Electrical properties of MOCVD-grown GaN on Si (111) substrates with low-temperature AlN interlayers*

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The electrical properties of the structure of GaN grown on an Si (111) substrate with low-temperature (LT) AlN interlayers by metal–organic chemical-vapour deposition are investigated. An abnormal P-type conduction is observed in our GaN-on-Si structure by Hall effect measurement, which is mainly due to the Al atom diffusing into the Si substrate and acting as an acceptor dopant. Meanwhile, a constant n-type conduction channel is observed in LT-AlN, which causes a conduction-type conversion at low temperature (50 K) and may further influence the electrical behavior of this structure.

Keywords: metal–organic chemical-vapour deposition, GaN-on-Si, electrical behavior, low-temperature AlN interlayers

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1. Introduction

GaN is known as a promising material for the next generation of power switching devices due to its wide band-gap nature, high breakdown field, and particular polarization effect. Semi-insulating GaN is the foundation of lateral conduction AlGaN/GaN heterostructure field effect transistors (HFETs) that require semi-insulating (SI) material beneath the device structure to enable sharp current pinch-off and device isolation.[1,2] In general, undoped GaN grown on sapphire and SiC by metal–organic chemical-vapour deposition (MOCVD) exhibits n-type conductivity,[3] which may result from the existence of the residual impurities or vacancy.[4,5] By introducing p-type compensation defects or intentionally doping with deep level impurities, one can obtain a high-resistivity GaN with large sheet resistance around 10^7 Ω/□ ∼ 10^{11} Ω/□ on sapphire.[6–11] While a high-resistivity undoped GaN grown by MOCVD on an Si substrate can be naturally obtained without any other special technique, which could easily enable the pinch-off operation for AlGaN/GaN HFETs. The mechanism of achieving this high-resistivity U-GaN on an Si substrate is still unclear, and until now little attention has been paid to the electrical behaviors of the GaN/Si epi-structure in spite of its extensive applications in GaN-based RF and power switching devices.[12–15] In the present work, the electrical property of MOCVD-grown GaN on an Si (111) substrate with low-temperature (LT) AlN interlayers is investigated. We find an abnormal p-type conduction phenomenon in the GaN-on-Si structure. Meanwhile, a low conduction property of the LT-AlN interlayer is observed and analyzed.

2. Experimental procedure

The GaN-on-Si structure (sample A shown in Fig. 1) investigated in this work was grown on a 2-inch diameter Si (111) in an Aixtron 2400G3 MOCVD planetary reactor. First, a high-resistivity Si (111) substrate with a sheet resistance larger than 10^4 Ω/□ (> 1000 Ω·cm) was chemically cleaned before growth to obtain a hydrogen-terminated surface. A 20-nm AlN buffer layer was then grown on the substrate around 1100 °C with short aluminium pre-deposition using trimethylaluminium (TMAl) before supplying ammonia (NH_3). Next, a ∼ 2-μm GaN layer was grown at 1100 °C and two 15-nm LT-AlN (∼ 700 °C) interlayers were inserted into the thick GaN epilayer for the purpose of strain engineering to obtain a crack-free surface. For studying the electrical properties of the

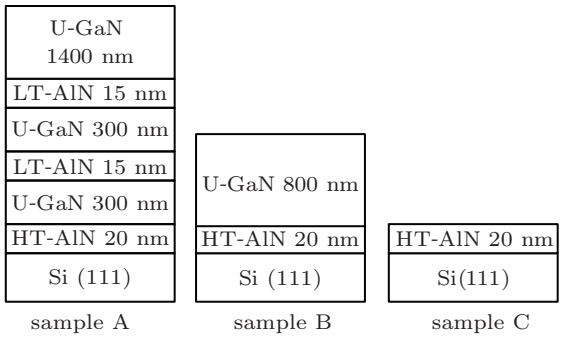


Fig. 1. The schematic structures of different epitaxy layers grown on Si substrates.

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sample A structure in detail, samples B and C were also prepared for comparison. For sample B, only an 800-nm unintentionally doped GaN (U-GaN) layer was grown on the AlN buffer layer without LT-AlN interlayers. For sample C, the growth procedure was stopped after the growth of a 20-nm AlN buffer layer with the same recipe of the sample A. Meanwhile, an AlGaN/GaN HFET structure was also grown on the sample A to verify the resistive property of this structure. The details of the device process can be found elsewhere in the literature.[12] The material electrical properties were characterized with the temperature-dependent Hall effect measurement (Lakeshore 7704) and the secondary ion mass spectroscopy.

3. Results and discussion

The high resistivity property of sample A is confirmed from the good pinch-off features of AlGaN/GaN HFETs based on sample A (See Fig. 2), in which the drain current reaches a general level as low as about $\sim 10^{-3}$ mA/mm (at $V_{ds} = 20$ V, $V_{gs} = -5.5$ V). However, the room-temperature Hall effect measurement data seem to give a contradictive result, in which sample A presents a rather low sheet resistance (667 $\Omega/\square$) with a very high p-type sheet carrier density up to 10^{14} cm^{-2} (see Table 1). This contradiction may be due to the combination effect of the multi-current-path in the epi-structure during the Hall effect measurement (such as the top-GaN layer, the LT-AlN interlayers, the AlN/Si interface, etc.) rather than only one current path through the top-GaN layer (see Fig. 3).

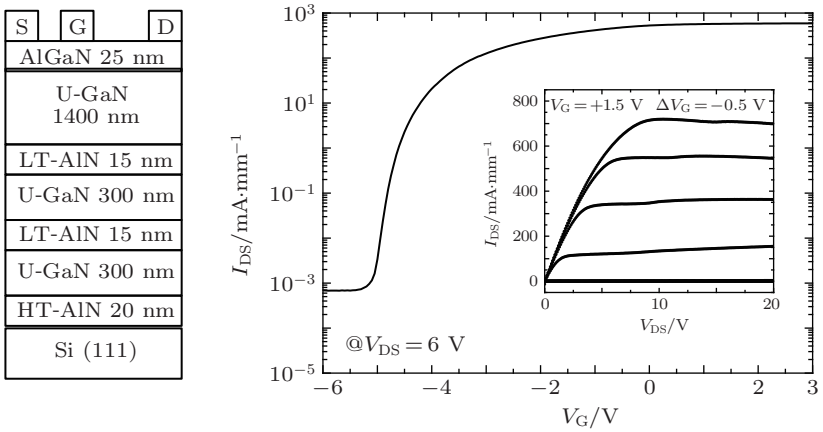


Fig. 2. Schematic structure of an AlGaN/GaN HFET grown on sample A (left), and its drain current I_{ds} as a function of gate voltage V_G (right).

Table 1. Hall effect measurements of the sheet resistance (R_{sh}), mobility (μ), sheet carrier density (ρ), and activation energy (E_D/E_A) of samples A, B, and C.

Sample	Type	$R_{sh}/(\Omega/\square)$	$\mu/(\text{cm}^2/\text{V}\cdot\text{s})$	ρ_{sh}/cm^{-2}	(E_D/E_A)/meV
A	p	667	51	1.8×10^{14}	53
B	p	1906	155	2.1×10^{13}	53
C	p	5626	193	5.7×10^{12}	54

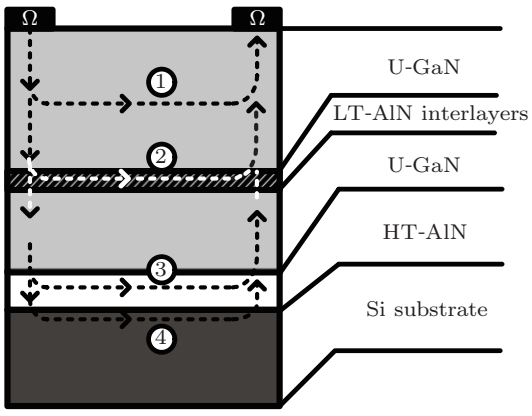


Fig. 3. The schematic current paths of sample A by Hall measurement.

Meanwhile, it can be figured out through the room-temperature Hall effect data in Table 1 that sample A grown on the Si substrate shows an abnormal p-type conduction phenomenon, while the common GaN sample grown on the sapphire substrate in the same MOCVD reactor presents a typical n-type conduction (not shown here). This p-type conduction phenomenon may possibly result from the GaN/HT-AlN or GaN/LT-AlN hetero-structure, which can theoretically produce two-dimensional hole gas at the GaN side due to the polarization effect[16–18] in sample A. But the p-type conduction (sheet carrier density $\sim 6\times10^{12}$ cm^{-2}) can also be observed in sample C, in which there is no GaN/AlN heterostructure but only an HT-AlN epilayer on a high-resistivity silicon substrate. This comparison shows that the AlN/Si interlayer may play a significant role in forming p-type conduction.

In order to understand this interesting phenomenon of the GaN-on-Si sample, the temperature-dependent Hall measurement is carried out. Figure 4(a) shows the plots of the sheet carrier density versus the reciprocal of temperature $(1000/T)$.

All the samples grown on the Si substrates present p-type conductions when the ambient temperature is in a range between 50 K and 300 K, in which the logarithms of the sheet carrier density of all the samples depend linearly on the reciprocal of temperature. Such a behavior is a typical phenomenon of impurity doping behavior rather than a phenomenon of two-dimensional electron gas (2DEG), which should keep a constant hole sheet carrier density with changing temperature. What is more, 2DEG cannot be observed in all the investigated samples, even at a temperature of less than 50 K, which means that the GaN/LT-AlN or GaN/HT-AlN heterostructures in the investigated samples (samples A and B) cannot produce 2DEG. This may be due to the fact that this 15 nm AlN interlayer grown at a relatively low temperature (700 °C) cannot provide a good-quality surface (AFM images are not shown here) for the subsequently grown GaN. So the 2DEG can be excluded from the formation of a p-type phenomenon from the room-temperature Hall effect measurements of samples A and B.

From the slopes of the curves shown in Fig. 4(a), the activation energy (E_D) of the impurity can be directly extracted (listed in Table 1). The activation energies of the GaN layers on AlN/Si (samples A and B), as well as the AlN buffer alone on the Si substrate (sample C), are all around ~ 54 meV, independent of the epitaxy structure. Such a value is very close to the activation energy of the aluminum acceptors (57 meV) in Si.[19] Thus, we speculate that it is the aluminum atoms that form the initial AlN layer that might diffuse into the Si substrate during the high-temperature growth and behave as an acceptor in Si. Secondary ion mass spectrometry (SIMS) analyses of samples A and C could further confirm our speculation. Obviously, as shown in Fig. 4(b) with the profile of aluminum atom concentration as a function of the detection depth of the sample, the aluminum elements exist not only in AlN buffer layer, but also in the Si near the AlN/Si interface, and the concentration of Al decreases while the detection depth increases into the Si substrate. We consider that during the high-temperature growth stage of AlN, aluminum atoms can move into the Si substrate by thermal etching and/or diffusion, incorporate themselves into the silicon crystal lattice, and then play the role of acceptor impurities, which results in a highly p-type conducting channel near the AlN/Si interface. Moreover, one can observe that the p-type concentration of the GaN/Si structure increases with the thickness (growth time) of the epitaxy layer increasing from 5.7×10^{12} cm^2 to 1.8×10^{14} cm^2 (see Table 1). This reveals that more aluminum atoms may diffuse into the substrate during the high-temperature growth over a longer growth time (the SIMS data in Fig. 4(b) also support this conclusion).

Furthermore, with the measurement temperature decreasing (below 50 K) (see Fig. 4(a)), it can be observed that the conduction property of sample A changes from p-type to n-type and that the sheet carrier density is gradually saturated to a constant level at low temperatures. It is considered that such a behavior may result from the competition in the carrier quantities between the original n-type carriers (electrons) in the epilayer and the p-type carriers (holes) gradually disappearing. As the temperature decreases, the activation ratio of the Al atoms decreases gradually and the original n-type carriers in the structure become dominant. More interestingly, such a conduction-type conversion phenomenon could not be observed in samples B and C, whose epi-structures do not contain LT-AlN interlayers. This indicates that the original n-type conduction might relate to the LT-AlN interlayers.

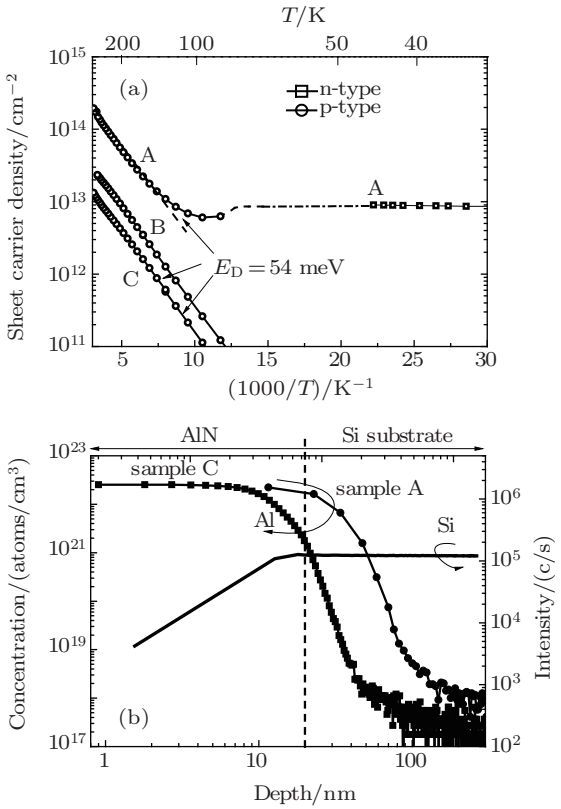


Fig. 4. (a) Plots of sheet carrier density versus the temperature reciprocal of samples A, B, and C. The dashed line between the p-type curve and the n-type curve of sample A is only a guidance for viewing, and (b) the SIMS profiles of impurity (Al, Si) recorded from samples A and C.

Taking into account the fact that the electron concentration of sample A is almost constant at low temperatures, we speculate that there may exist a 2DEG-like n-channel at the LT-AlN/GaN hetero-interface due to the spontaneous and/or piezoelectric polarization effect, which does not need ionization energy to be activated. On the other hand, the quality of GaN below LT-AlN is good enough to form a sharp interface for the formation of a 2DEG-like channel. Meanwhile,

the SIMS data of sample A in Fig. 5 show that the donor impurity (Si and O atoms) concentration in the LT-AlN interlayer is about two orders of magnitude more than that in the GaN layers. These impurities may enhance the effect of the polarization-related phenomenon. Figure 6 shows the plots of the sheet resistivity versus the temperature of the investigated samples. In samples B and C the sheet resistivity increases as the temperature decreases, and finally rises to a value larger than 10^8 Ω/□ at around 10 K due to the freeze-out effect of the impurity (Al). However, sample A shows low resistivity at low temperatures (< 50 K) because of the existence of the original 2DEG-like n-type channel in the LT-AlN/GaN heterostructure.

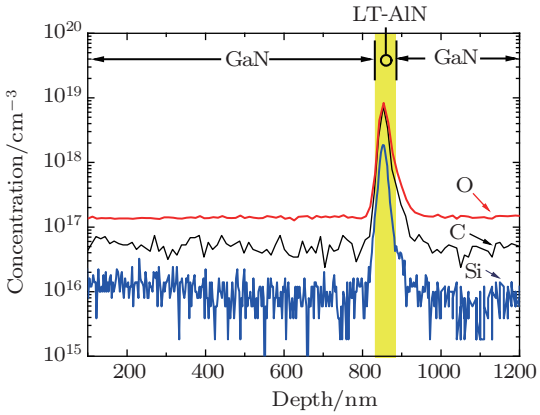


Fig. 5. (color online) SIMS measurements of the impurities, Si, C, O, etc, in the GaN-on-Si structure.

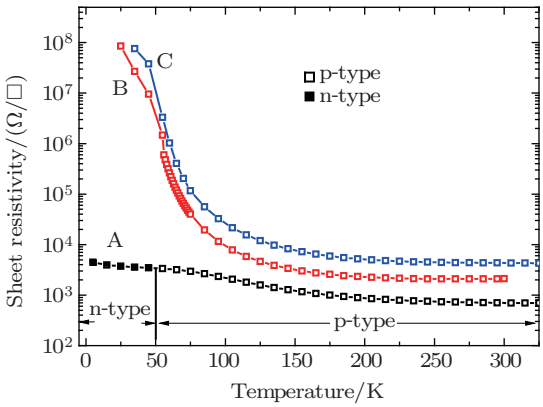


Fig. 6. (color online) Plots of the sheet resistivity versus the temperature of the investigated samples.

4. Summary

A p-type conduction phenomenon is observed in an MOCVD-grown GaN-on-Si epi-structure with LT-AlN interlayers. This is considered as being mainly due to Al atom diffusion into the Si substrate and acting as acceptor dopants according to the above analysis. It is believed that these p-type dopings should exist in all the GaN samples grown on Si substrates with HT-AlN buffer layers, which seems to influence the resistive properties of the GaN grown on them and further influence the devices based on this structure. Moreover, it is shown that the LT-AlN interlayer may introduce a 2DEG-like conduction current path and further influence the electrical properties of the structure, as well as the power switching devices based on this structure. This means that the LT-AlN scheme, which is used for the purpose of strain engineering to achieve a crack-free and thick GaN epitaxy layer, is not suitable for fabricating high-voltage devices.

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