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Short communication

Structural, morphological and magnetic characteristics of Tb-implanted GaN and AlGaN films

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ABSTRACT

Diluted-magnetic GaN:Tb and AlGaN:Tb films have been fabricated by implanting Tb^+ ions into c-plane (0 0 0 1) GaN and AlGaN films and a subsequent annealing process. The structural, morphological and magnetic characteristics of the samples have been investigated by means of X-ray diffraction (XRD), atomic force microscopy (AFM) and superconducting quantum interference device (SQUID), respectively. The XRD and AFM analyses show that the annealing process can effectively recover the crystalline degradation caused by implantation. According to the SQUID analysis, both the GaN:Tb and the AlGaN:Tb films exhibit clear room-temperature ferromagnetism. It is very interesting to find the saturation magnetization value of the AlGaN:Tb sample is almost two times that of GaN:Tb sample. The possible origin of the ferromagnetism of the samples was discussed briefly.

1. Introduction

GaN and AlGaN films, doped with rare-earth metals (RE), have widely potential applications in optical communications, optoelectronics, and flat panel displays due to their capability of emitting light with narrow linewidth ranging from infrared (IR) to ultraviolet (UV) [1–7]. Tb-doped GaN and AlGaN films have attracted extensive attention due to their capability of yielding light emission at visible wavelengths, especially due to its capability of emitting green light [8–11]. However, almost all the reports about GaN:Tb and AlGaN:Tb films just focus on their optical characteristics, while their magnetic properties are rarely mentioned. To the best our knowledge, Bang et al. [12] reported the paramagnetic property of Tb-doped GaN films prepared by molecular beam epitaxy (MBE) on sapphire substrate, and the magnetic property of Tb-doped AlGaN films has not been reported yet. The magnetic property of GaN:Tb and AlGaN:Tb films are very important because diluted magnetic semiconductors (DMSs) are good candidate materials for new generations of high speed, low dissipation, and nonvolatile magneto-electrical and magneto-optical devices. Moreover, high electron mobility transistors (HEMT) based on GaN/AlGaN heterostructures have a large potential application in the high frequency, high temperature and large power areas [13,14]. If GaN:Tb and AlGaN:Tb films can exhibit room temperature ferromagnetism, it is very possible to integrate magnetic, electrical and optical functionalities on a single chip, which is the foundation for the future spintronic devices. However, until now, the magnetic property of GaN:Tb and AlGaN:Tb films is still unclear. Therefore, in this paper, the structural, morphological and magnetic properties of GaN:Tb and AlGaN:Tb films have been studied in detail.

2. Experiment

Unintentionally doped GaN and AlGaN (with Al fraction of about 50%) films were grown by low-pressure metal organic chemical vapor deposition (MOCVD) on c-plane sapphire substrates. The thickness of the GaN and AlGaN films is about 2.0 μm and 1.0 μm, respectively (as-grown sample). The Tb^+ ions were implanted into the GaN and AlGaN films by dual energy ion implantation method (500 keV: 3×10^{15} cm^{-2} + 250 keV: 1.5×10^{15} cm^{-2}) at 400 °C (implanted sample). The Tb^+ ion beam was oriented 7° off perpendicular to the surface of the sample to prevent channeling. A subsequent annealing process was carried out at 800 °C for 5 min under the protection of flowing N_2 (annealed sample). All the samples have the same size of 6×6 mm^2. The distribution range of the Tb ions is about 150 nm and the average concentration is 5.0×10^{20}/cm^3, based on SRIM 2008 simulations [15].

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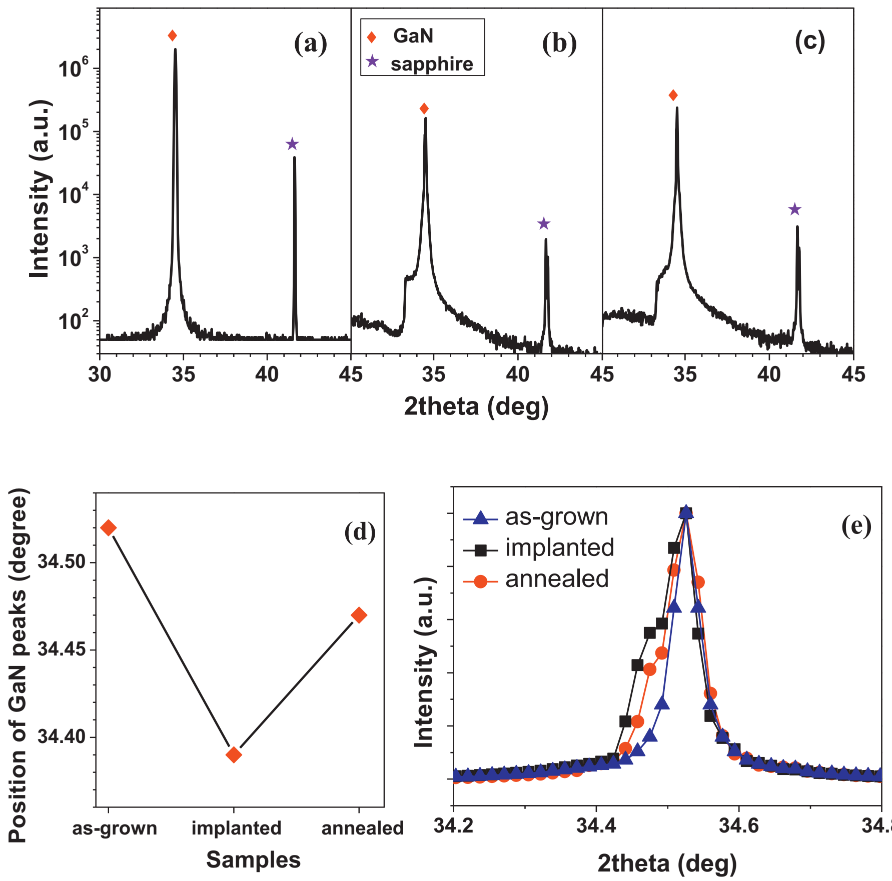

Fig. 1. Logarithmic scale XRD patterns of the (a) as-grown, (b) implanted and (c) annealed GaN:Tb samples. (d) The position of GaN(0 0 0 2) peaks for the as-grown, implanted and annealed GaN:Tb samples. (e) The zoomed view of the (0 0 0 2) peak of the samples.

The structure of the samples was studied by means of X-ray diffractometry (XRD, X'Pert Pro MPD). The morphological characteristic was investigated by using atomic force microscopy (AFM, Bruker Multimode 8). The magnetization measurement was carried out by employing the superconducting quantum interference device magnetometer (SQUID, MPMS XL-7). To preclude the influence of any contamination on the magnetic measurements by SQUID, all the samples have been cleaned carefully, avoiding possible contact with any metal materials, to ensure that the magnetic signal come from the samples. The Hall measurements revealed that all the samples are high resistance films.

3. Results and discussion

3.1. XRD analysis

The logarithmic scale XRD patterns of the as-grown, implanted and annealed GaN:Tb samples are shown in Fig. 1(a–c), respectively. As shown in Fig. 1(a), the as-grown sample exhibits diffraction peaks at about $2\theta = 34.52^\circ$ and $2\theta = 41.66^\circ$, corresponding to the GaN(0 0 0 2) and sapphire(0 0 0 6) crystal plane of the wurtzite structure, respectively. As shown in Fig. 1(b and c), the implanted and the annealed samples showed diffraction peaks similar to the as-grown sample, revealing that the wurtzite structure was retained after ion implantation and annealing process. No secondary phase and metal-related peak can be detected within the sensitivity of XRD measurement under the same experimental conditions. Compared with the as-grown sample, the GaN(0 0 0 2) peaks of the implanted and the annealed samples are much weaker due to the crystalline degradation during the ion implantation process. Because the intensity of the X-ray diffraction peak is closely related with the crystalline quality of the film, the higher crystalline quality of the film facilitates the greater the intensity of the diffraction peak. The GaN(0 0 0 2) peak of the annealed sample is stronger than that of the implanted sample, indicating that the annealing process can effectively recover the crystalline degradation introduced by implantation.

Fig. 1(d) shows the position of GaN(0 0 0 2) peaks for the as-grown, implanted and annealed samples. Compared with the as-grown sample, the peak position of the implanted sample is shifted to a lower angle, indicating the increment of the lattice parameters. This can be attributed to the impact of the interstitial Tb ions and Frankel defects after implantation. However, the peak position of the annealed sample shifts to the higher angle side compared with that of the implanted sample. This may be resulted from the substitution of Tb^+ into Ga^{3+} sites and the disappearance of Frankel defects during the annealing process [16]. The peak difference between the as-grown and the annealed sample is 0.05 degree, suggesting a slight crystal lattice expansion of GaN film after the implantation and annealing process due to the fact that the radius of Tb^+ ion is much larger than Ga^{3+} ion. This can be verified from the evolution of the (0 0 0 2) peak shown in Fig. 1(e). With regard to the AlGaN:Tb samples, the variation of the intensity and the position of the AlGaN(0 0 0 2) peak, before and after ion implantation and annealing, is similar to that of the GaN:Tb samples, shown in Fig. 2.

3.2. AFM analysis

The surface morphological characteristic of semiconductor film is very important for the device applications. Using AFM images,