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Photoreflectance Study of Electric Field Distributions in Semiconductors Heterostructures Grown on Semi-Insulating Substrates

H. SHEN

Geo-Center, Inc.
U.S. Army Electronics Technology and Device Laboratory
Ft. Monmouth, N.J. 07703

and

FRED H. POLLAK[a]

Physics Department
Brooklyn College of the City University of New York
Brooklyn, New York 11210

and

J.M. WOODALL

IBM Thomas J. Watson Research Center
Yorktown Heights, New York 10598

and

R. N. SACKS

United Technologies Research Center
E. Hartford, CT 06108

We have studied the photoreflectance (PR) spectra from a MBE grown heterostructure consisting of 200 nm of $Ga_{0.83}Al_{0.17}As$, a 800 nm GaAs buffer layer on a semi-insulating ⟨100⟩ LEC GaAs substrate. By varying both the pump beam wavelength and modulation frequency (up to 100 kHz) we are able to identify the component layers, their quality and the properties of the various interfaces. In this study we find evidence for a low density of interface states between the GaAs buffer layer and GaAlAs layer and a relatively large density of interface states between the substrate and buffer regions. These states, previously observed by Deep Level Transient Spectroscopy of doped structures, are presumably associated with the interface produced by MBE growth on etched and air exposed substrates. However, in our material, since the substrate is semi-insulating and the buffer layer is undoped, it is difficult to resolve these states spatially by C-V techniques. Our results show that the PR technique can be used to characterize low conductivity or semi-insulating structures such as enhancement mode MESFET and HEMT type devices and it may be useful for the in-situ characterization of epigrown surfaces and interfaces

Key words: Photoreflectance, heterostructure, interface states, semi-insulating substrate, GaAs/GaAlAs

I. INTRODUCTION

Photoreflectance (PR),[1] a contactless form of electromodulation, is a powerful tool to study the interface electric field distribution in semiconductor structures.[2–7] In PR the electric field in the material is modulated by the photo-injection of electron-hole pairs by a pump beam chopped at frequency Ω_m. It has been demonstrated that PR is indeed a form of electroreflectance yielding sharp, derivative-like spectra in the region of interband transitions in bulk or thin film semiconductors.[1–8] Since PR is the ac response of the system to the modulating electric field there is also important information in the other modulation parameters such as modulation frequency (Ω_m),[4–7] pump beam wavelength (λ_p),[7,9] pump beam intensity (I_p)[10], etc.

We have studied the PR spectra ($\Delta R/R$) at 300 K from a MBE grown $Ga_{0.83}Al_{0.17}As$/GaAs/GaAs (epilayer/buffer/substrate) heterostructure as a func-

[a]Also at Graduate School and University Center of the City University of New York; New York, NY 10036.

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tion of λ_p (820 nm–420 nm) and Ω_m (20 Hz-100 kHz). The sharp spectral features have allowed us to observe the direct band gaps of the various components of the structure. These are designated as E_o(A),E_o(B) and E_o(C) for the GaAlAs epilayer (region A), GaAs buffer (region B) and GaAs substrate (region C), respectively. For 420 nm pump radiation, which does not penetrate into either region B or C, we observe E_o(A) and E_o(B) but not E_o(C). All three peaks are seen for λ_p = 620 nm, which corresponds to an energy larger than E_o(A) and penetrates into region B but not into C. For λ_p = 820 nm the pump photon energy, (1.51 eV) is well below E_o(A) so that photoexcited electron-hole pairs are created in both the GaAs buffer and substrate regions. In this case the spectrum exhibits primarily E_o(C) with a small contribution from E_o(B). In addition E_o(A) and E_o(C) have different variations with Ω_m; the dependence of E_o(B) is related mainly to the modulation mechanism of region A with some contribution from region C. We interpret these results as evidence for a low density of interface states between the GaAs buffer layer and the GaAlAs epilayer and relatively large density of states between the substrate and buffer.

II. EXPERIMENTAL PROCEDURE

The heterostructure used in this study consisted of a 200 nm $Ga_{0.83}Al_{0.17}As$ epilayer grown on a 800 nm GaAs buffer on a semi-insulating (SI) ⟨100⟩ LEC GaAs substrate. All measurements were made at 300 K. The PR apparatus has been described in the literature.[11] However, in contrast to most previous PR experiments the source for λ_p was a Xenon arc filtered by a 1/4 meter monochromator[7,9] as well as a He-Ne laser. The intensity of the pump beam was about 2 mW. In all cases the observed lineshapes were independent of I_p indicating modulation in the low-field regime. A two-phase lock-in amplifier was used to record the in-phase and out-phase components of the PR signal relative to the phase of the pump beam. Measurements using the 633 nm line of the He-Ne laser were made up to 100 kHz using an acousto-optic modulation instead of a mechanical chopper (limit about 4000 Hz).[7] The experimentally measured variation of $\Delta R/R$ wiht Ω_m was normalized to the frequency dependence of the detector/amplifier/lock-in system to eliminate RC effects.

III. RESULTS AND DISCUSSION

Shown by the dotted line in Fig. 1 is the PR spectrum with λ_p = 420 nm and Ω_m = 200 Hz. The penetration depth d_o for the GaAlAs is 30 nm for this wavelength.[12] Hence, photoexcited carriers are created only in region A and not B or C. The configuration of the A, B and C regions of the sample as well as the region of absorption of λ_p (dashed vertical lines) are shown schematically in the lower portion of the figure. The solid line is a least-squares fit to the first-derivative of a Gaussian lineshape function.[13] Such a functional form is appropriate for bound states, such as excitons, at room temperature.[3,14]

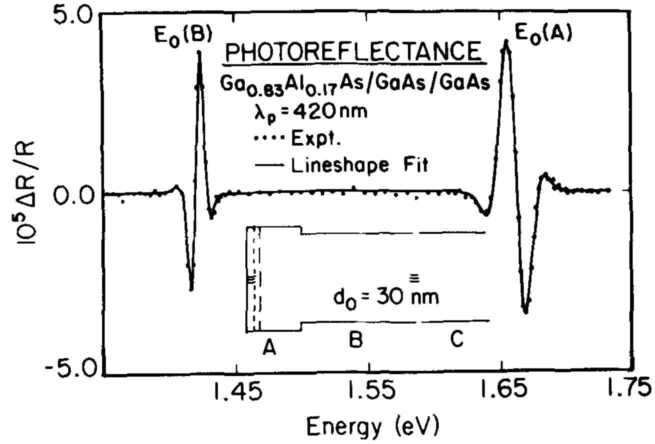

Fig. 1 — Photoreflectance signal vs photon energy for a GaAlAs/GaAs/GaAs structure (see text) for a pump beam wavelength of 420 nm.

The spectrum of Fig. 1 exhibits structure in the vicinities of the direct band gaps of GaAlAs and GaAs, which we denote as E_o(A) and E_o(B). The energies and broadening parameters are 1.662 eV, 8 meV and 1.420 eV, 4 meV, respectively. These values are comparable to those observed in other electromodulation experiments.[15,16] The position of E_o(A) enables us to determine the Al composition.[12,17]

Since d_o (GaAlAs) = 30 nm for this pump wavelength photo-excited carriers are created only in region A and not B or C. We can detect no substantial evidence for a signal originating in GaAs substrate (region C).

Displayed by the dotted line in Fig. 2 is the experimental PR spectrum for λ_p = 620 nm and Ω_m = 200 Hz. In this case d_o (GaAlAs) = 420 nm[12] and d_o (GaAs) = 240 nm.[18] Thus, electron-hole pairs are created in regions A and B but not C as shown schematically by the dashed vertical lines. The solid line

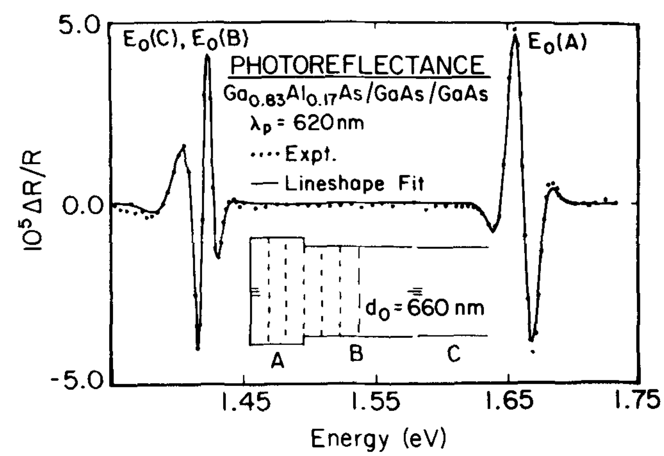

Fig. 2 — Photoreflectance signal vs photon energy for a GaAlAs/GaAs/GaAs structure (see text) for a pump beam wavelength of 620 nm.

is a least-square fit to the first-derivative of a Gaussian profile. In addition to E_o(A) and E_o(B), the lineshape fit indicates one more oscillator, E_o(C) at an energy of 1.413 eV with a linewidth of 11 meV. The features E_o(C) and E_o(B) originate in the GaAs substrate and buffer, respectively. The narrower linewidth for the E_o(B) is probably due to the better quality of MBE grown material in relation to bulk GaAs.

The experimental data for λ_p = 820 nm and Ω_m = 200 Hz is shown by the dotted line in Fig. 3. For this value of λ_p the GaAlAs is transparent and the penetration depth in GaAs is 830 nm.[18] The solid line is a least-square fit to the first derivative of a Gaussian lineshape form. In this fit, the energies and broadening parameters for E_o(B) and E_o(C) are fixed at the values given above. Only the oscillator strengths are variables. We found E_o(B) is only about 18% of E_o(C).

In Fig. 4 we have plotted the modulation frequency (Ω_m) dependence of the amplitude of the in-phase component of the various PR structures. The variation of E_o(A) and E_o(B) was evaluated from the spectrum produced by the 633 nm pump radiation from a He-Ne laser and an acousto-optic modulator as chopper. We have found that the spectrum for λ_p = 633 nm is very similar to Fig. 2. Since the feature around 1.42 eV has a contribution from E_o(B) that is 3 times larger than E_o(C) we have evaluated the Ω_m dependence of E_o(B) from the high energy side (1.43 eV) of this structure. The behavior of E_o(C) was taken from Ref. 7.

The dependence of $\Delta R/R$ with Ω_m can be accounted for on the basis of the following considerations. The chopped pump radiation can be considered as a square wave source. When light impinges on the sample, electron-hole pairs are created. These charges are then free to fill traps and modify the electric field strength. We assume that these excess carriers change the built-in field in a response time much faster than the shortest characteristic time of our modulation.[1] When the light is switched off, the trap population and hence electric-field strength are restored with a characteristic time τ. For chopping frequency Ω_m it can be shown that the Fourier transform of the in-phase component of the PR intensity, $[\Delta R(\Omega_m)/R]_{\text{in-phase}}$, is given by:[17,19]

$$[\Delta R(\Omega_m)/R]_{\text{in-phase}} = \sum_{L=1}^{n}[\Delta R(o)/R]\cdot f(\Omega_m\tau_i) \quad \text{(1a)}$$

$$f(\Omega_m\tau_i) = \{1 + 2\pi^2(\Omega_m\tau_i)^2 \cdot[1 - \exp(1 - {}^2/\Omega_m\tau_i)]\}/[1 + 4\pi^2(\Omega_m\tau_i)^2] \quad \text{(1b)}$$

when τ_i is the characteristic time constant of the i^{th} trap state and $[\Delta R(0)/R]_i$ is the PR signal produced by the modulation of the i^{th} trap state in the limit of $\Omega_m\tau_i \ll 1$. It can be shown that in order to employ the principle of superposition of the contribution of states with different trap times it is necessary to consider the in-phase component of $\Delta R(\Omega_m)/R$, not the amplitude.[19]

The solid lines in Fig. 4 are least-squares fits of Eq. (1) to the experimental data. The E_o(A) feature contains a contribution from only one time constant, τ_1(A) = 47 μs. This time constant was too fast to be observed in Ref. 7 for which Ω_m went only to 4000 Hz because of the limitations of the mechanical chopper. The behavior of E_o(C)is also determined by only one time constant with τ_1(C) = 0.33 ms, as reported in Ref. 7. However, E_o(B) contains contributions from two trap mechanisms with τ_1(B) = 45 μs and τ_2(B) = 0.37 ms as first suggested by our previous work.[7] The various τ_i for E_o(A), E_o(B) and E_o(C) are listed in Table I. For E_o(B) the ratio of the two contributions $[\Delta R(0)/R]_1/[\Delta R(0)/R]_2$ = 1.6. Thus, the main mechanism for the modulation of the GaAs buffer layer is from the fast states [τ_i(B) = 45 μs] associated with the GaAlAs with some contribution from the slower state. The latter is the modulation mechanisms for E_o(C) and probably originates in the interface states between the buffer and substrate since MBE grown GaAs does not have any bulk trap states.

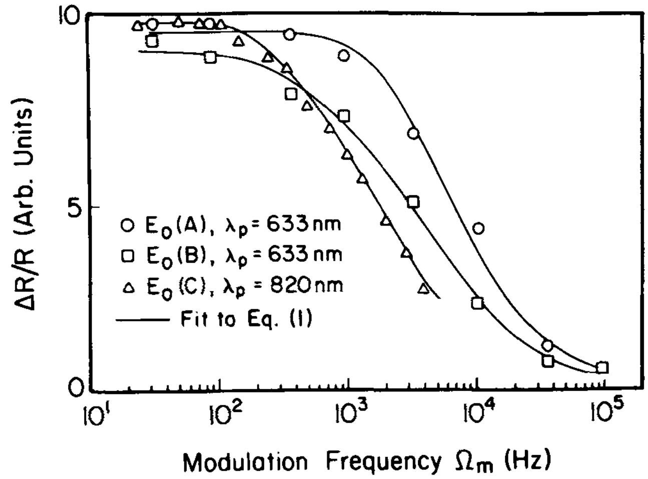

Fig. 4 — Photoreflectance signal vs pump beam modulation frequency, Ω_m.

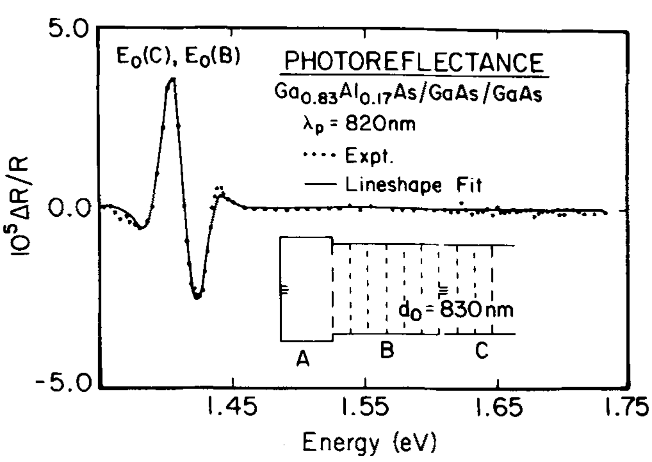

Fig. 3 — Photoreflectance signal vs photon energy for a GaAlAs/GaAs/GaAs structure (see text) for a pump beam wavelength of 820 nm.

Table I. Values of τ_i for E_o(A), E_o(B) and E_o(C)

Feature	$\tau_i(\mu s)$
$E_o(A)^{(a)}$	47 (i = 1)
$E_o(B)^{(a)}$	45 (i = 1)
	370 (i = 2)
$E_o(C)^{(b)}$	330 (i = 1)

(a) λ_p = 633 nm.
(b) λ_p = 820 nm.

In conclusion we have used the PR technique to characterize an undoped GaAlAs/GaAs/GaAs heterostructure. By varying both the wavelength of the pump beam and its modulation frequency, we are able to identify the component layers, their quality and the properties of the various interfaces. By using an acousto-optic modulator we have been able to make measurements up to 100 kHz. This has allowed us to obtain information about trap states with time constants as fast as about 40 μs. We believe that this technique applied to undoped or low conductivity structures to be complementary to electrical modulation techniques, *e.g.* electroreflectance, DLTS, etc., which are usually applied to conducting structures.

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