Zero-bias tunnel anomalies in single-barrier heterostructures

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Electron tunneling in heterostructures with single barriers and spacers of different thicknesses under a low bias (several millivolts) in a magnetic field have been experimentally studied. We have detected anomalous behavior of the tunnel current seen as a conductivity or resistance peak at zero bias (zero-bias tunnel anomalies). We have demonstrated that the conductivity peak in a structure with a relatively thick spacer is due to the resonant tunneling between 2D electron layers generated on both sides of the barrier due to the built-in positive charge in the barrier. The behavior of the conductivity peak versus magnetic field is interpreted in terms of a tunneling gap due to the correlation interaction of 2D electrons. The amplitude of the resistance peak in a structure with a thin spacer grows exponentially with a magnetic field aligned with the tunneling current. The origin of the resistance peak and its behavior in a magnetic field have not yet been accounted for. © *1996 American Institute of Physics.* [S1063-7761(96)01203-3]

1. INTRODUCTION

The term "zero-term tunnel anomalies," i.e., anomalies at zero bias across a heterobarrier, is applied to any peaks on the conductivity curve caused largely by tunnel processes, including deformations of the barrier potential by the bias voltage. A peak of resistance or, in some cases, a peak of conductance is observed in almost all experiments with normal (not superconducting) tunnel structures at zero bias. A detailed review of early experiments (till 1984) and a discussion of results are given in the monograph by Wolf.[1] Various models were proposed for specific tunnel systems to interpret the recorded zero anomalies, although some experimental data have not yet been accounted for.[2] Since 1980s semiconductor tunnel systems with heterobarriers manufactured using molecular beam epitaxy have been studied extensively. The composition of these structures is easier to control than that of metal–dielectric–metal structures, which were traditionally used in earlier tunnel experiments. After the development of techniques designed to manufacture structures with multiple heterojunctions, the interest of researchers has been focused largely on double-barrier structures, superlattices, etc.[3] The interest to single-barrier heterostructures has apparently flagged. Some researchers, nonetheless, reported on zero-bias anomalies like a resistance peak in structures with a single heterobarrier,[4] but the origin of these anomalies has not been determined.

The paper reports on an experimental study of zero-bias tunnel anomalies in tunnel structures with a single heterobarrier of two types. The main difference between them is the thickness of spacers, i.e., low doped regions near junction interfaces separating junctions from heavily doped contacts in order to prevent diffusion of dopants from contact regions to heterobarriers during their growth. In samples of the first type the spacer thickness is 60 nm. Samples of the second type have 5-nm spacers and are similar to those described in Ref. 4. A conductance peak was observed in type I samples at zero bias, and a resistance peak in samples of the second type. Our results lead us to a conclusion that the conductance peak at zero bias in type I samples type is due to the resonant tunneling between 2D electron accumulation layers generated on both sides of the barrier due to the built-in positive charge in the barrier. In type II samples, we have observed a resistance peak, which increases exponentially with a magnetic field normal to the interface. This growth in the peak amplitude is evidently not related by thermal activation phenomena. The conductance peak in type I samples splits under a normal to the interface magnetic field higher than 10 T. We interpret this effect in terms of a tunneling gap caused by the correlation interaction of 2D electrons in a quantizing magnetic field.

2. SAMPLES

All the samples were grown by the molecular beam epitaxy and include the following layers:

type I samples: GaAs contact layer with $n^+=2\cdot 10^{18}$ cm^{-3}; GaAs spacer with $n=2\cdot 10^{16}$ cm^{-3} 50 nm thick; undoped GaAs spacer 10 nm thick; undoped AlAs barrier 5 nm thick; undoped GaAs spacer 10 nm thick; GaAs spacer with $n=2\cdot 10^{16}$ cm^{-3} 50 nm thick; GaAs top contact layer with $n^+=2\cdot 10^{18}$ cm^{-3};

type II samples: GaAs contact layer with $n^+=3\cdot 10^{18}$ cm^{-3}; GaAs contact layer with $n^+=3\cdot 10^{17}$ cm^{-3} 5 nm

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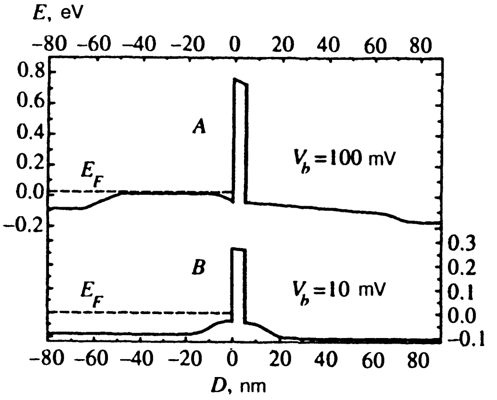

FIG. 1. Energy band diagrams of tunnel structures: *A*) type I structure under a bias of 100 mV; *B*) type II structure under a bias of 10 mV; *E* denotes energy and *D* separation from the barrier interface.

thick; undoped GaAs spacer 5 nm thick; undoped $Ga_{0.4}Al_{0.6}As$ barrier 5 nm thick; undoped GaAs spacer 5 nm thick; GaAs layer with $n^+=3\cdot10^{17}$ cm^{-3} 5 nm thick; GaAs top contact layer with $n^+=3\cdot10^{18}$ cm^{-3}.

Energy band diagrams of our samples calculated in the Thomas–Fermi approximation are given in Fig. 1.

3. MEASUREMENTS OF SAMPLES WITH 60-nm SPACERS (type I)

The differential resistance of a sample versus bias voltage V_b is shown in Fig. 2. Sample parameters were measured using an RCL bridge device produced by Hewlett–Packard, which allowed us to record $I=f(V_b)$, $\partial I/\partial V_b=f(V_b)$, and the effective barrier capacitance $C=f(V_b)$ (the latter is given in Fig. 3). The parameter of curves in Figs. 2 and 3 is the value of the magnetic field normal to the interface. Measurements were performed at 4.2 K. The bias was modulated at an amplitude of 1 mV. The curves recorded at modulation frequencies of 0.5 and 1.0 MHz are identical. The curves of both differential conductance and capacitance were essentially unchanged with temperature down to 1.3 K. A magnetic field aligned parallel to interfaces also did not change the shape of the differential conductance versus bias voltage.

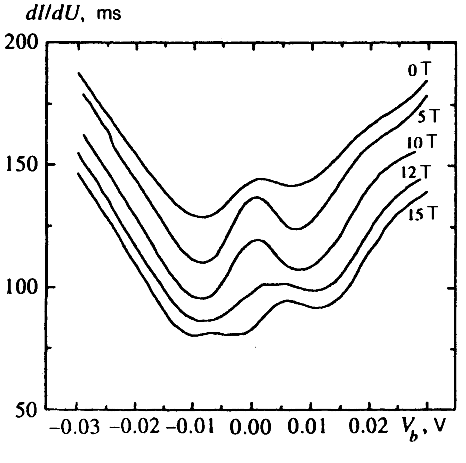

FIG. 2. Differential resistance versus bias. The parameter of the curves is the magnetic field aligned with the normal to the interface. The sample is type I with a 60-nm spacer.

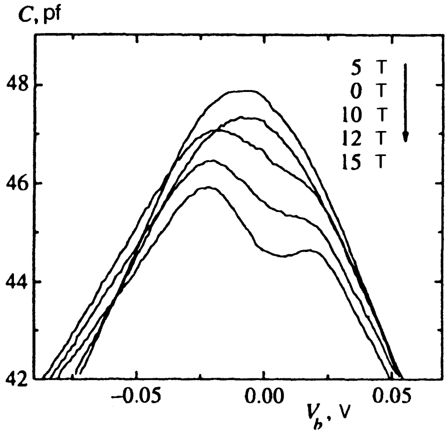

FIG. 3. Capacitance of tunnel structure versus bias. The parameter of the curves is the magnetic field aligned with the tunnel current. The sample is type I with a 60-nm spacer.

The main features of presented experimental data are the following:

a) there is a conductance peak on tunneling characteristics at zero bias voltage;

b) tunneling characteristics are slightly asymmetrical;

c) the peak on the curve of capacitance versus bias at zero magnetic field is shifted with respect to zero bias;

d) under a low magnetic field the conductance peak is sharper, and under a field beyond 10 T it is split, which indicates that the tunneling is suppressed at zero bias voltage;

e) there is a local minimum on the curve of capacitance versus bias voltage under a high magnetic field.

4. DISCUSSION OF MEASUREMENTS IN SAMPLES WITH 60-NM SPACER (type I)

Since samples are epitaxially grown layer by layer and the diffusion of impurities in the vertical direction is inevitable, it is impossible to fabricate absolutely symmetrical structures, therefore their tunnel characteristics are slightly asymmetrical, and the maximum on the curve of capacitance versus bias is shifted with respect to the zero voltage. The capacitance drops with the bias because a depletion layer is formed on the collector side of the structure. Note that the characteristics were measured using the two-terminal probe method, and the resistance of ohmic contacts to the semiconductor, which could not be measured independently, contributed to the tunnel characteristics. Our measurements indicate that this resistance is much smaller than the tunnel barrier resistance. Nevertheless, sometimes ohmic contacts degraded, hence the voltage across the junction should be interpreted with care.

Although the tunneling characteristics are clearly asymmetrical, the conductivity peak is centered at the zero bias to within the experimental accuracy. We suppose that this peak is due to the diffusion doping and electrically active defects in the barrier material. Positively charged defects in the barrier generate two-dimensional accumulation layers

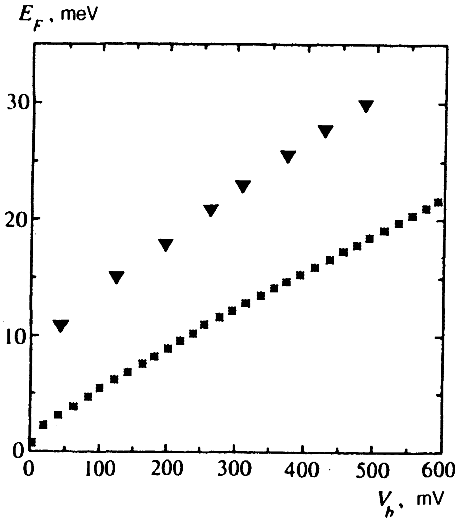

FIG. 4. Fermi energy of two-dimensional electron gas in the accumulation layer versus bias. The experimental points (▼) are derived from the period of quantum oscillations in magnetic field, the points marked by (*) are calculations.[5] The sample is type I with a 60-nm spacer.

on both sides of the barrier. The shape of the confining potential in the 2D layers is controlled by the electric field near the GaAs/AlAs interface due to the dopant distribution in GaAs, which is almost identical on both sides of the barrier. As a result, the accumulation layers on both sides are identical with equal ground-state energies, irrespective of the charge distribution in the barrier, like in the case of an infinite charged plane. Therefore the tunneling across the barrier is resonant at zero bias, and the bias drives the system out of the resonance, which leads to a drop in the conductance. The conductance is again higher at a bias beyond 10–15 mV because the barrier is reshaped by the external voltage. The existence of the built-in charge in the barrier is confirmed by measurements of the electron Fermi energy in the accumulation layer versus bias (Fig. 4). The Fermi energy, which is proportional to the electron density in the two-dimensional case, was derived from oscillations of the tunneling current with the magnetic field normal to the interface. These oscillations are related with Landau quantization of two-dimensional electrons.[5] The extrapolation of the measured Fermi energy and electron density to zero bias indicates that positive charges are present in the barrier. The electron density derived from measurements of the Fermi energy yields the upper estimate of the built-in charge since the real Fermi energy in the 2D layer may be smaller than the measured value.[5]

The most interesting feature of our experiments is the splitting of the conductivity peak under a magnetic field higher than 12 T. Note that there is also a local minimum on the capacitance characteristics under a magnetic field beyond 10 T. It is known that the so-called quantum capacitance[6] proportional to the density of states on the Fermi level of the 2D electron gas contributes to the measured capacitance. This contribution allows us to observe quantum oscillations of the capacitance periodic in $1/B$. Simultaneous measurements of the capacitance and conductance oscillations at various voltage biases demonstrate that the capacitance drops considerably only when the first Landau level is partly filled. Therefore we relate the minimum on the capacitance curve to the partial filling of the first Landau level in the accumulation layer. The bias increases the depth of the 2D electron well and the electron density which leads to a minimum on the curve of capacitance at zero voltage bias. In the ultraquantum limit, when only the first Landau level is partially filled, the splitting of the conductance peak cannot be related to transitions between any quantum levels. The spin splitting also should not affect the resonant nature of tunneling at zero bias. We assume that the observed splitting of the conductance peak is due to the suppression of tunneling by the magnetic field at zero voltage bias.

The suppression of the tunneling current in magnetic field was observed in several experiments.[7,8] Ashori *et al.*[7] reported in 1990 on their study of tunneling between 2D and 3D states in a magnetic field aligned with the tunneling current in the ultraquantum limit at a small bias applied to the structure so that the system should be in the thermodynamic equilibrium. They found that in this case the magnetic field suppressed the electron tunneling. The effect was independent of the filling of the ground Landau level. The authors interpreted their results as an indication of a gap in the density of states on the Fermi level induced by magnetic field. In 1992 similar experiments on tunneling between 2D electron systems were reported by Eisenshtein *et al.*[8] They also asserted that tunneling was suppressed by magnetic field, and this effect was named the tunnel gap. They assumed that the effect was due to a strong correlation between electrons at the ground Landau level. An additional energy needed for electron tunneling between "correlated electron liquids" is $e^2/\varepsilon\langle a\rangle$, where ε is the electron charge, ε is the dielectric constant, and $\langle a\rangle$ is the averaged distance between 2D electrons. This concept was developed in the theory by He *et al.*[9] In their later publication Ashori *et al.*[10] contended that some experimental data[7,10] disagree with the theoretical model of Ref. 8.

It is feasible that in our experiments the magnetic suppression of tunneling is of the same nature as in experiments of Refs. 7 and 8. Naturally, more experimental evidence is needed to prove this statement. We should make, however, some relevant remarks. Unlike samples studied by Ashori *et al.* and Eisenshtein *et al.*,[7,8] our samples have a considerably lower mobility of 2D electrons. Our estimates yield a mobility below 10^5 cm^2/V·s. This means that under a high magnetic field 2D electrons may be in a dielectric state. In this case magnetic field may suppress the tunneling because of a strongly localized electron of the 2D gas interacts with a hole in this gas that results in an additional tunnel barrier with a height of about $e^2/\varepsilon\langle a\rangle$.[10]

5. MEASUREMENTS OF SAMPLES WITH 5-nm SPACERS (type II) AND DISCUSSION

Curves of the differential resistance of type II samples versus bias voltage recorded using a lock-in amplifier at a modulation frequency of 1 kHz have peaks at zero bias. The peak amplitude is about 0.4% of the total sample resistance of about 10 Ω. Under a magnetic field normal to the interface the peak amplitude increases. At a bias voltage beyond

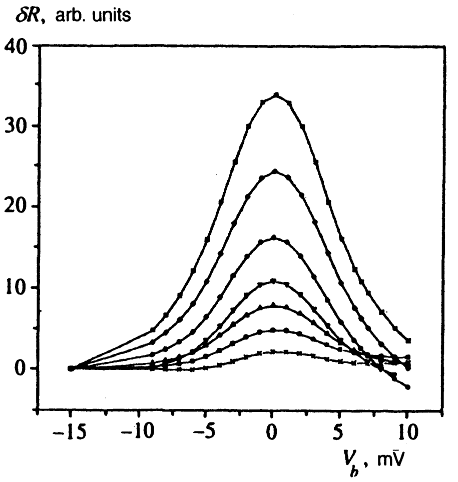

FIG. 5. Additional resistance δR due to magnetic field aligned with the tunnel current versus bias. The curves were measured under a magnetic field ranging between 2 and 8 T with an increment of 1 T. The peak amplitude grows with the magnetic field. The sample is type II with a 5-nm spacer.

20 mV the differential resistance is constant. A magnetic field parallel to the interface does not affect the differential resistance. In order to obtain more detailed data about the effect of magnetic field on the zero-bias peak, we employed the following procedure. The second derivative $\partial^2 V_b/\partial I^2 = f(V_b)$ was measured at various magnetic fields. The difference between measurements in magnetic field and without magnetic field was integrated numerically. The results of this procedure are shown in Fig. 6. Figure 6 shows the logarithm of the calculated peak amplitude versus magnetic field. One can see that the experimental points are well approximated by an exponential curve. The minimum modulation amplitude in our experiments was 0.6 mV and determined by the inherent noise of electronics. The modulation amplitude was higher than the temperature of 4.2 K, expressed in volts, at which measurements were performed. Experiments were performed at various modulation amplitudes, and in all cases the exponent parameter was constant with a 10% accuracy, which indicated that the magnetic field dependence of the resistance peak amplitude was not controlled by activation processes.

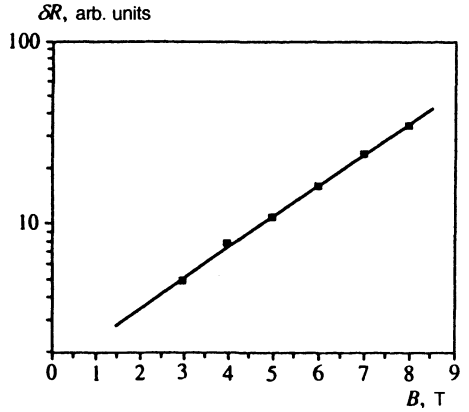

FIG. 6. Measurements of additional resistance δR at zero bias versus magnetic field. The solid line shows the function $\delta R = 1.58\ \exp(B/2.7)$ derived by the least-squares method. The sample is type II with a 5-nm spacer.

Presently we cannot account for the resistance peak at zero bias and the magnetic field dependence of its amplitude in type II samples. We attempted to interpret the peak at zero magnetic field in terms of a drop in the density of states around the Fermi level in heavily doped contact regions of the tunneling structure.[12] But the expected direct proportionality in this model between the conductance and $\sqrt{V_b}$ around zero bias was not observed.

6. CONCLUSION

We have detected anomalies in characteristics of tunnel structures at zero bias as the conductance peak in structures with a single heterobarrier and 60-nm spacers and the resistance peak in samples with 5-nm spacers. The conductance peak is due to the resonant tunneling between two-dimensional electron layers generated on both sides by positive charges in the barrier. Under a magnetic field normal to the interface the conductance peak is split. The most probable cause of this effect is the suppression of tunneling current by Coulomb correlations in the 2D electron gas. The resistance-peak amplitude in type II structures exponentially increases with the magnetic field. This behavior has not yet been accounted for.

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