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Effect of electron-electron interactions on a two-dimensional electron gas in II-VI $ZnS_{0.06}Se_{0.94}/Zn_{0.8}Cd_{0.2}Se$ quantum wells

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A magnetotransport study has been performed in II-VI $ZnS_{0.06}Se_{0.94}/Zn_{0.8}Cd_{0.2}Se$ quantum wells. We observed the quantum effects of weak localization and electron-electron interactions on the two-dimensional electron gas in the $Zn_{0.8}Cd_{0.2}Se$ well. The effective mass of electrons in this highly correlated system, determined from Shubnikov–de Haas measurements, exhibits a strong magnetic field dependence: $m^*/m_0=0.143+0.0027B^2$. The mass enhancement is attributed to the ''dressing'' of electrons by the many-particle effect due to electron-electron interactions. [S0163-1829(99)50540-7]

The wide band gap ZnSe-based II-VI semiconductor quantum wells have been extensively studied due to their application for blue-green laser devices.[1] The electro-optical performance of quantum well devices is governed by the electronic properties of a two-dimensional electron gas (2DEG) in the well. The quantum effects become significant and play a key role in the calculation of electronic properties. For example, the weak localization effect, which arises from the quantum interference of a single electron in a disordered potential, has been observed in $GaAs/Al_xGa_{1-x}As$ heterostructures.[2] The quantum effect of electron-electron interactions in $GaAs/Al_xGa_{1-x}As$ heterostructures, which results in a substantially modified energy vs wave-vector relation for noninteracting electron band structure, was studied by Paalanen *et al.*,[3] and a detailed study was made by Choi *et al.*[4] Up to date, it is found that there are three distinct quantum corrections to the conductivity of disordered 2DEG in a III-V compound: (i) the correction from weak localization $\Delta\sigma_L$, (ii) the correction from electron-electron interaction in the Cooper channel (particle-particle scattering channel) $\Delta\sigma_C$, and (iii) the correction from electron-electron interaction in the diffusion channel (particle-hole scattering channel) $\Delta\sigma_D$.[5] However, when the quantum well is made of a II-VI compound, which has a very different electron configuration (s^2d^{10}) with more ionic bonding than covalent bonding, the electron-electron interactions become more complicated and the diffusive motion of electrons is strongly influenced by the Zeeman spin-splitting effect.[6] If the Zeeman spin-splitting energy is too large to be treated as a perturbation in the noninteraction Hamiltonian, the band structure derived from the single-electron Hamiltonian is no longer valid and the many-body effect on the electron-electron interactions needs to be considered. Recently, Jaroszynski *et al.* observed the influence of the s-d exchange interaction on the universal conductance fluctuations in $Cd_{1-x}Mn_xTe$, and proposed a new driving mechanism based on the electron redistribution by the s-d exchange spin-splitting.[7] In those papers,[6,7] the authors assumed that the effective mass is independent of the magnetic field. However, the effective mass carries the information about the electron-electron interaction effect on the band structure. The actual effective mass is needed to understand the transport properties of the strong-electron-interaction system. In this paper, we present the results of the Shubnikov–de Haas (SdH) measurements in $ZnS_{0.06}Se_{0.94}/Zn_{0.8}Cd_{0.2}Se$ quantum wells and the observations of the effect of electron-electron interactions on the effective mass.

The sample structure used for this study is (from substrate to top cap): GaAs substrate, $\times 10$ $ZnSe/Zn_xS_{1-x}Se$ strained layer superlattice buffer, 0.6 μm $ZnS_{0.06}Se_{0.94}$ barrier, 10 nm $Zn_{0.8}Cd_{0.2}Se$ well, 10 nm $ZnS_{0.06}Se_{0.94}$ spacer, 8 nm Cl-doped $ZnS_{0.06}Se_{0.94}$ barrier, and 75 nm $ZnS_{0.06}Se_{0.94}$ cap. Disordering defects have been reported on the $ZnSe/Zn_xCd_{1-x}Se$ quantum wells by many authors.[8] A series of the samples were previously used to study the defect level and a negative persistent photoconductivity effect was observed.[9] In the magneto-transport experiment, the measured quantity is the resistivity ρ_{XX} instead of the conductivity σ_{XX}. By inverting the conductivity tensor, the magnetoresistance of 2DEG $\rho(B)$ can be written as [see Eq. (17) in Ref. 4]:

$$\rho(B)=\rho_0+[1+(\omega_c\tau)^2]\frac{\sigma_s}{\sigma_0^2}-[1-(\omega_c\tau)^2]\frac{\delta\sigma_i}{\sigma_0^2}, \qquad (1)$$

where $\rho_0=\sigma_0^{-1}$, and

$$\sigma_s=-\frac{\sigma_0}{1+(\omega_c\tau)^2}\,2\,\frac{(\omega_c\tau)^2}{1+(\omega_c\tau)^2}\,\frac{2\pi^2kT}{\hbar\omega_c}\times\mathrm{csch}\left[\frac{2\pi^2kT}{\hbar\omega_c}\right]\cos\left[\frac{2\pi E_F}{\hbar\omega_c}\right]\exp(-\pi/\omega_c\tau).$$

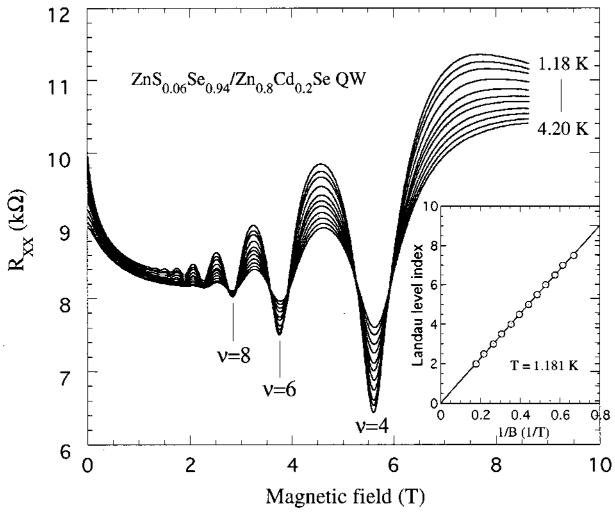

FIG. 1. The SdH measurements of the sample at temperatures from 4.20 K down to 1.18 K. The inset shows the Landau level index vs $1/B$ for the data of $T = 1.18$ K.

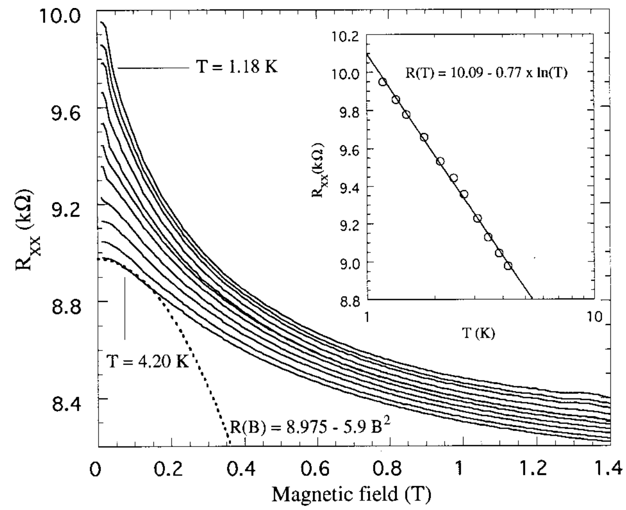

FIG. 2. The low field data of Fig. 1. The dashed line is a result of least-square-fit to the data of $T = 4.20$ K for $B < 0.16$ T. The inset shows a ln(T) dependence of the magnetoresistance at $B \sim 0.01$ T.

Here, σ_0 is the Drude conductivity, E_F is the Fermi energy ($E_F = h^2 n_e / 4\pi m^*$), $\omega_c = eB/m^*$, and $\delta\sigma_i$ is the conductivity correction from the electron-electron interactions. The second term of $\rho(B)$ is just the SdH oscillation in $1/B$, $A_{\mathrm{SdH}}(B,T)\cos(2\pi f_{\mathrm{SdH}}/B)$, and the effective mass m^* and scattering time τ can be evaluated from the amplitude $A_{\mathrm{SdH}}(B,T)$. The electron density n_e is directly determined by the frequency $f_{\mathrm{SdH}} = hn_e/2e$. The third term of $\rho(B)$ gives a parabolic negative magnetoresistance ($[e\tau B/m^*\sigma_0]^2 \delta\sigma_i$), which is contributed by the $\delta\sigma_i$ and has been observed in $GaAs/Al_xGa_{1-x}As$ heterostructures by Paalanen *et al.*[3] and by Choi *et al.*[4]

Figure 1 shows the magnetoresistance R_{XX} against magnetic field B at temperatures from 4.20 K down to 1.18 K. The SdH oscillations are observed for the fields above 1.5 T. The minima of the oscillations (e.g., at the filling factors $\nu = 4,6,8,\ldots$) do not shift with B as the temperature changes, indicating that the electron density holds constant in this temperature range. The Landau level index (equal to $\nu/2$) vs $1/B$ at the maximum and minimum peaks of the SdH oscillation is shown in the inset. The SdH frequency f_{SdH} derived from the slope of the straight line gives the electron density $n_e = (5.40 \pm 0.04) \times 10^{11}\ \mathrm{cm}^{-2}$. The electron scattering time τ was obtained from the nonlinear least-square-fit of the B-dependent SdH amplitude to Eq. (1), and equal to 0.37 ps. The mobility evaluated from τ is about 4 500 $\mathrm{cm}^2/\mathrm{V\,s}$. In Fig. 1, it is found that the zero-field resistance $R_{XX}(B \sim 0)$ logarithmically increases with the decreasing temperature. We plotted the low field data in Fig. 2. The magnetoresistance shows a ln(T) dependence at the low fields. An example of the data at $B \sim 0.01$ T is shown in the inset: $R(T) = 10.09 - 0.77 \ln(T)$. As we mentioned before, the correction of weak localization $\Delta\sigma_L$ will result in a ln(T) dependence at zero field for a disordered 2DEG in the ''dirty metal'' region.[10] However, in addition to the correction of weak localization $\Delta\sigma_L$, the corrections of electron-electron interactions in the Cooper channel $\Delta\sigma_C$ and the diffusion channel $\Delta\sigma_D$ also share the similar ln(T) dependence near the zero field.[11] Since each quantum correction has a different B dependence, we can separate the three corrections by applying the magnetic field. Because the weak localization effect is due to the quantum interference of coherent ''backscattering'' for Cooper propagators, the application of a perpendicular field breaks the time-reversal invariance of the ''backscattering,'' and consequently suppresses the weak localization effect. When the magnetic length of the Cooper propagator $(\hbar/2eB)^{1/2}$ is less than the elastic mean free path l_e, the localization effect will totally vanish.[12] Therefore, the weak localization effect can be ignored when the applied field B is greater than the characteristic field $B_1 = \hbar/2el_e^2$. We evaluated $B_1 \sim 0.11$ T, with $l_e = v_F\tau$, where $\tau = 0.37$ ps and the Fermi velocity v_F is given by the electron density ($5.40 \times 10^{11}\ \mathrm{cm}^{-2}$). Thus, the ln($T$) dependence of R_{XX} at low fields (e.g., <0.11 T) is contributed, in part, by the weak localization effect.

The third term of Eq. (1) gives a negative B^2-dependent magnetoresistance which is contributed by the electron-electron interactions.[3,4] The dashed line in Fig. 2 is the result of a least-square-fit for the data of $T = 4.20$ K, which has the least effect of weak localization, at low fields ($B < 0.16$ T): $R_{XX}(B) = 8.975 - 5.9B^2$. To distinguish the contributions of the electron-electron interactions between $\Delta\sigma_C$ and $\Delta\sigma_D$, we rotated the sample orientation against the magnetic field. Figure 3 shows the R_{XX} vs the perpendicular component of the magnetic field $B\cos\theta$, where the zero of the y axis has been offset for easy comparison. The minimum positions of the SdH oscillations shift along with $B\cos\theta$. It is a characteristic property of a 2DEG and Fig. 3 confirms that the electron carriers are two-dimensional. The data of $\theta = 89°$ and $-1°$ were plotted against B in the inset. For a 2DEG in the ''pure metal'' region, when the applied field is parallel to the 2DEG the SdH oscillations will vanish and R_{XX} is constant (i.e., independent of B). This is true even for the two-subband occupied 2DEG; for example, see $\theta = 90°$ in Fig. 2 of Ref. 13. However, for the data of $\theta = 89°$ in the inset of Fig. 3, the R_{XX} depends on B in two different ways: the negative B^2 dependence in low fields and the positive logarithmic B dependence in high fields (shown by the two dashed lines). The electron-electron interaction in the diffusion channel $\Delta\sigma_D$ is affected by a magnetic field only via the

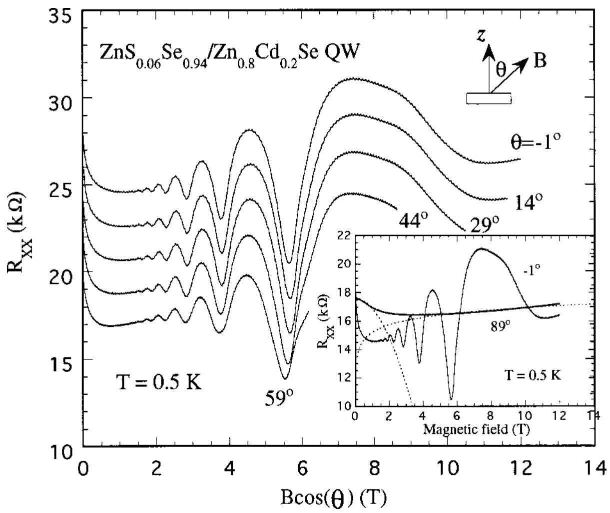

FIG. 3. The θ-dependent SdH measurements of the sample against $B\cos\theta$ at $T=0.5$ K. The inset shows the R_{XX} for $\theta=-1°$ and 89° vs the magnetic field B.

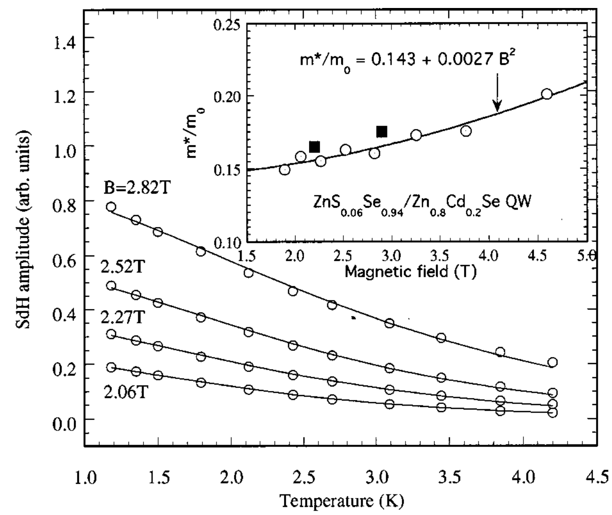

FIG. 4. The SdH amplitude obtained from Fig. 1 is plotted against temperature at different fields. The solid lines are the nonlinear least-square-fit to the second term of Eq. (1). The B^2-dependent effective mass obtained from the nonlinear fit is shown in the inset (open circles) and the results of Ref. 16 are shown in solid squares.

Zeeman spin-splitting energy. Because the Zeeman spin-splitting energy depends only on the total magnetic strength and is independent of the magnetic orientation, the B dependence of $\Delta\sigma_D$ is isotropic. On the contrary, both $\Delta\sigma_L$ and $\Delta\sigma_C$ are orbital effects (e.g., Cooper propagators) and depend on the perpendicular component of the magnetic field. They totally vanish when the applied field is parallel to the 2DEG. By comparing with the R_{XX} at $\theta\sim-1°$ (which is contributed by all three quantum effects), we found that the negative B^2-dependent magnetoresistance at $\theta\sim 89°$ (which is contributed only by $\Delta\sigma_D$) is reduced when the orbital effects ($\Delta\sigma_L$ and $\Delta\sigma_C$) are removed. But the negative B^2-dependent magnetoresistance does not completely vanish with the removal of $\Delta\sigma_L$ and $\Delta\sigma_C$. It means that, in addition to the orbital effects $\Delta\sigma_L$ and $\Delta\sigma_C$, the electron-electron interaction in the diffusion channel $\Delta\sigma_D$ also contributes to the R_{XX} even at the low fields. When $B>1.7$ T, which is the intersection of the two dashed lines, the positive logarithmic B dependence for the data of $\theta=89°$ becomes important and dominates the R_{XX} at higher fields. When the Zeeman spin-splitting energy of $\Delta\sigma_D$ becomes significant, the application of magnetic field increases the electron-electron interaction and hence a positive logarithmic R_{XX} is expected.[4] In this case, the correction of the magnetoconductivity due to $\Delta\sigma_D$ becomes: $\delta\sigma(B)-\delta\sigma(0)=-e^2Fg_2(x)/4\pi^2\hbar$, where F is the interaction parameter, $g_2(x)$ is a numerical function, and $x=g\mu_B B/kT$. Here, $g_2(x)=\ln(x/1.3)$ for $x\gg 1$, and $g_2(x)=0.084x^2$ for $x\ll 1$.[14] Because the electron-electron interaction of $\Delta\sigma_D$ reduces the conductivity and the applied magnetic field enhances the interaction, consequently, the magnetoresistance increases for $B>1.7$ T. The positive logarithmic R_{XX} was observed in the other $ZnS_{0.06}Se_{0.94}/Zn_{0.8}Cd_{0.2}Se$ quantum wells also. Therefore, we attribute the positive logarithmic R_{XX} to the effect of electron-electron interaction on the Zeeman spin-splitting energy in $\Delta\sigma_D$.

The electron-electron interactions result in a modification of the band structure, and therefore the effective mass. The effective mass is obtained from the T-dependent SdH oscillations in Fig. 1. Figure 4 shows the amplitude of SdH oscillations against T at some selected fields of the minimum and maximum SdH peaks. The solid lines are drawn from the nonlinear least-square-fit to the T-dependent amplitude of SdH oscillation in Eq. (1). The results of the calculated effective mass are plotted in the inset. It is found that the effective mass strongly depends on the magnetic field: $m^*/m_0=0.143+0.0027B^2$. The mass of the extrapolation to zero field, $m^*=(0.143\pm0.002)m_0$, is in very good agreement with the result of cyclotron resonance measurement, $m^*=(0.144\pm0.001)m_0$, recently obtained in $ZnSe/Zn_xCd_{1-x}Se$ quantum wells by Ng *et al.*[15] We also compared our results with the results obtained by Shao *et al.* (the solid squares shown in the inset), who used the same technique (SdH measurement) on a similar sample.[16] The effective mass obtained by Shao *et al.* shows a strong field dependence as well. As we mentioned before, when the electron-electron interactions become significant, the band structure derived from the noninteraction Hamiltonian is no longer valid. If the band structure is rigid and independent of B, then both the effective mass m^* and g factor of electron will hold constant under the magnetic field. However, Wang *et al.*[17] studied the spin interaction of electron-hole in $GaAs/Al_xGa_{1-x}As$ quantum wells and found that the Zeeman spin-splitting energy depends on B^2. Besides, it is found by further studies that the effective g factor of 2DEG in $GaAs/Al_xGa_{1-x}As$ shows a large exchange-induced enhancement and exhibits a strong dependence on the magnetic field.[18] Therefore, when the magnetic field is applied, the electron-electron interactions will result in a enhancement of effective mass. Since the Zeeman spin-splitting energy strongly depends on the magnetic field, so does the mass enhancement due to the electron-electron interaction of $\Delta\sigma_D$. We believe that the electron-electron interaction of $\Delta\sigma_D$ in our system (II-VI compound) is stronger than that in $GaAs/Al_xGaAs$, and results in the field dependent effective mass in Fig. 4. The B^2-dependent mass enhancement is due to the ''dressing'' of electrons by the many-particle effect of electron-electron interaction.

It is noted that in a bulk (3D) magnetic II-VI compounds, such as $Cd_{1-x}Mn_xSe$ (Ref. 6) or $Cd_{1-x}Mn_xTe$,[7] which contain partially filled d shells of Mn ions, the s-d exchange interaction itself contributes to the increasing electron-electron interaction $\Delta\sigma_D$.[6,7] When the 3D electron system turns into a two-dimensional system of quantum wells, the discontinuity in the band structure at the interface and the strong electric field in the potential well will influence the interaction between different bands and so lead to a variation in the measured band parameters like effective mass m^* and the g factor. In $GaAs/Al_xGa_{1-x}As$ quantum well, the nonlinear-field-dependent g factor has been experimentally observed,[18] and can be explained by the exchange effect among electrons in the Landau levels.[19] The direct measurement of Zeeman spin splitting of $GaAs/Al_xGa_{1-x}As$ quantum wells showed a B^2 dependence.[17] It reveals that even without the s-d exchange interaction, the Zeeman spin splitting of two-dimensional electron systems (e.g., $GaAs/Al_xGa_{1-x}As$ quantum wells) will influence the band structure and give a nonlinear dependence on magnetic field strength. Similar calculations have been worked out in InSb (Ref. 20) and GaSb/InAs.[21] In our samples, the $ZnS_{0.06}Se_{0.94}/Zn_{0.8}Cd_{0.2}Se$ quantum wells, although the ferromagnetic property is removed due to the absence of Mn ions, the Zeeman spin splitting still influences the band structure of two-dimensional electron systems in the well. Our data can be used to check the theoretical band parameters obtained by Puls *et al.*[22] In Puls' paper, they evaluated the band parameters by comparing the experimental data of the magnetoexcitons in $Zn_{1-x}Cd_xSe/ZnSe$ multiple quantum wells with a numerical solution of the Schrödinger equation for the in-plane motion of the magnetoexcitons. In their calculation, a noninteracting Hamiltonian was applied to a two-band model, and the effective mass was kept fixed when the magnetic field changed. They concluded that the effective mass is about 0.122 m_0, which disagreed with our data and the data of other groups.[15,16] Even in the exciton absorption results, particularly for $x_{Cd}=0.21$ [see Fig. 2(c) of Ref. 22], the deviation is obvious in the field range ($B>2$ T) for Fig. 2(c), where our experimental results showed a B^2-dependent effective mass. Therefore, from the comparison between the magnetoexciton study (Puls' results) and our magnetotransport study, we believe that the many-particle effect of electron-electron interaction needs to be included in the band calculation for degenerated 2DEG.

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[1] M. A. Haase, J. Qui, J. M. DePuydt, and H. Cheng, Appl. Phys. Lett. **59**, 1272 (1991); R. L. Gunshor and A. V. Nurmikko, Mater. Res. Bull. **10**, 15 (1995).

[2] H. Z. Zheng, H. P. Wei, D. C. Tsui, and G. Weimann, Phys. Rev. B **34**, 5635 (1986); K. K. Choi, D. C. Tsui, and K. Alavi, *ibid.* **36**, 7751 (1987); Appl. Phys. Lett. **50**, 110 (1987).

[3] M. A. Paalanen, D. C. Tsui, and J. C. M. Hwang, Phys. Rev. Lett. **51**, 2226 (1983).

[4] K. K. Choi, D. C. Tsui, and S. C. Palmateer, Phys. Rev. B **33**, 8216 (1986).

[5] For a review, see C. W. J. Beenakker and H. van Houten, in *Solid State Physics*, Vol. 44, edited by H. Ehrenreich and D. Turnbull (Academic Press, San Diego, 1991), pp. 26–95.

[6] M. Sawicki, T. Dietl, J. Kossut, J. Igalson, T. Wojtowicz, and W. Plesiewicz, Phys. Rev. Lett. **56**, 508 (1986); I. P. Smorchkova, N. Samarth, J. M. Kikkawa, and D. D. Awschalom, *ibid.* **78**, 3571 (1997). Here, the Zeeman Hamiltonian of the electron-electron interacting system can be compared to Eq. 4.82 in R. M. White, in *Quantum Theory of Magnetism*, Springer Series in Solid-State Sciences, Vol. 32, edited by P. Fulde (Springer-Verlag, New York, 1983), p. 130.

[7] J. Jaroszynski, J. Wrobel, M. Sawicki, E. Kaminska, T. Skoskiewicz, G. Karczewski, T. Wojtowicz, A. Piotrowska, J. Kossut, and T. Dietl, Phys. Rev. Lett. **75**, 3170 (1995).

[8] W. Chen, Z. Wang, Z. Lin, and L. Lin, Appl. Phys. Lett. **70**, 1465 (1997); J. W. Hutchins, B. J. Skromme, Y. P. Chen, S. Sivananthan, and J. B. Posthill, *ibid.* **71**, 350 (1997); A. Castadini, A. Cavallini, B. Fraboni, P. Fernandez, and Piqueras, *ibid.* **69**, 3511 (1996).

[9] Ikai Lo, S. J. Chen, Y. C. Lee, L.-W. Tu, W. C. Mitchel, M. Ahoujja, R. E. Perrin, R. C. Tu, Y. K. Su, W. H. Lan, and S. C. Tu, Phys. Rev. B **57**, R6819 (1998).

[10] B. L. Altshuler, D. Khmelnitzkii, A. I. Larkin, and P. A. Lee, Phys. Rev. B **22**, 5142 (1980); S. Hikami, A. I. Larkin, and Y. Nagaoka, Prog. Theor. Phys. **63**, 707 (1980).

[11] D. J. Bishop, R. C. Dynes, and D. C. Tsui, Phys. Rev. B **26**, 773 (1982).

[12] B. J. F. Lin, M. A. Paalanen, A. C. Gossard, and D. C. Tsui, Phys. Rev. B **29**, 927 (1984); K. K. Choi, *ibid.* **28**, 5774 (1983); B. L. Altshuler, A. G. Aronov, and P. A. Lee, Phys. Rev. Lett. **44**, 1288 (1980).

[13] Ikai Lo, W. C. Mitchel, M. Ahoujja, J.-P. Cheng, A. Fathimulla, and H. Hier, Appl. Phys. Lett. **66**, 754 (1995).

[14] P. A. Lee and T. V. Ramakrishnan, Phys. Rev. B **26**, 4009 (1982).

[15] H. K. Ng, I. P. Smorchkova, and N. Samarth, Bull. Am. Phys. Soc. **43**, 489 (1998).

[16] H. Shao, S. Scholl, H. Schafer, J. Gerschutz, B. Jobst, D. Hommel, and G. Landwehr, Solid State Commun. **100**, 739 (1996).

[17] H. Wang, M. Jiang, R. Merlin, and D. G. Steel, Phys. Rev. Lett. **69**, 804 (1992).

[18] Th. Englert and K. von Klitzing, Surf. Sci. **73**, 70 (1978); D. Stein, K. von Klitzing, and G. Weimann, Phys. Rev. Lett. **51**, 130 (1983); M. Dobers, K. von Klitzing, and G. Weimann, Phys. Rev. B **38**, 5453 (1988).

[19] F. J. Ohkawa and Y. Uemura, J. Phys. Soc. Jpn. **43**, 925 (1977).

[20] G. E. Marques and L. J. Sham, Surf. Sci. **113**, 131 (1982).

[21] J.-C. Chiang, S.-F. Tsay, Z. M. Chau, and Ikai Lo, Phys. Rev. Lett. **77**, 2053 (1996); Phys. Rev. B **56**, 13 242 (1997).

[22] J. Puls, V. V. Rossin, F. Henneberger, and R. Zimmermann, Phys. Rev. B **54**, 4974 (1996).