5–7 Atomic-Level Observation of Magnetic Ordering Process in Ferromagnetic Semiconductors

— Exploring the Mechanism of Ferromagnetism for Its Practical Use in Spintronics Devices —

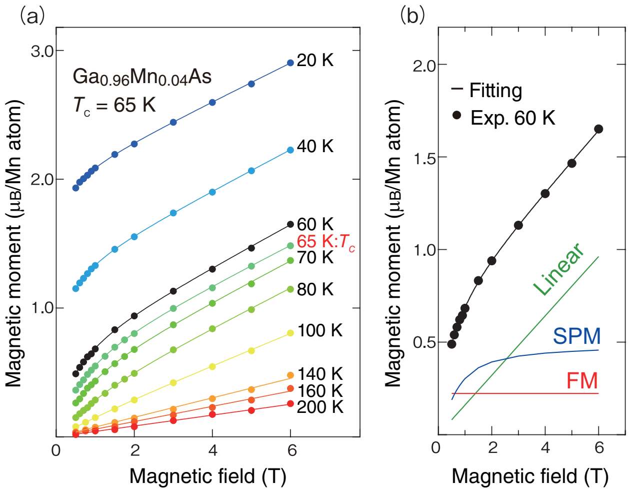

Fig.5-14 Temperature and magnetic field dependence of the XMCD for $Ga_{0.96}Mn_{0.04}As$
(a) Experimental and fitting results are represented by solid circles and lines, respectively. (b) Red, green and blue lines show the extracted FM, Linear magnetic, and SPM components, respectively; the black solid line shows the sum of these three components.

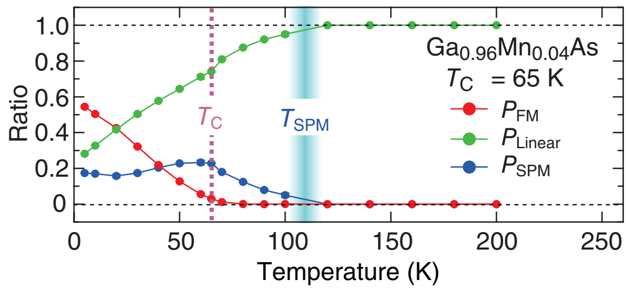

Fig.5-15 Temperature dependence of the ratio of each magnetic component
As the temperature continued to decrease after reaching the Curie temperature (T_C), the FM component (P_{FM}) increased. On the other hand, the SPM component (P_{SPM}) began increasing around a certain temperature (T_{SPM}), which is well above T_C.

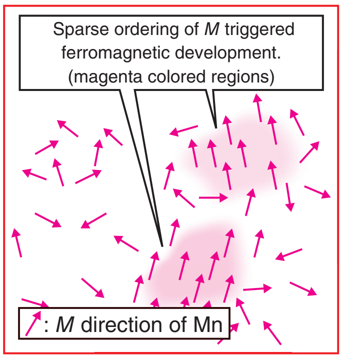

Fig.5-16 Schematic of the magnetic ordering process around T_{SPM}
Arrows represent the magnetic moment (*M*) of Mn atoms. FM domains (magenta-colored regions) begin developing sparsely around T_{SPM} and then overlap at T_C.

Ferromagnetic semiconductors (FMSs), which possess both semiconductor and ferromagnetic (FM) properties, have attracted attention as next-generation spintronics materials. The discovery of ferromagnetism in manganese-doped gallium arsenide ($Ga_{1-x}Mn_xAs$; (Ga, Mn)As) broadened the research field of FMSs. Despite enthusiastic investigations, however, there has been controversy over the origin of ferromagnetism for over 20 years. Ferromagnetism appears below the Curie temperature (T_C); to apply FMS to spintronics devices, it should be achieved at room temperature. The highest reported T_C of (Ga, Mn)As, however, is −73 °C.

To understand the mechanism of ferromagnetism, it is necessary to clarify the element-selective spin states of Mn responsible for the magnetic properties of (Ga, Mn)As and investigate how ferromagnetism develops. Therefore, we performed X-ray magnetic circular dichroism (XMCD) experiments at JAEA's beamline BL23SU of SPring-8 to observe the magnetic ordering process.

The observed dependence of the magnetic moment of the Mn 3d electrons on the temperature and magnetic field are shown in Fig.5-14(a), as estimated from the XMCD intensity for $Ga_{0.96}Mn_{0.04}As$ with T_C = 65 K. The magnetic moment becomes large as the temperature decreases and magnetic field increases, as shown in Fig.5-14(a). This behavior clearly shows development of the FM state at the low temperatures and high magnetic fields.

Fitting allowed three magnetic components to be identified: FM, linear, and superparamagnetic (SPM). Against the magnetic field, these components were constant, increased linearly, and increased non-linearly, respectively, as shown in Fig.5-14(b). The ratio of each component to the total magnetic moment was then defined as P_{FM}, P_{Linear}, and P_{SPM}, respectively (i.e., $P_{FM} + P_{Linear} + P_{SPM} = 1$ for each measured temperature). The observed temperature dependence of P_{FM}, P_{Linear}, and P_{SPM} is shown in Fig.5-15. Here P_{FM} began increasing as the temperature decreased below T_C. On the other hand, P_{SPM} began increasing around a certain temperature (T_{SPM}) above T_C, reached a maximum near the T_C, and then decreased. This behavior was also observed in other samples with different Mn concentrations and values of T_C. These results indicate that SPM regions begin forming at temperatures above T_C, i.e., T_{SPM}, and that SPM regions overlap at the T_C (Fig.5-16).

This result was selected as a featured paper and the cover of the issue, and an explanatory article was also published.

This work is a part of the results of a joint research project with the University of Tokyo and Kyoto Sangyo University, entitled "Development of functional magnetic semiconductor thin films and study of their electronic states using synchrotron radiation".

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Reference

Takeda, Y. et al., Direct Observation of the Magnetic Ordering Process in the Ferromagnetic Semiconductor $Ga_{1-x}Mn_xAs$ via Soft X-ray Magnetic Circular Dichroism, Journal of Applied Physics, vol.128, issue 21, 2020, 213902, 11p.