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Carbon-Induced Deep Traps Responsible for Current Collapse in AlGaN/GaN HEMTs*

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Abstract: Although outstanding microwave power performance of AlGaN/GaN HEMTs has been reported, drain current collapse is still a problem. In this paper, an experiment was carried out to demonstrate one factor causing the collapse. Two AlGaN/GaN samples were annealed under N_2-atmosphere with and without carbon incorporation, and the XPS measurement technique was used to determine that the concentration of carbon impurity in the latter sample was far higher than in the former. From the comparison of two I_d-V_{ds} characteristics, we conclude that carbon impurity incorporation is responsible for the severe current collapse. The carbon impurity-induced deep traps under negative gate bias stress can capture the channel carriers, which release slowly from these traps under positive bias stress, thus causing the current collapse.

Key words: AlGaN/GaN HEMT; current collapse; carbon impurity; deep trap
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1 Introduction

With the explosion of wireless technology, radio frequency (RF) and microwave power amplifiers have received more and more attention. Among the variety vying for market share, gallium nitride high-electron-mobility transistors (HEMTs) are extremely attractive for the gamut of power electronics applications from power conditioning to microwave transmitting for communication and radar[1]. Although very high output power densities have been demonstrated, significant developmental work remains to be done for GaN HEMTs. One of the key remaining issues is the current collapse that limits microwave output power[2,3]. Several causes have been proposed for the collapse, including the charging of a second virtual gate[4], thermal resistance increase due to high device temperature[5], gate bias-induced non-uniform strain[6], change of transport properties at high temperature[7], injection of hot carriers into regions adjacent to the conducting channel[8], surface states[9] and deep levels[10,11].

Intensive studies have been performed on the relationship between deep levels and current collapse. However, the results are still controversial. In this paper, we have studied the inseparably close relationship between the deep traps and carbon impurities. We found that the carbon incorporation related deep traps play a significant role in the current collapse observed in AlGaN/GaN HEMTs.

2 Device structure and fabrication

Figure 1 shows the layer structure of the transistor, which is an $Al_{0.2}Ga_{0.8}N$-AlN-GaN multilayer grown on a semi-insulation sapphire substrate. The 50mm epitaxial wafer grown by MOCVD was provided by the Institute of Semiconductors, Chinese Academy of Sciences. An average electron mobility of $1300cm^2/(V \cdot s)$ and a sheet carrier density of $1.6 \times 10^{13} cm^{-2}$ were obtained by room-temperature Hall measurement. The AlGaN/GaN HEMT fabrication commenced with the definition of the active device

Undoped AlGaN	25nm
AlN	1nm
High mobility GaN	0.1μm
GaN	3.5μm
Sapphire	

Fig.1 Layer structure for transistor grown by MOCVD

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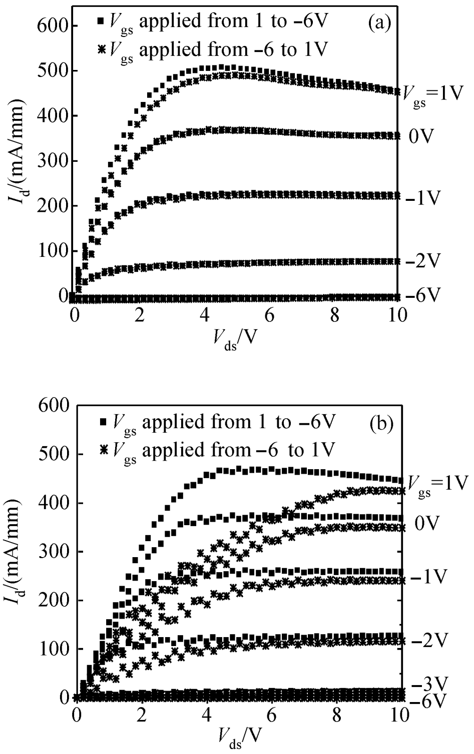

Fig.2 Comparison of I_d-V_{ds} characteristics of sample ＃1 (a) and sample ＃2 (b)

area. This isolation was implemented by ion implantation mesa. Next, the ohmic contacts were formed by depositing the ohmic metals Ti/Al/Ti/Au and then rapid thermal annealing (RTA) at 750℃ for 50s. These steps resulted in a low ohmic contact resistivity of $10^{-6}\Omega \cdot cm^2$. The Schottky gate was formed by Ni/Au evaporation and the subsequent lift-off process. The gate length and width were 0.8 and 80μm, respectively.

3 Experiment and result analysis

The fabrication process was described in the previous section. In this section, several experimental details will be shown. After the Ti/Al/Ti/Au ohmic metals were deposited, the wafer was divided into two parts. Then, one sample (sample ＃1) was annealed under nitrogen (N_2) atmosphere. The second sample (sample ＃2) was annealed under N_2 atmosphere in which we intentionally incorporated excess carbon while the rest of the conditions remained the same as for sample ＃1. In principle, the technique of carbon incorporation in sample ＃2 is a high-temperature environment for diffusion doping. After the gate was completed, the DC test was carried out on both samples.

Figure 2 shows a comparison of the I_d-V_{ds} characteristics of sample ＃1 and sample ＃2, with V_{gs} applied from 1 to −6V and from −6 to 1V, respectively. The I_d-V_{ds} characteristics of sample ＃2 were normal at a standard measurement condition if the gate voltage was applied from 1 to −6 V. However, if they were measured at the gate voltage applied from −6 to 1V, the drain current decreased drastically, and the drain current decrease is especially large at high gate voltage (1V). This is the current collapse caused by negative DC gate bias. Compared with sample ＃2, there was no negative DC gate bias-induced current collapse, as shown in Fig. 2 (a). The two distinct results strongly suggest that the negative DC gate bias-induced current collapse has a direct relation to the excess carbon incorporation. A reasonable explanation is that carbon incorporation-related deep traps under negative gate bias stress are responsible for the current collapse.

This bias stress technique is suitable for extracting the phenomena in the current collapse. If V_{gs} was swept from −6 to 1 V, the drain current had been measured under a very large negative gate bias stress of −6V before it was measured at the gate voltage of 1V. When a large reverse bias is applied on the gate electrode, electrons coming from the gate are soon captured by the carbon impurity-induced deep traps. Thus, the two-dimensional electron gas (2DEG) in the channel decreases, considering the charge neutrality condition in equilibrium. This can also be interpreted as the injection of channel carriers into adjacent regions of the device that contain deep traps. Next, when gradually increased voltage is applied to the gate electrode, the drain current cannot increase instantaneously due to the slow release of electrons from these deep traps, thus causing the current collapse.

The deep trap will be discussed below. In principle, deep trapping centers can reside at the surface, in the AlGaN barrier layer, at 2DEG interface, or in the GaN buffer layer. Until now, there are still a variety of conflicting explanations for these trapping effects. Using photo-transient measurements, investigators have attributed the current collapse to trapping at the surface, under the gate, and in the gate-drain access region[12]; if photoionization spectroscopy measurements are used, traps at the buffer and channel interface can be also identified[13,14]. Klein *et al*. not only used the photoionization spectrum for trap and defect identification, but also estimated the trap depth relative to the band edges[9]. Two broad absorptions were observed below the GaN band-gap, corresponding to the photoionization of carriers from two distinct traps, labeled trap1 and trap2. The fitted photoionization thresholds located the two traps at approximately 1.8 and 2.85eV below the conduction band, respec-

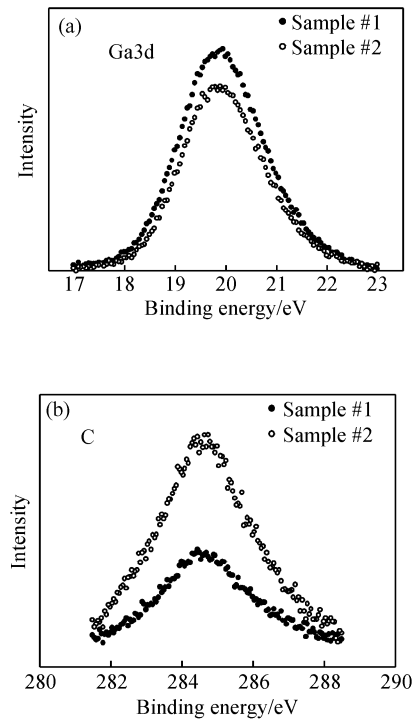

Fig.3 XPS of Ga3d and C spectra for sample #1 and sample #2

tively. Trap1 may be related to structural defects such as dislocations and grain boundaries and trap2 is a carbon impurity-related deep defect[15]. Klein *et al*. gave good evidence of the close connection between the deep trap2 and carbon impurity incorporation[16]. Carbon is a major background impurity in the AlGaN/GaN multilayer grown by MOCVD, and can be controlled to make GaN films semi-insulating (SI) for use as buffer layers in the fabrication of AlGaN/GaN HEMTs. They carried out studies on wafers with GaN layers grown at different MOCVD growth pressures in order to vary the carbon concentration. Plotting trap1 and trap2 concentrations as a function of the carbon concentration shows that the concentration of trap2 is proportional to the concentration of carbon and trap1 is not. This lends considerable weight to the idea that trap2 is a carbon-related defect center.

The experiment in this work also gives excellent evidence. The X-ray photo spectroscopy (XPS) technique was applied to analyze the chemical composition of the layers on the surface of both samples. The XPS results are shown in Fig. 3, where the Ga3d and C spectra of the sample #1 and sample #2 are displayed. From the Ga3d and C XPS spectra, we can find the chemical components change and determine their intensity ratio. The composition ratio of the C atoms to Ga atoms in the sample #1 was estimated to be 0.221, compared to 0.596 for the sample #2. That the relative intensity ratio of the C peak to the Ga peak differs markedly in the two samples indicates that, as a result of annealing under the carbon incorporation atmosphere, excess carbon is Fig. 3(a) at the surface during the annealing process in the sample #2 and forms deep traps there. Currently, the location of deep traps elsewhere in the sample #2 cannot be identified precisely. Further work is needed to clarify whether the carbon impurities penetrate deeply into the AlGaN barrier layer, the two-dimensional electron gas interface, or the GaN buffer layer.

4 Conclusion

Current collapse is one of the most prominent issues that limits the microwave power performance of AlGaN/GaN high-electron-mobility transistors. In this paper, one factor responsible for the collapse was demonstrated. The X-ray photo spectroscopy technique was used to demonstrate that carbon impurity-induced deep traps under negative gate bias stress can cause the current collapse. A large negative DC gate bias was applied and the channel carriers injected into adjacent regions of the device that contain carbon-induced deep traps. Then, a positive gate bias was applied, but the drain current cannot increase instantaneously due to the slow response of electrons in the traps, thus causing the current collapse.

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碳致深能级引起的 AlGaN/GaN HEMT 电流崩塌现象*

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摘要：AlGaN/GaN HEMT 良好的功率特性虽然被大量报导，但其电流崩塌现象仍是一个令人困扰的问题，作者通过实验证明了导致其电流崩塌的一个因素.两个 AlGaN/GaN 样片被分别放在纯氮气和掺碳的氮气气氛中快速退火，利用 XPS 证明了后者中的碳元素含量远远大于前者.比较二者的 *I-V* 特性曲线，可发现碳杂质的引入可使 AlGaN/GaN HEMT 电流崩塌程度大大增加.分析表明：由碳杂质引入导致的深能级使得负栅压下俘获沟道中的载流子在正栅压下不能立刻释放，从而引起 AlGaN/GaN HEMT 中的电流崩塌现象.

关键词：AlGaN/GaN HEMT；电流崩塌；碳杂质；深能级

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