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Linear electro-optic reflectance modulated spectra of GaAs (001) around E_1 and $E_1+\Delta_1$ transitions

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We report on the determination of the linear electro optic (LEO) reflectance modulated spectra of GaAs (100). LEO spectra were obtained from photoreflectance (PR) measurements. Experiments were carried out in an energy range around the E_1 and $E_1+\Delta_1$ interband transitions. Two samples were employed, an undoped homepitaxial GaAs and a GaAs bulk crystal doped with Te donors in the low $10^{17}/cm^3$ range. We show that, although LEO spectra amplitudes for the two samples differ for one order of magnitude, their line shape is essentially the same. We further report on RD measurements aimed to obtain LEO spectra. We employed the same GaAs samples for, both, PR and RD measurements in order to contrast the information provided by these two techniques.

1. Introduction

There is a growing interest in the use of optical reflectance techniques for the determination of doping levels in zincblende semiconductors.[1,2] Optical techniques result very attractive for this application as they are non destructive, require no sample preparation, and are flexible enough to allow for *in situ* measurements.

To determine doping concentrations by a reflectance technique one take advantage of the breakdown of the zincblende symmetry by the sample surface electric field (SEF).[3] This field changes the crystal symmetry from cubic to orthorhombic and renders the semiconductor optically anisotropic through a linear electro optic (LEO) effect.[4] A quantitative measurement of the sample reflectance anisotropy at energies around the E_1 and $E_1+\Delta_1$ inter band transitions (2.5-3.5 eV) allows for the determination of its SEF strength and from this of its doping level. We further note that the sample conductivity type can be determined from the sign of the measured LEO reflectance anisotropy.

Reflectance-difference (RD) spectroscopy,[5] that measures the difference in optical reflectance between two orthogonal polarizations, provides a means of measuring reflectance anisotropies and thus doping concentrations. In this regards, RD spectroscopy have been employed for the contactless determination of doping levels of epitaxial layers grown by, both , MBE[6,7] and MO-CVD.[8]

Nevertheless, measuring LEO spectra through RD spectroscopy results rather involved due to the fact that, besides the LEO line shape, RD spectra usually comprise components with origins other than electro optic.[9,10,11] Thus, to isolate the LEO component from an RD spectrum we must subtract all the non-LEO components. This may prove to be difficult specially for samples with low doping levels.

In previous papers,[3,12,13] we have reported on a technique for the determination of LEO line shapes from photoreflectance (PR) experiments. With such technique we do not need to take care of non electro-optic line shape components since PR line shapes are entirely due to an electro-optic effect. We note, however, that care should be taken of the quadratic electro-optic component that is known to dominate PR line shapes in many cases.[14]

In this paper we report on PR measurements employing two n-type GaAs (100) samples, an undoped epitaxial layer 2.5 μm thick grown on GaAs:Cr and a bulk crystal doped with Te donors in the low $10^{17}/cm^3$ range, aimed to determine their LEO line shapes. We show that, although LEO spectra amplitudes for the two samples differ for one order of magnitude, their line shape is essentially the same. We further report on RD spectra for the two GaAs samples employed in the PR experiments, and contrast the information provided by these techniques.

2. Experimental

It is known that in the low field limit the PR spectrum for normal incidence on the (001) surface can be written as,[15]

$$\frac{\Delta R}{R} = 2\lambda\mu P_{123} F + Q_{12} F^2 \ , \qquad (1)$$

where F is the strength of the surface electric field, P_{123} and Q_{12} are components of the tensors (third and fourth-rank, respectively) describing the linear and quadratic electro-optic effects, respectively, and λ and μ are the direction cosines of the polarization vector of the incident light. From Eq. (1) we can see that, while the PR LEO component is polarization-dependent, the quadratic spectrum is isotropic. Thus, PR spectra taken with unpolarized light should comprise only the quadratic component, since the linear component averages out to zero. In contrast, a PR spectrum taken with light polarized along either [110] or $[1\bar{1}0]$ should comprise, both, linear and quadratic components. By taking advantage of this fact, the LEO reflectance spectra reported in this paper were obtained by subtracting the PR spectrum taken with unpolarized light, to the corresponding PR spectrum taken with light polarized along [110]. According to above discussion, the subtracted spectra should comprise only the LEO component.

Regarding RD spectroscopy, it measures the difference in reflectivity for linear polarizations along [110] and $[1\bar{1}0]$. Thus, from Eq. (1) we can see that the amplitude of the experimental LEO component is given by

$$\frac{\Delta R}{R} = 4 P_{123} F \ . \qquad (2)$$

Above expression shows that, for the geometry we are considering, the RD spectrum does not comprise a quadratic electro optic component.

The spectrometer employed for the RD measurements is schematically shown in Fig. 1. In this setup, light coming from a Xe lamp is focused at the entrance slit of a 0.25 m monochromator. Light at the output of the monochromator is passed through a polarizer prism (quartz Rochon) and a photoelastic modulator and then focused at near normal incidence on the sample surface. The polarizer prism and photo-elastic modulator in tandem allow for the polarization of the light incident on the sample surface to be modulated at a frequency of 50 kHz between two orthogonal, linearly polarized states. For the experiment, the sample is aligned so that the two extreme polarization states coincide with the $[1\bar{1}0]$ and [110] directions. Upon reflection, the light beam is focused on the active area of a UV-enhanced silicon photo detector whose electric output is feed to a lock-in amplifier tuned to twice the photo-elastic modulator frequency. To suppress parasitic signals in the measured RD spectra we have employed the procedure described elsewhere.[16]

PR experiments were carried out with the same spectrometer employed to measure RD spectra. To modulate the sample surface electric we used a 10 mWatt He-Ne laser and a mechanical chopper tuned to the lock-in amplifier. The experimental set up allows for the measurement of PR spectra with both, polarized and unpolarized light. Polarized light measurements were carried out by turning the photo-elastic modulator off. Unpolarized light spectra were taken with the photo-elastic modulator turned on, by taking advantage of the large difference between the laser chopping frequency (450 Hz) and the polarization modulation frequency (100 kHz). Further details on the PR experimental set up can be found elsewhere.[3]

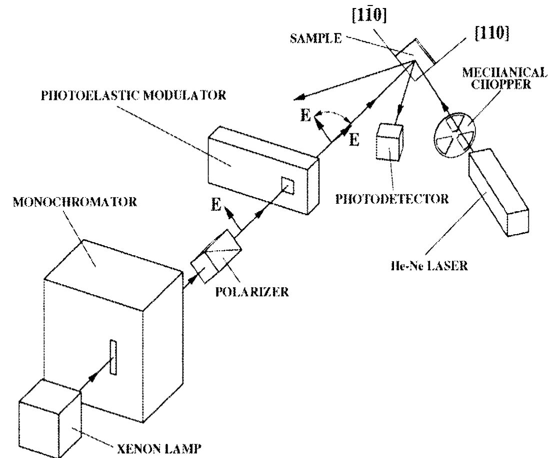

Fig. 1. Schematics of the experimental arrangement for the measurement of PR and RD spectra. The ratio of the polarization modulation frequency to the mechanical chopper frequency is of the order of 250.

3. Experimentals results and disscusion

Thin solid and dashed lines in Fig. 2 show, respectively, the polarized an unpolarized PR spectra for the Te-doped sample. As discussed above, while the unpolarized spectrum corresponds entirely to the quadratic PR line shape, the polarized spectrum contains, both, linear and quadratic components. Thus, the difference between these two spectra, shown by the thick continuos line in Fig. 2, gives the LEO line shape. As we can see in this figure, for this doping range the LEO spectrum amplitude, although measurable with good precision, is relatively small when compared to the quadratic PR spectra.

Because the quadratic spectrum amplitude scales with doping level faster than does the linear amplitude, we may expect the LEO component to become more prominent as the doping level is decreased. This was indeed found to be true as shown in Fig. 3, where thin solid and dashed lines correspond, respectively, to polarized and unpolarized PR spectra for the undoped GaAs sample, while the thick solid line displays the LEO

spectrum.. As we can see, in this case LEO and quadratic spectral amplitudes are comparable.

From Figs. 2 and 3 we can see that the LEO spectrum amplitude for the Te-doped sample is larger than the corresponding amplitude for the undoped sample for a factor of about 9. This allows us to conclude that the doping concentration of the undoped sample is in the lower 10^{15}/cm^3 range. Furthermore, from the sign of the LEO line shape we as well conclude that it has the same conductivity type (n-type) than that of the Te-doped crystal.

In Fig. 4 we show the measured RD spectra for the GaAs samples. Upper and lower curves correspond to undoped and Te-doped samples, respectively. As pointed out above, the RD spectra of GaAs (001) may comprise, both, LEO and non electro-optic components. In the case of the RD spectrum shown by the upper curve of Fig. 4, however, the LEO component is negligible due to its low doping level. In contrast, for the Te-doped sample the LEO component is quite prominent as it is evident from Fig. 4.

By assuming that the non electro-optic component of the Te-doped sample is the same as that of the undoped crystal, we could isolate the LEO spectral component for the Te-doped sample by subtracting the two spectra of Fig

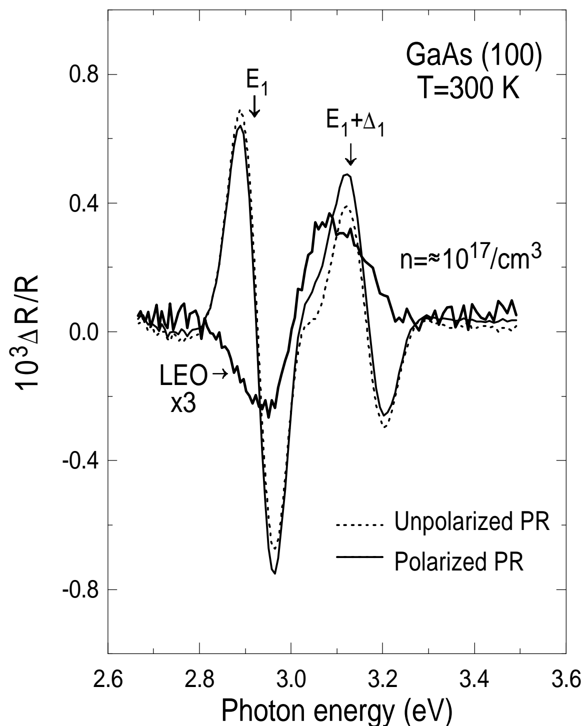

Figure 2. Thin lines: PR spectra for an n-type GaAs (100) sample with a concentration of Te donors in the low 10^{17}/cm^3 range; Thin solid and dashed lines correspond to light polarized along [110] and to unpolarized light, respectively. Thick solid line: LEO spectra obtained by subtracting above PR spectra.

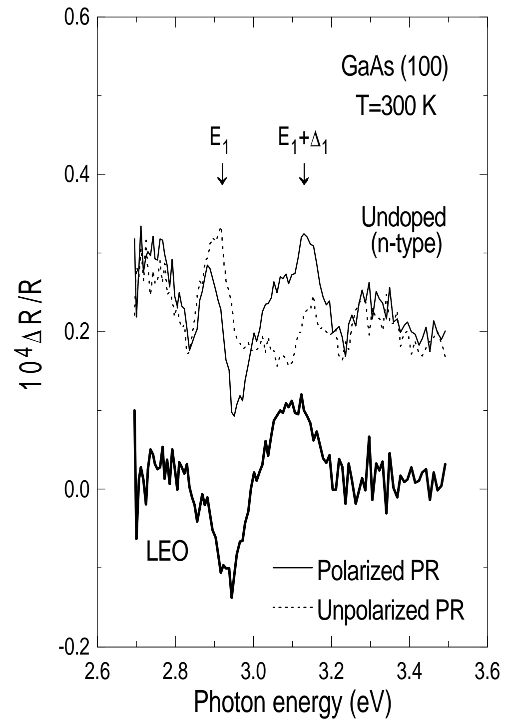

Figure 3. Same as figure 2 but for an undoped n-type GaAs sample. Thin solid and dashed line spectra were displaced upwards for the sake of clarity.

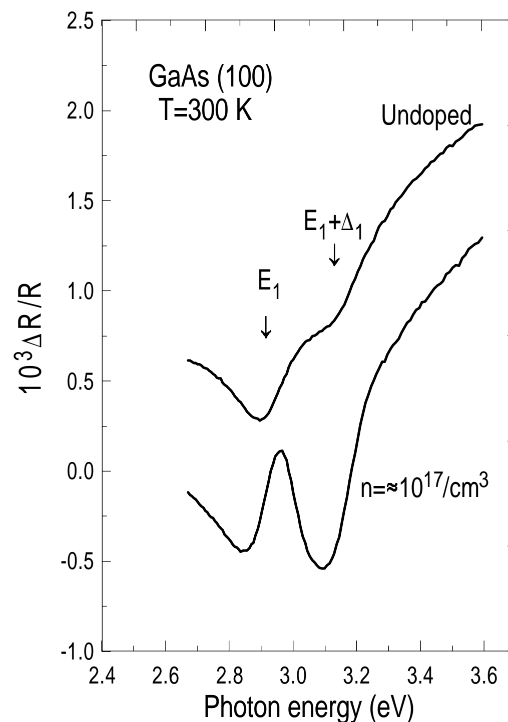

Figure 4. RD spectra for same GaAs (100) samples of Figs. 2 and 3.

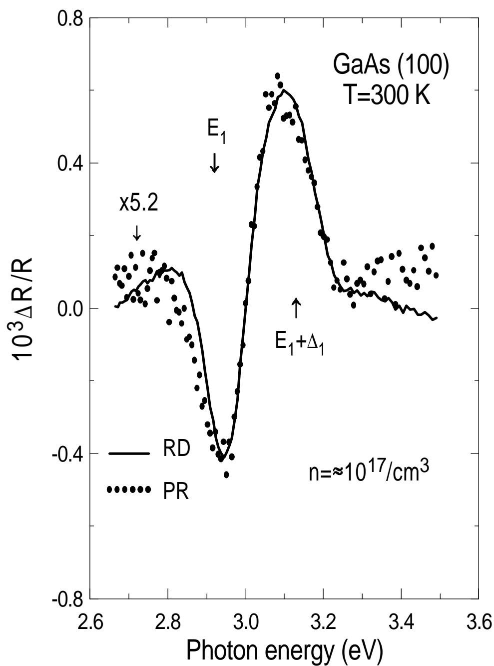

Figure 5. Solid line: LEO spectra obtained by subtracting the two RD spectra. of Fig. 4. Filled circles: Same LEO spectrum of Fig. 2 but scaled so to fit the solid line spectrum.

4. The solid line in Fig. 5 show the result of this subtraction. For the sake of comparison, in the same figure we show with filled circles the LEO spectrum of Fig. 2 scaled so to fit the continuos line spectrum. As we can see from Fig. 5, the LEO-RD spectrum shows a good agreement with the corresponding LEO-PR line shape. This agreement is however not perfect, indicating that the non electro-optic component of the two RD spectra of Fig. 4 are actually not the same.

4. Conclusion

In conclusion, we have reported on the determination of LEO reflectance line shapes of GaAs (001) crystals. LEO line shapes were obtained from, both, PR and RD experiments. It is shown that the line shape of the LEO-PR spectrum is the same for the two crystals studied, which have a two order of magnitude difference in doping levels. The LEO line shape obtained from RD measurements shows a good agreement with the LEO-PR line shape.

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