From insulator to quantum Hall liquid at low magnetic fields

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We have performed low-temperature transport measurements on a GaAs two-dimensional electron system at low magnetic fields. Multiple temperature-independent points and accompanying oscillations are observed in the longitudinal resistivity between the low-field insulator and the quantum Hall (QH) liquid. Our results support the existence of an intermediate regime, where the amplitudes of magneto-oscillations can be well described by conventional Shubnikov–de Haas theory, between the low-field insulator and QH liquid.

Magnetic-field-induced transitions in two-dimensional (2D) systems have attracted much interest recently.[1–4] To date, despite many existing experimental and theoretical studies on these transitions, there are still some interesting but unresolved issues. In particular, it is still under debate whether a direct transition from an insulator (I) to a high Landau level filling factor ($\nu \geq 3$) quantum Hall (QH) state at low magnetic fields B is a genuine phase transition. Experimentally, a *single* approximately temperature (T)-independent point is observed in the longitudinal resistivity ρ_{xx} at a transition magnetic field B_c.[3] For $B < B_c$, ρ_{xx} decreases as the temperature is increased, reminiscent of an insulator. For $B > B_c$, ρ_{xx} increases with increasing T, characteristic of a QH liquid. The low-field I-QH transition[3] can be described by the destruction of the extended state within the tight-binding model.[3,5] However, Huckestein[6] argued that such a low-field transition is not a phase transition, but can be identified as a crossover from weak localization to strong localization due to Landau quantization. In his argument, the onset of QH liquid occurs as Landau quantization dominates with increasing B and the crossover covers a very narrow region in B so that it looks like a point. Nevertheless, recent experimental results[7] demonstrate that the crossover from low-field insulator to Landau quantization can cover a wide range of B (~ 0.45 T), which indicates that we shall consider corrections to the argument raised by Huckestein.[8,9] In fact, it has been shown that a QH liquid can be irrelevant to Landau quantization,[10] and more studies are necessary to develop the related microscopic picture.[11,12]

In addition to insulating and QH transport, actually the existence of a metallic regime[1,13–17] has been discussed in the literature although such a regime may be unstable with respect to the disorder.[1] Based on the tight-binding model, there can be a metallic phase between the low-field insulator and QH liquid.[14] It is believed that electron-electron (e-e) interaction plays an important role in the appearance of a metallic phase.[13] Recently a unifying model for various 2D transport regimes was proposed by Dubi, Meir, and Avishai.[16,17] In their work, percolation[18,19] and dephasing are both considered. In this Brief Report, we present an experiment to study various 2D transport regimes at low magnetic

fields. In our case, multiple T-independent points and oscillations in ρ_{xx} are observed between the low-field insulator and the QH liquid. By analyzing the amplitudes of these oscillations, we show the importance of metallic behavior described by conventional Shubnikov–de Haas (SdH) theory, which is derived by considering Landau quantization without resulting in strong localization.[20] By changing the applied gate voltage, we are able to observe a single T-independent point in ρ_{xx} which corresponds to the conventional low-field I-QH transition as reported previously.[3] Our experimental results suggest that the insulating behavior and metallic regime can coexist. Moreover, the Landau quantization effect can modulate the density of states of a 2D system without causing the formation of QH liquid.

Our sample was grown by molecular-beam epitaxy and consists of a 20-nm-wide AlGaAs/GaAs/AlGaAs quantum well. The following layer sequence was grown on a GaAs (100) substrate: 50 nm undoped $Al_{0.33}Ga_{0.67}As$, 20 nm GaAs, 40 nm undoped $Al_{0.33}Ga_{0.67}As$, 40 nm doped $Al_{0.33}Ga_{0.67}As$, and finally the 17 nm GaAs cap layer. The growth of the 20-nm-wide GaAs quantum well was interrupted at its center; the wafer was cooled from 580 °C to 525 °C. The shutter over the In cell was opened for 80 s, allowing the growth of 2.15 monolayer of InAs. 5 nm GaAs cap layer was then grown at 530 °C, before the substrate temperature was increased to 580 °C for the remainder of the growth. In our sample, the self-assembled InAs quantum dots, typically 4 nm in height and 28 nm in diameter, are formed near the center of the GaAs quantum well. Earlier studies on InAs quantum dots grown in the vicinity (15–80 nm) of a two-dimensional electron system (2DES) show that a dot-induced potential modulation drastically reduces the mobility.[21] When InAs quantum dots are placed close to the 2DES (≤ 20 nm), charging effects were observed.[22,23] Studies on scattering introduced by InAs quantum dots grown 3 nm from the $GaAs/Al_{0.33}Ga_{0.67}As$ interface show that self-assembled InAs quantum dots can tailor the electronic properties of a 2DES.[24] It has been proved that a 2DES containing InAs quantum dots is suitable for studying low-field I-QH transitions.[4] The device was made into a Hall pattern by standard lithography and etching processes and a
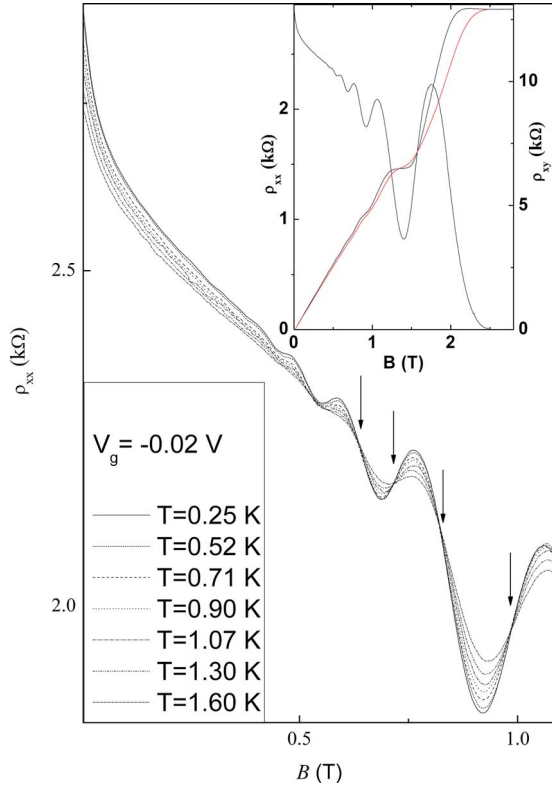
FIG. 1. (Color online) Longitudinal resistivity ρ_{xx} as a function of magnetic field B for $V_g = -0.02$ V at various temperatures T. Four approximately T-independent points are indicated by arrows. The inset shows $\rho_{xx}(B)$ ($T = 0.25$ K) and Hall resistivity $\rho_{xy}(B)$ at $T = 0.25$ K (higher Hall slope at low B) and $T = 1.6$ K (lower Hall slope at low B) for $V_g = -0.02$ V.

NiCr/Au gate was evaporated on the surface. At $V_g = 0$ V, the carrier density of our 2DES is 1.4×10^{15} m^{-2} with a mobility of ≈ 1.0 m^2/Vs. Four-terminal magnetoresistivities were measured in a He^3 cryostat using standard ac phase-sensitive lock-in techniques with a current of 10 nA.

Figure 1 shows the longitudinal resistivity $\rho_{xx}(B)$ for $V_g = -0.02$ V at various T. At low B, the 2DES behaves as an insulator in the sense that ρ_{xx} decreases as T is increased. The inset of Fig. 1 shows $\rho_{xx}(B)$ and Hall resistivity $\rho_{xy}(B)$ for $V_g = -0.02$ V. At $B > 2.5$ T, we can see a well-developed $\nu = 2$ QH state characterized by the Hall plateau and zero longitudinal resistivity. Therefore the 2DES behaves as an insulator at low fields and becomes a QH liquid with increasing B. Interestingly, between the QH state and the low-field insulator we observe four approximately T-independent points in Fig. 1 as indicated by arrows, in sharp contrast to only a single point reported in most experimental results.

The multiple T-independent points in ρ_{xx} suggest an intermediate regime, which is neither weakly insulating nor quantum Hall-type, between the low-field insulator and QH liquid. The existence of such a regime is a key ingredient in the unifying model for various 2D transport regimes as reported in Refs. 16 and 17. We note that a 2DES in such a regime behaves as a metal, to which the e-e interaction effect characterized by the T-dependent Hall slope may be important.[13] As shown in the inset of Fig. 1, the Hall slope at T
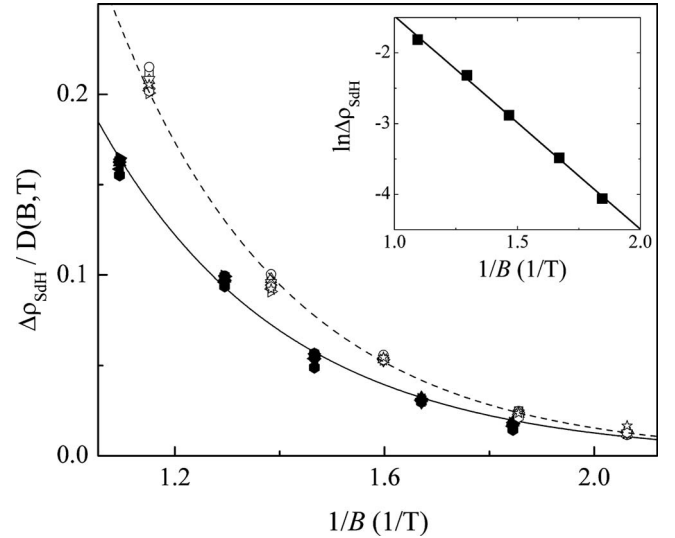

FIG. 2. $\Delta\rho_{\mathrm{SdH}}/D(B,T)$ as a function of $1/B$ for $V_g = -0.02$ V and $V_g = -0.06$ V. The full symbols denote the SdH amplitudes at $V_g = -0.02$ V when the temperature $T = 0.25$, 0.52, 0.71, 0.90, 1.07, 1.30, and 1.60 K. The open symbols denote the amplitudes at $V_g = -0.06$ V when $T = 0.25$, 0.32, 0.47, 0.61, 0.78, 0.93, 1.01, 1.22, and 1.37 K. The solid and dashed lines correspond to fits to $\Delta\rho_{\mathrm{SdH}}/D(B,T) = C\exp(-\pi/\mu B)$, where C is a constant independent of B and T when $V_g = -0.02$ V and -0.06 V, respectively. The inset shows $\ln\Delta\rho_{\mathrm{SdH}}$ as a function of $1/B$ at $T = 0.25$ K when $V_g = -0.02$ V. The solid line corresponds to a fit to $\Delta\rho_{\mathrm{SdH}} = C\exp(-\pi/\mu B)$.

$= 0.25$ K is higher than that at $T = 1.6$ K, suggesting that the e-e interaction effect is present in our system.

It is well known that low-field Landau quantization in the metallic regime is well described by SdH formula.[20] In our case, the observed magneto-oscillations in the intermediate regime shown in Fig. 1 are periodic in $1/B$, characteristic of Landau quantization effects. In order to test whether the conventional SdH theory, originally derived in the metallic region, is valid in the intermediate regime, we fit the amplitudes of the observed oscillations shown in Fig. 1 to the SdH formula[20,25,26]

$$\Delta\rho_{\mathrm{SdH}}(B,T) = C\exp(-\pi/\mu B)D(B,T), \qquad (1)$$

with $D(B,T) = (2\pi^2 k_B m^* T/\hbar e B)/\sinh(2\pi^2 k_B m^* T/\hbar e B)$. Here μ, m^*, T, k_B, and $\hbar$ are the mobility, effective mass, temperature, Boltzmann constant, and Planck constant divided by 2π, and C is a constant independent of B and T. It is expected that C is four times the zero-field resistivity although there are reports on its deviations. As shown in the solid line in Fig. 2, the amplitudes $\Delta\rho_{\mathrm{SdH}}$ are well described by Eq. (1). At the lowest temperature $T = 0.25$ K, as shown in the inset of Fig. 2, $\ln\Delta\rho_{\mathrm{SdH}}$ is linear with respect to $1/B$, which is consistent with Eq. (1) under which $\Delta\rho_{\mathrm{SdH}} \propto \exp(-\pi/\mu B)$ when T is so small that $D(B,T) \rightarrow 1$. Taking $\Delta\rho_{\mathrm{SdH}}^{(0)}(B)$ as $\Delta\rho_{\mathrm{SdH}}$ at $T = 0.25$ K, we find that the ratio $\Delta\rho_{xx}(B,T)/\Delta\rho_{\mathrm{SdH}}^{(0)}(B)$ with $T > 0.25$ K tends to decrease as B increases, which is also consistent with Eq. (1) of which the T-dependent factor $D(B,T)$ is a function of T/B. Moreover, using Eq. (1), we find that at $V_g = -0.02$ V the measured
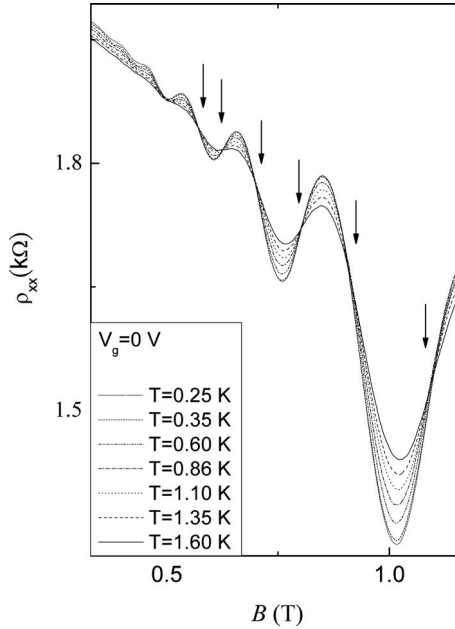
FIG. 3. $\rho_{xx}(B)$ for $V_g=0$ at various T. Six approximately T-independent points are indicated by arrows.

effective mass $m^*=(0.0698\pm0.0012)m_0$, close to the expected value $0.067m_0$ in GaAs. Here m_0 is the rest mass of a free electron. Our experimental results therefore clearly demonstrate that metallic behavior (magneto-oscillations governed by SdH theory) exists in this intermediate regime.

According to the SdH theory, $\rho_{xx}\sim\rho_0+\Delta\rho_{SdH}\cos[\pi(\nu-1)]$, where ρ_0 represents the nonoscillatory part. In the original derivation, ρ_0 is taken as a constant and is equal to the longitudinal resistivity at zero magnetic field. Thus a series of T-independent points are expected when $\cos[\pi(\nu-1)]=0$, which occurs when
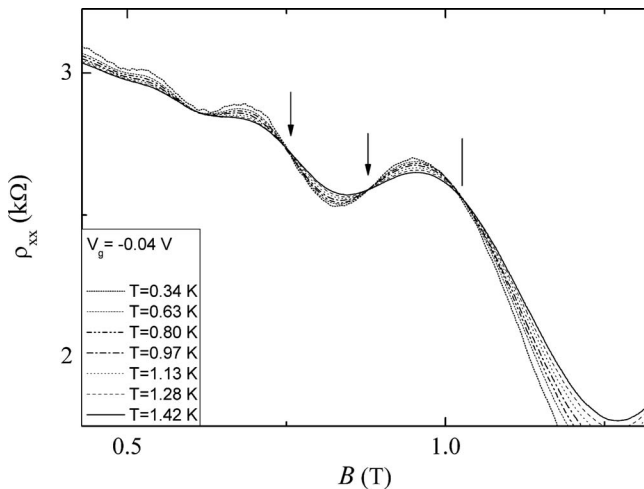

FIG. 4. $\rho_{xx}(B)$ for $V_g=-0.04$ V at various T. Two crossing points are indicated by arrows and the crossing point at the highest B is indicated by a vertical solid line.
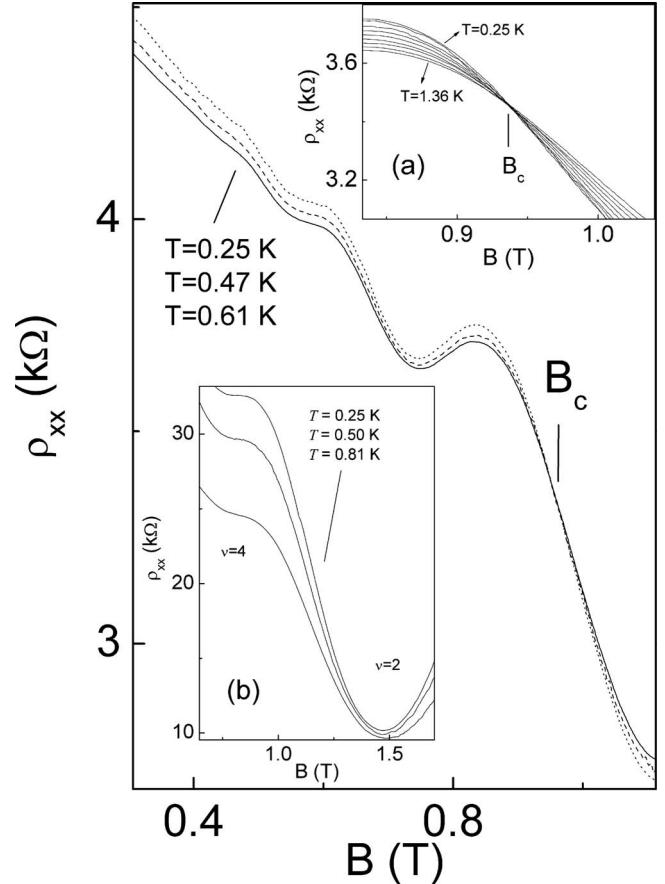

FIG. 5. Traces of $\rho_{xx}(B)$ for $V_g=-0.06$ V at different T. The transition field B_c is indicated by a vertical solid line. Inset (a) shows a zoom-in of ρ_{xx} near the transition field B_c at various temperatures. From top to bottom at $B=0.9$ T, $T=0.25$, 0.32, 0.47, 0.61, 0.78, 0.93, 1.01, 1.22, and 1.37 K. Inset (b) shows $\rho_{xx}(B)$ for $V_g=-0.117$ V at various T.

$$\nu=n\pm\frac{1}{2},\qquad(2)$$

where n is an integer. The positions in B of the four T-independent points labeled by arrows can be well described by Eq. (2), indicating that these points could be crossing points in the SdH oscillations. However, we would like to point out that this is only a possible explanation since the nonoscillatory background cannot be taken as a constant in our case. As shown in Fig. 3, with further increasing the gate voltage to 0 V, we observed two more crossing points governed by Eq. (2). On the other hand, only three crossing points are observed between the low-field insulator and QH liquid as we decrease V_g to -0.04 V as shown in Fig. 4. While the positions in B of T-independent points labeled by arrows are well described by Eq. (2), the crossing point indicated by a vertical line at the highest B is so close to a SdH maximum that its location does not follow Eq. (2). By further decreasing the gate voltage, as shown in Fig. 5, only such a crossing point is between the low-field insulator and QH liquid at $V_g=-0.06$ V. The inset (a) of Fig. 5 shows a zoom-in of $\rho_{xx}(B)$ near the crossing point at various T. We

can see that the transition point is T-independent within the experimental errors. Hence we can unify the prediction of the intermediate regime and the conventional I-QH transition. The 2DES enters a $\nu=4$ QH state directly from the insulator at the single transition point B_c, and such a transition is a direct 0–4 transition. Here the numbers 0 and 4 correspond to the insulator and $\nu=4$ QH state. In our study, ρ_{xx} does not equal to ρ_{xy} at $B=B_c$. However, we find that $\mu B_c \sim 1$ where mobility μ is obtained from the observed SdH oscillations. Therefore, well-separated Landau bands are important to a direct transition in our study[3] while Landau quantization can result in SdH oscillations when $\mu B < 1$.[25] We note that different mobilities should be introduced to understand the transport and universality[3] near the low-field I-QH transition.[8,9]

As mentioned earlier, conventional SdH theory is derived based on Landau quantization in the metallic regime. As shown in Fig. 5, for $B < B_c$ oscillations in ρ_{xx} are observed in the insulator when $V_g=-0.06$ V. The amplitudes of these oscillations are also well described by the SdH theory, as shown in open symbols and a dashed line in Fig. 2. We also find that the determined effective mass is close to the well-established value $0.067m_0$. Our results indicate that the magneto-oscillations may follow the SdH formula in the low-field insulator, where there could be metallic puddles responsible for such a formula, though more studies are required for understanding the deviations of ρ_0 from the zero-field resistivity.[27,28] Hence metallic and insulator behavior can coexist in our system.

As shown in the inset (b) of Fig. 5, at a sufficiently large negative gate voltage $V_g=-0.117$ V, the 2DES behaves as an insulator even at $\nu \sim 2$ and hence the corresponding QH state is destroyed by strong disorder. The destruction of such a QH state, which is the most robust and lowest one under the unresolved spin-splitting in our study, indicates that the 2DES is an insulator at all B. In such a case, we can still observe oscillations in ρ_{xx} due to Landau quantization as reported before.[4,7] Therefore, our study provides another piece of evidence to support that Landau quantization can modulate the density of states of a 2D system without resulting in the formation of a QH liquid.[10] We note that the tight-binding model and percolation theory may explain the coexistence of Landau quantization and the insulator.[14]

In our gated 2DES, when V_g is varied from 0 to -0.117 V, the carrier density is changed from 1.4×10^{15} m^{-2} to 7.1×10^{14} m^{-2}, and the zero-field resistivity is changed from 2.26 kΩ to 57.7 kΩ at $T=0.25$ K. In our system, a small change in gate voltage (≈ 0.12 V) can result in such a large change in both n and ρ_{xx}, thereby causing a dramatic change in the observed SdH pattern. These results may be related to the unique structure of our sample.

In conclusion, we have observed multiple crossing points in ρ_{xx} between the low-field insulator and QH liquid. Magneto-oscillations following conventional SdH theory can be observed before the appearance of a QH liquid with increasing B. By decreasing the gate voltage, we observe the conventional transition so that there is only one transition point between the low-field insulator and QH liquid. Therefore we are able to obtain a unified picture which relates the prediction on the metallic regime to the direct I-QH transitions.

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[1] S. Kivelson *et al.*, Phys. Rev. B **46**, 2223 (1992).

[2] H. W. Jiang *et al.*, Phys. Rev. Lett. **71**, 1439 (1993); T. Wang *et al.*, *ibid.* **72**, 709 (1994); R. J. F. Hughes *et al.*, J. Phys.: Condens. Matter **6**, 4763 (1994); D. Shahar *et al.*, Phys. Rev. B **52**, R14372 (1995); G. H. Kim *et al.*, *ibid.* **61**, 10910 (2000); H. P. Wei *et al.*, Phys. Rev. Lett. **61**, 1294 (1988); R. B. Dunford *et al.*, Physica B **298**, 496 (2001).

[3] S. H. Song *et al.*, Phys. Rev. Lett. **78**, 2200 (1997).

[4] G.-H. Kim *et al.*, Phys. Rev. B **69**, 073311 (2004).

[5] D. N. Sheng and Z. Y. Weng, Phys. Rev. Lett. **80**, 580 (1998).

[6] B. Huckestein, Phys. Rev. Lett. **84**, 3141 (2000), and references therein.

[7] T.-Y. Huang *et al.*, Physica E (Amsterdam) **22**, 240 (2004).

[8] H. I. Cho *et al.*, Phys. Rev. B **71**, 245323 (2005).

[9] Yu. G. Arapov *et al.*, arXiv:cond-mat/0512678 (unpublished).

[10] S. S. Murzin *et al.*, Phys. Rev. Lett. **80**, 2681 (1998); S. S. Murzin *et al.*, *ibid.* **92**, 016802 (2004).

[11] A. M. M. Pruisken and I. S. Burmistrov, Phys. Rev. Lett. **95**, 189701 (2005).

[12] S. S. Murzin and A. G. M. Jansen, Phys. Rev. Lett. **95**, 189702 (2005).

[13] E. A. Abrahams *et al.*, Rev. Mod. Phys. **73**, 251 (2001), and references therein.

[14] M. Nita *et al.*, Phys. Rev. B **62**, 15367 (2000).

[15] M. Nita *et al.*, Phys. Rev. B **69**, 073106 (2004).

[16] Y. Dubi *et al.*, Phys. Rev. B **71**, 125311 (2005).

[17] Y. Dubi *et al.*, Phys. Rev. Lett. **94**, 156406 (2005).

[18] S. A. Trugman, Phys. Rev. B **27**, 7539 (1983).

[19] E. Shimshoni *et al.*, Phys. Rev. Lett. **80**, 3352 (1998).

[20] P. T. Coleridge, Semicond. Sci. Technol. **5**, 961 (1990).

[21] H. Sakaki *et al.*, Appl. Phys. Lett. **67**, 3444 (1995).

[22] N. Horiguchi *et al.*, Appl. Phys. Lett. **70**, 2294 (1997).

[23] G. Yusa and H. Sakaki, Appl. Phys. Lett. **70**, 345 (1997).

[24] E. Ribeiro *et al.*, Phys. Rev. B **58**, 1506 (1998).

[25] G. W. Martin *et al.*, Phys. Rev. B **68**, 241309(R) (2003), and references therein.

[26] A. F. Brana *et al.*, J. Appl. Phys. **88**, 932 (2000).

[27] D. R. Hang *et al.*, Solid State Commun. **141**, 17 (2007).

[28] J.-H. Chen *et al.*, J. Korean Phys. Soc. **50**, 776 (2007).