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Interference effects in photoreflectance of epitaxial layers grown on semi-insulating substrates

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Interferences were observed in the photoreflectance spectra of homoepitaxial layers grown on semi-insulating GaAs and InP substrates. The modulation mechanism responsible for the interference effect was studied from the frequency and temperature dependence of the interference amplitude and the effect of continuous wave illumination. The results are in agreement with the model that the modulation is due to electrons drifting to the interface from the surface. A simple model was used to fit the interference spectra to the Lorentzian wave forms from the substrate and the epitaxial layer.

Photoreflectance (PR) is widely used for the characterization of the band structure in semiconductor quantum well and superlattice structures.[1] Like other modulation spectroscopic methods, PR offers the advantage of high resolution at room temperature. In order to obtain a maximum amount of information from the PR spectra, a fitting procedure must be used to identify each optical transition. The identification is complicated by the very sensitivity of the modulation spectroscopy, which produces spectra containing many transitions. Further, near the fundamental band gap of the semiconductor material the fit can be made difficult by two unrelated effects: Franz–Keldysh oscillations[2] on the high-energy side and interference oscillations on the low-energy side of the fundamental transition. The interference has been shown to originate from the modulated beam reflected from the epilayer-substrate interface and can therefore be used to measure the thickness of the epitaxial layer.[3,4] The interference fringes have been observed on homo- and heteroepitaxial structures grown on *n*-type GaAs substrates but not on semi-insulating or *p*-type substrates. On the basis of this observation two possible modulation mechanisms were proposed by Huang *et al.*:[3] impurity band filling in the doped substrate or the Franz–Keldysh effect at the interface.

Kallergi *et al.* also observed interferences on samples grown on *n*-type GaAs substrates.[4] By thinning the layers through chemical etching they found that the amplitude of the interferences increases exponentially with decreasing thickness, indicating that the pump beam modulates the reflected beam directly at the interface. However, by using shorter wavelength pump light they were able to show that for thick samples the intensity of the pump beam is too low to cause the modulation directly. Instead, they proposed that, for thick samples at least, the modulation is caused indirectly by charge carriers diffusing from the surface region of the sample.

In this letter we show that the interferences can also be observed in samples grown on semi-insulating substrates and discuss the probable modulation mechanism responsible for this phenomenon.

PR measurements were made by monochromatizing the probe beam from a 100 W tungsten lamp with a computer-controlled 0.5 m monochromator. A silicon *p-i-n* diode or a photomultiplier tube was used as the detector. The samples were mounted on the cold head of a variable temperature (12–475 K) closed cycle He cryostat and the measurements were repeated at several different temperatures. The 488 nm line of a 1 W argon-ion laser was used as the pump beam. The power density was reduced with neutral density filters to a suitable level (usually approximately 20 mW/cm^2). The pump beam was modulated using a chopper. The modulation frequency was varied from 220 Hz to 2.4 kHz. In some measurements a 5 mW He–Ne laser was used for pumping and the sample was simultaneously illuminated with cw light from the Ar-ion laser.

Two samples will be described in this letter. Sample A was a nominally undoped, 4.7-μm-thick InP layer on Fe-doped semi-insulating InP and sample B an undoped 13-μm-thick layer of GaAs on undoped semi-insulating GaAs. Both samples were grown by molecular beam epitaxy. Sample A was *n* type with $n \sim 10^{16}$ cm^{-3} due to the unintentional background sulfur doping[5] whereas sample B was highly resistive and probably fully depleted of free carriers at room temperature.

Interferences are often observed in samples grown on *n*-type substrates, but usually not from layers grown on semi-insulating substrates. However, we have obtained interferences from epitaxial InP grown on semi-insulating InP and GaAs grown on semi-insulating GaAs. The reason why interferences are usually not seen on semi-insulating substrates is that the PR signal originating from the substrate is quite narrow and lacks the extended tail seen from the doped *n*-type substrates. Consequently the interference fringes are attenuated very quickly as the wavelength increases. To illustrate this, Fig. 1 shows the PR spectrum from A and B samples. The interferences are clearly visible, but in sample B they die out, extending only a few tens of meV from the fundamental E_0 transition. The interferences are visible only because the epitaxial layer in B is exceptionally thick and the interference peaks are therefore very close to each other. In sample A, however, the interferences are visible over a much wider wavelength range

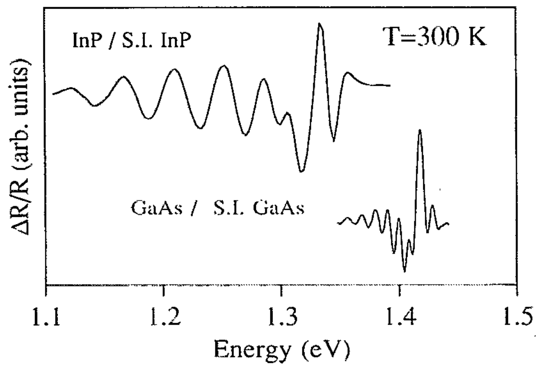

FIG. 1. Below band gap interference oscillations in the photoreflectance spectra of the InP and GaAs samples.

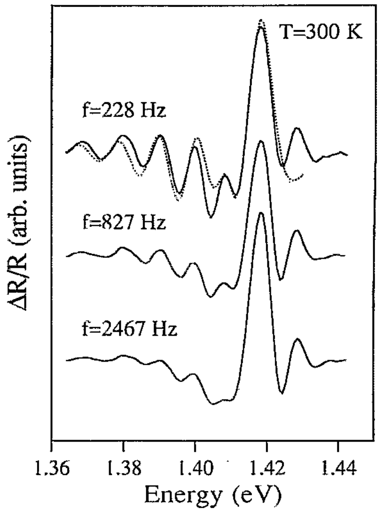

FIG. 3. PR spectra of the GaAs sample at three different lock-in phase angles. $\phi=0°$ is the in-phase angle for the dominant E_0 feature. The dotted line shows the line shape calculated from Eq. (3).

and the spectrum resembles those obtained from epitaxial layers on n-type substrates. The PR spectra measured from Fe-doped InP substrates typically exhibit a narrow transition similar to those measured from undoped GaAs substrates. Therefore, it is likely that the broad interference is caused by heavy n-type doping of the interface. At the epilayer-substrate interface n-type impurities such as sulfur and silicon are usually accumulated due to the difficulty of achieving a clean substrate surface.

The fact that the fundamental E_0 transition and the interference signal have different origins is illustrated in Fig. 2 where the phase of the lock-in amplifier has been varied. The two signals have a phase difference of about 45° and either signal can be made to disappear simply by choosing the phase correctly. If the modulation of the interference signal is due to electrons being trapped at the interface they can be expected to recombine quite slowly and the interference should therefore disappear before the fundamental E_0 peak as the modulation frequency is increased. Figure 3 confirms this effect. As the frequency is increased from 228 to 2467 Hz the amplitude of the interferences is greatly reduced while the amplitude of the E_0 transition remains constant. By fitting the model of Shen *et al.*[6] to the amplitude versus frequency data an estimate of 2 ms is obtained for the recombination lifetime at room temperature.

A similar difference is found in the temperature dependence of the interference and the E_0 transition shown in Fig. 4. As the temperature is reduced, the amplitude of the E_0 transition is reduced due to the surface photovoltage effect.[7] The photovoltage reduces the surface electric field and therefore the photogenerated electrons find it more difficult to drift from the surface to the interface.

The line shape of the interference signal can be modeled as shown in Refs. 3 and 4. We have used a slightly different approach which allows the line shape parameters of the different transitions to be taken into account more explicitly. For simplicity, consider light with only a single

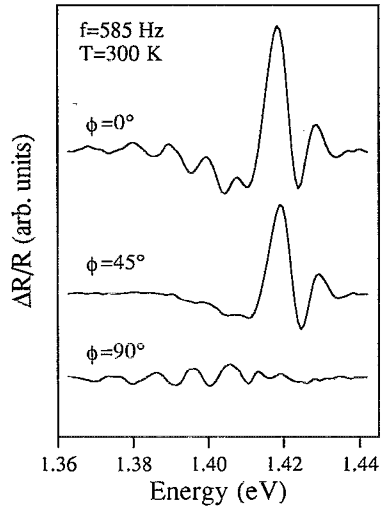

FIG. 2. PR spectra at 300 K of the GaAs sample with the modulation frequencies of 228, 827, and 2467 Hz.

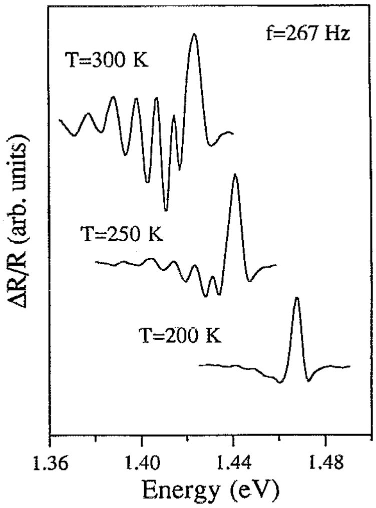

FIG. 4. Temperature dependence of the PR for the GaAs sample. The amplitude of the interference oscillation is seen to decrease as the temperature is lowered.

polarization and the amplitude reflection coefficients r and r' from the surface and interface, respectively. The intensity reflection coefficient, R, is given by the expression

$$R=r^2+2rr'(1-r^2)^2e^{-yk}\cos(yn+\delta)+r'^2(1-r^2)^2e^{-2yk}, \tag{1}$$

where n is the index of refraction, k denotes the extinction coefficient, δ is a phase factor, and y is the effective thickness given in terms of the wavelength, λ, the layer thickness, d, and the angle of refraction, θ_r:

$$y=2d\cos(\theta_r)\frac{2\pi}{\lambda}. \tag{2}$$

On the basis of Eq. (1) the modulation reflectivity can be approximated by replacing the reflection coefficient terms with Lorentzian forms[1] (L):

$$\frac{\Delta R}{R}\approx L_1+L_2e^{-yk}\cos(yn+\delta)+L_3e^{-2yk}. \tag{3}$$

The first term in Eq. (3) gives the modulated reflectance from the surface, the third term is caused by the reflectance from the substrate attenuated by the absorption in the epitaxial layer, and the second term is due to the interference. By using the published values for n and k,[8] Eq. (3) can be fitted to the PR spectra. As shown in Fig. 3 the calculated line shape fits quite well even near the E_0 transition.

From our results it is clear that the observation of the interference fringes is not dependent on the type of the substrate even though the PR line shape from an n-type substrate is usually the most likely to produce strong interferences. Because many of our samples with a strong interference effect were not heavily doped it seems that the modulation mechanism cannot be the band filling of impurity states. It is more probable that the modulation is caused by the Franz–Keldysh effect, i.e., the electric field strength at the interface is modulated by the trapped mobile charge. This charge is caused by the electron-hole pairs created by the absorption of the pump light near the surface. The surface states pin the Fermi level near the middle of the band gap. At the epilayer-substrate interface, however, the Fermi level is pinned close to the conduction band. Therefore, electrons tend to drift from the surface to the interface, where they slowly recombine with holes. The second possibility for the modulation is that the electron-hole pairs are created near the interface and are separated by the interface field. However, as has been pointed out by Kallergi *et al.*,[4] in thick epitaxial layers the intensity of the pump beam reaching the interface is so small that the direct modulation by electron-hole pairs created at the interface cannot be the modulation mechanism responsible for the interferences. In addition, we have also observed that illumination by a cw light source reduces the intensity of the interferences relative to the E_0 transition. The cw illumination reduces the surface electric field through the photovoltaic effect, whereas the effect on the interface field is negligible due to the small intensity of the 488 nm light penetrating to the interface. Therefore, the strength of the surface electric field affects directly the amplitude of the interference signal.

In conclusion, we have observed interferences in the photoreflectance spectra of epitaxial layers grown on semi-insulating GaAs and InP substrates. On the basis of the frequency and temperature dependence and the effect of cw illumination on the interference amplitude, we conclude that the modulation is due to electrons drifting from the surface to the interface.

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