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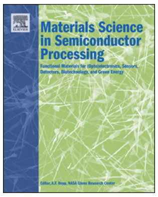

pn-Junction photodiode based on GaN grown on Si (111) by plasma-assisted molecular beam epitaxy

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ABSTRACT

The growth and characterization of pn-junction photodiode based on GaN grown on Si (111) by RF-plasma assisted molecular beam epitaxy (MBE) are described. The structural and optical properties of samples were studied by HR-XRD and Fourier FTIR spectroscopy, respectively. For IR reflectance analysis, GaN-like and AlN-like E_2 TO optical modes have been detected. By using the thermal evaporator, Ni/Ag and Al contacts were evaporated at the front and back of samples. The application of thermal annealing treatment in oxygen ambient has been shown to significantly reduce the dark current of GaN pn-junction photodiode. The electrical characteristics of all samples were conducted using Keithley's *I–V* measurement system. Under 460-nm wavelength, at bias voltages of 0.5, 1, and 2 V, the photocurrents rise and decay times were investigated.

1. Introduction

The wide-band gap GaN based semiconductor has become a basic material for new types of optoelectronic applications featuring high temperature, high power, and high frequency electronic devices [1,2]. Due to the huge market and economic profit, the material and device fabrication techniques of light emitting diodes (LEDs) and laser diodes (LDs) have been developed [3]. Due to the lack of bulk GaN substrate for the homoepitaxial growth, GaN-based materials are grown heteroepitaxially on SiC, sapphire and Si substrates [4]. Among them, Si has attracted much attention recently because of its acclaimed advantages such as low cost, large size (up to 12 in. diameter) and ease of availability [5]. Molecular beam epitaxy (MBE) and metalorganic chemical vapor deposition (MOCVD) have been demonstrated and reported to be two of the advanced growth techniques for fabricating III-nitrides compound semiconductors with high crystal quality for device applications. However, MBE offers a number of potential advantages over MOCVD for the growth of III-nitride materials, for instances, more efficient use of source materials, higher accuracy in controlling the epilayers, as well as no requirement for post-growth annealing for the activation of p-type dopant [6]. Ni/Ag ohmic contact has been used for this work. Nickel (Ni) was selected to form the interface between metal and semiconductor due to its ability to diffuse through (potential oxide contamination layer) between Ni and GaN thus producing good contact with GaN itself. The selection of silver (Ag) as capping layer over aluminum (Al) was motivated by the thermal stability of the metals. The melting point for Ag is at 962 °C while Al is at a very low temperature which is 660.4 °C. Therefore, samples with fabricated Ni/Ag contacts were able to be annealed up

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to 800 °C in order to investigate the electrical properties as well as the thermal stability of the contacts. In this paper we attempt to study the thermal annealing effects of Ni/Ag on GaN pn-junction photodiode by investigating the electrical characteristics after annealing in oxygen gas. The structural properties of the samples were investigated by using high resolution X-ray diffraction (HR-XRD). Fourier transform infra-red (FTIR) spectrometer (Spectrum GX FT-IR, Perkin-Elmer) was used to perform the IR reflectance measurement.

2. Experimental

The film growth has been performed in a Veeco Gen II MBE system, using standard effusion sources for evaporation of aluminum (6N5), and gallium (7N). Nitrogen with 7N purity was channeled to an RF source to generate reactive nitrogen species. The plasma was operated at typical nitrogen pressure of 2 μPa under a discharge power of 300 W. Prior to the growth of GaN pn-junction layer on 3-in. Si substrate, the Si substrate was first cleaned using the RCA method. The substrate was then mounted on the wafer holder and loaded into the MBE system. Then Si substrate was heated at 900 °C for the outgassing of the sample, and at 850 °C, a few monolayers of Ga were deposited on the substrate to remove the SiO_2 by formation of Ga_2O_3. Reflection high energy electron diffraction (RHEED) showed the typical Si (111) 7 × 7 surface reconstruction pattern with the presence of prominent Kikuchi lines, indicating a clean Si substrate. Before the growth of GaN pn-junction layer, a few monolayers of Al were also deposited on the Si substrate to avoid the formation of Si_xN_y which is deleterious for the subsequent epilayers. GaN pn-junction layer was grown by RF plasma-assisted molecular beam epitaxy (PA-MBE) on Si substrate. The buffer or wetting layer, AlN was first grown on the Si substrate. To grow AlN buffer layer, the substrate temperature was raised up to 870 °C, and both of the Al and N shutters were opened simultaneously for 15 min. Subsequently, n-GaN epilayer was grown on top of the buffer layer followed by p-GaN epilayer. Both pn-junction layers were grown for 45 min with substrate temperature set at 870 °C (see Fig. 1(a) and (b)). For GaN pn-junction layers, silicon and magnesium were used as n and p dopants, respectively. In order to make GaN pn-junction photodetector on silicon, ohmic contacts have been fabricated. Ohmic contacts were made by thermal evaporation of Ni/Ag and Al on p-GaN and silicon substrate, respectively. The visible light source and 460 nm LED were used as light sources for photo-current and photoresponse measurements, respectively. The optical properties studies were performed using FTIR spectroscopy. FTIR spectrometer (Spectrum GX FT-IR, Perkin-Elmer) with a potassium bromide (KBr) beam splitter is used to perform the polarized IR reflectance measurement. A wire grid zinc selenide (ZnSe) IR polarizer is used to obtain s- and p-polarization spectra, where the electric field vector (***E***) is perpendicular (***E***⊥C) and parallel (***E***||C) to the crystal axis. The vacuum furnace tube was used to investigate the effect of thermal annealing on Ni front contact for 10 min in ambient oxygen. The back contact Al was deposited after the completion of thermal treatment.

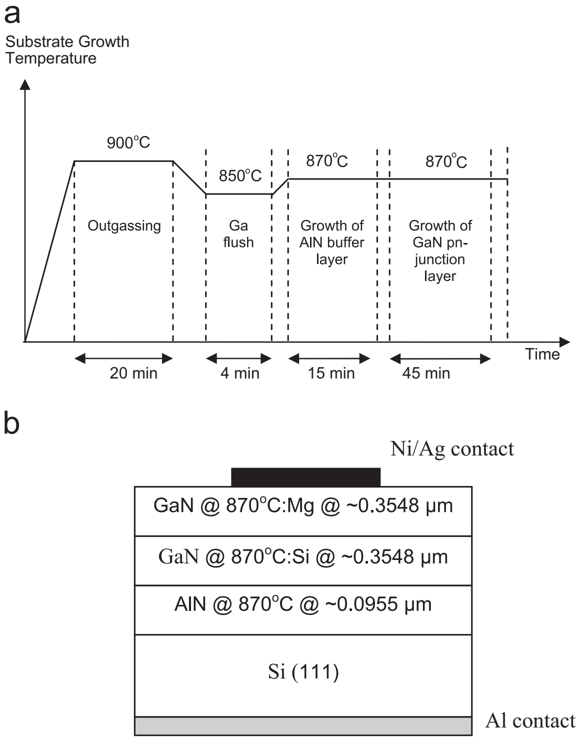

Fig. 1. Schematic presentation of GaN pn-junction/AlN/Si growth process.

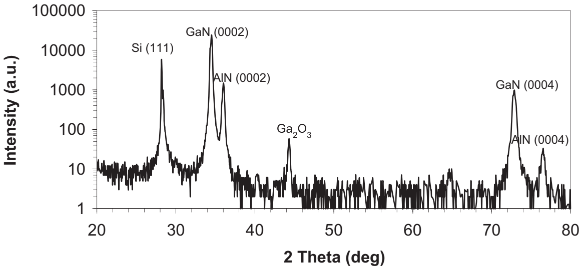

Fig. 2. XRD spectra of GaN pn-junctions on Si (111).

3. Results and discussion

The XRD measurement shows that the heterostructures of GaN pn-junction were epitaxially grown on silicon substrate (Fig. 2) [7]. It can be seen from the presence of the peak at 34.515° which is identified as wurtzite GaN (0002) diffraction, and other peaks at 36.028°, 44.325° [8], 72.846° and 76.503°, which correspond to AlN (0002), cubic Ga_2O_3, GaN (0004) and AlN (0004) respectively.

The peak at 28.245° is from the Si (111) substrate. X-ray diffraction peaks for GaN should be observed at around 32.3°, 34.6°, and 36.8° which correspond to (1010), (0002), and (1011) planes of the hexagonal crystalline GaN [9]. The XRD spectra indicate that there are no signs of cubic phase GaN found within the detection limit of the XRD, thus it can be confirmed that the samples possessed hexagonal structure. In addition, by applying Bragg's law, the lattice parameter c of the GaN and AlN are calculated as 5.193 and 4.982 Å, respectively. These values are in good agreement