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Description	

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Percolation transition of the quasi-two-dimensional hole system in δ-doped GaAs structures

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The transition from thermally activated conduction to metallic conduction in Be δ-doped GaAs structures was investigated. At room temperature, samples with lower Be concentrations exhibited the thermally activated conduction, and other samples with higher Be concentrations showed the metallic conduction. The activation energy for the conduction of the insulating samples changes linearly with the Be concentration, vanishing at a critical Be concentration. The slope of the linear change corresponds to the density of states in the quasi-two-dimensional hole system of GaAs, suggesting the existence of the mobility edge in this system. A model of percolation via quantum point contacts is used for the analysis of the temperature-dependence of the resistivity in the samples with high Be concentrations. The thermally activated conduction in these samples at low temperatures is explained by assuming the existence of more than one percolation thresholds which result from the nature of quantum point contacts. The temperature dependence of the resistivity at high temperatures for all investigated samples collapses onto a single curve in each of the insulating and metallic side with one scaling parameter T_0. The value of T_0 has a power-law relation with the hole concentration in both insulating and metallic sides with critical exponents being 0.94 ± 0.05 and 1.19 ± 0.16, respectively.

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I. INTRODUCTION

One of the main conclusions of the scaling theory of localization, which was presented by Abrahams *et al.*,[1] is that there is no true metal-insulator transition in two-dimensional disordered electronic systems in zero magnetic field; instead of a singularity resulting from a continuous phase transition, there is a smooth and continuous crossover from logarithmic to exponential behavior of the conductivity in the two-dimensional systems. Results of earlier experiments[2,3] supported this conclusion, and, hence, the absence of a metal-insulator transition in real two-dimensional electronic systems, which more or less suffer disorder of potentials, had become a widely accepted view.

In 1994 Kravchenko *et al.* reported a finding of a possible metal-insulator transition in high-mobility Si metal-oxide-semiconductor field-effect transistors (MOSFETs) in zero magnetic field.[4] Their results showed that Si MOSFET samples with high electron concentrations exhibited metallic conduction at temperatures down to the measurable lowest temperature, 35 mK.[5] It was shown that the temperature dependence of the resistivity in both metallic and insulating sides of the transition was able to scale with a single parameter T_0; the value of T_0 depended on the electron concentration with a power-law relation.[6] These characteristics strongly suggest that it is a true metal-insulator transition in two dimensions in a zero magnetic field. It has been suggested that the occurrence of this transition may be attributed to electron-electron interactions which are not accounted for by the above-mentioned scaling theory,[7] but the origin of the possible metal-insulator transition has not yet been fully clarified at present. Similar possible metal-insulator transitions have been observed in other two-dimensional electron systems since the finding of the transitions in Si MOSFET samples.[8–11] Some of those transitions exhibited the scaling behavior of the temperature dependence of the resistivity.[7] As another common characteristic of these transitions, the resistivity at the transitions was found to be close to the quantum unit of resistance h/e^2,[7] the possible origin of which was explained by a percolation-type description of the metal-insulator transitions.[12]

Recently we reported a finding of a transition from the thermally activated conduction to the metallic conduction in Be δ-doped structures grown by molecular-beam epitaxy (MBE).[13] The structure is made of a combination of a Be δ-doped layer and a low-temperature-grown GaAs(LT-GaAs) ultrathin layer containing a high concentration of antisite As atoms. With an increase in the Be doping concentration, an activation energy for the conduction continuously decreases towards zero. Beyond a certain Be concentration the metallic conduction occurs. The interesting aspects of this transition are that it occurs at room temperature and the resistivity at the transition is very close to $\frac{1}{2}h/e^2$.

At low temperatures, typically below 250 K, the resistivity of the Be δ-doped structures in the metallic side starts to increase with lowering the temperature. They, therefore, may not be metallic at their ground states, and this transition may not be a true metal-insulator transition. However, a continuous decrease in the activation energy towards zero with the Be concentration approaching a critical value suggests that this transition may be a continuous phase transition of an electronic system. This paper presents results of the investigation of this possibility by the analysis of the quantitative dependence of the resistivity on the Be concentration in the δ-doped layer. One main result of the analysis is that the change of the activation energy of the thermally activated conduction with the Be concentration directly corresponds to the density of states in a quasi-two-dimensional hole system. As another main result, the origin of thermally activated conduction at low temperatures in the metallic side is explained with a model of percolation via quantum point contacts. Finally the present study shows that the temperature depen-

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dence of the resistivity in both insulating and metallic side at high temperatures exhibits a scaling behavior with one scaling parameter T_0.

II. EXPERIMENT

Seventeen Be δ-doped GaAs structures with different Be concentrations were grown by utilizing a MBE system. The Be concentrations in δ-doped layers in these samples range from 4.2×10^{13} to 9.1×10^{13} cm^{-2}. Detailed growth conditions and the layer configuration were described in an earlier report.[13]

In the present study, the following procedures were used in order to investigate quantitative dependence of the resistivity on the Be concentration in the δ-doped layer. Instead of the substrate temperature 520 °C used for the Be δ doping and the growth of a spacer layer in the earlier study,[13] a lower substrate temperature of 450 ° C was used. The lower temperature minimizes the diffusion and surface segregation of Be during the δ doping and the growth of the spacer layer and, hence, can give rise to a nearly ideal dopant distribution in the δ-doped layer. A substrate temperature lower than 450 °C, on the other hand, was found to roughen the surface of the spacer layer and tend to result in the formation of extended defects in an ultrathin LT-GaAs layer. The realization of a nearly ideal Be distribution in the δ-doped layer was strongly suggested by the direct correlation of the dependence of the activation energy for the conduction on the Be concentration with the density of states in a two-dimensional hole system, which will be described later in the present paper.

Another special procedure taken in this study is the use of the same substrate holder throughout all growth experiments. The substrate temperature for the growth of LT-GaAs layer was set with the combination of pyrometer and thermocouple readings as described in the earlier report.[13] It is known that the difference between the thermocouple reading and the actual substrate temperature in the MBE growth strongly depends on substrate holders even if a substrate is mounted on a substrate holder with Indium in the same manner. The use of the same substrate holder, hence, improves the reproducibility of the substrate temperature for the growth of LT-GaAs layer and results in nearly identical antisite As concentrations among the samples.

For van der Pauw measurements of resistivity, a square 5×5-mm^2 sample was cut from each MBE-grown sample, and an In contact was made at each corner of the sample. More details of these procedures were described in the earlier report.[13]

III. RESULTS AND DISCUSSION

Figure 1 shows the temperature dependence of the resistivity of 17 samples in the temperature range from 5 to 350 K. The Be doping concentration decreases monotonically from sample 1 to sample 17. The resistivity of the samples increases with a decrease in the Be concentration. The resistivity of nine samples with lower Be concentrations, from samples 9 to 17, which are denoted by open symbols, monotonically increases with lowering the temperature in the whole measurement temperature range. The resistivity of eight samples with higher Be concentrations from the samples 1–8, which are denoted by solid symbols, initially decreases with lowering the temperature, exhibiting a metallic behavior, but starts to increase in the temperature range approximately between 255 and 200 K. With further lowering the temperature towards 0 K, the resistivity of these samples continues to increase. The resistivity of sample 9, whose Be concentration is the middle of those of 17 samples, remains nearly constant in the temperature range from 350 to 275 K, and shows an insulating behavior in the lower temperature range.

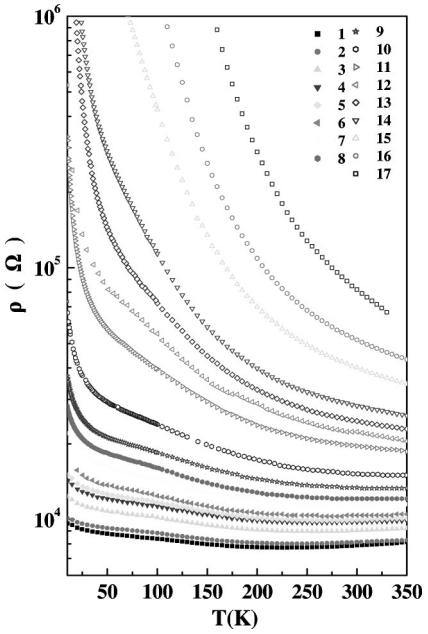

FIG. 1. Temperature dependence of the resistivity of 17 samples with different Be doping concentrations.

In the Arrhenius plots of the resistivity of nine samples with lower Be concentrations, there are three temperature ranges with respect to the temperature dependence of the resistivity, similarly to the plots shown in Fig. 4 of our earlier paper.[13] In the higher temperature range above 250 K, the plots of the all samples become asymptotically linear changes. An extrapolation of these linear changes towards $1/T=0$ converges the value of $\frac{1}{2}h/e^2$. In the intermediate temperature range from 150 to 250 K, the plots change superlinearly; apparent activation energies continuously increase with lowering temperature in this temperature range. In the lower temperature range below 150 K the activation energies significantly decrease with lowering temperature, which is attributed to a gradual replacement by the hopping conduction of localized holes. At temperatures above 150 K, the mobility is nearly 100 cm^2/Vs and slowly decreases with an increase in the temperature, indicating that the conduction occurs via thermal excitation of localized holes to extended states.

Figure 2 shows the relationship between the Be concentrations and the activation energies ε_1 which were derived from nearly linear changes of the Arrhenius plots of the

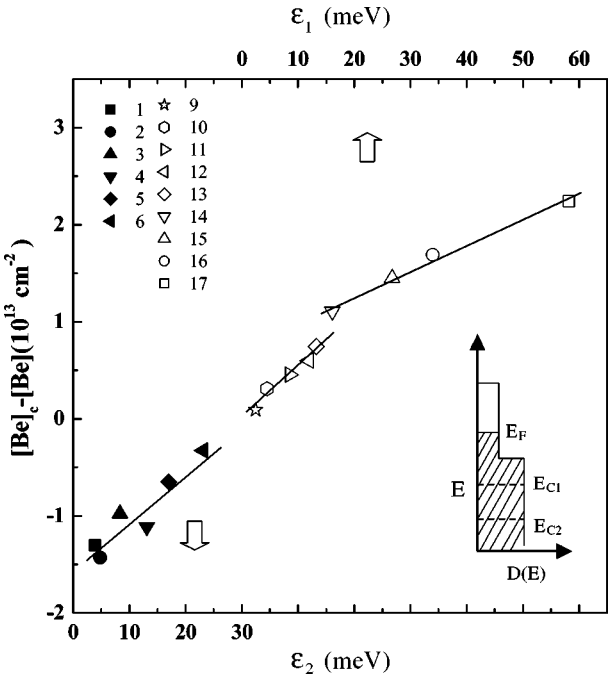

FIG. 2. Relationship between the Be concentrations and the activation energies ε_1 and ε_2. The former, denoted by open symbols, were derived from the resistivity of nine samples which exhibit thermally activated conduction at room temperature. The latter, denoted by solid symbols, were derived from six samples in higher Be concentrations. The inset schematically shows the energy band of the Be δ-doped layer where E_F, E_{c1}, and E_{c2} are the Fermi level, the first percolation threshold, and the second percolation threshold, respectively.

samples from 9 to 17. The plots of ε_2, denoted by solid symbols in the figure, will be explained later. In the figure, [Be] is the Be concentration of a sample, and $[\mathrm{Be}]_c$ is the critical Be concentration 6.40×10^{13} cm^{-2} whose value was determined by extrapolating a linear change of activation energies ε_1 of the sample from 13 to 9 towards zero. Figure 2 shows two parts of linear changes of ε_1 with a smaller slope in the high activation energy part.

The density of states in a quasi-two-dimensional electron system is given by

$$D(E)=j\frac{4\pi m^*}{h^2}, \tag{1}$$

where j is the number of occupied subbands and m^* is an effective mass. Effective masses of a heavy hole and a light hole of GaAs are $0.62m$ and $0.08m$, respectively,[14] where m is the free electron mass. For heavy holes which dominate the density of states at a given energy according to Eq. (1), the value of $4\pi m^*/h^2$ is 2.58×10^{11} meV^{-1} cm^{-2}. The slopes of linear changes in Fig. 2 were found to be in the order of this value. Hence, by assuming that the slopes correspond to $D(E)$ of heavy holes, the numbers j were derived for two parts of the linear change of ε_1 by using the least square method; they are 2.08 ± 0.23 and 1.03 ± 0.07 for the low and high activation energy parts, respectively. The close agreement between the slopes of linear changes in Fig. 2 and the density of states in the quasi-two-dimensional hole system implies that holes in the Be δ-doped layers behave as a quasi-two-dimensional system even at room temperature, where the activation energy corresponds to the energy difference between the Fermi level and the energy of the critical extended state. The values of j further suggest that the Fermi level is located in the lowest subband of heavy holes in the high activation energy part and the critical extended state is located in the second lowest subband; as shown by the inset of Fig. 2.

Once the Fermi level has passed the critical extended state, the system is expected to become metallic without any activation energy for the carrier transport. As seen in Fig. 1, however, at lower temperatures thermally activated conduction occurs in the samples whose resistivity has the metallic temperature dependence at room temperature. These samples, therefore, may not be metallic at their ground states. One may, hence, consider that the above-mentioned transition is merely a result of competition between strong localization and temperature-dependent Drude resistivity resulting from carrier-phonon scattering; as the resistivity decreases with an increase in the Be concentration, the temperature dependence of the Drude resistivity overwhelms the temperature dependence resulting from the thermal activation of localized carriers. It is, however, very unlikely that such competition happens to lead to the linear change of the observed activation energy with the Be concentration towards zero and the slope of the linear change being nearly equal to the density of states in a two-dimensional system. It is also difficult to explain with such a competition that the resistivity at the transition is very close to the quantum unit of resistance.

According to the scaling theory of localization,[1] there is a crossover in two dimensions between strong localization and weak localization, that is, the exponential temperature dependence of the resistivity and the logarithmic temperature dependence. This crossover is predicted to occur gradually without any behavior resulting from singularity. An earlier study on this crossover in Si MOSFET samples[3] showed that for a resistivity lower than 10 kΩ the temperature dependence was logarithmic, while for a resistivity higher than 15 kΩ the temperature dependence was exponential. In the range between 10 and 15 kΩ a gradual transition from a logarithmic dependence to an exponential dependence occurred. In contrast to the results of the earlier study, there is a sharp transition in the present case from the exponential temperature dependence to the metallic temperature dependence. The exponential temperature dependence continues until the resistivity reaches the value of $\frac{1}{2}h/e^2$, namely, 12.9 kΩ, and below this resistivity the metallic temperature dependence occurs at room temperature. The room temperature resistivity of sample 9 is 13.3 kΩ which is the lowest among those having the exponential temperature dependence, while the room temperature resistivity of sample 8 is 12.0 kΩ which is the highest among those having the metallic temperature dependence at room temperature.

Mott proposed that there was a sharp energy boundary called a mobility edge which separated localized and nonlocalized states in a conduction band of a disordered system.[15] If the Fermi level is located among localized states, the conduction occurs via thermal excitation of localized car-

riers from the Fermi level to the mobility edge, and, hence, the activation energy corresponds to the energy difference between the Fermi level and the mobility edge. The result shown in Fig. 2 strongly suggests that there is a sharp energy separation resembling the mobility edge in the band of the Be δ-doping well.

The apparent existence of the mobility edge in the present system deviates from the prediction of the scaling theory of localization, according to which a gradual crossover is expected to occur between strong and weak localization in two dimensions.[1] One possible cause which makes the crossover close to a phase transition in the present system may be significant contribution of electron-electron interactions. In a nearly homogeneous system, electron-electron interactions are enhanced at lower carrier concentrations due to the competition between the Fermi level and electron-electron interaction energy. In Si MOSFET samples, a possible metal-insulator transition was found to occur at low electron concentrations in the order of 10^{10} cm^{-2}, suggesting a significant role of electron-electron interactions.[7] In the present case, on the other hand, hole concentrations in the Be δ-doped layer are significantly high, being in the order of 10^{13} cm^{-2}. Hence, an explanation similar to those for other possible metal-insulator transitions in two dimensions cannot be used in the present case. One possible explanation for the nature of the transition observed in the present system may be given by utilizing a model proposed by Meir.[12] This model combines quantum point contacts and global classical percolation, with which the origin of the quantum unit of resistance at the percolation threshold is explained. In the δ-doped layer random potential fluctuation due to Be and antisite As ions may lead to an inhomogeneous distribution of holes. At a certain hole concentration in the δ-doped layer, a percolation transition may occur, and the macroscopic two-dimensional resistivity may be determined by the quantum conductance at individual percolation channels. Although this model was proposed in order to explain the origin of the possible metal-insulator transition in a Si MOSFET, it could be applicable to the present case; the inhomogeneity of the hole distribution in the δ-doped layer occurs on a very fine scale and, hence, resulting percolation channels may exhibit quantum conductance even at room temperature.

There is further support in the present results for this percolation description of the transition. Once the Fermi level has passed the percolation threshold, more quantum point contacts form, and widths of existing quantum point contacts increase in the conducting network. Even under this condition, the macroscopic resistivity of the two-dimensional system at low temperatures is still determined by the worst resistor in the conductive network; the resistivity at 0 K is expected to remain at the value of $\frac{1}{2}h/e^2$ in spite of the further increase in the hole concentration. At a certain hole concentration, however, the second percolation threshold will occur. The conductive network will be completely connected with quantum point contacts whose two lowest subbands are filled by holes and, hence, have the resistance $\frac{1}{4}h/e^2$. At the second percolation threshold the resistivity of the system is expected to change discontinuously into the

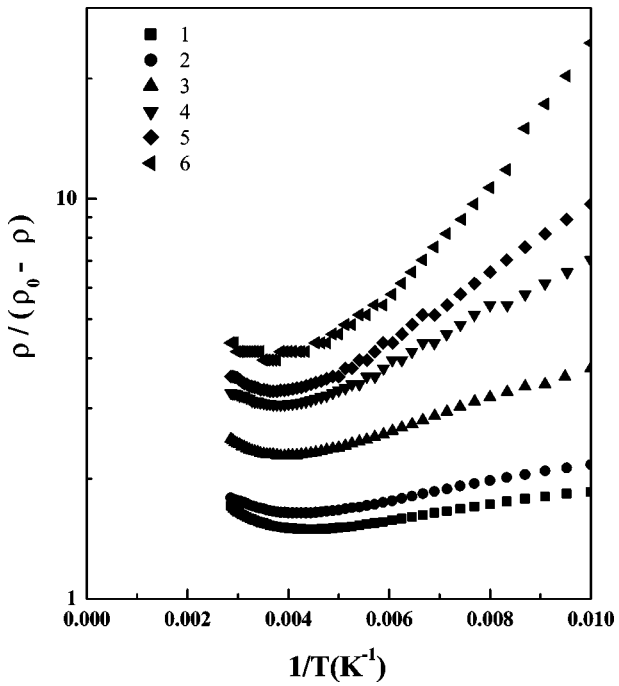

FIG. 3. Plots of logarithms of $\varrho/(\varrho_0-\varrho)$ of the samples 1–6 as a function of $1/T$.

value of $\frac{1}{4}h/e^2$ at 0 K. At high temperatures, on the other hand, a gradual decrease in the resistivity will occur when the Fermi level moves from the first percolation threshold to the second one because of thermal activation of carriers to the latter one. In this range of the hole concentration, the resistivity of the system will increase with lowering temperature due to the reduced thermal activation of carriers to the second percolation threshold.

The resistivity at finite temperatures with the Fermi level located between the first and second percolation thresholds is given by

$$1/\varrho(T)=1/\varrho_0[1+exp(-\varepsilon_2/kT)], \tag{2}$$

where $\varrho_0=\frac{1}{2}h/e^2$, and ε_2 is the energy difference between the Fermi level and the second percolation threshold. According to this relation, the resistivity $\varrho(T)$ approaches $\frac{1}{2}h/e^2$ near 0 K and $\frac{1}{4}h/e^2$ at infinitely high temperatures. In order to investigate the applicability of the relation to the present case, logarithms of $\varrho/(\varrho_0-\varrho)$ of the samples from 1 to 6 are plotted against $1/T$ in Fig. 3. The resistivity of samples 7 and 8 could not be used for this analysis because their resistivity is too close to ϱ_0 to give rise to accurate results by using Eq. (2). Relation (2) is expected to give rise to a linear change with its slope equal to ε_2/k and a unity value for $\varrho/(\varrho_0-\varrho)$ at $1/T=0$. Figure 3 shows nearly linear changes in the temperature range approximately from 100 to 200 K with their slopes monotonically decreasing from sample 6 to sample 1. The energy differences ε_2 estimated from Fig. 3 are plotted in Fig. 2 as solid symbols. As seen in Fig. 2, ε_2 changes linearly with the Be concentration, and its slope is nearly equal to that of ε_1 in the higher Be concentration range. With Eq. (1) and the heavy hole mass, the slope corresponds to 2.02 ± 0.35 for the parameter j in Eq.

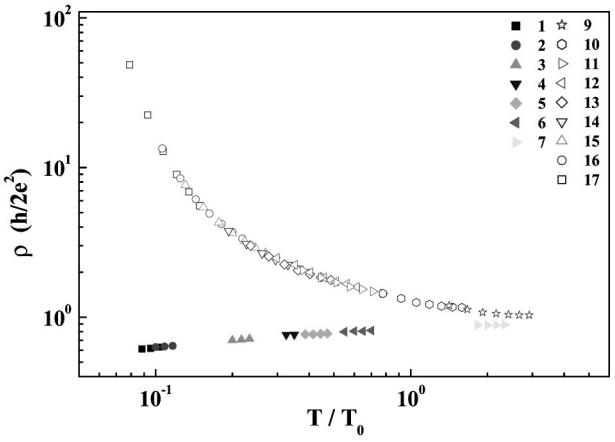

FIG. 4. Scaling plots of the temperature dependence of the resistivity of 16 samples.

(1). The extrapolated values of $\varrho/(\varrho_0-\varrho)$ of the linear changes at $1/T=0$ range between 1.2 and 1.5, which implies that high temperature limits of ϱ are greater than $\frac{1}{4}h/e^2$ by 10% to 20% of the latter value.

There are many other processes which affects the temperature dependence of the resistivity in this system, including hopping conduction of localized carriers and phonon-carrier coupling. In spite of such processes, the above-mentioned simple model successfully explains the main feature of the present results. This strongly suggests that the percolation transition does occur in this quasi-two-dimensional hole system. The thermally activated conduction in the samples from 1 to 6 below 200 K, therefore, does not necessarily imply that these samples are nonmetallic. Figure 2 further suggests that the second percolation threshold is located in the second subband of the δ-doped potential well approximately 30 meV above the first percolation threshold as shown by the inset of Fig. 2. The 30-meV energy difference between the two thresholds corresponds to the few nanometers width of a quantum point contact on the basis of the parabolic potential model.[16]

The analysis described above suggests that there is a two-dimensional percolation transition in this system. Unlike the conventional percolation, however, percolation in the present case results from the formation of quantum point contacts. In addition, different percolation thresholds occur successively as a result of the nature of the quantum point contacts. There is, therefore, a possibility for one to drive a new fundamental aspect of two-dimensional electron systems from the critical properties of the present transition. For this purpose, the scaling of the temperature dependence of the resistivity was made by following the procedure used in earlier studies on a possible metal-insulator transition.[6] Figure 4 shows scaling plots of the temperature dependence of the resistivity of 16 samples which were made by assuming the relation

$$\varrho(T,p_s)=\varrho[T/T_0(p_s)], \tag{3}$$

where T_0 is a scaling parameter and p_s is the two-dimensional hole concentration. Based on the results shown in Fig. 2, the Be concentration is regarded as the two-

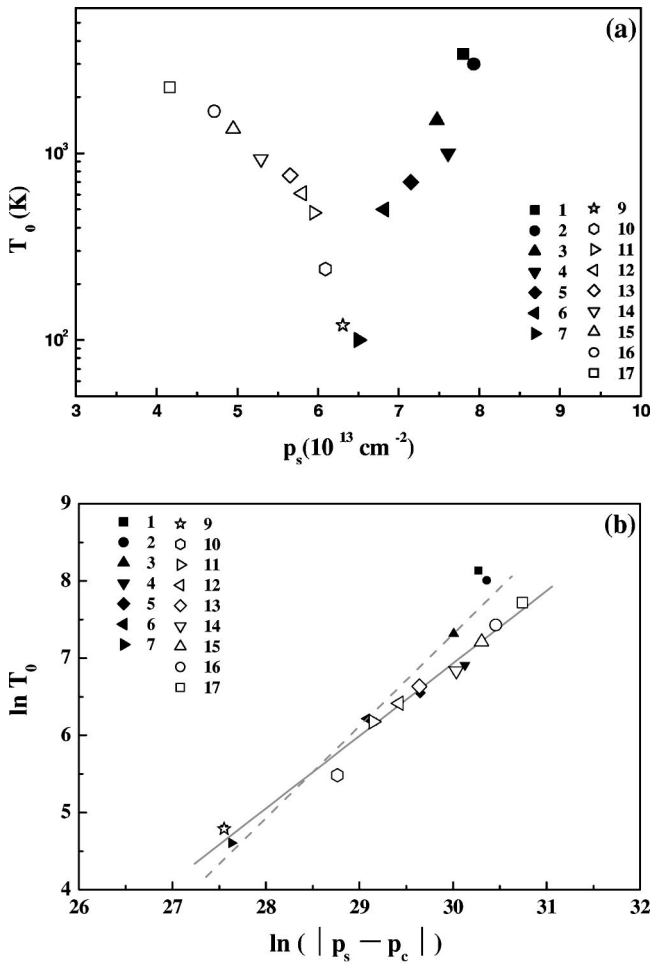

FIG. 5. (a) Plots of the scaling parameter T_0 as a function of the hole concentration p_s. (b) Plots of the scaling parameter T_0 as a function of $|p_s-p_c|$ on a log-log scale where p_c is the critical hole concentration.

dimensional hole concentration. In the figure, the resistivity data were plotted at an interval of 25° for each sample in order for one to be able to distinguish symbols of different samples. For the insulating side, the resistivity of nine samples in the temperature range from 150 to 350 K was used in the scaling. The temperature-dependence of the Hall mobility in these samples indicates that the significant contribution of the hopping conduction to the resistivity occurs below 150 K. With inclusion of the data of the resistivity at temperatures below 150 K, any choice of the parameter T_0 could not give rise to a single monotonic curve like the one shown in Fig. 4. For the metallic side, on the other side, only the temperature range where the resistivity increases with an increase of the temperature was used from the data of each sample. The plots of sample 8 was not included because its resistivity remains constant from 275 to 350 K.

The values of T_0 were chosen so as to give rise to a monotonic continuous curve. For the insulating side, the arbitrariness of the choice of T_0 is highly limited because of sufficient overlapping of the curves of different samples. The figure shows that plots of nine samples on the insulating side dramatically collapse onto a single curve, suggesting the

manifestation of a true scaling behavior. For the metallic side, on the other hand, there is a certain degree of arbitrariness in the choice of T_0 due to narrow usable temperature ranges. For an example, T_0 of sample 3 can be varied within several percent without resulting in a significant deviation from the monotonic curve.

Figure 5(a) plots the scaling parameter T_0 as a function of the hole concentration p_s. The figure shows that T_0 varies with p_s in a nearly symmetric manner for the insulating and metallic side and approaches zero at the transition. Figure 5(b) plots T_0 as a function of $|p_s - p_c|$ on a log-log scale. The value of the critical hole concentration p_c is 6.40×10^{13} cm^{-2}, corresponding to the Be concentration at which the activation energy ε_1 becomes zero. The figure shows the linear relation of the plots, especially for the insulating side, suggesting the power law relation between T_0 and $|p_s - p_c|$,

$$T_0 = |p_s - p_c|^{\beta}. \tag{4}$$

The exponents β derived from the linear relations are 0.94 ± 0.05 and 1.19 ± 0.16 for the insulating and metallic side, respectively. The critical conductance exponents of two-dimensional percolation systems have been estimated in a number of studies[17–19] and range between 1.1 and 1.38. The exponent β of the metallic side in the present case may correspond to the critical conductance exponent and appears to be close to the reported values. It is, however, difficult to draw a definite conclusion because of highly fragmental scaling plots of the metallic side in Fig. 4. The scaling plots of the insulating side, on the other hand, provides further support for one to conclude that the transition observed in the present system is a continuous phase transition of an electronic system. The exponent derived from the scaling plots 0.94 ± 0.05, therefore, is expected to become an important result for further clarification of the nature of the transition.

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