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Lattice disorder produced in GaN by He-ion implantation

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ABSTRACT

The lattice disorders induced by He-ion implantation in GaN epitaxial films to fluences of 2×10^{16}, 5×10^{16} and $1 \times 10^{17}\ \mathrm{cm}^{-2}$ at room temperature (RT) have been investigated by a combination of Raman spectroscopy, high-resolution X-ray diffraction (HRXRD), nano-indentation, and transmission electron microscopy (TEM). The experimental results present that Raman intensity decreases with increasing fluence. Raman frequency “red shift” occurs after He-ion implantation. Strain increases with increasing fluence. The hardness of the highly damaged layer increases monotonically with increasing fluence. Microstructural results demonstrate that the width of the damage band and the number density of observed dislocation loops increases with increasing fluence. High-resolution TEM images exhibit that He-ion implantation lead to the formation of planar defects and most of the lattice defects are of interstitial-type basal loops. The relationships of Raman intensity, lattice strain, swelling and hardness with He-implantation-induced lattice disorders are discussed.

1. Introduction

Because of excellent electronic and optical properties, GaN has been used in the laser diodes, microwave, and ultrahigh power switches applications [1]. Due to an attractive process for selective region doping of semiconductor devices, ion implantation has widely been applied to GaN fabrication processing [2]. However, ion implantation introduces extensive damage that can degrade the performance, properties as well as lifetimes of the devices. Thus, it is very important to understand the ion-beam damage processes in the fabrication of GaN-based devices. The effects of ion implantation into GaN have been extensively investigated [3,4]. A typical feature is that implantation led to the formation of planar defects parallel to the basal plane [5–8]. Bruel firstly put forward the ‘smart cut’ technology, which has been widely used for fabrication of silicon-on insulator materials [9]. Tauzin et al. used the light ions (H,He) as for the transfer of thin GaN films by means the ‘smart cut’ technology [10]. Understand the relationship between lattice disorder and implantation fluence is very important for the application of the ‘smart cut’ technology on the GaN materials. Until now the dependence of the He-ion implantation-induced lattice disorder on implantation fluence has been less investigated [11,12]. In the present work, we have investigated the He-ion implantation-induced defects as a function of the implantation fluence.

2. Experimental process

The 30 μm thick *n*-type wurtzite GaN layers used in the experiment were grown on a sapphire (0001) substrate by metal organic chemical vapor deposition (MOCVD) technique. The samples were implanted with He^{+} ions with a kinetic energy of 230 keV to fluences of 2×10^{16}, 5×10^{16} and $1 \times 10^{17}\ \mathrm{cm}^{-2}$ with a ion flux of $10^{13}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ at RT in a chamber with a vacuum at 10^{-5} mbar in the ECR-320 kV High-voltage Platform in the Institute of Modern Physics, Chinese Academy of Sciences. The irradiations were carried out under normal incidence with respect to the sample surface. The depth profiles of displacement per atom (dpa) and He concentration are simulated via the Monte-Carlo code Stopping and Range of Ions in Matter (SRIM2008) using the density of GaN of 6.15 g/cm^3 and a threshold displacement energy of 25 eV for both

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the Ga and N [13]. The result is shown in Fig. 1. The projected range R_p is approximately 763 nm with a straggling ΔR_p of 137 nm.

The Raman spectrometry was performed at RT with a JY-HR800 spectrometer by using the 514.5 nm line of the Ar^+ laser as the excitation source. With an optical absorption coefficient $\alpha = 100\ cm^{-1}$ of GaN at the laser wavelength, the Raman probing depth $d = 1/2\alpha$ is equal to 50 μm [14]. The Raman spectra were detected in backscattering geometry with the z direction parallel to the c-axis of the GaN layers. The resolution of the Raman spectra was better than $0.5\ cm^{-1}$. HRXRD measurements were carried out in the Bragg geometry on a four-circle diffractometer with the pure Cu $K\alpha_1$ line using a Bruker D8 Discovery instrument at RT. A ω-2θ scanning mode was used near the (0002) Bragg reflection plane with a resolution of 0.001°. Nano-indentation experiments were carried at RT with a nanohardness tester with a diamond Berkovich indenter (triangular based pyramid) in CSM mode. Cross-sectional transmission electron microscope (XTEM) images were performed using a Tecnai G20 microscope equipped with a double tilt goniometer stage at 200 kV to study the lattice disorder induced by He-ion implantation. The XTEM samples of the GaN by He-ion implantation were prepared for TEM analysis by mechanical thinning followed by Ar ion-beam thinning. The observed images of He-ion implantation-induced stacking faults and dislocation loops were taken from cross sections of GaN along a [1–10] zone axis. Using the two-beam bright-filed mode and dark-field mode with the image condition: $(g, 3g)$, $g = 0002$ near $z = 11–20$ to examine the damaged layer.

3. Results and discussion

3.1. Raman scattering

The Raman spectra of the GaN samples before and after implanted by 230 keV He^+ to fluences of 2×10^{16}, 5×10^{16} and $1 \times 10^{17}\ cm^{-2}$ are illustrated in Fig. 2. The virgin GaN normally crystallizes in hexagonal wurtzite structure, which exhibits three peaks at 144, 570 and $736\ cm^{-1}$. The 144, 570 and $736\ cm^{-1}$ assigned to E_2 (low), E_2 (high) and A_1 (LO), respectively, are observed as expected from the Raman selection rules in semiconductors with wurtzite crystal structure [15]. Because the penetration depth is over the thickness of the film, the sapphire substrate signal corresponding to $418\ cm^{-1}$ can be observed in the virgin sample. It is worth noting that the background intensity increased after He-ion implantation due to the Rayleigh scattering from the defects induced by He-ion implantation [16]. The inset in Fig. 1 depicts magnified portion of the spectrum around the E_2 (high). From the Fig. 1 we can see that Raman frequency of the E_2 (high) decreased with increasing fluence, which can be attributed to implantation-induced lattice disorder [17] and lattice strain [16,18]. In addition, the intensities of Raman scattering decreased due to the increase of optical absorption induced by He-ion implantation produced defects [16]. We recently used UV–visible transmittance spectroscopy to detect the absorption coefficient change in H-implanted GaN, and the absorption coefficient increases to approximately $2.5 \times 10^4\ cm^{-1}$after H-implanted GaN to 0.5 dpa [16]. Therefore, it is reasonable to regard that the penetration depth of the laser is less than the projected range of He ions. After He implantation, the Raman signal originates from the implanted layer. For the Raman spectra of the virgin GaN, the E_2 (high) mode is affected by biaxial stress. The biaxial strain, which coexists with hydrostatic strain induced by the defects, can cause an additional shift of the E_2 (high) peak. The E_2 (high) peak moved to the direction of low frequency, which demonstrates the tensile stress formed in the damaged layer of GaN after He-ion implantation, resulting in the lattice swelling. The lattice expansion has been observed in Ar [18] and O implanted GaN [19]. Note that E_2 (low), E_2 (high) and A_1 (LO) can be still observed for $1 \times 10^{17}\ cm^{-2}$ implantation, which demonstrates the maintenance of characteristics of the hexagonal crystal phase GaN after He-ion implantation. No amorphous layer was detected in the damaged layer. In addition, after implantation the Raman scattering modes induced three additional peaks located at 300, 420 and $670\ cm^{-1}$, which were observed after implanting H_2^+, O^+, Ar^+ and Xe^+ into GaN [16,20]. Some researchers regarded a broad peak at $300\ cm^{-1}$ can be attributed to the disorder-activated Raman scattering modes (DARS) [20]. On the other hand the structures around 420 and $670\ cm^{-1}$ are due to scattering from vacancy-type defects probably in the N sublattice [21].

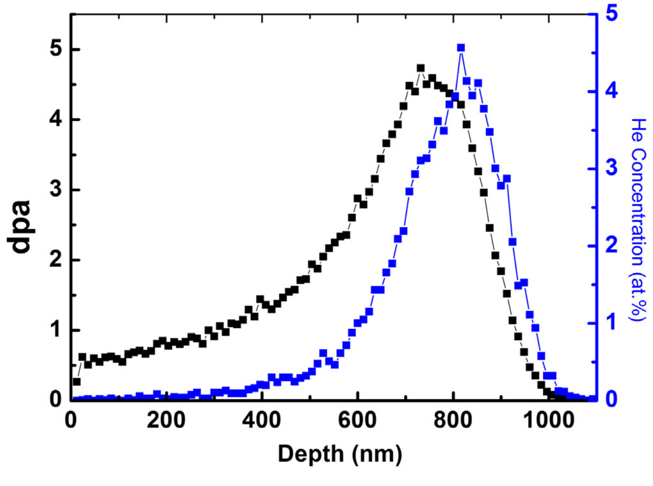

Fig. 1. Depth distribution of displacement damage (in dpa) and He concentration in GaN implanted with 230 keV He^+ ions to a fluence of $1 \times 10^{17}\ cm^{-2}$, according to SRIM-2008 simulations.

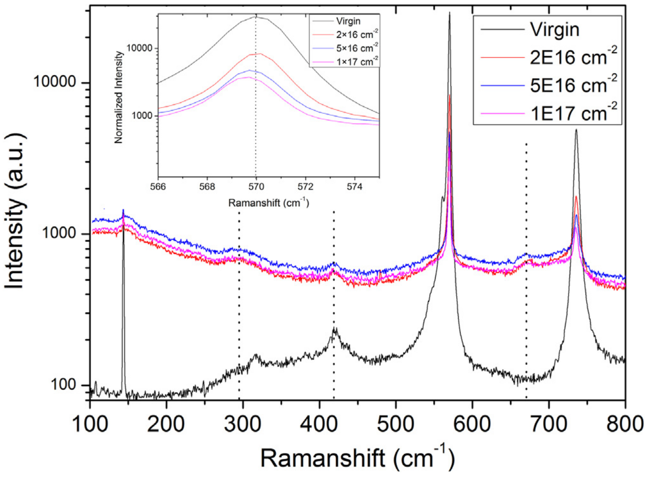

Fig. 2. Raman spectra of the GaN samples before and after the implantation with He^+ ions. The inset depicts magnified portion of the spectrum around the E_2 (high) peak.

3.2. High-resolution X-ray diffraction

Fig. 3 shows the HRXRD spectra of virgin GaN and implanted GaN with fluences of 2×10^{16}, 5×10^{16} and $1 \times 10^{17}\ cm^{-2}$ at RT. One remarkable characteristic is the strongest intensity of the peak at the $2\theta = 34.53°$ for virgin sample, which is the GaN (0002) peak. The tail of scattered intensity shifted toward the low angle side of

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