Superconducting proximity effects in Nb/rare-earth bilayers

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A systematic study of the superconducting proximity effects in Nb/rare-earth (RE) bilayers is reported, where RE indicates Gd, Tb, Dy, and Ho (the first four heavy RE elements in the periodic table). Gd, Tb, and Dy are in the ferromagnetic state below 293 K, 222 K, and 85 K, respectively, while Ho exhibits conical ferromagnetism (inhomogeneous magnetism) below ~20 K.

Using the epitaxial growth of $Al_2O_3(11\bar{2}0)$/Nb(110)/RE(0002), a single-crystal layer of RE was fabricated. The thickness of the RE layer, t_{RE}, was varied from 10 nm to 20 nm with an interval of Δt_{RE}=0.4 nm. The superconducting transition temperature T_c of the samples was measured. We carried out a periodicity analysis on the $T_c(t_{RE})$ data using a quantitative fast Fourier transform (FFT) method. The results of the analysis are summarized in Fig. 1. With the exception of the longest period (~3.5 nm) for Gd, two types of variations are confirmed in the element dependence of the oscillation period. Here, we refer to the longer periods (more than 1 nm) as λ_L and the shorter periods (about 1 nm) as λ_S. The spin modulation period intrinsic to Ho, λ_{spin}^{Ho}(=3.4 nm; open circle), is located within a broad distribution of λ_L for Ho. We identify a linear change in λ_L (shown as a broken line) from Gd to Dy. The line is extrapolated to Ho, giving an extrapolated value of 2.45 nm at Ho.

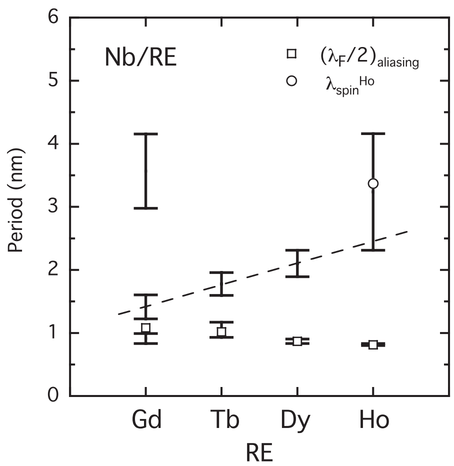

Fig. 1. Summary of the FFT analysis: periods of the oscillation components in $T_c(t_{RE})$ for Gd, Tb, Dy, and Ho (in order of atomic number). The broken line represents a linear extrapolation of the λ_L values for Gd, Tb, and Dy, to Ho. We observe a good agreement between $(\lambda_F/2)_{aliasing}$ (open squares) and the short-wavelength period λ_S. The helical spin-modulation period in bulk Ho at low temperatures (~2K) corresponds to λ_{spin}^{Ho}=3.4 nm (open circle).

According to the picture of the RKKY interaction between valence electrons and 4*f* moments, the exchange energy E_{ex} at 0 K scales linearly with the 4*f* spin moment *S*, where *S*=7, 6, 5, and 4 μ_B for Gd, Tb, Dy, and Ho, respectively. The spatial period of the FFLO-like oscillation, λ_{FFLO}, in the REs therefore increases from Gd to Ho at low temperatures, as long as $\lambda_{FFLO} \propto v_F/E_{ex}$ holds (a clean ferromagnet) and the Fermi velocity v_F is almost unchanged for the REs. The broken line actually suggests that λ_L increases as $S(\propto E_{ex})$ decreases. Further, the values of λ_L for Gd and Ho are in good agreement with the literature data for λ_{FFLO}.[1,2] Hence, we infer that the broken line indicates the element dependence of λ_{FFLO}.

The Fermi wavelength λ_F of each RE was calculated from λ_{FFLO} (the broken line) and the experimental values of E_{ex} for the Δ_2 valence states.[3] To date, there is little experimental data of v_F and λ_F for REs. The open squares show the calculated results of $(\lambda_F/2)_{aliasing}$, i.e., the aliased $\lambda_F/2$ by discrete-thickness sampling. We recognize that the values of $(\lambda_F/2)_{aliasing}$ reproduce λ_Ss well. This suggests that λ_Ss reflect the formation of quantum well states (QWSs) in the RE layer, as observed in the superconducting Pb film.[4] QWSs require the full penetration of Cooper pairs into the RE layer through the entire thickness. Accordingly, the presence of λ_Ss indirectly proves the presence of triplet pairs in the REs. It is possible that some local probes supplied by RI beams detect the triplet pairs converted from the singlet pairs of Nb owing to the exchange field in REs.

References

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