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On the origin of Franz–Keldysh oscillations in AlGaAs/GaAs modulation-doped heterojunctions

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We have performed a series of photoreflectance measurements in a modulation-doped AlGaAs/GaAs heterojunction containing a high mobility two-dimensional electron gas. Measurements were performed as a function of temperature in the range 2 K$\leqslant T \leqslant$300 K. We studied the Franz–Keldysh oscillations associated with the E_0 transition of both the GaAs and AlGaAs. The fields obtained from these oscillations for both sides of the heterojunction are quite different. Also, the temperature dependence of these fields are radically different. In fact, the temperature dependence of the field in the GaAs side of the modulation-doped heterojunction sample is very similar to that of the field in a single undoped GaAs film deposited on a GaAs substrate, where no two-dimensional electron gas is present. This shows that the field producing the observed oscillations on the GaAs side of the modulation-doped heterojunction sample is not related to the field that confines the two-dimensional electron gas.

I. INTRODUCTION

The presence of an electric field, F, introduces distinctive changes in the modulated absorption and reflectivity spectra of semiconductors.[1] In bulk, direct gap semiconductors these changes (Franz–Keldysh effect) take the form of an exponential tail below the absorption edge, E_0, and a series of oscillations at photon energies higher than E_0 with periodicity given by[2]

$$E_n = E_0 + \hbar\Omega X_n, \quad (n=1,2,...) \tag{1a}$$

with

$$\hbar\Omega = (e^2F^2/8\mu)^{1/3} \tag{1b}$$

and

$$X_n = [3\pi(n-1/2)]^{2/3}. \tag{1c}$$

Here E_n are the photon energies at which the oscillations extrema occur, numbered sequentially from the exponential tail, and e and μ are the electronic charge and electron-hole reduced effective mass, respectively. This behavior is the result of optical transitions between electron and hole states reflected at their respective classical turning points, as illustrated in Fig. 1. A new situation arises in the region of intense electric field confining a two-dimensional electron gas (2DEG) in several semiconductor structures such as metal-oxide-semiconductor junction (MOS),[3] a modulation-doped heterojunction (MDHJ),[4–9] or samples with δ doping.[9] In these cases, the electrons are confined in quantized subbands while the holes are freely accelerated by the field, leading to the situation sketched in Fig. 1(b). When the potential is narrow and only a small number of subbands exist, a quantum mechanical version of the Franz–Keldysh effect might take place. The modulated absorption or reflectivity spectra for these cases would contain only a finite number of oscillations whose periodicity would be governed [Eq. (1)] by the field value at or around the Fermi energy of the 2DEG. From the number and periodicity of these oscillations, the intersubband spacings could be obtained. On the other hand, if the confining region is very wide, the summation over a large number of closely spaced quantized levels would reproduce the bulk situation[10] of Fig. 1(a). These two cases define, for homogeneous fields, the bulk and quantum-confined versions of Franz–Keldysh effects. If, however, the field is very inhomogeneous, summing even over a small number of subbands would wash out the distinctive structures of the

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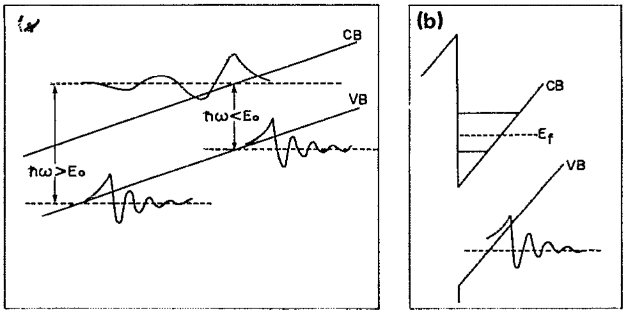

FIG. 1. Schematic representation of the optical transitions that lead to the Franz–Keldysh effect in (a) bulk semiconductors and (b) the space-charge region containing a 2DEG.

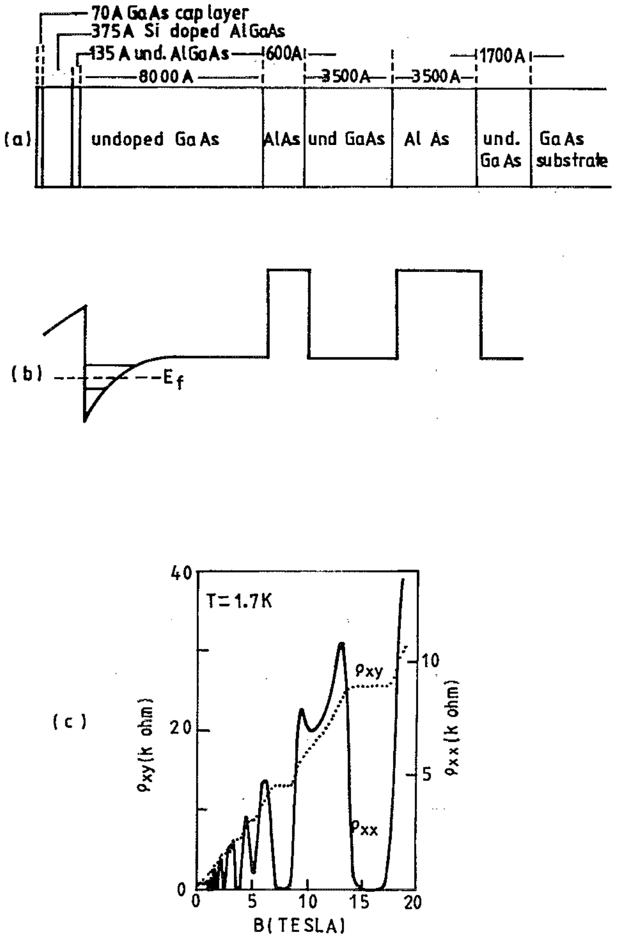

FIG. 2. (a) Layer composition of the modulation doped AlGaAs/GaAs heterojunction (sample A), (b) idealized conduction band profile for this sample for $T=0$ K and (c) magnetoresistance (ρ_{xx}) and quantum Hall effect (ρ_{xy}) data for sample A, from Ref. 13.

quantum-confined Franz–Keldysh effect (QCFKE). Thus the observation of this effect depends critically on parameters such as the width of the space-charge region, homogeneity of the field, effective masses, etc. Based on a favorable conjunction of these parameters, Zass *et al.*[3] have identified the structure observed in the 2-K electroreflectance spectrum of a HgCdTe-MOS structure as a manifestation of QCFKE. Also, the photo- and electroreflectance ($T>150$ K) of some $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ MDHJs have shown oscillations above the GaAs E_0 gap that were attributed to this effect.[6–8] Recently, Bernussi *et al.*[9] reported a series of photoreflectance measurements in $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ MDHJ and in a GaAs sample with Si δ doping, performed over a wide temperature range (14 K$<T<$300 K). The field obtained from the oscillations [Eq. (1)] in their spectra decreases sharply as temperature decreases. Below 150 K this decrease is much faster than that predicted by a self-consistent calculation of the potential profile confining the 2DEG. This discrepancy led the authors of Ref. 9 to suggest that the observed oscillations are a bulk effect related to the fields at the surface of the GaAs capping layer or the interface between the GaAs substrate and the MBE deposited GaAs layer. Such fields have produced FKOs in photoreflection spectra of MBE GaAs layers and heterojunctions even in the absence of a 2DEG,[11,12] some of which show a temperature dependence very similar to those as Ref. 9. These results cast some doubts on the validity of associating oscillations in the high temperature modulated reflectivity spectra of this type of sample with the quantum confined variety of Franz–Keldysh effect. In an attempt to clarify this issue, we performed a series of photoreflectance experiments in a modulation doped $\mathrm{Al}_{0.35}\mathrm{Ga}_{0.65}\mathrm{As/GaAs}$ heterojunction containing a high mobility 2DEG. Our measurements were carried out in a wide temperature range (2 K$<T<$300 K). We studied the Franz–Keldysh oscillations (FKOs) associated with the E_0 transition of both the GaAs and AlGaAs layers, since the field at both sides of the heterojunction should be of the same order of magnitude and have identical temperature dependence. Contrary to this, our results show that the field obtained from the FKOs on the GaAs side has a radically different behavior for $T<100$ K than that obtained from the oscillations on the AlGaAs side of the heterojunction. In fact, the temperature dependence of the former is analogous to that obtained from an epitaxial layer of GaAs deposited on a GaAs substrate, i.e., a sample containing neither a heterojunction nor a 2DEG. This shows conclusively that the observed FKOs are a bulk effect not related to the expected QCFKE in the 2DEG region.

II. EXPERIMENTAL DETAILS

The samples (A and B) used in our experiments were epitaxially grown on semi-insulating (100)-GaAs substrates. Sample A was grown by MBE and contains an $\mathrm{Al}_{0.35}\mathrm{Ga}_{0.65}\mathrm{As/GaAs}$ heterojunction with Si doping in the AlGaAs barriers of $N_D \cong 10^{18}\,\mathrm{cm}^{-3}$. The layer structure of this sample and the expected energy profile ($T=0$ K) for electrons are shown in Figs. 2(a) and 2(b), respectively. The good quality of the sample was indicated by small linewidth ($\Gamma \cong 0.7$ meV) of the $T=2$-K photoluminescence (PL) and photoreflectance (PR) excitonic lines from the GaAs portions of the sample far from the 2DEG. Magnetotransport measurements,[13] also at 2 K, show both integer and fractional quantum Hall effect [Fig. 2(c)] and a mobility close to 10^6 cm^2/Vs. These measurements establish the density of the 2DEG which was $N_s = 3.4 \times 10^{11}$ cm^{-2} in the dark and $N_s = 6.0 \times 10^{11}$ cm^{-2} under the weak illumination of a pocket flashlight. In both cases, Shubnikov–de Haas experiments establish that only the first electronic subband is occupied. The increase in the density of the 2DEG upon illumination is produced by activation of the D_x centers in the AlGaAs barrier with very long recombination times. Hence, this process does not contribute to the photomodulated signal which is measured in the frequency range of 5 Hz$<f \leqslant 10^3$ Hz. We also measured the photoreflection of a sample (B) consisting of a single, undoped, GaAs layer (3.0-μm thick) deposited by metalorganic chemical vapor deposition (MOCVD) on a (100)-GaAs semi-insulating substrate. This sample does not contain a heterojunction or a 2DEG, so any electric field effects observed in the spectra are due to the pinning of the Fermi energy either at the sample surface or at the substrate/layer interface.

The experiments were performed with the samples immersed in liquid helium at 2 K or in a cold finger-type cryostat with temperature varying in the range 8 K$<T<$300 K. The photoreflectance setup is standard,[1] with the probe beam obtained from a 55-W-tungsten-halogen lamp, filtered by a 0.5-m monochromator with a 1200-lines/mm grating and slit width in the range 0.1 mm$<W<$0.5 mm. The modulating beam was obtained from an argon-ion laser attenuated by various neutral density filters and mechanically chopped at 200 Hz. Changing this frequency from 5 to 10^3 Hz does not alter substantially our results. Sample illumination was kept at low intensity ($I<1$ μW/cm^2), to avoid complications produced by photovoltaic effects.[9] Reflected light was detected with a Si photodiode whose output was fed into Princeton Applied Research model 124 lock-in amplifier. Both ac and dc outputs were digitalized and stored in the memory of an IBM-type microcomputer, which also controlled the spectrometer scan.

III. RESULTS AND DISCUSSION

In Fig. 3 we show a typical low temperature (100 K) photoreflectance spectrum of sample A. The left-hand side of this figure shows the photon energy region around the E_0 transition of GaAs. The spectrum shows the strong excitonic line associated with the E_0 gap and a series of FKOs towards higher photon energies. The first originates in GaAs regions of the sample far from the strong electric field of the 2DEG region [see Fig. 2(b)]. The oscillations are of the same nature as those observed in other MDHJ samples.[4,6–9] At higher photon energies (right-hand side of Fig. 3), the structures associated with the E_0 gap of the $Al_{0.35}Ga_{0.65}As$ barrier material appear. Here we also observe a series of oscillations above the E_0 gap, but with a much larger period than those associated with the GaAs transitions. The inset of Fig. 3 shows a plot of the oscillations extrema, E_n, vs the quantity X_n defined in Eq. (1c). The linear relationship between these quantities predicted by Eq. (1a) is well observed by our data, thus identifying both sets of oscillations as FKOs. From the slope of these straight lines we calculate the fields producing the oscillations on the GaAs ($F_1 = 11$ kV/cm) and the AlGaAs ($F_2 = 235$ kV/cm) sides of the spectra. The barrier material is narrow and only appears in the sample close to the heterojunction [see Fig. 2(a)]. Hence, F_2 is the electric field value associated with the space-charge region on the AlGaAs side. If the interpretation of Refs. 4–6 were true, F_1 would be the continuation of this field on the GaAs side of the heterojunction. Even allowing for screening by the 2DEG, the field at or around the Fermi energy [Fig. 2(b)] should be such that the ratio between F_2 and F_1 could not be greater than a factor of 4.[4] Instead, the experimental data of Fig. 3 gives a ratio $F_2/F_1 \cong 20$. Repeating this procedure for the data obtained at different temperatures, we obtain the temperature dependence of fields F_1 and F_2, which we display in Fig. 4(a) as open triangles. Again, if F_1 were the continuation of field F_2 on the GaAs side of the heterojunction the temperature dependence of both fields should be very similar, i.e., the ratio F_2/F_1 should not depend very much on temperature. In contrast, Fig. 4(a) shows very different temperature dependences for both fields, especially for $T<100$ K. While F_2 exhibits a weak, almost linear decrease as T decreases, F_1 falls very quickly at low temperatures. In fact, for $T = 15$ K, the ratio

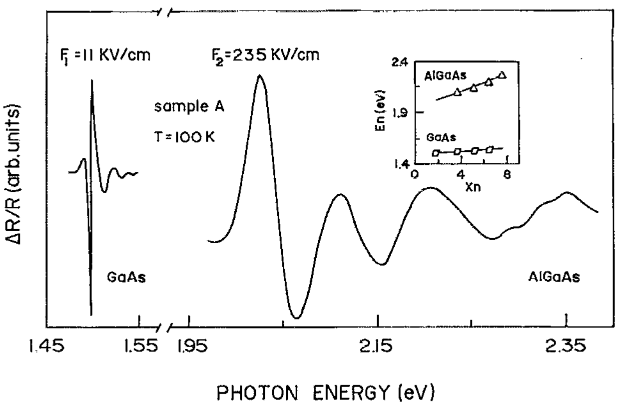

FIG. 3. Photoreflectance spectrum of sample A. The inset shows plots of Eqs. (1) for the extrema of the FKOs from which values of fields are obtained.

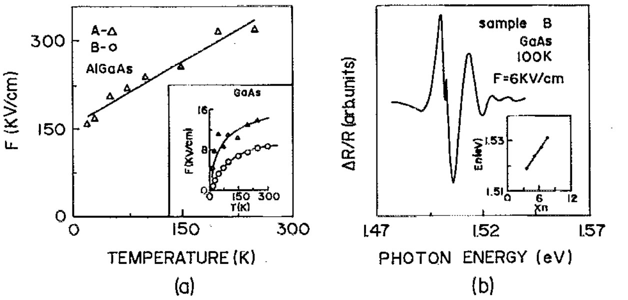

FIG. 4. (a) Temperature dependence of the fields F_1 and F_2 of sample A (open triangles) and sample B (open circles). (b) Photoreflectance spectrum and FKO plot for sample B.

F_2/F_1 is already $\cong 130$. Worse even, the sequence of points for F_1 seems to extrapolate to zero as $T \to 0$. In fact, the spectrum for $T=2$ K shows no oscillations at all on the GaAs side, while giving a regular set of FKOs at the AlGaAs side which yield $F_2 \cong 150$ kV/cm. The absence of FKOs on the GaAs side means that the electro-optic energy [$\hbar\Omega$ in Eqs. (1)] is less than the lifetime broadening (Γ) of the E_0 transition. Since at this temperature $\Gamma \cong 0.7$ meV, we can establish an upper limit for F_1 at this temperature [Eq. (1b)]: $F_1 \leqslant 0.15$ kV/cm. This results in a ratio $F_2/F_1 > 10^3$. Thus the experimental ratio between F_2 and F_1 would grow from about 20 at $T \geqslant 150$ K to a value *larger than* 10^3 *at 2 K*. This is clearly impossible within the interpretation of Refs. 4–6, which predicts a relatively small and temperature independent ratio. A more plausible explanation is to assume that the field F_1 which produces the FKOs on the GaAs side of the spectrum is not associated with the heterojunction, but that it originates in other regions of the sample, as suggested in Ref. 9. This notion is reinforced by analyzing the results of performing the same type of experiments on a sample with no heterojunction or 2DEG, i.e., our sample B which is simply a thin GaAs layer deposited on a GaAs layer substrate. Figure 4(b) shows the PR spectrum of this sample for $T=100$ K. This spectrum is very similar to that of the GaAs side of sample A shown on the left-hand side of Fig. 3. The oscillations from the spectrum of Fig. 4(b) yield a linear FKO plot (inset) from which a field of $F=6$ kV/cm is obtained. The temperature dependence of this field is shown with open circles in Fig. 4(a). This temperature dependence is almost identical to that of the field F_1 in sample A (open triangles in the same figure). In sample B the field producing the FKOs in the PR spectrum comes from the band bending region either at the surface or at the substrate/layer interface, and is due to Fermi energy pinning. This pinning is produced by traps with activation energies of about 20–40 meV. Under illumination and at low temperatures, the GaAs layer far from the heterojunction would be in flat-band condition ($F_1 = 0$), as shown in Fig. 2(b). At higher temperatures ionization of the trapped carriers gives rise to an electric field in the depletion region ($F_1 > 0$). The characteristic temperature dependence of these fields, shown in Fig. 4(a), have also been obtained independently by Lui *et al.*[12] The similarity in magnitude and temperature dependence between the fields in the GaAs layers of samples A and B is further evidence that both have the same origin. This means that the field F_1 which produces the FKOs on the GaAs side of the spectrum in sample A is not the same field as that which produces the confinement of the 2DEG. This result is also suggested by the room temperature experiments of Pan *et al.*,[11] who studied with PR several doped and undoped heterojunctions. The difference in the temperature dependence of the electric fields in the GaAs (undoped) and AlGaAs (doped) portions of the sample can be explained on the basis of the photovoltage induced by the pump and probe beams. The measured electric field (F) shown in Fig. 4 is the difference between the built-in field (F_{bi}) and the forward bias due to the photovoltage (F_{pv}). For example, the recently reported temperature dependence of F for undoped GaAs structures with uniform electric fields[14] is very similar to the results of Fig. 4(a). This behavior has been explained by a modification of the theory of Hecht.[15,16] The net photovoltage is due to the balance between the photoinduced and saturation currents. At low temperatures the former process is dominant, and hence even a small amount of light produces an *appreciable* F_{pv}. At higher temperatures the latter mechanism becomes increasingly more important so that F_{pv} becomes zero, i.e., F satures. In doped materials the saturation current becomes larger, and hence the F approaches F_{bi} at lower temperatures, as shown in Fig. 3 of Ref. 15.

In summary, our results show that the field producing FKOs on the GaAs layer of a modulation-doped GaAs/AlGaAs heterojunction at $T \leqslant 100$ K is not the same as that which confines the 2DEG, and therefore the observed oscillations are not due to the quantum confined variety of the Franz–Keldysh effect.

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