PHYSICAL REVIEW B VOLUME 29, NUMBER 12 15 JUNE 1984

Excitonic polaritons in electric fields at GaAs surfaces

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(Received 30 January 1984)

We report line-shape analyses of reflectance spectra in *n*-type GaAs obtained for various illumination intensities and applied electric fields. We describe the excitonic motion under an inhomogeneous surface field by using a dielectric model with field-dependent eigenenergies and damping. The excellent agreement between theoretical spectra and experimental data leads to the determination of surface-field parameters. It is found that a decreasing illumination intensity and/or an increasing external electric field enhance the surface charge and space charge, leading to an increase of the internal surface field.

I. INTRODUCTION

Reflectance studies in direct-band-gap semiconductors have increased our knowledge about the motion of excitons near a surface.[1–10] An exciton approaching the crystal boundary is repelled by an image charge potential,[1,6] giving rise to a transition layer depleted from excitons. Additionally, an electric surface field caused by surface charges interacts with the exciton and modifies the excitonic motion.[2–5] Most of the theoretical studies are concerned with intrinsic effects.[6–8] Spatial dispersion and an exciton-free surface layer are found to determine the reflectance line shape at least for a vanishing surface field. The influence of an electric surface field is considered theoretically only by a few authors.[4,5,9] Their approaches are restricted either to low field strengths[5] or do not allow the determination of the properties of the electric field.[4,9] Experimentally, it is found that reflectance spectra depend on surface treatment,[11] illumination intensity,[3,12,13] and external electric fields.[3,14,15] However, an unambiguous interpretation of these data is not attained so far.

The purpose of the present paper is to elucidate the influence of the illumination intensity and of externally applied electric fields on the internal electric surface field, as well as on the excitonic resonance. Recent progress in experimental techniques[5] allows one to discriminate the field-dependent features in the reflectance spectra.

We give the experimental details in Sec. II. In Sec. III we present a local dielectric model which includes an inhomogeneous surface field and neglects spatial dispersion. Line-shape analyses of reflectance data confirm the existence of a transition region with field-dependent excitonic eigenenergies and damping. These analyses yield the field parameters. In Sec. IV we discuss the photocreation of free carriers and its role on the reflectance line shape. Section V is concerned with the influence of a lateral electric field. We propose a field-induced enhancement of the space charge and the surface charge via carrier extraction leading to an increase of the surface field. In Sec. VI we report reflectance measurements at the GaAs-Au Schottky barrier. The observed *current*-related alterations of the surface field substantiate the mechanism of field-induced extraction of electrons from the space-charge region as presented in Sec. V. In Sec. VII we give a conclusive description of those mechanisms acting on the surface field and thus on the reflectance line shape.

II. EXPERIMENTAL

We used for the experiments high-purity *n*-type GaAs samples grown by liquid-phase epitaxy. The carrier concentration at 77 K was in the range of 10^{13} cm^{-3} with a typical mobility of 50 000 cm^2/Vs. The Schottky barrier was prepared by evaporating a 7-nm-thick gold film onto the GaAs surface. The Ohmic contacts were formed by alloying with Sn. The current-voltage characteristic at 7 K exhibited typical Schottky behavior in the dark as well as under illumination. The photovoltage was about 1.02 V, the short circuit current about 10 μA. The sample was mounted on the cold finger of an evaporator cryostat and held at 7 K. The reflectance experiment was performed using a tungsten iodine lamp with an angle of incidence of 70°. The light was polarized parallel to the plane of incidence in order to increase the reflectivity amplitude over the background reflectivity. The reflected light was detected by a double grating monochromator with a spectral resolution of 0.015 nm and a photomultiplier with a GaAs cathode. The spectra were recorded with a single-photon counting system. For energy-to-wavelength conversion we used a factor of 1239.852 eV nm.[16] Additionally, the refractive index of air was included.[17]

III. THEORY

Let us consider an exciton which is created in the vicinity of a semiconductor surface and is subjected there to an electric surface field. A comprehensive theoretical description of such an exciton must include this inhomogeneous surface field as well as the spatial dispersion originating from the wave-vector dependence of the excitonic eigenenergies. Only a few attempts have been made to solve this problem.[4,5,9] From a microscopic viewpoint one must solve the effective-mass equation, which is, however, not separable. The adiabatic approximation[6] may lead to a solution, at least if the masses of the electron and the hole are sufficiently different; however, extensive cal-

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culations are needed to achieve high accuracy for a comparison with experiment. The implementation of simplifications has restricted the solution to the low-field case.[5]

Dielectric theories assuming an oscillatorlike response offer a more feasible calculational procedure. However, the inclusion of spatial dispersion is suitable only for low electric fields.[4] Otherwise, the calculation procedures again become too extensive, thus preventing line-shape analyses.[9,10] Our treatment is based on a classical oscillator model. We deal with a local dielectric response neglecting spatial dispersion. This model enables fast computations of the reflectance spectra.

Let us first consider an exciton in a homogeneous electric field. This case has been studied by Ralph[18] and later by Blossey.[19,20] These authors have calculated the dielectric response for various electric field strengths by numerically solving the effective-mass equation. The electric field modifies the potential between the electron and the hole. A small widening of the Coulomb well for low-field strengths gives rise to the quadratic Stark shift of the $1s$ excitonic level. In addition, the lip of the well is lowered causing the bound states to mix and broaden into continuum states. For high electric fields the latter effect dominates and shifts the $1s$ excitonic level back to higher energies.

Simultaneously, the tunneling probability increases until the exciton is no longer bound by the Coulomb potential. According to a classical viewpoint, the exciton is ionized if the electric field E_{ion} provides a potential drop across the effective Bohr radius a_0 corresponding to the binding energy E_B,

$$E_{\text{ion}}=\frac{E_B}{ea_0}\ , \tag{1}$$

where e is the elementary charge. The actual ionization field is lower than the field of Eq. (1) because the binding energy decreases with increasing field.

We have matched the field-dependent shift $\Delta\omega(E)$ of the eigenfrequency calculated by Blossey[20] at the field strengths $E_1=0E_{\text{ion}}$, $E_2=0.45E_{\text{ion}}$, and $E_3=2E_{\text{ion}}$ by

$$\hbar\Delta\omega(E)=E_B\begin{cases}-\frac{9}{8}\left[\frac{E}{E_{\text{ion}}}\right]^2+3.15\left[\frac{E}{E_{\text{ion}}}\right]^{4.23} & \text{for } E\le 0.45E_{\text{ion}} \quad \text{(2a)}\\ -0.12+0.43\left[\frac{E}{E_{\text{ion}}}\right]^{3/2} & \text{for } E\ge 0.45E_{\text{ion}}\ . \quad \text{(2b)}\end{cases}$$

For low fields the eigenfrequency decreases quadratically with the field strength E as known from the hydrogen atom.

The field-induced broadening of the $1s$ excitonic level is correlated with the half width of an absorption spectrum. This broadening can be described by a damping term. Comprehensive results for low and high fields are not known. For low fields one can approximate the damping with a WKB expression,[18,21]

$$\hbar\Delta\Gamma(E)=Ae^{-B/E}\ , \tag{3}$$

where the constants A and B are determined from the half widths of the absorption spectra calculated by Ralph.[18] The coefficients are $A=0.35E_B$ and $B=0.32E_{\text{ion}}$.

In the case of an electric surface field one must include the depth dependences of the field strength and of the image charge force. In our local model we replace an exciton at a depth z by an oscillator whose eigenfrequencies and damping depend on the local-field strength. This requires a nearly constant field across the Bohr radius of the exciton. This condition is fulfilled if the field penetration depth l is larger than the Bohr radius.

The image-charge potential is incorporated according to Hopfield,[1]

$$\hbar\Delta\omega(z)=\frac{E_B}{2}\frac{\epsilon_s-1}{\epsilon_s+1}(a_0/z)^3\ , \tag{4}$$

where ϵ_s is the static dielectric constant. This leads to a transition region, approximately 1 Bohr radius in width which is out of resonance; i.e., it is free from excitons. A corresponding lifetime broadening can be taken into account,[3,22]

$$\hbar\Delta\Gamma(z)=E_Be^{-z/a_0}\ . \tag{5}$$

The excitonic resonance is therefore smeared out in a transition layer close to the surface.

The total transverse (T) and longitudinal (L) eigenfrequencies and the damping depending on the electric field and the depth are

$$\omega_{\text{T}}(E,z)=\omega_{\text{T}V}+\Delta\omega(E)+\Delta\omega(z)\ , \tag{6}$$

$$\omega_{\text{L}}(E,z)=\omega_{\text{L}V}+\Delta\omega(E)+\Delta\omega(z)\ , \tag{7}$$

$$\Gamma(E,z)=\Gamma_V+\Delta\Gamma(E)+\Delta\Gamma(z)\ , \tag{8}$$

where $\omega_{\text{T}V}$ and $\omega_{\text{L}V}$ are the unperturbed excitonic eigenfrequencies and Γ_V is the empirical damping constant in the bulk. The oscillator strength is taken as constant. Thus the dielectric response of an oscillator model becomes depth dependent:

$$\epsilon(\omega,z,E(z))=\epsilon_\infty\left[1+\frac{\omega_{\text{L}V}^2-\omega_{\text{T}V}^2}{\omega_{\text{T}}^2(z,E(z))-\omega^2-i\omega\Gamma(z,E(z))}\right]\ , \tag{9}$$

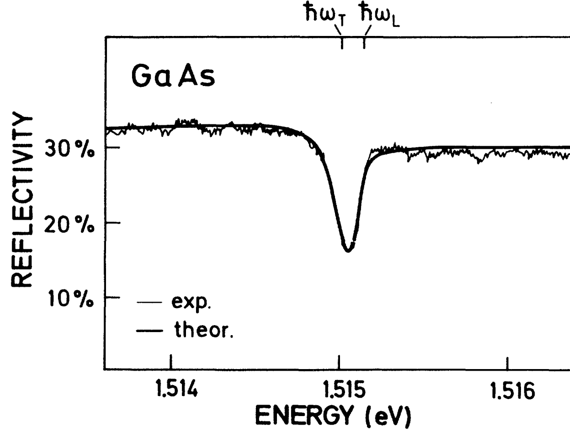

FIG. 1. Experimental (weak-line) and theoretical (strong-line) reflectance spectra of the excitonic polariton in GaAs recorded under flatband conditions (for details see Ref. 5). The upper scale gives the longitudinal and transverse eigenenergies obtained from the fit.

where ϵ_∞ is the background dielectric constant and ω the frequency. Assuming a field dependence $E(z)$, one must solve Maxwell's equations to obtain the reflectivity at the crystal boundary. For the numerical calculations we have approximated Eq. (9) by a step function. Then, one must match the amplitudes of the plane waves at the boundaries of the resulting multilayer system to obtain the reflectivity. We used 200 steps in all the fits reported in this work. A further increase of the number of steps does not yield better results.

Equations (4) and (5) contain an exciton-free surface layer which is inherent in all the dielectric models. We have fitted the reflectance data obtained under a flat band condition[5] to determine the properties of this layer. Figure 1 shows the experimental and theoretical reflectance spectra in the excitonic energy region of GaAs cleaved in liquid helium. The agreement between theory and experiment is excellent and fixes the width of the exciton-free surface layer a_0. In addition, the excitonic eigenenergies and damping in the bulk are obtained. The complete set of parameters is listed in Table I.

TABLE I. Excitonic parameters of GaAs obtained from fit to the reflectance spectrum of Fig. 1.

$\hbar\omega_{TV}$ (eV)	1.515 008
$\hbar\omega_{LV}$ (eV)	1.515 138
$\hbar\Gamma_V$ (μeV)	80
a_0 (nm)	11
$E_B = 4.2$ meV[a]	
$\epsilon_\infty = 12.6$[a]	
$E_{ion} = 3.6$ kV/cm	

[a]Taken from Ref. 2.

IV. INFLUENCE OF ILLUMINATION INTENSITY ON THE EXCITONIC REFLECTANCE

Most of the semiconductor surfaces exhibit charged surface states. In the case of GaAs, their high density pins the Fermi level at about midgap at the surface.[23] The surface charge is compensated by a depletion layer of ionized donors and acceptors, giving rise to an electric field which decreases into the bulk. The electron bands are bent. In a simple Schottky model[24] the band bending V_0, the density of surface charges N_{ss}, the field penetration depth l and the field strength at the surface E_0 of a linearly decreasing field, and the net space-charge concentration $N_{D^+} - N_{A^-}$ are connected by

$$N_{ss} = (N_{D^+} - N_{A^-})l \; , \tag{10}$$

$$E_0 = \frac{e}{\epsilon_0 \epsilon_s}(N_{D^+} - N_{A^-})l \; , \tag{11}$$

$$V_0 = \frac{e}{\epsilon_0 \epsilon_s}(N_{D^+} - N_{A^-})\frac{l^2}{2} \; , \tag{12}$$

where ϵ_0 is the permittivity of a vacuum. A typical band bending of 0.8 V and a space-charge concentration of 10^{15} cm^{-3} causes a field with a penetration depth of 1 μm and a maximal field strength at the surface of $E_0 = 15$ kV/cm. The density of the surface charge is $N_{ss} = 10^{11}$ cm^{-2}.

Optical measurements in the energy region of the 1s exciton usually involve the generation of free-electron-hole pairs. The photocreated carriers are separated in the surface field. The electrons neutralize the ionized donors in the bulk while the holes discharge the surface states. The electron bands flatten. Field cancellation may occur for a high illumination level and a corresponding high excess carrier concentration. A calculation of the field dependence for a given photon flux necessitates a detailed knowledge of the field- and depth-dependent recombination rates. Additionally, the question whether the Fermi level of the surface states coincides with the Fermi level of the bulk is crucial for a possible field cancellation.[25]

Experimentally, reflectance measurements with various illumination intensities have already been performed by several groups.[3,12,13] Figure 2 shows the experimental results of Ref. 3. The reflectance spectra were recorded with a monochromatic probe beam of an intensity of $I_p = 130$ nW/cm^2. The sample was illuminated by an additional laser beam of an intensity of $I_L = 150$ nW/cm^2. For high illumination levels one obtains reflectance spectra as shown for $I = I_p + 250 I_L$, which exhibit a strong spike in the energy region of the longitudinal-transverse splitting. A decrease of the illumination intensity by 1 order of magnitude causes a red shift of the reflectance minimum and spike. A second minimum appears at the longitudinal eigenenergy. At low illumination levels a further change of the reflectance line shape is observed. The reflectance structure is shifted to lower energies, and a second reflectance maximum arises at the longitudinal eigenenergy. Their amplitudes diminish with decreasing illumination intensity.

In order to perform line-shape analyses using the model described in Sec. III one must start with a spatial field dependence. To incorporate a continuous space-charge

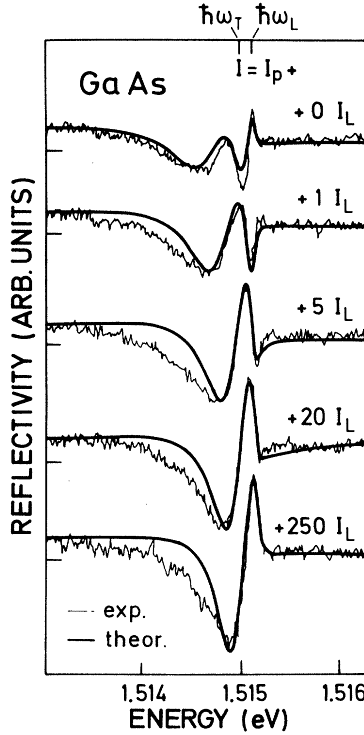

FIG. 2. Experimental (weak-line) reflectance spectra of GaAs for various illumination intensities taken from Ref. 3. I_p denotes the intensity of the probe beam. I_L is the intensity of an additional laser beam. The horizontal lines assign equal reflectivities. The fit with theoretical (strong-line) spectra yields the field parameters listed in Table II.

concentration, we have chosen

$$E(z)=E_0\left[1-\frac{z}{l}\right]^2 . \quad (13)$$

Reflectance spectra calculated with the bulk parameters of Table I are also shown for different fields in Fig. 2. The agreement with the experiment is excellent. The field parameters E_0 and l obtained from the fit are listed in Table II.

The fitting procedure yields the field parameters with a high reliability. The uncertainty of the penetration depth and the field strength is about 5%. Increasing penetration depth at a fixed field strength exchanges the reflectance maxima and minima in the energy region of the longitudinal-transverse splitting. The amplitude of the reflectance structure decreases. On the contrary, for increasing field strength but fixed penetration depth the reflectance structure shifts to lower energies with an increasing amplitude.

The complicated behavior of the reflectance line shape with decreasing illumination intensity can be explained by an increasing surface field. The field-induced exchange of the reflectance maxima and minima in the energy region of the longitudinal-transverse splitting indicates an interference effect on the polariton in a spatially inhomogeneous medium. Previous investigations[14,15] concerned with these line-shape changes have claimed the existence of a dead layer with a field-dependent width in which the excitons are ionized. However, the surface field as deduced from our fit is not sufficiently strong to ionize excitons but the surface field modifies the excitonic resonance.

The second important feature of the field-induced reflectance change is the shift of a reflectance minimum to lower energies. For the highest field this minimum lies 0.4 meV below the transverse eigenenergy. This value is slightly lower than the maximum eigenenergy shift of 12% of the binding energy as predicted by Blossey.[20] The red shift of the reflectance minimum gives direct evidence for local excitonic resonances with lowered eigenenergies due to the Stark shift.

From the field parameters of the surface field, additional information can be obtained. Applying Gauss's law yields an effective density of surface charges N_{eff},

$$eN_{\text{eff}}=\epsilon_0\epsilon_s E_0 . \quad (14)$$

The surface charge is compensated by a linearly decreasing space-charge distribution with a concentration P_0 at the surface,

$$P_0=\frac{2N_{\text{eff}}}{l} . \quad (15)$$

In general, this charge consists of the excess carriers and the net space charge.

In the dark case one can assume a net space-charge concentration in the range of 10^{14}–10^{15} cm^{-3}.[3] The resulting penetration depths of the fields are 1–3 μm with densities of the surface charge in the range of $(3–10)\times 10^{10}$ cm^{-2}.

For low illumination levels we obtain a surface charge density and a corresponding total space charge which are considerably lower than in the dark case. Even at a photon flux of 10^{11} photons/cm^{2}s (see Table II) most of the

TABLE II. Penetration depths l and field strengths E_0 of the surface field for various illumination intensities I obtained from the line-shape analyses (see Fig. 2). From the field parameters the effective density of the surface charges N_{eff} and space-charge concentration P_0 is determined.

$I-I_p$	Photon flux (photons/cm^2 s)	E_0 (E_{ion})	l (nm)	N_{eff} (cm^{-2})	P_0 (cm^{-3})
$0I_L$	4.35×10^{11}	0.5	390	1.2×10^{10}	6.15×10^{14}
$1I_L$	7.6×10^{11}	0.42	320	1.0×10^{10}	6.25×10^{14}
$5I_L$	2.08×10^{12}	0.36	260	8.6×10^{9}	6.62×10^{14}
$20I_L$	6.93×10^{12}	0.35	230	8.4×10^{9}	7.30×10^{14}
$250I_L$	8.16×10^{13}	0.33	200	7.9×10^{9}	7.90×10^{14}

surface states are discharged. The field has not reached the dark values.

With increasing illumination level the generation rate of electron-hole pairs increases. The photocreated holes are captured by the ionized acceptorlike surface states, the photocreated electrons neutralize the ionized donors in the bulk. The surface charge decreases and so does the total space charge. This behavior is shown in Table II for the surface charge density estimated from the field strength with Eq. (14). For high illumination levels the density of the surface charge remains constant. A possible saturation mechanism is discussed in the following.

The space-charge *concentration* P_0 estimated from Eq. (15) increases with increasing illumination intensity. This enhancement can hardly be explained by a steady-state excess-hole concentration. Hole lifetimes of 1 ns or even of 1 μs are not sufficiently high to explain a concentration enhancement of 1.75×10^{14} cm^{-3}. An explanation can be given by the hole capture of ionized acceptors in the space-charge region. This neutralization of acceptors leads to an increase of the space-charge concentration. The enhancement of the space-charge concentration is limited by the concentration of ionized acceptors which is significantly lower in n-type GaAs than the concentration of donors, but may lie in the same range.[26] The lifetime of the hole bound to an ionized acceptor depends on the electric field and determines the efficiency of the enhancement. A high electric surface field suppresses the recombination (eA^0) because of the spatial separation of the electrons and the neutral acceptors. The hole lifetime may be quite long, at least in the high field close to the surface.

The saturation behavior of the surface charge and the total space charge with increasing illumination level can be explained by various mechanisms. First, one must consider the field dependence of the carrier lifetime in the space-charge region. This effect leads to a decreasing excess carrier concentration with a decreasing electric field. Second, surface recombination, which is more probable for a low electric surface field, is an efficient mechanism to reduce the excess carrier concentration at high illumination levels. Additionally, one must consider surface states which interact only weakly with the carriers of the bulk. For very high illumination intensities the surface charge is screened by free holes. The field strength may increase while the penetration depth shortens.[25]

V. INFLUENCE OF A LATERAL ELECTRIC FIELD ON THE EXCITONIC REFLECTANCE

Alteration of the reflectance line shape in GaAs has also been observed by applying a lateral electric field with two Ohmic contacts on the surface.[3,27] In Fig. 3 we show previous reflectance spectra for various field strengths.[3] It is seen that the line shape changes with increasing lateral field in the same way as is observed by reducing the illumination intensity. The similarity of both influences becomes clearer if the illumination level is decreased additionally. In Fig. 4 the reflectance spectra for the case $I=I_p+5I_L$ of Ref. 3 are shown with different applied field strengths. Note that for the highest applied field the

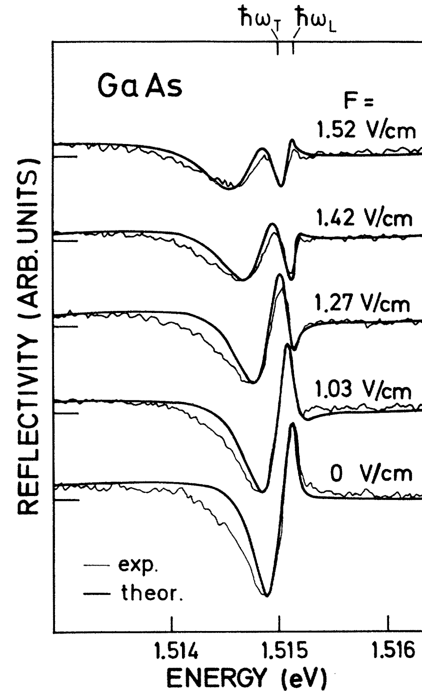

FIG. 3. Experimental reflectance spectra (weak line) of GaAs for various lateral field strengths F taken from Ref. 3. The horizontal lines assign equal reflectivities. The theoretical spectra (strong line) are calculated with the field parameters listed in Table III(a).

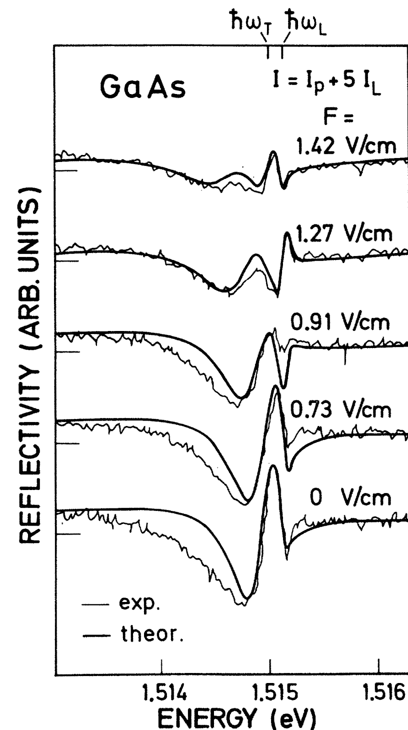

FIG. 4. Experimental reflectance spectra (weak line) of GaAs for various lateral field strengths F and a low illumination intensity of $I=5I_L$ taken from Ref. 3 are compared to theoretical spectra (strong line). The horizontal lines assign equal reflectivities. The parameters obtained from the fit are listed in Table III(b).

reflectance structure exhibits two maxima and three minima.

We have performed line-shape analyses of both series of spectra of Figs. 3 and 4. The agreement with the experiments is impressive. The different line shapes are caused by different electric surface fields. The field parameters obtained from the fits are listed in Table III.

From this data it is seen that reduced illumination intensity and/or increased lateral field cause an increase of the field strength and the penetration depth of the surface field. It is interesting to note that nearly the same line shape is obtained for a high illumination level and a high lateral field ($F = 1.52$ V/cm), and for a low illumination level and a lower field ($F = 1.27$ V/cm). This indicates that reduced illumination intensity and applied lateral field act in the same way on the surface field.

Table III(a) indicates that the surface charge and the total space charge increase with increasing lateral field, whereas the space-charge concentration decreases. This behavior can be obtained by a field-induced reduction of electron-hole pairs in the space-charge region. Recombination and extraction of free carriers must be considered. The field strength of the lateral field is too small to alter the recombination rates in the space-charge region significantly. In the illuminated part of the space-charge region, the excess carrier concentration is higher than in the adjacent parts. An additional lateral field causes an additional lateral separation of photocreated electrons and holes, at least in those parts of the space-charge region where the internal surface field is weaker than the lateral field. Under the influence of this field electrons and holes leave the illuminated region in opposite direction. The holes recombine with majority carriers. The loss of the free photocreated carriers in the space-charge region causes the total space charge and surface charge to increase. This leads to an increase of the surface field.

The extraction of the carriers is expected to be efficient only in high-purity semiconductors with a corresponding high resistivity because of the need of an external electric field in the illuminated region. The generation of electron-hole pairs acts as source of an extraction current, thus enabling steady-state conditions under illumination and applied lateral field. A change of this quasiequilibrium can be obtained by a lateral field as well as by an alteration of the illumination, whereas both perturbations act in opposition. The observed additivity of decreased illumination intensity and increased lateral field on the internal surface field confirms this explanation.

It should be mentioned that an additional field-induced impact ionization of the excitons by free carriers as proposed in Refs. 3 and 28 may be possible. However, this mechanism cannot explain the reflectance data.[3]

TABLE III. Penetration depths l and field strengths E_0 of the surface field for various illumination intensities I and lateral applied fields F obtained from the line-shape analyses in Figs. 3 and 4.

F (V/cm)	E_0 (E_{ion})	l (nm)
	(a) High intensity	
1.52	0.44	380
1.42	0.43	340
1.27	0.37	270
1.03	0.35	230
0	0.33	200
	(b) Low intensity ($I = I_p + 5I_L$)	
1.42	0.56	460
1.27	0.5	390
0.91	0.38	350
0.73	0.37	280
0	0.36	260

VI. EXCITONIC REFLECTANCE AT THE GaAs-Au SCHOTTKY BARRIER

In this section we report reflectance measurements at a GaAs-Au Schottky barrier under a constant voltage at the semitransparent gold film. The results are shown in Fig. 5. The reflectance line shape remains constant for voltages in the range of +3 V (forward) to −25 V (backward). Increasing the voltage beyond these thresholds leads to a drastic change of the line shape in the forward as well as in the backward direction. Figure 5 shows that the line shape depends rather on the current as on the ap-

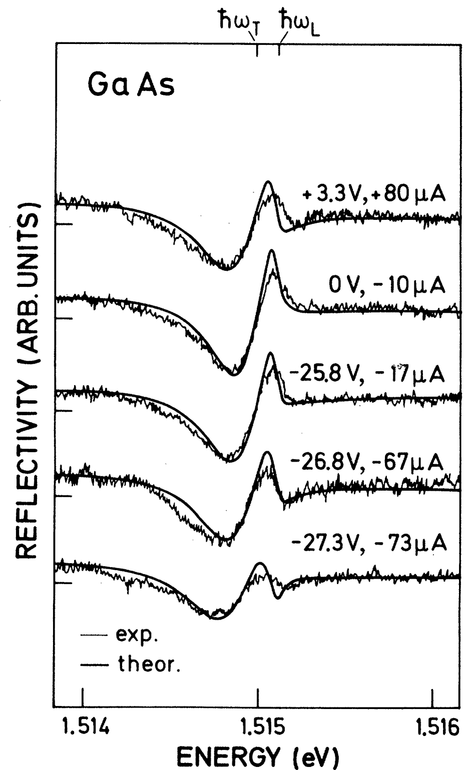

FIG. 5. Experimental (weak-line) and theoretical (strong-line) reflectance spectra of the GaAs-Au Schottky barrier obtained under an angle of incidence of 70°. The reflected light is polarized parallel to the plane of incidence. The refractive index of the gold film is assumed as $n_{Au} = 4 + 2\times i$. The horizontal lines assign equal reflectivities. The parameters obtained from the fit are listed in Table IV.

TABLE IV. Penetration depths l and field strengths E_0 of the surface field for applied voltages U perpendicular to the surface obtained from the line-shape analyses in Fig. 5.

U (V)	E_0 (E_{ion})	l (nm)
+3.3	0.28	300
0	0.26	240
−25.8	0.27	270
−26.8	0.28	300
−27.3	0.30	360

plied voltage (see $U=+3.3$ and -26.8 V).

Line-shape analyses of these spectra yield the parameters of a modified surface field. They are listed in Table IV. The excitonic parameters are the same as in the fitting procedures of Secs. IV and V.

For none of the applied voltages does the surface field vanish. Flat electron bands are not obtained, as one would expect from a simple Schottky theory.[24] This indicates that surface charges are present being only slightly affected by the external electric field. The origin of the surface charges may be explained by oxygen-induced surface states because of the preparation in ambient air conditions. Contrary to recent electroreflectance studies[14,15] with modulated voltages, the surface field is altered only in a small range. Our stationary experimental condition allows a screening of the external field by photocreated carriers. Only for sufficiently high voltages and currents the surface field is changed.

The *current*-related line-shape features directly support the mechanism of field-induced extraction of electrons from the space-charge region as discussed in Sec. V. If one considers a volume of 0.12×10^{-5} cm^3 in which free carriers are generated, an extraction current of 1 μA corresponds to a "loss rate" of 5×10^{18} carriers/cm^{3}s from the space-charge region, a value which lies in the typical range of photogeneration rates (see Table II) of a reflectance experiment. An exact determination of the field-induced loss of the total space charge is as yet not possible because the current measured in our experiment consists of both extraction current and photocurrent.

VII. CONCLUSIONS

We conclude that the excitonic reflectance obtained for various illumination levels and various applied electric fields is affected by the presence of an internal surface field. Line-shape analyses using a refined model with field-dependent excitonic eigenenergies and damping have substantiated that local excitonic resonances due to the Stark shift in the surface field modify the experimental spectra.

We have studied qualitatively the dependence of the surface field from the external perturbations in n-type GaAs. Photocreation of free carriers is shown to shorten the field penetration depth and to reduce the field strength of the surface field. With increasing illumination intensity the total space charge and the surface charge decrease. Additionally, the space-charge concentration is enhanced via neutralization of ionized acceptors. External electric fields applied parallel to the surface as well as perpendicular also increase the surface and space charge. We explain this behavior with a field-induced extraction of photocreated carriers from the space-charge region which acts in opposition to the photogeneration of free carriers.

ACKNOWLEDGMENTS

We thank E. Bauser for supplying the GaAs crystals. We are also grateful to W. Keller and H. J. Queisser for many helpful discussions and to W. Heinz for technical assistance.

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[1]J. J. Hopfield and D. G. Thomas, Phys. Rev. 132, 563 (1963).
[2]D. D. Sell, S. E. Stokowski, R. Dingle, and J. V. DiLorenzo, Phys. Rev. B 7, 4568 (1973).
[3]J. Lagois, E. Wagner, W. Bludau, and K. Lösch, Phys. Rev. B 18, 4325 (1978).
[4]J. Lagois, Phys. Rev. B 23, 5511 (1981).
[5]L. Schultheis and I. Balslev, Phys. Rev. B 28, 2292 (1983).
[6]S. Sakoda, J. Phys. Soc. Jpn. 40, 152 (1976).
[7]A. Stahl, Phys. Status Solidi B 106, 575 (1981).
[8]See, for instance, P. Halevi and G. Hernandez-Cocoletzi, Phys. Rev. Lett. 48, 1500 (1982).
[9]V. A. Kiselev, Pis'ma Zh. Eksp. Teor. Fiz. 29, 369 (1979) [JETP Lett. 29, 332 (1979)].
[10]V. A. Kiselev, Fiz. Tverd. Tela (Leningrad) 20, 2173 (1978) [Sov. Phys.—Solid State 20, 1255 (1978)].
[11]F. Evangelisti, A. Frova, and F. Patella, Phys. Rev. B 10, 4253 (1974).
[12]J. L. Shay and R. L. Nahory, Solid State Commun. 7, 945 (1969).
[13]J. U. Fischbach, W. Rühle, D. Bimberg, and E. Bauser, Solid State Commun. 18, 1255 (1976).
[14]F. Evangelisti, A. Frova, and J. U. Fischbach, Phys. Rev. Lett. 29, 1001 (1972).
[15]F. Evangelisti, A. Frova, and J. U. Fischbach, Surf. Sci. 37, 841 (1973).
[16]CODATA Bull. 11, 7 (1973).
[17]H. S. Stewart and R. F. Hopfield, in *Applied Optics and Optical Engineering,* edited by R. Kingslake (Academic, New York, 1965), Vol. I, p. 127.
[18]H. I. Ralph, J. Phys. C 1, 378 (1968).
[19]D. F. Blossey, Phys. Rev. B 2, 3976 (1970).
[20]D. F. Blossey, Phys. Rev. B 3, 1382 (1971).
[21]J. Callaway, Phys. Rev. 134, A998 (1964).
[22]K. Lösch, Ph.D. thesis, University of Stuttgart, 1977.
[23]W. L. Spicer, R. W. Chye, R. R. Skeath, C. Y. Su, and J. Lindau, J. Vac. Sci. Technol. 16, 1422 (1975).
[24]A. Many, Y. Goldstein, and N. B. Grover, in *Semiconductor Surfaces* (North-Holland, Amsterdam, 1971).
[25]A. Frova, F. Evangelisti, and M. Zanini, Phys. Status Solidi A 24, 315 (1974).
[26]D. D. Sell, in *Proceedings of the 11th International Conference on the Physics of Semiconductors, Warsaw, 1972* (PWN—Polish Scientific Publishers, Warsaw, 1972).
[27]W. Bludau, E. Wagner, and J. Lagois, Phys. Rev. B 18, 4550 (1978).
[28]W. Bludau and E. Wagner, Phys. Rev. B 13, 5410 (1976).