Near-field optical beam induced current measurements on heterostructures

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(Received 7 April 1995; accepted for publication 22 July 1995)

We report near-field optical beam induced current (NOBIC) measurements on semiconductor quantum well (QW) structures. A subwavelength fiber tip is coupled with a tunable laser source and scanned over a sample surface. The induced photocurrent reveals the compositional profile of quantum structures. Semiconductor QW structures were designed and fabricated by molecular beam epitaxy (MBE) to study the wavelength dependence and resolution capability of NOBIC. We demonstrated that the resolution of this technique strongly depends on the aperture size. For aperture sizes that allow for coupling of evanescent fields from the tip into the semiconductor as propagating fields, the resolution strongly depends on the excitation wavelength due to the variation of the optical penetration depth. For smaller apertures, the optical field remains evanescent in the semiconductor and resolution is essentially independent of the wavelength. © *1995 American Institute of Physics.*

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 $\sim\lambda/40$, or $\sim$15 nm for visible wavelengths.[2] Spectroscopic information is obtained by coupling the collected signal to a grating spectrometer. High resolution characterization of materials and devices can be performed by near-field optical beam induced current (NOBIC) measurements where the tip provides the excitation.[4–7]

Semiconductor *p-i-n* diodes with quantum well (QW) structures in the depletion region were designed and fabricated by molecular beam epitaxy (MBE) to study the wavelength dependence and resolution capability of near-field optical beam induced current. NOBIC measurements using a tunable excitation source reveal the compositional profile of the quantum structures in the induced photocurrent.[8] Study of the wavelength dependence of the NOBIC resolution displayed a strong dependence on the aperture size. For tip apertures small enough to couple evanescent fields into the semiconductor resolution is essentially independent of wavelength. For relatively larger tips, a strong dependence of NOBIC resolution on the excitation wavelength is observed.

Figure 1 displays a schematic diagram of the experimental setup used for NOBIC imaging of the investigated QW structures. The sample is mounted facet-up on a piezoelectric tube and scanned in the $\hat{x}$-$\hat{y}$ plane beneath the probe tip. A tunable Ar^+ pumped Ti:sapphire laser provides excitation through the tip. The photoinduced current in the reversed biased diode is monitored by a current amplifier. Simultaneous shear-force measurements provide an independent measure of the surface topography to maintain a fixed proximity ($\sim$10 nm) between tip and sample.[9,10] The shear-force topography is used to reference various optical imaging techniques with the physical device structure.

This experimental setup can also be used in collection mode for active devices. In this case, light emitting devices are driven by bias sources and the emission is collected in the near-field by the tip and transmitted to a detector.[5,11,12] Reflection mode imaging is performed by exciting with the tip and collecting with coaxial mounted optics in the far-field. The combined capability of NOBIC and collection mode measurements on the same device is used to map the emission mode profiles on the compositional layer structure of heterostructure laser diodes.[5] The projected usefulness of NOBIC for analyzing semiconductor devices presents the issue of the ultimate resolution capability.

We have designed and fabricated semiconductor structures consisting of three sets of GaAs QW pairs surrounded by $Al_{0.35}Ga_{0.65}As$ barriers placed in the depletion region of a *p-i-n* diode. The layers were grown by molecular beam epitaxy (MBE). Three pairs of 30 nm thick GaAs quantum

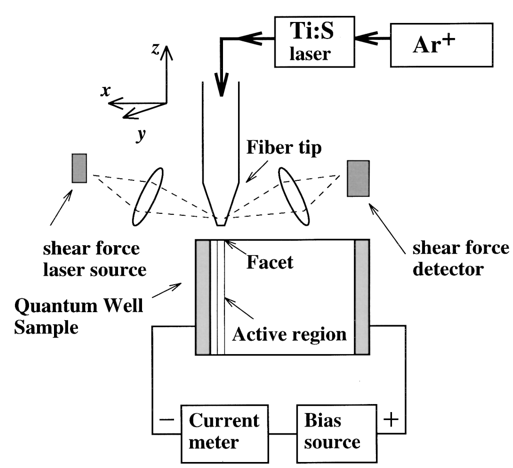

FIG. 1. Block diagram of the measurement for near-field optical beam induced current (NOBIC) compositional analysis. Simply changing connections, collection mode measurement can also be performed on the same section of the device. The lenses to the side of the fiber tip provide the shear-force signal for topography.

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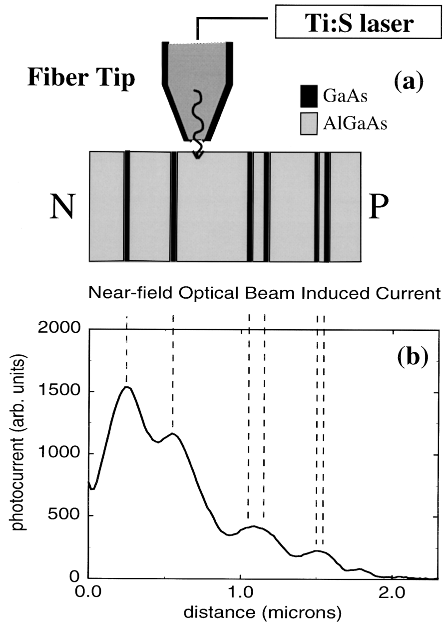

FIG. 2. Near-field optical beam induced current (NOBIC) line scan (b) with a depiction of the layer structure and the fiber tip (a). The GaAs QW are 30 nm wide and are separated by distances of 300, 120, and 50 nm. The sample was reverse biased at 2 V.

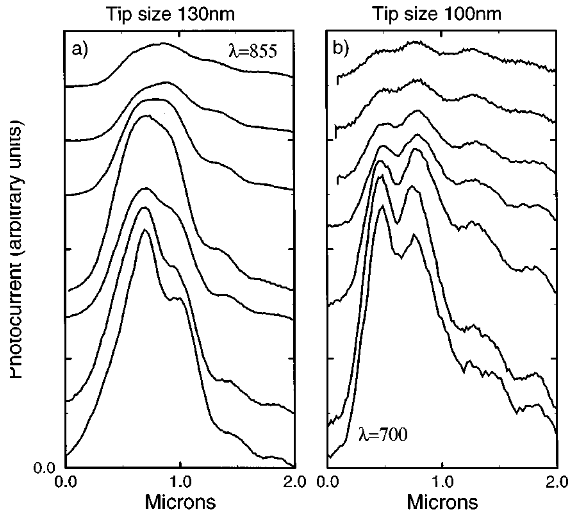

FIG. 3. Near-field optical beam induced current (NOBIC) line scans as a function of excitation wavelength for two different tip sizes, (a) 130 nm diameter tip and (b) 100 nm diameter tip. The wavelength varies from 700 nm (bottom) to 855 nm (top). In (a) the resolution degrades for increasing wavelength, while for smaller tips in (b) the resolution is largely maintained.

wells (QW) were placed in the $Al_{0.35}Ga_{0.65}As$ *i*-region. The spacing between the QWs is varied from 300 to 50 nm and the pairs are separated by 500 nm. 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. Figure 2(a) shows a schematic representation of the investigated structures. Note also that the QW structures are semi-infinite in depth.

Figure 2 shows a NOBIC line scan at $\lambda=700$ nm in the epitaxial growth direction and its correlation to the layer structure (the response is uniform in the direction parallel to the substrate). The QWs separated by 300 nm are clearly resolved. In this experiment, we were unable to resolve more closely spaced QW pairs due to the relatively large tip diameter (~125 nm), and incomplete depletion caused by a high *p*-type background in the unintentionally doped region resulting in a p-π-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-π junction, which results in a reduced collection efficiency for the carriers optically generated close to the sample surface and ultimately limits the image resolution away from the junction.[13]

The near-field profile from a subwavelength 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.[14,15] 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 NOBIC resolution would not be observed. However, since the semiconductor is a much denser medium ($n\sim3.5$ for GaAs) than the silica ($n\sim1.5$) 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 QWs determines the maximum resolving power for NOBIC imaging of semi-infinite structures.

To demonstrate the significance of optical penetration, NOBIC scans across the QW structures were performed as a function of excitation wavelength with a 130 nm diam tip. The results are shown in Fig. 3(a) for wavelengths ranging from 700 to 855 nm in successive scans are across the 300 nm separated QWs. The highest resolution is obtained with the shortest wavelength, and the peak separation is gradually lost as the wavelength is increased. By $\lambda=755$ nm the two QWs are not resolved. For wavelengths from 700 to 855 nm the barriers ($Al_{0.35}Ga_{0.65}As$) are transparent, while the absorption coefficient in bulk GaAs decreases from $\sim4\times10^4$ to $\sim1\times10^4$ cm^{-1} with increasing wavelength. Since the widths of the GaAs QWs are relatively large (300 Å), we expect the variation of the absorption coefficient at room temperature to be similar to bulk GaAs. This corresponds to optical penetration depths from 250 nm at $\lambda=700$ nm to 1 μm 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 allows for deeper penetration of the optical field into the semi-infinite 2D 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 AlGaAs barriers would no longer be transparent, abrogating all NOBIC contrast.

For near-field probes small enough to couple evanescent fields into the semiconductor the resolving capability is expected to be independent of wavelength. To demonstrate the significance of the aperture size, similar NOBIC scans were performed with a 100 nm tip and the results are shown in Fig. 3(b). In this case, NOBIC scans across the sample as a function of wavelength maintain the same resolution even at longer wavelengths where the optical absorption coefficient is small. At longer wavelengths, the smaller absorption coefficient of GaAs results in reduced NOBIC signal and signal to noise ratio. The best full width at half-maximum (FWHM) of the NOBIC is ~350 nm which is significantly larger than the tip size. We believe that this is due to the surface depletion at the GaAs-air interface resulting in trapping of carriers at the surface, effectively introducing a spacer layer between the tip and optically active semiconductor region as also observed by Karrai and Grober.[13] Since the optically active region is away from the tip, FWHM of the NOBIC signal is significantly larger than the actual tip size due to rapidly diverging optical field. The surface depletion also partially accounts for the reduced photocurrent when the excitation is away from the junction.

Based on the experimental data we conclude that to obtain near-field resolution in semiconductor structures, the aperture size should be chosen according to the refractive index (n) of the material. A comparison of experimental data from Figs. 3(a) and 3(b) reveal that even a small variation in tip size (100 nm versus 130 nm) is extremely important. At 130 nm, the tip aperture is larger than half wavelength in GaAs ($\lambda/2n$, $n=3.5$) for the 700–855 nm wavelength range resulting in strong coupling into propagating modes as indicated by the wavelength dependent resolution capability. In contrast, the 100 nm tip is smaller than $\lambda/2n$ for the entire wavelength range and the optical fields remain evanescent. In this case, the resolution is independent of the excitation wavelength, however, it is limited by the aperture size and the surface depletion due to high density of states on the GaAs surface.

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 or air. It will also hold for other near-field optical imaging techniques such as high resolution photoluminescence and reflectivity measurements. In the reflectivity mode, a relatively short excitation wavelength excitation should be used allowing for large absorption coefficients in the investigated semiconductors. The absorption depth does not limit the spatial resolution whenever the sample being studied is thinner than the penetration depth or the lateral feature size. This is largely the case in most NSOM studies to date.[2,3,16]

A comparison can be made between our results and those of Grober *et al.*[17] where a T-junction cleaved edge overgrowth GaAs quantum wire sample was studied in collection mode. Grober found a resolution in collection mode photoluminescence with a FWHM given by the tip diameter. Collection mode NSOM is somewhat different since its resolution is dominated by the proximity of emitters near the surface. Assuming isotropic emission, and a small, fixed numerical aperture of the tip, geometric arguments show that the probability of coupling photons into the tip drops off as the depth squared directly above the active region, and faster when the tip is laterally removed. In addition, the quantum wire region was of higher index than the surrounding AlGaAs, creating a waveguide for the luminescence. Both these effects were seen in the near-surface electroluminescence versus waveguide emission in Buratto *et al.*[12] Finally, Grober was examining a single quantum wire region, so overlapping emission from neighboring regions was not a factor.

In conclusion, NOBIC provides high resolution imaging of semiconductor materials which allows the correlation of layer composition directly with local optical properties in optoelectronic devices. We demonstrated that the resolution of NOBIC and its wavelength dependence are strongly dependent on the aperture size in semi-infinite structures. The larger refractive index allows for the coupling between evanescent near-field and propagating modes in the semiconductor. For aperture sizes that allow for coupling of evanescent fields from the tip into the semiconductor as propagating fields, the resolution strongly depends on the excitation wavelength due to the variation of the optical penetration depth. For smaller apertures, the optical field remains evanescent in the semiconductor and resolution is essentially independent of the wavelength. We experimentally determined the critical tip diameter to achieve true near-field resolution for NOBIC on semiconductors to be less than half of the wavelength of the optical excitation in the semiconductor material, i.e., $a<\lambda/2n$.

This research is partially supported by the National Science Foundation under Grant Nos. ECS-9309607 and DMR91-58097, and by ONR Grant No. N00014-93-1-1186.

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