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The physics of superconductor–ferromagnet hybrid structures (Mini-review)

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In this review, we summarize the foundations underlying a variety of phenomena in superconductor–ferromagnet hybrid structures, with a focus on recent advances in several key areas. These include: (i) the fundamental understanding of proximity effects in superconductor– ferromagnet based systems; (ii) spin-valve effects in superconductor– ferromagnet and superconductor–ferromagnet–superconductor Josephson junctions; and (iii) the design and realization of superconducting memory elements, particularly in hybrid Josephson junctions. We also discuss the experimental progress in fabricating and characterizing spin-valve structures.

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Superconductor–ferromagnet (SF) hybrids exhibit rich quantum phenomena due to competing spin-singlet pairing and ferromagnetic polarization [1–3]. The exchange field H in the F-layer induces spatial oscillations in the superconducting order parameter, analogous to the Fulde–Ferrel–Larkin–Ovchinnikov (FFLO) state [4, 5]. This oscillatory proximity effect is characterized by a complex coherence length $\xi = \xi_1 + i\xi_2$, where ξ_1 (decay) and ξ_2 (oscillation period) typically differ due to spin-flip/spin-orbit scattering. SF structures enable superconducting spin valves and memory elements. Devices like Co/Nb spin-valves show tunable magnetic reconfiguration at low fields [6]. The oscillatory pair amplitude causes non-monotonic behavior of T_c vs F-layer thickness d_F in SF nultilayers [7]. Reentrant superconductivity – where T_c vanishes then reappears with increasing d_F – observed in $Nb/Cu_{1-x}Ni_x$ confirms FFLO-like states [8]. In SFS Josephson junctions the critical current I_c oscillates and decays as a function of the F-layer thickness d_F: $I_c \propto \exp(-d_F/\xi_1)\sin(d_F/\xi_2 + \pi/4)$. Negative I_c corresponds to a π-state with the ground-state phase difference π, first observed in $Nb/Cu_{1-x}Ni_x/Nb$ structures [9]. Controllable 0–π transitions have been realized in [10] in Nb–Ni–Nb junctions fabricated by focused ion beam (FIB) etching (see Fig. 1). SIsFS junctions provide independent control of critical current (via SIs part) and ground state phase (via sFS part) enabling π-junctions or memory applications [14]. Future research directions include circuit integration and miniaturization for cryogenic and quantum applications [15].

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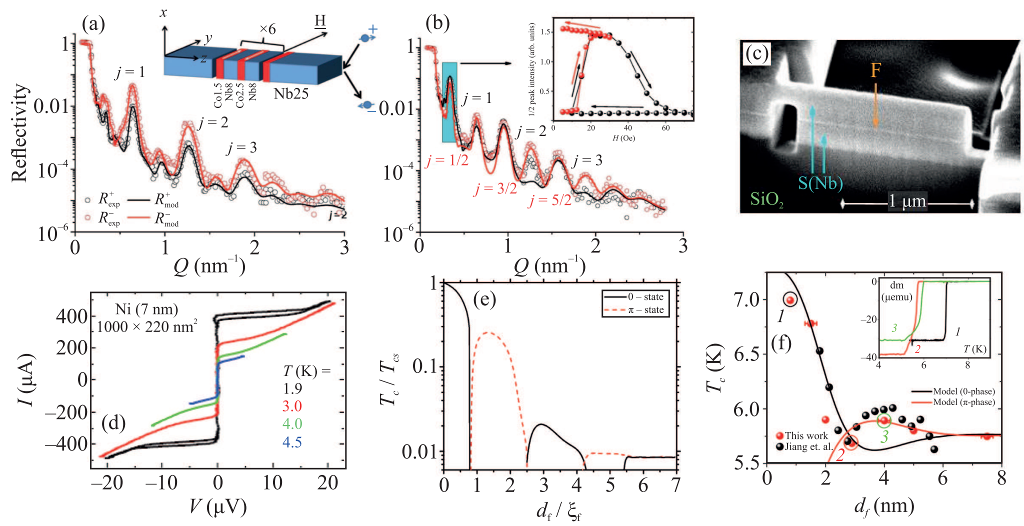

Fig. 1. (Color online) (a), (b) – Experimental (dots) and simulated (solid lines) specular neutron reflectivity curves at $T = 13$ K in magnetic fields of $H = 300$ Oe (a) and $H = 30$ Oe (b). Insets: (a) – schematic of the sample; (b) – magnetic field dependence of the $j = 1/2$ Bragg peak (blue). The sample consists of a periodic [Co(2 nm)/Nb(8 nm)]×12 spin-valve structure [6]. Numbers above the peaks denote the Bragg reflection order. (c) – SEM image of an SFS junction fabricated using FIB etching. (d) – I–V characteristics of a Nb/Ni (7 nm)/Nb junction [10]. (e) – Calculated values of dependence of T_c on d_F [11]. (f) – Experimental $T_c(d_F)$ data from [12] (red dots) and [15] (black dots). Solid lines are theoretical fits for 0 and π states [11] in S/F/S structures using parameters from the measurements [12, 13]. Inset shows the temperature dependence of the magnetic moment for the set of samples marked in the main panel (from [14]. Inset: the curves 1–3 show the temperature dependence of the magnetic moment for the set of samples marked in the main panel

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