Observation of abrupt first-order metal-insulator transition in GaAs-based two-terminal device

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An abrupt first-order metal-insulator transition (MIT) as a jump of the density of states is observed for Be doped GaAs, which is known as a semiconductor, by inducing very low holes of approximately \( n_p \approx 5 \times 10^{14} \text{ cm}^{-3} \) into the valence band by the electric field; this is anomalous. In a higher hole doping concentration of \( n_p \approx 6 \times 10^{16} \text{ cm}^{-3} \), the abrupt MIT is not observed at room temperature, but measured at low temperature. A large discontinuous decrease of photoluminescence intensity at 1.43 eV energy gap and a negative differential resistance are also observed as further evidence of the MIT. The abrupt MIT does not undergo a structural phase transition and is accompanied with inhomogeneity. The upper limit of the temperature allowing the MIT is deduced to be approximately 440K from experimental data. The abrupt MIT rather than the continuous MIT is intrinsic and can explain the “breakdown” phenomenon (unsolved problem) incurred by a high electric field in semiconductor devices.

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I. INTRODUCTION

In two-dimensional (2D) systems such as Si-metal-oxide-semiconductor field-effect-transistors (Si-MOSFETs) and GaAs/AlGaAs heterostructures, theoretical calculations for electrical conductivity predicted that these systems were not expected to be conducting, even though interaction between carriers is weak (or absent) or very strong [1–3]. The theoretical predictions appeared to be proved by experiments where thin metallic films and Si-MOSFETs displayed faithful logarithmic increase in resistivity [4] and Si-MOSFET with low electron densities also showed exponential increase in resistivity [5]. However, a metal-insulator transition (MIT) was observed below 1 K in GaAs/AlGaAs heterostructures [6,7] and in low-disordered Si-MOSFETs and GaAs/AlGaAs heterostructures [8,9]. As an explanation of the MITs at extremely low temperature, it was suggested that non-Fermi-liquid states can induce perfect conductors only when interactions between electrons are sufficiently strong [10]. Other possible explanations were also given in a review paper [11].

Recent studies on the MIT for GaAs samples such as dilute 2D GaAs systems have been focused to analyze characteristics of resistivity and spin-susceptibility at low temperatures [12–14]. At high temperature such as room temperature, GaAs samples with lower doping concentrations exhibited the behavior of thermally activated conduction, while those samples with higher doping concentrations showed the metallic conduction feature [15]. The latter revealed a continuous MIT as hole doping concentration was increased.

The MITs observed in 2D systems up to now are continuous for low voltage and temperature excitations, which doesn’t account necessarily for the possibility of breakdown of the energy gap because there is the linear metallic regime of conductivity caused by impurity levels at low applied voltages [16]. However, an abrupt MIT rather than a continuous MIT seems to be more intrinsic [16]. An abrupt MIT can exist when a continuous MIT is true. The abrupt MIT has not been observed in semiconductors such as low-disordered Si-MOSFETs and GaAs/AlGaAs heterostructures. The long unsolved MIT problem in GaAs can be consistently resolved when not only a continuous MIT but also a abrupt MIT are simultaneously observed.

As a similar research, an abrupt MIT in the representative strongly correlated material, VO₂, was measured and accompanied with the structural phase transition (SPT) at 67°C [17]. It was also reported that the abrupt MIT induced by electric field does not undergo SPT and is accompanied by inhomogeneity [16,18,19]. The mechanism was also revealed by the hole-driven MIT theory (or extended Brinkman-Rice picture) and the Mott criterion [22], as shown in Fig. 1. The key idea is doping of a very low hole concentration in GaAs, which indicates an excitation of holes in the hole levels produced by dopants into the valence band by electric field. This research focuses on observation of the abrupt MIT irrespective of theoretical analysis because a
continuous MIT has already been observed in GaAs [15]. Furthermore, the breakdown phenomenon as an unsolved problem in semiconductor physics is discussed in light of the abrupt MIT. Note that any band theory cannot self-consistently account for this abrupt MIT in GaAs, which may be rather explained by strong correlation. Therefore, GaAs of a band insulator with 8 electrons in sp$^3$ orbital is inevitably assumed as a Mott insulator such as VO$_2$ [16] and is applied to a hole-driven MIT theory to reveal the abrupt MIT, even if the assumption can be a contradiction in theory; this is left as an open problem.

When $\rho \neq 1$ for an inhomogeneous system, the effective mass is the effect of measurement and an average of the true effective mass in the Brinkman-Rice picture (see reference 20,21,23). Electric conductivity, $\sigma \propto (\frac{m^*}{m})^2$ (see reference 24). Mott transition occurs just below $\kappa \rho = 1$ by hole doping of $\Delta \rho'$ (low concentration). When Mott criterion, $n_{c}^{1/3}a_{0} \approx 0.25$ (see reference 24) is used, $n_{c} \equiv \Delta \rho' < 0.001 \% \approx 3.3 \times 10^{16} \text{ cm}^{-3}$ (see reference 22) to the number of carriers in the half-filled band is calculated. $\Delta \rho'$, when low concentration holes, are doped in a Mott insulator created by the critical on-site Coulomb energy of $U_c$ (the thick line of left side), a breakdown of Coulomb energy occurs from $U_c$ to a large constant $U (< U_c)$ (the thin line of right side); this is the Mott transition. The system becomes inhomogeneous due to doped holes (the right side of Fig. 1b). The metal of region B follows the Brinkman-Rice picture. This is the hole-driven MIT theory (extended Brinkman-Rice picture).

II. EXPERIMENTS

Two-terminal devices were patterned by a lift-off process with Be doped p-type GaAs films deposited on GaAs substrates by molecular beam epitaxy, as shown in Fig. 2. Doped hole concentrations of $n_p \approx 5 \times 10^{14} \text{ cm}^{-3}$ for devices 1, 2, 3 and 4 and $n_p \approx 6 \times 10^{16} \text{ cm}^{-3}$ for device 5 were estimated at room temperature by Hall measurement. Au/Cr electrodes as source and drain were prepared for Ohmic contact by sputtering. The channel intervals between the source and drain were $L_{ch}=3 \mu$m for devices 1, 2, and 3, $L_{ch}=5 \mu$m for device 5, and $L_{ch}=10 \mu$m for devices 4, 6 and 7. The thickness of the GaAs film for devices 1, 2, 3 and 4 is approximately 350nm. Device 6 used an undoped GaAs film which shows a p-type feature. The thickness of the GaAs film for devices 5, 6, and 7 is approximately 100nm.

FIG. 2. Schematic diagram of devices with two terminals. The dotted line in the GaAs film is a channel (or path) where current flows.

Electric characteristics of the devices were measured by a precision semiconductor parameter analyzer (HP4156B). In the measurements, a short pulse mode in HP4256B was used to prevent Joule heat from occurring for a long pulse; the pulse width is about 64µsec. To protect devices from excess current, the maximum current was limited to the compliance (or restricted) current. The temperature dependence of Figs. 6 and 8 was measured in a cryostat.

Micro-photoluminescence measurements were carried out with device No. 6 at room temperature using an Acton spectrometer with a liquid-nitrogen-cooled CCD camera and a high-NA ($\times 100$) corrected lens. The spectrally dispersed luminescence from 2µm-diameter regions between the source and drain electrodes was observed. An Ar-ion laser of wavelength $\lambda \approx 488$nm was used as the exciting light source.

III. RESULTS AND DISCUSSION

Figure 3 shows the temperature dependence of resistance measured for a bare GaAs film with a doping con-
centation of $n_p \approx 5 \times 10^{14}$ cm$^{-3}$. Resistance is an order of $2 \times 10^5 \ \Omega$ below 380 K and decreases exponentially with increasing temperature above 380 K; this constitutes semiconducting behavior. This indicates that GaAs is a valuable material for devices operating near room temperature. The activation energy above 380 K is approximately 0.67eV. An abrupt resistance change is not shown below 460 K because the temperature of the structural phase transition of GaAs is approximately 1503 K [25].

Asymmetry of jump 1 and jump 2 is discussed in the Ohmic characteristic, and the high current density $\Delta J/E \equiv \Delta \sigma \propto (n^* / m)^2$ in Eq. 1 where $E$ is an electric field at the jump and is the same phenomenon as the jump measured in VO$_2$ [16]. Thus, the jump of the DOS, the Ohmic characteristic, and the high current density are characteristics of the first-order metal-insulator transition. Asymmetry of jump 1 and jump 2 is discussed in a next section.

Figure 4 shows drain-source (DS) current, $I_{DS}$, and drain-source voltage, $V_{DS}$, curves measured at room temperature for device No. 1 with channel length $L_{ch}=3 \mu m$ and channel width $W_{ch}=50 \mu m$. Abrupt discontinuous current jump 1 and jump 2 are observed at $V_{M_{MIT}} \approx 24V$ and $V_{M_{MIT}} \approx 20V$, respectively. The derivative of a jump, $dJ/dV$, as shown in the inset, corresponds to the density of states (DOS). Ohmic behaviors as metal characteristics are exhibited above $V_{M_{MIT}}$, and are caused by an internal resistance. Current density, $J$, just below the Ohmic behavior at current 3.7 mA is approximately $7.5 \times 10^4 \ \text{A/cm}^2$. This value is much higher than that (below $10^2 \ \text{A/cm}^2$) measured in a semiconductor and corresponds to an order of current density in a very dirty metal due to internal resistance in the film and the effect of measurement, which is described in a next section. The jump corresponds to the jump of the effective mass of a quasiparticle (or the increase of conductivity); $\Delta J/E \equiv \Delta \sigma \propto (n^* / m)^2$ in Eq. 1 where $E$ is an electric field at the jump and is the same phenomenon as the jump measured in VO$_2$ [16]. Thus, the jump of the DOS, the Ohmic characteristic, and the high current density are characteristics of the first-order metal-insulator transition. Asymmetry of jump 1 and jump 2 is discussed in a next section.

Figure 5 shows hysteresis loops observed by $I_{DS}$-$V_{DS}$ curve measurements for device No. 2 with $L_{ch}=3 \mu m$. Measurement was performed in a series of “start $\rightarrow$ 1 $\rightarrow$ 2 $\rightarrow$ 3 $\rightarrow$ 4 $\rightarrow$ end”. Double hysteresis at jumps 1 and 4 and jumps 2 and 3 are exhibited. Jump 1 (or jump 3) and jump 2 (or jump 4), respectively, are asymmetrical in magnitude of jumps and $V_{M_{MIT}}$ of jumps, but measurement (◦) of jumps 1 and 2 and measurement (•) of jumps 3 and 4 are symmetrical. Jump 2, the transition from insulator to metal, results from doping a low concentration of hole $n_c$ [22] and is not accompanied by heat, whereas jump 3, the transition from metal to insulator, is accompanied by Joule heat produced by scattering of carriers in metal. The Joule heat causes an extra excitation, which results from doping a very small hole concentration $\alpha$; $n_c \gg \alpha$. That is, jump 2 is due to doping of $n_c$ and jump 3 is attributed to doping of $n_c + \alpha$. On the basis of the hole-driven MIT theory, the magnitude of the jump and $V_{M_{MIT}}$ when $n_c + \alpha$ is doped are less than those when $n_c$ is doped; this causes asymmetry. Thus, the observation of hysteresis indicates that the abrupt jump for GaAs is evidence of the first-order MIT.

**FIG. 3.** Temperature dependence of resistance for a p-GaAs film with a hole doping concentration of $n_p \approx 5 \times 10^{14}$ cm$^{-3}$.

**FIG. 4.** $I_{DS}$-$V_{DS}$ curve measured for device No. 1 fabricated with a p-GaAs film with a hole doping concentration of $n_p \approx 5 \times 10^{14}$ cm$^{-3}$. The first and the second measurements are denoted by circle (◦) and solid (•), respectively. The inset shows a derivative, $dJ/dV$, regarded as the density of states.

**FIG. 5.** $I_{DS}$-$V_{DS}$ curve measured for device No. 1 with a p-GaAs film with a hole doping concentration of $n_p \approx 5 \times 10^{14}$ cm$^{-3}$. The first and the second measurements are denoted by circle (◦) and solid (•), respectively. The inset shows a derivative, $dJ/dV$, regarded as the density of states.
explained by the hole-driven MIT theory. Furthermore, a line just below the jump measured at 350 K indicates an exponential increase with increasing an applied voltage. This is a semiconducting behavior and suggests that the abrupt MIT occurs by way of the semiconduction as mentioned in a previous paper [16].

The temperature dependence also provides decisive information for revealing the mechanism of the abrupt jump. When the number of total holes, $n_{\text{tot}}$, in the hole levels is given by $n_{\text{tot}} = n_b + n_{\text{free}}(T, E)$, where $n_b$ is the number of bound holes in the levels and $n_{\text{free}}(T, E)$ is the number of holes freed by temperature $T$ and electric field $E$ from the levels, $n_b$ decreases with increasing $n_{\text{free}}(T, E)$. For the abrupt jump, $\Delta n = n_c - n_{\text{free}}=0$ should be satisfied. At $T_{\text{tr}} \approx 440$ K determined in the next section, it is suggested, as decisive evidence of the Mott transition, that the abrupt current jump disappears, because $n_{\text{free}}(T \approx 440K, E=0)=n_c$ (i.e. $\Delta n=0$) is excited only by temperature. Below $T_{\text{tr}} \approx 440$ K, the abrupt MIT voltage decreases with increasing temperature, because, from $n_c= n_{\text{free}}(T, E)= n_{\text{free}}(T) + n_{\text{free}}(E)$, the increase of $n_{\text{free}}(T)$ with increasing temperature decreases $n_{\text{free}}(E)$. Thus, it is revealed that the mechanism of the abrupt MIT excited by temperature is the same as that by an electric field. Temperature and electric field are a means of exciting hole charges.

FIG. 5. Hysteresis loops measured for device No. 2 fabricated with a p-GaAs film with a hole doping concentration of $n_p \approx 5 \times 10^{14} \text{ cm}^{-3}$.

FIG. 6. Temperature dependence of $I_{DS}-V_{DS}$ curve measured for device No. 3 fabricated with a p-GaAs film with a hole doping concentration of $n_p \approx 5 \times 10^{14} \text{ cm}^{-3}$.

On the other hand, we also investigate the trend of $I_{DS}-V_{DS}$ curves at higher temperature. Fig. 6b shows the increase of MIT-$V_{DS}$ at 380 K and 410 K, the decrease of the magnitude of jump, and a large increase of slope of the Ohmic behavior below jump; this is quite a different new phenomenon from that seen in Fig. 6a. This appears to be attributed to thermal excitation from bound electrons in sub-band of energy gap 1.45eV into carriers, because the excitation probability of bound elec-

FIG. 7. Electrode dependence of $I_{DS}-V_{DS}$ curve measured for two-terminal devices fabricated with the same configuration of $L_{ch}=5\mu m$, $L_{w}=50\mu m$ over a p-GaAs film with a hole doping concentration of $n_p \approx 5 \times 10^{14} \text{ cm}^{-3}$. Both Au/W/In/Ni (solid bold) and Au/Cr (circle) were used for source and drain electrodes. Compliance current of 1 mA was applied to protect the device.
trons across the energy gap increases with increasing temperature. The jump is not observed above 440 K. The Ohmic behaviors at 440 K and 460 K are similar. Thus, GaAs undergoes a MIT near 440 K and shows metallic characteristics above 440 K which is far below the structural-phase-transition temperature of 1503 K. Thus, the MIT is far from the structural change.

Figure 7 shows a large decrease of MIT-V$_{\text{DS}}$ from $V_{\text{MIT}}=27$V to 10V and additional increase of leakage current near zero voltage for a device patterned with electrodes of source and drain of Au/W/In/Ni (instead of Au/Cr), which had lower resistance on contact surface with a GaAs film. This phenomenon is similar to the temperature dependence of the MIT in Fig. 6a and denies that the abrupt MIT (or jump) occurs only by very high electric field.

Figure 8 shows the resistance dependence of $I_{\text{DS}}$-$V_{\text{DS}}$ curves measured with device No. 4. Resistance is connected in a serial configuration with the device, as shown in the inset of Fig. 8. With increasing external resistance, the magnitude of the current jump decreases and $V_{\text{MIT}}$ decreases by 5KΩ and again increases from 5KΩ to 50KΩ. The increase of external resistance is interpreted as an increase of the insulator region (region A in Fig. 1b) not undergoing the abrupt MIT in the measurement region. As for the increase of $V_{\text{MIT}}$ with increasing resistance from 5KΩ to 50KΩ, since the increase of region A in the right side of Fig. 1b decreases conductivity $\sigma$, $V_{\text{MIT}}$ increases when $J's$ are constant at $V_{\text{MIT's}}$ and the magnitude of the jump decreases when $E$ is constant; $\sigma=J/E$ and $E=V/d$ where $d$ is channel length. Note that $J's$ at $V_{\text{MIT's}}$ from 5KΩ to 50KΩ had nearly similar values in the logarithmic picture although $V_{\text{MIT's}}$ are not shown in Fig. 8. Furthermore, step jumps in the $I_{\text{DS}}-V_{\text{DS}}$ curves of 10KΩ, 20KΩ and 50KΩ may be due to inhomogeneity in the GaAs film.

We take into account that internal resistance in a GaAs film makes it possible to observe Ohmic behavior, as shown in Figs. 4, 5, and 6. The Ohmic behavior indicates that channel layers in devices (or GaAs) are inhomogeneous. The magnitude of an observed jump is not an intrinsic value but the effect of measurement and increases with decreasing the internal resistance. When only the metal region in Fig. 1b is measured, the magnitude of the current jump might be of an order of $10^7$ A/cm$^2$, the current density of a good metal. This indicates that the observed $I_{\text{DS}}$ changes with external resistance, even though the intrinsic metal characteristics remain unchanged. Thus, the observed current density, $J_{\text{DS}}$, of an order of $10^{4}$ A/cm$^2$, as shown in Fig. 4, is merely an average of the metal region over the measurement region. The average is the effect of measurement. Thus, a true current jump cannot be measured in an inhomogeneous system, as suggested by the hole-driven MIT theory [16,21].

Figure 9 shows the temperature dependence of $I_{\text{DS}}$-$V_{\text{DS}}$ curves measured with device No. 5 fabricated with a p-GaAs film with a hole doping concentration of $n_p\approx6\times10^{16}$ cm$^{-3}$.

![Figure 8](image8.png)

**FIG. 8.** Resistance dependence of resistance measured for device No. 4 fabricated with a p-GaAs film with a hole doping concentration of $n_p\approx5\times10^{14}$ cm$^{-3}$.

![Figure 9](image9.png)

**FIG. 9.** $I_{\text{DS}}$-$V_{\text{DS}}$ curves measured for device No. 5 fabricated with a p-GaAs film with a hole doping concentration of $n_p\approx6\times10^{16}$ cm$^{-3}$.
310 K, line 2 without jump denotes the Ohmic metallic behavior rather than an exponential semiconducting behavior, as shown by line 3 in the inset; line 3 does not fit all data above $V_{DS}=8V$ in the logarithmic plot. This indicates that, when a much higher hole concentration than $n_c$ is doped into the valence band, a continuous MIT instead of an abrupt MIT occurs due to the decrease of the magnitude of the jump, as predicted in the hole-driven MIT theory. That is, disappearance of the small jump at 310 K are because $n_{free}(E)$ related to the jump at 140 K became zero at 310 K and $n_{free}(T)$ at 310 K was a larger than $n_c$ (see Fig. 6). Therefore, the continuous MIT is not intrinsic and may be MITs observed in MOS-FET and GaAs/AlGaAs structures [6–9]. Furthermore, it is explained why an semiconducting effect is not observed above $V_{DS}=8V$ in the logarithmic plot. This in-turns above $V_{DS}=8V$ in the I-V curve measured at 310 K. Since region A in Fig. 1b plays a role of resistance to current $I$ in the relatively smaller region A (semiconductor) than region B (metal region) after the abrupt MIT and acts as a semiconductor with an exponential current characteristic in the I-V curve, the magnitude of current measured in a semiconductor with an exponential current characteristic in region B (metal region) after the abrupt MIT and acts as a conductor at room temperature). First, below $V_{DS}=8V$, the energy gap is approximately 1.43 eV. The intensity of spectra decreases as $V_{DS}$ increases, and disappears at $V_{DS}=80V$. In particular, a discontinuous change in the intensity of spectra between $V_{DS}=8V$ and $V_{DS}=10V$ ($\Delta V_{DS}=2V$) is observed. $\Delta V_{DS}$ corresponds to a change of voltage while a MIT jump in an $I_{photocurrent}$-V curve (●) occurred, as shown in Fig. 11a; the PL spectra and the $I_{photocurrent}$-V curve (●) were measured simultaneously in an exposed state of laser light. Note that, as shown in Fig. 11, when device No. 6 was exposed to the laser light, a considerable amount of photocurrent due to photoexcited holes and electrons occurred; as a result, $V_{MIT}$ decreased due to $n_c$ as indicated by arrow A, the current (or photocurrent) increased as indicated by arrow B, and the MIT jump decreased largely as indicated by arrow C.

![Fig. 10](image1.png)

**FIG. 10.** Photoluminescence (PL) spectra measured for device No. 6 fabricated with an undoped GaAs film/GaAs substrate.

Figure 10 shows photoluminescence (PL) spectra measured by an Ar-ion laser light of wavelength 488nm with device No. 6 fabricated by using an undoped GaAs film on GaAs substrate, in order to observe the change in the energy gap of GaAs. Device No. 6 displays a clean abrupt jump characteristic in I-V curve (●) in Fig. 11a.

The discontinuous change in Fig. 10 can be interpreted on the basis of the hole-driven MIT theory as follows. Since the abrupt MIT jump in a homogeneous Mott insulator is caused by hole doping of a low concentration, the undoped GaAs becomes inhomogeneous and has two phases after the abrupt MIT, as shown in Fig. 1b. One phase (phase 1) undergoing the abrupt MIT is a homogeneous Mott insulator, but the other phase (phase 2) not undergoing the abrupt MIT is an insulator (or semiconductor at room temperature). First, below $V_{DS}=8V$,
because phase 1 is a Mott insulator, the PL is observed as one spectrum, i.e., as spectrum 1 in Fig. 11b. Second, at $V_{DS}=10\,\text{V}$, because phase 1 undergoes the abrupt MIT, spectrum 1 becomes spectrum 2 without the energy gap, as shown in Fig. 11b, and because phase 2 appears after the MIT, a new spectrum (spectrum 4) as spectrum 3 appears as shown in Fig. 11c. The new spectrum is an average of spectrum 2 and spectrum 3 and is nearly the same as spectrum 3, because spectrum 2 is nearly too small. The intensity of the spectrum 3 can be smaller than spectrum 1, because region A in Fig. 1b is smaller than region B and decreases little by little with increasing $V_{DS}$. Spectrum 3 is regarded as a pseudogap. Third, phase 2 finally undergoes a continuous MIT in a high applied voltage (or electric field), as shown in Fig. 10, and is regarded as an internal resistance (or insulating) phase causing Ohmic behaviors in Figs 4 and 6. At the applied voltages of $V_{DS}=8\,\text{V}$ and $V_{DS}=10\,\text{V}$, the corresponding spectra can be represented as shown in Fig. 11d. Thus, the discontinuous change of spectra is attributed to the extinction of the energy gap in phase 1 due to the abrupt MIT. Conversely, when the abrupt MIT does not occur, the spectra in Fig. 9 monotonously decrease without a discontinuous change. Furthermore, the pseudogap is similar to pseudogaps observed in high-$T_c$ superconductors [26,27].

![Graph](image_url)

**FIG. 12.** Negative differential resistance measured for device No. 7 fabricated with p-GaAs film with a hole doping concentration of $n_p\approx5\times10^{14} \, \text{cm}^{-3}$.

As further MIT evidence, the negative differential resistance (NDR) was also measured by the current-controlled method by device No. 7 for p-GaAs film with $n_p\approx5\times10^{14} \, \text{cm}^{-3}$. However, the NDR was not observed in devices fabricated with p-GaAs film with $n_p\approx6\times10^{16} \, \text{cm}^{-3}$. The NDR is regarded as an MIT due to doping of $n_c$ holes excited by an increase of temperature caused by current, as in the case of VO$_2$ [28]. The mechanism of the NDR is the same as that of electric-field induced MIT due to $n_c$, although the excitation method is different.

The abrupt first-order MIT observed in GaAs, not undergoing a structural phase transition, is a new phenomenon that cannot be explained by well-known semiconductor theories or MIT theories except the Brinkman-Rice (BR) picture and the extended BR picture (Hole-driven MIT theory) with singularity. The MIT is the same as that observed in VO$_2$. Thus, the abrupt MIT observed in the devices with p-GaAs film is different from continuous MITs, in the 2D systems [6-9,12-14], which may be due to over-doping rather than $n_c$ or it may be a metallic behavior by an excitation of bound charges in impurity levels below the abrupt jump in Fig. 6.

Furthermore, on the basis of the hole-driven MIT theory, the abrupt first-order MIT can occur even in other semiconductors with both an energy gap of less than 2 eV and hole levels and parent materials BaBiO$_3$, La$_2$CuO$_4$, and PrBaCuO$_7$ of high-$T_c$ superconductors and parent material LaMnO$_3$ of a colossal magnetoresistance. In a semiconductor such as InP/InGaAs/InP substrate with doped electrons of very low concentration, an abrupt MIT (or jump) was not observed.

**IV. COMPARISON OF ABRUPT MIT AND BREAKDOWN**

The jump in the abrupt MIT is similar to a phenomenon "avalanche breakdown" which is caused by a high electric field in a pn junction device such as a Zener diode, but doesn’t show the metallic behavior [29,30]. The breakdown is a longtime unsolved problem in semiconductor physics; what is the identity of the breakdown and why can the breakdown happen to be a jump even though avalanche phenomenon is continuous [31,32]. The breakdown causes a degradation of film quality or device breakdown, which might occur due to Joule heating arising from a trapped high current ($J\approx\sim10^{7-8} \, \text{A/cm}^2$) at defects just after the abrupt MIT happened. Its main characteristic is to remove repeatability of data in experiments. That is, the breakdown does not take place in as clean films as devices used in this research; for example, pure metals does not suffer from breakdown even if high current flows. Likewise, the breakdown ahead of the abrupt MIT is hard to occur for a stoichiometric GaAs with less impurities; we experimentally checked the absence of the abrupt MIT (or breakdown) in GaAs in the even harsh conditions, 20MV/m and 100°C and, as a result of the experiment, the semiconducting behavior was observed. Moreover, we have confirmed that there was no even trace of an abrupt MIT for n-type semiconductor such as InP substrate. This can be explained not in view of breakdown but by the fact that the abrupt jump does not occur due to the absence of the critical hole doping $n_c$, as the MIT theory suggests. Because the breakdown is not theoretically well-established, it does not account consistently for the Ohmic behavior above the jump, hysteresis, temperature dependence of the jump, electrode
dependence of the jump, resistance dependence of the jump, doping dependence of the jump, negative differential resistance, breakdown of the energy gap, as shown in this paper. On the contrary, the abrupt MIT theory can explain the breakdown phenomenon.

V. CONCLUSION

An abrupt first-order MIT for GaAs occurs by hole doping of very low concentration, irrespective of the critical magnitude of the applied electric field, and is accompanied with inhomogeneity. The MIT does not undergo a structural phase transition. Continuous MIT takes place at a larger hole concentration than a critical hole doping $n_c$ in GaAs. A self-consistent theory needs to be developed to explain the abrupt MIT in GaAs irrespective of a band insulator. Furthermore, the abrupt MIT will be very valuable for new multi-functional devices for next generation.

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