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Proximity-Induced Superconductivity in a Ferromagnetic Semiconductor (In,Fe)As

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Abstract. We observed supercurrent through an *n*-type ferromagnetic semiconductor (In,Fe)As. For the purpose we prepared S/F/S (S: superconductor, F: ferromagnet) junctions, which exhibited zero resistance up to 1 μ m of junction width with critical current over 1 μ A below 1 K. The long reach of the superconducting proximity effect suggests that the induced superconductivity is brought about by spin-triplet paring in (In,Fe)As.

1. Introduction

The superconductor(S)/ferromagnet(F)/superconductor(S) structure is attracting attentions as a new platform of unconventional superconductivities. In a simple thought, the exchange interaction between spins destroys the conventional spin-singlet Cooper pairs in ferromagnetic materials[1]. In some limited cases, however, the proximity effect in the SFS devices enables superconductivity to go into ferromagnets far away from the interfaces[2]. The theoretical and experimental works suggest that the superconductivities deep inside the ferromagnets are driven by a spin-triplet type electron pairing, which is created in the vicinity of interfaces under certain conditions[2, 3, 4]. Such spin-triplet pairs particularly in so called half-metallic ferromagnets, i.e., materials with perfect spin polarization, can have the penetration depth as long as that of conventional spin-singlet pairs in normal metals[5, 6, 7].

One of the big findings of ferromagnetic materials is that of III-V based ferromagnetic semiconductors (FMSs), which have comparatively high transition temperatures and good connectivity to highly elaborated quantum structures. And above all, the magnetism can be controlled through the carrier concentration. An interesting idea here is to form an S/F/S junction with an FMS and superconducting metals. Many of the FMS have been reported to be half-metallic and the ferromagnetic interaction is mediated by electric carriers[8, 9]. For good electric contacts with metals, narrow-gap semiconductor like InAs is appropriate for the base material. InAs has natural surface two-dimensional electrons and, the carrier type should be n. Recently found (In,Fe)As just fits to these good-contact conditions. Here we report the

transport properties of Nb/(In,Fe)As/Nb junctions with low interface barriers. They showed finite superconducting critical currents with long proximity length, which suggests spin-triplet type pairing.

2. Experimental

(In,Fe)As with Fe concentration of 6% was grown by low temperature molecular beam epitaxy on a (001) GaAs substrate with buffer layers[10]. The mobility and the concentration of carriers were estimated at 3.5 K to be 100 cm²/Vs and 8 × 10¹⁸ cm, respectively. The Curie temperature was estimated to be about 120 K from the temperature dependence of the magnetic susceptibility. The sample structure is illustrated in Fig.1(a). Nb/Ti electrodes with the width of 30 μ m patterned by electron-beam lithography were deposited immediately after surface cleaning by Ar plasma, on top of the (In,Fe)As film with ion-beam sputtering. An optical micrograph image of a junction is shown in Fig.1(b). We fabricated two junctions with the separation between the electrodes (gap) L of 1 μ m (junctions A, B) and the one with 1.5 μ m (junction C). The current directions were along [110] for junction A and [110] for junctions B and C.



Figure 1. (a) Schematic cross sectional view of the samples. (b) Optical microscope image of junction A. (c) Temperature dependence of the zero-bias resistance of junction A. The AC current modulation is 100 nA-rms at the frequency of 19 Hz.

The junctions were cooled down in a dilution fridge down to 0.1 K. Each wire passes through a 2 k Ω resistor as a low-pass filter anchored at the mixing chamber. The differential resistance R = dV/dI of the junctions were measured by a lock-in technique with AC current modulation. All data presented in this paper were taken under zero magnetic fields.

3. Results and discussion

The Nb/Ti electrodes undergo superconducting transition at around 5 K, to which zerotemperature superconducting gap Δ_0 of 0.9 meV corresponds. Figure 1(c) displays the temperature dependence of the zero-bias resistance of junction A. The resistance is almost constant below the transition temperature and above 1.6 K, below which it decreases again with the temperature. This temperature dependence manifests that the superconducting coherence penetrates into the F-regions of the junctions via the proximity effect. At the lowest temperature around 0.1 K, all the junctions show non-linear *I-V* characteristics, that is a dip structure in dV/dI at zero-bias current. As shown in Fig.2, zero-bias resistance of each junction at the lowest temperature is less than half of its normal resistance, exceeding the conductance enhancement by the Andreev reflection. Especially, junction B exhibits clear zero resistance plateau at around zero bias. IOP Conf. Series: Journal of Physics: Conf. Series 969 (2018) 012036





The proximity length of 1 μ m is even longer than that reported for ballistic two-dimensional electrons in a pure InAs quantum well[11, 12]. The supercurrent over such a long distance in ferromagnetic (In,Fe)As strongly suggests spin-triplet pairing because it is well known that spin-singlet pairs survive in ferromagnets only for a few tens of nanometers[13, 14, 15]. The spatial dependence of the spin-singlet order parameters in ferromagnets is calculated from the Usadel equations[16] or the Eilenberger equations[17]. The decay length ξ_d in dirty limit and ξ_c in the clean limit are written as follows:

$$\xi_{\rm d} = \sqrt{\frac{D}{\sqrt{(\pi T)^2 + E_{\rm ex}^2 \pm \pi T}}},$$
(1)

and
$$\xi_{\rm c} = \frac{\xi_0 l}{\xi_0 + l}, \quad \xi_0 = \frac{v_{\rm F}}{2\pi T}$$
 (2)

where D, $E_{\rm ex}$, l and $v_{\rm F}$ are the diffusion coefficient, exchange field, mean free path, and the Fermi velocity in ferromagnets, respectively. In (In,Fe)As, from the parameters $D = 1.4 \times 10^{-3} \text{ m}^2/\text{s}$, $E_{\rm ex} = 31.7$ -50 meV, l = 3.7 nm, and $v_{\rm F} = 1.1 \times 10^6$ m/s, the characteristics length $\xi_{\rm d}$ and $\xi_{\rm c}$ are calculated as 4.2-5.3 nm and 3.7 nm at 0.1 K, respectively[9].

The applicability of the above discussion can further be tested from the temperature dependence of the critical current I_c . Because the rise of the resistance is rather soft as shown in Fig.2, we here define I_c as the bias current where the resistance is equal to 1 Ω . The data in Fig.3 were obtained in the following way. After a magnetization process of (In,Fe)As, in which the magnetic field along [110] (in-plane) was cycled between 0 and 3 kOe with ending up at 0 Oe at the lowest temperature, the specimen was warmed up over 7 K and cooled down to the lowest temperature again at zero field in order to eliminate the magnetic flux pinning in superconducting electrodes. After this process, the I_c increased to 1 μ A below 0.1 K. Then with increasing temperature, I_c was measured.

The I_c decreases monotonically with increasing temperature, in accordance with the previous works on S/ (half metallic) F/S junctions[6, 18]. The asymmetry of the I_c against the current direction reflects the broken time reversal symmetry due to the ferromagnetic exchange in (In,Fe)As. The curves of the I_c are slightly concave upward, indicating that the present junction is not in the tunnelling regime but in the weak-links regime, and the theories for weak-links are applicable[19]. This temperature dependence assures that we can apply the estimation of monotonic decay of the order parameter even though the (In,Fe)As is ferromagnetic, as predicted for the triplet pairing in ferromagnet[20]. Hence the results in Fig.3 are consistent with the emergence of spin-triplet superconductivity in the ferromagnetic (In,Fe)As layers.



Figure 3. Temperature dependence of the critical current I_c in junction B without external magnetic field. The AC current modulation for the measurement of dI/dV vs I characteristics to obtain the I_c is 10 nA-rms at the frequency of 870 Hz.

For the spin-triplet superconductivity to emerge in the proximity effect, inhomogeneous magnetization around the interfaces is required as a spin mixing matrix, which interconnects the singlet pairs and the triplet pairs[3]. In this theory of proximity induced spin-triplet superconductivity, S/F'/F/F'/S structures are proposed to realize such inhomogeneous magnetization. However in the present case, such inhomogeneity is expected to be formed naturally at the surface of FMS due to the strain in the crystal generated from the layered structure. The crystal direction dependence of the critical current shown in Fig.2 probably comes from the directional dependence of the strain that gives difference in the amplitude of spin-mixing matrix elements.

4. Conclusion

We fabricated S/F/S junctions from an *n*-type III-V based FMS (In,Fe)As and observed finite supercurrents through them. This is the first realization of proximity driven superconductivity in FMSs. The supercurrents are presumably carried by spin-triplet Cooper pairs induced at the interfaces just like those observed in superconductor/half-metal junctions.

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