High-Temperature Ferromagnetism in Heavily Fe-Doped Ferromagnetic Semiconductor (Ga,Fe)Sb

NGUYEN THANH TU
UNIVERSITY OF TOKYO

Bridging semiconductor and magnetism is desirable because it would provide new opportunities for utilizing spin degrees of freedom in semiconductor devices. To fulfill this purpose, ferromagnetic semiconductors (FMSs) have been widely studied since they exhibit both properties of semiconductors and magnetic materials. In FMSs, non-magnetic atoms of the host semiconductors (e.g., InAs, GaAs, GaSb) are partly replaced by magnetic atoms (e.g., Mn, Fe, Cr), which have local magnetic moments. Ferromagnetic coupling between local magnetic moments induces macroscopic ferromagnetism in the host semiconductors, while other important features of the host semiconductors are preserved. By using FMSs, one can design new devices with very attractive functions, such as spin diodes and spin transistors that have spin-dependent output characteristics. Spin transistors are expected to be used as the basic element of low-power-consumption, non-volatile and reconfigurable logic circuits. For the past two decades, most of the studies on FMSs have been carried out on manganese (Mn)-doped III-V semiconductors such as (In,Mn)As and (Ga,Mn)As, but they failed to obtain ferromagnetism at room temperature (~300 K). The maximum Curie temperature (T_C) of (Ga,Mn)As and (In,Mn)As obtained so far are 200 K and 90 K, respectively. Here, T_C of ferromagnetic materials is the temperature above which the material loses its ferromagnetic properties.

Recently, researchers from the University of Tokyo (Japan), Tokyo Institute of Technology (Japan), and Ho Chi Minh University of Pedagogy (Vietnam) have made a breakthrough by growing a new iron-doped semiconductor (Ga,Fe)Sb that shows ferromagnetism up to room temperature for the first time in III-V semiconductors [1]. Figure 1(a) shows the schematic structure of the studied $(Ga_{1-x},Fe_x)Sb$ samples (x = 23% and 25%) grown by low-temperature molecular beam epitaxy. The scanning transmission electron microscopy (STEM) lattice images of a representative $(Ga_{1-x},Fe_x)Sb$ sample (x = 25%) indicate that the crystal structure of the (Ga,Fe)Sb layer is of zinc-blende type without detectable second-phase precipitations (see Fig. 1(b)). The intrinsic ferromagnetism of the (Ga,Fe)Sb thin films was confirmed by magnetic circular dichroism (MCD) spectroscopy and superconducting quantum interference device (SQUID) magnetometry measurements. Figure 1(c) shows the MCD spectra of the $(Ga_{1-x},Fe_x)Sb$ samples (x = 23 and 25%) at 300 K with a magnetic field of 1 T applied perpendicular to the film plane. As a reference, the MCD spectrum of an undoped GaSb is also shown, in which the MCD intensity is very small. In contrast, the MCD spectra of the GaFeSb samples show a strongly enhanced peak at E_1 (~2.1 eV) corresponding to the optical critical point energy of the GaSb band structure. This result indicates that the band structure of the (Ga,Fe)Sb samples is of zinc-blende type. Figure 1(d) shows the normalized MCD – magnetic field (H) characteristic of the sample (25%) at 300 K. Clear hysteresis was observed, demonstrating the presence of ferromagnetic order at room temperature. Furthermore, the result also agrees with the normalized magnetization *vs.* magnetic field (M - H) measured by SQUID, and this supports intrinsic ferromagnetism in GaFeSb. In particular, T_C of the (Ga_{1-x},Fe_x) Sb samples (x = 23% and 25%) are 300 K and 340 K, respectively, which are the highest values so far reported in III-V FMSs, despite the fact that GaSb is a narrow-gap semiconductor. This result is in fact against the traditional views of the material design for FMSs. One of

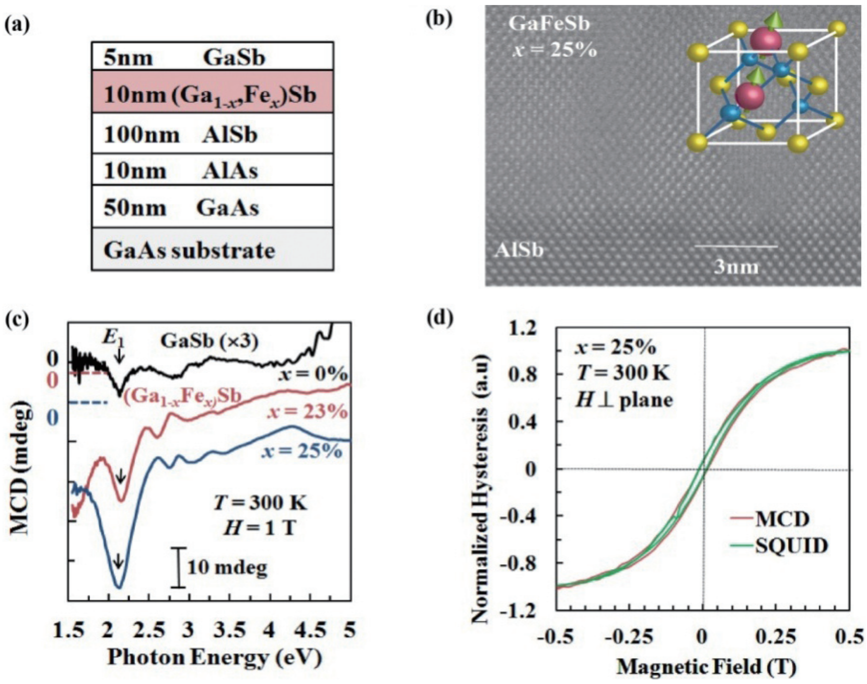

Fig. 1: (a) Schematic sample structure. (b) Cross-sectional scanning transmission electron microscopy (STEM) image of the $(Ga_{1-x}, Fe_x)Sb$ sample ($x = 25\%$). The STEM image indicates that the crystal structure of this sample is of zinc-blende type. Inset shows the zinc-blende-type crystal structure of (Ga,Fe)Sb. (c) Reflection MCD spectra measured at 300 K under a magnetic field of 1 T applied perpendicular to the film plane for the $(Ga_{1-x}, Fe_x)Sb$ samples ($x = 23\%$ and 25%). The MCD spectrum of a reference undoped GaSb sample is also shown. (d) Comparison of the normalized magnetic field dependences of MCD and magnetization measured at 300 K for the $(Ga_{1-x}, Fe_x)Sb$ sample ($x = 25\%$).

the most famous theories of FMSs predicted that wide-gap semiconductors would show strong ferromagnetism and thus high T_c. Therefore, this result not only demonstrates the potential of (Ga,Fe)Sb as a key component of room-temperature semiconductor spintronic devices, but also requires the reconsideration of some conventional theories of magnetism in semiconductors.

References

[1] N. T. Tu, P. N. Hai, L. D. Anh and M. Tanaka, Appl. Phys. Lett. 108, 192401 (2016).

Nguyen Thanh Tu is a postdoctoral researcher at the University of Tokyo (Japan). He is also a lecturer at Ho Chi Minh City University of Pedagogy (Viet Nam). After receiving his Ph.D from Graduate School of Engineering at the University of Tokyo in 2015, he worked as an overseas researcher under the Postdoctoral Fellowship Program of the Japan Society for the Promotion of Science (JSPS). His research focuses on semiconductor spintronics and new ferromagnetic semiconductors.