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$_x$As; (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 is necessary to clarify the element-selective spin states of Mn using soft X-ray magnetic circular dichroism (XMCD) experiments at JAEA’s beamline BL23SU of SPring-8.

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$_{0.98}$Mn$_{0.04}$As with $T_C = 65$ K. The magnetic moment becomes larger 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 $T_C$.

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