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Electroreflectance and photoreflectance study of the space-charge region in semiconductors: (In-Sn-O)/InP as a model system

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We have investigated the electroreflectance (ER) and photoreflectance (PR) spectra from the space-charge region (SCR) of the model Schottky- barrier system $(In_2O_3)_{0.91}(SnO_2)_{0.09}$ on *p*-type InP [(In-Sn-O)/InP]. Both ER and PR were studied as a function of reverse dc bias, V_{bias}. The observed Franz-Keldysh oscillations provide a direct measure of the surface dc electric field, $\mathcal{E}^s_{dc}$. The ac modulating voltage (for small modulation) affects only the envelope of the FKO but not the period. A generalized Franz-Keldysh theory, taking into consideration the presence of dc fields, accounts for the above experimental results. From a plot of $(\mathcal{E}^s_{dc})^2$ as a function of V_{bias} we have obtained the built-in potential and net carrier concentration of the structure. Our work demonstrates that electromodulation in Schottky barriers can be used as an optical Mott-Schottky method.

I. INTRODUCTION

Modulation spectroscopy,[1-6] particularly electromodulation, is becoming an important tool to study semiconductors (bulk or thin film),[1-9] semiconductor structures (superlattices, quantum wells, heterojunctions)[10-24] and semiconductor interfaces (Schottky barriers, metal-insulator-semiconductor systems, semiconductor-electrolyte systems, etc.).[1-3,5,6,25-30] Electromodulation is the most useful of the modulation methods since it yields, in general, the sharpest structure[31] and is sensitive to surface (interface) electric fields.[1-3,5,6,25-30] Most of the work in electromodulation has utilized the former aspect, i.e., the sharpness of the structure and its line shape. Relatively little work has been done in the latter area, i.e., electromodulation as an optical probe of surface or interface electric fields.

Electromodulation can be produced by applying the electric field in a contact mode[1-3,5,6] [referred to as electroreflectance (ER)] such as Schottky barrier, metal-insulator-semiconductor, semiconductor-electrolyte, etc., or the contactless method of photoreflectance (PR).[16,32,33] In PR electromodulation is achieved by the photoinjection of electron-hole pairs by a secondary (pump) beam. Because it is a contactless technique, and hence nondestructive, PR is being widely used to study semiconductor structures such as superlattices, quantum wells, and heterojunctions.[16-23] Also because of its contactless nature PR may prove to be an extremely valuable technique for the *in situ* characterization of semiconductors, semiconductor structures, and semiconductor interfaces.

All published theories of the electric-field-induced changes in the dielectric function of a solid have considered only modulation from the flatband condition,[1-4] i.e., the difference in the dielectric function with finite field and zero field. These approaches have not taken into account the presence of a dc electric field, either built-in or externally applied. For example, the space-charge region (SCR) of a semiconductor may have dc fields as large as 10^4-10^6 V/cm.[34]

In this paper we present an experimental and theoretical study of electromodulation, both ER and PR, under conditions of large dc electric fields in the SCR of a semiconductor. The experiments were performed on the model Schottky-barrier system of indium-tin-oxide material on *p*-type InP [(In-Sn-O)/InP]. Both our experiments and calculations show that for $\mathcal{E}_{ac}/\mathcal{E}_{dc} \lesssim 0.15$ [where $\mathcal{E}_{ac}$ and $\mathcal{E}_{dc}$ are the ac (modulating) and dc electric fields, respectively] the period of the observed Franz-Keldysh oscillations (FKO), is related to $\mathcal{E}_{dc}$, while the envelope function is determined by $\mathcal{E}_{ac}/\mathcal{E}_{dc}$. This is in contrast to most former electromodulation studies (both theory and experiment) in which only modulation from flatband was considered so that the FKO were determined by $\mathcal{E}_{ac}$.[1-5] Our work shows that electromodulation can be used as an optical Mott-Schottky method and that in these structures the mechanism of PR is indeed a form of ER.[30]

II. EXPERIMENTAL DETAILS

The sample for this study consisted of 650 Å of $(In_2O_3)_{0.91}(SnO_2)_{0.09}$ on the ⟨100⟩ surface of *p*-type InP (Zn-doped) with a nominal net carrier concentration of 1.6×10^{16} cm^{-3}. The surface was prepared by polishing with 1-μm diamond paste and then by 0.3 and 0.05-μm alumina polishing powder, respectively. This was followed by a chemo-mechanical polish in 0.05-mol % Br_2–methanol mixture and a rinse in NH_4OH. The In-Sn-O (ITO) was deposited by ion-beam sputtering and had a carrier concentration of about 10^{21} cm^{-3}. The ITO-InP interface forms a good Schottky barrier and has the advantage that ITO is transparent in the visible region of the spectrum. All experiments were performed at room temperature.

A schematic representation of the experimental arrangement for ER is shown in Fig. 1. Light from an appropriate lamp source passes through a monochromator (probe monochromator). The exit radiation at wavelength λ is focused onto the sample by means of a lens (or mirror). The intensity of the light striking the sample is designated $I_0(\lambda)$. Electromodulation of the sample is produced by V_{ac} at frequency Ω_m. In addition, the electric field in the SCR can be altered by means of the dc voltage, V_{bias}. In our case V_{ac} was a square-wave potential at a frequency of 220 Hz. The reflected beam is collected by a second lens (or mirror) and focused onto a detector, which in our case was a Si photodiode. For the sake of simplicity we have not shown the two lenses (mirrors).

The light striking the detector contains two signals: the dc (or average value) is given by $I_0(\lambda)R(\lambda)$, where $R(\lambda)$ is the dc reflectance of the material, while the modulated value (at frequency Ω_m) is $I_0(\lambda)\Delta R(\lambda)$, where $\Delta R(\lambda)$ is the modulated reflectance. The ac signal from the detector, proportional to $I_0 \Delta R$, is measured by a lock-in amplifier. In order to evaluate the quantity of interest $\Delta R(\lambda)/R(\lambda)$ a normalization procedure must be used to eliminate the uninteresting common feature I_0. In Fig. 1 normalization is achieved by a new procedure.[35] A variable neutral-density filter (VNDF) connected to a servomotor is placed in the optical path after the probe monochromator. The dc signal from the detector is used as input to the servo motor which varies the VNDF and hence $I_0(\lambda)$ in order to keep this dc signal a constant. Thus, in our procedure the operating conditions of the experiment, i.e., detector amplification, instrumental resolution, etc., are kept constant.

In PR, a contactless form of electromodulation, the electric field in the SCR of the semiconductor (or semiconductor structure) is modulated by photoinjected electron-hole pairs created by a secondary (pump) light source. This is shown schematically in Fig. 2. In many cases this pump beam is from a laser although a second monochromator and light source may also be employed.[11] For our experiment the PR pump source was a 1-mW He-Ne (6328-Å) laser chopped at 220 Hz (Ω_m). For the PR study the dc field in the SCR also was varied by means of an externally applied dc bias (V_{bias}) across the ITO/InP Schottky barrier.

III. THEORETICAL BACKGROUND

We now consider the situation in which the dielectric function of the semiconductor is modulated by an ac electric field, $\mathcal{E}_{ac}$, in the presence of a large dc electric field, $\mathcal{E}_{dc}$. This latter field can be due to either a built-in potential, such as that related to Fermi-level pinning, or can be externally applied. In our treatment we neglect any broadening effects. Within this context we will calculate the change in the dielectric function $\delta\epsilon(E,\mathcal{E}_{dc},\mathcal{E}_{ac})$ due to the modulating ac field in the presence of the dc field. The photon energy is denoted by E.

The function $\delta\epsilon(E,\mathcal{E}_{dc},\mathcal{E}_{ac})$ can be written as

$$\delta\epsilon(E,\mathcal{E}_{dc},\mathcal{E}_{ac})$$

$$=\epsilon(E,\mathcal{E}_{dc}+\mathcal{E}_{ac})-\epsilon(E,\mathcal{E}_{dc}-\mathcal{E}_{ac}) \tag{1a}$$

$$=\Delta\epsilon(E,\mathcal{E}_{dc}+\mathcal{E}_{ac})-\Delta\epsilon(E,\mathcal{E}_{dc}-\mathcal{E}_{ac}) , \tag{1b}$$

where

$$\Delta\epsilon(E,\mathcal{E})=\epsilon(E,\mathcal{E})-\epsilon(E,0) . \tag{1c}$$

It has been shown that for an M_0 critical point the quantity $\Delta\epsilon(E,\mathcal{E})$ of Eq. (1c) can be written as [1,2,5]

$$\Delta\epsilon(E,\mathcal{E})=(B/E^2)\theta^{1/2}[G(\eta)+iF(\eta)] , \tag{2a}$$

where the quantity B (related to matrix element effects) is

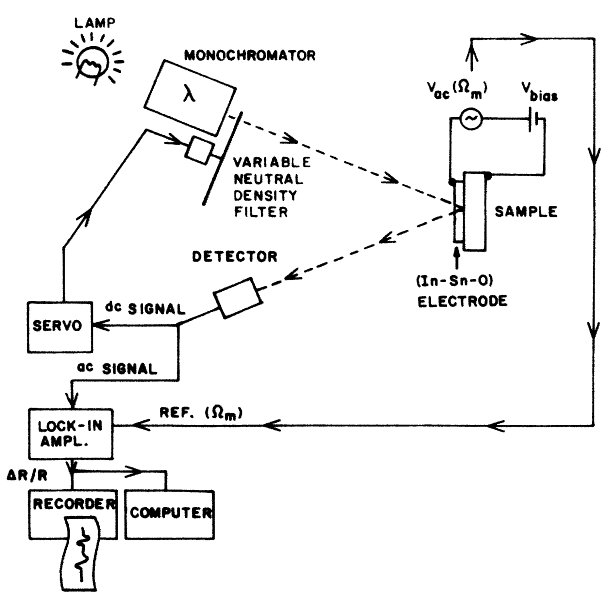

FIG. 1. Schematic representation of the electroreflectance apparatus.

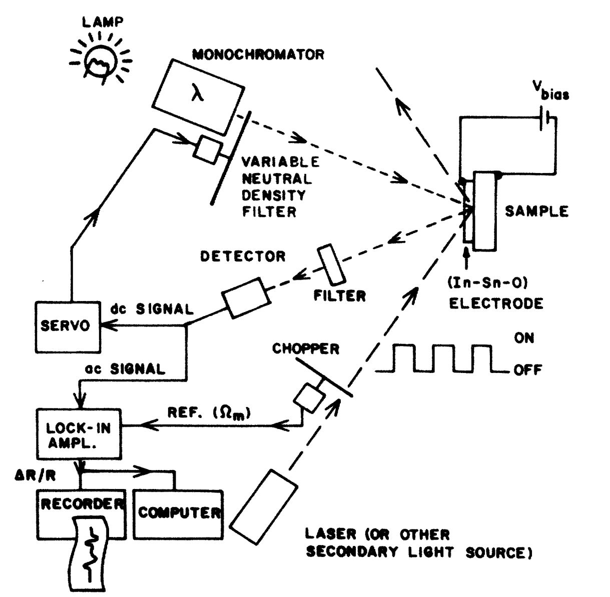

FIG. 2. Schematic representation of the photoreflectance apparatus.

defined on p. 172 in Ref. 1. The parameters $\hbar\theta$ and η are

$$(\hbar\theta)^3 = e^2\hbar^2\mathcal{E}^2/2\mu_{\parallel} , \tag{2b}$$

$$\eta = (E_g - E)/\hbar\theta , \tag{2c}$$

where $\mu_{\parallel}$ is the reduced interband effective mass in the direction of $\vec{\mathcal{E}}$, and E_g is the energy gap. The parameters $G(\eta)$ and $F(\eta)$ are electrooptic functions given by[1]

$$F(\eta) = \pi[\mathrm{Ai}'^2(\eta) - \eta\,\mathrm{Ai}^2(\eta)] - (-\eta)^{1/2}H(\eta) , \tag{2d}$$

$$G(\eta) = \pi[\mathrm{Ai}'(\eta)\mathrm{Bi}'(\eta) - \eta\,\mathrm{Ai}(\eta)\mathrm{Bi}(\eta)] + \eta^{1/2}H(\eta) . \tag{2e}$$

In Eqs. (2d) and (2e) $\mathrm{Ai}(\eta)$, $\mathrm{Bi}(\eta)$, $\mathrm{Ai}'(\eta)$, and $\mathrm{Bi}'(\eta)$ are Airy functions and their derivatives and $H(\eta)$ is the unit step function.[1] By neglecting broadening effects we are in the regime where $\Gamma \ll \hbar\theta$, where Γ is a phenomenological broadening parameter.

We now consider the general case in which $\mathcal{E}_{ac} < \mathcal{E}_{dc}$. Several approximations and assumptions will be made. We denote as z the distance into the SCR as measured from the surface and as ρ the net charge density. For p-type material $\rho = e(N_A - N_D)$, where N_A and N_D are the acceptor and donor concentrations, respectively. Also we assume that no significant free carriers are created either in ER or PR, i.e., ρ remains a constant. For the SCR the abrupt junction approximation is made so that $\mathcal{E}(z)$ is a linear function of z given by[36]

$$\mathcal{E}(z) = \mathcal{E}^s[(W - z)/W] \tag{3a}$$

$$= (4\pi\rho/\epsilon_0)(W - z) , \tag{3b}$$

where $\mathcal{E}^s$ is the surface electric field and W is the width of the SCR.

In the nonuniform field regime the quantity $\delta\epsilon(E, \mathcal{E}_{dc}, \mathcal{E}_{ac})$ can be expressed as[37]

$$\delta\epsilon(E,\mathcal{E}_{dc},\mathcal{E}_{ac}) = 2iK \int dz\, e^{-iKz}\Delta\epsilon(E,\mathcal{E}_{dc},\mathcal{E}_{ac}) , \tag{4}$$

where K is the complex propagation vector of the light in the solid. We next assume that K is real and that $KW \ll 1$. These are reasonable assumptions in the vicinity of a direct gap of a semiconductor such as InP (or GaAs).

From the linear relationship between $\mathcal{E}$ and z we can change variables from dz to $d\mathcal{E}$. It can be shown that Eq. (4) is given by

$$\delta\epsilon(E,\eta_{dc},\xi) = (-2iK\epsilon_0/4\pi\rho)(B/E^2)(e\hbar^2/2\mu_{\parallel})^{1/6} \times (\mathcal{E}^s_{dc})^{1/3}(\mathcal{E}^s_{ac}) \times [\tilde{F}(\eta_{dc},\xi) - i\tilde{G}(\eta_{dc},\xi)] , \tag{5}$$

where $\mathcal{E}^s_{dc}$ and $\mathcal{E}^s_{ac}$ are the surface dc and ac electric fields, respectively. The other quantities in Eq. (5) are given by

$$\tilde{F}(\eta^s_{dc},\xi) = (1/2\xi)\int_{1-\xi}^{1+\xi} \chi^{1/3}F(\eta^s_{dc}/\chi^{2/3})d\chi , \tag{6a}$$

$$\tilde{G}(\eta^s_{dc}\xi) = (1/2\xi)\int_{1-\mathcal{E}}^{1+\mathcal{E}} \int \chi^{1/3}G(\eta^s_{dc}/\chi^{2/3})d\chi , \tag{6b}$$

where

$$\eta^s_{dc} = (E_g - E)/\hbar\theta^s_{dc} , \tag{7a}$$

$$(\hbar\theta^s_{dc})^3 = e^2\hbar^2(\mathcal{E}^s_{dc})^2/2\mu_{\parallel} , \tag{7b}$$

$$\xi = \mathcal{E}^s_{ac}/\mathcal{E}^s_{dc} , \tag{7c}$$

$$\chi = \mathcal{E}/\mathcal{E}^s_{dc} . \tag{7d}$$

The electromodulated reflectivity $\Delta R/R$ can be written as

$$\Delta R/R = \alpha\delta\epsilon_1 + \beta\delta\epsilon_2 , \tag{8}$$

where α,β are the Seraphin coefficients and $\delta\epsilon_1$ and $\delta\epsilon_2$ are the real and imaginary components of $\delta\epsilon$, respectively.

Plotted in Fig. 3 are $\tilde{F}(\eta,\xi)$ and $\tilde{G}(\eta,\xi)$ as generated from a numerical integration of Eqs. (6a) and (6b) for values of $\xi = 0.01$ (solid line), 0.10 (dashed line), and 0.15 (dotted line). For the range of η shown the period of the FKO are the same for the former two values of ξ although the envelope function is affected. The reason for the dependence of the envelope function on ξ is the inhomogeneous nature of the electric field. For $\xi = 0.15$ the FKO period becomes different for $\eta \geq 5$ in relation to the $\xi = 0.01$ and $\xi = 0.10$ cases. It should be pointed out that in comparing $\xi = 0.01$ and $\xi = 0.10$ for values of η larger than those plotted in Fig. 3 the periods of the FKO begin to exhibit small variations because of the finite values of ξ. It is important to note that for the approximations made in evaluating Eq. (4) and under the condition that $\xi \lesssim 0.15$ the FKO are related to the *dc surface electric field*, not the average electric field in the SCR.[30]

Reference 1 reports that Aspnes has evaluated the averages of $F(\eta)$ and $G(\eta)$ for the case of the linear electric field in the Schottky barrier. However, this calculation also involves only modulation from flatband and does not consider the effects of a large dc electric field.

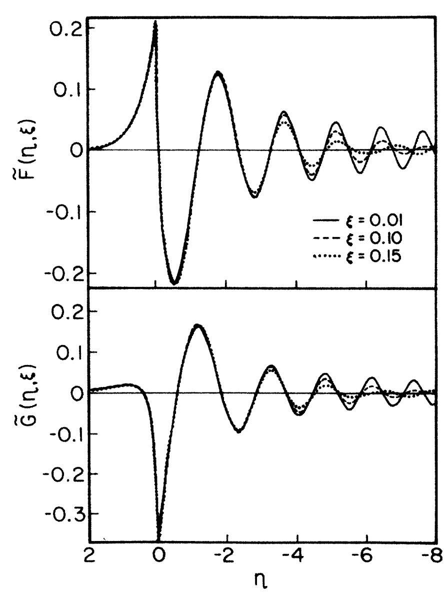

FIG. 3. Theoretical values of the electrooptic functions $\tilde{F}(\eta,\xi)$ and $\tilde{G}(\eta,\xi)$ for $\xi = 0.01$ (solid line), $\xi = 0.10$ (dashed line), and $\xi = 0.15$ (dotted line).

IV. EXPERIMENTAL RESULTS AND INTERPRETATION

Plotted in Fig. 4 are the ER spectra of the ITO/InP Schottky barrier in the region of the direct gap (E_0) of InP at 300 K for $V_{\text{bias}}=6.0$ and two values of the modulating voltage (V_{ac}), i.e., $V_{\text{ac}}=0.1$ V (solid line) and $V_{\text{ac}}=1.0$ V (dashed line). Note that the former curve has been amplified by a factor of 10. We shall return to this difference later. Since the sample is *p* type it is under reverse bias for this sign of V_{bias}. The features labeled *A*, *B*, and *C* are due to excitonic effects in a portion of the SCR where the electric fields are low enough not to quench the exciton. Similar phenomenon have been reported for 300 K electrolyte electroreflectance in GaAs (Ref. 38) and have been discussed further by Kisilev.[39] We shall return to these features later.

The peaks labeled $D-O$ are the FKO originating in the SCR. Note that the extrema in the FKO are unaffected by the change in the modulating voltage. However, the envelope function is influenced by V_{ac}, the higher value leading to a more rapid damping of the FKO.

In Fig. 5 are displayed the ER spectra for the case in which the modulating voltage is kept constant ($V_{\text{ac}}=0.1$ V) and the dc bias is changed. The solid line corresponds to $V_{\text{bias}}=10.0$ V while the dashed line represents $V_{\text{bias}}=1.0$ V. Because of the complexity of this figure we have labeled the features of the latter spectrum with primes. Again $A\,(A')$, $B\,(B')$, and $C\,(C')$ are due to the exciton. The other extrema, i.e., $D-N$ for $V_{\text{bias}}=10.0$ V, and $D'-M'$ for $V_{\text{bias}}=1.0$ V again are the FKO. In this particular case the position of the extrema are changed because of the difference in V_{dc}. However, as in Fig. 4 the larger ratio of $V_{\text{ac}}/V_{\text{bias}}$ produces a more rapid damping of the FKO.

Shown in Fig. 6 are the PR spectra at 300 K of the ITO/InP sample at $V_{\text{bias}}=0$ for pump power densities of 1.4 mW/cm^2 (solid line) and 4.0 mW/cm^2 (dashed line), where the former curve has been amplified by a factor of

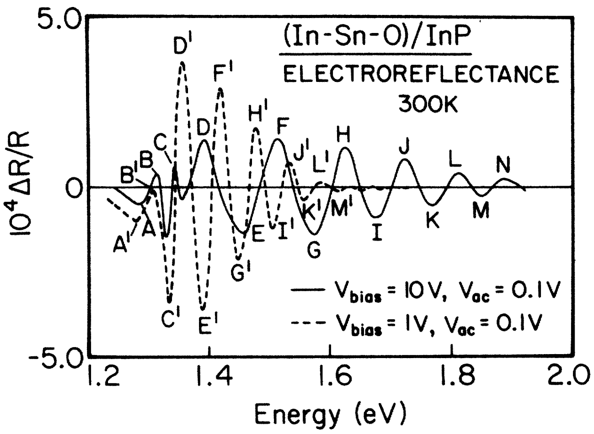

FIG. 5. Experimental electroreflectance spectra for $V_{\text{ac}}=0.1$ V with $V_{\text{bias}}=10.0$ V (solid line) and $V_{\text{bias}}=1.0$ V (dashed line).

2.7. The line shape of the two curves and hence the FKO, are identical. This shows that under these conditions the ac modulating field is very small compared to the built in dc field ($V_{\text{bias}}=0$).

Displayed in Fig. 7 are the PR spectra at 300 K of the ITO/InP sample using the 6328-Å line of a He-Ne laser as the pump (4.0 mW/cm^2 power density) for various values of V_{bias}.[25] Note that as V_{bias} increases the FKO spread out and they are less damped. Since the amplitude of the modulating pump beam is a constant for the various values of V_{bias}, the bottom spectrum corresponds to the lowest value of $\mathcal{E}_{\text{ac}}/\mathcal{E}_{\text{dc}}$.

The extrema in the FKO in electromodulation are given by[5]

$$n\pi=\varphi+\tfrac{16}{3}[(E_n-E_g)/\hbar\theta]^{3/2}\,, \tag{9}$$

where *n* is the index number of the *n*th extremum, φ is an arbitrary phase factor, E_n is the energy of the *n*th oscillation, and E_g is the energy gap. In Figs. 4–7 $D\,(D')$ corresponds to $n=1$, the feature $E\,(E')$ has $n=2$, etc. The

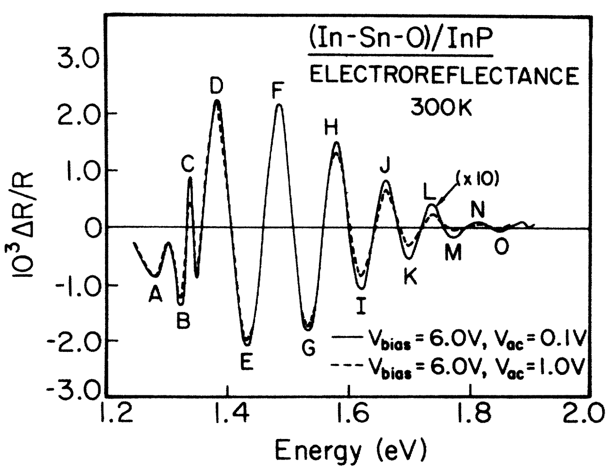

FIG. 4. Experimental electroreflectance spectra for $V_{\text{bias}}=6.0$ V with $V_{\text{ac}}=0.1$ V (solid line) and $V_{\text{ac}}=1.0$ V (dashed line). The former curve has been magnified by a factor of 10.

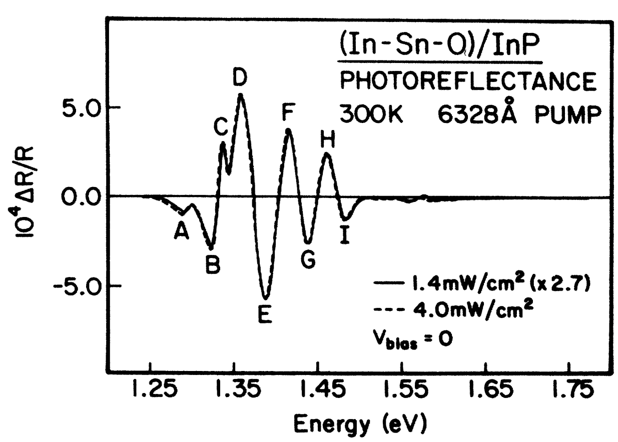

FIG. 6. Experimental photoreflectance spectra for $V_{\text{bias}}=0$ V with 6328 Å pump power densities of 1.4 mW/cm^2 (solid line) and 4.0 mW/cm^2 (dashed line). The former curve has been magnified by a factor of 2.7.

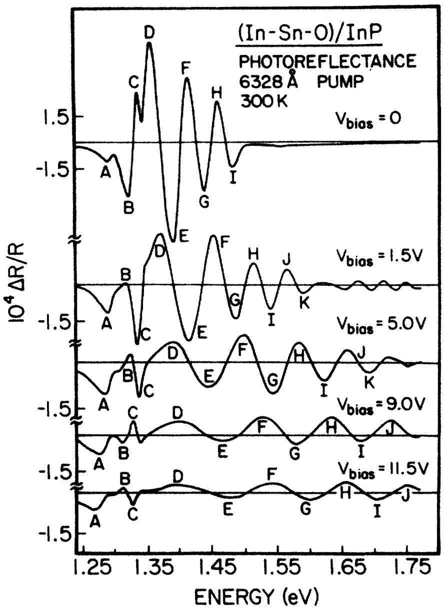

FIG. 7. Experimental photoreflectance spectra for several values of V_{bias}.

quantity $\hbar\theta$ is given by Eq. (2b) or (7b). However, in our case the electric field that appears in $\hbar\theta$ is $\mathcal{E}^s_{\text{dc}}$, the dc surface field, so Eq. (7b) is relevant.

We have performed a systematic study of the variations of the FKO in both ER and PR as a function V_{bias}. Thus we can evaluate $\mathcal{E}^s_{\text{dc}}$ as a function of the applied bias voltage. Plotted in Fig. 8 is $(\mathcal{E}^s_{\text{dc}})^2$ as a function of V_{bias}. Both methods (ER and PR) yield the same result for the change in the FKO with applied dc bias voltage. The values of $\mathcal{E}^s_{\text{dc}}$ have been evaluated from the extrema in the FKO using Eqs. (7b) and (9). We have taken $\mu_{\parallel}=0.073m_0$, where m_0 is the free-electron mass. This value of $\mu_{\parallel}$ assumes that the electromodulation spectra are due predominantly to transitions from the heavy-hole band to the conduction band.[40,41] The light-hole to conduction transitions should be a factor of three smaller due to matrix element effects.

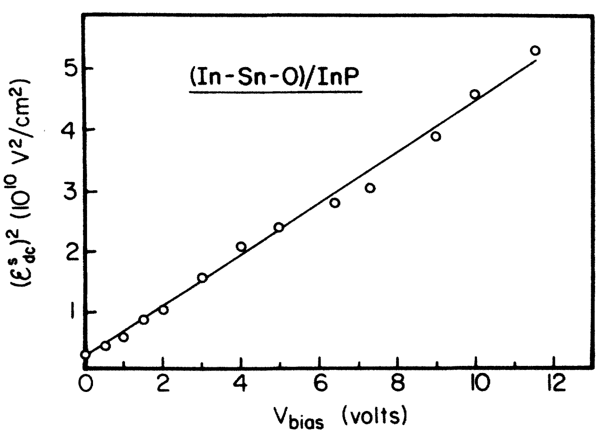

FIG. 8. The square of the dc surface electric field $(\mathcal{E}^s_{\text{dc}})^2$ as a function of V_{bias}. The values of $\mathcal{E}^s_{\text{dc}}$ were obtained from the Franz-Keldysh oscillations in the experimental electroreflectance and photoreflectance spectra.

In a fully depleted p-type SCR the surface electric field and potential, V, are related by[36]

$$(\mathcal{E}^s)^2=[4\pi e^2(N_A-N_D)/\epsilon_0]V \ . \tag{10a}$$

We can also write

$$\mathcal{E}^s=\mathcal{E}^s_{\text{dc}}+\mathcal{E}^s_{\text{ac}}\cos(\Omega_m t) \ , \tag{10b}$$

$$V=V_{\text{BI}}+V_{\text{bias}}+V_{\text{ac}}\cos(\Omega_m t) \ , \tag{10c}$$

where V_{BI} is the built-in potential and V_{ac} is the externally applied modulating voltage.

For $\mathcal{E}^s_{\text{ac}} \ll \mathcal{E}^s_{\text{dc}}$ from Eqs. (10) it can be shown that

$$(\mathcal{E}^s_{\text{dc}})^2=[4\pi e^2(N_A-N_D)/\epsilon_0](V_{\text{BI}}+V_{\text{bias}}) \ , \tag{11a}$$

$$\mathcal{E}^s_{\text{ac}}=[4\pi e^2(N_A-N_D)/2\mathcal{E}^s_{\text{dc}}\epsilon_0]V_{\text{ac}} \ . \tag{11b}$$

As can be seen in Fig. 8 the quantity $(\mathcal{E}^s_{\text{dc}})^2$ is linear in V_{bias}, thus allowing us to determine V_{BI} and N_A-N_D from Eq. (11a). We find that $V_{\text{BI}}=-0.45\pm0.1$ V and $N_A-N_D=(1.55\pm0.1)\times10^{16}$ cm^{-3}, in good agreement with the net carrier concentration obtained from Hall-effect measurements. The value of V_{BI} measured in this experiment is somewhat smaller than those deduced from prior studied on InP, which has Fermi-level pinning states at 1.2 and 0.9 eV above the valence band.[42] Thus, the surface preparation and ITO treatment of our samples has served to lower the built-in potential of the InP.

The factor of 10 difference in the two curves of Fig. 4 can be accounted for on the basis of Eqs. (5), (8), and (11b). These equations can be combined to show that $\Delta R/R \sim V_{\text{ac}}$ and hence the factor of 10 difference in modulating voltage leads to a factor of 10 in the amplitude, at least for the first few FKO. For larger values of η the differences in ξ between the two cases results in a change in the envelope function terms in $\tilde{F}(\eta,\xi)$ and $\tilde{G}(\eta,\xi)$. The above mentioned consideration can also be used to gain information about the influence of pump beam intensity on $\mathcal{E}^s_{\text{ac}}$ in PR as shown in Fig. 7. Based on the relation of the amplitude of these curves we can deduce that there is a factor of 2.7 in $\mathcal{E}^s_{\text{ac}}$ for the two different pump power densities.

Let us now return to the exciton features $A-C$ ($A'-C'$). The sensitivity of these structures to V_{bias} arises from a surface interference effect.[38,39] In the SCR there is a spatial variation in the dielectric constant due to the exciton oscillator strength for a particular photon energy. Over most of the SCR absorption due to the excitons is negligible because the dc electric field (which varies linearly with distance from the surface) exceeds that necessary to ionize the exciton (of order several kV/cm). However, near the "boundary" between the SCR and the bulk, the field is low enough for excitons to become stable and thus interact with the light. Thus an interference effect occurs between the light reflected from the ITO/InP interface and the light reflected from the region of the SCR where the exciton is not quenched. As V_{bias} is changed the width of the SCR also varies thus giving rise to an interference pattern in the electromodulation spectra for photon energies somewhat below E_g.

Note that in the PR spectra of Fig. 6 there is a change of phase of the exciton feature between 0 and 1.5 V bias, between 5.0 and 9.0 V bias, and again between 9.0 and 11.5 V.

Glosser and Bottka have recently reported a study of the comparative responses of ER and PR in GaAs in the Schottky-barrier configuration.[30] However, they concluded that the observed FKO were related to the average electric field in the SCR while this work demonstrates that the FKO are determined by the surface electric field.[25]

V. SUMMARY

In summary we have investigated the ER and PR spectra from the SCR of the model Schottky-barrier system ITO/InP as a function of reverse dc bias. For ER we have also varied the amplitude of the ac modulating voltage. In addition to excitonic effects we have observed FKO which are functions of V_{bias} but not V_{ac} (for small modulation). In this regime the latter quantity affects the envelope function but not the period of the FKO. The period of these FKO oscillations is a direct measure of the surface dc electric field $\mathcal{E}^s_{\mathrm{dc}}$ and not the modulating field. A generalized Franz-Keldysh theory, taking into consideration large built-in electric fields, is presented which accounts for the observed experimental results. From a plot of $(\mathcal{E}^s_{\mathrm{dc}})^2$ as a function of V_{bias} we have obtained the built-in potential and net carrier concentration of the SCR of the device. Information about the effect of the ac modulation voltage on the surface electric field can also be obtained. Our work demonstrates the electromodulation in Schottky barriers can be used as an optical Mott-Schottky method and that PR can be used as a contactless method to determine surface electric fields.

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