Electric field distributions in a molecular-beam epitaxy Ga$_{0.83}$Al$_{0.17}$As/GaAs/GaAs structure using photoreflectance

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We have studied the photoreflectance (PR) spectra from a molecular-beam epitaxially (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 (SI) (100) (LEC) GaAs substrate. By varying both the pump beam wavelength and modulation frequency we are able to identify the component layers, their quality, and the quality of the various interfaces. In this study we find evidence for a low density of interface states between the GaAs buffer layer and the GaAlAs layer, and a relatively large density of interface states, between the substrate and buffer layers. These states, previously observed by deep-level transient spectroscopy (DLTS) of doped structures, are presumably associated with the interface produced by MBE growth on etched and air exposed substrates. However, in our experiment 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 metal-semiconductor field effect transistor (MESFET) and high electron mobility transistor (HEMT) type devices and it may be useful for the in situ characterization of epigrown surfaces and interfaces.

I. INTRODUCTION

Photoreflectance,\textsuperscript{1} a contactless form of electromodulation, is a powerful tool to study the interface electric field distribution in semiconductor structures.\textsuperscript{2-5} In photoreflectance (PR) the electric field in the material is modulated by the photoionization of electron–hole pairs by a pump beam chopped at frequency $\Omega_m$. It has been demonstrated that PR is indeed a form of electoreflectance yielding sharp, third-derivative spectra in the region of interband transitions in bulk or thin-film semiconductors.\textsuperscript{1-5} 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 ($\Omega_m$),\textsuperscript{6,7} pump beam wavelength ($\lambda_p$),\textsuperscript{8} pump beam intensity ($I_p$), etc.

We have studied the PR spectra at 300 K from a molecular-beam epitaxially (MBE) grown Ga$_{0.83}$Al$_{0.17}$As/GaAs/GaAs (epilayer-buffer/substrate) heterostructure as a function of $\lambda_p$ (820–420 nm) and $\Omega_m$ (20–4000 Hz). The sharp spectral features have allowed us to observe the direct band gaps of the various components of the structure. These are designated $E_o(A)$, $E_o(B)$, 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 $\lambda_p = 620$ nm, which corresponds to an energy larger than $E_o(A)$ and penetrates in region B but not into C. When the pump photon energy (1.51 eV) is well below $E_o(A)$ 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 $\Omega_m$: 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 a 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) liquid encapsulated Czochralski (LEC) GaAs substrate. All measurements were made at 300 K. The PR apparatus has been described in the literature.\textsuperscript{1}\textsuperscript{1} However, in contrast to most previous PR experiments the source for $\lambda_p$ was a Xenon arc filtered by a one-quarter meter monochromator instead of a He–Ne laser.\textsuperscript{9} The intensity of the pump beam was ~2 mW. In all cases the observed line shapes 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. The range of modulating frequency was limited by the properties of the mechanical chopper.

III. RESULTS AND DISCUSSION

Shown by the dotted line in Fig. 1 is the PR spectrum with \( \lambda_p = 820 \) nm and \( \Omega_m = 200 \) Hz. For this value of \( \lambda_p \) the GaAlAs is transparent and the penetration depth \( (d_0) \) in GaAs is 830 nm. The solid line is a least-squares fit to the Asnnes low-field third-derivative functional form for a direct band gap.\(^5\)

\[
\Delta R / R = \text{Re} \left[ A e^{i \phi (E - E_0 + i \Gamma)} \right]^{-3/2},
\]

where \( A \) is the amplitude, \( \phi \) is a phase factor, \( E \) is the photon energy, \( E_0 \) is the energy gap, and \( \Gamma \) is the broadening parameter. The line shape fit yields \( E_0 \) and \( \Gamma \) as well as the amplitude \( A \).

In Eq. (1) the amplitude \( A \) can be expressed as:

\[
A = e^{\frac{e \phi F^2}{8 m^*}}
\]

where \( F \) is the modulating electric field, \( m^* \) is the reduced interband effective mass in the direction of \( F \), and \( F \) is a function of pump beam parameters such as \( \lambda_p \), \( \Omega_m \), and \( I_p \). Thus, Eqs. (1) and (2) demonstrate that PR signals contain information not only in the sharp, derivative-like spectral features but also can be used as an optical probe of interface electric fields.

The spectrum of Fig. 1 exhibits structure in the vicinity of the direct band gap of GaAs but no signal is observed in the GaAs substrate and buffer, respectively. The features \( E_{0(C)} \) and \( E_{0(B)} \) originate in the GaAs substrate and buffer, respectively. The narrower linewidth for the latter peak is probably due to the better quality of MBE grown material in relation to bulk GaAs.

Displayed by the dotted line in Fig. 2 is the experimental PR spectrum for \( \lambda_p = 620 \) nm and \( \Omega_m = 200 \) Hz. In this case \( d_0(\text{GaAlAs}) = 420 \) nm (Ref. 12) and \( d_0(\text{GaAs}) = 240 \) nm.\(^6\) Thus, electron-hole pairs are created in regions A and B but not C. The solid line is a least-square fit to Eq. (1). In addition to \( E_{0(C)} \) and \( E_{0(B)} \), which have a ratio of \(-1/3\), we also observe \( E_{0(A)} \) at an energy of 1.662 eV with \( \Gamma = 8 \) meV. The position of \( E_{0(A)} \) enables us to determine the Al composition.\(^{12,13}\)

The experimental data for \( \lambda_p = 420 \) nm and \( \Omega_m = 200 \) Hz is shown by the dotted line in Fig. 3. Since \( d_0(\text{GaAlAs}) = 30 \) nm (Ref. 12) for this pump wavelength photoexcited carriers are created only in region A and not B or C. The solid line is a least-square fit to Eq. (1). Only two peaks, \( E_{0(B)} \) and \( E_{0(A)} \), are observed in this experimental condition. We can detect no substantial evidence for \( E_{0(C)} \) in the line shape \(-1.42 \) eV.

In Fig. 4 we have plotted the modulation frequency \( (\Omega_m) \) dependence of the amplitude of the in-phase component of the various PR structures. Since \( \lambda_p = 420 \) nm produces \( E_{0(A)} \) and \( E_{0(B)} \) with no evidence for \( E_{0(C)} \), the data for the former two peaks were evaluated at this pump wavelength. We have detected no spectra with only \( E_{0(C)} \) and

![Fig. 1. Photoreflectance signal vs photon energy for GaAlAs/GaAs/GaAs structure (see the text) for a pump beam wavelength of 820 nm.](image1)

![Fig. 2. Photoreflectance signal vs photon energy for GaAlAs/GaAs/GaAs structure (see the text) for a pump beam wavelength of 620 nm.](image2)

![Fig. 3. Photoreflectance signal vs photon energy for GaAlAs/GaAs/GaAs structure (see the text) for a pump beam wavelength of 420 nm.](image3)

![Fig. 4. Photoreflectance signal vs pump beam modulation frequency.](image4)
hence for this feature the variation with \( \Omega_{m} \) was recorded using \( \lambda = 820 \text{ nm} \) since \( E_{0}(B) \) produces only an 18% contribution.

The dependence of \( \Delta R/R \) with \( \Omega_{m} \) can be accounted for on the basis of the following considerations. The chopped pump radiation can be considered as a square-wave source. 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 (\( \sim 0.04 \text{ ms} \)). When the light is switched off, the trap population and hence electric-field strength are restored with a characteristic time \( \tau_{c} \).

Since the maximum signal produced by the \( \Omega_{m} \) can be shown that the Fourier transform of the in-phase component of the PR intensity, \( \Delta R(\Omega_{m})/R \), is given by:

\[
\Delta R(\Omega_{m})/R \propto \sum_{\tau} \left( f(\Omega_{m}, \tau_{i}) \right) \exp \left( -2 \pi \nu \tau_{i} \right) \exp \left( -2 \pi \nu \tau \right)
\]

where \( \tau_{i} \) is the characteristic time constant of the \( i \)-th trap state. For multiple trap states with different trap times it is necessary to consider the in-phase component of \( \Delta R(\Omega_{m})/R \), not the amplitude.\(^{1,4,5}\)

If we assume that \( \Omega_{m} \gg 1 \), for \( i > 2 \), where \( \Omega_{m} \) is the maximum \( \Omega_{m} \), then Eq. (3a) can be written in the simplified form

\[
\Delta R(\Omega_{m})/R \propto A_{i} f(\Omega_{m}, \tau_{i}) + A_{0}
\]

where \( A_{i} = \Delta R(0)/R \), and \( A_{0} \) represents the contribution of states with faster than \( \tau_{i} \). Since the maximum \( \Omega_{m} \) in our experiment is 4000 Hz the fastest \( \tau_{i} \) we can detect is \( \sim 0.04 \text{ ms} \). States with faster trap times make a small contribution to the out-of-phase signal in the frequency range of our investigation.

The solid lines in Fig. 4 are least-squares fit of Eq. (3c) to the experimental data. The observed values of \( \tau_{i}, A_{i}, \) and \( A_{0} \) are listed in Table 1. The \( E_{0}(A) \) feature has essentially a flat response in our range of \( \Omega_{m} \) indicating a trap state whose \( \tau \lesssim 0.04 \text{ ms} \). The values of \( A_{i} \) and \( A_{0} \) for \( E_{0}(B) \) indicate that the main mechanism for the modulation of this structure is from these fast states with some contribution from a 0.3-ms state. The latter is the modulation mechanism for \( E_{0}(C) \) and probably originates in the interface state between the buffer and substrate.

<table>
<thead>
<tr>
<th>Feature</th>
<th>( \tau_{i} ) (ms)</th>
<th>( A_{i} )</th>
<th>( A_{0} )</th>
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<tbody>
<tr>
<td>( E_{0}(A) )(^{*})</td>
<td>0.04</td>
<td>0</td>
<td>4.2</td>
</tr>
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<td>( E_{0}(B) )(^{*})</td>
<td>0.32</td>
<td>1.0</td>
<td>3.2</td>
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<td>( E_{0}(C) )(^{**})</td>
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<td>2.7</td>
<td>0.8</td>
</tr>
</tbody>
</table>

\(^{*}\lambda = 820 \text{ nm} .\)

\(^{**}\text{Small contribution from } E_{0}(B) .\)

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15. In Eq. (1b) of Ref. 5, \( \Delta R(\Omega_{m})/R \) is the magnitude of the PR signal, which is the square root of the sum of the squares of the in-phase and out-of-phase signals. This quantity does not obey the principle of superposition. Thus, it is rigorously correct only for a single trap state. For multiple trap states it is necessary to evaluate the frequency dependence of the in-phase component (with respect to the pump beam) in order to employ the superposition of different contributions.