Chapter 5

Magnetic properties of RE:GaN

Besides for photonic application, RE has long been studied also for magnetic functional material. Permanent magnets such as YCo_5, $SmCo_5$, $Nd_2Fe_{14}B$, etc., and giant magneto resistance material such as $RE_{1-x}A_xMnO_3$, (A; alkaline-earth metal) can be good examples. Recently, semiconductor spintronics have become a hot issue and are gradually starting to attract more interests. Among them, diluted magnetic semiconductor(DMS)s based on GaN are regarded as fascinating material since they are expected to show Curie temperature higher than room temperature. In this chapter, the author introduces magnetic properties of RE doped GaN as for materials for DMS applications.

5.1 Semiconductor spintronics

Semiconductor and magnetic materials are two very important materials in the current electronics industry as well as being two big branches of solid-state physics. Most electronic and optical devices are made of semiconductors, while magnetic materials are used for nonvolatile memory, magnetic sensors, optical isolators, etc. However, integration of semiconductors and magnetic materials is very difficult, because the two materials are generally very dissimilar.

"Semiconductor spintronics" generally designates the novel approaches to graft the above two most successful technological branches in modern physics. To control magnetic compounds or over individual spins in semiconductor nanostructures could lead to new functionalities in classical and quantum information hardware. Fig. 5-1 shows the novel phenomena which is expected to occur in semiconductor spintronics, and applications will possibly propagate from them[5-1].

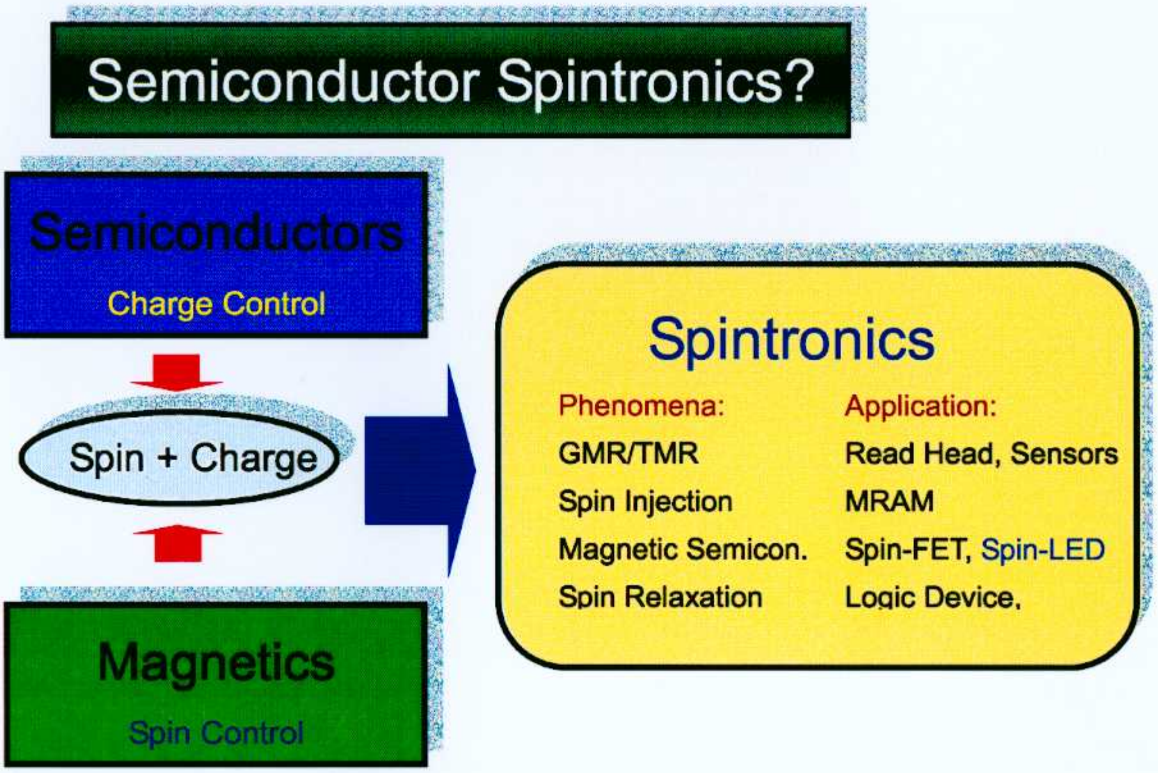

Figure 5-1: Novel phenomena in spintronics and its possible applications [5-1].

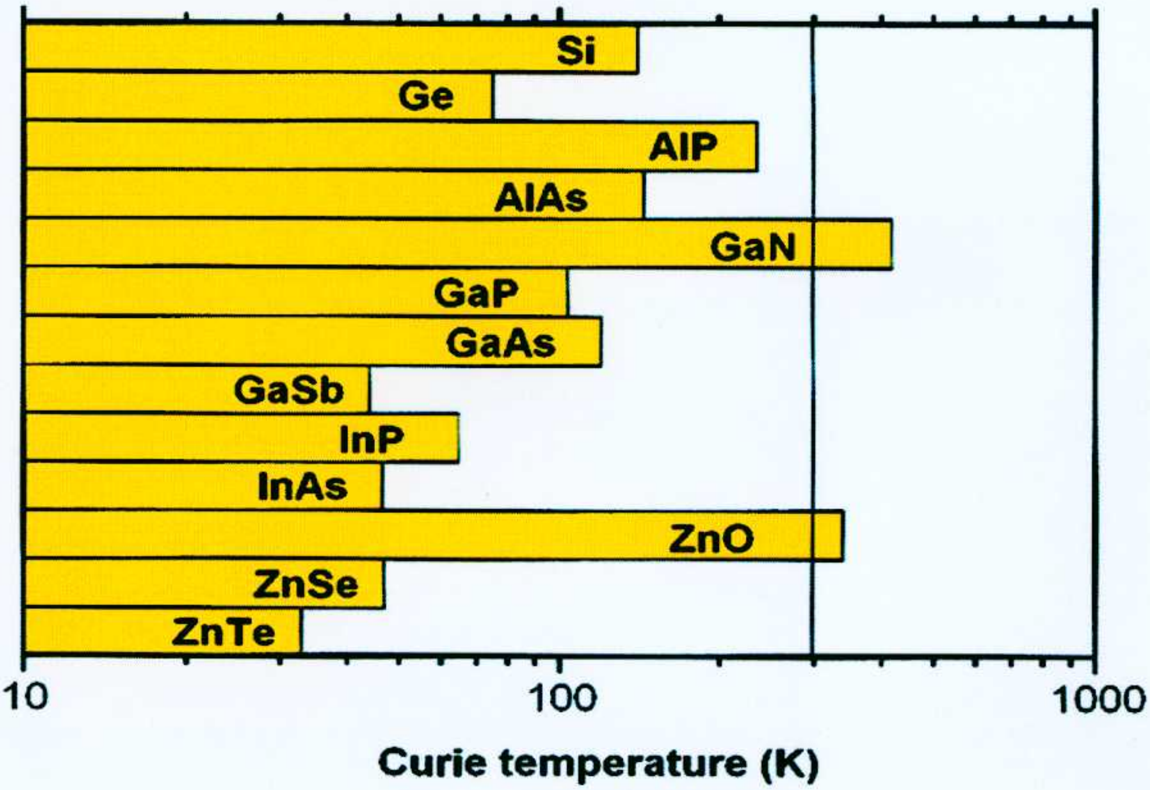

Figure 5-2: Computed values of the Curie temperature for various p-type III-V compounds containing 5% of Mn in the S= 5/2 high-spin state and 3.5 $\times 10^{20}$ holes per cm^3[5-2].

Recently, spintronics using GaN became a considerable issue since the ferromagnetism in over room temperature was predicted using transition metal (manganese (Mn)) doping (Fig. 5-2) [5-2]. This is very promising anticipation on DMS applications. Although there are many controversies on the experimental results [5-3, 4, 5, 6], a lot of numbers of group are participating on research about DMS application using GaN[5-7, 8, 9].

5.2 Magnetic properties of RE doped GaN

As theoretically predicted by the electronic structure calculation using the Korringa-Kohn-Rostoker method combined with the coherent potential approximation (Fig. 5-3) [5-10], rare-earth-doped GaN is also a fascinating candidate materials for diluted magnetic semiconductors (DMSs). However, very little has been studied on rare-earth-doped GaN experimentally [5-11]. In this dissertation, the author introduces the magnetic properties of Er-doped GaN and Tb-doped GaN based on SQUID measurements. Fig. 5-4 (a), (b) and (c) show magnetization (M-H) curves of 2 at.% Tb-doped GaN and 1.2 at.% and 2.5 at.% Er doped GaN, respectively. The measurements were carried out over

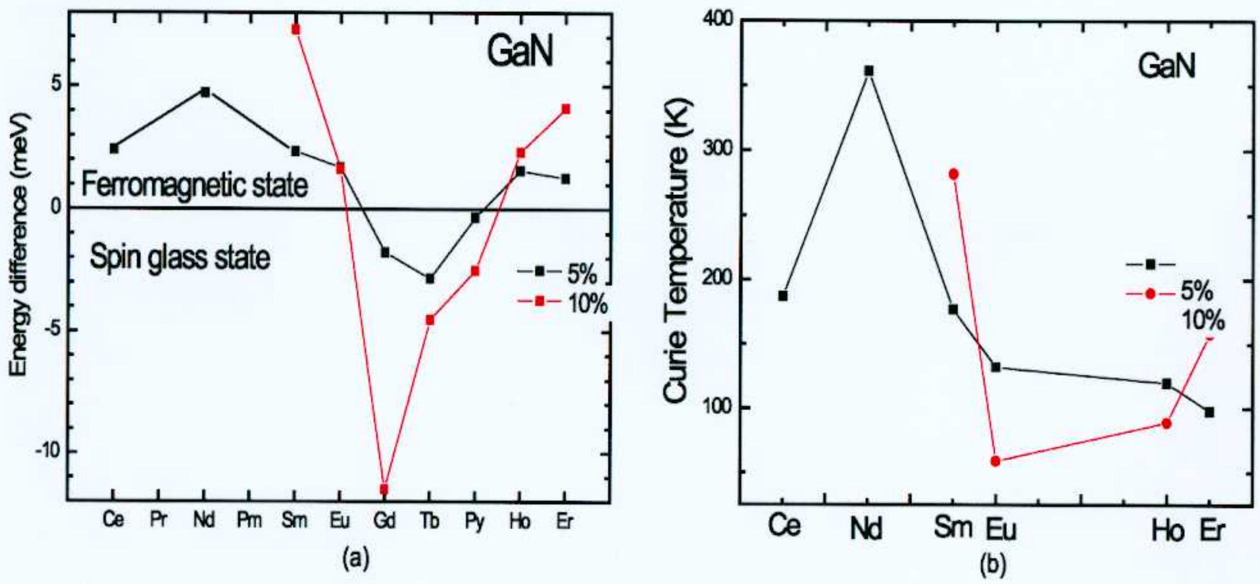

Figure 5-3: Theoretical prediction of magnetic properties of rare earth doped GaN by the electronic structure calculation using the Korringa-Kohn-Rostoker method combined with the coherent potential approximation [5-10].

the temperature range of 5 to 300K with the external magnetic field parallel to the growth direction (perpendicular to the sample plane). No clear hysteresis was observed in the range of measured temperature for either sample, and at 300K the magnetization was almost quenched out on Tb-doped GaN and 1.2 at.% Er doped GaN. In 2.5 at.% Er-doped GaN, as shown in the inset of Fig. 5-4 (c), small but clear finite steps, which suggest the existence of small portion of a ferromagnetic component, were observed around zero field even at 300K.

Although the possibility of small cluster formation, which cannot be detected, by EXAFS or XRD cannot be excluded, we do not consider the ferromagnetic components were originated from precipitates or substrate since precipitates such as Er, or ErGa known to do not show ferromagnetism in room temperature[5-12, 13]. Our conclusion for the most plausible reason of the ferromagnetic components is the weak Ruderman-Kittel-Kasuya-Yoshida (RKKY) interaction between concentration-fluctuated Er ions and carrier electron[5-14]. Fig. 5-5 shows magnetic moment versus reduced field, divided by temperature (H/T) for the sample of (a) Tb doped GaN and (b) 2.5% Er doped GaN, in magnetic fields both parallel and perpendicular to the sample plane. The solid lines are calculated Brillouin functions with the parameter of total angular momentum J and g factor equal to 6, 1.5 for the Tb^{3+} ion and 15/2, 1.2 for the Er^{3+} ion, respectively. We took into consideration the uncertainty of the rare earth concentration and give the values of 1.6 at% and 2.2% for Tb^{3+} and Er^{3+} ions, respectively. For Tb-doped GaN, when the magnetic field is induced perpendicular($\perp$)to the sample plane, the

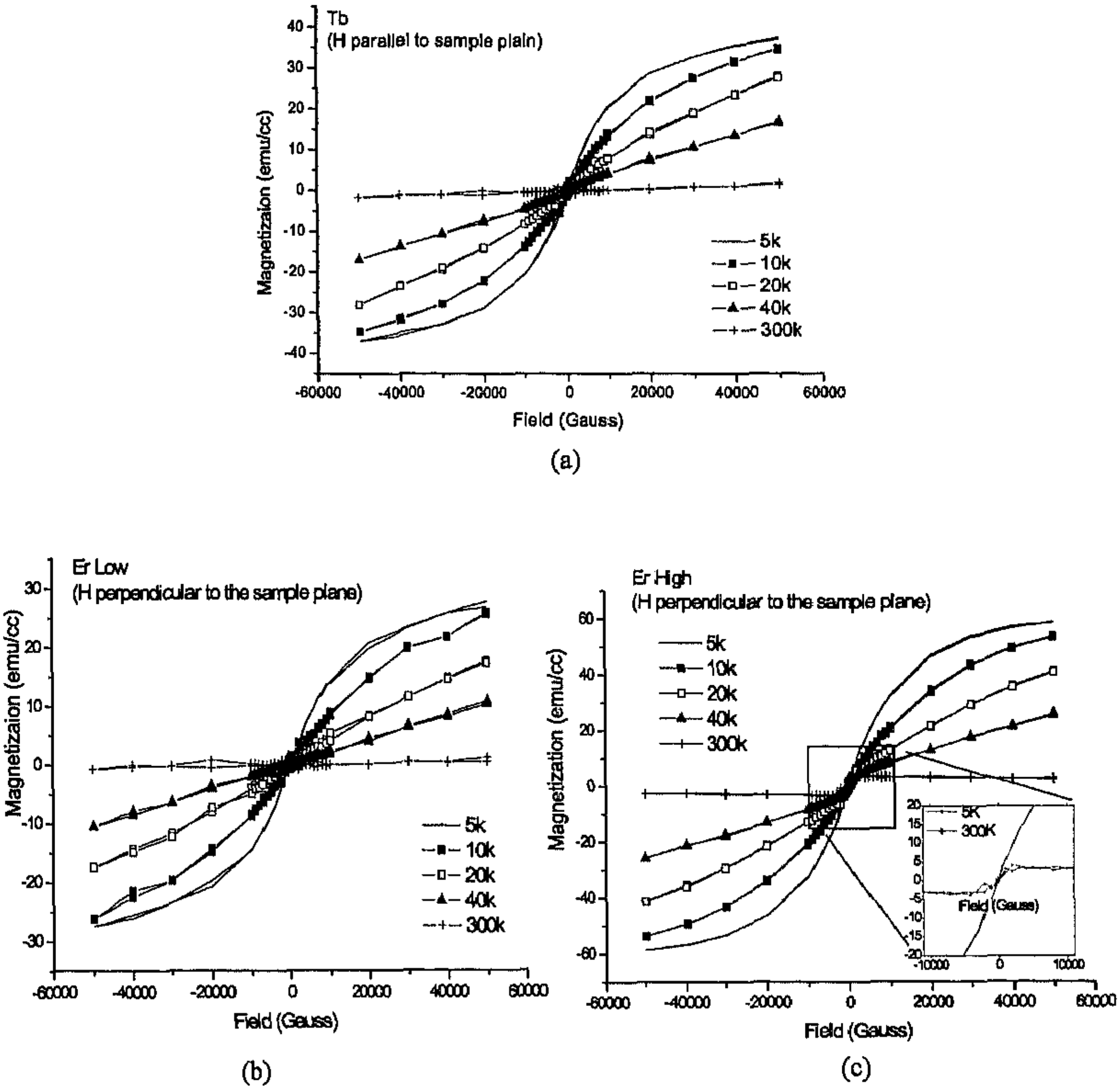

Figure 5-4: Magnetization (M-H) curves of (a) 2 at.% Tb-doped GaN and (b) 1.2 at.% and (c) 2.5 at.% Er doped GaN.

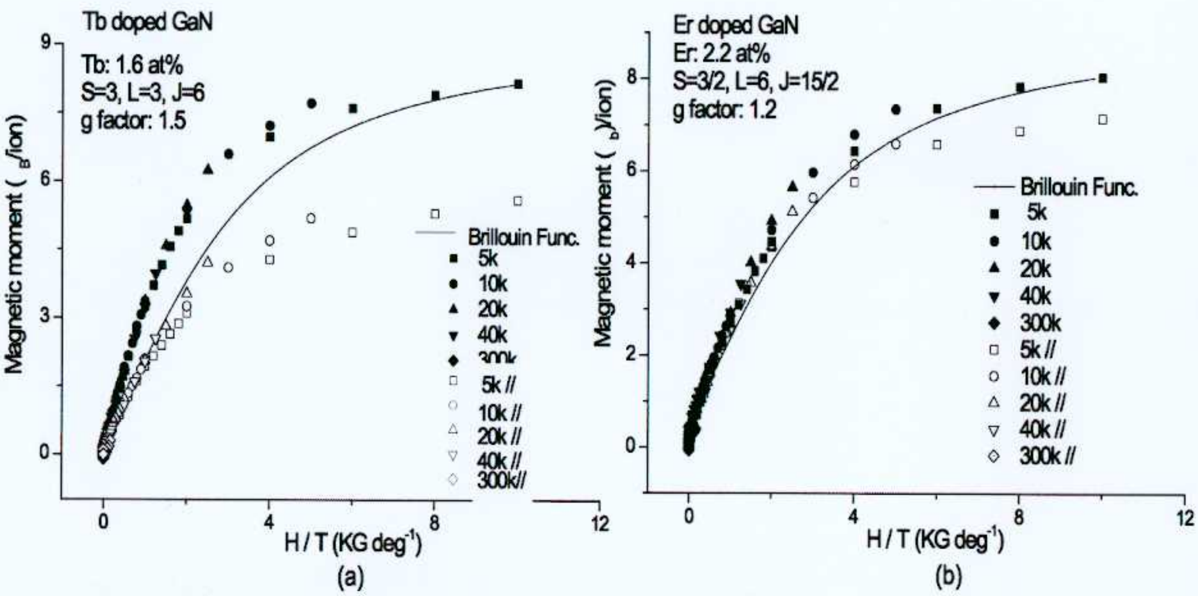

Figure 5-5: Magnetic moment versus H/T for (a) Tb-doped GaN and (b)Er-doped GaN with the magnetic field both perpendicular (⊥) and parallel (//) to the sample plane. The solid lines represent calculated Brillouin functions.

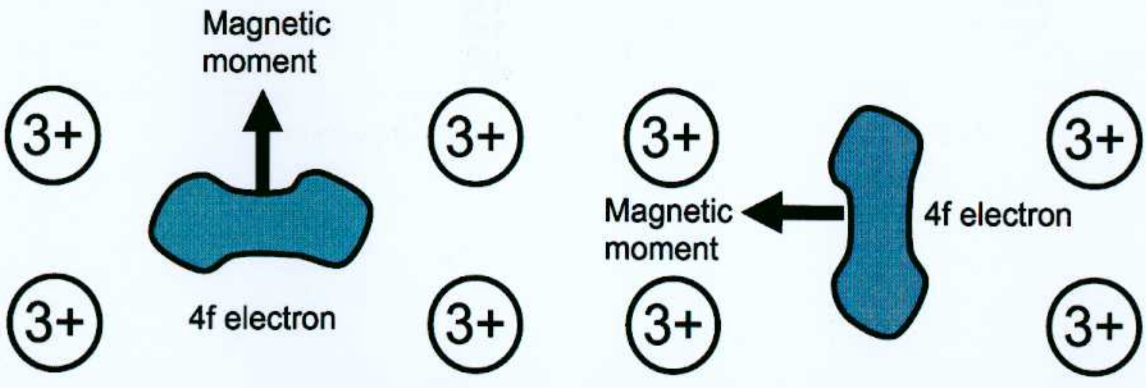

Figure 5-6: Magnetic anisotropy of Tb in the hexagonal crystal field of the GaN

magnetization curves of various temperatures collapse on a single universal curve that slightly differs from the Brillouin function. This result suggests that most of the Tb ions exhibit a paramagnetic character. As shown in Fig. 5-5 (a), when the magnetic field is induced parallel to the sample plane(//), the magnetization curves show different dependence, and were obviously different from the Brillouin function. We suppose that the above phenomenon observed in Tb-doped GaN is due to magnetic anisotropy of Tb in the hexagonal crystal field of the GaN system (Fig. 5-6). In case of Er-doped GaN, the magnetization curves measured under the magnetic field both perpendicular and parallel to the sample plane show close agreement with the Brillouin function, indicating that Er ions are in paramagnetic order with magnetic isotropy. Together with the result of M-H curve of Er-doped GaN, this result suggests coexistence of dominant paramagnetic component and a small portion of a ferromagnetic component.

In brief, predominant paramagnetic behavior with magnetic anisotropy was observed in Tb:GaN. For Er:GaN, small portion of ferromagnetic component was also contributed with dominant paramagnetic components. More systematical studies are required to clarify the origin of ferromagnetism.

Chapter 5 References

[5-1] Fiigures from http://spintronics.korea.ac.kr/research_map1.htm

[5-2] T. Dietl, Sience 287, 1020 (2000).

[5-3] Y. L. Soo, G. Kioseoglou, S. Kim, S. Huang, Y. H. Kao, S. Kuwabara, S. Owa, T. Kondo, and H. Munekata, Appl. Phys. Lett. 79 3926 (2001).

[5-4] Saki Sonoda, Saburo Shimizu, Takahiko Sasaki, Yoshiyuki Yamamoto and Hidenobu Hori, J. Cryst. Grwoth 237-239, 1358 (2002).

[5-5] Takahiko Sasaki, Saki Sonoda, Yoshiyuki Yamamoto, Ken-ichi Suga, Saburo Shimizu, Kouichi Kindo and Hidenobu Hori, J. Appl. Phys. 91, 7911 (2002).

[5-6] K. Ando, Appl. Phys. Lett. 82, 100 (2003).

[5-7] Masahiko Hashimoto, Yi-Kai Zhou, Masahito Kanamura and Hajime Asahi, Solid State Commun. 122, 37 (2002).

[5-8] Sang Eon Park, Hyeon-Jun Lee, Yong Chan Cho, Se-Young Jeong, Chae Ryong Cho, and Sunglae Cho, Appl. Phys. Lett. 80, 4187 (2002).

[5-9] H. Akinaga, S Nemeth, J. De Boeck , L. Nistor , H. Bender, G. Borghs, H. Ofuchi, M. Oshima, Appl. Phys. Lett. 77, 4377 (2000).

[5-10] M. Hashimoto, K. Araki, K. Sato, Y. K. Zhou, H. Asahi and H. Katayama-Yoshida, Extended Abstracts for the 63rd autumn meeting of the JSAP 438P (26p-ZA-5) (2002).

[5-11] Nobuaki Teraguchi, Akira Suzuki, Yasushi Nanishi, Yi-Kai Zhou, Masahiko Hashimoto and Hajime Asahi, Solid State Commun. 122, 651 (2002).

[5-12] J. W. Cable, E. O. Wollan, W. C. Koehler, and M. K. Wilkinson, Phys. Rev. 140, A1896 (1965).

[5-13] N.Shohata J. Phys. Soc. Jpn. 42, 1873 (1977).

[5-14] F. Matsukura, H. Ohno, A. Shen, and Y. Sugawara , Phys. Rev. B 57 2037 (1998).