Role of Ga vacancies in enhancing the leakage current of GaN Schottky barrier ultraviolet photodetectors*

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The leakage current of GaN Schottky barrier ultraviolet photodetectors is investigated. It is found that the photodetectors adopting undoped GaN instead of lightly Si-doped GaN as an active layer show a much lower leakage current even when they have a higher dislocation density. It is also found that the density of Ga vacancies in undoped GaN is much lower than in Si-doped GaN. The Ga vacancies may enhance tunneling and reduce effective Schottky barrier height, leading to an increase of leakage current. It suggests that when undoped GaN is used as the active layer, it is necessary to reduce the leakage current of GaN Schottky barrier ultraviolet photodetector.

Keywords: Ga vacancies, MOCVD, GaN, Schottky barrier photodetector
PACC: 7850G, 7280E

1. Introduction

Due to their extensive applications in missile detection, secure space-to-space communication and atmosphere monitoring, GaN based ultraviolet photodetectors have been investigated for many years. Various structures such as Schottky barrier, metal–semiconductor–metal and p–i–n photodetectors have been fabricated, in addition, solar-blind focused plane array have been realized.[1] Although great achievements have been obtained in the GaN material growth and device fabrication, there are many problems needed to be solved. For example, the mechanism for the leakage current of GaN ultraviolet photodetector remains under debate. Many researchers paid attention to studying the influence of dislocations on the leakage current of ultraviolet photodetector.[2−7] However, there are many kinds of defects in GaN materials besides the dislocations, for example, the point defects are also important defects in GaN.[8] How these point defects influence the leakage current of photodetectors needs to be clarified. In addition, understanding the mechanism of leakage current is very significant for the development of GaN-based devices.

In this paper, the leakage current of GaN Schottky barrier photodetectors is investigated. It is found that the Schottky barrier ultraviolet photodetectors with employing undoped GaN instead of Si-doped GaN as the active layer show a much lower leakage current, even when they have a higher dislocation density. It is also found that the density of Ga vacancies in undoped GaN is much lower than in Si-doped GaN layer as demonstrated by positron annihilation measurements. It is deduced that the Ga vacancies enhance tunneling and reduce effective Schottky barrier height, leading to an increase of leakage current. It is suggested that the performance of GaN Schottky barrier ultraviolet photodetectors could be improved by employing undoped GaN as the active layer.

2. Experiment

Two kinds of GaN Schottky barrier ultraviolet photodetectors are prepared for comparison. They have the same device structures, but different active layers. The epilayers grow on *c*-plane sapphire substrates by metalorganic chemical vapour deposition.

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These photodetectors used have the n^-–GaN/n^+–GaN structure, whose schematic diagram is shown in the inset of Fig. 1. During the material growth, firstly a thin GaN buffer layer is deposited at 540 °C, then a $\sim 3\mu$m-thick heavily Si-doped n^+-GaN layer ($n = 5 \times 10^{18}$ cm^{-3}) grows, followed by a $\sim 0.4\mu$m-thick n^--GaN layer growing at a high temperature. The top transparent Schottky barrier is formed on the n^--GaN layer by using a Ni/Au (3 nm/3 nm) metal film, and the bottom Ohmic contact to the n^+-GaN layer is made by using Ti/Al/Ti/Au metal. In Table 1 listed are the carrier concentration in the n^--GaN layer and the full width at half maxium (FWHM) of double crystal x-ray diffraction (DCXRD) for the two kinds of samples, i.e. sample 1 with Si-doped n^--GaN layer and sample 2 with undoped n^--GaN layer. The DCXRD experiments are performed on a Rigaku SLX-1AL x-ray diffractometer to obtain the FWHM of the ω-scan rocking curve. The current–voltage (I–V) characteristics are measured by Keithley 6430 source meter. All measurements are carried out at room temperature.

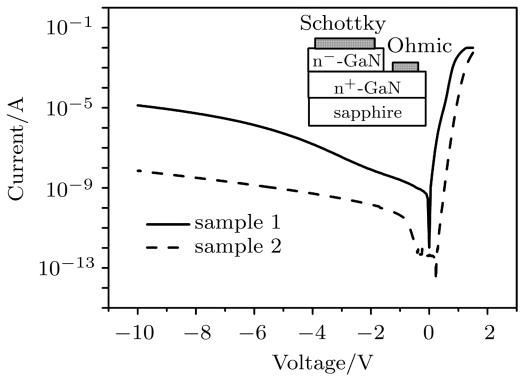


Fig. 1. I–V curves of GaN Schottky barrier ultraviolet photodetector samples 1 and 2, and the schematic diagram of the devices shown in the inset.

Table 1. Main differences in structure parameters and epilayer XRD characterization and device measurement result between two photodetectors samples.

samples No.	XRD FWHM/arcsec		n^--GaN Layer	ideality factor	barrier height/eV
	(002)	(102)			
1	190	195	Si-doped, $n \approx 1.6\times10^{16}$ cm^{-3}	1.9	0.64
2	230	245	Undoped,$n \approx 2.0\times10^{16}$ cm^{-3}	1.4	1.0

3. Results and discussion

Figure 1 shows the I–V curves of samples 1 and 2. A remarkable difference can be observed between the two curves. At the bias voltage –10 V, the values of reversed current are 1.3×10^{-5} A and 7.0×10^{-9} A for samples 1 and 2, respectively. The reversed current of sample 1 is much larger than that of sample 2. According to the formula of I–V characteristic, the ideality factor and Schottky barrier height are calculated.[9] As shown in Table 1, the ideality factors are 1.9 and 1.4, and the values of Schottky barrier height are 0.64 and 1.0 eV for samples 1 and 2, respectively. Due to the fact that the same metal and the same surface treating processing are adopted, the great difference in effective barrier height results in different leakage currents, so that the leakage current is much larger in sample 1 than in sample 2. In addition, the higher ideality factor implies that there is a higher reverse current generated from the deep defect levels in the active region of sample 1. Many papers have been published to deal with the leakage current of GaN devices. Most of these studies were involved with the role of dislocations in the leakage current, and it was believed that the dislocations could lead to an increase of leakage current.[2–7] However, the situation is slightly different from the present experiment. As shown in Table 1, the (002) and (102) FWHM values of DCXRD in sample 1 are much smaller than those in sample 2. It is known that the screw and edge components of the threading dislocations are indirectly represented by the FWHMs of DCXRD at (002) and (102) planes, respectively.[10,11] In other words, the two kinds of dislocation densities of sample 1 are much lower than those of sample 2. Therefore, it indicates that other factors play a more important role in enhancing the leakage current of GaN photodetectors than the dislocations. We know that there are many kinds of point defects such as Ga vacancies, N vacancies and O impurities in GaN except for the dislocations.[8] Probably certain point defects lead to the increase of leakage

current in GaN photodetectors with Si-doped active layer even they have a lower dislocation density.

Positron annihilation measurement is a powerful tool for characterizing the concentration of point defects in materials.[12,13] Therefore, positron annihilation experiments are conducted to gain further insight into the point defects in GaN. In these experiments, the Doppler broadening spectrum of the annihilation line is recorded by using a high-purity Ge detector. The broadening is described by the conventional low momentum parameter S and the high momentum parameter W.[14,15] Figures 2(a) and 2(b) show the parameters S and W each as a function of positron incident energy for the two GaN photodetector epilayers of samples 1 and 2, respectively. From Fig. 1(a), it is observed that the value of parameter S for sample 1 is larger than that for sample 2. However, from Fig. 2(b), it can be observed that the value of parameter W for sample 1 is smaller than that for sample 2. The Ga vacancies in GaN are negatively charged, when positrons are annihilated at Ga vacancies, the value of parameter S increases and that of parameter W decreases, since a larger fraction of annihilation happens to the low-momentum valence electrons. In other words, a larger value of parameter S and a smaller value of parameter W imply a higher density of Ga vacancies.[14,15] Therefore, the result of Fig. 2 suggests that there is a much higher density of Ga vacancies in sample 1 than in sample 2. To further obtain the information about the point defects existing in the devices, the relationship between parameter S and parameter W for the two samples is studied. As shown in Fig. 3, it is observed that the parameter S changes with parameter W linearly in both samples. The two curves have nearly an equal slope. The result indicates that there is only one kind of point defect in these two device samples, i.e. the point defect may be just the Ga vacancies.[14]

The Ga vacancies are regarded as deep level centres in the forbidden gap of GaN. Recently it has been found that the minority carrier diffusion length decreases by the Ga vacancies in GaN due to the influence of deep level defects.[16] Therefore, it is deduced that the defect levels formed by Ga vacancie may lead to an increasing probability of tunneling current. Furthermore, the Ga vacancies will generate electrons under the reverse bias voltage.[17] It will increase not only the reverse current, but also the ideality factor. As a result, the reverse leakage current can be enhanced because of the existence of Ga vacancies. It is also noted that in both simple GaN films and GaN layers in the complex device structures, when they are slightly doped with Si, they will have a much higher density of Ga vacancies than in undoped GaN, i.e. a slight Si doping could lead to an increase of Ga vacancy. In fact, our experimental results are consistent with the reported theoretical model which suggests that the formation of Ga vacancies in GaN is enhanced by the complex formation with Si impurities.[18] Therefore, to fabricate high performance of GaN Schottky barrier ultraviolet photodetectors, it is necessary to employ undoped GaN instead of Si-doped GaN as the active layer in the device structure.

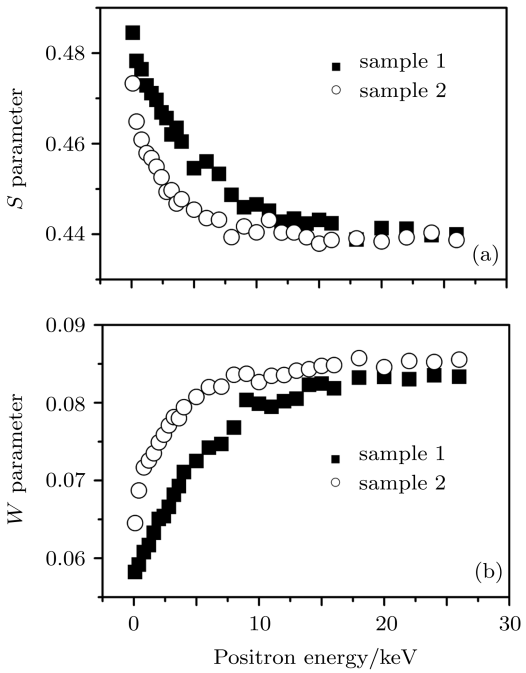


Fig. 2. Parameter S (a) and parameter W (b) each as a function of positron incident energy for the two GaN photodetector epilayers of samples 1 and 2, respectively.

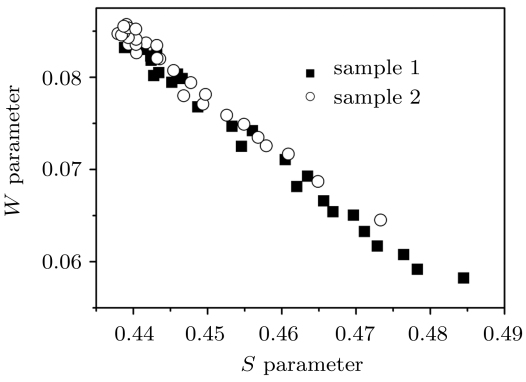


Fig. 3. Relationship between parameter S and parameter W for the two GaN Schottky barrier ultraviolet photodetectors samples 1 and 2.

4. Conclusion

The leakage current of GaN Schottky barrier ultraviolet photodetectors is investigated. It is found that the photodetectors employing undoped GaN instead of Si-doped GaN as an active layer show much lower leakage current, even when they have a higher dislocation density. It is found that the density of Ga vacancies in undoped GaN is much lower than in Si-doped GaN, as demonstrated by positron annihilation measurements. It is suggested that the Ga vacancies may enhance tunneling and reduce effective Schottky barrier height, leading to the enhancement of leakage current. It is necessary to improve the performance of GaN Schottky barrier ultraviolet photodetectors by employing undoped GaN as the active layer.

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