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Journal of Magnetism and Magnetic Materials 316 (2007) e199–e202
www.elsevier.com/locate/jmmm

Magnetic and structural properties of Fe ion-implanted GaN

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Available online 27 April 2007

Abstract

The magnetic and structural properties of Fe ion-implanted GaN was investigated by various measurements. XRD results did not show any peaks associated with second phase formation. The magnetization curve at 5 K showed ferromagnetic behavior for 900 °C-annealed sample. In zero-field-cooled (ZFC) and field-cooled (FC) magnetization measurements, the irreversibility and a cusp-like behavior of the ZFC curve were observed for 900 °C-annealed sample. These behaviors are typically observed in superparamagnetic or spin glass phase. While the temperature dependence magnetization of 800 °C-annealed sample showed non-Brillouin-like curve and it is not exhibited ferromagnetic hysteresis at 5 K. In XPS measurement, the coexistence of metallic Fe (Fe^0) and Fe–N bond (Fe^{2+} and Fe^{3+}) for Fe 2p core level spectra is observed in as-implanted sample. But 700–900 °C-annealed samples showed only Fe–N bond (Fe^{2+} and Fe^{3+}) spectra. For Ga 3d core level spectra only Ga–N bonds showed for as implanted with 700–900 °C-annealed samples. From XPS results, it could be explained that magnetic property of our films originated from FeN structures.

PACS: 75.50.Pp; 75.70.Ak

Keywords: Ion implantation; Magnetic semiconductor

1. Introduction

In recent years, III–V diluted magnetic semiconductors (DMSs) have attracted much attention as materials for application in spintronic devices [1,2]. In the area of DMS related to III–V compound semiconductors, wide bandgap semiconductor GaN have very recently received great interest as promising host material for making DMS, since its Curie temperature (T_c) higher than room temperature is predicted by theoretical studies [3]. Although Mn-doped GaN is the most intensively investigated depending on the theoretical studies, the GaN system doped with other transition elements such as Fe, Co, and Ni may also offer suitable properties. GaN-based DMSs materials can be fabricated by molecular beam epitaxy (MBE) or ion implantation. Akinaga et al. [4] reported ferromagnetic properties at <100 K in Fe-doped GaN grown by low-temperature MBE. Also Theodoropoulou et al. [5,6] reported ferromagnetic properties of Fe and Ni ion implanted *p*-GaN. The 3 at% Fe ion implanted *p*-GaN sample with 700 °C post-annealing showed apparent ferromagnetic behavior up to ~250 K and the ferromagnetic behavior of 3 at% Ni ion implanted *p*-GaN sample is observed to persist up to 200 K. Meanwhile, the magnetic property of Co ion-implanted GaN samples showed a ferromagnetic-like ordering up to 320 K or superparamagnetism [7,8]. Ion implantation provides an alternative way to investigate the nature and the origin of ferromagnetism for DMS materials [9].

In this study, we report on magnetic and structural properties of Fe ion-implanted GaN with as a function of annealing temperature.

2. Experimental

We prepared 2 μm thick undoped GaN epilayer grown on Al_2O_3 substrate by metal-organic chemical vapor

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doi:10.1016/j.jmmm.2007.04.025

deposition (MOCVD), and 80 KeV Fe^{-} ions with a dose of $3\times10^{16}\,cm^{-2}$ were implanted into GaN at 350 °C. The implanted samples were post-annealed at 700–900 °C by rapid thermal annealing (RTA) in N_2 atmosphere for 5 min to recrystallize the samples and to remove implantation damage. The crystalline structure was investigated by high-resolution X-ray diffraction (HRXRD) with Cu K_α radiation. Magnetization measurements were carried out using a superconducting quantum interference device (SQUID) magnetometer system. In all the magnetization measurements, the magnetic field was applied parallel to the sample plane. In order to extract information regarding chemical states of the elements, X-ray photoelectron spectroscopy (XPS) were used with Mg K_α radiation source ($h\nu = 1253.6$ eV). The charge shifted spectra were corrected using the adventitious C 1 s photoelectron signal at 285 eV.

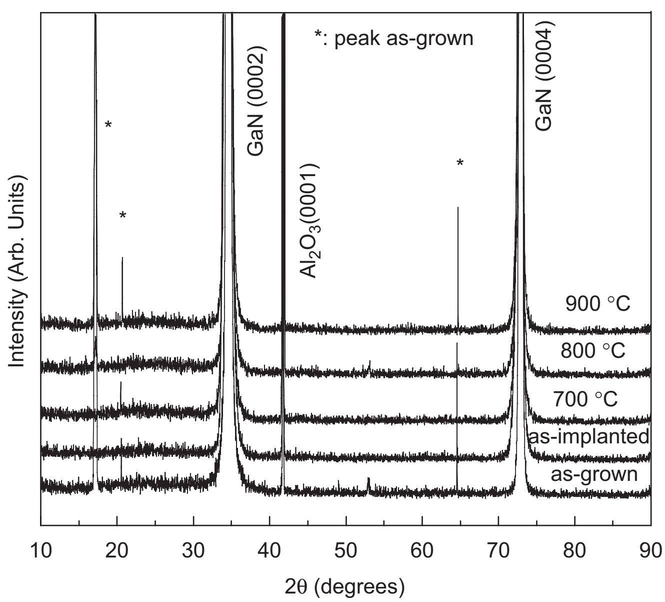

Fig. 1. XRD profile for Fe ion-implanted GaN at various annealing temperatures.

3. Results and discussion

Fig. 1 shows the XRD profiles of Fe ion-implanted GaN with various annealing temperatures. In the as-grown sample, three main peaks correspond to the expected diffraction from the GaN epilayer and sapphire substrate structure. We examined the possibility of Fe cluster or the reaction between Fe and GaN formed during the implantation and post-annealing process. Compared to the as-grown sample, no second phase was observed in the as-implanted and 700–900 °C-annealed samples. The diffraction pattern reveals only the presence of peaks corresponding to GaN layer and substrate structure. Though XRD measurements showed the absence of impurity phases as Fe clusters, Fe–Ga alloys or Fe–N compound, we do not exclude the possibility of the presence of Fe, Fe–Ga or Fe–N nanoscale precipitates, which cannot be measured by XRD for its insensitivity on nanoscale [10–12]. The magnetization behavior of the implanted samples was investigated with SQUID magnetometer. The magnetization curves were obtained with the samples annealed at 800 and 900 °C. In these curves, the diamagnetic background of GaN substrate was subtracted. Fig. 2(a) shows magnetization loops at 5 and 300 K for samples annealed at 800 and 900 °C. The magnetization

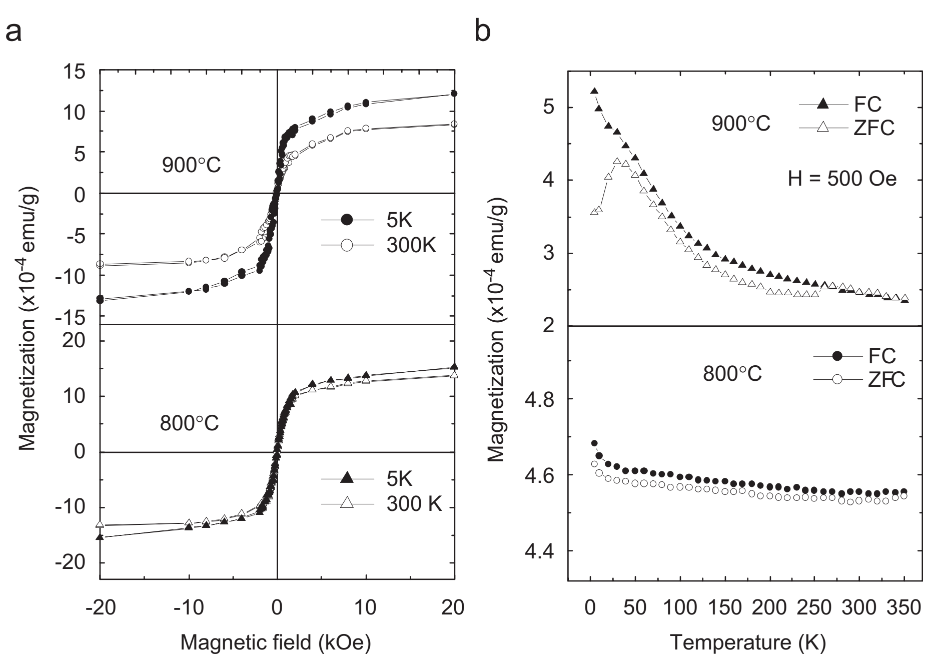

Fig. 2. (a) Magnetization loops at 5 and 300 K for samples annealed at 800 and 900 °C of Fe ion-implanted GaN and (b) the temperature dependence of FC and ZFC magnetization for samples annealed at 800 and 900 °C.