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Semiconductor characterization by a new contactless electroreflectance technique employing surface acoustic waves

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Abstract. The interaction between an amplitude modulated surface acoustic wave on a piezoelectric substrate and the surface band bending and charge trapping at an adjacent semiconductor surface is employed to produce a modulated d.c. electric field in the near-surface region of the semiconductor. This field perturbs the optical reflectivity of the semiconductor, allowing derivative reflectance spectra to be obtained in a manner analogous to the familiar technique of photomodulated reflectance. This new contactless electroreflectance technique has been demonstrated by obtaining spectra, including structure above the bandgap, of (In)GaAs/AlGaAs multiple quantum well structures grown by molecular beam epitaxy.

Contactless modulated optical spectroscopy of semiconductors is of current interest for evaluating epitaxially grown layered structures before device processing and for conducting fundamental semiconductor studies on as-grown samples [1]. Two advantages of modulation techniques are (i) the high sensitivity and selectivity afforded by the derivative nature of the spectra and (ii) the ability to study electronic transitions above the semiconductor bandgap. Typical methods of contactless electroreflectance being used currently include photomodulated reflectance (photoreflectance) [2] and 'contactless electroreflectance' [3]. In both of these techniques a low-frequency, oscillatory, normally directed electric field is induced across the surface region of the sample, and the resultant modulated reflectance $\Delta R/R$ is measured as a function of wavelength using synchronous detection. In 'contactless electroreflectance' the electric field is induced capacitively through a small air gap by the application of an external a.c. voltage. In photoreflectance it is produced via changes in the density of trapped surface charge caused by photogenerated electrical carriers [4].

In the present work we have developed a new method of generating the modulating electric field, namely by employing the nonlinear interaction of a surface acoustic wave (SAW) propagating on a piezoelectric substrate in near proximity to the semiconductor surface. Early studies of the semiconductor–SAW interaction emphasized the small-signal d.c. 'acoustoelectric' fields induced by the inherent nonlinearity of the coupled carrier-field equations [5]. Later investigations pointed out the importance of carrier trapping at surface states [6, 7], specifically the importance of changes in the steady-state trapped charge density and the concomitant surface band bending. For example, Fischler *et al* [6] measured reductions of up to 75% in the conductance of thin Si samples coupled to 2 MHz elastic waves on piezoelectric lead zirconate titanate plates. The generally accepted mechanism for this phenomenon is as follows [7]. The rf electric field accompanying the SAW induces a strong rf band bending in the semiconductor near-surface region. Majority carriers are transported to the surface and rapidly trapped during one half of the rf wave cycle, but released from the traps only very slowly during the other half cycle, resulting in a rapid buildup of a steady-state surface charge. In our experiments, we produce a surface-field modulation by gating the rf excitation of the SAW at a low frequency (10s–100s of Hz) to effect a periodic charging and discharging of the traps. As in photoreflectance measurements, the electric field accompanying the surface charge modulates the semiconductor band structure, leading to sharp spectral features near the band structure's critical points.

Figure 1 is a schematic diagram of our experimental arrangement. Monochromatic light from a miniature tungsten lamp and 0.25 m grating monochromator combination was focused onto the semiconductor sample through the quartz SAW delay line. The reflected light was detected with an InGaAs or Si photodiode and the a.c. and d.c. components of the signal were measured with a lock-in amplifier and a digital voltmeter respectively. An

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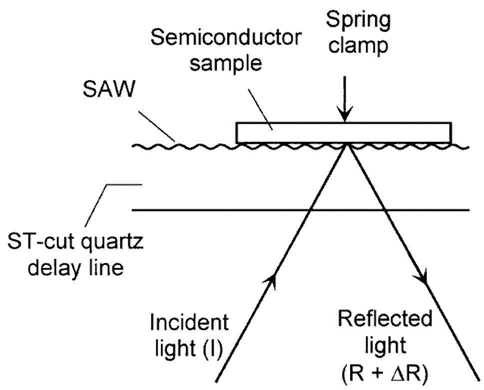

Figure 1. Schematic of the surface acoustic wave electroreflectance (SAW-ER) experiment. The rf electric field carried by the SAW interacts with free carriers in the semiconductor sample, causing a steady-state change in the trapped surface charge density. Gating the SAW at low frequency leads to synchronous changes in the sample's reflectivity, analogous to the changes obtained with other electromodulation techniques.

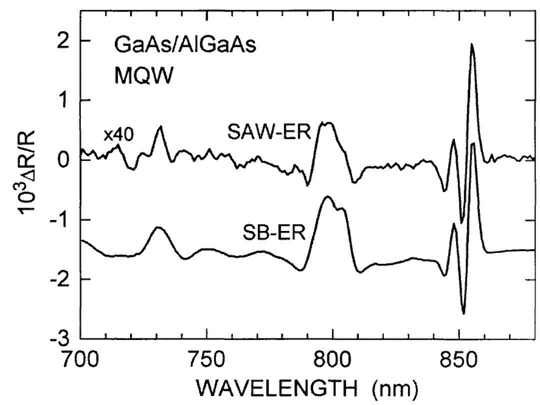

Figure 2. Comparison of the modulation spectra of a GaAs/AlGaAs multiple quantum well structure obtained using the new SAW-ER and the standard Schottky barrier electroreflectance (SB-ER) techniques. The spectra have been shifted vertically for clarity. The results are virtually identical.

ST-cut quartz delay line already on hand was chosen for SAW generation, although other types (for example yz-cut $LiNbO_3$) would produce higher electric fields. The delay line's interdigitated SAW transducers were resonated with series inductors and driven by a signal generator at 97 MHz and 22 V peak-to-peak.

The semiconductor samples were cleaved into small bars about 2×4 mm^2 and placed over the SAW path as shown in figure 1. The samples were mounted near the centre of the delay line—well away from the delay line's interdigital transducers—so that there was no direct excitation of surface acoustic waves in the samples†. In our set-up, the delay line was clamped in a brass fixture and the samples were held against the delay line by one or two small, adjustable spring clips attached to the fixture. The clips applied a light force, enough to minimize the air gap without mechanically damping the SAW. Sample mounting is critical for obtaining a useful signal. We found it necessary to apply a non-uniform force to the sample, so that several optical interference fringes were visible at the quartz–semiconductor interface. This helped minimize a spurious signal that is due, we believe, to electrostatic forces modulating the thickness of the air gap.

Two semiconductor quantum-well structures were used to demonstrate our new technique. The samples were grown by molecular beam epitaxy starting with (001) n-type GaAs substrates on which GaAs and $Al_{0.3}Ga_{0.7}As$ buffers were grown. The first sample had 33 periods of GaAs (10 nm thick) quantum wells and $Al_{0.3}Ga_{0.7}As$ (5 nm) barriers. The second sample had 33 periods of $In_{0.17}Ga_{0.83}As$ (10 nm) wells and $Al_{0.3}Ga_{0.7}As$ (5 nm) barriers. Both samples were lightly doped in the quantum well regions at a level of $n = 1 \times 10^{16}$ cm^{-3}, and both were capped with 10 nm of undoped GaAs. In order to compare our results to standard electroreflectance measurements, separate devices (from the same wafers) were used to make Schottky barrier electroreflectance (SB-ER) measurements. These devices were electroded on their top surfaces with semitransparent $AuGa_2$ metal, forming Schottky diodes with low reverse leakage and sharp diode knees in forward bias. Some of our work on the SB-ER spectra of these and other related samples have been discussed in previous publications [8, 9].

In figure 2 we show the SAW-ER and SB-ER spectra for the GaAs/AlGaAs quantum well structure. These data were obtained from different positions on the wafer and have been shifted slightly (< 2 nm) to line up their band-edge peaks. The SAW-ER intensities have been scaled by $40\times$ to show peak heights comparable to the SB-ER data. The SAW-ER data were taken with ~ 150 mW of rf excitation power, gated at 325 Hz, into the SAW delay line; the SB-ER result was obtained with a modulation level of 0.8 V peak-to-peak at 870 Hz. The modulated spectra obtained using the two techniques are virtually identical to each other and are similar to electromodulation spectra obtained by others on similar structures. Near 850 nm are two lines due to the $n = 1$ principal quantum well transitions for the heavy and light holes (denotes as 11H and 11L respectively, where the first two integers designate the electron and hole quantum numbers and H or L designates the heavy- or light-hole state). Near 800 nm is a double-peaked structure due to the 22H and 21H transitions. The 33H transition near 730 nm is also seen in both spectra, although the signal to noise ratio in the SAW experiment is rather poor because of a smaller incident optical intensity at the shorter wavelengths. The magnitude of the SAW-ER signal is similar to that typically seen in photoreflectance studies of multiple quantum wells. We believe the signal strength could be increased by about an order of magnitude by using a SAW medium with a higher piezoelectric coupling coefficient and by increasing the rf drive amplitude.

† Since our compound-semiconductor samples are slightly piezoelectric, the composite wave in the quartz–semiconductor interface region carries small acoustic component in the semiconductor. The presence of this small rf component does not affect our proposed mechanism for the generation of reflectance modulation from the semiconductor surface.

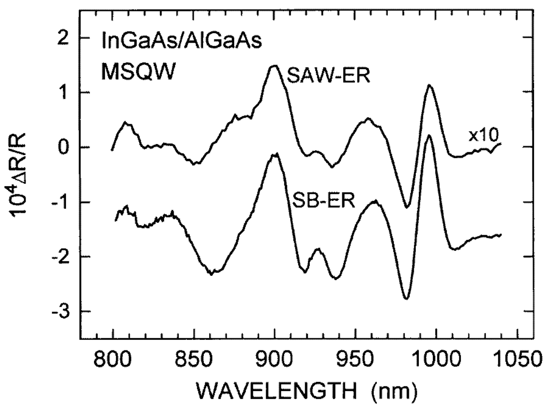

Figure 3. Comparison of SAW-ER and SB-ER spectra of an InGaAs/AlGaAs multiple strained quantum well structure. Some small differences in the spectra are seen around 870 nm, where the SB-ER results are highly sensitive to d.c. bias and a.c. modulation depth.

As a second example of typical spectra obtained with the SAW-ER technique, we show data for the InGaAs/AlGaAs structure (described above) in figure 3. Overall, the spectra are again quite similar to each other. The optical transitions are broader than in the previous example, probably due to a combination of effects including incomplete and non-uniform strain relaxation and tunnelling processes stemming from defects. We have discussed the latter of these effects previously [8]. In figure 3 the lines near 990 nm are due to the 11H transition and the broad features near 960 nm are due to the strain-split 11L transition. A strong 22H transition is seen near $\sim$ 900 nm. In the SB-ER measurements we found the intensity and shape of the feature near 870 nm to depend strongly on the applied d.c. bias field and on the amplitude of the field modulation. This effect, whatever its cause, is probably responsible for the difference in the spectra of figure 3 in this wavelength region. To obtain fairly similar spectra, as in figure 3, we took the SB-ER data with a modulating voltage of 0.2 V peak-to-peak and a d.c. bias slightly less than the flat band voltage.

In summary, we have proposed and demonstrated a novel method for obtaining electroreflectance spectra of semiconductors. The method involves low-frequency gating of a surface acoustic wave propagating on a medium proximate to the semiconductor sample to induce a surface band bending synchronous with the gating. Our initial studies on multiple quantum well semiconductor structures have yielded modulation spectra similar to those observed with the standard Schottky barrier diode method, without the need for providing electrical contacts to the samples. Fractional modulation signals of $\Delta R/R \approx 5 \times 10^{-5}$ have been readily attained using an ST-cut quartz delay line driven at 150 mW. We believe the signal level could be increased significantly by choosing an optimal SAW configuration.

The modulation signal levels we have observed are comparable to those typically obtained in photoreflectance studies. Our technique may offer an advantage over photoreflectance in eliminating the pump laser needed for photoreflectance. The pump laser often causes problems by scattering into the probe beam detector and by generating a photoluminescence signal that interferes with the reflectivity measurement.

Acknowledgments

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