Effect of dc and ac excitations on the longitudinal resistance of a two-dimensional electron gas in highly doped GaAs quantum wells

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Linear ac (888 Hz) resistance of highly mobile two-dimensional electrons in GaAs heavily doped quantum wells is studied at different magnitudes of dc and ac (10 KHz to 20 GHz) excitations. In the dc excitation regime the differential resistance oscillates with the dc current and external magnetic field similar to that observed earlier in AlGaAs/GaAs heterostructures [C. L. Yang *et al.*, Phys. Rev. Lett. **89**, 076801 (2002)]. At external ac excitations the resistance is also found to be oscillating with the magnetic field. However the form of the oscillations is considerably different from the dc case. We show that at frequency below 100 KHz the difference is the result of a specific average of the dc differential resistance during the period of the external ac excitations.

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I. INTRODUCTION

Nonlinear properties of highly mobile two-dimensional electrons in AlGaAs/GaAs heterojunctions is a subject of considerable current interest. Several new transport phenomena have been observed in these systems recently.[1–3] In the pioneer work[2] strong oscillations of the longitudinal resistance induced by microwave radiation have been observed at magnetic fields, which satisfy the condition $\omega=n\times\omega_c$, where ω is the microwave frequency and ω_c is the cyclotron frequency. At higher level of the microwave excitations minimums of the oscillations can reach very low values, which are close to zero.[3–5] This so-called zero resistance state (ZRS), initiated extensive interest to the problem. Several theoretical approaches have been proposed to explain the strong oscillations of the conductivity as well as the ZRS.[6–10]

Another interesting nonlinear phenomenon has been observed in the response of the 2D highly mobile electrons to dc excitations.[1] Oscillations of the longitudinal resistance, which are periodic in inverse magnetic field, have been found at dc biases, satisfying the condition $\hbar\omega_c=2R_cE_H$, where R_c is Larmor radius of electrons at Fermi level and E_H is Hall electric field, induced by the dc bias in the magnetic field. The effect has been attributed to Zener tunneling between Landau orbits, tilted by the Hall electric field.[1]

In this paper we report an observation of the resistance oscillations with magnetic field in dc biased GaAs quantum well with 2D electron density of an order of magnitude higher than reported earlier.[1] Moreover we have found similar resistance oscillations with magnetic field in response to low frequency (10 and 100 KHz) and high frequency (1 MHz to 20 GHz) ac excitations. The particular form of the resistance oscillations at the ac excitations is considerably different from the dc case. We show experimentally that for the low frequencies (10, 100 KHz) the difference is the result of an average of the dc differential resistance during a period of ac excitations. Although at high frequencies we were not able to measure unambiguously the magnitude of the ac current through the sample, we propose, that similar average could be applied for the oscillations of 2D resistance, induced by rf and microwave excitations.

II. EXPERIMENT

Our samples were cleaved from a wafer of a high-mobility GaAs quantum well grown by solid source molecular beam epitaxy on semi-insulating (001) GaAs substrates. The width of the GaAs quantum well was 13 nm. AlAs/GaAs type-II superlattices served as barriers, which made it possible to obtain a high-mobility 2D electron gas with high electron density.[11] In dark, the electron density and mobility of the 2D electron gas in our samples were $n_e=1.18\times10^{16}$ m^{-2} and $\mu=91$ m^2/V s, respectively. After brief light illumination, the electron density and mobility of the 2D electron gas in our samples were $n_e=1.28\times10^{16}$ m^{-2} and $\mu=111$ m^2/V s, respectively. Measurements were carried out at $T=4.2$ K in magnetic field up to 1 T on 50 μm wide Hall bars with distance of 250 μm between potential contacts. Microwave radiation was supplied to the sample through a coaxial cable and was fed to the 2D electron gas through current contacts of the Hall bars. The longitudinal resistance was measured using 1 μA current at frequency of 888 Hz. Three samples are measured. All samples demonstrate the same behavior.

III. RESULTS

Dependence of the longitudinal resistance r_{xx} of the 2D electron gas is presented in Fig. 1 at different values of the dc bias. A positive magnetoresistance of the sample is observed at zero dc bias. At a finite dc bias a strong negative magnetoresistance occurs. We did not study the effect in this paper. With an increase of the dc current through the sample a nonmonotonic, oscillating behavior of the longitudinal re-

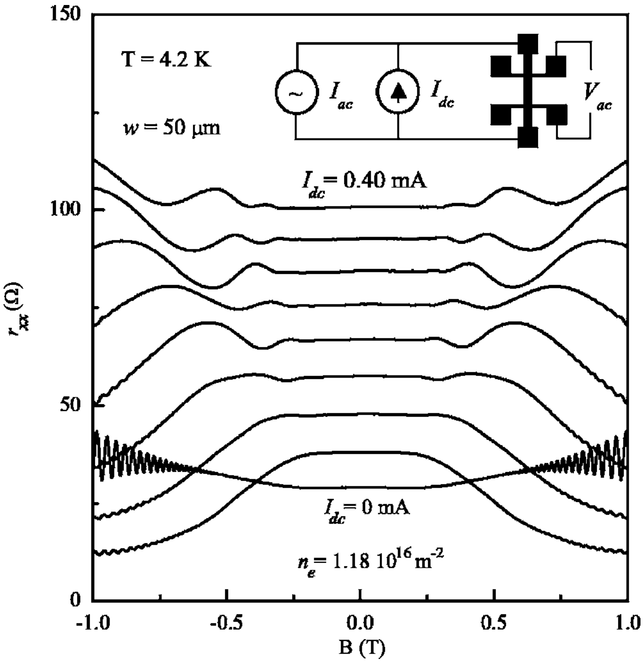

FIG. 1. Dependence of differential resistance r_{xx} on magnetic field at different dc current from 0 to 0.4 mA in steps of 0.05 mA. For clarity, the curves are shifted vertically by $n \times 8$ Ohm, where $n=0,1,\ldots,8$. The experimental setup is shown on the top. Sample No. 1 before light illumination.

sistance is found, similar to that reported earlier.[1] Positions of maximums (minimums) of the oscillations depends on the dc bias. To make a direct comparison with the previous measurements, we obtain numerically the first derivative of the curves with respect to magnetic field. The result is presented in Fig. 2(a). Apparent oscillations of the dr_{xx}/dB are periodic in the inverse magnetic field. It is shown in the inset to Fig. 2(a). The positions of the oscillation maximums B_l in magnetic field correspond to the condition $l \times \hbar\omega_c = \gamma R_c \times eE_H$, where $\gamma \approx 2$.[1] At this condition "horizontal" transitions between tilted Landau levels are possible with a momentum transfer $\Delta k_x \approx 2k_F$, where k_F is the electron wave vector at Fermi level.

The positions of the maximums of the dr_{xx}/dB are proportional to current density [see Fig. 2(b)]. From slopes of the linear dependencies of the dr_{xx}/dB maximums on the dc density we have found γ=2.06, 2.13, and 2.18 for l=1, 2, and 3 correspondingly. These values are close to ones obtained in the previous work.[1]

As we mentioned in the introduction the main experimental and theoretical efforts have been applied toward understanding the microwave induced oscillations of the resistance and the ZRS in the 2D electron gas.[2–5] The observed oscillations occur at microwave frequency ω, which is close to a multiple cyclotron frequency $n \times \omega_c$: $\omega \approx n \times \omega_c$, where $n=1,2,\ldots$, is an integer. The oscillations exist in, so-called, cyclotron resonance regime, at which the frequency of microwave radiation is much higher than the momentum relaxation rate $1/\tau_p$ $\omega \gg 1/\tau_p$, where the τ_p is transport mean free time. The low frequency excitation regime $\omega\tau_p < 1$ has not been explored yet. However, as we have shown above, in the

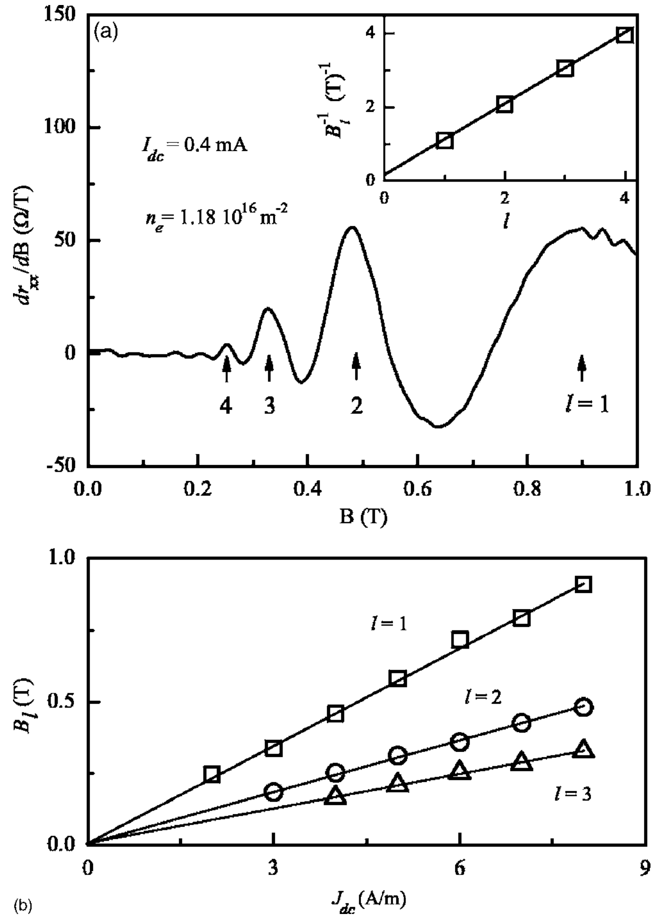

FIG. 2. (a) Dependence of the derivative dr_{xx}/dB on magnetic field at I_{dc}=0.4 mA. The inset demonstrates the $1/B$ periodicity extracted from the dr_{xx}/dB trace. (b) Positions of oscillation maximums B_l (l=1,2,3) versus dc current density J_{dc}. A linear fit reveals the relation $B_l \sim J_{dc}/l$. Sample No. 1 before light illumination.

pure dc case there is a very rich nonlinear physics. Below we present study of magneto-oscillations of the 2D longitudinal resistance induced by ac external excitations observed in a broad frequency range corresponding to the condition $\omega\tau_p < 1$.

A dependence of the longitudinal (888 Hz) resistance on magnetic field at different level of ac excitation (100 kHz) is presented in Fig. 3(a). Recognizable oscillations of the linear resistance with magnetic field are detected. Positions of the resistance maximums B_N indicated by arrows in Fig. 3(a) are plotted as function of the magnitude of the 100 kHz excitation current in Fig. 3(b). The position of the maximums are proportional to the magnitude of the ac density J_F. The maximum positions are periodic in the inverse magnetic field.

Similar oscillations of the linear resistance with magnetic field are found at different level of rf and microwave excitations in the frequency range from 1 MHz to 20 GHz. One of the dependencies is presented in Fig. 4(a) at excitation frequency 11 GHz. The oscillations are found to be periodic in the inverse magnetic field. The periodicity is shown in Fig. 4(b). Positions of the oscillation maximums depend on the microwave power: maximums move to higher magnetic fields at higher level of the microwave power P_ω. For a lin-

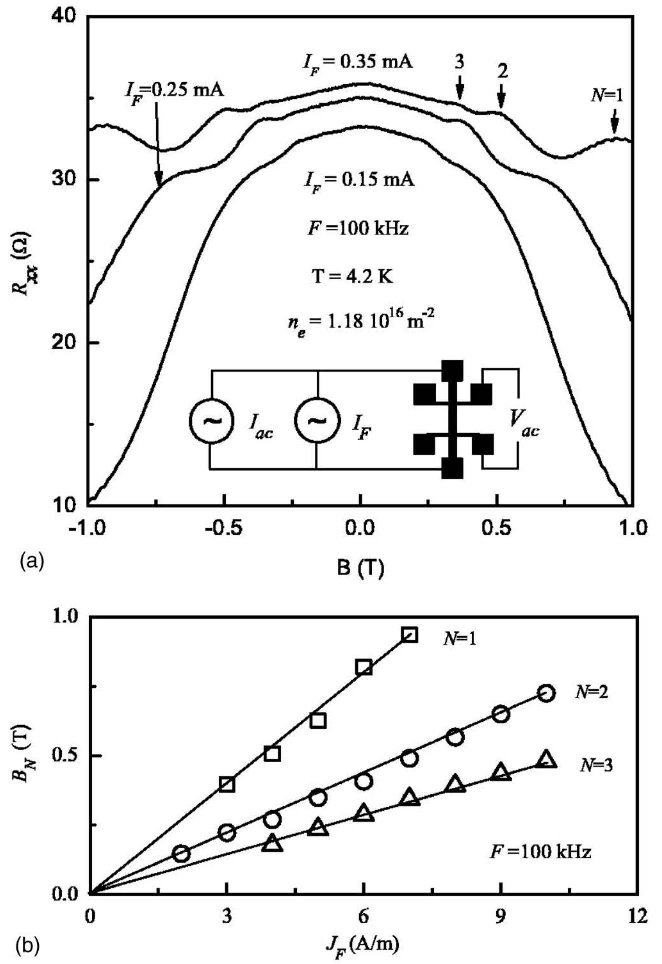

FIG. 3. (a) Magnetoresistance R_{xx} at different amplitudes of ac excitation. Maximums of the resistance oscillations are marked by arrows. Positions of the maximums are approximately periodic in $1/B$. A diagram for the electrical measurement is presented at the bottom of the figure. (b) The oscillation maximums B_N ($N=1,2,3$) versus current density J_F. Linear fit reveals the relation $B_N \sim J_F/N$. Sample No. 1 before light illumination.

ear microwave circuit current density through the sample should be proportional to square root of the input microwave power $J_\omega \sim (P_\omega)^{1/2}$. We have found that the positions of the maximums in the magnetic field is not proportional to the $(P_\omega)^{1/2}$ [see Fig. 4(c)]. We suggest that due to strong dependence of the sample resistance on the external microwave radiation the actual magnitude of the microwave current applied to the sample does not follow the square root rule. Additional microwave experiments are required to check the dependence of the maximums on the applied microwave current. This was beyond capabilities of our experimental setup.

Below we are focusing on the response to the low frequency (10 KHz, 100 KHz) excitations with well controlled current amplitude (see Fig. 3). We will show that oscillations of the resistance at frequency 888 Hz with magnetic field are a result of a special average of dc I-V curves. In other words the ac nonlinear response at frequency below 100 kHz is a direct consequence of the nonlinearity at zero frequency.

To accomplish this goal we have to consider what is measured in the experiment. The low-frequency experimental

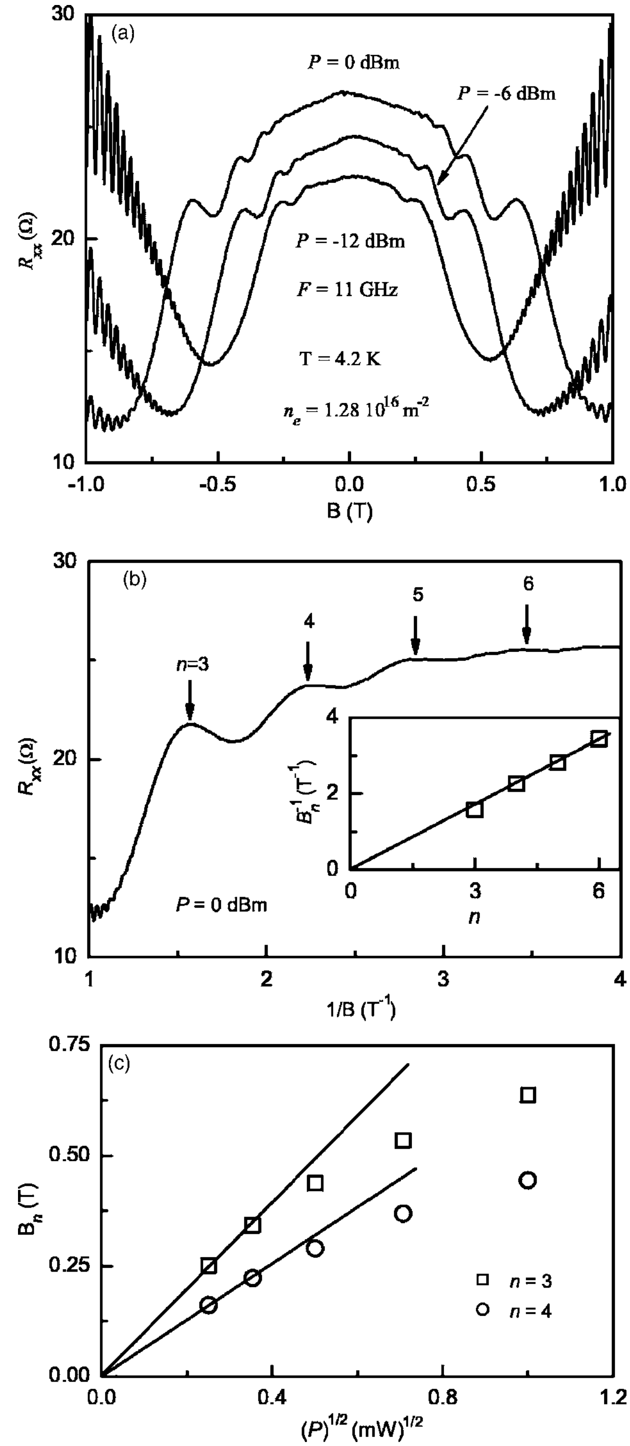

FIG. 4. (a) Magnetoresistance R_{xx} at different levels of microwave power as labeled. (b) Dependence of the longitudinal resistance on inverse magnetic field $1/B$ at microwave excitation $P=0$ dBm. Insert demonstrates the $1/B$ periodicity of the oscillations. (c) Position of the oscillation maximums vs square root of input microwave power. (b) and (c) are obtained with the same conditions as (a). Sample No. 1 after light illumination.

setup is shown in Fig. 3(a). The testing current I_{ac} at frequency 888 Hz and ac excitation current I_F at frequency $F=10/100$ kHz were applied through current leads of the sample, using twisted pairs of conducting wires. Due to negligible effect of the current leakage through a capacitance between the wires at used frequencies, the ac currents were fixed with accuracy better than 5% during measurements. The ac voltage V_{ac} at frequency 888 Hz were measured using standard lockin amplifier synchronized with the testing current I_{ac}.

Since at frequency 888 Hz the response is found to be linear with respect to the testing current I_{ac} we approximated the response by Ohm's law:

$$V_{ac} = R_{xx}(I_f) \times I_{ac}, \tag{1}$$

where $R_{xx}(I_F)$ is a resistance of the sample, which depends on the external ac current $I_F = I_0 \cos(2\pi F t)$, where I_0 is amplitude of the ac excitation. One can expand the resistance $R_{xx}(I_F)$ in a sum of all possible harmonics $(i \times F)$ of the external ac current:

$$R_{xx}(I_f) = \Sigma R_i(I_0) \times \cos(i \times 2\pi F t), \tag{2}$$

where $R_i(I_0)$ a Fourier component of the $R_{xx}(I_F)$ at a frequency $i \times F$ and $i = 0, 1, 2, \ldots$, is an integer.

The lockin amplifier locked at frequency 888 Hz measures exclusively the zero frequency $(i=0)$ harmonic R_0, because only the R_0 provides a term oscillating at frequency 888 Hz in Eq. (1). Thus to find the resistance $R_{xx}(H)$ at magnetic field H one has to obtain the zero frequency harmonic of the $R_{xx}(I_0, H)$:

$$R_0(H) = 1/T \int R_{xx}[I_0 \cos(2\pi F t) dt], \tag{3}$$

where $T = 1/F$ is a period of the ac excitation.

In order to perform the integration in Eq. (3), we need to know the dependence of the resistance R_{xx} on the driving current I. This is done at zero frequency (dc case). The dependence of R_{xx} on the current I_{dc} [in fact, the differential resistance r_{xx} (see Fig. 1)] was measured at different magnetic fields. The dependence is presented in Fig. 5(a) at several magnetic fields as labeled. Using the experimental data, the integration in Eq. (3) was performed numerically. Values of the average resistance R_0 were obtained for different magnetic fields. Calculated resistance R_{xx} is presented in Fig. 5(b) (circles) as a function of the magnetic field at two different amplitudes of the ac excitation.

Measured dependencies of the resistance $R_{xx}(H)$ on magnetic field at two different amplitudes of the external ac excitations are also shown in the figure for comparison (solid lines). We note that there are no adjusting parameters between measured and calculated curves. Similar results are obtained at 100 KHz frequency (not shown). The agreement indicates a valid approach for interpretation of the ac induced oscillations of the longitudinal conductivity at low frequency of the ac excitations. We believe that the approach can be extended to higher frequency including microwave region.

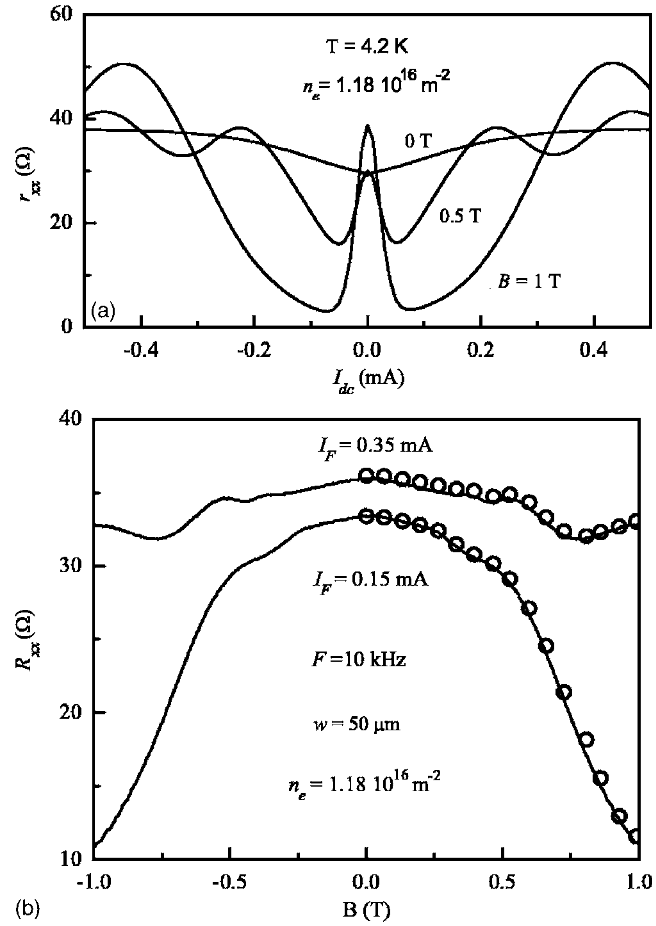

FIG. 5. (a) Dependence of differential resistance r_{xx} on dc bias at different magnetic field B as labeled. (b) Measured magnetoresistance R_{xx} at two different levels of ac excitations as labeled (solid lines). Calculated magnetoresistance obtained from the dc biased measurements in (a) (open dots). The procedure is described in text. No adjusting parameters are used for the comparison. Sample No. 1 before light illumination.

IV. CONCLUSION

Effect of dc and low frequency ac excitations on longitudinal resistance of the two-dimensional electron gas in highly doped GaAs quantum wells is studied. A strong, periodic (in inverse magnetic field oscillations) of the resistance is found in the dc biased samples. The position of the oscillation maximums is found to be proportional to the dc density. Similar oscillations are observed with ac excitations applied to the samples at different frequency in the range 10 KHz to 20 GHz. We have shown that the resistance oscillations observed at frequency below 100 KHz are due to the nonlinear response of the dc biased 2D electron systems.

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

[2] M. A. Zudov, R. R. Du, J. A. Simmons, and J. L. Reno, Phys. Rev. B **64**, 201311(R) (2001); P. D. Ye, L. W. Engel, D. C. Tsui, J. A. Simmons, J. R. Wendt, G. A. Vawter, and J. L. Reno, Appl. Phys. Lett. **79**, 2193 (2001).

[3] R. G. Mani, V. Narayanamurti, K. vonKlitzing, J. H. Smet, W. B. Jonson, and V. Umansky, Nature (London) **420**, 646 (2002).

[4] M. A. Zudov, R. R. Du, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **90**, 046807 (2003).

[5] R. L. Willett, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **93**, 026804 (2004).

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

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

[8] P. W. Anderson and W. F. Brinkman, cond-mat/0302129 (unpublished).

[9] J. Shi and X. C. Xie, Phys. Rev. Lett. **91**, 086801 (2003).

[10] I. A. Dmitriev, M. G. Vavilov, I. L. Aleiner, A. D. Mirlin, and D. G. Polyakov, Phys. Rev. B **71**, 115316 (2005).

[11] K.-J. Friedland, R. Hey, H. Kostial, R. Klann, and K. Ploog, Phys. Rev. Lett. **77**, 4616 (1996).