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Resonant magnetotunneling in GaAlAs-GaAs-GaAlAs heterostructures

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We report the observation of resonant tunneling of electrons through Landau levels in double-barrier GaAlAs-GaAs-GaAlAs heterostructures, in the presence of a strong magnetic field perpendicular to the interfaces. This is a two-dimensional magnetotunneling effect which manifests itself as periodic structures in the current-voltage characteristics, with a period proportional to the electron cyclotron energy in the GaAs quantum well, from which the electron mass is determined.

The transmission probability of an electron through a double-barrier potential becomes unity when its energy is equal to that of the quantum states in the well, independently of the barrier widths; away from this resonant condition, that probability drops exponentially. This phenomenon, called resonant tunneling, was predicted in the 1960s (Ref. 1) and subsequently observed in GaAlAs-GaAs-GaAlAs heterostructures.[2,3] Recently the same phenomenon has been shown in similar structures for the transmission of both light and heavy holes.[4]

In this Rapid Communication we show experimentally resonant magnetotunneling of electrons through GaAlAs barriers whenever their energy coincides with any of the Landau levels of a GaAs quantum well, in the presence of a strong magnetic field perpendicular to the heterostructure interfaces. The results indicate that elastic scattering is dominant in the magnetotunneling process and provide a simple way of determining the effective mass of carriers in two-dimensional systems.

In the past, there have been reports of electrons tunneling from Landau levels in an accumulation (inversion) layer into a metal.[5,6] Although our observations also have their origin in the formation of magnetic states, they differ substantially from previous ones in that the Landau levels in the quantum well serve as "intermediate" resonant states, through which tunneling takes place, and remain unoccupied otherwise.

We start the description of this new effect by summarizing the process of resonant tunneling, at zero magnetic field, in a double-barrier heterostructure composed of two GaAlAs barriers with a GaAs quantum well in between. The source and drain of electrons are n^+-GaAs electrodes on each side of the structure [see Fig. 1(a)]. We will assume that during the tunneling process both the total energy and the momentum parallel to the interface are conserved. In addition, for simplicity we will consider the case in which both barriers are identical and the temperature $T=0$. In a heterostructure like the one shown in Fig. 1(a) the energy E of an electron in the GaAs electrodes is in general different from the energies (E_0, E_1, . . .) of the quantum states in the well. An external electric field is usually applied between the two electrodes, so that for a certain voltage V the resonance condition is satisfied: $E=E_0-eV$. (We define V as the voltage drop between one of the electrodes and the center of the quantum well, that is, half of the total voltage between the two electrodes, which is the quantity measured experimentally.) In practice, since there is a possible range of energies for the incoming electron ($0 \leq E \leq E_F$) the tunneling probability is unity in this range. The tunnel current is obtained through the integration of all states of wave vector $\mathbf{k}$ ($\mathbf{k}_\parallel, k_z$) that satisfy the conservation laws. Figure 1(b) illustrates the contribution to the current of the different states with increasing voltage. For $eV < E_0 - E_F$, no tunneling is possible, until the threshold voltage V_1^0 ($eV_1^0 = E_0 - E_F$) is reached. From then on, more states become available, and with increasing V the current increases monotonically. Finally, when $eV > eV_2^0 \equiv E_0$, parallel momentum conservation precludes tunneling.[7] Thus, the I-V characteristic of a resonant tunneling structure would be roughly triangular, with an abrupt drop on the high-voltage side.

In the presence of a magnetic field B perpendicular to the interfaces (z direction) the situation is quite different. The field quantizes the motion of the electrons in the x,y plane, giving rise to Landau levels with energies $(N+\frac{1}{2})\hbar\omega_c$, where N is the level index ($N=0,1,2,\ldots$) and $\hbar\omega_c$ is the cyclotron energy ($\hbar\omega_c = e\hbar B/m^*$). For simplicity, spin has been ignored. The electrons can move freely along the z direction, in the three-dimensional (3D) electrode, but their motion is completely quantized in the two-dimensional (2D) quantum well. This situation is illustrated in Fig. 1(c), where we depict the 3D dispersion relation together with the 2D density of states at representative voltages. In analogy with the $B=0$ case, for $eV < eV_1^B \equiv (E_0 - E_F) + \hbar\omega_c^{2D}/2$, tunneling does not occur (ω_c^{2D} is the electron cyclotron frequency in the well). Thus, the threshold voltage V_1^B is increased by $\hbar\omega_c^{2D}/2$ with respect to V_1^0. For voltages above V_1^B tunneling is possible through the $N=0$ level, but since the density of states has a δ-function character, an increase in voltage should not result in an additional current, until the next Landau level ($N=1$) crosses the Fermi energy, when more states become available. The resulting I-V characteristic, for a given B, would be a series of steep rises followed by flat regions, although the inherent Landau level broadening would tend to smooth those features.

For voltages such that the ground-state Landau level in the well is lower than the bottom of the conduction band of the electrode, the conservation of Landau index would prevent any tunneling, and would give rise to negative conductivity. This critical voltage V_2^B would be $eV_2^B = E_0 + \frac{1}{2}\hbar(\omega_c^{2D} - \omega_c^{3D})$, and would coincide with the zero-field voltage V_2^0 only when the electron effective mass for the electrode and the quantum well were the same. (ω_c^{3D} is the electron cyclotron frequency in the electrode.)

Thus, resonant magnetotunneling is expected to produce a series of periodic maxima and minima in the conductivity (whose period would be proportional to the magnetic field) and a shift of the negative conductivity structure towards higher or lower voltages, depending on the relative electron masses in the electrode and in the well.

The experiments to study resonant magnetotunneling were done on n^+-GaAs-$Ga_{0.6}Al_{0.4}As$-GaAs-$Ga_{0.6}Al_{0.4}As$ heterostructures, grown by molecular-beam epitaxy on n^+-GaAs substrates. Both the GaAlAs barriers and the GaAs well in between were undoped, and the doping of the electrodes was $\sim 10^{18}$ cm^{-3}. Two symmetric-barrier (100 Å thick) structures were prepared, with well widths of 40 Å (sample A) and 60 Å (sample B), respectively, and their *I-V* and *dI/dV-V* characteristics studied at various temperatures between 300 and 0.55 K.

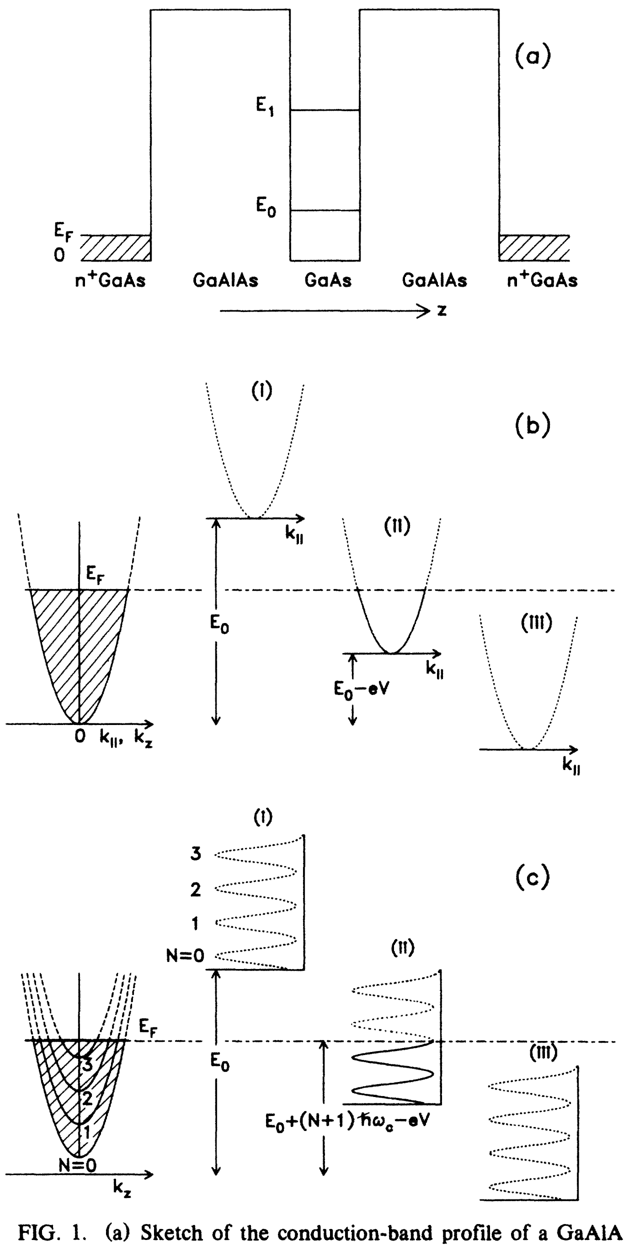

FIG. 1. (a) Sketch of the conduction-band profile of a GaAlAs-GaAs-GaAlAs double-barrier heterostructure, sandwiched between two n^+-GaAs electrodes. E_0 and E_1 correspond to the energies of the allowed states in the GaAs quantum well. Resonant tunneling through the barriers is induced by applying a voltage 2 V between the electrodes. (b) Band dispersion and relative alignment of the electrode and quantum well bands for three representative voltages. (c) Dispersion of the electrode subbands in the presence of a magnetic field B in the z direction, and density of states of the quantum well for representative voltages. In (b) and (c), (i) corresponds to $V=0$, (ii) to the case when resonant tunneling occurs, and (iii) to larger voltages, when momentum conservation prohibits tunneling.

The characteristics were symmetric with respect to the voltage origin, confirming the symmetry of our heterostructures. In this case, the voltage drop is the same in each barrier, and the total resonant voltage corresponds to twice the energy of the quantum state in the well. (To avoid confusion, in the following, when we refer to experimental voltages we mean half of the total voltage between the electrodes.) Below ~ 100 K well-defined negative resistance regions were observable in both samples: One at 0.128 V in sample A, and two in sample B at 0.056 and 0.217 V. These values are in good agreement with the calculated energies of the quantum states: 0.101 eV (sample A), and 0.063 and 0.241 eV (sample B). In the calculation we used the envelope-function formalism[8] with the following parameters: 0.296 eV for the barrier height and $0.066m_0$ and $0.101m_0$ for the electron mass m^* in GaAs and $Ga_{0.6}Al_{0.4}As$, respectively. The electric-field induced shift of the energy levels, as well as the asymmetry introduced by the field, was ignored.[9,10] The agreement between the calculated and measured values confirms that no appreciable voltage drops occur at the electrodes. In the remainder of this Rapid Communication we concentrate on sample A.

The bottom trace of Fig. 2 shows the *dI/dV* vs *V* characteristic for one-voltage polarity, in the absence of any magnetic field. The conductance line shape, with a very flat region followed by an abrupt drop to negative values, reflects a triangularlike *I-V* characteristic, with no conduction away from the tunneling voltage region, which is of the order of 0.075 V. This voltage is in reasonable agreement with the Fermi energy of the n^+-GaAs electrodes. Although this spectrum was taken at 0.55 K, no significant difference was apparent in the range 4.2–0.55 K.

The presence of a magnetic field perpendicular to the interface planes (that is, parallel to the tunneling direction)

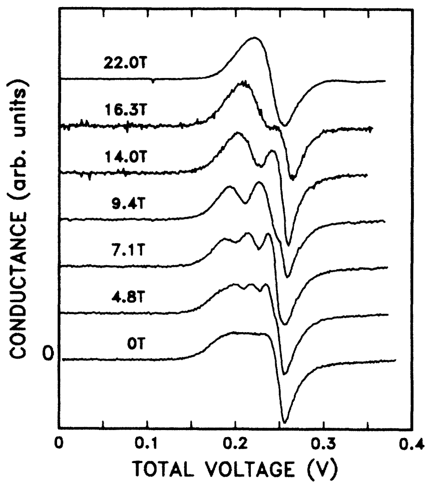

FIG. 2. Conductance vs total voltage applied to sample A (see text) for various magnetic fields. The voltage drop between an electrode and the center of the quantum well is half of the total voltage. The traces shown were taken at 0.55 K but no difference was found with data taken at 4.2 K.

affects very weakly the strong negative conductance minimum at 0.128 V, but alters significantly the flat portion of the spectrum. For fields >3 T small dips become visible, whose amplitudes increase with field and whose positions are shifted to higher voltage with increasing B, until they merge with the principal minimum. For $B>13$ T only one extra dip is observable, and a complete merge occurs at $B\sim 20$ T (see Fig. 2).

If the magnetic field is applied parallel to the interface planes none of these effects are present, although drastic changes with respect to the zero-field tunneling are still observable. The negative conductance minimum shifts to higher voltage, probably as a result of an increasing magnetoresistance, and decreases in amplitude, but no additional minima are present. A detailed analysis of this behavior is left for a subsequent publication.

The positions of the various minima of Fig. 2 are plotted versus magnetic field in Fig. 3. The field-induced minima shift linearly with B, and the slopes, different for each series, are approximately in the ratio 1:2:3:4. Moreover, all minima seem to converge to a common voltage in the $B=0$ limit.

These results are explained in terms of the resonant magnetotunneling effect described above. When a Landau level in the quantum well passes through the Fermi level of the electrode the tunneling current increases initially, but then remains constant until the next level goes through. The conductance should have a minimum (and ideally go to zero) at voltages such that E_F is between Landau levels, as given by the expression

$$eV_{\min}=E_0-E_F+(N+\phi)\hbar\omega_c^{2D},\quad N=0,1,2,\ldots, \quad (1)$$

where the phase ϕ is ideally 1. Thus, at low B the small separation ($\hbar\omega_c^{2D}$) between Landau levels leads to several conductance minima, and the number of them decreases with increasing B. At large fields, when $\hbar\omega_c/2\sim E_F$, these additional minima disappear.

A least-squares fit of the experimental voltages to Eq. (1) yields the values of the parameters $\Delta\equiv E_0-E_F$, the effective mass m^* and ϕ. The solid lines in Fig. 3 represent the result of that fit, with the values $\Delta=0.087\pm0.001$ eV, $\phi=1.04\pm0.02$ and $m^*/m_0=0.063\pm0.002$, for the Landau levels $N=0,1,2,3$. The closeness of ϕ to 1 gives additional support to the level indexing. Since, experimentally, $E_0=0.128$ eV, it is $E_F=0.041$ eV, in reasonable agreement with the value 0.054 eV which would be obtained for an electrode with 10^{18}-cm^{-3} electrons.

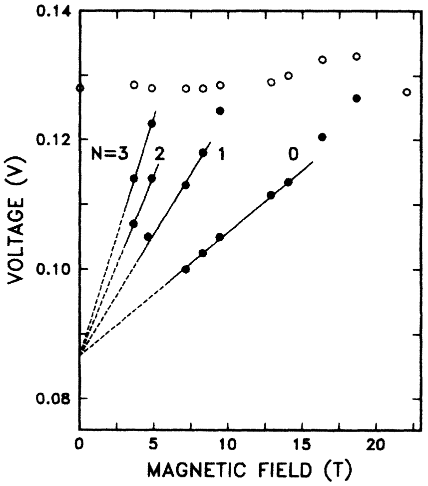

FIG. 3. Position of the negative conductance minimum (open circles) in Fig. 2, and of the field-induced minima (closed circles) as a function of the magnetic field B. The voltages plotted correspond to half of the total voltage between the two electrodes. The solid lines ("fan chart") correspond to a least-squares fit to Eq. (1) in the text; only those oscillations that were well defined were included in the fit. The quantum index N of each series is shown.

In our simple analysis we have ignored the variation of E_F with magnetic field as well as any nonparabolicity effects. The fact that even at high fields the positions are proportional to B suggests that those simplifications are not too drastic. Each of the two negative resistance minima of sample B showed a similar behavior to sample A, although some deviations from linearity in the corresponding "fan charts" were present at the highest fields.

The effective-mass value $m^*=0.063m_0$ is in agreement with the bulk GaAs mass ($0.066m_0$), and significantly smaller than the value obtained from cyclotron resonance measurements ($\sim 0.071m_0$) in heavily doped GaAs-GaAlAs heterostructures.[11,12]

In general, a difference between the 3D electron mass (in the electrode) and the 2D mass (in the quantum well) should give rise to a field-induced shift of the negative resistance structure. While an upshift of up to 0.005 V is observed experimentally at 18 T, it is nonlinear, and more significantly, for $B>21$ T is reduced to zero. This high-field behavior is not well understood.

In cases where the difference between the 2D and 3D mass of the particle were large, the mentioned shift could be particularly noticeable, and could be either positive or negative, depending on the sign of the mass difference. This could explain the results obtained in resonant hole tunneling,[4] where some negative-resistance minima showed an upshift induced by the magnetic field, whereas others exhibited a downshift. The presence of 2D heavy- and light-hole states with effective masses significantly different from bulk GaAs (Ref. 13) could account qualitatively for the observations.

Our magnetotunneling model predicts a shift, by $\hbar\omega_c^{2D}/2$, of the onset of the tunneling process, in the absence of any Landau-level broadening. In Fig. 2 the onset of conductance is seen to shift with magnetic field, but a quantitative comparison is difficult due to finite-temperature effects and to field-dependent level broadening.

Finally, the fact that no additional structures are observed at voltages higher than the principal minimum indicates that in resonant magnetotunneling the quantum number N is conserved, in analogy to the parallel momentum conservation at zero field. However, preliminary data in extremely high fields ($B\leqslant 28$ T) show weak additional minima beyond the negative resistance structure, suggesting a possible breakdown of that conservation law. Additional experiments are needed before this interpretation can be confirmed.

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