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Photocurrent Property of GaN on the Si Photodetector with a Nearly Polycrystalline α-Al_2O_3 Buffer Layer *

JIANG Ruo-Lian(江若琏), WANG Jun-Zhuan(王军转), CHEN Peng(陈鹏), ZHAO Zuo-Ming(赵作明),
MEI Yong-Feng(梅永丰), SHEN Bo(沈波), ZHANG Rong(张荣), WU Xing-Long(吴兴龙),
ZHENG You-Dou(郑有炓)
Department of Physics, Nanjing University, Nanjing 210093

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Using nearly polycrystalline α-Al_2O_3 as the buffer layer, GaN epilayers were grown on Si(111) substrates by low-pressure metal–oragnic chemical vapour deposition. The nearly polycrystalline α-Al_2O_3 was formed by anodic porous alumina annealed at high temperature. Prototype photoconductive detectors were fabricated with these materials. The spectral response of these detectors exhibits a relatively sharp cut-off near the wavelength of 360 nm and a peak at 340 nm with a shoulder near 360 nm. Under 5 V bias, the responsivities at 340 nm and 360 nm were measured to be 3.3 A/W and 2.4 A/W, respectively. The relationship between the responsivity and the bias voltage shows that the responsivity is saturated when the bias voltage reaches 5 V.

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Gallium nitride (GaN) has been considered to be one of the most promising materials for the fabrication of high-responsivity and visible-blind ultraviolet (UV) detectors due to its direct and wide bandgap, high-saturation electron drift velocity and the excellent physical and chemical properties. GaN UV photodetectors are essential for applications such as atmosphere UV radiation detecting, flame sensors, engine monitoring, future fibre-optical communications, and biological research. In recent years, the growth technology of GaN on sapphire (α-Al_2O_3) has been relatively mature. GaN films grown on Si substrates are more attractive due to their low cost, large size, and the possibility of integrating GaN devices with Si-based electronics techniques. However, there are still difficulties in growing high-quality GaN films on Si substrates due to the large lattice mismatch (17%), thermal mismatch (37%), and difficult nucleation between GaN and Si. Thus, it is quite important to select and study appropriate buffer layer materials between GaN and Si. Some materials have been used as the buffers, such as SiC, AlN, GaAs, Al_2O_3, ZnO, and so forth.[1–5] AlN is a good buffer material, but it is difficult to obtain optimal growth conditions in different growth systems.

Since high-quality GaN can be grown on sapphire (α-Al_2O_3), we expected that, using α-Al_2O_3 as the buffer layer, it would be possible to grow GaN on Si. In this Letter, we report that nearly polycrystalline α-Al_2O_3 was used as the buffer layer between GaN and Si substrates. The nearly polycrystalline α-Al_2O_3 was formed by anodic porous alumina annealed at high temperature. Prototype photoconductive detectors were fabricated with these materials. The photocurrent properties of the detectors are described and discussed.

The aluminium film was deposited on the high-resistivity (111)-oriented Si substrate using electron-beam evaporation. The thickness of this film was about 250 nm. Then the aluminium film was anodized in real-time controlled anodization equipment, which is monitored by the anodic $I-t$ curve. The controlling process has been published elsewhere.[6] Using a platinum plate as the cathode, the anodization was carried out in 15 wt% sulfuric acid under a constant dc voltage of 10 V. It was proven in the experiment that using lower voltage can obtain anodic porous alumina of smaller aperture (a magnitude of about a few nanometres). After anodization, the samples were annealed in the rapid thermal process/low-pressure metal–organic chemical vapour deposition (RTP/LP-MOCVD) system[7] under nitrogen protection for 30 min at the temperature of 1000°C. The x-ray diffraction (XRD) measurement showed that the status of anodic porous alumina was different after annealing at different temperatures. When the annealing temperature was lower than 800°C, the anodic porous alumina was amorphous; when it was increased to 1000°C, polycrystalline peaks of α-Al_2O_3 appeared. The higher the annealing temperature, the more peaks and the higher the peak intensity.[8] In this experiment, the samples were only annealed at 1000°C due to the temperature limit of the RTP/LP-MOCVD system. The nearly polycrystalline α-Al_2O_3 was obtained after it was annealed. Then GaN layers were grown on the annealed anodic alumina buffer in two steps. Firstly, about 30 nm thick low-temperature GaN was grown *in situ* at 500°C. The temperature was then in-

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creased to 950°C to grow the final GaN epilayer, the thickness of which is 500 nm. The annealed anodic porous alumina and thin low-temperature GaN buffer layers will relax some of the strains and are helpful to restrain the Si diffusion at high temperature.[9]

The metal–semiconductor–metal (MSM) photoconductive prototype detectors were fabricated with the above material. In order to increase photocurrent gain, defects were sometimes introduced intentionally into the material. With the above mentioned polycrystalline material, photoconductive detectors were fabricated and investigated. The interdigitated finger electrodes of the detectors were 10 μm wide and 550 μm long with 20 μm wide spacing. In order to obtain good ohmic contacts, the electrode metal on the n-type GaN is Ti/Al/Pt/Au whose thicknesses were taken to be 30 nm, 100 nm, 40 nm and 200 nm, respectively. The metal electrode was alloyed at the temperature of 650°C for 10 min under nitrogen protection. The current–voltage properties between two electrodes were measured with a semiconductor parameter analyser. It showed that they were of ohmic contacts. The typical value of the dark resistance between two electrodes was about 3 kΩ.

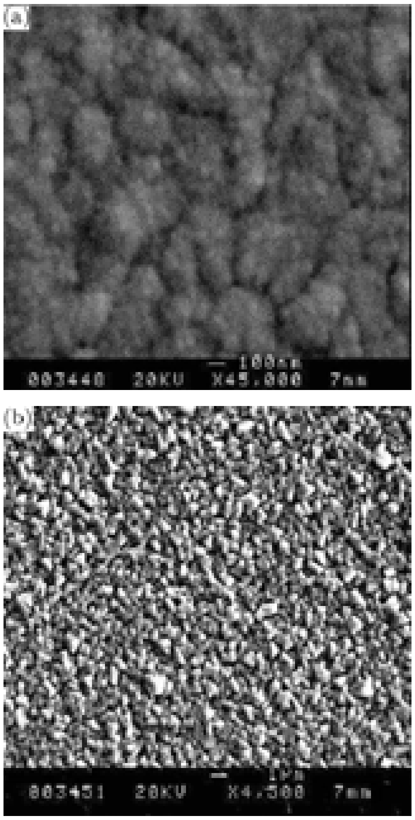

Fig. 1. SEM image of the surface of the GaN films on Si substrates with (a) nearly polycrystalline α-Al_2O_3 buffer layer and (b) AlN buffer layer.

The above material was measured and the result showed that the (400) and (104) peaks of the α-Al_2O_3 phase appeared in XRD spectra of annealed anodic porous alumina on the Si(111) substrate. This indicated that the annealed anodic porous alumina was nearly polycrystalline α-Al_2O_3.[8] The scanning electron microscopy (SEM) measurement showed that the surface of theGaN epilayer with annealed anodic porous alumina buffer was smoother than the GaN layer with AlN buffer grown in the same system (see Fig. 1). However, the XRD measurement showed that the GaN was polycrystalline, because there are also (1010), (1011) and (1120) peaks of polycrystalline GaN besides the (0002) and (0004) peaks. The electrical properties of GaN films were determined by Hall measurements. The unintentionally doped GaN films were n-type. The background carrier concentration was about $3.4 \times 10^{18}\,\mathrm{cm}^{-3}$, and the Hall mobility was $43\,\mathrm{cm}^2/\mathrm{Vs}$. A detailed description of the materials will be published elsewhere.

The spectral responses of the prototype photodetectors were measured using a system including mainly a xenon light source, a monochromator, a lock-in amplifier and computer-controlled data sampling equipment. The samples were illuminated from the front side. The photo-power incident upon the detector was measured using GG3001B photo-power tester. The voltage-dependent responsivity was measured using the same system.

The responsivity as a function of wavelength for a GaN/nearly polycrystalline α-Al_2O_3/Si detector is shown in Fig. 2. It shows a relatively sharp cut-off near the wavelength of 360nm and a peak at 340 nm with a shoulder near 360 nm. The responsivity increases with bias. Under 5 V bias, the responsivities at 340 nm and 360 nm were measured to be 3.3 A/W and 2.4 A/W, respectively. The responsivity declines in the wavelength range from 340 to 250 nm.

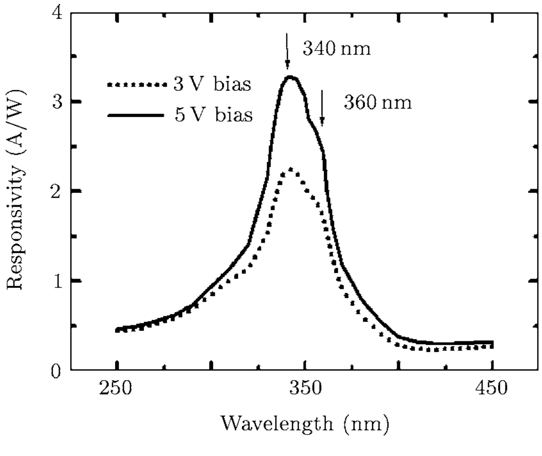

Fig. 2. Spectral response of a GaN/nearly polycrystalline α-Al_2O_3/Si detector under 3 V and 5 V bias.

It is known that the maximum responsivity should be near 360 nm if the light is absorbed only by the GaN layer; while in Fig. 2, the maximal peak responsivity is at 340 nm but not at 360 nm. The reason may be that the insufficiently oxidized aluminium was diffused into the GaN layer during the high-temperature growth and formed $Al_xGa_{1-x}N$, for which the bandgap is wider than GaN. The responsivity is weak at the short wavelength of 250–320 nm. The explanation is that GaN has a large absorption coefficient for short wavelength. The light of short wavelength cannot penetrate in too deeply, so the quantity of photo-induced carriers is small. In addition, the photo-induced carriers are mostly recombined by the surface recombination and defect recombination, which makes the photo-induced carriers contribute little to the outer circuit.

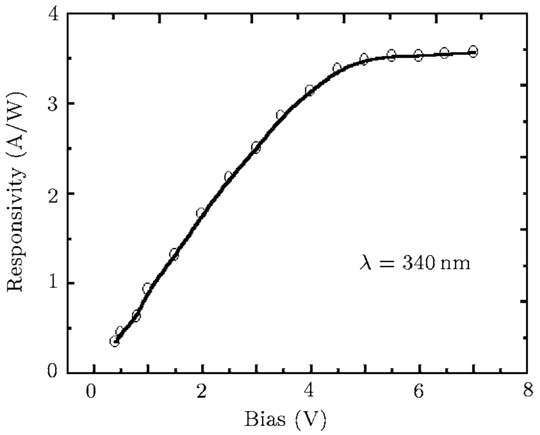

Fig. 3. Voltage-dependent responsivity of the GaN/nearly polycrystalline α-Al_2O_3/Si detector at 340 nm.

Figure 3 shows the voltage-dependent responsivity of the detectors at 340 nm. Below 4 V, the responsivity increased almost linearly with the bias voltage. When the bias was higher than 4 V, the increase slowed down. Above 5 V, the responsivity saturated. According to the theory of the photoconductive detector, the higher the bias voltage is, the stronger the photocurrent will be, and the responsivity will increase linearly.[8] For photoconductive detectors, the saturation of responsivity is explained to be caused by the minority carrier sweep-out effects[9] which are determined mainly by the carrier mobility, carrier lifetime, the space between two electrodes and bias voltage. Because of the sweep-out effects and the power consumption of the detector, the applied bias cannot be increased without limits.

In conclusion, nearly polycrystalline α-Al_2O_3 was obtained after anodic porous alumina on Si(111) substrates were annealed at high temperature ($\geq$ 1000°C). Using this material and a low-temperature GaN thin layer as the buffer layers, GaN epilayers were grown on Si. The surface of the GaN layer is smooth, but it is polycrystalline. Prototype photoconductive detectors were fabricated with these materials. The spectral response of these detectors exhibited a relatively sharp cut-off near the wavelength of 360 nm and a peak at 340 nm with a shoulder near 360 nm. Under 5 V bias, the responsivities at 340 nm and 360 nm were measured to be 3.3 A/W and 2.4 A/W, respectively. The relationship between the responsivity and the bias voltage shows that the responsivity saturates when the bias voltage reaches 5 V. The results indicate that further studies are needed to use annealed anodic porous alumina as the buffer layer between GaN and Si. If the annealing temperature is increased, better results may be obtained.

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