Growth and characterization of ferromagnetic Fe-doped InAs quantum dots with high Curie temperature

Karumuri Sriharsha,[1,a)] Le Duc Anh,[1,2,3b)], and Masaaki Tanaka[1,4,c)]
[1]Departmen of Electrical Engineering & Information Systems, The University of Tokyo.
[2]Institute of Engineering Innovation, The University of Tokyo
[3]PRESTO, Japan
[4] Center for Spintronics Research Network (CSRN), The University of Tokyo

Semiconductor quantum dots (QDs) have been extensively studied because of their potential to be used in devices such as highly efficient semiconductor lasers or qubits for quantum computation. Furthermore, it is expected that the low-dimensional confinement of carriers in ferromagnetic QDs allows a highly effective gate-voltage control of their magnetic properties and Curie temperature (T_C)[1]. Recently, we have reported the growth of Fe doped GaSb QDs which showed very high T_C (> 400 K)[2]. However, in these QDs, a new cubic phase containing Fe and Ga as primary constituents was formed instead of zinc-blende (ZB) (Ga,Fe)Sb.

In this work, we investigate Fe doped InAs QDs grown in a Stranski-Krastanow (SK) growth mode on semi-insulating GaAs (001) substrates by molecular beam epitaxy. We grew a sample with nominal Fe concentration x = 12% at a substrate temperature of 400°C. The growth rate was 0.01 monolayer (ML)/s and the As back pressure was maintained at 4×10^{-6} Pa. The RHEED patterns (Fig. 1(a)) of the QDs after growth of 6 ML (nominal thickness) showed clear chevron-like patterns which are typical for InAs QDs. Atomic force microscopy (AFM) characterization of the surface topography of the sample reveals formation of QDs. By scanning tunnelling electron microscopy (STEM) imaging, we confirmed the pyramid-like structure of the QDs with a size of ~40 nm. ZB crystal structure is observed both in the GaAs buffer and inside the QD, as also confirmed with the electron diffraction (ED) patterns. The dark field STEM image (Fig. 2) and the energy dispersive X-ray spectroscopy (EDS) mapping reveal that all the Fe atoms are concentrated near the bottom of the QD. This is in contrast to the case of Fe doped GaSb QDs, which show concentration of Fe at the top of the QDs. The magnetization of the QDs, characterized by magnetometry measurements, shows a clear hysteresis curve even at 300 K, implying that T_C is higher than 300 K (Fig. 3). These high-T_C Fe-doped InAs QDs, together with the previous Fe-doped GaSb QDs, are promising for device applications operating at room temperature.

This work was supported by Grants-in-Aid for Scientific Research (17H04922, 18H05345, 19K21961, and 20H05650), CREST (No. JPMJCR1777) and PRESTO (No. JPMJPR19LB) Programs of JST, and Spintronics Research Network of Japan (Spin-RNJ).

References: [1] F. Xiu, *et al.*, Nat. Materials **9**, 337 (2010). [2] K. Sriharsha, *et al.*, APL Materials **8**, 091107 (2020).

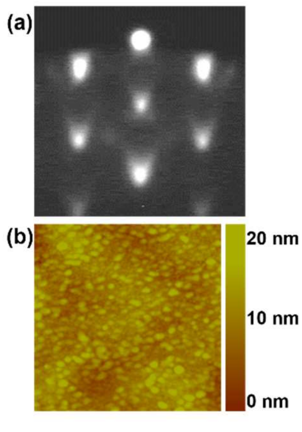

Fig 1. (a) RHEED pattern of the sample taken along the [-110] direction (b) AFM image (1μm × 1μm) of QDs.

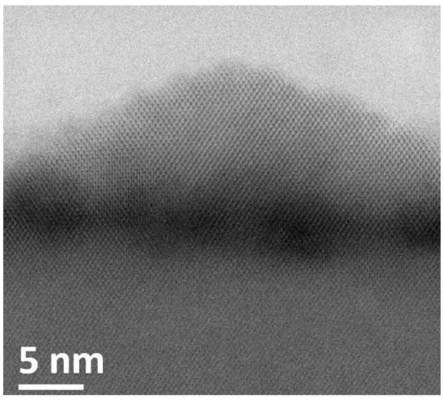

Fig 2. STEM lattice image of an (In,Fe)As QD. Both the buffer layer and the dot show ZB crystal structure.

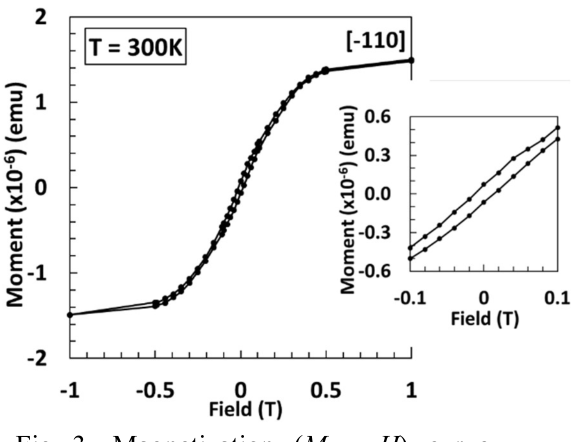

Fig 3. Magnetization ($M - H$) curve showing a hysteresis curve at room temperature. The $M - T$ curve measured with a magnetic field of 10 Oe showing magnetization even at 300 K.