Wigner Crystallization and Metal-Insulator Transition of Two-Dimensional Holes in GaAs at $B = 0$

Jongsoo Yoon,[1] C. C. Li,[1] D. Shahar,[2] D. C. Tsui,[1] and M. Shayegan[1]
[1]*Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544*
[2]*Department of Condensed Matter Physics, Weizmann Institute, Rehovot 76100, Israel*
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We report the transport properties of a low disorder two-dimensional hole system (2DHS) in the GaAs/AlGaAs heterostructure, which has an unprecedentedly high peak mobility of 7×10^5 cm^2/V s, with a hole density of $4.8 \times 10^9 < p < 3.72 \times 10^{10}$ cm^{-2} in the temperature range of 50 mK $< T <$ 1.3 K. From their T, p, and electric field dependences, we find that the metal-insulator transition in zero magnetic field in this exceptionally clean 2DHS occurs at $r_s = 35.1 \pm 0.9$, which is in good agreement with the critical r_s for Wigner crystallization $r_s^c = 37 \pm 5$, predicted by Tanatar and Ceperley for an ideally clean 2D system. [S0031-9007(99)08518-X]

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It is well known that the ground state of a two-dimensional (2D) electron or hole system realized in semiconductors at $B = 0$ is expected to be a Wigner crystal (WC) in the low density limit when carrier-carrier interaction becomes dominant over the kinetic energy of the carriers. Tanatar and Ceperley [1] from their Monte Carlo simulation for ideally clean systems find that the critical density, expressed in terms of the dimensionless parameter r_s, is $r_s = 37 \pm 5$. We note that r_s is the Coulomb energy to Fermi energy ratio, given by $r_s = (p\pi)^{-1/2} m^* e^2/4\pi\hbar^2\varepsilon\varepsilon_0$, where m^* is the effective mass, p the charge carrier density, and ε the dielectric constant. Disorder, which is always present in any experimental system, also plays important roles. In the clean limit, it is expected to pin the WC, rendering the system into an insulator. In the highly disordered dirty limit, the Coulomb interaction is negligible, or can be treated as a small perturbation; the system is better described by single particle localization. In between, when both interaction and localization are equally important, neither the electronic processes nor the nature of the phase is known and there is no clear physical picture for the system at the present time. Also, it is believed that if the disorder is not too strong, it can enhance Wigner crystallization. Chui and Tanatar [2] found from their Monte Carlo studies that the disorder they put in their model can stabilize the WC phase at r_s as low as 7.5.

On the experimental side, a number of publications [3–10], since the discovery by Kravchenko *et al.* [3] of a 2D metal-insulator transition (MIT) in high mobility Si metal-oxide-semiconductor field-effect transistors (Si MOSFET's) at $r_s \approx 10$, have reported transport studies in the large r_s regime of 2D electron or hole systems in several different semiconductor heterostructures. These studies generally do not address the properties in the insulating phase. They focus mostly on the nature of the metallic phase and the scaling behavior near the MIT. Their results agree with the conclusion of Kravchenko *et al.* [3] that there is a MIT in high mobility samples, and the critical density for the transition varies from $r_s \approx 5$ in $Si_{0.88}Ge_{0.12}$ to $r_s \approx 28$ in p-GaAs. In the case of the low mobility samples, the origin and nature of the insulating phase can be inferred from earlier Si MOSFET experiments, where a crossover from weak localization to strong localization is observed as the carrier density is decreased. In high mobility samples, which show MIT's at $r_s \approx 10$, Pudalov *et al.* [11] first studied the transport characteristics in the insulating phase and attributed them to those of a pinned WC. However, Shashkin *et al.* [12] and Mason *et al.* [13] subsequently found that single particle localization gives a better description and the transport is via hopping in the presence of a Coulomb gap. It thus appears that in the regime where disorder and localization must be treated on equal footing, transport and I-V characteristics do not allow us to identify whether the insulating phase is a WC. A more desirable approach to the problem has to come from clear identification of a 2D system in the clean limit, where the physics is expected to be simpler and theoretical predictions more reliable.

In this Letter, we report transport measurements on a 2D hole system (2DHS) in GaAs/Al_xGa_{1-x}As, which has an unprecedentedly high peak mobility, $\mu_p = 7 \times 10^5$ cm^2/V s. This mobility, approximately twice as high as previously studied 2DHS, allowed us to reach p as low as 4.8×10^9 cm^{-2}. From a systematic study of density, temperature, and bias dependences of the hole transport, we find a MIT at $r_s = 35.1 \pm 0.9$, which is in good agreement with $r_s = 37 \pm 5$ predicted for the WC transition by Tanatar and Ceperley. We also examine the dependence of r_s at the MIT, from all 2D electron and hole systems that have been reported to show MIT's, on the disorder in the sample and show that our sample is indeed in the clean limit. In the rest of this paper, we present this result and also describe in detail related new transport characteristics from our 2DHS.

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The 2DHS is created in a modulation doped $GaAs/Al_xGa_{1-x}As$ heterostructure grown on the (311)*A* surface of a GaAs substrate by molecular-beam epitaxy. A backgate, used to change the density, is situated 250 μm away from the 2DHS and does not screen the carrier-carrier interaction. Since the holes are produced by modulation doping, the background neutralizing charges are immobile. In contrast, the 2D carriers in the insulated gate field-effect transistors used in other experiments [3–7] are capacitively induced by applying a voltage to a metallic gate located close to the 2D systems. In such transistors, the background neutralizing charges are mobile and the carrier-carrier interaction is screened.

The sample was a rectangle of 4.2×0.4 mm^2 cut along the $[\bar{2}33]$ direction, after the wafer was thinned to 250 μm. Resistivity (ρ) was measured by a four probe method. To avoid sample heating, the current was limited to below 1 nA, and the voltage was measured across two contacts separated by 0.7 mm located near the center. An ac technique using a lock-in amplifier at a frequency <10 Hz was used whenever possible. At low densities where capacitive coupling becomes significant, a dc method was employed. The sample was cooled in the mixing chamber of a dilution refrigerator. Three samples cut from the same wafer were studied, and all showed MIT's with the same characteristics. However, the data reported in this Letter were collected over three cooldowns on the same sample. The sample was warmed up to room temperature between cooldowns.

Figure 1 shows the T dependence of ρ, measured in the zero current limit, in the range 50 mK $< T <$ 1.3 K, for $4.8 \times 10^9 \leq p \leq 3.72 \times 10^{10}$ cm^{-2} or $16.0 \leq r_s \leq 44.4$. For $p > 2 \times 10^{10}$ cm^{-2} (the two bottom traces), the sign of $d\rho/dT$, which has been usually used to distinguish the metallic phase from the insulating phase, is positive in the entire T range, showing metallic behavior. For $p \leq 7.2 \times 10^9$ cm^{-2} (the four top traces), $d\rho/dT$ is always negative exhibiting the characteristic of an insulator. In the intermediate range of p, however, there is a peak in ρ resulting from $d\rho/dT < 0$ at high T and $d\rho/dT > 0$ at low T. This peak starts to appear at $p = 1.98 \times 10^{10}$ cm^{-2}; it becomes more pronounced and shifts to a lower temperature as p decreases. The maximum is at $T \approx 0.7$ K at $p = 1.98 \times 10^{10}$ cm^{-2}, and $T \approx 0.18$ K at $p = 9.0 \times 10^9$ cm^{-2}. The presence of such a peak makes it ambiguous to tell whether the 2DHS is in the metallic phase or insulating phase using the sign of $d\rho/dT$ as the criterion. For example, at $p = 9.0 \times 10^9$ cm^{-2}, if the measurements are made only down to 0.3 K, one would conclude from the fact $d\rho/dT$ is negative that the 2DHS is in the insulating phase, while the data below 0.18 K indicate that the 2DHS is, in fact, in the metallic phase.

However, this ambiguity can be avoided if we define the phase as metallic when the *I-V* curve is superlinear ($d^2I/dV^2 < 0$) and insulating when it is sublinear ($d^2I/dV^2 > 0$). Figure 2 is the differential conductance

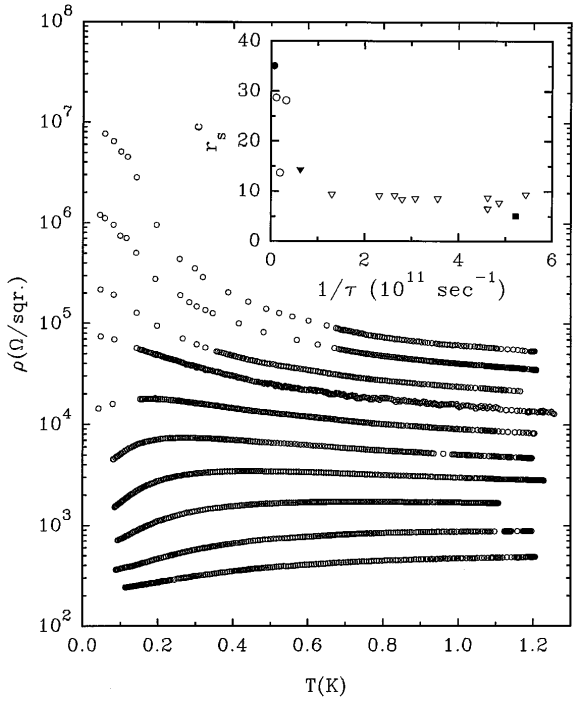

FIG. 1. T dependence of ρ: from the top curve, $p = 0.48$, 0.55, 0.64, 0.72, 0.90, 1.02, 1.27, 1.98, 2.72, and 3.72 in units of 10^{10} cm^{-2}. The inset shows the dependence of r_s^c on $1/\tau$, from various 2D systems; this work (filled circle), 2DHS in GaAs/AlGaAs (open circles [7–9]), 2DES AlAs/GaAlAs (filled triangle [6]), 2DHS in $Si_{0.88}Ge_{0.12}$/Si (filled square [10]), and 2DES in Si MOSFET (open triangles [3–5]). $m^*/m_e =$ 0.37, 0.46, 0.18, and 0.19 for *p*-GaAs [17], *n*-AlAs [18], *p*-$Si_{0.88}Ge_{0.12}$ [19], and *n*-Si MOSFET.

(dI/dV) plotted against V at $p = 9.0 \times 10^9$ cm^{-2}, taken at several temperatures below and above the ρ maximum, as marked by the arrows in the inset. In sharp contrast to $d\rho/dT$, which shows a metallic behavior below and an insulating behavior above $T = 0.18$ K, the dI/dV vs V taken at all four temperatures show superlinear *I-V* characteristics, i.e., dI/dV decreases with increasing V. Such a superlinear *I-V* characteristic is observed down to $p = 8.1 \times 10^9$ cm^{-2}. When p is reduced below 7.3×10^9 cm^{-2}, where ρ shows monotonic increase with decreasing T, the *I-V* curve becomes sublinear, indicative of an insulating phase. It should also be pointed out that identifying the metallic phase and the insulating phase based on the sign of d^2I/dV^2 gives exactly the same result as that obtained using the sign of $d\rho/dT$ at our lowest T.

Using the sign of d^2I/dV^2, we locate the MIT at $p = 7.7 \pm 0.4 \times 10^9$ cm^{-2}, or equivalently at $r_s = 35.1 \pm 0.9$ using $m^*/m_e = 0.37$. At the MIT, ρ is approximately 35 kΩ at $T \to 0$, and E_F is calculated to be 0.58 K. The critical r_s for the MIT in our sample is approximately 4 times that in high mobility Si MOSFET's and 25% larger than that in previously studied highest mobility 2DHS in GaAs/AlGaAs, of which $\mu_p \approx 4 \times 10^5$ cm^2/V s is approximately half that in our 2DHS. It is

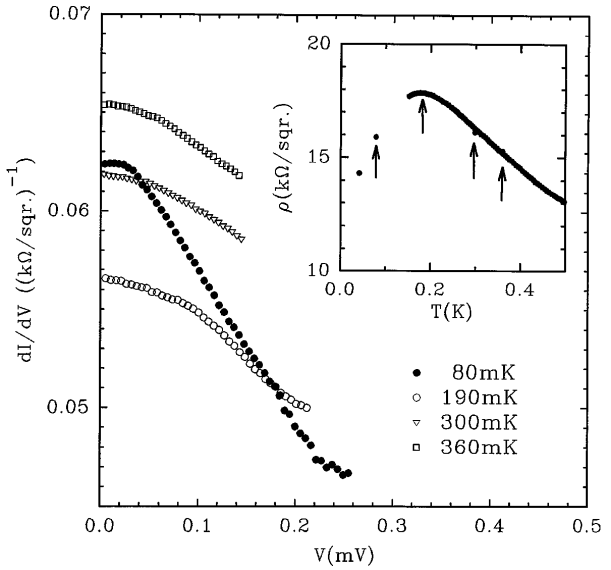

FIG. 2. dI/dV in the metallic phase near the MIT ($p = 9.0 \times 10^9$ cm^{-2}) at four different temperatures marked by the arrows in the inset. Qualitatively same nonlinear I-V characteristics are seen at all four temperatures. In contrast, $d\rho/dT$ shows a metallic behavior below and an insulating behavior above $T = 0.18$ K.

clear from this result that the r_s, at which the 2D MIT is observed, depends strongly on the disorder in the 2D system. In the inset of Fig. 1, we plot r_s^c, the 2D MIT critical r_s, from all samples reported in the literature as a function of the scattering rate of the 2D carriers, defined by $1/\tau = e/(m^*\mu_p)$, which gives a simple measure of the disorder and also takes into account the differences in the effective mass m^* of the charge carriers in different material systems. It is clear that for $1/\tau > 1 \times 10^{11}$ sec^{-1}, where all the high mobility Si MOSFET data lie, r_s^c is approximately constant. The data from the 2D systems in GaAs/AlGaAs heterostructures, which are known to have low disorder and show fractional quantum Hall effect characteristics in high magnetic fields, are all in the $1/\tau < 1 \times 10^{11}$ sec^{-1} regime. In this low scattering rate region, r_s^c shows a steep increase with decreasing $1/\tau$ and extrapolates to $r_s^c = 30 \sim 40$ as $1/\tau \to 0$. Our data, shown as the filled circle in the figure, are in the clean limit, and the observed $r_s^c = 35.1 \pm 0.9$ is in good agreement with the $r_s = 37 \pm 5$ for the WC transition predicted by Tanatar and Ceperley.

In the clean limit, a WC is expected to be pinned, giving rise to a depinning threshold voltage, which is characterized by a sudden increase in current as the applied voltage exceeds the threshold. In Fig. 3, the dV/dI taken at $r_s = 44.4$ is plotted against V. At 50 mK, the dV/dI is nearly constant until V reaches about 1.5 mV, beyond which it drops rapidly by an order of magnitude at $V \approx 3$ mV. This is suggestive of the depinning threshold expected for a pinned WC. In the WC conduction model proposed by Chui [14], where the WC is weakly pinned by the potential of remote dopants, transport is expected to be mediated by the creation of dislocation pairs through quantum tunneling. The energy needed to create a dislocation pair leads to a conduction threshold voltage. The observed threshold voltage of 1.5 mV, corresponding to a field of 2.1 V/m, is in reasonable agreement with Chui's model, according to which the depinning threshold field estimated for our sample is $E_d = 0.09 n_i a^2 e^2/\varepsilon d^3 = 2.5$ V/m. Here, $n_i = 8 \times 10^{11}$ cm^{-2} is the remote doping impurity density, $a = (\pi p)^{-1/2}$, and the doping impurity setback distance $d = 1200$ Å. However, there are caveats. The pinning gap deduced from E_d, $\Delta_p = \hbar(eE_d/m^*a)^{1/2} \approx 2.7$ K, is not consistent with the observation that no well-defined depinning threshold feature is seen when the thermal energy is still much smaller than the gap. In Fig. 3, the data show no clear threshold at T as low as 145 mK. Moreover, as shown in the inset of Fig. 3, the I-V curve at T as low as 50 mK is linear within the experimental resolution at voltages below 1.5 mV. This Ohmic conduction below the depinning threshold voltage cannot be explained by a possible backgate leakage current, which is much less than 1 pA.

Finally, we turn to the overall symmetry in the nonlinear transport properties of our low disorder 2DHS as its density is varied across the MIT. Shahar *et al.* [15] recently reported a new symmetry across the quantum Hall liquid to Hall insulator transition. They find that the I-V curves in the quantum Hall liquid phase can be mapped into the I-V curves in the Hall insulator phase by simply interchanging I with V. This I-V inversion symmetry can be viewed as reflecting the charge-flux duality symmetry in the composite boson description of the fractional quantum Hall effect. More recently, Kravchenko *et al.* [4] and Simonian *et al.* [16] reported a similar reflection symmetry across the 2D MIT, although its origin is still unclear at the

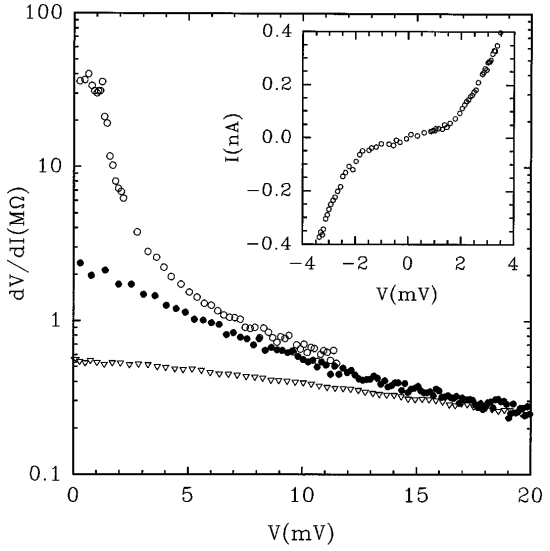

FIG. 3. dV/dI at $p = 4.8 \times 10^9$ cm^{-2} is plotted against V at $T = 50$ mK (open circles), 145 mK (filled circles), and 284 mK (triangles). The inset shows the I-V curve at $T = 50$ mK.

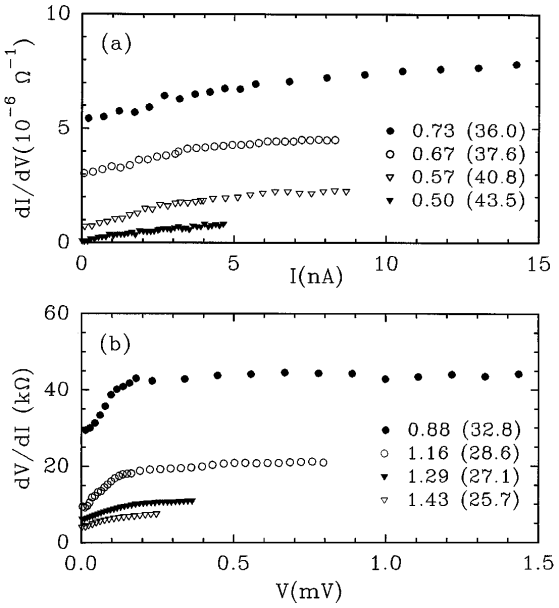

FIG. 4. (a) dI/dV vs I in the insulating phase and (b) dV/dI vs V in the metallic phase at 50 mK. The numbers shown next to the symbols are the densities in units of 10^{10} cm^{-2}. The corresponding r_s values are in parentheses.

present time. We have made a detailed comparison of the I-V characteristics in the metallic and insulating phases in our sample and find that they are qualitatively different. Instead of comparing I-V with V-I in the two phases, we compare their derivatives which are more sensitive to changes in the curvature. In Figs. 4(a) and 4(b), dI/dV in the insulating phase and dV/dI in the metallic phase are shown against I and V, respectively. In the metallic phase, as V increases, dV/dI initially increases, but stops increasing at $V \approx 0.15$ mV. Above this characteristic voltage, dV/dI stays constant to I as high as 100 nA, the highest current used in our measurements. If we assume a reflection symmetry with respect to a straight line in the I-V curve corresponding to a sheet resistivity $\rho = 35$ kΩ at the MIT, the characteristic voltage of 0.15 mV in the metallic phase implies a characteristic current of 2.5 nA in the insulating phase, above which dI/dV should remain constant. It is clear from Fig. 4(a) that such a characteristic current is absent in all traces of the dI/dV vs I in the insulating phase. We conclude that the I-V reflection symmetry across the 2D MIT is not observed in our data in the ranges of I and V shown in Fig. 4.

To summarize, we presented transport properties of a 2DHS that undergoes a MIT at $r_s^c = 35.1 \pm 0.9$, which is unambiguously determined using the sign of d^2I/dV^2 rather than $d\rho/dT$. The dependence of r_s^c on disorder, from all 2D electron and hole systems that have been reported to show MIT's, indicates that our 2DHS is in the clean limit, and the value of r_s^c in our sample is in good agreement with $r_s = 37 \pm 5$ expected for the WC transition by Tanatar and Ceperley. In the insulating phase, a conduction threshold that is quantitatively consistent with the WC conduction model of Chui is found, but the pinning gap estimated from the observed threshold field is too large compared with our observations. We also find that the I-V reflection symmetry across the MIT is absent in our low disorder 2DHS.

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[1] B. Tanatar and D. M. Ceperley, Phys. Rev. B **39**, 5005 (1989).
[2] S. T. Chui and B. Tanatar, Phys. Rev. Lett. **74**, 458 (1995).
[3] S. V. Kravchenko, G. V. Kravchenko, J. E. Furneaux, V. M. Pudalov, and M. D'Iorio, Phys. Rev. B **50**, 8039 (1994).
[4] S. V. Kravchenko, D. Simonian, and M. P. Sarachik, Phys. Rev. Lett. **77**, 4938 (1996).
[5] D. Popovic, A. B. Fowler, and S. Washburn, Phys. Rev. Lett. **79**, 1543 (1997); S. V. Kravchenko, Whitney E. Mason, G. E. Bowker, J. E. Furneaux, V. M. Pudalov, and M. D'Iorio, Phys. Rev. B **51**, 7038 (1995); V. M. Pudalov, JETP Lett. **66**, 175 (1997); D. Simonian, S. V. Kravchenko, M. P. Sarachik, and V. M. Pudalov, Phys. Rev. Lett. **79**, 2304 (1997); V. M. Pudalov, G. Brunthaler, A. Prinz, and G. Bauer, JETP Lett. **65**, 932 (1997).
[6] S. J. Papadakis and M. Shayegan, Phys. Rev. B **57**, R15 068 (1998).
[7] Y. Hanein, U. Meirav, D. Shahar, C. C. Li, D. C. Tsui, and H. Shtrikman, Phys. Rev. Lett. **80**, 1288 (1998).
[8] M. Y. Simmons, A. R. Hamilton, M. Pepper, E. H. Linfield, R. D. Rose, D. A. Ritchie, A. K. Savchenko, and T. G. Griffiths, Phys. Rev. Lett. **80**, 1292 (1998).
[9] M. Y. Simmons, A. R. Hamilton, T. G. Griffiths, A. K. Savchenko, M. Pepper, and D. A. Ritchie, Physica (Amsterdam) **249B–251B**, 705 (1998).
[10] P. T. Coleridge, R. L. Williams, Y. Feng, and P. Zawadzki, Phys. Rev. B **56**, R12 764 (1997).
[11] V. M. Pudalov, M. D'Iorio, S. V. Kravchenko, and J. W. Campbell, Phys. Rev. Lett. **70**, 1866 (1993).
[12] A. A. Shashkin, V. T. Dolgopolov, and G. V. Kravchenko, Phys. Rev. B **49**, 14 486 (1994).
[13] W. Mason, S. V. Kravchenko, and J. E. Furneaux, Surf. Sci. **361/362**, 953 (1996).
[14] S. T. Chui, Phys. Lett. A **180**, 149 (1993); J. Phys. Condens. Matter **5**, L405 (1993).
[15] D. Shahar, D. C. Tsui, M. Shayegan, E. Shimshoni, and S. L. Sondhi, Science **274**, 589 (1996).
[16] D. Simonian, S. V. Kravchenko, and M. P. Sarachik, Phys. Rev. B **55**, R13 421 (1997).
[17] K. Hirakawa, Y. Zao, M. B. Santos, M. Shayegan, and D. C. Tsui, Phys. Rev. B **47**, 4076 (1993).
[18] T. S. Lay, J. J. Heremans, Y. W. Suen, M. B. Santos, K. Hirakawa, M. Shayegan, and A. Zrenner, Appl. Phys. Lett. **62**, 3120 (1993).
[19] S.-H. Song, D. C. Tsui, and F. F. Fang, Solid State Commun. **96**, 61 (1995).