Control of Ferromagnetic Behavior in TM/RE-doped GaN Thin Films

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1. Introduction

Considerable research effort has been placed in doping of III-N semiconductor materials with transition metal (TM) or rare earth (RE) elements to produced special optical or magnetics properties. Strong, room temperature (RT) photo-and electro-luminescence has been observed from RE-doped III-N thin films at visible, infrared, and ultraviolet wavelengths. [1,2]. Based on theoretical predictions, TM-doped GaN thin films have displayed ferromagnetic (FM) behavior at RT [3]. In addition, similar FM behavior at RT has been observed in RE-doped GaN thin films [4,5]. While the optical results, including electrical injection to produce light emission, are well established, reports of FM behavior in such samples are the source of controversy. Furthermore, in order to produce realistic spin-based devices, control of FM behavior needs to be demonstrated. In this talk, experimental results will be presented on electrical control of FM in Mn-doped GaN thin film structures as well as strain enhancement of FM effects in RE-doped GaN thin films.

2. Experimental Results

2a. Electric field control of the FM

We have grown *i*-GaMnN/*p*-GaN/*n*-GaN (*i*-*p*-*n*) multilayer structures and altered the carrier depletion in the *p*-*n* junction by an applied voltage bias which changed the hole concentration in the *p*-region, thus leading to control of the FM of the GaMnN film [6]. The GaMnN film, with a thickness of 0.5 µm, was grown on a *p*-GaN/*n*-GaN/ GaN/sapphire stack using metal-organic chemical-vapor deposition (MOCVD). To enhance the hole concentration, the *p*-type region was grown as Mg-doped $Al_{0.2}Ga_{0.8}N$/GaN superlattice with a period of ~ 16.6 nm. The Mn dopant concentration was on the order of 10^{20} cm^{-3} as determined by secondary ion mass spectrometry measurements. An alternating gradient magnetometer (AGM) was used for magnetic characterization. The GaMnN *i*-*p*-*n* structures with different *p*-GaN layer thickness (X_p) were fabricated using photolithography and inductively coupled plasma dry etching. The size of each *i*-*p*-*n* device was about 2x2 mm^2. Rectifying contacts were deposited on the *p*-GaN and *n*-GaN layers. Several GaMnN *i*-*p*-*n* structures with different *p*-GaN thicknesses were grown. A strong dependence of the GaMnN film FM on X_p was observed. The GaMnN film grown on sapphire substrate without the *p*-GaN layer was paramagnetic (PM). By applying voltage to the GaN *p*-*n* junction it was possible to control the FM behavior of the structure. Figure 1 shows the saturation magnetization (*Ms*) of a typical *i*-*p*-*n* device at different reverse bias voltages (V_R) for X_p=0.25 µm. The inset shows the associated hysteresis curves at different values of V_R. For V_R<3 V, the M_s is unchanged. The depletion width at V_R~3 V is about 0.221 µm leaving unaltered ~30 nm of *p*-GaN close to GaMnN/*p*-GaN interface. The penetration depth for the hole wave function into the *i*-GaMnN layer is believed to be less than 30 nm, which explains the constant value of M_s. For V_R ~ 4 V, M_s begins to decrease. For V_R~5 V the *p*-layer is fully depleted and the GaMnN film is nearly PM. Thus, as V_R increases, the depletion width at the *p*-*n* junction increases and depletes the holes at the junction that interact with the localized Mn ion spins. For fully depleted *p*-GaN region, there are few remaining holes to mediate FM behavior and the film is PM. Several devices were fabricated with similar results.

2b. Strain field effects on FM

Erbium-doped GaN epilayers (GaN:Er) were grown by MOCVD on several different substrates including GaN/Al_2O_3, AlN/Al_2O_3, GaN/Si (111), and bulk c-GaN [7]. The PL characteristics, crystalline quality, and surface morphology of each sample were measured. All growths were started with deposition of a thin GaN layer followed by a GaN:Er layer with a thickness of ~1 µm. The growth temperature was 1040 °C and the Er concentration was ~6x10^{19} cm^{-3}. The biaxial stress was estimated for each film based on X-ray diffraction (XRD) measurements. The XRD and PL data indicate that luminescence from the GaN:Er epilayers is clearly dependent upon the strain present in the films. The magnetic properties of these GaN:Er epilayers were examined using AGM and resonant PL spectroscopy combined with an applied magnetic field. The AGM measurements were made at RT with the magnetic field applied both normal to the sample surface as well as parallel to the sample surface, see Fig. 2. The in-plane hysteretic data, Fig. 2 (a), show that the GaN:Er sample grown on the GaN/Al_2O_3 template had the highest M_S value. This was followed by the sample grown on the GaN/Si (111), the other films displayed either weak or PM behavior. Data from out-of-plane measurements, Fig. 2(b), were similar but with lower M_S values.

3. Conclusions

Results of these experiments provide strong evidence that FM behavior of TM/RE-doped GaN layers grown by MOCVD. can be controlled either by an applied electric field or induced strain. However, these experiments represent only initial attempts to control magnetic properties of DMS films. Further experimental and theoretical work is need to establish functional devices for practical spintronic applications.

4. Open Questions

- Why is there still doubt concerning RT FM in TM/RE-doped III-nitrides?
- Do highly doped semiconductors (>1%) qualify as DMS materials?
- Can the present results be extended to other III-N doped with TM or RE ions?
- Can the conductivity of TM/RE-doped GaN layers be increased for device performance?
- Is there a fundamental difference in the physical mechanism for FM behavior of the TM vs RE ion in GaN?

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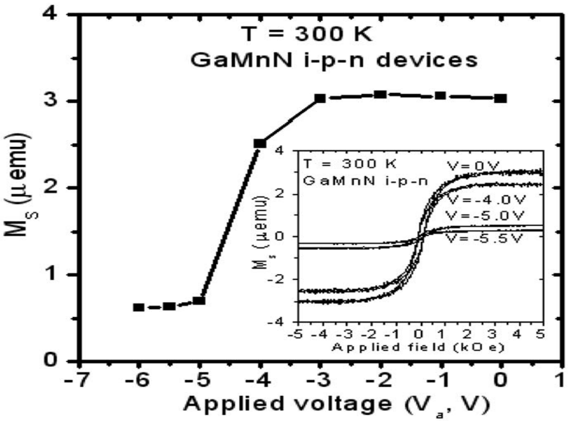

Fig. 1 Saturation magnetization *Ms* of a GaMnN *i-p-n* device at different values of reverse bias voltage. Inset shows the hysteresis curves as a function of *VR*.

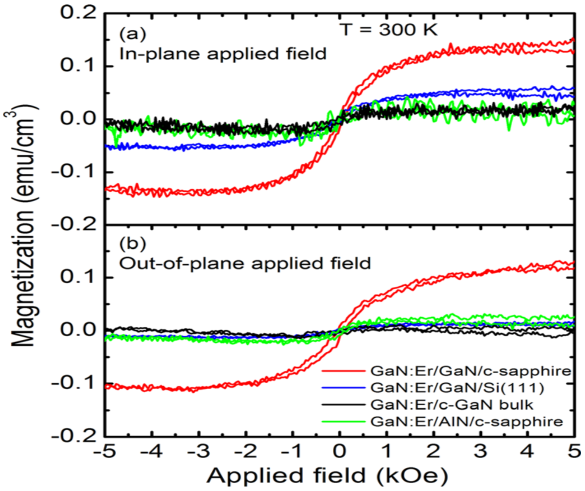

Fig. 2 Results of AGM measurements made at RT for GaN:Er epilayers grown on different templates: (a) in-plane hysteretic data and (b) out-of-plane hysteretic data. In either orientation, the saturation magnetization was highest for the GaN:Er sample grown on the GaN/Al_2O_3 template.