Superconducting proximity effect in epitaxial Nb(110)/Au(111)/Nb(110) trilayers

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Superconducting electronics, in which currents are carried by superconducting pairs of electrons, have great potential for future application in quantum computing. An essential element of superconducting circuits is the π junction, in which the phase of a superconducting wave function is inverted. One promising approach to building such a junction is to exploit the interplay between superconductivity and magnetism in superconductor (SC)/ferromagnet (FM)/SC heterostructures. Such multilayer structures are widely believed to achieve a Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state, in which the superconducting proximity effect drives a superconducting order with oscillating phase within the FM layer.[1)] However, this approach suffers from a serious drawback that the ferromagnetic elements tend to suppress superconductivity, forcing devices to operate at lower temperatures and with lower critical current densities.

In this study, we show that, in epitaxial Nb(110)/Au(111)/Nb(110) trilayers, the equilibrium superconducting state presents strong evidence of 0-π state transitions as a function of the Au-layer thickness (t_{Au}). Through the analysis of experimental data, we make a reasonable argument that a form of order-parameter oscillation, similar to the FFLO-like state in FM for SC/FM/SC junctions, is intrinsic to the proximity-induced Cooper pairs in the Au(111) layer. We tentatively ascribe this effect to the spin-orbit coupling (SOC) within the Au layer. Where SOC lifts the degeneracy between "up" and "down" spin electrons, electron pairs can form with a non-zero momentum. This leads to FFLO-like oscillations of the superconducting order parameter in real space. In the fcc lattice of Au, inversion symmetry is broken in the direction perpendicular to the (111) plane because of the ABCABC... stacking sequence of atomic planes, and the lack of inversion symmetry leads to the emergence of SOC.

We prepared a series of Nb(110)/Au(111)/Nb(110)

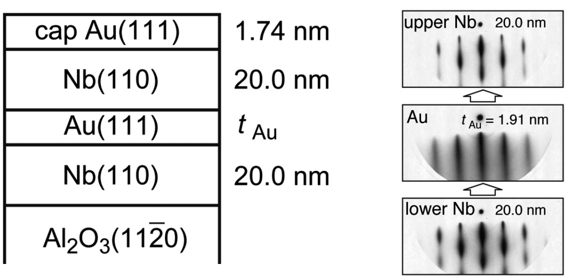

Fig. 1. Schematic diagram of a vertical section of the sample and the reversal images of RHEED patterns obtained in the growth process (right).

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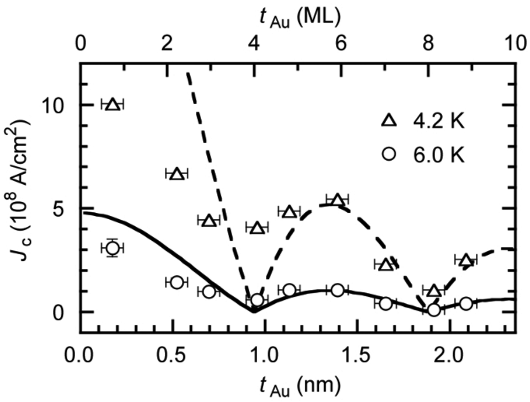

Fig. 2. Critical current density J_c of the Nb/Au[t_{Au}]/Nb trilayers at 4.2 K and 6.0 K (ML: atomic monolayer).

trilayers on single crystals of $Al_2O_3(1120)$ using MBE method. The sample structure is shown in Fig. 1. We will focus on single-domain samples ($0 < t_{\mathrm{Au}} \leq 2.10$ nm), the superconducting properties of which are uniquely determined by t_{Au}. The superconducting critical current density J_c in zero magnetic field was estimated from the width of the M-H hysteresis curve for $H//$ sample plane by using a Bean model.[2)] The data in Fig. 2 appear exactly like those for FM/SC multilayers, which have been confirmed to exhibit the 0-π state transitions as a function of t_{FM}.[3)] Following previous articles,[3,4)] we used the equation:

$$J_c = J_c^0|\sin y|/y, \quad \text{where} \quad y = 2\pi E_{\mathrm{ex}}^{\mathrm{eff}} t_{\mathrm{Au}}/hV_f^{\mathrm{Au}}. \qquad (1)$$

The solid and dashed lines in Fig. 2 show theoretical fits to the data for 6.0 K and 4.2 K, respectively. Fits are obtained as a function of $E_{\mathrm{ex}}^{\mathrm{eff}}$ (= 84.6 meV) for $\nu_f^{\mathrm{Au}} = 1.39 \times 10^6$ m/s and the ratio $J_c^0(4.2\ \mathrm{K})/J_c^0(6.0\ \mathrm{K}) = 5.0$, where $E_{\mathrm{ex}}^{\mathrm{eff}}$ is an effective parameter characterizing the order-parameter oscillations in the Au layer, ν_f^{Au} the Fermi velocity of Au, and J_c^0 the overall scale for J_c.

The value of $E_{\mathrm{ex}}^{\mathrm{eff}}$ (=84.6 meV) is consistent with the SOC strength (120 meV) of conduction electrons in Au. A pairing state should occur between two electrons on the SOC-induced split parts of the Fermi surface. One might refute this argument on the grounds that a difference of 84.6 meV in energy between the spin-split bands is too large for the electrons to form a pair since the superconducting gap is no more than 1.40 meV in Nb. However, this is not the case with regard to the proximity effects.[5)] Clearly, a theory is needed that treats the SOC effect on the proximity-induced Cooper pairs in a SC/normal metal/SC system.

References

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