creased, as previously discussed by MacPherson *et al.*[7]

We wish to acknowledge a series of interesting discussions with W. Buckel, P. de Chatel, and J. Wittig. In addition, we would like to thank Mrs. S. Britz for assistance with the computations.

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Electric-Field–Induced Interference Effects at the Ground Exciton Level in GaAs

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(Received 12 June 1972)

Interference effects, due to quenching of the $n=1$ exciton in the depletion layer of a GaAs-Au Schottky barrier at ~1.8°K, are reported for the first time. The results bear out the strong dependence of the exciton reflectance line shape on the surface conditions (through local electric fields). It is shown that the reflecting boundary for the exciton polariton occurs at some depth from the surface, with known potential barrier, allowing quantitative investigation of spatial dispersion.

The degenerate valence-band exciton at the fundamental gap of GaAs has been given much attention in recent years, in particular after good quality epitaxial material became available. The interest, raised by the study of photoluminescence,[1] has prompted theoretical investigations, with the inclusion of band degeneracy and anisotropy,[2] as well as careful reflectance[3] and transmission[4] measurements at low temperature. The reflectance spectra by Sell *et al.*[3] seem to present a nonclassical line shape with a spike falling (in the spatial dispersion picture of the exciton polariton given by Hopfield[5]) at the longitudinal exciton energy. Differences in line shape are, however, observed from sample to sample,[3] so it may not be justified to draw immediate conclusions on the exciton polariton by experiments which involve probing of the sample properties in a region close to the surface, as in reflectance and luminescence.

By the present electroreflectance (ER) experiment, designed to permit a careful control of the surface conditions, we intend to demonstrate that the line shape of the $n=1$ exciton level is dominantly affected by surface fields to the extent that, throughout most of the surface depletion region, the field is usually too high to allow bound exciton states. There is a layer of material which is virtually transparent to photons of energy less than the band gap: All information on the exciton is therefore associated with reflection from an inner boundary. The above conclusions are supported by our capability of producing interference effects across the depletion layer and of controlling them by an electric field. To our knowledge we report here the first observation of this effect in a semiconductor. Interference appears to increase further the strong dependence of the exciton line shape on surface conditions.

The experimental conditions are as follows. The material was n type, 9×10^{14} cm^{-3} carriers, grown by liquid epitaxy on a degenerate substrate.[6] 45°-incidence ER at ~1.8°K was investigated using a Schottky barrier configuration, where the field at the surface of GaAs is controlled by a nearly transparent gold dot. The surface field and the depletion depth were investigated by capacitance-voltage measurements[7]: These gave, along with photovoltage and I-V measurements, a value of the built-in barrier, $V_{bi}=0.87$ V. An important result is that in the sample a depletion layer of finite thickness is present even at ~1.8°K. The field extends as far as ~1.2 μm at $V=0$ (see Fig. 1, top). This distance increases with the $\frac{1}{2}$ power of $V_{bi}-V$, and so does the surface field $\mathcal{E}_s$. At breakdown (11 V), the depletion depth is about 5 μm.

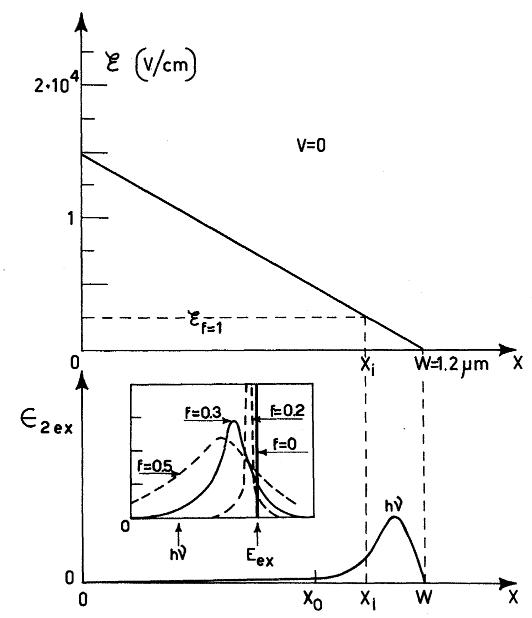

FIG. 1. Top, electric field at zero applied voltage versus distance from interface in GaAs-Au Schottky barrier at ~1.8°K (as deduced from capacitance measurements and built-in potential $V_{bi}=0.87$ V.) Bottom, schematic representation of $n=1$ exciton level contribution to the imaginary part of the dielectric constant, $\epsilon_{2\,ex}$, versus distance from interface at energy $h\nu$ shown in inset. Inset, $\epsilon_{2\,ex}$ for different values of ionization factor f given in Eq. (1) (from Ralph, Ref. 8).

Let us now consider the field which would cause ionization of the $n=1$ level. Following a discussion by Ralph[8] and Blossey,[9] we can define this field by

$$f=e\mathcal{E}r_B/E_R \geq 1, \tag{1}$$

i.e., by the condition that the perturbing potential energy over a Bohr radius r_B is not less than the binding energy E_R. In our case, this condition is verified over a large portion of the depletion region (upper half of Fig. 1). In this limit, the exciton oscillator strength becomes essentially a constant with respect to energy and is almost negligible compared to the zero-field exciton peak. At fields which do not satisfy Eq. (1), the exciton line shape changes as shown in the inset of Fig. 1. As a consequence, the absorption at or near the exciton level varies, in the depletion region, as illustrated in the lower part of Fig. 1 for one particular energy value (the behavior can be very different at other energies). Similar arguments apply to the real part $\epsilon_{1\,ex}$ of the dielectric constant. In presence of light, there occurs reflection at $x=0$ due to the large refractive-index discontinuity (however, without appreciable energy dependence): The light reflected from the deep-lying stratified medium of thickness $w-x_i$ ≃2000 Å should combine with the former to give interference effects limited to the energy range where the exciton structure is present. Since w varies with surface field (without changes in $w-x_i$), we expect to go through the various interference orders by changing the applied voltage and, in particular, to reproduce periodically the initial line shape.

Figure 2 gives the signal for square-wave modulation of 110 mV at $\lambda=8182.5$ Å as a function of $(V_{bi}-V)^{1/2}$, which is directly proportional to the depletion depth w. The constancy of the period of oscillations confirms that the effect is associated with the motion of the depletion boundary. Because of the uncertainty in the absolute determination of w,[7] a one-to-one relationship between order number and depletion depth may not be obtained. We shall mention that, following the procedure outlined in Ref. 7, we deduce an experimental separation between maxima of 1600 Å, to be compared with a half-wavelength in the medium equal to ~1200 Å. Figure 3 shows ER spectra as a function of wavelength for different bias voltages. Curves 1 and 4 correspond to maxima

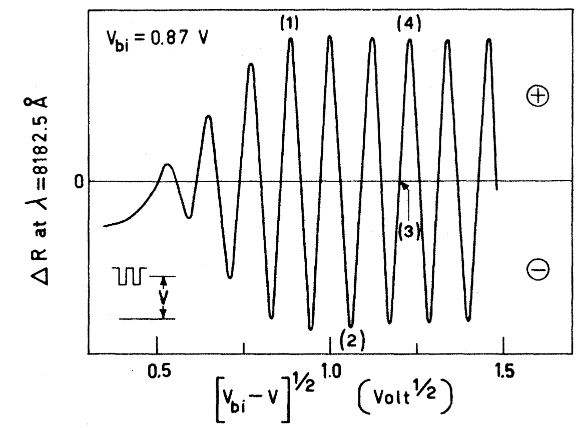

FIG. 2. Electroreflectance interference effects across the region where exciton quenching occurs, as observed by varying the voltage applied to the GaAs-Au structure. The data correspond to the peak wavelength $\lambda = 8182.5$ Å.

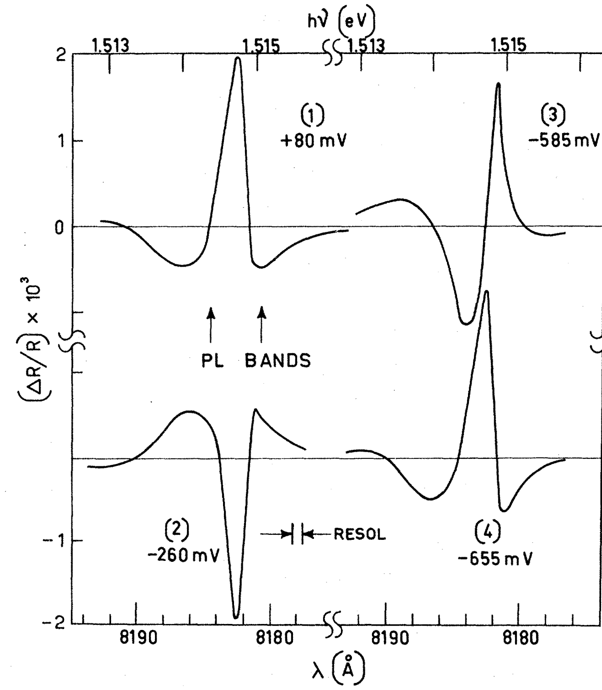

FIG. 3. Electroreflectance about the $n=1$ exciton level for different values of the voltage across the Schottky barrier. Arrows indicate the position of the observed photoluminescence bands, as measured by us in the limit of no screening effects (Ref. 13). The reciprocal wavelength-energy conversion factor used is 1.239 44 eV/μm. Our energies are smaller by 0.4 meV than those of Ref. 3. The magnitude of the signal should be corrected for the attenuation due to the gold layer. Taking for a 150-Å thick layer reflectance $R=0.8$ and transmittance $T=0.2$, we estimate an effective $\Delta R/R$ at the main peak equal to 14%, i.e., comparable to the absolute exciton contribution to R measured by Sell *et al.* (Ref. 1).

in the plot of Fig. 2, curve 2 to a minimum, and curve 3 to a null. Note that, despite the large difference in field and distance from the surface, curves 1 and 4 are identical, showing that the depletion region is relatively transparent to photons of energy near the exciton gap. Curve 2 is out of phase, while curve 3 has zeros where the others have extrema and vice versa. Intermediate cases are possible. A variety of line shapes can therefore be obtained out of one sample. The problem which is left now is to ascertain how the "intrinsic" line shape is affected by the nonuniform field at the reflecting boundary. We have to take into account the finite extension of the inhomogeneous layer $w - x_i$, where the exciton line shape differs from point to point. Following the treatment first introduced by Abelès[10] for stratified media, we schematize our system in Fig. 1 as follows: $x<0$, vacuum with $\epsilon = 1$; $0 \leq x < x_0$, exciton-free semiconductor layer with $\epsilon = \epsilon_b$ (real); $x_0 \leq x \leq w$, inhomogeneous semiconductor with $\tilde{\epsilon} = \epsilon_b + \tilde{\epsilon}_{ex}(\mathcal{E})$, where $\tilde{\epsilon}_{ex}$ is complex and depends on x through the electric field; and finally, $x > w$, bulk semiconductor with $\tilde{\epsilon} = \epsilon_b + \tilde{\epsilon}_{ex}(0)$, where $\tilde{\epsilon}_{ex}(0)$ is the zero-field contribution from the exciton. We derive the following expression for the reflectance:

$$R = \frac{(I_1^2 + I_2^2 + I_3^2 + I_4^2) + (I_1^2 - I_2^2 - I_3^2 + I_4^2)\cos(4\pi x_0 \cos\theta'/\lambda_m) + 2(I_1 I_2 + I_3 I_4)\sin(4\pi x_0 \cos\theta'/\lambda_m)}{(D_1^2 + D_2^2 + D_3^2 + D_4^2) + (D_1^2 - D_2^2 - D_3^2 + D_4^2)\cos(4\pi x_0 \cos\theta'/\lambda_m) + 2(D_1 D_2 + D_3 D_4)\sin(4\pi x_0 \cos\theta'/\lambda_m)} \quad (2)$$

where λ_m is the wavelength in the medium, θ' is the angle of refraction, and the I_j's and D_j's are expressions which contain integrals, over the inhomogeneous layer, of the real and imaginary exciton dielectric functions.[11] It is seen that the simultaneous occurrence of the sine and cosine functions with different coefficients, which is retained in the expression for ΔR, is capable of accounting for the evolution of the line shape through the various interference conditions. From a quantitative point of view, R in Eq. (2) can be calculated if $\epsilon_{1\,ex}$ and $\epsilon_{2\,ex}$ are known as a function of field. Analytical expressions are not available; however, values obtained by numerical integration of the Schrödinger equation are given by

Ralph[8] and Blossey.[9] We shall treat this problem in a more extended publication.

To study the importance of the effects described here on the free-exciton luminescence spectra, we have measured photoluminescence and have found no significant variation with the applied voltage. Two bands are observed, at energies 1.5143 and 1.5151 eV, as shown by arrows in Fig. 3. They are symmetrically located with respect to the central ER peak at 1.5147 eV. The two luminescence bands, respectively attributed to the upper and lower polariton branches by Sell *et al.* and Bimberg and Schairer,[1,12] are not sensitive to voltage even at medium-low pump power, where no screening-induced shifts[13] are taking place. Photovoltage data show that the photoexcited carrier density is always too high, for our sample doping, to permit an effective change of surface field. We expect, however, that surface-field dependence may become important at very low laser intensity. In a complementary experiment it will be of interest to explore, with the adequate resolution, the changes in exciton reflectance under heavy laser illumination.

In conclusion, we have reported the first observation of field-induced interference effects due to quenching of the ground exciton level in a thick layer below the surface. Our results indicate that the reflecting boundary for the polariton is removed from the surface and that the line shape is dominantly affected by the presence of fields. We have also presented and discussed some photoluminescence results, which confirm previously measured energy parameters of the free exciton. Further investigation is in progress.

The authors are indebted to M. Pilkuhn and F. Conradt for helpful discussion and to F. Scholz for assistance in part of the experiment.

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