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Electron tunneling through single-barrier heterostructures in a magnetic field

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Shubnikov–de Haas-like oscillations of the tunnel current were observed at 4.2 K in GaAs/AlAs/GaAs single-barrier heterostructures with 50-, 35-, and 25-Å-thick barriers and 600-Å spacer layers. An accumulation layer was formed at the emitter side of the barriers under external bias. Analysis of the experimental data showed that the concentration of two-dimensional (2D) electrons in the accumulation layer could not be determined from the oscillation period. Only the total number of 2D states on the emitter side of the barrier, below the Fermi level of the emitter bulk, could be determined.

During electron tunneling through a single-barrier heterostructure, oscillations in the tunnel current can occur with a period proportional to the inverse magnetic field[1–4] when the field is perpendicular to the interface. These oscillations, observed when the emitter has a slightly doped spacer-layer region closest to the barrier, are believed to be related to Landau quantization of a two-dimensional electron gas (2DEG) in an accumulation layer adjacent to the barrier. This 2DEG arises when an external voltage bias is applied to the structure. Structures of n^+-type GaAs/n^--type GaAs/Al$_x$Ga$_{1-x}$As/n^+-type GaAs and n^+-type (InGa)As/n^--type GaAs/InP/n^+-type GaAs have been used in the experiments.[1–4] In these structures the thickness of the n^- spacer layer was rather thick, 1 μm, while the thickness of the barriers varied from 160 to 500 Å.

Because the tunnel current is independent of the momentum component parallel to the interface, the main difficulty in interpretation of experimental results[1–4] is to correlate oscillations with the quantization of the electron motion parallel to the interface. A most comprehensive theoretical treatment of the observed oscillations was presented by Chan *et al.*[5] It was shown that oscillation in the current was due to modulation of the 2D electron concentration N_s and barrier height induced by the magnetic field. The latter was caused by a change of the 2D ground-state position. The problem was solved self-consistently, assuming that only 2D electrons tunnel and the tunneling rate was small compared with the diffusion rate of electrons through the n^- layer. This means that the Fermi level μ_{2D} of the 2DEG aligns with the Fermi level μ_e of the bulk n^- layer at thermodynamic equilibrium in the emitter. The value of N_s can be determined from the oscillation period with $1/B$, similar to Shubnikov–de Haas oscillations. Calculated oscillations in the tunnel current have a distinct triangular shape, which agrees with experimental findings.[1–4]

With the exception of the previously used 1 μm the spacer-layer thickness separating contact layer and barrier is usually in the range 50–600 Å. When the spacer layer is above 200–300 Å thick the emitter is considered to be two dimensional, because of the formation of an accumulation layer.[6] However, if the transparency of the barrier is comparable in magnitude with that of a spacer region (e.g., thinner barriers and spacers than in Refs. 1–4), then the assumptions made in Ref. 5 about thermodynamic equilibrium are invalid, and part of the applied voltage will drop in the spacer-layer region.

In this paper we have studied the electron tunneling in GaAs/AlAs/GaAs single-barrier heterostructures with relatively thin spacer layers, where a different tunneling condition from that described in Ref. 5 could be expected. Periodic oscillations in the tunnel current were observed against $1/B_\perp$, where $B_\perp$ is the component of the field normal to the interface. It was found that N_s cannot be determined from the oscillation period, since only the total value of the 2D states in the energy range E_0 to μ_e can be determined, where E_0 is the ground-state energy of the 2D electrons and μ_e is the Fermi level in the emitter bulk.

Samples were grown by molecular-beam epitaxy on a (100)-oriented Si-doped n^+-type GaAs wafer ($N_d = 2\times10^{18}$ cm^{-3}). The structure consists (in the order of growth) of a lightly Si-doped, 500-Å-thick GaAs layer ($N_d = 2\times10^{16}$ cm^{-3}); undoped GaAs layer 100 Å thick; undoped, 50-Å-thick AlAs barrier layer; 100-Å-undoped GaAs; 500-Å lightly Si-doped GaAs ($N_d = 2\times10^{16}$ cm^{-3}); and a GaAs cap layer ($N_d = 2\times10^{18}$ cm^{-3}), which was 0.4 μm thick. To fabricate Ohmic contacts a AuGe/Ni/Au metallic film was evaporated on the n^+-type GaAs cap layer. Mesa structures (80 μm in diameter) were defined by wet etching (2 μm depth) using the metal as a mask. Another Ohmic contact was prepared on the back side of the wafer by In soldering. A standard annealing process (400 °C, 2 min in N$_2$ atmosphere) gave good Ohmic contacts (10^{-6}–10^{-5} Ω cm^2).

Figure 1 shows the differential resistance $\partial V_b/\partial I$ as a

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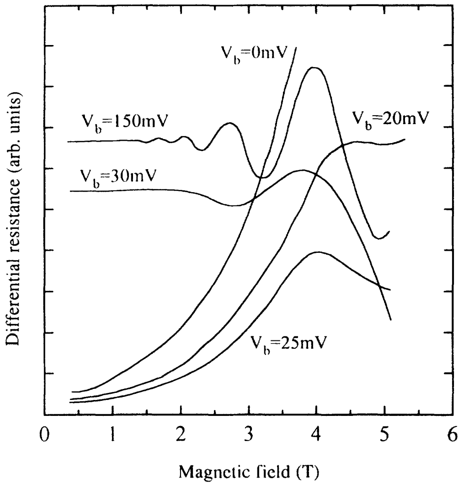

FIG. 1. The differential resistance $\partial V_b/\partial I$ as a function of the magnetic field for a structure with 50-Å-thick AlAs barrier. The parameter V_b is a voltage bias applied to the structure. The magnetic field is perpendicular to the barrier interface. Curves are shifted arbitrarily in the vertical direction.

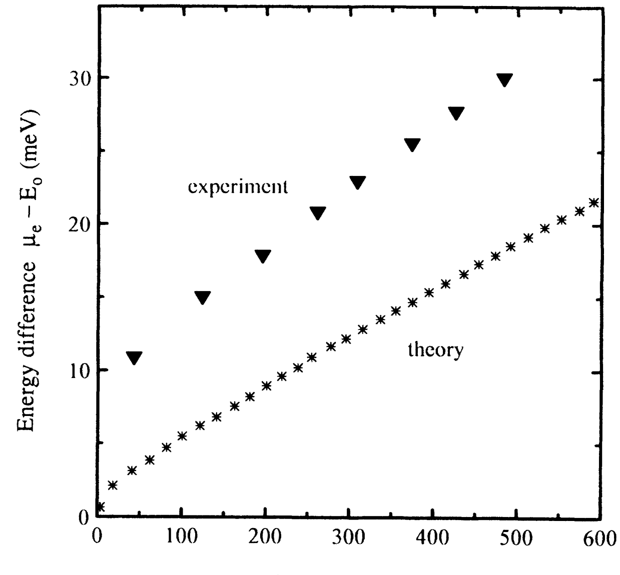

FIG. 2. The energy difference between the Fermi level of the emitter bulk and 2D ground state, $(\mu_e - E_0)$, as a function of applied bias V_b for the sample with 50-Å-thick AlAs barrier. The data were obtained from the oscillation periods measured at different V_b (experiment) and calculated (theory). Details are in the text.

function of magnetic field $B_\perp$ at 4.2 K for different bias V_b applied to the structure. These curves, obtained by lock-in technique, have some characteristic features. At low bias, $V_b \leq 20$ mV, only a monotonic change in magnetoresistance was observed. At $V_b \approx 25$ mV oscillations with a period $\propto 1/B_\perp$ appeared. This period depended only on the B component normal to the interface. The amplitude of the oscillations did not exceed 1% of the total differential resistance of the structure. The monotonic magnetoresistance disappeared simultaneously with the appearance of oscillations.

In Fig. 2 the dependence of energy difference $(\mu_e - E_0)$ on bias voltage V_b for a sample with a 50-Å-thick barrier is demonstrated. This was obtained in the standard way from the oscillation period measured at different bias. Below we will return with the reasons for using the value $(\mu_e - E_0)$ to present our results instead of the Fermi energy of the 2DEG, $E_{F(2D)}$. Calculated values for $(\mu_e - E_0)$ are also shown in Fig. 2. These were obtained by a self-consistent solution of the Poisson equation in the Thomas-Fermi approximation,[7] considering a 100-Å-wide region of the emitter adjacent to the barrier to be a 2DEG sheet with a constant density of states. Calculations were made with the constant Fermi level μ_e at the emitter side of the barrier giving Fermi energy of the 2DEG, $E_{F(2D)} = (\mu_e - E_0)$. It is evident in Fig. 2 that the experimental data are markedly higher than the calculated values. Similar results were obtained for a 35-Å-thick barrier but the amplitude of the oscillations decreased for $V_b \geq 600$ mV and merged into the background noise. Oscillations for a 25-Å-thick barrier were too weak to provide any reliable value for $(\mu_e - E_0)$.

Our samples differ from those used in the previous experiments[1–4] since both spacers and barriers are thinner. It was noted above that the model of Chan *et al.*[5] can be applied only if the diffusion current through the spacer is much higher than the tunneling current from the accumulation layer. Otherwise part of the external voltage will drop in the spacer region. Moreover, in our samples the electron escape time τ related to the tunneling through the main barrier becomes comparable with and even smaller than the relaxation time on acoustic phonons, $\tau_{\mathrm{ac}} \approx 10^{-10}$ s, when the barrier thickness decreases. For 50-, 35-, and 25-Å-thick barriers we estimate $\tau \approx 10^{-7}$, 10^{-9}, and 10^{-11} s, respectively.[8] In the last case the tunneling time is so small that 2D electrons are not thermalized and there is a nonequilibrium occupancy of the states.

Evidently electrons in structures with relatively thin spacers can tunnel from the emitter volume into empty states in the accumulation layer. The schematic energy-band diagram under applied voltage is shown in Fig. 3. To estimate the tunneling transparency T we used the experimental results of Gueret *et al.*,[9] who found that $T \propto \exp(-L\sqrt{\varphi})$ for low and long barriers, where L is the length and φ is the height of the barrier. In our case T is comparable for the main and the spacer barrier in magnitude when $(\mu_e - E_0) = 10$ mV. In addition, theoretical calculations of Groshev and Schön[10] indicate that an undoped spacer barrier is 1–2 meV above the Fermi level due to the image forces. Based on these facts, we assume that tunneling through the spacer barrier plays a key role in the electron transfer in our structures.

If electrons tunnel without scattering, the momentum component parallel to the interface is conserved and barrier transparency is determined by the energy E_0 of the ground state of the 2DEG. At equilibrium occupancy of the 2D states in the accumulation layer the current through the spacer region is $j_s \propto T_s N_{(\mu_e - \mu_{2D})}$, where T_s is the transparency of the spacer barrier[11] and $N_{(\mu_e - \mu_{2D})}$ is

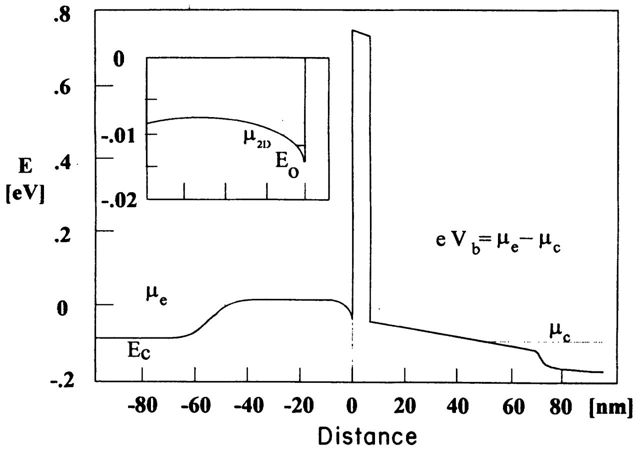

FIG. 3. The schematic conduction-energy-band diagram for the structures at an applied external bias V_b. In the inset is shown the magnified region of an accumulation layer joined close to the barrier. E_0 indicates the ground state energy, μ_{2D} is a Fermi level of the 2DEG. The last is aligned with the emitter bulk Fermi level μ_e, only at the thermodynamics equilibrium in the emitter.

the concentration of empty states in the accumulation layer. The current through the main barrier is $j_j \propto T_m N_s$, where T_m is the transparency of the main barrier. We consider that T_s, T_m, and $(\mu_e - E_0)$ are independent of the magnetic field, because the amplitude of the oscillations does not exceed 1% of the total signal. Then it follows from the continuity of the current $j_m = j_s$,

$$\frac{N_{(\mu_e-\mu_{2D})}}{N_s}=\alpha\frac{T_m}{T_s} \tag{1}$$

or

$$j_m=j_s \propto N_{(\mu_e-E_0)}\frac{T_m}{T_m+T_s}\ , \tag{2}$$

where $N_{(\mu_e-E_0)}$ is the total number of 2D states per unit area in the accumulation layer in the range E_0 to μ_e, α is a constant. It follows from Eq. (2) that the tunnel current oscillates with the same period as the variation of total number of 2D states in the range E_0 to μ_e. The former oscillation is periodic in $1/B$, current minima occur at fields $B=B_f/n$, where $B_f=m^*(\mu_e-E_0)/e\hbar$, and m^* is the effective mass.[5] Thus, only the difference of the energy levels $(\mu_e - E_0)$ can be determined from the oscillation period and, hence, the total number of 2D states in the accumulation layer, $N_{(\mu_e-E_0)}$.[12]

The charge modulation resulting from the oscillation in the 2DEG electron concentration will change the potential distribution along the structure. This in turn modulates the position of the ground state. A more rigorous theoretical analysis requires self-consistently determining the tunneling current, 2D electron concentration, and ground-state position. However, our principal conclusion that current oscillation will correlate with the total number of 2D states in the $(\mu_e - E_0)$ range remains valid.

The proposed model qualitatively accounts for the difference between experimental and calculated values presented in Fig. 2. Another explanation of this difference is the presence of a built-in charge in the barrier (segregation of impurities at the first interface boundary). Extrapolation of the measured results to $V_b=0$ gives a built-in charge concentration $N_{s0} \approx 5\times10^{11}$ cm^{-3}, which seems unreasonable. However, the built-in charge cannot account for the nonparallel character of the curves in Fig. 2. Furthermore, the oscillation amplitude did not depend on the sign of the external bias. This provides evidence for the lack of a predominant segregation of impurities, related to the direction of the structure growth, to any of the main barrier interfaces.

We have also obtained some other results that cannot be accounted for in the model of Chan *et al.*[5] The peak positions in the curves of $\partial I/\partial V_b = f(B)$ were determined by the expression $B = B_f/(n+\phi)$, where B_f is the fundamental magnetic field, n is an integer, and ϕ is a phase factor, $\phi=0.1$. If a redistribution of the potential due to a change in the 2D electron concentration, N_s, were small, then $\phi=0$. It turned out that $\phi \approx 0.25$ for the samples with a 50-Å-wide barrier. The phase factor ϕ is plotted in Fig. 4 as a function of bias. The most interesting result was obtained for $L=35$ Å (circular symbols). Above $V_b \approx 250$ mV, the value of ϕ is equal to zero. This is possible only when N_s decreases with voltage. As the bias increases, the transparency of the main barrier increases with voltage, as usual. Beginning with some N_s value, the situation where $\phi=0$ can be experimentally realized. For $L=50$ Å the required conditions apparently cannot be achieved. Magneto-oscillations were not observed for $L=25$ Å, because the Landau levels were broadened owing to the high transparency of the barrier. It should be noted that in the 35-Å barrier the amplitude of oscillations also decreased at $V_b \geq 600$ mV because of

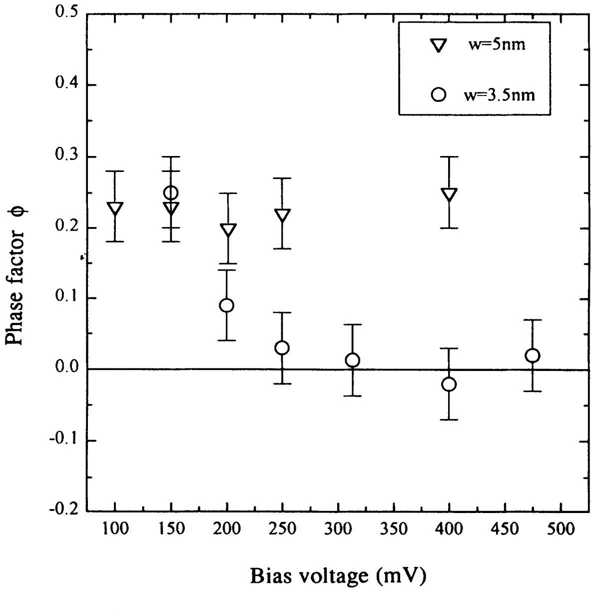

FIG. 4. The phase factor ϕ as a function of applied bias V_b for the samples with 35-Å- (circles) and 50-Å- (triangles) thick AlAs barriers.

increased barrier transparency.

The reason for monotonic magnetoresistance detected at $V_b \approx 0-20$ mV (see Fig. 1) is not fully understood. Its disappearance at higher bias may be attributed to both the appearance of a tunnel channel and disappearance or bypassing of a diffusion current in the spacer region. This interpretation is valid for the case with a small built-in charge in the barrier. However, the structure in this case is very complicated and the disappearance of the monotonic magnetoresistance may be due to some other reasons. Further experiments are required, including measurements in stronger magnetic fields, to elucidate the processes that occur.

Thus, oscillations of the tunnel current with a period $\propto 1/B_\perp$, where $B_\perp$ is the normal to the interface component of the magnetic field, were experimentally observed in the measurements on GaAs/AlAs/GaAs heterostructures with 50-, 35-, and 25-Å-thick AlAs barriers and having spacer layer about 600 Å thick. Analysis of the experimental data showed that the concentration of 2D electrons in the accumulation layer could not be determined from the oscillation period. Only the total number of 2D states that are below the Fermi level of the emitter bulk could be determined.

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[11] If the top of the spacer barrier is below μ_e, then there can be a current over the barrier proportional to the density of empty $2D$ states. Simple estimates for a spacer barrier 1 meV below μ_e show this current to be comparable with tunnel current. In this case T_s can be used, with account taken of the electron transfer over the barrier.

[12] If the 2D electrons do not thermalize, the current through the spacer barrier is still determined by the available number of free states in the accumulation layer, which has a stationary electron concentration. Equations (1) and (2) are still valid and we have a sequential resonant-electron tunneling through the 2D states in the accumulation layer.