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HRXRD and Raman study of irradiation effects in InGaN/GaN layers induced by 2.3 MeV Ne and 5.3 MeV Kr ions

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ABSTRACT

$In_{0.15}Ga_{0.85}N$/GaN bilayers irradiated with 2.3 MeV Ne and 5.3 MeV Kr ions at room temperature were studied by high-resolution X-ray diffraction (HRXRD) and micro-Raman scattering. The Ne ion fluences were in the range from 1×10^{12} to 1×10^{15} cm^{-2}, and the Kr ion fluences were in the range from 1×10^{11} to 1×10^{13} cm^{-2}. Results show that the structures of both $In_{0.15}Ga_{0.85}N$ and GaN layers remained almost unchanged for increasing fluences up to 1×10^{13} and 1×10^{12} cm^{-2} for Ne and Kr ion irradiations, respectively. After irradiation to higher fluences, the GaN layer was divided into several damaged layers with different extents of lattice expansion, while the $In_{0.15}Ga_{0.85}N$ layer exhibited homogenous lattice expansion. The layered structure of GaN and the different responses to irradiation of the GaN and $In_{0.15}Ga_{0.85}N$ layers are discussed.

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1. Introduction

Due to its band gap being continuously variable from 0.7 to 3.4 eV, InGaN is an attractive material for light-emitting and photovoltaic devices, such as light-emitting diodes (LEDs), laser diodes (LDs), and multi-junction solar cells [1,2]. In the past decade, there have been intense research efforts to determine the growth and the optical and electronic properties of InGaN and InGaN/GaN heterostructures.

Because outer space is one of the primary locations for applications of InGaN-based optoelectronic devices, there is also strong interest in the study of irradiation effects of InGaN alloys by high-energy particles in space. Like other Group-III-nitride materials, InGaN exhibits high irradiation hardness for energetic electrons, protons, He ions, neutrons, and γ-ray irradiation [2–5]. However, there is still very limited knowledge on the effects of ion irradiation in InGaN-based materials [6,7], especially concerning irradiation using heavy ions with energies on the order of MeV.

In this paper, HRXRD and Raman investigations of $In_{0.15}Ga_{0.85}N$/GaN layers irradiated with 2.3 MeV Ne and 5.3 MeV Kr ions, supplied by an ion accelerator at different fluences, are presented.

2. Experiment

The samples studied are $In_{0.15}Ga_{0.85}N$/GaN bilayers grown by metal-organic chemical vapor deposition (MOCVD). The layers were grown on the *c*-plane of sapphire (Al_2O_3) by first growing a 150 nm-thick GaN buffer layer. Second, a 1.5 μm-thick Si-doped GaN layer was grown, followed by a 150 nm-thick Mg-doped $In_{0.15}Ga_{0.85}N$ film. The Mg- and Si-doping levels of $In_{0.15}Ga_{0.85}N$ and GaN films were 5×10^{17} and 1×10^{18} cm^{-3}, respectively.

These samples were irradiated with heavy ions supplied by the ECR (electron cyclotron resonance) ion source high-voltage platform at the Institute of Modern Physics (IMP) in Lanzhou. The irradiations were performed at room temperature under normal incidence with respect to the sample surface. A set of samples was irradiated with 2.3 MeV Ne^{8+} ions to fluences of 10^{12} and 10^{13} cm^{-2} at a beam flux of 1.7×10^{11} cm^{-2} s^{-1} and to fluences of 10^{14} and 10^{15} cm^{-2} at a beam flux of 2.9×10^{11} cm^{-2} s^{-1}. Another set of samples was irradiated with 5.3 MeV Kr^{23+} ions to fluences of 10^{11}, 10^{12}, and 10^{13} cm^{-2} at a beam flux of 1.0×10^{11} cm^{-2} s^{-1}. The homogeneity of the irradiation was granted by a 2×2 cm^2 raster beam scan in the irradiation terminal.

HRXRD employing a triple-crystal diffractometer (Bruker D8) was used to perform exact ω–2θ scans at the $In_{0.15}Ga_{0.85}N$/GaN (0 0 0 2) pole. Using the 532 nm line of a diode-pumped solid-state laser as excitation source, the Raman measurements were carried out at room temperature on a Horiba Jobin–Yvon HR 800 UV micro-Raman system. The Raman spectra were detected in backscattering geometry with the *z* direction parallel to the *c*-axis of the $In_{0.15}Ga_{0.85}N$/GaN layers and recorded by a liquid nitrogen-cooled, charge-coupled-device (CCD) detector. The laser beam was focused onto a spot with a diameter of approximately 1 μm at the sample surface using a microscope system. The resolution of the Raman spectra was better than 1 cm^{-1}.

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3. Results and discussion

Fig. 1 shows the ion ranges, damage distributions in terms of displacement per atom (dpa), and electronic and nuclear energy losses of ions in the samples irradiated by (a) 2.3 MeV Ne ions to a fluence of 1×10^{15} cm^{-2} and (b) 5.3 MeV Kr ions to a fluence of 1×10^{13} cm^{-2}. These results were obtained using TRIM 2008 full-cascade simulations under the assumptions of a sample density of 6.25 g/cm^3 for $In_{0.15}Ga_{0.85}N$, which was given by the composition-weighted average of GaN and InN densities, and 6.15 g/cm^3 for GaN. A threshold displacement energy of 25 eV was assumed for all atoms in $In_{0.15}Ga_{0.85}N$ and GaN. As indicated in Fig. 1, both Ne and Kr ions located in the samples show concentration maxima at a depth of 1.75 μm. The maximum Ne and Kr ion concentrations are less than 0.03 at.% and 2×10^{-4} at.%, respectively, so the effect of impurity atoms on the structures of irradiated samples is negligible. Under each irradiation condition, the electronic energy loss is several times to several tens of times larger than the nuclear energy loss at the beginning of the ion range. With increasing depth along the ion range, the electronic energy loss decreases, while the nuclear energy loss and the lattice damage due to elastic collisions increase and reach a maximum at the end of the ion range. In fact, due to possible ion-channeling effects induced by normal incidence and an overestimation of the electronic stopping power in the TRIM simulation [8], the peaks of the ion range curve, and the damage distribution in Fig. 1 should be closer to or at the interface of GaN/Al_2O_3.

Fig. 2a illustrates the HRXRD spectra of $In_{0.15}Ga_{0.85}N$/GaN samples before and after Ne ion irradiation at different fluences at room temperature. Well separated $In_{0.15}Ga_{0.85}N$ and GaN (0 0 0 2) peaks are observed. The intensity maximum of the peaks in the spectra is normalized to the GaN (0 0 0 2) peaks. Both the $In_{0.15}Ga_{0.85}N$ and GaN diffraction peaks stay almost unchanged with increasing fluence up to 1×10^{13} cm^{-2}. At a fluence of 1×10^{14} cm^{-2}, the $In_{0.15}Ga_{0.85}N$ peak shifts from $2\theta = 33.96°$ to 33.91°, while the GaN peak is split into three peaks.

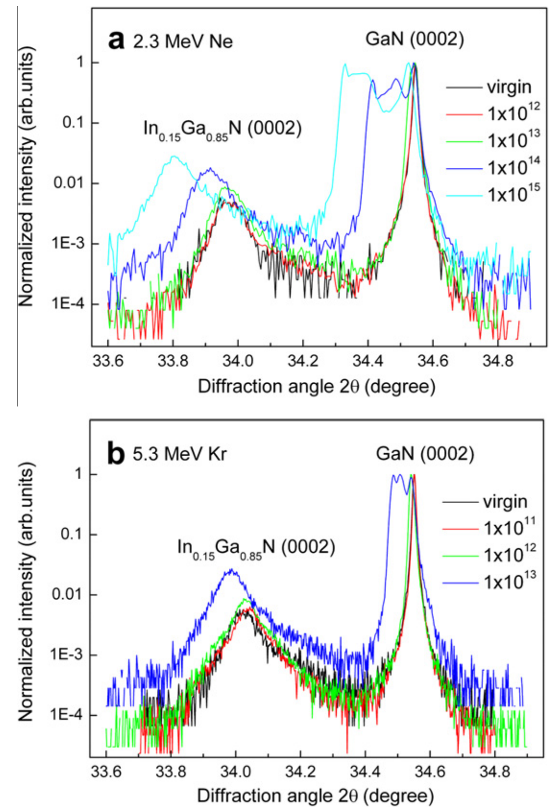

Fig. 2. Normalized HRXRD spectra of $In_{0.15}Ga_{0.85}N$/GaN samples before and after (a) Ne ion and (b) Kr ion irradiation to different fluences at room temperature.

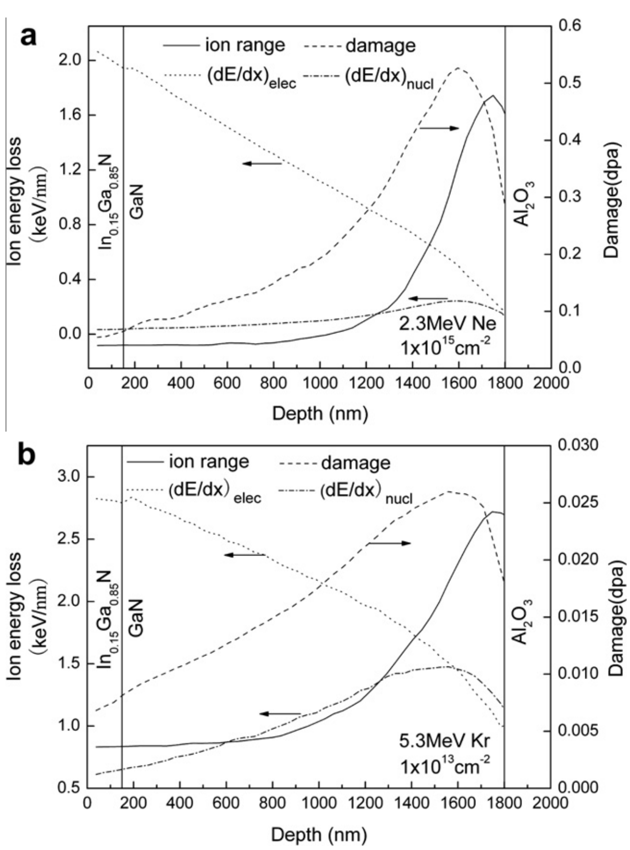

Fig. 1. TRIM results of the samples irradiated with (a) 2.3 MeV Ne ions to a fluence of 1×10^{15} cm^{-2} and (b) 5.3 MeV Kr ions to a fluence of 1×10^{13} cm^{-2}. $(dE/dx)_{elec}$ denotes the electronic energy loss. $(dE/dx)_{nucl}$ denotes the nuclear energy loss.

Previous studies have indicated that a layered structure is produced by ion irradiation in GaN [9–11]. In addition to a bulk-damaged layer in the region of the maximum of nuclear energy deposition, a surface-damaged layer is formed due to the strong sink for mobile point defects at the surface [9,10]. In different damaged layers, the extents of lattice expansion depending on the accumulations of irradiation defects (e.g., N_2 gas bubbles and stacking faults or dislocation loops) are different, leading to the splitting of the GaN diffraction peak. In our case, due to the larger ion ranges, the efficiency of the GaN surface to trap mobile point defects should be reduced. Alternatively, the large electronic energy deposition in the front of the GaN layer may be the main reason for the production of the surface-damaged layer. It is assumed that the split peaks at $2\theta = 34.41°$ and 33.49° correspond to the GaN surface- and bulk-damaged layers, respectively, as discussed in detail below. The split peak at $2\theta = 34.54°$ coincides with the virgin GaN (0 0 0 2) peak, therefore, it should originate from the region between the GaN surface- and bulk-damaged layer, which was damaged less during irradiation.

In contrast to the GaN peak, no splitting is found in the $In_{0.15}Ga_{0.85}N$ diffraction peak. This finding can be explained as follows. Because the thickness of the $In_{0.15}Ga_{0.85}N$ epilayer is much less than the projective range of the 2.3 MeV Ne ions (Fig. 1a), especially considering possible ion-channeling effects induced by normal incidence, the irradiation resulted in an almost homogenous damage distribution in the $In_{0.15}Ga_{0.85}N$ layer. In consequence, the lattice change was homogenous throughout the entire $In_{0.15}Ga_{0.85}N$ layer.

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