Room-temperature local ferromagnetism and its nanoscale domain growth in the ferromagnetic semiconductor $Ge_{1-x}Fe_x$

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Group-IV-based ferromagnetic semiconductor (FMS) $Ge_{1-x}Fe_x$ is expected to become efficient spin injectors and detectors in group-IV-based semiconductor devices, because it can be epitaxially grown on Si and Ge substrates and the conductivity can be controlled by boron (B) doping independently of the Fe concentration x [1]. Furthermore, T_C can be increased up to 210 K by annealing [2]; however, detailed microscopic understanding of the ferromagnetism is lacking. In this study, we investigate the local magnetic behavior of GeFe by using X-ray magnetic circular dichroism (XMCD) at various magnetic fields and temperatures.

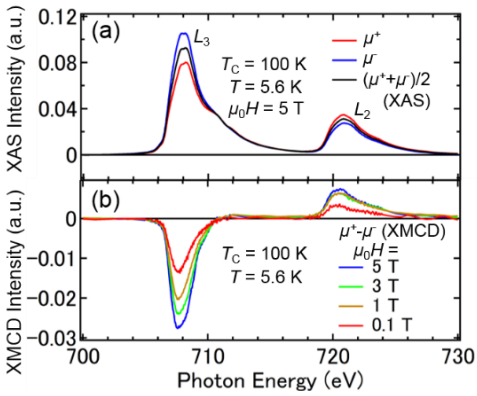

Fig. 1(a)(b) : (a) XAS and (b) XMCD spectra of the $Ge_{0.935}Fe_{0.065}$ film grown at 240°C.

We have carried out XMCD measurements of the $Ge_{0.935}Fe_{0.065}$ films grown at 160°C (T_C = 20 K) and 240°C (T_C = 100 K) by low-temperature molecular beam epitaxy (LT-MBE) [3]. Figure 1 (a) shows the X-ray absorption spectroscopy (XAS) spectrum [μ^+, μ^-, and $(\mu^+ + \mu^-)/2$] at the Fe L_2 (~721 eV) and L_3 (~708 eV) absorption edges in the $Ge_{0.935}Fe_{0.065}$ film grown at 240°C measured at 5.6 K with a magnetic field μ_0H of 5 T applied perpendicular to the film surface. The main peak at around 708 eV is assigned to Fe^{2+} states in GeFe, which means that almost all the doped-Fe atoms are in the 2+ state. Figure 1 (b) shows the XMCD (= $\mu^+ - \mu^-$) spectra at the Fe L_2 and L_3 absorption edges in the same sample measured at 5.6 K with μ_0H = 0.1, 1, 3, and 5 T. Figure 2 shows the effective magnetic-field H_{eff} dependence of the XMCD intensity at 707.66 eV, which corresponds to the negative peak of XMCD in Fig. 1 (b), in the $Ge_{0.935}Fe_{0.065}$ film grown at 240°C at various temperatures. Here, the total magnetization M [= spin magnetic moment (m_{spin}) + orbital magnetic moment (m_{orb})] obtained by using the XMCD sum rules is also plotted by filled red symbols, and μ_0H_{eff} is obtained by subtracting the demagnetization from μ_0H. The fitted curves using the linear-H_{eff} plus Langevin functions, corresponding to the paramagnetic and superparamagnetic components, respectively, are also shown in these figures (dashed black curves). As shown in a blow-up near zero magnetic field in the insets, one can see a clear hysteresis below T_C (= 100 K). In Fig. 2, the theoretical curves (dashed black curves) are well fitted to the experimental data above T_C. This means that local ferromagnetic domains, which exist at room temperature, expand with decreasing temperature, followed by the ferromagnetic transition of the entire system at T_C.

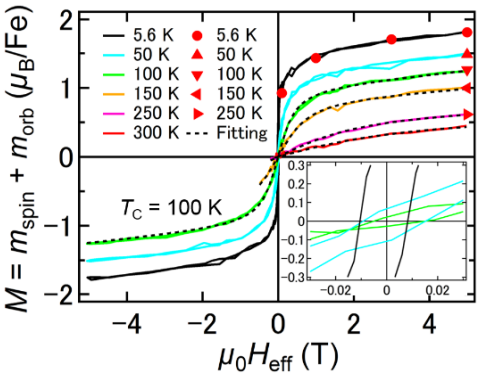

Fig. 2. : Effective magnetic-field H_{eff} dependence of the XMCD intensity at 707.66 eV for the $Ge_{0.935}Fe_{0.065}$ film grown at 240°C measured at various temperatures. The total magnetization M (= m_{spin} + m_{orb}) obtained by the XMCD sum rules is also plotted by filled red symbols.

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