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High-temperature current conduction through three kinds of Schottky diodes*

Li Fei(李 菲), Zhang Xiao-Ling(张小玲), Duan Yi(段 毅),
Xie Xue-Song(谢雪松), and Lü Chang-Zhi(吕长志)

Department of Electronic Information and Control Engineering, Beijing University of Technology, Beijing 100124, *China*

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Fundamentals of the Schottky contacts and the high-temperature current conduction through three kinds of Schottky diodes are studied. N-Si Schottky diodes, GaN Schottky diodes and AlGaN/GaN Schottky diodes are investigated by *I–V–T* measurements ranging from 300 to 523 K. For these Schottky diodes, a rise in temperature is accompanied with an increase in barrier height and a reduction in ideality factor. Mechanisms are suggested, including thermionic emission, field emission, trap-assisted tunnelling and so on. The most remarkable finding in the present paper is that these three kinds of Schottky diodes are revealed to have different behaviours of high-temperature reverse currents. For the n-Si Schottky diode, a rise in temperature is accompanied by an increase in reverse current. The reverse current of the GaN Schottky diode decreases first and then increases with rising temperature. The AlGaN/GaN Schottky diode has a trend opposite to that of the GaN Schottky diode, and the dominant mechanisms are the effects of the piezoelectric polarization field and variation of two-dimensional electron gas charge density.

Keywords: Schottky diodes, Schottky barrier height, ideality factor, reverse current

PACC: 7280E, 7360L

1. Introduction

Schottky diodes, which have fascinating properties including rectification and barrier height, are of considerable scientific and technological importance.[1] They have broad applications to electronic, optoelectronic, and electrochemical devices. With the requirement for ever reducing sizes of devices within an integrated circuit, a further understanding of their fundamentals is needed. Electronic transport through Schottky contacts is characterized mainly by the barrier height, which is the difference in energy between the Fermi level ($E_{\rm F}$) and the respective majority carrier band edge in the interface.

Among various semiconductors, Si is a traditional material used for the Schottky diode, and III–V nitrides are currently under extensive research. A detailed understanding of GaN barrier properties administers to the optimization of III–V nitride devices, such as solar-blind detectors and solar batteries. Moreover, thorough study of AlGaN/GaN Schottky diodes is beneficial to the optimization of high electron mobility transistors (HEMTs).[2] During the past several years, lots of effort has been made to study the Si and III–V nitride Schottky diodes.[3−5] Our present study aims to extend the scope of those efforts to shed light on the fundamental chemistry, physics, and materials science of Schottky contacts formed by metal deposition on Si, GaN and AlGaN/GaN heterostructures, separately. We are particularly interested in the high-temperature current conduction of these Schottky diodes.

2. Experimental method

The Al/n-Si plastic package Schottky diodes selected for our experiment are of type SB140 with maximum forward current $I_{\rm FM} = 1$ A and reverse breakdown voltage $V_{\rm BR} = 40$ V. The schematic layer structures of the GaN Schottky diode and AlGaN/GaN Schottky diode are shown in Figs.1(a) and 1(b), respectively. For the GaN Schottky diode, a 60 nm thick GaN buffer layer was first deposited on a 400 μm thick sapphire substrate by the metal-organic chemical vapour deposition (MOCVD) method, followed by growing a 1.1 μm thick (1.0×10^{18} cm^{-3}) Si-doped GaN layer. For the $Al_xGa_{1-x}N$/GaN diode, a 60 nm thick GaN buffer layer was first deposited on a 400 μm thick sapphire substrate by the MOCVD method, followed by growing a 2 μm thick undoped GaN layer, a 5 nm thick undoped $Al_xGa_{1-x}N$ layer, a 10 nm

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thick (5.0×10^{18} cm^{-3}) Si-doped $Al_xGa_{1-x}N$ ($x \approx 0.2$) layer, and finally a 5 nm thick (1.0×10^{19} cm^{-3}) Si-doped GaN layer sequentially.

Several samples were cleaned first by degreasing in potassium stearate solution, and next by using 3-min ultrasonic baths (T = 273 K) in trichloroethylene, acetone, and methanol sequentially. Then the samples were immersed in boiling aqua regia solution for 5 min to remove the surface oxide/hydroxide layers. Schottky diodes were fabricated by using two-step photolithography.[6] The ohmic electrode was of Ti/Al/Pd/Au (200 Å/600 Å/400 Å/500 Å) multilayer contact starting with the Ti layer. The 200 μm diameter Schottky contacts were aligned inside the 300 μm diameter opening in the ohmic contacts by evaporating 1000 Å of Ni followed by 300 Å of Au. After annealing, high-temperature characterization of all the diodes was studied by current–voltage–temperature (I–V–T) measurement using an Agilent 4155C. The testing temperature ranged from 300 to 523 K. The temperature dependence of Schottky barrier height and ideality factor of these diodes was extracted from the I–V–T plots.

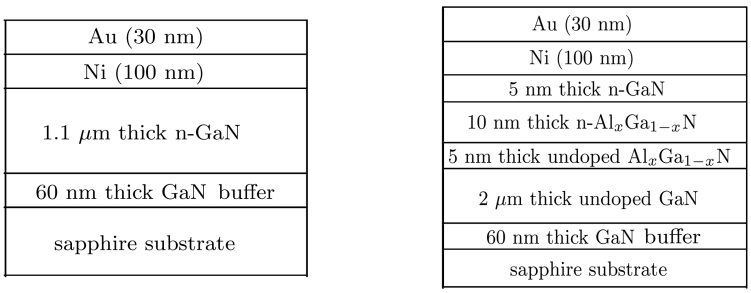


Fig.1. Layer structure growth for the fabrication of (a) GaN Schottky diodes and (b) $Al_xGa_{1-x}N$/GaN Schottky diodes.

3. Results and discussion

3.1. Schottky barrier height

The value of the Schottky barrier height (Φ_B) is extracted from the I–V–T measurement by a modified method. The forward current–voltage (I_F–V_F) characteristics of the n-Si Schottky diode, the GaN Schottky diode and the AlGaN/GaN Schottky diode at various temperatures are shown respectively in Figs.2, 3 and 4.

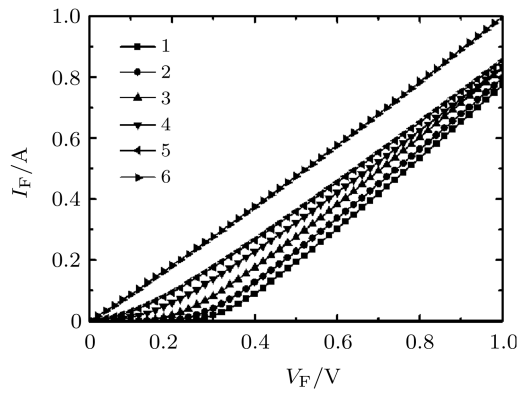


Fig.2. Forward current–voltage characteristics of Si Schottky diodes at various temperatures. Curves 1, 2, 3, 4, 5 and 6 correspond to 300, 323, 373, 423, 473 and 523 K respectively.

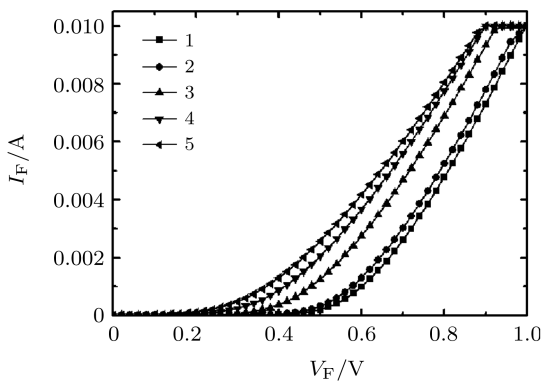


Fig.3. Forward current–voltage characteristics of GaN Schottky diodes at various temperatures. Curves 1, 2, 3, 4, and 5 correspond to 300, 323, 423, 473 and 523 K respectively.

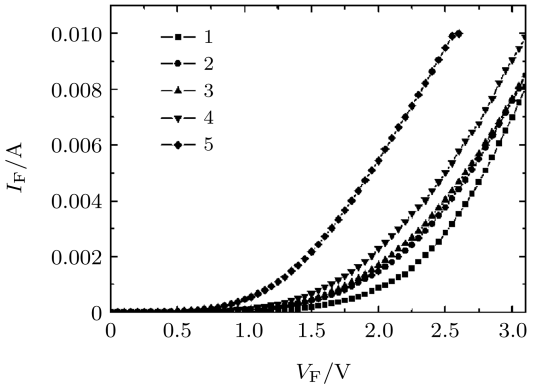


Fig.4. Forward current–voltage characteristics of AlGaN/GaN Schottky diodes at various temperatures. Curves 1, 2, 3, 4, and 5 correspond to 300, 323, 423, 473 and 523 K respectively.

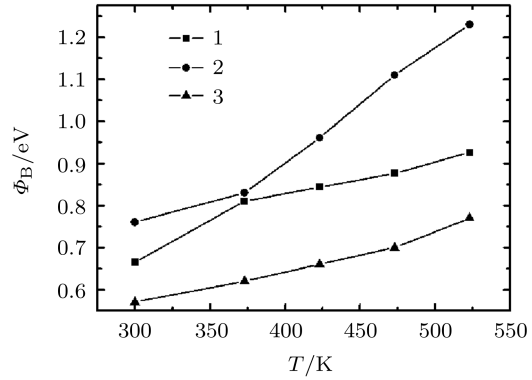


Fig.5. Temperature dependences of the Schottky barrier height of the various samples. Curve 1 is for GaN diodes, curve 2 for AlGaN/GaN diodes, and curve 3 for Si diodes.

For Schottky diodes, the trend of the variation in current with applied voltage bias appears to follow the thermionic emission theory which is given by[7]

$$I = I_0 \left[\exp\left(\frac{qV - IR_s}{nkT} \right) - 1 \right] , \tag{1}$$

where V is the applied voltage drop across the rectifying barrier, T is the absolute temperature in kelvin, n is the diode ideality factor, and I_0 is the reverse saturation current given by

$$I_0 = AA^*T^2 \exp\left(-\frac{q\Phi_B}{kT} \right) , \tag{2}$$

where A is the diode area and A^* is the effective Richardson constant. Ignoring the series resistance, the barrier height can be given by

$$\Phi_B = \frac{kT}{q} \ln\left(\frac{AA^*T^2}{I_0} \right) . \tag{3}$$

Figure 5 shows a comparison between temperature dependences of the Schottky barrier heights of the Si Schottky diodes, the GaN Schottky diodes and the AlGaN/GaN Schottky diodes. As is evident from Fig.5, these three kinds of diodes have similar trends for the temperature dependence of barrier height. As temperature rises, the barrier height of the Schottky diode increases. According to expression (3), the rise of temperature is the main reason for the increase of Φ_B, since the change of I_0 is considerably small. Moreover, metallurgical reaction[8,9] at high temperature is a possible impact factor.

As is evident from Fig.5, with increasing temperature, the barrier height of the AlGaN/GaN Schottky diode has a more significant increase than those of the n-Si Schottky diode and the GaN Schottky diode. For the Si Schottky diode and the GaN Schottky diode, at high temperature, the thermally activated metal electrons tunnel into the semiconductor depletion region, and they end up being captured by ionized donor atoms. Unlike the Si Schottky diode and the GaN Schottky diode, the AlGaN/GaN Schottky diode has a quantum well and interface polarization charges resulting from the piezoelectric polarization field across the AlGaN/GaN interface, where two-dimensional electron gas (2DEG) is formed.[10−12] As a result, some of the thermally activated metal electrons, while tunnelling into the semiconductor, are nullified by the induced polarization positive charges; others are transported into the quantum well. More AlGaN donor atoms are thus ionized at higher temperatures, and the free electrons drift into the quantum well. The M/S depletion region is consequently widened and the Schottky barrier height is enlarged.

3.2. Ideality factor

For a perfect metal-semiconductor interface, provided the current flow is merely determined by thermionic emission, the ideality factor should be equal to unity. However, due to various reasons, the ideality factor usually deviates from that of the ideal case. The ideality factor n is determined by the slope of the linear region of the ln$I$–V characteristics, and it is given by

$$n = \frac{q}{kT} \cdot \frac{1}{\text{slope}} . \tag{4}$$

Figure 6 depicts the temperature dependences of the ideality factor. For the three kinds of diodes, the

ideality factor decreases with increasing temperature. At room temperature (300 K), transport mechanisms such as field emission, trap-assisted tunnelling and thermionic emission take effect together. Therefore the ideality factor is deviated from unity. However, thermionic emission is more sensitive to the temperature than other mechanisms, and thermionic emission current increases rapidly with temperature rising. As a result, at higher temperatures, the forward current is dominated by the thermionic emission and hardly affected by other mechanisms. Moreover, the slope barely changes during the experiment, thus the rise of temperature is the main reason for the decrease of n according to expression (4).

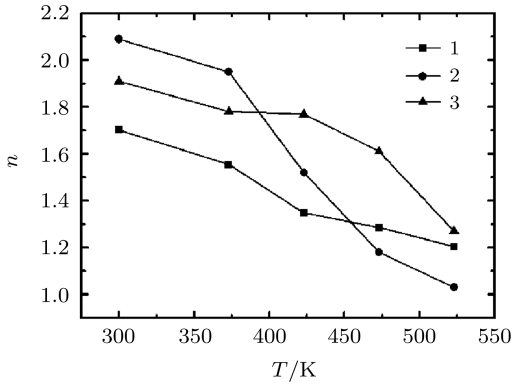


Fig.6. Temperature dependences of the ideality factor of the various samples. Curve 1 is for Si diodes, curve 2 for GaN diodes, and curve 3 for AlGaN/GaN diodes.

In addition, the transport mechanisms above are highly sensitive to barrier height.[13] Their dominant currents decrease almost exponentially as barrier height increases. As both barrier height and ideality factor vary with temperature, and both depend on the inner fundamental of transport mechanisms, the observed variation in ideality factor may be explained in terms of the variation of Schottky barrier height. For the AlGaN/GaN Schottky diodes, the increase of the barrier height is more than for the Si and the GaN Schottky diodes under temperatures from 300 to 523 K. Consequently the ideality factor of the AlGaN/GaN Schottky diodes decreases more than those of other two kinds of Schottky diodes.

3.3. Reverse current

The temperature dependences of the reverse current (I_R) of the Si Schottky diodes, the GaN Schottky diodes and the AlGaN/GaN Schottky diodes are shown respectively in Figs.7, 8 and 9. For these three kinds of Schottky diodes, the changing trends of the reverse current are different. For the Si Schottky diodes, the reverse current increases as temperature rises. The reverse current is very low at room temperature, but quite high at 523 K. The mechanism is decided by trap-assisted tunnelling and semiconductor surface defects, both of which lead to positive temperature coefficient.

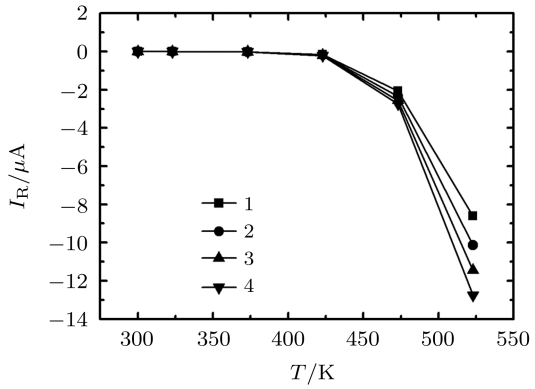


Fig.7. Reverse currents of Si Schottky diodes at various temperatures. Curves 1, 2, 3 and 4 correspond to $V_G = -1$, –2, –3, and –4 V respectively.

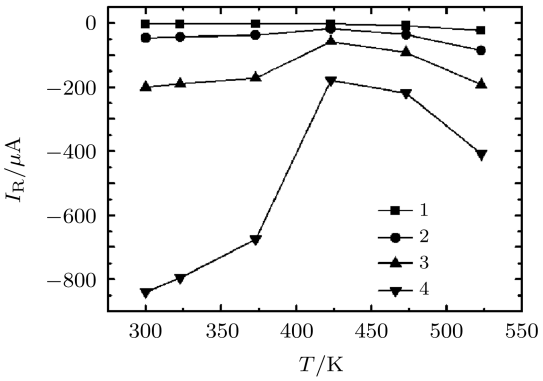


Fig.8. Reverse currents of GaN Schottky diodes at various temperatures. Curves 1, 2, 3 and 4 correspond to $V_G = -1$, –2, –3, and –4 V respectively.

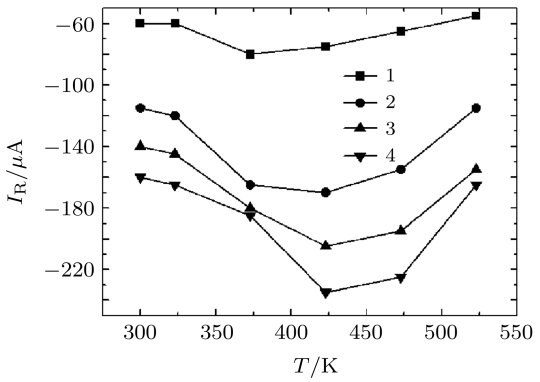


Fig.9. Reverse currents of AlGaN/GaN Schottky diodes at various temperatures. Curves 1, 2, 3 and 4 correspond to $V_G = -1$, –2, –3, and –4 V respectively.

It is interesting that for the GaN Schottky diodes, the reverse current decreases first and then increases

with temperature, while the changing trend of reverse current of the AlGaN/GaN Schottky diodes is contrary to that of the GaN Schottky diodes. The AlGaN and GaN layers grow on the lattice mismatched sapphire substrate, hence exhibiting strains and defects in the material structure. Some of these defects extend up to the semiconductor surface, and induce the growth of steps and dense pits. These pits lead to high reverse leakage current in both the GaN Schottky diodes and AlGaN/GaN Schottky diodes at room temperature.

The difference between two kinds of diodes may be attributed to the relaxation of strain of the AlGaN/GaN heterostructure. For the GaN Schottky diodes, impact ionization mechanism degrades leakage, but trap-assisted tunnelling promotes leakage. Therefore, the reverse leakage current depends on which one of them dominates at a certain temperature. As may be noted from Fig.8, the reverse current reaches the minimum value at 423 K. So the impact ionization mechanism may be the main factor for temperatures below 423 K, and trap-assisted tunnelling is the dominant mechanism for higher temperatures. For AlGaN/GaN Schottky diodes, the reverse current increases first until 423 K, and then decreases at higher temperatures. The trend of this current reflects the higher thermal stability of leakage. The piezoelectric polarization and the discontinuity of the spontaneous polarization at the AlGaN/GaN heterostructure create induced polarization charges and influence the 2DEG at the AlGaN/GaN interface, both of which have a great influence on the barrier height.[14] Trap-assisted tunnelling may be the main factor below 423 K. As the temperature rises, the barrier height increases and the ideality factor decreases rapidly, thereby weakening the trap-assisted tunnelling effect. At the same time, the relaxation of strains and the decrease in the polarization charge at the interface lead to a reduction in reverse current.

4. Conclusions

Thorough and deep research is carried out to understand the temperature dependence carrier transport and interface properties of three different kinds of Schottky diodes. The characteristics of AlGaN/GaN Schottky diodes are compared with those of GaN Schottky diodes and Si Schottky diodes. The study is extremely important for the realization of photoelectric detectors and HEMTs. Our study suggests that temperature dependences of the Schottky barrier height and the ideality factor of the three kinds of diodes are dominated by thermionic emission at high temperatures, while they are affected a lot by trap-assisted tunnelling and field emission at room temperature. In addition, the piezoelectric polarization field and 2DEG charge density play crucial roles in improving the high-temperature electronic performance of AlGaN/GaN Schottky diodes.

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