【Grant-in-Aid for Scientific Research (S)】

Broad Section C

Title of Project： **Creation of New Spin-Functional Materials and Devices by Renaissance of Ferromagnetic Semiconductors**

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【Purpose and Background of the Research】

By integrating different characteristics and functions of semiconductors and ferromagnets, we can create high-speed, and low-power semiconductor devices with nonvolatile memory functionalities, leading to innovative information systems. As a new class of materials which have both the properties of semiconductors and ferromagnets, ferromagnetic semiconductors (FMSs) are most promising. Not only Mn-doped FMSs such as (Ga,Mn)As we have investigated so far, we extend our research to new Fe-doped zinc-blende type narrow-gap FMS thin films, heterostructures and nanostructures. We aim to explore and control the properties, and apply them to spin-based devices. Herewith we solve all the main problems and issues of FMSs: 1) We create both n-type and p-type FMSs. 2) We increase the Curie temperature (T_C) of FMSs to be higher than room temperature (300 K) and control the properties of FMSs at room temperature. 3) We understand the mechanism of ferromagnetism in FMSs in a unified way. 4) We realize new low-power devices, such as spin transistors with non-volatility and flexible information processing functions, quantum devices using spin-dependent band structures, and functional devices using topological states, which will be suitable for future information technology.

【Research Methods】

(1) We grow Fe-doped and Mn-doped FMS thin films and heterostructures by molecular beam epitaxy.
(2) We explore the properties of FMS thin films and heterostructures, including their quantum effects.

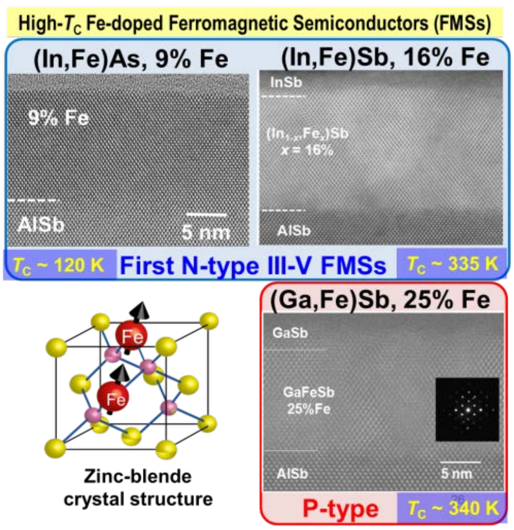

Fig. 1 Fe-doped III-V ferromagnetic semiconductors (FMSs) with high T_C.

(3) We aim to control the various quantum effects in FMS thin films, heterostructures and nanostructures, and related giant spin-related responses, such as giant magnetoresistance ((1) ~ (3) will be carried out by Tanaka, Ohya and Anh).
(4) We electrically control the magnetic properties of FMS quantum wells in field effect transistor (FET) structures using wave-function engineering (by Anh, Ohya, Tanaka).
(5) Along with these experiments, we design the materials and devices by theoretical calculations (by Yoshida, Tanaka).
(6) We fabricate spin transistors and topological transistors using FMS heterostructures with low power consumption (by all members).

【Expected Research Achievements and Scientific Significance】

We solve all the main problems of FMSs: 1) Create both n-type and p-type FMSs. 2) Increase the Curie temperature of FMSs to be higher than room temperature and control the properties of FMSs at room temperature. 3) Understand the mechanism of ferromagnetism in FMSs in a unified way. 4) Realize new spin-functional devices with low power, such as spin transistors with non-volatility and flexible information processing functions, quantum devices using spin-dependent band structures, and functional devices using topological states, which will be suitable for future information technology.

【Publications Relevant to the Project】

- Kosuke Takiguchi, Le Duc Anh, Takahiro Chiba, Tomohiro Koyama, Daichi Chiba, Masaaki Tanaka, "Giant gate-controlled proximity magnetoresistance in semiconductor-based ferromagnetic/nonmagnetic bilayers", Nature Physics **15**, 1134 (2019).
- Miao Jiang, Hirokatsu Asahara, Shoichi Sato, Toshiki Kanaki, Hiroki Yamasaki, Shinobu Ohya, and Masaaki Tanaka, "Efficient full spin-orbit torque switching in a single layer of a perpendicularly magnetized single-crystalline ferromagnet", Nature Commun. **10**, 2590 (2019).
- Nguyen Thanh Tu, Pham Nam Hai, Le Duc Anh, and Masaaki Tanaka, "Heavily Fe-doped n-type ferromagnetic semiconductor (In,Fe)Sb with high Curie temperature and large magnetic anisotropy", Appl. Phys. Express **12**, 103004 (2019).

【Term of Project】 FY2020 - 2024

【Budget Allocation】 151,800 Thousand Yen

【Homepage Address and Other Contact Information】

http://www.cryst.t.u-tokyo.ac.jp/home/