RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 52, NUMBER 24 15 DECEMBER 1995-II

Resonant tunneling through two impurities in disordered barriers

A. K. Savchenko and V. V. Kuznetsov
Department of Physics, Exeter University, Stocker Road, Exeter EX4 4QL, United Kingdom

A. Woolfe, D. R. Mace, M. Pepper, D. A. Ritchie, and G. A. C. Jones
Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, United Kingdom

(Received 2 October 1995)

In short lateral barriers of GaAs metal-semiconductor field-effect transistor, we have observed resonant tunneling through two impurities. Contrary to a steplike feature in $I(V)$ due to an elementary one-impurity resonance, the two-impurity resonance manifests itself as a peak in the current. A magnetic field strongly suppresses the peak amplitude but has little effect on its width. We analyze the magnetic-field and temperature dependences of the two-impurity resonances.

The presence of localized states in a tunneling barrier changes dramatically the conductance of the barrier.[1-10] At low temperatures resonant tunneling (RT) through localized states is responsible for conduction. In mesoscopic barriers with a small area an elementary conductance channel has been resolved: resonant tunneling through one impurity.[1-4,7-9] In lateral transistor structures[1-3] RT through one impurity is seen as a distinct spike in the Ohmic conductance, G, versus the gate voltage, V_g. Resonance corresponds to the alignment of the Fermi level in the contacts, μ, with the energy of the localized state, ε_i. The amplitude of the conductance spike is determined by the ratio of the leak rates from the impurity to the contacts: $\Gamma_{L,R} \approx \varepsilon_0 \exp(-2r_{L,R}/a)$, where $r_{L,R}$ is the distance between the impurity and the left (right) contact, a is the electron localization radius, and $\varepsilon_0 \approx \hbar^2/2ma^2$ is the height of the barrier. If $\Gamma_L = \Gamma_R$ the spike amplitude has its maximum value $G \approx e^2/h$. For a rectangular barrier this condition corresponds to an impurity placed in the middle of the barrier. When the impurity is shifted from the optimal position the spike amplitude decreases exponentially: $G \approx (e^2/h)\Gamma_{\min}/\Gamma_{\max}$.

In this work we have studied an elementary RT channel through two impurities. The authors of Ref. 6 ascribe to RT through several impurities an anomalous length dependence of averaged conductance in Si metal-oxide-semiconductor field-effect transistors which is temperature independent below 100 mK. They suggest that this conductance is determined by a large number of tunneling paths and this number increases with increasing length of the gate from 1 to 8 μm. However, the authors of Ref. 6 admit that there is no satisfactory theoretical explanation yet for this effect. Here, with smaller GaAs barriers we have directly detected an individual RT channel through two impurities. RT through two impurities has been discussed in theory.[11] It occurs when the electron energy in the contacts coincides with that of two aligned localized states (see Fig. 1). It also gives a spike in the conductance, with an amplitude which depends on the distance between the impurity and the nearest contact, $r_{L,R}$, and also on the separation between the impurities r_{ij}. The maximum value of the conductance e^2/h is now realized at the condition $|H_{ij}|^2 = \Gamma_L \Gamma_R$, where $H_{ij} \approx \varepsilon_0 \exp(-r_{ij}/a)$ is the overlap integral between the impurities. For a rectangular barrier this means that the distance r_{ij} is half the barrier length.

There is a direct way to distinguish between one- and two-impurity RT: by measurement of the $I(V)$ characteristics. With increasing source-drain bias along the barrier, $V_{\rm sd}$, all the localized states are shifted down (Fig. 1) and the closer the state is to the drain contact the larger its shift. In the one-impurity case, the current through the impurity switches on when the impurity level passes through the

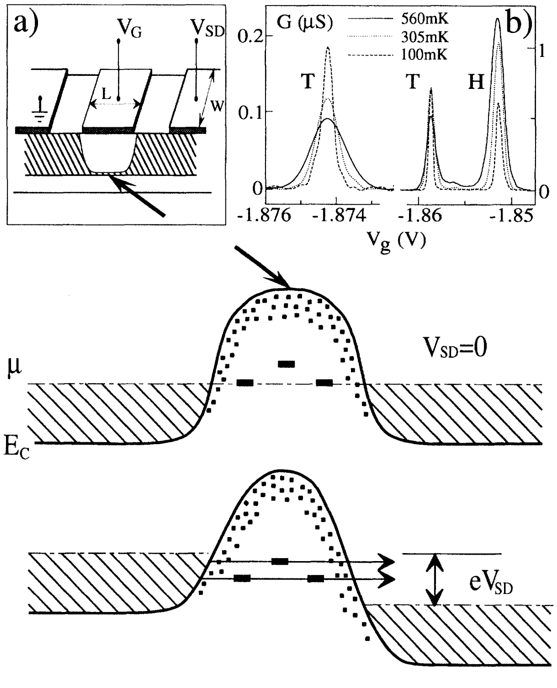

FIG. 1. Schematic diagram of the barrier with RT through one and two impurities in the Ohmic regime, $V_{\rm sd}=0$, and at a positive $V_{\rm sd}$. Insets: (a) cross section of the transistor structure with metalliclike source and drain (shaded area) and the barrier between them (indicated by the arrow); (b) spikes in the Ohmic conductance versus gate voltage at different temperatures: T, resonant tunneling, H, hopping.

0163-1829/95/52(24)/17021(4)/$06.00 52 R17 021

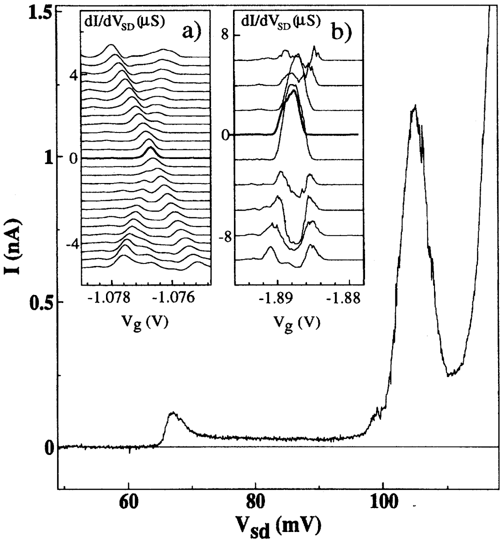

FIG. 2. $I(V_{sd})$ at $V_g = -2.1$ V with a step and a peak in the current, $T = 50$ mK. Insets: differential conductance as a function of gate voltage for different V_{sd}; (a) for one-impurity RT and (b) for two-impurity RT. Highlighted curves correspond to $V_{sd} = 0$; the offset curves are measured for both directions of V_{sd} with step (a) $\Delta V_{sd} = 40$ μV and (b) $\Delta V_{sd} = 220$ μV.

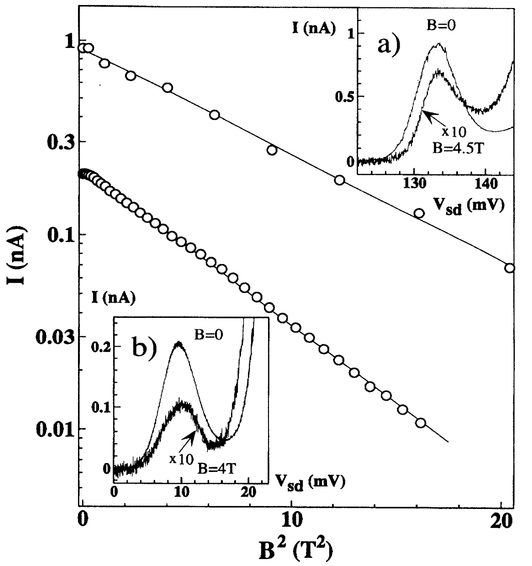

FIG. 3. Exponential suppression of the peak amplitude by perpendicular magnetic field, $T = 4.2$ K. Insets: two peaks with and without magnetic field; (a) "first" and (b) "second."

Fermi level in the left contact, and a further increase of V_{sd} does not change the current significantly. This should produce a steplike feature in the $I(V_{sd})$. A feature similar to such a step has been seen in diode vertical structures: a-Si/SiO$_x$ (Ref. 4) and GaAs/Ga$_x$Al$_{1-x}$As,[8] although in the latter it was modified by the "Fermi singularity."[12] In the case of two impurities, however, the resonance occurs only at a particular V_{sd} corresponding to the alignment of the two levels. With an increase of V_{sd} the levels will move out of resonance due to the difference in their shift rate. Thus a peak in the $I(V_{sd})$ should appear with a region of negative differential conductance.

The peak in the current will only occur if the two states are placed along the barrier length. In a thin vertical barrier, for instance, with two coupled states in the plane of the barrier, "donor molecule,"[9] the current feature will not be different from the one-impurity step. It was shown in Ref. 11 that the conductance of the two-impurity RT channels becomes comparable with that of the one-impurity channels if the barrier length and the density of localized states, g, increase. This is why lateral barriers, longer than vertical ones, are better for the observation of two-impurity RT. In addition, in these structures the value of g can be varied significantly by changing V_g.

Our samples are based on a doped GaAs layer of 0.15 μm thickness grown on an insulating substrate, inset (a) to Fig. 1. A high donor concentration of $\sim 10^{17}$ cm^{-3} provides metalliclike conduction in the source and drain. The Fermi level in the contacts is positioned against the tail of localized states in the barrier under the gate. The gate length in the direction of the current, L, is 0.2 μm and in the perpendicular direction it is 10–100 times larger, $W = 2-20$ μm, in order to increase the probability of two-impurity configurations. The measurements of the current were performed in the temperature range 50 mK–10 K, together with measurements of the differential conductance dI/dV_{sd} at $V_{sd} = 0$ and at different V_{sd} biases.

In the $G(V_g)$ we have seen well-separated spikes as in inset (b) to Fig. 1. The spikes behave in a quite different way with increasing temperature. The spikes with increasing amplitude are connected with inelastic tunneling, i.e., hopping via a few impurities.[13] The spikes with decreasing amplitude have been associated with RT through either one or two impurities. We apply to the two-impurity RT the same logic as for one-impurity RT which was developed in Ref. 14 and used in experiment.[1] This means that the decrease of the spike amplitude with a simultaneous increase of its width is a result of the smearing of the resonance by inelastic processes, if $\Gamma^{in} \gg \Gamma^e$, or by the Fermi distribution in the contacts, if $3.5k_BT \gg \Gamma^e$.

To distinguish between one- and two-impurity RT we have studied the $I(V_{sd})$ characteristics. Ten samples have been measured and in all of them peaks in the current have been seen at some resonant combination (V_{sd}, V_g). These two voltages control the exact position of the energy levels in the barrier with respect to the Fermi level.[10] A tendency has been established that the number of resonances in the current increases with increasing width of the gate W from 2 to 20 μm. In addition to the peaks we have also seen steps in $I(V_{sd})$. In Fig. 2 an example of $I(V_{sd})$ at a fixed V_g is shown where both a steplike feature, with a plateau after the current threshold, and a peak in the current occur. The step in this figure is clearly disturbed at the current threshold. A divergent peculiarity appears when the resonant state passes the Fermi level and possibly indicates some interaction of the tunneling electrons with the contacts. A similar feature in a vertical GaAs structure[8] was explained as the "Fermi singularity."[12] We are not inclined, however, to connect the observed peculiarity with the Fermi singularity. This effect is potentially strong for a very short barrier, when $\lambda_F/L > 1$

and electron interaction with the contacts is not screened, while our lateral barrier is ten times longer than that in the vertical diodes.

The amplitude of the current step due to one-impurity RT is $I_0 \sim \partial I/\partial V(\Gamma^{(1)}_{\mathrm{min}}/e) \sim (e^2/h)(\Gamma^{(1)}_{\mathrm{min}}/\Gamma^{(1)}_{\mathrm{max}})(\Gamma^{(1)}_{\mathrm{max}}/e) \sim (e/h)\Gamma^{(1)}_{\mathrm{min}}$. As we will show below the amplitude of the current peak due to the two-impurity RT can be expressed in a similar form: $I_0 \sim (e/h)\Gamma^{(2)}_{\mathrm{min}}$. The value of $\Gamma^{(1)}_{\mathrm{min}}$ is expected to be much less than $\Gamma^{(2)}_{\mathrm{min}}$ since a typical separation $r^{(1)}$ with one impurity in the barrier is larger than $r^{(2)}$ with two impurities. This agrees with Fig. 2, where the amplitude of the plateau is much smaller than the amplitude of the peak.

The difference between one- and two-impurity RT is also seen in the evolution of the differential conductance $dI/dV_{\mathrm{sd}}(V_g)$ with applied source-drain bias (insets to Fig. 2). At a fixed V_{sd} and sweeping V_g the states are moved with respect to the Fermi levels in the contacts which are now shifted by eV_{sd} (Fig. 1). Thus the one-impurity conductance spike is split into two spikes corresponding to the two moments when the impurity level passes the Fermi level [Fig. 2, inset (a)]. The separation between the split spikes ΔV_g increases with V_{sd} as $\Delta V_g = \Delta V_{\mathrm{sd}}/\alpha$, where the coefficient $\alpha = \Delta E/\Delta V_g \sim 0.2$ characterizes the rate of the energy-level movement with V_g. The splitting of the conductance spike is also seen in the two-impurity case [Fig. 2, inset (b)]. A characteristic difference from Fig. 2, inset (a), however, is a region of negative differential conductance which appears with applying V_{sd}.

The peaks in the current are suppressed by a perpendicular magnetic field. We compare the magnetic-field dependence of two peaks observed in two identical samples (Fig. 3). These peaks have a similar width, $\Delta V_{\mathrm{sd}} \approx 3$ mV, which is hardly affected by magnetic field. On the other hand, the amplitude of the peaks exponentially decreases with magnetic field: $I_0(B) = I_0(B=0)\exp(-A_I B^2)$, with $A_I = 0.12$ and 0.18 T^{-2} for the first and second peaks, respectively.

To analyze the magnetic-field dependence of the peaks we have integrated the differential conductance for the two-impurity RT from[11]

$$g(\varepsilon) \approx (2e^2/\pi\hbar)\frac{\Gamma_L\Gamma_R|H_{ij}|^2}{|(\varepsilon-\varepsilon_i+i\Gamma_L)(\varepsilon-\varepsilon_j+i\Gamma_R)-|H_{ij}|^2|^2}, \tag{1}$$

where ε is the electron energy, ε_i and ε_j are the energies of the two impurities, $\Gamma_{L,R}$ is the leak rate from one impurity to the nearest contact, and H_{ij} is the overlap integral. We consider the case when eV_{sd} and the Fermi energy in the contacts, $\varepsilon_F \sim 10$ meV, are larger than the energy width of the resonance, i.e., the two levels lie well below the Fermi level in the left contact (Fig. 1). Then the current at $T=0$ is

$$I(V) \approx (2e/\hbar) \times \frac{\Gamma_L\Gamma_R|H_{ij}|^2}{(V^2\Gamma_L\Gamma_R)/(\Gamma_L+\Gamma_R)+(\Gamma_L+\Gamma_R)(\Gamma_L\Gamma_R+|H_{ij}|^2)}, \tag{2}$$

where $eV = \varepsilon_i - \varepsilon_j$ is the separation between the two levels. With a V_{sd} applied it varies as $\Delta V = \beta \Delta V_{\mathrm{sd}}$ with a coefficient $\beta < 1$ determined by the position of the impurities and the electric-field distribution along the barrier. The expression (2) gives the Lorentzian shape of the peak with the amplitude and width dependent on three parameters: Γ_L, Γ_R, and H_{ij}. In general, the amplitude is determined by the largest, r_{max}, separation among r_L, r_R, and r_{ij}, while the width is determined by the smallest separation, r_{min}. The magnetic field decreases all three parameters H_{ij}, Γ_L, and Γ_R due to the squeezing of the electron wave functions. However, this decrease is stronger for the parameter determined by the larger separation. This explains why the peak amplitude is more strongly affected by magnetic field than its width.

In more detail, in the two-impurity RT there are two physically different situations: $|H_{ij}|^2 > \Gamma_L\Gamma_R$ when the impurities are close to each other, and $|H_{ij}|^2 < \Gamma_L\Gamma_R$ when they are closer to the contacts. In the first case, a strong overlap of the two states near the resonance will split the resonant level and in (1) there will be two spikes separated by an energy of about $|H_{ij}|^2$. In the second case the shape of resonance in $G(V_g)$ is similar to that for the one-impurity RT. From the simple shape of the spikes in Fig. 1, inset (b) we conclude that we are dealing with the situation when the separation r_{ij} between the impurities is relatively large. This could result from an increased density of localized states near the contacts, as is seen in Fig. 1. It follows from (2) that in the case $|H_{ij}|^2 < \Gamma_L\Gamma_R$ the peak amplitude I_0 and peak width ΔV (i.e., the value of V when the current is half the amplitude) are

$$I_0 \approx (2e/\hbar)|H_{ij}|^2/\Gamma_{\mathrm{max}} = (2e/\hbar)\varepsilon_0\exp[-2(r_{ij}-r_{\mathrm{min}})/a], \tag{3}$$

$$e\Delta V = (\Gamma_L+\Gamma_R) \approx \Gamma_{\mathrm{max}} = \varepsilon_0\exp(-2r_{\mathrm{min}}/a). \tag{4}$$

The exponential magnetic-field dependence of the amplitude agrees with the behavior of a localized wave function in a small magnetic field:[15] $\psi(r) = \psi_{(B=0)}\exp(-ar^3/24\lambda^4)$, where $\lambda = (\hbar/eB)^{1/2}$ is the magnetic length. In (3) the magnetic field affects primarily the smallest value $|H_{ij}|^2$ which is determined by the largest separation r_{ij}. Since the value of $|H_{ij}|^2$ is proportional to the square of the wave function the coefficient A_I is $(e^2/12\hbar^2)ar^3_{ij}$. The magnetic-field dependence of the width from (4) is determined by a similar coefficient $A_{\Delta V} = (e^2/12\hbar^2)ar^3_{\mathrm{min}}$, which is about 0.008 T^{-2} for the first peak. Comparing A_I and $A_{\Delta V}$ gives the ratio $r_{ij}/r_{\mathrm{min}} \approx 2.5$. Then solving equations for A_I and (3) gives for the first peak $r_{ij} \approx 450$ Å and $a \approx 60$ Å, and the corresponding values $\varepsilon_0 \approx 14$ meV, $r_{\mathrm{min}} \approx 190$ Å, and $\Gamma_{\mathrm{max}} \approx 30$ μeV. For the second peak we have used the above value of Γ_{max} and in a similar way obtained $r_{ij} \approx 510$ Å and $a \approx 65$ Å. Larger values of r_{ij} can now explain a stronger magnetic-field dependence for the amplitude of the second peak (Fig. 3). The estimation of the effective barrier length gives $L \sim 2r_{ij} \sim 1000$ Å which is half the geometrical length of the gate. We attribute this to the fact that the barrier shape for short gates is not strictly rectangular and in addition the barrier length is shortened by the applied electric field.

The peaks become temperature dependent only at $T > 4.2$ K and disappear in the background current at $T \sim 10$ K. In Fig. 4(a) the temperature dependence of the second peak is shown. With the background current subtracted, Fig. 4(b), it is seen that the peak amplitude decreases and the peak increases with increasing temperature. In the presence of a source-drain voltage $eV_{\mathrm{sd}} \gg k_BT$ the smearing

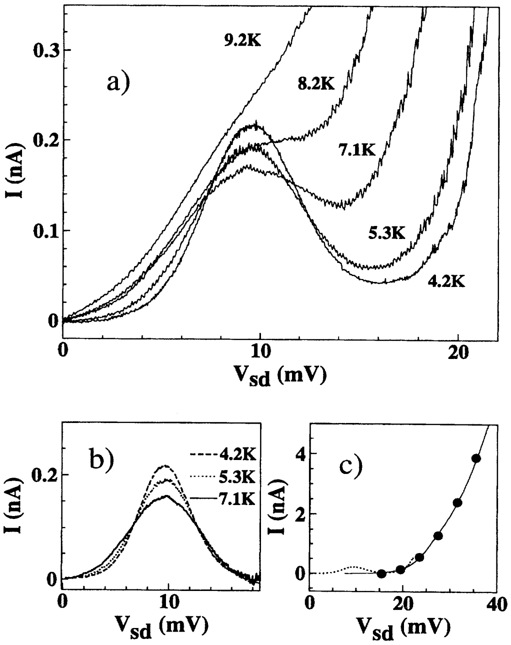

FIG. 4. (a) Temperature dependence of the second current peak. (b) Peak with the background subtracted. (c) Fitting of the background current by the $I(V_{sd})$ due to two-impurity hopping chains (Ref. 16) (the removed resonant peak is shown by the dotted line).

of the Fermi function in the contacts should not affect the width of a resonance. Thus we expect that this smearing is due to inelastic processes, when at the condition $\Gamma^{in}(T) \geqslant \Gamma^{e}_{max}$ the width of the resonance becomes $\Gamma_{max}(T) \approx \Gamma^{e}_{max} + \Gamma^{in}(T)$. The increase of the width should be accompanied by the decrease of the peak amplitude (3) and this is seen in the experiment.

We connect the background current with inelastic tunneling along many parallel impurity chains, presumably with the same number of impurities as in the RT channel. It was shown experimentally in Ref. 5 that $I(V)$ is sensitive to the number of impurities in a hopping chain. Using the density of localized states at the Fermi level, g, as an adjustable parameter we fit the background current with the expected $I(V_{sd})$ for two-impurity hopping chains:[16] $\langle I(V_{sd})\rangle \approx (\Lambda^2 \varepsilon_0 / \rho s^5)^{1/3} e g^2 a^3 (L/2) S \varepsilon_0 \exp(-L/3a)(eV)^{7/3}$, where $\Lambda \approx 12$ eV is the deformation potential constant,[17] $\rho \approx 5.7 \times 10^3$ kg m^{-3} is the density of GaAs, $S \approx Wa$ is the area of the barrier across the current, and L is the barrier length. The analysis of the background current has been done after sample thermal cycling resulting in the disappearance of the peak in $I(V_{sd})$. Figure 4(c) shows points of a fitting curve with $g \sim 10^{14}$ cm^{-3} meV^{-1}.

We have explained the observed resonances in the current by RT through two impurities. However, a feature with negative differential conductance could also be due to RT through more than two impurities. We will now show that for the estimated barrier length and density of localized states the resonant tunneling through more than two impurities is improbable, while one- and two-impurity channels have similar probabilities. It follows from Ref. 11 that the conductance of one- and n-impurity channels is proportional to the effective number of channels $N_{(1)}$ and $N_{(n)}$, where $N^{(1)} = gSa\Gamma^{(1)}$ and $N^{(n)} = g^n S(\Gamma^{(n)})^n (L/n)^n (La/n)^{n-1}$, $n \geqslant 2$. Thus $N^{(2)}/N^{(1)} \sim g\varepsilon_0 L^3$ and for $n \geqslant 2$, $N^{(n+1)}/N^{(n)} \sim g\varepsilon_0 a L^2$. Then for $L \sim 1000$ Å, $a \sim 100$ Å, and $g \sim 10^{14}$ cm^{-3} meV^{-1}, the condition $N^{(2)}/N^{(1)} \sim 1$ is satisfied while $N^{(3)}/N^{(2)} \approx N^{(4)}/N^{(3)} \sim 0.1$. This supports our suggestion that primarily two and not more than two impurities are responsible for the peaks.

In conclusion, on mesoscopic GaAs transistor barriers of 0.2 μm length we have obtained experimental evidence for two-impurity resonant tunneling which coexists with one-impurity resonant tunneling and also with inelastic tunneling through a few localized states.

[1] A. B. Fowler, G. L. Timp, J. J. Wainer, and R. A. Webb, Phys. Rev. Lett. **57**, 138 (1986).

[2] T. E. Kopley, P. L. McEuen, and R. G. Wheller, Phys. Rev. Lett. **61**, 1654 (1988).

[3] P. L. McEuen, B. W. Alphenaar, R. G. Wheller, and R. N. Sacks, Surf. Sci. **229**, 312 (1990).

[4] S. J. Bending and M. R. Beasley, Phys. Rev. Lett. **55**, 324 (1985); M. Naito and M. R. Beasley, Phys. Rev. B **35**, 2548 (1987).

[5] Y. Xu, A. Matsuda, and M. B. Beasley, Phys. Rev. B **42**, 1492 (1990).

[6] D. Popovic, A. B. Fowler, and S. Washburn, Phys. Rev. Lett. **67**, 2870 (1991); D. Popovic, S. Washburn, and A. B. Fowler, in *Hopping and Related Phenomena 5*, edited by C. J. Adkins, A. R. Long, and J. A. McInnes (World Scientific, Singapore, 1993). p. 22.

[7] M. W. Dellow P. H. Beton, C. J. G. M. Langerak, T. J. Foster, P. C. Main, L. Eaves, M. Henini, S. P. Beaumont, and C. D. W. Wilkinson, Phys. Rev. Lett. **68**, 1754 (1992).

[8] A. K. Geim, P. C. Main, N. La Scala, Jr., L. Eaves, T. J. Foster, P. H. Beton, J. W. Sakai, F. W. Sheard, M. Henini, G. Hill, and M. A. Pate, Phys. Rev. Lett. **72**, 2061 (1994).

[9] A. K. Geim, T. J. Foster, A. Nogaret, N. Mori, P. J. McDonnel, N. La Scala, Jr., P. C. Main, and L. Eaves, Phys. Rev. B **50**, 8074 (1994).

[10] A. K. Savchenko, A. Woolfe, V. V. Kuznetsov, M. Pepper, J. E. F. Frost, D. A. Ritchie, M. P. Grimshaw, and G. A. C. Jones, in *Hopping and Related Phenomena 5* (Ref. 6), p. 41.

[11] A. I. Larkin and K. A. Matveev, Zh. Éksp. Teor. Fiz. **93**, 1030 (1987) [Sov. Phys. JETP **66**, 580 (1987)].

[12] K. A. Matveev and A. I. Larkin, Phys. Rev. B **46**, 15 337 (1992).

[13] E. I. Laiko, A. O. Orlov, A. K. Savchenko, E. A. Il'ichev, and E. A. Poltoratskii, Zh. Éksp. Teor. Fiz. **93**, 2204 (1989) [Sov. Phys. JETP **66**, 1258 (1987)].

[14] A. D. Stone and P. A. Lee, Phys. Rev. Lett. **54**, 1196 (1985).

[15] B. I. Shklovskii and A. L. Efros, *Electronic Properties of Doped Semiconductors* (Springer, Berlin, 1984).

[16] L. I. Glazman and K. A. Matveev, Zh. Éksp. Teor. Fiz. **94**, 332 (1988) [Sov. Phys. JETP **67**, 1276 (1988)].

[17] S. S. Paul, A. K. Ghorai, and D. P. Bhattacharya, Phys. Rev. B **48**, 18 268 (1993).