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Growth of III-nitrides on Si(111) and its application to photodiodes

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In this paper, we investigated growth of GaN and $Al_{0.09}Ga_{0.91}N$ epilayer grown on silicon (111) by using II MBE system. The major characterization tools used for this study were high resolution X-ray diffraction (HRXRD), and micro photoluminescence (PL) spectroscopy. Also reported is our attempt to fabricate and characterize metal-semiconductor-metal photodiode based on these films. The responsivity as a function of wavelength for an MSM GaN/Si(111) detector is a sharp cut-off wavelength at 362 nm. A maximum responsivity of 0.256 A/W was achieved at 358 nm. For $Al_{0.09}Ga_{0.91}N$ film, there is a sharp cut-off wavelength at 340 nm. A maximum responsivity of 0.263 A/W was achieved at 338 nm. In UV spectral region, the detector shows a little decrease from 340 to 200 nm. The responsivity of the MSM drops by nearly an order of magnitude across the cut-off wavelength.

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Keywords: photodiodes; PL; Raman

1. Introduction

Ultraviolet (UV) photodetectors are important devices that can be used in various commercial and military applications. For example, visible-blind UV photodetectors can be used in space communications, ozone layer monitoring and flame detection. With the advent of optoelectronic devices fabricated on wide direct band-gap materials, it becomes possible to produce high-performance solid-state photodetector arrays that are sensitive in the UV region [1].

GaN is a wide direct band-gap material that can be used in the UV region. In the past few years, various types of GaN-based photodetectors have been proposed, such as a p-n junction diode [2], p-i-n diode [3-4], p-π-n diode [5], Schottky barrier detector [6], and metal-semiconductor-metal (MSM) photodetector [7-8].

$Al_xGa_{1-x}N$ is extremely important materials with widespread applications for photodetector because they have a direct wide energy bandgap, which ranges from 6.2 to 3.4 eV. Characteristics of $Al_xGa_{1-x}N$ photodetectors are degraded with increasing aluminum molar fraction because of the degradation of the crystal quality with increasing aluminum content.

Silicon substrate presents the obvious advantages of a well-known technology, availability of high-quality, large-area and low-cost wafers. However, its high lattice- and thermal-mismatch with III-nitrides and the high diffusion-coefficient of Si at growth temperatures have delayed the progress in the fabrication of efficient optoelectronic devices on this substrate. The use of proper buffer layers, which attenuate these inconveniences, is required.

In this paper, we have investigated growth of GaN and $Al_{0.09}Ga_{0.91}N$ epilayer grown on silicon (111) by using Veeco model Gen II MBE system. The major characterization tools used for this study were high resolution X-ray diffraction (HRXRD), and micro photoluminescence (PL) spectroscopy. Also reported is our attempt to fabricate and characterize metal-semiconductor-metal photodiode based on these films.

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2. Experimental details

The film growth has been performed in a MBE system, using standard effusion sources for evaporation of Al (6N5) and Ga (7N) and using a RF-source to supply activated nitrogen. Growth mode and surface superstructures have been monitored by a 15 kV RHEED system. The base pressure in the system was below 5 x 10^{-11} Torr. Prior to loading into MBE chamber, the Si (111) wafers (resistivity < 0.02 ohm-cm, n-type) were ultrasonically degreased in solvents and etched in buffered HF. The substrate was immediately transferred into the chamber from the solution and the chamber was pumped down. In the preparation chamber, the substrates were outgassed for 10 min at 400 °C prior to growth.

The plasma was operated at typical nitrogen pressure of 1.5×10^{-5} Torr under a discharge power of 300 watts. The light emission from the rf nitrogen plasma source appear bright orange to the eyes when operated under suitable condition. Atomic nitrogen generated by an rf plasma will provide efficient nitrogen activation as a group V precursor, hence improve the growth rate and crystalline quality. In the growth chamber, Si substrate was heated at 750°C, a few monolayers Ga was deposited on the substrate for the purpose of removing the SiO_2 by formation of GaO_2.

A RHEED reconstruction with prominent Kikuchi lines is then observed, that turns into clean Si (111) surfaces at 750 °C. A way to avoid this amorphous Si_xN_y layer formation is to start the growth with an AlN buffer layer, because the bond formation between Al and N atoms prevails over the Si-N one. Due to the formation of Si_xN_y, LT GaN is not a suitable buffer for GaN epitaxy. Then, AlN buffer layer deposition is started by opening both Al and N cell shutters simultaneously. The role of this layer is not only to improve the crystalline quality of the latter AlGaN layer, but also to electrically insulate the epitaxial film from the conductive substrate. Sample I (GaN/AlN/Si), grown with 0.31 µm AlN followed by 0.06 µm GaN. Sample II nominally consisted of 0.20 µm AlN followed by 0.23 µm AlGaN.

High resolution XRD (PANalytical X'pert MRD) was used to assess the crystalline quality. The surface morphology of the sample was investigated by atomic force microscopy (AFM). The optical quality of the films was studied by photoluminescence (PL) spectroscopy. PL was performed at room temperature by using Jobin Yvon HR800UV system, i.e. an integrated confocal micro Photoluminescence. A He-Cd laser (325 nm) was used as an excitation source for PL spectroscopy. For measurements, the incident laser power was 20 mW. GaN-based metal-semiconductor-metal photodiode have also been fabricated on the GaN and $Al_{0.09}Ga_{0.91}N$ films. The result indicate that high quality GaN-based films on Si(111) can be obtained using the AlN buffer layer.

For the MSM photodiodes, the structure of the MSM photodiode consists of two interdigitated Schottky contact (electrode) with finger width of 230µm, finger spacing of 400µm, and the length of each electrode was about 3.3mm. It consists of 4 fingers at each electrode as shown in Fig. 1. Nickel (Ni) is used as the Schottky contact metal for all the fabricated devices due to its high metal work function (ϕ_m = 5.15 eV) [9] and its availability in our lab. Thermal evaporation method is employed for all the Ni Schottky contact formation by using a metal mask in patterning of the contact structure. For the wafer cleaning process prior to metallization of the contact metal, the samples were dipped in a 1:20 $NH_4OH:H_2O$ solution for 15 s followed by a 10 s dip in a 1:50 $HF:H_2O$ solution. Then, it was rinsed with distilled water and blown dry with normal gas blower.

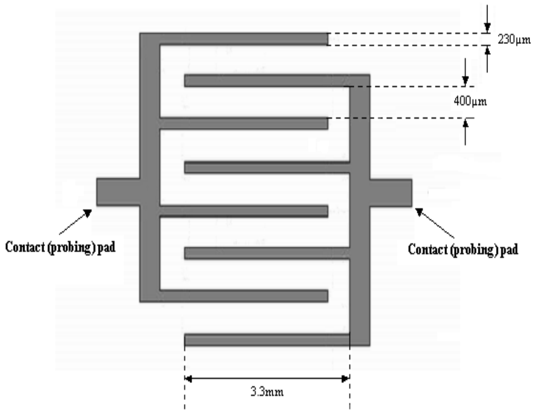
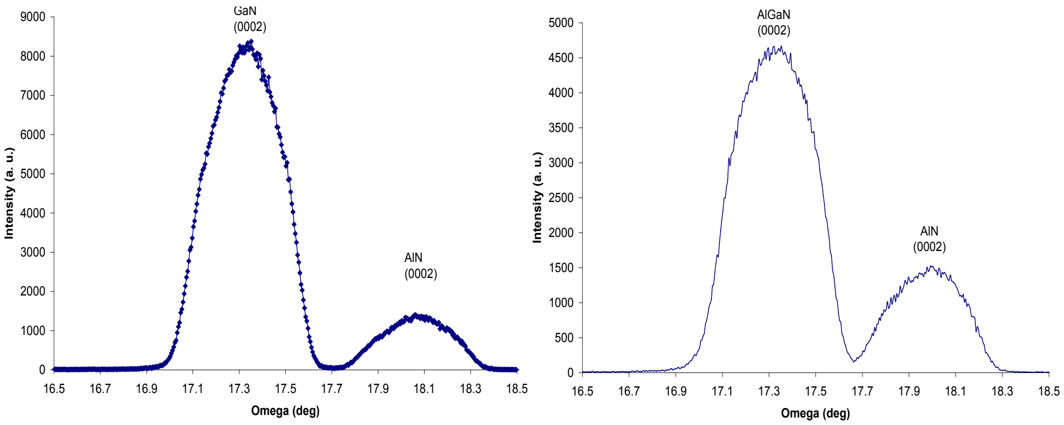


Fig. 1. Schematic diagram of the MSM structure.

3. Results and Discussion

In order to examine the quality of the films, ω/2θ scan of XRD rocking curves at (0002) plane were carried out. The corresponding (0002) rocking curves are shown in detail in Fig. 2. For GaN film (Fig. 2(a)), it can be seen that two intense and sharp peaks corresponding to GaN(0002) and AlN(0002) diffraction peaks are observed at 17.3° and 18.1° respectively. The FWHM of the rocking curve for the GaN (0002) peak of sample is 0.24° (14.40 arcmin). For $Al_{0.09}Ga_{0.91}N$ (Fig. 2(b)), it can be seen that intense and sharp peaks corresponding to $Al_{0.09}Ga_{0.91}N$ (0002) and AlN(0002) diffraction peaks are observed at 17.422° and 18.005° respectively. On the other hand, the FWHM of the rocking curve for the $Al_{0.09}Ga_{0.91}N$ (0002) and AlN(0002) diffraction peaks are 0.30° (18.00 arcmin).



(a) *(b)*

Fig. 2. ω/2θ scan of XRD rocking curves on Si(111) substrate: (a)GaN, (b)$Al_{0.09}Ga_{0.91}N$.

From the literature, the use of Si (111) substrate for growth of III-nitrides, particularly GaN, always produces relatively low crystal quality [10-13]. Rocking curve with high value of FWHM, i.e. from 20 to 70 arcmin were typically reported, this suggests that it is difficult to grow high quality GaN-based materials on Si (111) substrate. The growth of poor crystal quality of the GaN-based epilayers is mainly attributed to the large difference in lattice constant, crystal structure and thermal expansion coefficient between the Si and GaN-based materials. However, the control of the buffer layer thickness was very important, a thick buffer layer could not serve as smooth and planar template for the GaN layer, resulting in a rough surface.

PL spectroscopy is a good characterization tool to identify the appearance of defect-related levels (or defect induced luminescence) in the sample. Fig. 3 shows the room temperature PL spectrum of GaN/AlN/Si. From Fig. 3, a strong near band edge emission at 361.78 nm was observed which is attributed to the band edge emission of GaN. This value is comparable to those quoted by Oshinky *et al.* [14] and Zhang *et al.* [15]. We assign this intense band edge emission to the neutral-donor bound exciton (I_2). A strong near band edge emission of sample is at 340.47 nm which is attributed to the band edge emission of $Al_{0.09}Ga_{0.91}N$. The measurement resulted in an emission spectra with a peak intensity centered at 340.47 nm which correspond to a band gap value of ~3.642 eV. No yellow band emission is observed, this indicates that the film is of good optical quality.

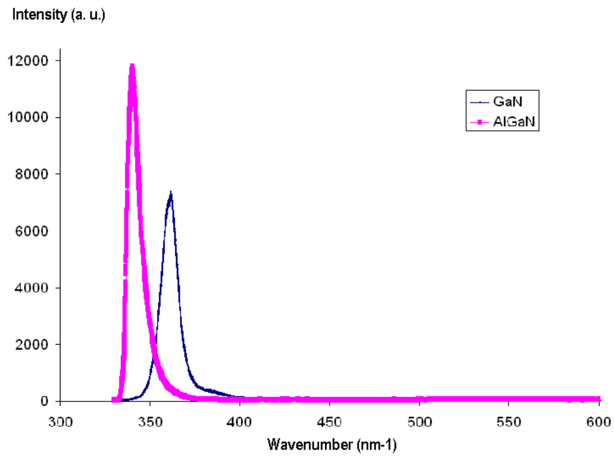


Fig. 3. Room temperature micro-PL spectrum of GaN and $Al_{0.09}Ga_{0.91}N$ on silicon.

The responsivity as a function of wavelength for an MSM GaN/Si(111) detector is shown in Fig. 4. For GaN film, there is a sharp cut-off wavelength at 362 nm. A maximum responsivity of 0.256 A/W was achieved at 358 nm. For $Al_{0.09}Ga_{0.91}N$ film, there is a sharp cut-off wavelength at 340 nm. A maximum responsivity of 0.263 A/W was achieved at 338 nm. In UV spectral region, the detector shows a little decrease from 340 to 200 nm. The responsivity of the MSM drops by nearly an order of magnitude across the cut-off wavelength.

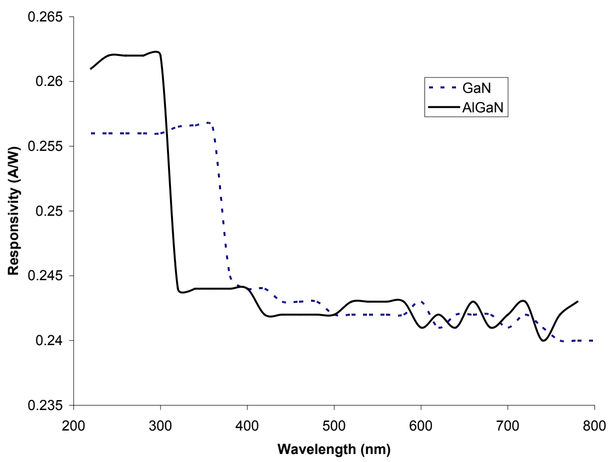


Fig. 4. The responsivity as a function of wavelength for an Metal-Semiconductor-Metal MSM GaN and $Al_{0.09}Ga_{0.91}N$ detector.

4. Conclusions

High quality GaN-based epilayers were grown on Si(111) by plasma-assisted MBE using AlN buffer layer. It is found that pre-seeding Al to Si surface is a critical condition for AlN growth on Si. The GaN-based films quality as determined by X-ray rocking curve, micro photoluminescence (PL), and micro-Raman spectroscopy. All the results verify the high quality of GaN-based on Si(111) substrate with AlN buffer layer. Metal-semiconductor-metal photodiode was fabricated on the GaN/Si(111) and $Al_{0.09}Ga_{0.91}N$/Si(111) film.

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