Reflection of electrons from an N^-/N^+ junction in GaAs

E. E. Vdovin, Yu. V. Dubrovskiĭ, I. A. Larkin, Yu. N. Khanin
Institute of Problems of the Technology of Microelectronics and Highly Pure Materials, Russian Academy of Sciences, 142432 Chernogolovka, Moscow Region, Russia

T. G. Andersson
Department of Physics, Chalmers University of Technology and Göteborg University, S-412 Göteborg, Sweden

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A resonance tunneling through virtual and hybrid magnetoelectric states in a wide quantum pseudowell has been observed. The pseudowell is bounded on one side by a real heterobarrier and on the other by a smooth drop of the bottom of the conduction band in a region in which the dopant concentration changes (an N^-/N^+ junction in GaAs). © *1995 American Institute of Physics.*

Studies of ballistic transport of electrons in GaAs have shown that about 15% of electrons with energies up to 0.3 eV which are injected across a barrier can travel distances of more than 700 Å without undergoing collisions and without a disruption of phase coherence.[1] As a result, many diverse effects associated with an interference of electrons have been observed in heterostructures with a wide quantum well (300–1000 Å) bounded by two barriers.[2–8] Interference effects have been observed when an electron current flows along the direction perpendicular to the heterolayers, as the result of reflection of electrons from offsets of the bottom of the conduction band. These offsets are produced, in particular, by choosing appropriate combinations of III–V semiconductors. Current oscillations due to a tunneling of electrons through quantum states in a wide well were observed experimentally in Refs. 2 and 3. The oscillations were attributed by the authors to a tunneling through virtual states, i.e., above-barrier energy levels. More experimental effects have been observed when a magnetic field is applied to the structures in a direction perpendicular to the current. The onset of a new series of oscillations in the current was observed in a strong magnetic field $B \perp J$ on the order of 11 T in Ref. 4. These oscillations were linked with hybrid states in a quantum well in crossed electric and magnetic fields. Further study of electron transport in crossed fields in wide quantum wells[5–7] resulted in the observation of oscillations of a different type, caused by tunneling through hybrid magnetoelectric states. This research also resulted in a physical classification of these states ("skipping," "well-traversing," and "bulk-like orbits"). In a logical continuation of earlier research, Fromhold *et al.*[8] studied the energy spectrum of electron states is a trapezoidal potential well in a tilted magnetic field. As the angle through which the magnetic field was tilted with respect to the tunneling current was varied, various series of resonances were observed. The authors attributed them to unstable closed orbits in a chaotic dynamic system.

In this letter we are reporting a study of tunneling resonances in a wide quantum

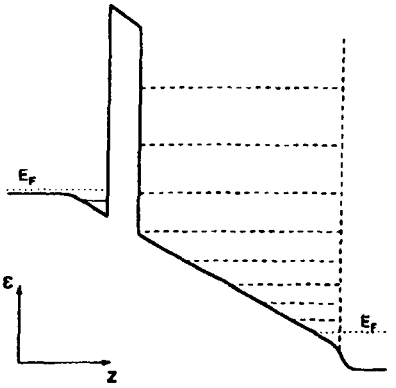

FIG. 1. Schematic energy-band diagram of a test sample at a bias voltage V_b.

pseudowell bounded on one side by a real heterobarrier and on the other by a smooth drop of the bottom (a potential) of the conduction band (Fig. 1). In the absence of a magnetic field we observe aperiodic current oscillations as a function of the applied voltage. We attribute these oscillations to resonance tunneling through virtual quantum levels in the pseudowell. The application of a magnetic field perpendicular to the current suppresses these oscillations and gives rise to a new series of current oscillations, due to a tunneling through hybrid magnetoelectric states in the quantum pseudowell. Our situation differs in a qualitative way from all the experiments mentioned above in that one of the heterobarriers bounding the well is absent. Its function is served by a smooth drop of the bottom of the conduction band at the boundary at which the dopant concentration changes. The reflection coefficient R of a potential drop of this sort turns out to be sufficient for experimental observation of an interference of electrons in the pseudowell.

The test samples were grown by molecular beam epitaxy on a heavily doped N^+-GaAs substrate. The samples consisted of the following sequence of layers: N^+-GaAs, 2×10^{18} cm^{-3}, 4000 Å thick; N^--GaAs, 2×10^{16} cm^{-3}, 500 Å thick; undoped GaAs, 100 Å thick; undoped AlAs, 35 Å thick; undoped GaAs, 100 Å thick; N^--GaAs, 2×10^{16} cm^{-3}, 500 Å thick; N^+-GaAs, 2×10^{18} cm^{-2}, 4000 Å thick. Ohmic contacts were formed by depositing a Ni–Ge–Au system and then annealing it. The standard chemical-etching technique was used to create a mesa structure 100 μm in diameter.

Figure 2 shows the differential conductance $\partial I/\partial V_b$ versus the bias voltage in the absence of a magnetic field at $T=4.2$ K. In the observed interval of bias voltages V_b we see eight resonances (minima on the plot of $\partial I/\partial V_b$ versus V_b), which correspond to resonance tunneling through eight low-lying levels in the quantum pseudowell.

Figure 3 shows the second derivative of the current with respect to the voltage, $\partial^2 I/\partial V_b^2$, for various values of a magnetic field $B\perp J$. The average distance between resonances in the absence of a magnetic field, $\Delta V_b\approx45$ mV, agrees with the corresponding values in Refs. 2–4 and 9, after we correct for the width of the quantum well and the effective electron mass. The amplitude is smaller by two or three orders of magnitude.

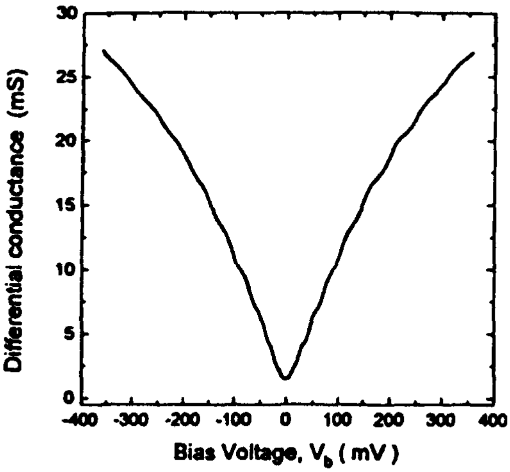

FIG. 2. The differential conductance $\partial I/\partial V_b$ versus the bias voltage V_b at $B=0$ T and $T=4.2$ K.

The resonance structure weakens and shifts slightly toward higher voltages as the magnetic field is raised to $B\sim3.5$ T. This effect has been observed previously[4] and has been explained on the basis of changes in the transverse angular momentum by an amount eBd, because of the Lorentz-force-induced tunneling. Here d is the barrier thickness. The decrease in the amplitude of the resonances in our case cannot be attributed to a decrease in the total current due to a magnetoresistance. This fact was confirmed by direct measurements. Once the magnetic field reaches the value $B\sim4$ T, a new oscillation structure

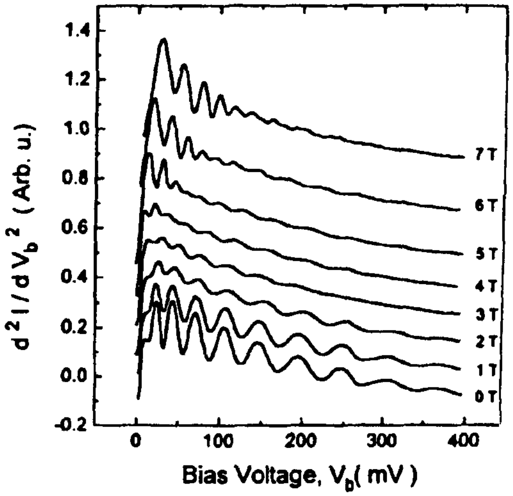

FIG. 3. Second derivative of the current, $\partial^2 I/\partial V_b^2$, versus the bias voltage V_b in a magnetic field perpendicular to the current ($B\perp J$). The parameter here is the strength of the magnetic field. The curves are shifted arbitrary distances in the vertical direction.

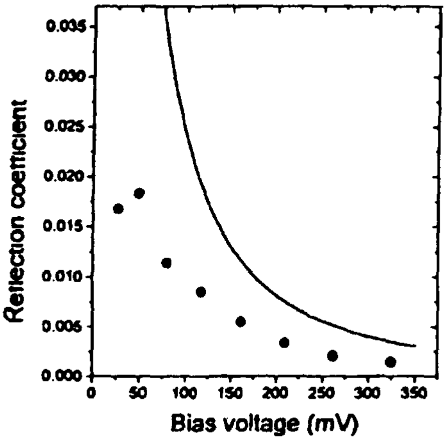

FIG. 4. Theoretical behavior of the reflection coefficient R at a sharp step 87 mV high (solid curve) and experimental values of the relative increase in the current at the resonances, equated to the reflection coefficient, versus the bias voltage V_b.

begins to form on the second derivative at low voltages. This structure also shifts toward higher voltages as the magnetic field is raised. Such oscillations are customarily attributed to hybrid magnetoelectric states in a quantum well.[5] The application of a magnetic field parallel to the current causes only a negligible increase in the amplitude of the resonances with respect to that in a zero magnetic field. This effect, too, has been observed previously, in double-barrier structures with a wide quantum well.[2] It has been attributed to a weakening of scattering in the well due to a decrease in the number of final states to which the scattering can lead.

As was mentioned above, the primary distinctive feature of our structure is that one of the potential barriers flanking the potential well is not actually present. The role of this barrier is played in our case by a drop of the bottom of the conduction band at the boundary at which the dopant concentration changes. This potential drop has a reflection coefficient ranging from 3% to 0.3% over the energy interval of interest here. The solid curve in Fig. 4 shows the reflection coefficient of a steep step 87 mV high (which agrees with the potential drop in our structure) calculated as a function of the energy of the incident electron under the assumption that the energy of the electron is the same as the external voltage applied to the structure. It follows from the theory of resonance tunneling[10] that, for a system consisting of a quantum well flanked by two barriers with very different transmissions, the contribution of the resonance component to the total current, $\Delta I/I$, should be equal to the reflection coefficient R of the barrier which is the better transmitter (in our case, the potential drop). Experimental values of the relative change in the current at the resonance as function of the applied voltage are shown in Fig. 4. The discrepancy with the theoretical curve can be explained easily, on the basis of the smoothness of the potential drop in the real structure, which leads to a decrease in the reflection coefficient by an amount on the order of[11] $\exp(-\Delta W/\lambda)$, where ΔW is the distance over which the potential changes, and λ is the wavelength of the electron.

We believe that this comparison of our experimental data with the results of measurements in wide quantum wells[2-9] and the good agreement between the measured reflection coefficient and the theoretical estimates confirm that the current oscillations which we have observed are associated with a resonance tunneling through virtual states in a quantum pseudowell bounded on one side by a heterobarrier and on the other by a smooth drop of the bottom of the conduction band.

In summary, we have observed a resonance tunneling through virtual and hybrid magnetoelectric states in a quantum pseudowell. The electron-interference effects which were detected were observed by virtue of reflection from the boundary at which the dopant concentration changes (N^-/N^+) in the GaAs.

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