Abnormal current–voltage characteristics and metal–insulator transition of amorphous carbon film/silicon heterojunction

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Abstract

The amorphous carbon film/n-Si (a-C/n-Si) heterojunctions have been fabricated by direct current magnetron sputtering at room temperature, and their current–voltage characteristics have been investigated. The results show that these junctions have good rectifying properties in the temperature range 80–300 K. The interesting result is that the current–voltage curve changes dramatically with increasing applied voltage and temperature. For the forward bias voltages, the junction shows Ohmic mechanism characteristic in the temperature range 240–300 K. However, the conduction mechanism changes from Ohmic for the low bias voltages to space charge limited current for the high bias voltages in the temperature range 80–240 K. While for the reverse bias voltages, it changes from Schottky emission to breakdown with increasing voltage. Another important phenomenon is that the temperature dependence of the junction resistance shows a metal–insulator transition, whose transition temperature can be controlled by the bias voltage.

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1. Introduction

Amorphous carbon (a-C) films have attracted considerable interest in the past few years due to their potential applications in the field emission [1–3], microelectronic devices [4–6] and hard coating [7,8]. The properties of these films are characterized by the microstructure and volume fraction of the sp³ bonds, which is controlled by the deposition method and condition [9, 10]. In order to get various kinds of carbon films, several methods have been applied in fabricating amorphous carbon films. In the past, research on the carbon films was focused on the microstructure, electrical structure, fabrication methods and the related applications [11,12].

In this Letter, we deposited a-C films on n-Si substrates by magnetron sputtering at room temperature. The interesting result is that the current–voltage curve changes dramatically with increasing applied voltage and temperature. For the forward bias voltages, the junction shows Ohmic mechanism characteristic in the temperature range 240–300 K. However, the conduction mechanism changes from Ohmic for the low bias voltages to space charge limited current (SCLC) for the high bias voltages in the temperature range 80–240 K. While for the reverse bias voltages, it changes from Schottky emission to breakdown with increasing voltage and which can be repeated. The resistance–temperature (R-T) curves of the junctions show metal–insulator (M-I) transition, whose transition temperature can be controlled by the electrical field. The transition temperature increases with increasing applied voltage. The M-I transition phenomenon had been reported in some manganites junctions as we noticed [13–16]. However, M-I transition observed in a-C/Si junction can not be understood by the double exchange interaction mechanism in the manganites.

2. Experimental

Amorphous carbon films were deposited on n-Si (100) substrates using direct current magnetron sputtering from graphite
target. The sputtering power is 50 W. The target is cold-presses graphite disk and the purity of the graphite is better than 99.9%. The silicon substrates are n-type materials with resistivity in the range of 2–5 $\Omega\cdot\text{cm}$. Before deposition, the Si substrates were ultrasonically cleaned in ethanol and then acetone, etched in diluted HF solution, and rinsed in deionized water. The deposition took place inside a chamber and the base pressure is $2 \times 10^{-4}$ Pa. During deposition, the argon pressure was kept at 2 Pa and the Si substrates were kept at room temperature.

The current–voltage (I-V) curves of the films deposited on Si substrates were measured at various temperatures by using two-probe method with a Keithley 2400 SourceMeter. Hall measurement of the a-C films has been done, the result indicates that these films are just like insulator which carrier concentration is very small so that it cannot be obtained by current measurement. The experimental results show the indium electrodes have Ohmic contact to the carbon films and the Si substrates. The thickness of the a-C films is about 100 nm, which is measured by the ellipsometer.

3. Results and discussion

3.1. Anomalous I-V properties of the a-C/Si junctions

Fig. 1 shows the Raman spectrum of the a-C film deposited at room temperature. It is well known that the Raman spectrum of carbon materials can be fitted to the D band at 1350 cm$^{-1}$ and the G band at 1580 cm$^{-1}$. The variation of the D and G peaks and the ratio of their intensities provide information on sp$^2$/sp$^3$ and the sp$^2$ cluster size in the films. The spectrum shows that the film is a disordered diamond-like carbon system. Because there is a large difference in the work function between the a-C film and n-Si substrate\[17–19\], the a-C/n-Si junction will be regarded as a Schottky barrier and related analyze according.

Fig. 2 (a) shows the anomalous I-V characteristics of the a-C/Si junction at various temperatures. It can be seen, the a-C/Si junction has a good rectifying behavior during the temperature range (80–300 K). The inset shows the schematic illustration of electrical measurement.

In order to understand the I-V properties more clearly, the relation between log(I) and V of the junction is shown in Fig. 2(b). We can find that the junction has a good rectifying behavior in the voltage range besieged in the ellipse (as drawn in Fig. 2(b)). When the value of the reverse voltage is larger than a threshold, the leak current begins to increase abruptly with increasing reverse voltage. The phenomenon shows that the a-C/Si junction has been broken down by tunneling phenomenon. This behavior may be attributed to the decrease of the barrier width. The potential barrier of the junction can be approximated by a triangular potential barrier. With the increase of the reverse voltage, the electrical field increases, the energy-band changes more incline and the barrier width decreases. When the value of the reverse voltage is larger than a threshold and the barrier width shorter than a threshold, there are lots of electrons can pass through the potential barrier by tunneling phenomenon. Therefore, the leak current begins to increase abruptly with increasing reverse voltage.

Fig. 2. (a) I-V characteristic of the a-C/Si junction measured at various temperatures. The inset shows the schematic illustration of the electrical measurement. (b) The relation between log(I) and V of the a-C/Si junction.

Fig. 1. Raman spectrum of the a-C/Si deposited at room temperature. Fitting of Raman D and G bands with two Gaussians is also shown.
Fig. 3 shows the resistance-voltage characteristics of the a-C/Si junction measured at various temperatures. As we can see from the curve, the resistance of the a-C/Si junction decreases with increasing reverse voltage at first ($V_{bias} \leq 2$ V), and then increases with increasing reverse voltage ($2$ V $\leq V_{bias} \leq 5.5$ V). Finally it decreases again with increasing reverse voltage ($5.5$ V $\leq V_{bias}$). It can be noted that the onset of the large decrease in resistance corresponds with the breakdown voltage, which indicates that when the reverse voltage reaches the breakdown voltage, the barrier width will be shorter than a threshold, so that lots of electrons can pass through the potential barrier by the tunneling phenomenon and the resistance begins to decrease quickly.

### 3.2. The temperature dependence of the resistance of a-C/n-Si junction

Fig. 4 shows the relation between log($I$) and log($V$) of the a-C/Si junction. For the forward bias voltages, the slopes of the log($I$)–log($V$) change from 1.2 for low bias voltages to 5.2 for high bias voltages in the temperature range 80–240 K, which suggest that the dominating current mechanism changes from Ohmic to Space Charge Limit Current (SCLC) with increasing bias voltage [14]. This transition happens when the injected carrier density exceeds the volume-generated free carrier density [20]. But for higher temperature (240–300 K), the slope of the log($I$)–log($V$) is 1.2 and it is unchanged with increasing bias voltage in our measurement, which indicate that the dominating current mechanism is Ohmic. As shown in Fig. 4, we can find that the dominating current mechanism also changes from Ohmic to SCLC with increasing reverse bias voltage.

Fig. 5(a) shows the R-T characteristics of the a-C/Si junction at different reverse $V_{bias}$. As can be seen from the figure, when reverse $V_{bias} \leq 2$ V the resistance of the junction shows an insulating behavior with a negative temperature coefficient in the temperature range of 80–300 K. For a large reverse $V_{bias}$, the resistance shows an M-I transition and whose transition temperature increases with increasing $V_{bias}$. The M-I transition observed in these junctions cannot be understood by the double exchange interaction mechanism in the manganites [21]. We propose a possible mechanism to understand these phenomena. For the lower forward bias voltages ($V_{bias} \leq 3$ V), the I-V characteristics of the a-C/Si junction is just as the normal Schottky junction, shows the positive temperature dependence and the current measured under high temperature is several magnitudes larger than that measured under low temperature. However, for the low temperature range, the carriers can not get enough energy form the thermal excitation to across the junction barrier by tunneling phenomenon, which induce many carriers gather in the interface and the dominating current mechanism begins to change from Ohmic to SCLC with increasing forward bias voltages. The reservoir of the carriers in the interface decreases with increasing temperature, but it increases with increasing bias voltage (injected current), so that the voltage of the transition from Ohmic to SCLC increases with increasing temperature (Fig. 4).

When a larger electrical field was applied, the current measured both at high temperature (Ohmic mechanism) and low temperature (SCLC mechanism) increases with increasing elec-
Fig. 5. (a) R-T characteristic of the a-C/Si junction measured at different reverse bias voltages. (b) R-T characteristic of the a-C/Si junction measured at different forward bias voltages.

trical field. However, the increasing speed of the current at low temperature is larger than that at high temperature. Therefore, the current at lower temperature will get larger than that at higher temperature with increasing bias voltage, so that the M-I transition appears and the M-I transition temperature increases with increasing bias voltage. Moreover, the a-C/Si junction will show metal characteristic if the bias voltage applied is large enough (Fig 4 (b) shows the trend). According to the discussion above, the M-I transition temperature can be controlled by the bias voltage and whose transition temperature increases with increasing bias voltage.

4. Conclusion

In summary, some a-C/n-Si junctions have been fabricated by direct current magnetron sputtering at room temperature, and their I-V characteristics have been investigated. The results show that these junctions have good rectifying properties in the temperature range 80–300 K. The interesting result is that the I-V curve changes dramatically with increasing applied voltage and temperature. For the forward bias voltages, the junction shows Ohmic mechanism characteristic at high temperature. However, the conduction mechanism changes from Ohmic for the low bias voltages to SCLC for the high bias voltages at low temperature. While for the reverse bias voltages, it changes from Schottky emission to breakdown with increasing voltage. Another important phenomenon is that the temperature dependence of the junction resistance shows a metal–insulator transition, whose transition temperature can be controlled by the bias voltage. A possible mechanism is given to understand the abnormal electrical properties.

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References