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Magnetic, optical and transport properties of GaN-based ferromagnetic/nonmagnetic semiconductor heterostructures

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Abstract

A ferromagnetic/nonmagnetic semiconductor DyN/GaN superlattice sample showed a large coercivity H_c of about 1800 Oe at 7 K, which originates from DyN layers. Ferromagnetic order was also observed at 300 K, which may come from GaDyN alloy layers formed at GaN/DyN interfaces. For this superlattice sample, spin tunnel resistance characteristics were observed at low temperatures. GaCrN/GaN/GaCrN trilayer structures were grown by radio frequency molecular beam epitaxy. Clear hysteresis and clear saturation characteristics were observed in the magnetization versus magnetic field curves at all measuring temperatures. A hysteresis loop was observed in the magnetic field dependence of vertical electrical resistance.

1. Introduction

Since the discovery of carrier-induced ferromagnetism in InMnAs [1] and GaMnAs [2], diluted-magnetic semiconductors (DMSs) have been gathering much interest from the industrial viewpoint because of their potential as a new functional material which will open up a way to introduce the spin degree of freedom into semiconductor devices. In particular, low dimensional ferromagnetic semiconductor structures, such as multilayer structures, superlattices (SLs), quantum wires and quantum dots, are interesting in the application to spintronics and quantum computing. Recently, we reported room temperature ferromagnetism in GaN-based diluted magnetic semiconductors, such as GaCrN [3]. Transition metal (TM)- or rare earth (RE)-doped GaN are considered to be very important materials for room temperature spintronics. In this paper we will present the magnetic, optical and transport properties of DyN/GaN SLs and GaCrN/GaN/GaCrN trilayer structures.

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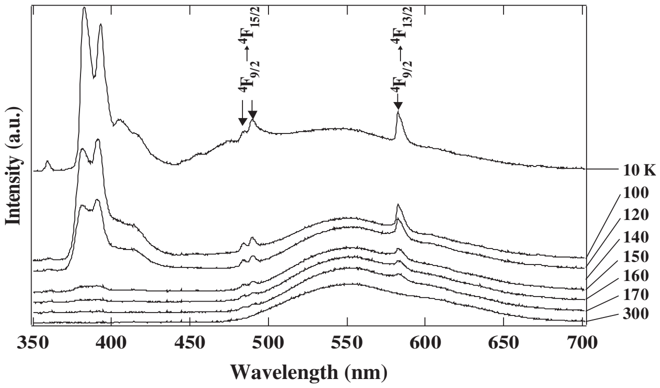

Figure 1. PL spectra for the DyN/GaN SL sample at several temperatures.

2. DyN/GaN superlattices

2.1. Growth of DyN/GaN SLs

50 periods of DyN ($>$10 nm)/GaN (20 nm) SLs were grown on a 6H-SiC(0001) substrate by radio frequency molecular beam epitaxy (RF-MBE). A 20 nm-thick AlN buffer layer was first grown on a SiC substrate. Then, a 700 nm-thick GaN buffer layer was grown. On this surface, DyN/GaN SLs were grown followed by a 20 nm-thick GaN cap layer. Detailed growth procedures and conditions are described elsewhere [4].

2.2. Crystalline and optical properties

DyN/GaN SL samples were investigated by θ–2θ scan x-ray diffraction (XRD) in the range of $2\theta = 20°$–$100°$. Several diffraction peaks were observed from the hexagonal GaN and SiC as well as DyN, but no other peak was observed [5, 6]. Raman scattering data, measured in the backscattering configuration at room temperature using the 488 nm line of an Ar ion laser, showed characteristic features for the pure GaN such as the E_2^h mode peak at 568 cm^{-1} and the A_1 LA modes associated with SiC at 505 and 513 cm^{-1} [7]. In addition to these peaks, a new peak (556 cm^{-1}) was also observed, which was assigned to be a $Ga_{1-x}Dy_xN$ phonon peak and indicates the formation of alloy layers at DyN/GaN interfaces. Photoluminescence (PL) spectra (figure 1) were obtained with a 325 nm line of a 27 mW He–Cd laser as an excitation light source and they showed several peaks from Dy^{3+} ions. These peak positions are the same as observed for GaDyN alloy samples. This also indicates the formation of GaDyN alloy layers at DyN/GaN interfaces.

2.3. Magnetic properties

Magnetization for the DyN/GaN SL sample was measured using a superconducting quantum interference device (SQUID) magnetometer under a magnetic field parallel to the sample plane. Figure 2 shows the magnetization versus temperature (M–T) curve with an applied magnetic field of 300 G and the magnetization versus magnetic field (M–H) curves at 7 and 300 K. We observed that the magnetization decreases rapidly with increasing temperature in the low temperature region ($<$50 K), then it decreases very slowly up to 350 K. Large coercivity H_c of about 1800 Oe was observed at 7 K. Due to the co-existence of different coercivity regions

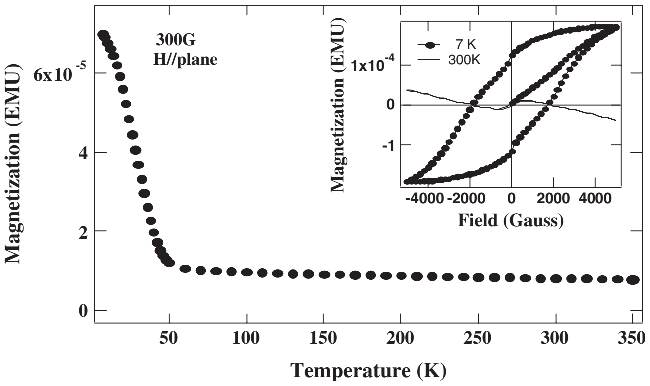

Figure 2. M–T curve at 300 G and M–H curves at 7 and 300 K for the DyN/GaN SL sample.

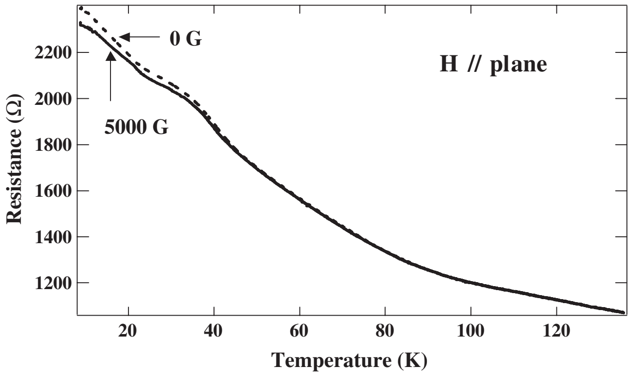

Figure 3. Temperature dependence of the vertical electrical resistance for the DyN/GaN SL structure at the magnetic field applied parallel to the sample plane at 10–140 K.

in the DyN/GaN SL sample, a step-like magnetization curve was observed at low magnetic fields, as shown in the inset of figure 2. Ferromagnetic hysteresis was also observed, even at 300 K. It is plausible that the high temperature ferromagnetic order observed in the DyN/GaN SL sample results from the $Ga_{1-x}Dy_xN$ DMS formed at DyN/GaN interfaces. Therefore, the results of the SQUID data agree with those of the PL and Raman scattering data.

2.4. Transport properties

Vertical electrical resistance was measured on the DyN/GaN SL sample at 10–140 K. The current flow was perpendicular to the sample plane and the magnetic field was applied parallel to the sample plane. Figure 3 shows the temperature variation of the vertical electrical resistance at 0 and 5000 G. The electrical (spin tunnel) resistance was decreased with increasing temperature. However, we clearly observed that this vertical tunnel electrical resistance at 5000 G is lower than that at 0 G in the low temperature region ($<$100 K). And the tunnel magnetoresistance (TMR) ratio is as high as 2.5% at 7 K. This result means that the direction of spins in all ferromagnetic layers are aligned along the same direction at the applied magnetic field of 5000 G.

Table 1. Growth conditions for the GaCrN/GaN/GaCrN trilayer structure samples.

	A	B	C
T_{sub} (°C)	700	700	700
T_{Ga} (°C)	840	840	840
N_2 (SCCM)	1.1	1.15	1.15
T_{Cr} of 1st GaCrN layer	980	990	970
T_{Cr} of 2nd GaCrN layer	980	994	1007

3. GaCrN/GaN/GaCrN trilayer structure

3.1. Growth of GaCrN/GaN/GaCrN

Three types of GaCrN/GaN/GaCrN trilayer structure samples were grown on sapphire (0001) substrates by RF-MBE. Elemental Ga, Cr and RF plasma-enhanced N_2 were used as sources. Growth conditions for the GaCrN/GaN/GaCrN trilayer structures are shown in table 1. Cr cell temperatures (T_{Cr}) for the first GaCrN layers are 980, 990, 970 °C, and those for the second GaCrN layers are 980, 994, 1007 °C, respectively, for the three types of sample. Reflection high-energy electron diffraction (RHEED) patterns along the $[11\bar{2}0]$ azimuth showed six-fold symmetric, (1×1) streaks together with Kikuchi lines, indicating a flat surface.

3.2. Crystalline and optical properties

Grown GaCrN/GaN/GaCrN trilayer structure samples were investigated by θ–2θ scan x-ray diffraction (XRD) measurements in the range of $2\theta = 20°$–$100°$. For all samples, peaks from sapphire (0006) and (0 0 0 12) diffractions as well as peaks near GaN (0002) and (0004) diffractions, which come from the Cr doped layer, were clearly observed. This indicates that the *c*-axis-oriented hexagonal GaCrN/GaN/GaCrN trilayer structures were successfully obtained. PL emission was observed from all samples. Two peaks were mainly observed at ~360 and ~380 nm. The ~360 nm peak was assigned to be due to the free excitonic transition in hexagonal GaN, which comes from the GaN buffer layer. The ~380 nm peak is a newly observed peak, and it is considered that this PL peak comes from the GaCrN layer [8].

3.3. Magnetic properties

M–H curves for the GaCrN/GaN/GaCrN trilayer structure samples are shown in figure 4, where the signal from the sapphire substrate (diamagnetic) was extracted. A well-defined hysteresis loop was observed even at 300 K. The saturation field is about 4000 G and the coercivity H_c is about 130 Oe at 300 K for all samples. These results confirm that the samples are ferromagnetic even at room temperature. For the samples B and C, the step-like magnetization curve was observed at 10 K in figure 4 (inset). This result means that these samples consist of GaCrN ferromagnetic layers with different coercivity H_c values.

3.4. Transport properties

Figure 5 shows the magnetic field dependence of the electrical (spin tunnel) resistance at 12 K. A hysteresis loop was observed for all samples by varying the magnetic field from −5000 to 5000 G. The sample C showed the largest hysteresis loop among the three samples. This result indicates that the saturation magnetization and the coercivity of the first GaCrN layer

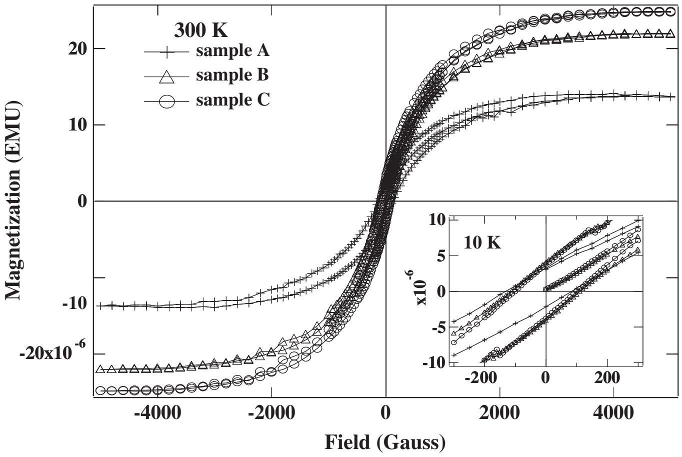

Figure 4. Magnetization versus magnetic field curves at 10 and 300 K with external magnetic field parallel to the sample plane.

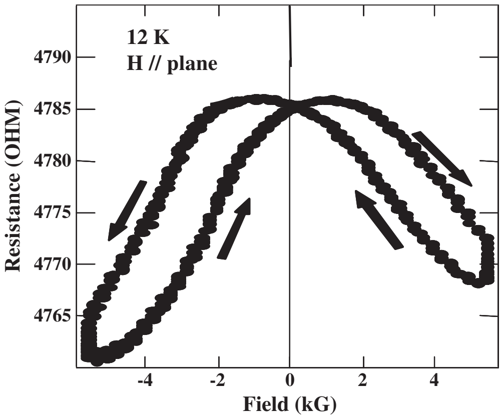

Figure 5. Magnetic field dependence of tunnel resistance for the GaCrN/GaN/GaCrN trilayer under a magnetic field parallel to the plane (sample C).

are slightly different from those of the second GaCrN layer, due to the difference in Cr content between two GaCrN layers.

4. Summary

We have studied the magnetic, optical and transport properties of a DyN/GaN SL sample and GaCrN/GaN/GaCrN trilayer structure samples grown by RF-MBE. For the DyN/GaN SL sample, two temperature regions were observed in the ferromagnetic behaviour. Ferromagnetic behaviour at low temperatures (<50 K) was considered to originate from DyN and at room temperature which results from GaDyN DMS alloy layers formed at DyN/GaN interfaces. For this DyN/GaN SL sample, a tunnel magnetoresistance (TMR) ratio as high as 2.5% was observed at 7 K. For the GaCrN/GaN/GaCrN trilayer structure samples, well-defined and step-like hysteresis was observed even at 300 K. Furthermore, in the magnetic field dependence curves of the vertical electrical resistance, a clear hysteresis loop was observed for all samples at 12 K. Novel functional devices that control charges (electrons, holes), spins and photons, such as spin tunnel devices and circular polarization light emitting devices, are considered to be fabricated by using these DMSs.

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