PHYSICAL REVIEW B **83**, 041306(R) (2011)

Evidence for zero-differential resistance states in electronic bilayers

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(Received 17 November 2010; published 31 January 2011)

We observe zero-differential resistance states at low temperatures and moderate direct currents in a bilayer electron system formed by a wide quantum well. Several regions of vanishing resistance evolve from the inverted peaks of magneto-intersubband oscillations as the current increases. The experiment, supported by a theoretical analysis, suggests that the origin of this phenomenon is based on instability of homogeneous current flow under conditions of negative differential resistivity, which leads to formation of current domains in our sample, similar to the case of single-layer systems.

DOI: 10.1103/PhysRevB.83.041306 PACS number(s): 73.43.Qt, 73.63.Hs, 73.21.−b, 73.40.−c

Studies of nonlinear transport in a high-quality two-dimensional electron system (2DES) have revealed many interesting phenomena that occur in a perpendicular magnetic field at large filling factors. In the presence of ac excitation by microwaves, there exist microwave-induced resistance oscillations (MIROs)[1] that obey the periodicity ω/ω_c, where ω and ω_c are the radiation frequency and the cyclotron frequency, respectively. The minima of these oscillations evolve into zero-resistance states (ZRS) for high electron mobility and elevated microwave power.[2] The MIROs have been found also in bilayer and trilayer electron systems,[3] where they interfere with magneto-intersubband (MIS) oscillations[4] because of the presence of more than one populated subband. Recently, it has been demonstrated[5] that ZRS exist in bilayer systems despite additional intersubband scattering. Stimulated by experimental findings, theorists have proposed several microscopic mechanisms that reasonably explain nonlinear transport caused by microwave excitation.[6–9]

A direct current (dc) excitation of high-quality 2DES leads to another group of nonlinear phenomena caused by Landau quantization and is, therefore, distinct from electron heating effects observed under similar conditions in samples with lower mobilities. The Hall-field induced resistance oscillations (HIROs) are found in numerous experiments[10–13] and are explained[10,14] in terms of large-angle elastic scattering between Landau levels (LLs) tilted by the Hall field. Further, even a moderate dc causes a considerable decrease of the resistance,[15] which, in high-quality samples, may lead to the zero-differential resistance phenomenon. The zero-differential resistance states (ZdRS) found in single-layer systems emerge either from the inverted maxima of Shubnikov–de Haas (SdH) oscillations at relatively high magnetic fields[16] or from a minimum of HIROs.[17] In the second case, ZdRS appear at low magnetic fields, before the onset of SdH oscillations, and extend over a continuous range of fields. The two seemingly different regimes, however, are explained within the same model assuming formation of current domains when the negative resistance conditions are reached and the homogeneous current picture becomes unstable.[18] To learn more about the origin of ZdRS, clear understanding of the domain model is required. In this connection, studies of the systems that differ from standard 2DES are of crucial interest.

In this Rapid Communication, we report observation of ZdRS in a high-quality bilayer electron system formed by a wide quantum well (WQW). Owing to scattering of electrons between two populated two-dimensional (2D) subbands, ZdRS in bilayer electron systems evolve from inverted MIS oscillations for relatively low dc and obey MIS oscillation periodicity. In contrast to both regimes of ZdRS in single-layer systems,[16,17] ZdRS occur in the intermediate regime from overlapping to separated LLs (0.1 T $< B <$ 0.3 T). A theoretical consideration of magnetoresistance in dc-driven electronic bilayers shows that negative differential resistance (NDR) can be reached in our system, thereby supporting the domain model.

Our experiments are carried out on high-quality WQWs with a well width of $w = 45$ nm, high electron density $n_s \simeq 9.1 \times 10^{11}$ cm^{-2}, and a mobility of $\mu \simeq 1.9 \times 10^6$ cm^2/V s after a brief illumination with a red-light-emitting diode. Several samples in Hall bar geometry (length $L = 500$ μm and width $W = 200$ μm) have been studied, while we focus here on two samples (A and B, with a slightly higher electron density for sample B). Measurements have been performed at mK temperatures in a dilution refrigerator (base temperature 50 mK) (sample A) and up to 4.2 K in a cryostate with a variable temperature insert (sample B). We record longitudinal resistance using a current of 0.5 μA at a frequency of 13 Hz. Direct current $I_{\rm dc}$ was applied simultaneously through the same current and leads us to measure the differential resistance $r_{xx} = dV_{xx}/dI_{\rm dc}$.

In Fig. 1, we show differential resistance r_{xx} as a function of the magnetic field for $I_{\rm dc} = 0$, $I_{\rm dc} = 5$ μA, and $I_{\rm dc} = 15$ μA. Dark magnetoresistance exhibits well-developed MIS oscillations and confirms the existence of two populated subbands.[4] The inversion of MIS oscillations for $B < 0.17$ T is caused by the alternating current of 0.5 μA. The position of the inversion field is in a reasonable agreement with our theoretical estimates.[19] At this low temperature, we also observe SdH oscillations, which are superimposed on MIS oscillations for $B > 0.15$ T. If we apply a constant dc, the MIS oscillations are

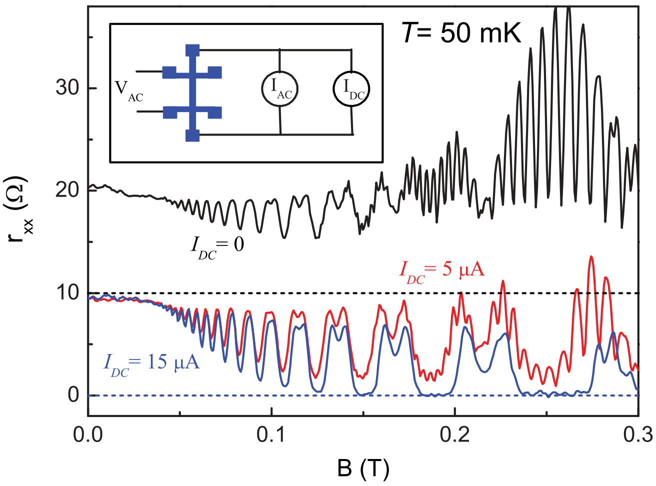

FIG. 1. (Color online) Differential magnetoresistance r_{xx} as a function of the magnetic field at $I_{dc} = 5$ μA and 15 μA for sample A. The top trace, which is shifted up for clarity, shows magnetoresistance ($I_{dc} = 0$) that exhibits MIS oscillations together with SdH oscillations. Experimental setup is shown in the inset.

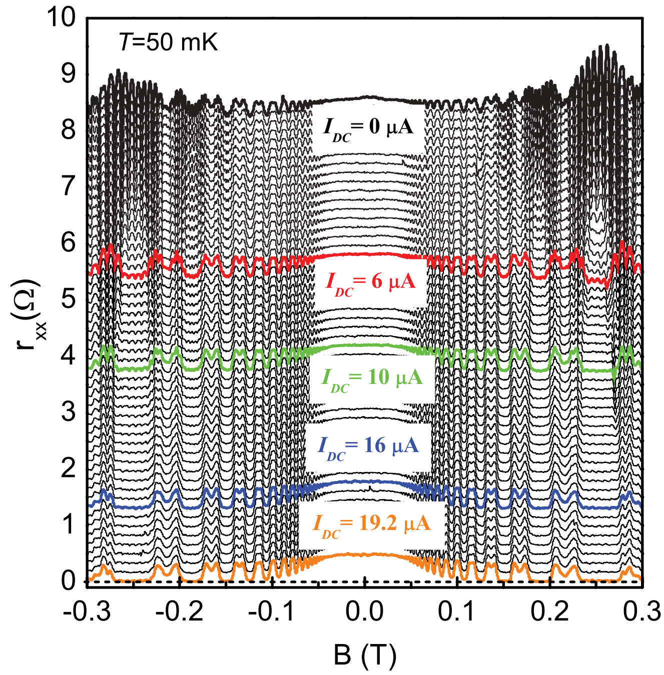

FIG. 2. (Color online) Evolution of differential magnetoresistance r_{xx} with increasing dc bias from $I_{dc} = 0$ to $I_{dc} = 19.2$ μA (step $\Delta I_{dc} = 0.4$ μA). For the highest current, we find four ZdRS for $B > 0.12$ T.

inverted in the whole range of magnetic fields for $I_{dc} = 5$ μA at a temperature of 50 mK. For $I_{dc} = 15$ μA, we observe ZdRS for $B > 0.14$ T, which are developed from the inverted MIS oscillations. Having a closer look at magnetic fields 0.1 T $< B <$ 0.3 T, we see that the maxima between ZdRS are split, which also occurs when applying a strong ac or dc excitation separately[19] and can be explained by the influence of Landau quantization on inelastic scattering of electrons in two-subband systems (see also Fig. 4).

As concerns temperature dependence, we have to apply a higher dc to maintain ZdRS at higher temperature [see Fig. 4(a) later]. The reason for this is rooted in the fact that the nonlinear response to a dc bias weakens with increasing temperature due to an increase in electron-electron scattering.[9,14]

To give a more detailed overview of the evolution from MIS oscillations ($I_{dc} = 0$) to the regime where inversion of all MIS peaks takes place until we reach zero-differential resistance, we plot in Fig. 2 r_{xx} as a function of the magnetic field starting from $I_{dc} = 0$ (top trace) to $I_{dc} = 19.2$ μA (bottom trace) at a constant temperature of 50 mK for both negative and positive magnetic-field orientation in steps of $\Delta I_{dc} = 0.4$ μA. Starting from $I_{dc} = 16$ μA, the widths of ZdRS remain constant. A further increase in I_{dc} leads to heating of the electron gas in the sample; therefore, our studies at $T = 50$ mK are limited to a maximal current of $I_{dc}^{max} = 20$ μA.

Since ZdRS in electronic bilayers occur neither at nearly discrete values of B (Ref. 16) nor in a wide region of magnetic fields,[17] and are separated by maxima in r_{xx}, it is important to illustrate this phenomenon by sweeping I_{dc} at a constant magnetic field (see Fig. 3). We fix the magnetic field at several positions (split maxima and ZdRS in r_{xx}), mark them by arrows with numbers (1) to (5) in Fig. 3(a), and plot differential magnetoresistance $r_{xx}(I_{dc})$ in Fig. 3(b). For $B = 0.254$ and 0.189 T, we are situated in the center of ZdRS. Both ZdRS are developed at $I_{dc} > 10$ μA. For $B = 0.254$ T, we find small kinks in r_{xx} at ±5.8 μA before r_{xx} is stabilized near zero. Beyond ZdRS, we show similar plots for the two maxima in r_{xx} at $B = 0.204$ and 0.224 T, which occur between the ZdRS and in the transition from these maxima to ZdRS at $B = 0.2$ T. The longitudinal voltage V_{xx} as a function of I_{dc} is plotted in Fig. 3(c) for the ZdRS around $B = 0.25$ T. This trace is obtained by integrating the data at $B = 0.254$ T and

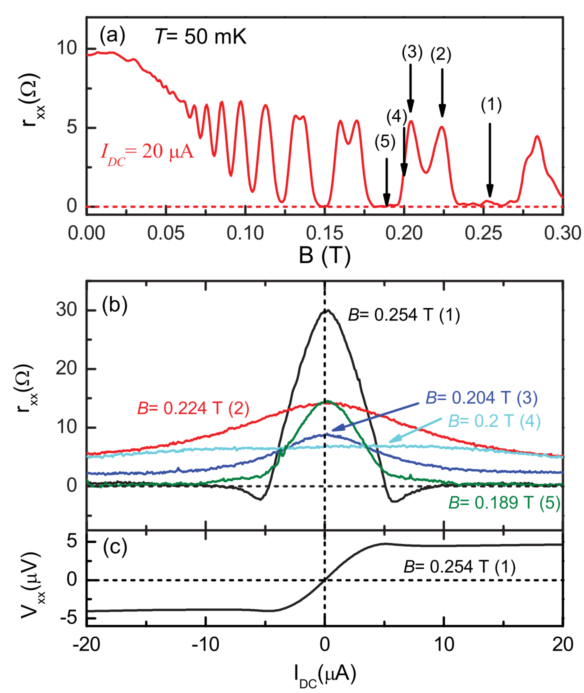

FIG. 3. (Color online) (a) Differential resistance r_{xx} for $I_{dc} = 20$ μA. (b) Dependence of r_{xx} on the dc at several chosen magnetic fields as labeled at a temperature of 50 mK. (c) Corresponding voltage V_{xx} at $B = 0.254$ T.

shows a typical voltage-current characteristic with saturation of V_{xx} corresponding to the onset of ZdRS.

We now analyze and discuss our experimental observation. First, we point out that the occurrence of ZdRS in electronic bilayers is distinct from the case of single-layer systems where ZdRS emerge in a wide range of magnetic fields well below the onset of SdH oscillations. In a two-subband system, several ZdRS emerge from the peaks of inverted MIS oscillations and follow the $1/B$ periodicity of these oscillations determined by the subband separation Δ. In other words, each ZdRS appears around the magnetic fields given by the set of cyclotron energies $\hbar\omega_c = \Delta/k$, where k is an integer. Next, the other important properties of ZdRS, such as the dependence of r_{xx} on the dc and the voltage-current characteristics, are very similar to those reported for single-layer systems.[16,17]

From the theoretical point of view, it is quite possible that the differential dissipative resistance $r_{xx} = dV_{xx}/dI_{\rm dc}$ (or even absolute resistance R_{xx}) in high-mobility samples approaches zero with increasing current, since an application of the current leads to a considerable decrease in the resistivity. Such a decrease, observed both in single-[15] and double-layer[19] systems, is reasonably explained by the theory of Ref. 9 based on a modification of the electron distribution function due to current-induced diffusion of electrons in the energy space in the presence of Landau quantization. This nonequilibrium distribution function is stabilized by inelastic electron-electron collisions described through the inelastic scattering time $\tau_{\rm in}$ (inelastic mechanism). A more rigorous theory, which includes another (displacement) mechanism of nonlinear response and remains valid at higher currents, has been developed in Ref. 14. To investigate the possibility of NDR for our samples, and to explain other characteristic features of the observed magnetoresistance, we have generalized the theory of Ref. 14 beyond the regime of overlapping Landau levels and for the case of multisubband occupation. In the following, we present the results valid both for single-subband systems and for the systems with two closely spaced subbands (our samples). In the regime of classically strong magnetic fields, the magnetoresistance of the system of electrons interacting with the static potential of impurities is found from the following relation between the density of the applied current $j = I_{\rm dc}/W$ and longitudinal electric field $E_{||} = V_{xx}/L$:

$$E_{||} = j\rho_0 \left[1 - \sum_{k(k\neq 0)} a_k^2 \gamma_k'' - \sum_{kk'} a_k a_{k-k'} A_{k'} (\gamma_k' - \gamma_{k-k'}') \right], \tag{1}$$

where $\rho_0 = m/e^2 n_s \tau_{\rm tr}$ is the classical Drude resistivity (e and m are the electron charge and the effective mass). The contribution of SdH oscillations is neglected. The sums are taken over the cyclotron harmonics, k are integers, a_k are the coefficients of expansion of the density of electron states in such harmonics, and $D(\varepsilon) = \sum_k a_k \exp(ik\frac{2\pi\varepsilon}{\hbar\omega_c})$, where $D(\varepsilon)$ is the density of states in units of $m/\pi\hbar^2$. For two-subband systems, one should use $D(\varepsilon) = (D_{1\varepsilon} + D_{2\varepsilon})/2$, where $D_{i\varepsilon}$ is the density of states in the subband i. In both cases, a_k are taken as real, which is attainable by a proper choice of the reference point for energy. The coefficients $A_{k'}$, which describe harmonics of nonequilibrium oscillating correction to the distribution function, are found from the linear system of equations $\sum_{k'} C_{kk'} A_{k'} = a_k \gamma_k'$ with

$$C_{kk'} = \frac{\tau_{\rm tr}}{\tau_{\rm in}} \left[a_{k-k'}^3 + a_k^2 (a_{k+k'} - 2a_{k-k'}) \right] + a_{k-k'} (\gamma_{k-k'} - \gamma_k). \tag{2}$$

The first part of the matrix $C_{kk'}$ is determined by taking into account the Landau quantization in the linearized electron-electron collision integral (see details in Ref. 19). The coefficients γ_k describe the effect of the current and are defined by averaging over the scattering angle θ: $\gamma_k \equiv \gamma(\zeta k) = \overline{J_0[2\zeta k \sin(\theta/2)]\tau_{\rm tr}/\tau(\theta)}$, where $J_0(x)$ is the Bessel function, $\zeta = \sqrt{4\pi^3 j^2/e^2 n_s \omega_c^2}$ (for single-subband systems one should multiply ζ by $\sqrt{2}$), and $1/\tau(\theta) = (m/\hbar^3) w[2k_F \sin(\theta/2)]$ is the angular-dependent scattering rate [k_F is the Fermi wave number and $w(q)$ is the correlator of random scattering potential]. The transport time $\tau_{\rm tr}$ is given in the usual way, i.e., $1/\tau_{\rm tr} = \overline{(1-\cos\theta)/\tau(\theta)}$. Finally, γ_k' and γ_k'' denote, respectively, the first and the second derivatives of the function $\gamma(\zeta k)$ over its argument.

To carry out the calculations, we numerically computed the density of states in the self-consistent Born approximation, using the quantum lifetime of electrons $\tau_0 = 6.6$ ps determined from linear low-temperature magnetoresistance measurements. Next, we applied the theoretical[9] estimate $\tau_{\rm in} \simeq \hbar\varepsilon_F/T_e^2$, where ε_F is the Fermi energy and T_e is the electron temperature. Heating of electron gas by the current is taken into account by considering energy loss due to electron-phonon interaction[3,20] (for $I_{\rm dc} = 50\,\mu$A, the heating is appreciable only at low temperatures; at $T = 1.4$ K we find $T_e \simeq 1.6$ K). To describe elastic collisions, we used the model of long-range scattering potential $w(q) \propto \exp(-l_c q)$ (where $l_c \gg 1/k_F$ is the correlation length), which produces $\tau_{\rm tr} = \tau_0(1+\chi)/\chi$ with $\chi = 1/(k_F l_c)^2$ and $\gamma(\zeta) \simeq (\tau_{\rm tr}/\tau_0)/\sqrt{1+\chi\zeta^2}$.[14]

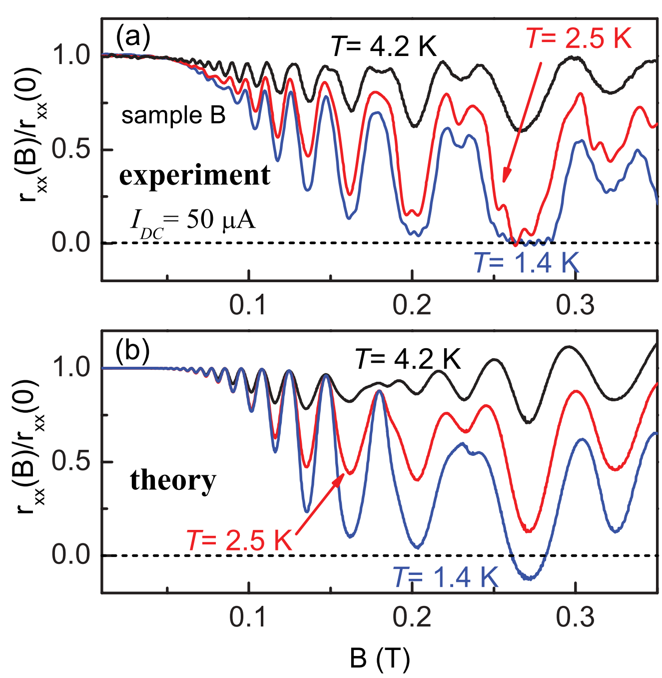

FIG. 4. (Color online) (a) Differential magnetoresistance r_{xx} in experiment and (b) theory for three chosen temperatures (sample B).

In Fig. 4, the calculated differential magnetoresistance plots are compared with experimental data recorded on sample B with a subband separation energy $\Delta = 1.4$ meV. Note that this separation is slightly larger than in sample A, so the positions of inverted MIS peaks (and of the corresponding ZdRS) are slightly shifted toward higher magnetic fields with respect to sample A. Applying $I_{\mathrm{dc}} = 50\ \mu$A, we observe ZdRS around $B = 0.27$ T at low temperatures (see the plot for $T = 1.4$ K) and its disappearance at $T > 2.5$ K. The calculation shows a similar behavior with a NDR region around $B = 0.27$ T. The other important feature of magnetoresistance, the peak splitting leading to minima at 0.23 and 0.32 T, is also reproduced in the calculations; see Ref. 19 for a detailed description of this phenomenon. Therefore, a direct calculation of magnetoresistance demonstrates that NDR is attainable for our samples. In the NDR regions, according to Ref. 18, the homogeneous flow of the current becomes unstable and the system exhibits a transition to current domains. The simplest two-domain structure discussed in Refs. 16 and 17 can also describe ZdRS in our experiment.

To summarize, we have found evidence for zero-differential resistance in a bilayer (two-subband) electron system where ZdRS develop from inverted magneto-intersubband oscillations under a relatively small direct current. This experimental result, together with a theoretical consideration, suggests that the ZdRS occur as a result of current instability under negative differential resistance conditions. The domain model proposed for explanation of ZdRS in single-subband 2DEG[16,17] very likely applies to multisubband systems.

Note added in proof. We have recently become aware of a related experimental work on a similar system, by Ref. 21.

We acknowledge support from COFECUB-USP (Project No. U_c Ph 109/08), FAPESP, and CNPq (Brazilian agencies).

[1] M. A. Zudov, R. R. Du, J. A. Simmons, and J. L. Reno, Phys. Rev. B **64**, 201311(R) (2001); P. D. Ye *et al.*, Appl. Phys. Lett. **79**, 2193 (2001).

[2] R. G. Mani, J. H. Smet, K. von Klitzing, V. Narayanamurti, W. B. Johnson, and V. Umansky, Nature (London) **420**, 646 (2002); M. A. Zudov, R. R. Du, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **90**, 046807 (2003); R. L. Willett, L. N. Pfeiffer, and K. W. West, *ibid.* **93**, 026804 (2004).

[3] S. Wiedmann, G. M. Gusev, O. E. Raichev, T. E. Lamas, A. K. Bakarov, and J. C. Portal, Phys. Rev. B **78**, 121301(R) (2008); S. Wiedmann, N. C. Mamani, G. M. Gusev, O. E. Raichev, A. K. Bakarov, and J. C. Portal, *ibid.* **80**, 245306 (2009).

[4] N. C. Mamani, G. M. Gusev, T. E. Lamas, A. K. Bakarov, and O. E. Raichev, Phys. Rev. B **77**, 205327 (2008).

[5] S. Wiedmann, G. M. Gusev, O. E. Raichev, A. K. Bakarov, and J. C. Portal, Phys. Rev. Lett. **105**, 026804 (2010).

[6] V. I. Ryzhii, Fiz. Terd. Tela **11**, 2577 (1969) [Sov. Phys. Solid State **11**, 2078 (1970)]; V. I. Ryzhii, R. A. Suris, and B. S. Shchamkhalova, Fiz. Tekh. Poluprovodn. **20**, 2078 (1986) [Sov. Phys. Semicond. **20**, 1299 (1986)].

[7] A. C. Durst, S. Sachdev, N. Read, and S. M. Girvin, Phys. Rev. Lett. **91**, 086803 (2003).

[8] M. G. Vavilov and I. L. Aleiner, Phys. Rev. B **69**, 035303 (2004).

[9] I. A. Dmitriev, M. G. Vavilov, I. L. Aleiner, A. D. Mirlin, and D. G. Polyakov, Phys. Rev. B **71**, 115316 (2005); I. A. Dmitriev, A. D. Mirlin, and D. G. Polyakov, *ibid.* **75**, 245320 (2007).

[10] C. L. Yang, J. Zhang, R. R. Du, J. A. Simmons, and J. L. Reno, Phys. Rev. Lett. **89**, 076801 (2002).

[11] A. A. Bykov, J. Q. Zhang, S. Vitkalov, A. K. Kalagin, and A. K. Bakarov, Phys. Rev. B **72**, 245307 (2005).

[12] W. Zhang, H.-S. Chiang, M. A. Zudov, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **75**, 041304(R) (2007).

[13] A. T. Hatke, M. A. Zudov, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **79**, 161308(R) (2009).

[14] M. G. Vavilov, I. L. Aleiner, and L. I. Glazman, Phys. Rev. B **76**, 115331 (2007).

[15] J.-Q. Zhang, S. Vitkalov, A. A. Bykov, A. K. Kalagin, and A. K. Bakarov, Phys. Rev. B **75**, 081305(R) (2007).

[16] A. A. Bykov, J.-Q. Zhang, S. Vitkalov, A. K. Kalagin, and A. K. Bakarov, Phys. Rev. Lett. **99**, 116801 (2007).

[17] A. T. Hatke, H.-S. Chiang, M. A. Zudov, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **82**, 041304(R) (2010).

[18] A. V. Andreev, I. L. Aleiner, and A. J. Millis, Phys. Rev. Lett. **91**, 056803 (2003).

[19] N. C. Mamani, G. M. Gusev, O. E. Raichev, T. E. Lamas, and A. K. Bakarov, Phys. Rev. B **80**, 075308 (2009).

[20] Y. Ma, R. Fletcher, E. Zaremba, M. D'Iorio, C. T. Foxon, and J. J. Harris, Phys. Rev. B **43**, 9033 (1991); R. Fletcher, J. J. Harris, C. T. Foxon, and R. Stoner, *ibid.* **45**, 6659 (1992).

[21] A. Bykov, E. G. Mozulev, and S. A. Vitkalov, Pis'ma Zh. Eksp. Teor. Fiz. **92**, 523 (2010) [JETP Lett. **92**, 475 (2010)].