounding AlGaAs local maxima, and the overall signal-to-noise ration decreases drastically. Thus short wavelength NOBIC scans depict the local reflectivity, and while the spatial resolution may be greater, the reflectivity contrast mechanism produces a much reduced dynamic range.

These results are not in disagreement with the work cited above [6], [28] since in both these studies, the depletion regions separating the n and p neutral regions were very small and of minor consequence. Taken together, the factors limiting NOBIC and NPC resolution are that in depleted regions where there is a large electric field, the optical penetration depth is the limiting factor for tips approximately larger than half the excitation wavelength in the semiconducting medium since all photoexcited carriers are collected as photocurrent, while in doped neutral regions the diffusion of the minority carriers is the more important concern.

Kolb et al. [28] has studied the photocurrent as a function of distance above the sample and found an exponential increase in signal response within the last 50 nm of tip-to-sample approach. A model including an evanescent decaying optical intensity added to a geometrically corrected constant far-field term works well to fit the data. The exponential term yields a decay length of 35 nm at a wavelength of 633 nm in free space. Wavelength dependent data in their study could then be used to determine the decay length in the semiconductor, providing an independent measure of the ratio of near- to far-field intensity.

The distinction of the two regimes of resolution capability will be true in general on semi-infinite samples whenever the material being imaged is a significantly denser medium than the fiber-tip. It will also hold for other near-field optical imaging techniques such as high resolution photoluminescence and reflectivity measurements in thick (s > 1/a) semiconduc-tor samples. In reflectivity mode, a relatively short excitation wavelength can be used allowing for large absorption coefficients in the investigated semiconductor. It should also be noted that at short wavelengths, NOBIC is essentially a reflectivity measurement, since the differences in the material response are due largely to changes in the reflectivity. In NOBIC, greater resolution can be obtained by having higher barriers with a larger band discontinuity allowing for the use of
B. NSOM Collection Mode Imaging of Laser Diode

Near-field collection mode imaging of active optoelectronic devices has the capability to examine, with sub-wavelength resolution, optical mode profiles, carrier leakage, nonradiative recombination centers, microscopic doping profiles, and local heat generation. Such detailed information is useful in examining reliability, failure modes, and operational characteristics of laser diodes. Reliability of semiconductor lasers is an important issue especially for applications in which replacing a failed device is costly [31], [32]. Failure can occur from local heating in an under-doped region, strain generated cracks at interfaces [33], performance degradation due to poor mode confinement and mode shifting, or catastrophic optical mirror damage (COD) [34], [35].

We have studied the mode structure and layer composition of high power, strained (In,Ga)As graded-index separate confinement heterojunction (GRINSCH) laser diodes using the super-resolution capabilities of NSOM. The lasers are designed to pump Erbium doped fiber amplifiers in a configuration optimized for a single transverse laser mode. The maximum operation power of these laser diodes are not limited by catastrophic failure modes. At high current levels, coupling efficiency of the lasers decrease due to broadening of the spot size and the onset of multiple transverse modes, which limit the maximum useful power. Sub-micron collection mode imaging and spectroscopic mapping of the emission mode structure as a function of laser pulse length and current easily identify a regime of operation where multiple transverse modes are observed. The evolution of multiple transverse modes corresponds to a kink observed in the light-output versus current ($I-V$) curve. Near-field microscopy enables the mode profile and spectral image to be correlated with the layer structure of the device. In this study, we demonstrate the capability of NSOM in characterizing the laser modes which may not be observable by far-field techniques.

NOBIC is used to identify the active region and surrounding mesa structure and the collection mode emission profile can then be correlated to the actual device structure. Fig. 7 displays a contour map of the low-power emission profile superimposed on a two-dimensional NOBIC scan in grey scale. At low current levels, the emission profile indicates a single transverse mode that peaks in the active region and is centered under the mesa. NOBIC line scans on this sample are displayed in Fig. 6, which shows a narrow peak centered on the active region for wavelengths longer than 750 nm enabling the identification of the active region position with ~100 nm resolution.

In our near-field measurements the laser diodes were biased with pulsed excitation. Lock-in techniques enabled the detection of the low signal levels resulting from the small collection efficiency of the sub-wavelength aperture. Relatively long pulse lengths (20–50 μs) were used to ensure that the laser emission is not dominated by transient effects. The near-field image (Fig. 8) of the mode profile at relatively low bias currents (up to ~100 mA) displays a single Gaussian
shape. At medium bias levels (around 150 mA), the emission profile is a bi-modal structure (Fig. 9). When the bias current is further increased, first a single Gaussian mode with larger beam waist (at ∼200 mA), then higher order modes (at ∼250 mA) are observed. The source of change in the emission mode and higher order transverse mode operation can be slight nonuniformities in the index-guiding layer, or nonuniform thermal gradients at high current levels.

Spectra of the laser diode emission for the low current levels shows multiple longitudinal modes around 976 nm. When the power is increased a second transverse mode is observed in the spectra at lower energy (∼980 nm), as displayed in Fig. 10. The onset of the higher order transverse modes corresponds to a kink in the L-T curve.

Using a spectrometer in collection mode imaging, spectral maps of the emission profile were obtained. At medium and high current levels, the spectra of the laser diodes consistently displayed two sets of longitudinal modes and each set was attributed to a different transverse mode. By tuning the spectrometer to the center wavelength of each set, the spatial distribution of emission was measured for the different transverse modes. The most interesting results were obtained at medium current levels. As shown in Fig. 11, the spatial profiles for the longer and shorter wavelength sets of longitudinal modes displayed Gaussian-like shapes. The peaks of the two modes, however, were displaced by approximately 200 nm. This spatial displacement corresponds to the bi-modal structure observed in the total emission strength (Fig. 9). At higher current levels (at ∼200 mA), the two spectral modes overlap in space resulting in a single peak in the total intensity. When the current is further increased (at ∼250 mA) the longer wavelength set displays a higher order transverse mode. Other structures we have examined also display deformation of the emission mode at high current levels. The origin of the shift of the two spectral emission peaks remains unclear. We expect that additional detailed spectral mapping of emission modes and their correlation to the physical device structure at various current levels will be very useful in understanding the onset of higher order modes in these laser diodes.

Previous work on collection mode NSOM of laser diodes [4]–[6] has observed a variety of processes. Buratto et al. [6] examined InGaAsP buried heterostructure multiquantum-well lasers with re-grown current blocking layers as a function of drive current. They confirmed that the collection mode NSOM is sensitive to both near-surface electroluminescence as well as the waveguide mode of the laser output. Current leaking into the substrate and radiatively recombining is observed as electroluminescence and is correlated in this device to poor confinement of the lasing mode. Due to the re-growth, Buratto is able to observe local nonradiative regions, as well as map the extra heat deposited in them with the change in surface topography as measured by the shear-force signal.

C. NSOM Studies of Photonic Waveguides and Switches

In addition to studies of the material properties of semiconductors, the characteristics of active opto-electronic devices, and the optical processes in sub-micron structures, NSOM is applicable to waveguides and optical switches. In general, the details of index guiding of waveguide modes can be accessed by measuring the evanescent field which penetrates the top layer and couples into the NSOM tip. Monitoring the evanescent field as a function of height and position along the structure then provides a complete picture of the index confinement and invaluable information about local loss and scattering mechanisms. Recent results [10], [11], [36], [37] on optical fibers and waveguides have been used to map the
propagating modes through detection of the evanescent fields. Choo et al. [11] examined both single mode optical channel waveguides and directional couplers made from Si$_3$N$_4$ material and confirmed the transverse cosine squared dependence of the mode by detecting the evanescent field. They also mapped out the optical power transfer function in a directional coupler. Toda et al. [36] measured LiTaO$_3$ waveguides and determined that local deformations and inhomogeneity of composition caused significant scattering which could be resolved at the 500 nm scale with the NSOM. They also compared the measured intensity profile of the guided mode fields to calculations to determine the map of the refractive index.

In the area of photonic switches, NSOM is expected to be a useful tool, especially since modal evolution appears to be the best current candidate for high-speed switching [38]. Modal evolution switching involves weak guiding which allows interaction between adjacent optical waveguides. Switching is achieved by modulating the refractive index of the waveguide branches by applied current or voltage. Coupling between the branches is by virtue of overlapping evanescent tails of the guided modes. NSOM is ideal for the characterization of these evanescent optical field distributions which can not be detected by far field methods, as demonstrated in the work of Choo et al. [11].

IV. CONCLUSION

Near-field scanning optical microscopy is emerging as a powerful new tool to examine the sub-micron optical and electrical characteristics of semiconductor structures. Recent results in the application of NSOM have yielded information on composition, defects, mode structure in emission, local heating, carrier diffusion, local scattering, and waveguide mode patterns. Near-field optical beam induced current provides high resolution imaging of semiconductor materials which allows the correlation of layer composition directly with local optical properties in optoelectronic devices. We demonstrate that NOBIC resolution is a strong function of the amount of evanescent field coupling into the semiconductor. For relatively large apertures the resolution is fundamentally limited by the penetration of optical fields into the semiconductor material. The onset of multiple modes at high current levels in InGaAs GRINSCH lasers is observed as a bi-modal distribution of the spectrally and spatially resolved near-field emission.

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