

Interplay of Ferromagnetism and Superconductivity in Fe-Doped Ferromagnetic Semiconductors

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The interplay between superconductivity and ferromagnetism gives rise to unconventional phenomena, including Josephson π -junctions, spin-triplet pairing, and superconducting diode effects, and offers opportunities for exploring Majorana physics. Fe-doped narrow-gap III–V ferromagnetic semiconductors (FMSs) provide a distinctive platform for investigating this interplay by combining ferromagnetic exchange coupling with semiconductor functionality and electrical tunability. Unlike conventional ferromagnetic Josephson junctions, their carrier density and magnetic interactions can be controlled through electrostatic modulation. Our earlier Nb/(In,Fe)As Josephson junctions exhibited long-range proximity-induced superconductivity and unusual magnetic interference patterns, providing evidence for spin-triplet electron pairing [1].

Here, we present two recent advances in epitaxial superconductor/FMS heterostructures grown in situ by molecular beam epitaxy. First, Al films deposited directly on strained (In,Fe)As exhibit superconductivity below 1.1–1.4 K [2]. The dominant Al growth orientation changes from (110) to (111) with increasing the in-plane lattice constant of (In,Fe)As, while superconducting properties correlate with Al morphology and grain size. An anomalous decrease in the critical magnetic field below 0.5 K suggests possible magnetic coupling across the Al/(In,Fe)As interface.

Second, Al/InAs/(Ga,Fe)Sb heterostructures integrate superconducting and magnetic proximity effects in an InAs channel with atomically sharp interfaces [3]. Electrostatic gating can modulate the carrier density in InAs and its wavefunction overlap with the adjacent FMS (Ga,Fe)Sb, offering a route to controlling both Josephson coupling and magnetic proximity interactions. The fabricated junctions exhibit gate-tunable supercurrents and multiple Andreev reflections up to sixth order. Hysteretic and asymmetric Fraunhofer interference patterns provide evidence of induced ferromagnetism and broken time-reversal symmetry. Nonreciprocal critical currents demonstrate a superconducting diode effect with efficiency reaching 20%, while interference analysis suggests enhanced supercurrent near the channel edges. These results establish a promising platform for electrically tunable superconducting spintronics and motivate further exploration of unconventional pairing, topological superconductivity, and Majorana modes.

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[1] T. Nakamura, L. D. Anh, Y. Hashimoto, S. Ohya, M. Tanaka, and S. Katsumoto, “Evidence for Spin-Triplet Electron Pairing in the Proximity-Induced Superconducting State of an Fe-Doped InAs Semiconductor,” *Phys. Rev. Lett.* 122, 107001 (2019).

[2] H. Hara et al., “Orientation selection and superconducting properties of epitaxial Al on ferromagnetic semiconductor (In,Fe)As,” *APL Materials* (2026, in press); arXiv:2609.04744.

[3] H. Hara, L. Baker et al., “Interplay of superconductivity and ferromagnetism in ferromagnetic-semiconductor-based Josephson junctions,” *Communications Materials* (2026, in press); arXiv:2603.17101.

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Supplementary Information:

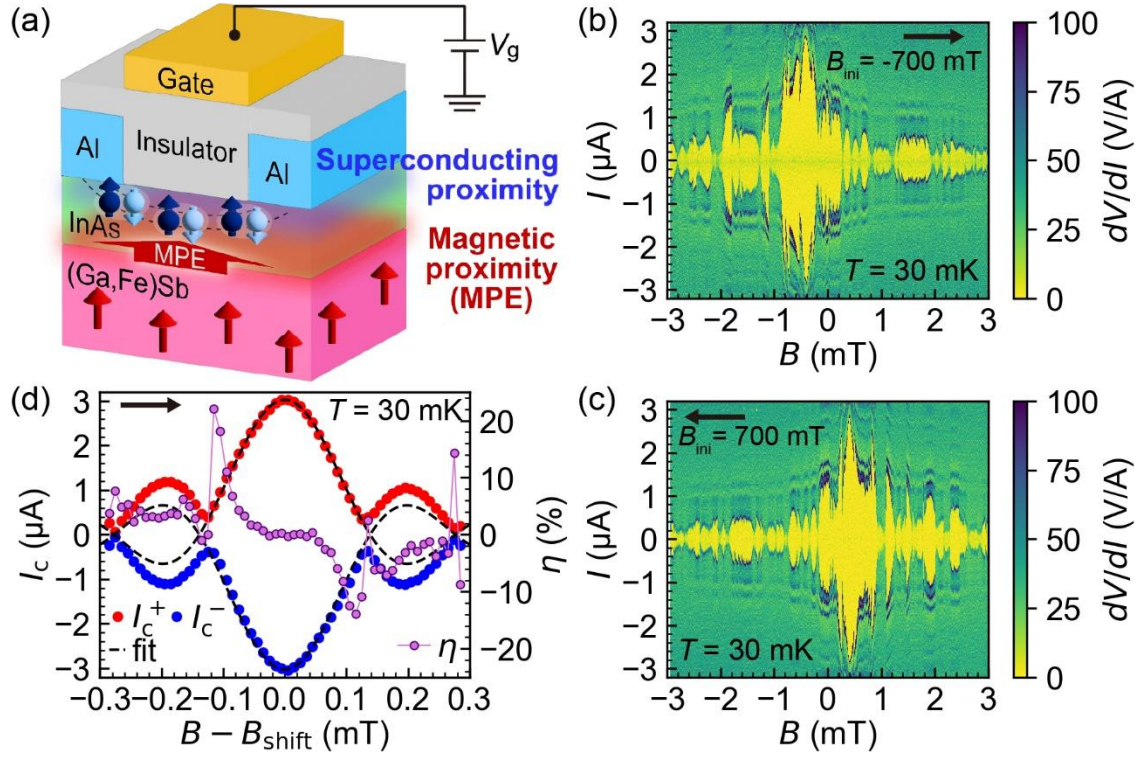


Figure 1. Interplay of ferromagnetism and superconductivity in Al/InAs/(Ga,Fe)Sb heterostructures. (a) Schematic illustration of a planar Josephson junction and the central concept of this study. Superconductivity and ferromagnetism are induced in the nonmagnetic semiconductor InAs layer via proximity effects. Both the proximitised superconductivity and the magnetic proximity effect are controlled by applying a gate voltage. (b), (c) Fraunhofer interference patterns (Differential resistance of the junction as a function of the perpendicular magnetic field B and in-plane current I) obtained from the Josephson junction in this work. Black arrows indicate the sweeping directions of B , and B_{ini} denotes the initial field applied before sweeping. (d) Fine-field dependence of the critical current I_c and superconducting diode efficiency η . B_{shift} corresponds to the field at which the maximum critical current is observed in the measurement setup of (b). No initial field was applied in this measurement. In all panels, the magnetic field is applied perpendicular to the junction plane.