Epitaxial growth and characterization of superconductor Al / Fe-doped III-V ferromagnetic semiconductor hybrid structures on GaAs substrates

°(M2)Yooho Choi[1], Keita Ishihara[1], Le Duc Anh[1,2,3], Masaaki Tanaka[1,3]
[1]Department of Electrical Engineering and Information Systems, The University of Tokyo.
[2]PRESTO, JST. [3]Center for Spintronics Research Network (CSRN), The University of Tokyo.
E-mail: zzang825528@g.ecc.u-tokyo.ac.jp

Majorana fermions (MFs) are a promising candidate for fault-tolerant topological quantum computing [1]. Topological superconductors, which is believed to host MFs, can be realized by interfacing a material with strong spin-orbit coupling (SOC) to a superconductor. At this interface, the SOC materials, such as semiconductor nanowires or topological insulator, become superconducting by a proximity effect [2]. Simultaneously, a strong external magnetic field is usually required to induce spin splitting in the material band structure with SOC, which hinders the scalability of the quantum bits implemented by MFs. A promising new method to realized MFs *without* strong magnetic field is preparing hybrid structures of narrow-gap III-V ferromagnetic semiconductor (FMS) and superconductor. However, there is no study so far to form high-quality interfaces of superconductor and ferromagnetic semiconductor, which should be epitaxially grown *in situ*.

In this work, we report on the growth and characterization of superconductor Al on Fe-doped narrow-gap FMS structures, including (In,Fe)As [3] and InAs/(Ga,Fe)Sb bilayers [4], using molecular beam epitaxy (MBE). These FMS structures have strong SOC and large spin splitting in the band structure, which can be electrically controlled by a gate voltage. The 20 nm-thick Al layer and the (In,Fe)As (Fe 6%, 15 nm) or InAs (15 nm)/(Ga,Fe)Sb (Fe 20%, 20 nm) structures were grown *in situ* at -10°C and 250°C, respectively, on GaAs (001) substrates, between which a 200 nm-thick AlSb buffer is used to relaxed the lattice mismatch [Fig. 1(a)]. Reflection high energy electron diffraction (RHEED) and atomic force microscopy (AFM) characterizations indicate good crystal structure and a flat interface in the Al/FMS structures [Fig. 1(b)]. We confirmed the ferromagnetism of (In,Fe)As [Fig. 1(c)] and (Ga,Fe)Sb using magnetic circular dichroism (MCD). The electron mobility values of (In,Fe)As and InAs in the InAs/(Ga,Fe)Sb bilayer structure are 385 cm^2/Vs and 2877 cm^2/Vs, respectively, which are improved by four times from previous reports [3][4], suggesting a stronger superconducting proximity effect in these FMSs. Our results present a promising material candidate for realizing MFs with high scalability.

This work was partly supported by Grants-in-Aid for Scientific Research, CREST and PRESTO programs of JST, UTEC-UTokyo FSI program and the Spin-RNJ.

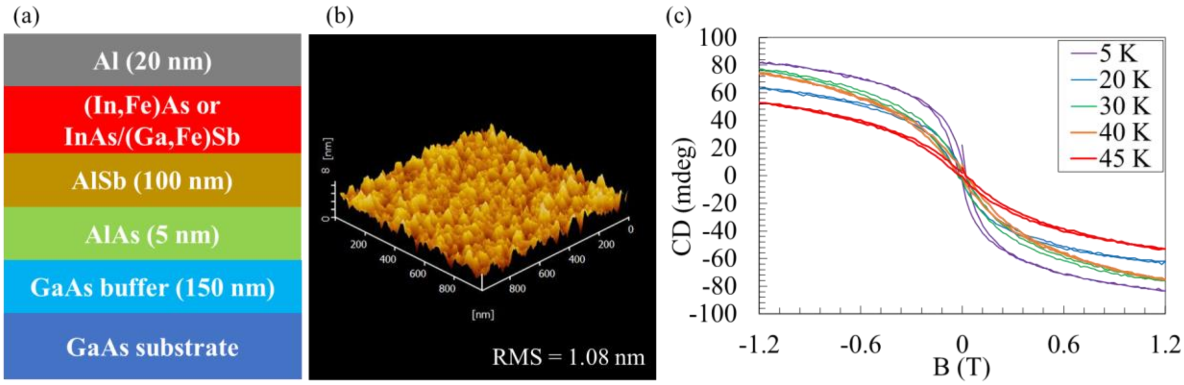

Fig. 1. (a) Structure of superconducting Al/Fe-doped III-V semiconductor. (b) AFM image of Al grown on $In_{0.94}Fe_{0.06}As$. (c) MCD *vs* magnetic field of $(In_{0.94},Fe_{0.06})As$. T_C = 30 K is estimated using the Arrott plot.

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