

Suppression of superconductivity in superconductor/ferromagnet multilayers

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Abstract

Suppression of the superconducting transition temperature (T_c) of NbN thin films in superconductor/ferromagnet multilayers has been investigated. Both superconducting NbN and ferromagnetic FeN layers were deposited on thermally oxidized Si substrate at room temperature by using reactive magnetron sputtering in an Ar- N_2 gas mixture. The thickness of FeN films was fixed at 20 nm, while the thickness of NbN films was varied from 3 nm to 90 nm. T_c suppression was clearly observed in NbN layers up to 70 nm thickness when NbN layer was in proximity with FeN layer. For a given thickness of NbN layer, the magnitude of T_c suppression was increased in the order of Si/FeN/NbN, Si/NbN/FeN, and Si/FeN/NbN/FeN structure. This result can be used to design a spin switch whose operation is based on the proximity effect between superconducting and ferromagnetic layers.

Keywords: Proximity effect, NbN/FeN bilayer, NbN/FeN trilayer

1. INTRODUCTION

When a superconducting layer is in contact with a ferromagnetic layer, the superconducting transition temperature (T_c) is significantly reduced due to the proximity effect since the superconducting order parameter, which is composed of a single spin configuration of the Cooper pairs in the superconducting layer, is strongly influenced by the electron spin states in the ferromagnetic layer where parallel spin alignment is preferred. Variety of superconducting (S) and ferromagnetic (F) materials has been employed to investigate the proximity effect between two antagonistic long-range orderings. For the S layer, Nb [1-9] or Pb [10] was mostly used and, for the F layer, Fe [10], Co [8], Ni [3] elements or CuNi [1, 2, 9] and NiFe alloys [4-7] have been widely used.

Suppression of T_c due to proximity effect between S/F layers has been intensively investigated [9, 10] and the dependence of T_c on the thickness of the S or F layer has been analyzed with theoretical models [9-12]. One of drastic results observed in F/S multilayers is the oscillation of T_c with varying the F layer thickness. The other is that the interface between the S and F layer showed a strongly reduced transparency. The reason for the reduced transparency has been attributed to the formation of non-magnetic alloy layer in the interface, which behaves as a barrier against the Cooper pair propagation. Presumably because of this, an ideal performance of spin switch has never been observed experimentally so far.

As a first step toward ideal transparency between the S and F layer, we intend to reduce the alloying effect at the interface, that is, to reduce the thickness of non-magnetic alloy layer. One solution might be to use same nitride materials for both S and F layers. Suitable materials are NbN for the S layer and FeN for the F layer. In such case,

both materials contain nitrogen in common so that a direct alloying of Fe and Nb could fortunately be reduced.

One way to probe transparency of the interface, although indirect, is to measure the suppression of T_c since it can be a barometer for the strength of the proximity effect between the S and F layers. In this work, we present a systematic study of T_c suppression of NbN thin films in NbN/FeN bilayer and trilayer structures. For the bilayer structure, two different structures, NbN layer on FeN layer and NbN below FeN layer, were used.

2. EXPERIMENTAL

Both superconducting NbN and ferromagnetic FeN thin film multilayer have been prepared on thermally oxidized Si substrates by reactive magnetron sputtering in an Ar- N_2 gas mixture. The details of the fabrication conditions for each layer have been published elsewhere [13,14]. The base pressure of the multi-target sputtering system after overnight pumping was lower than 3×10^{-7} Torr. The sputtering power was 100 W and the substrate holders were cooled with coolant at 5 °C. During the deposition of NbN layer, total sputtering gas pressure was maintained at 1.2×10^{-3} Torr while the partial pressure of N_2 gas was fixed at 8.2%. For the FeN layer, total pressure was 1.4×10^{-3} Torr and the partial pressure of N_2 gas was 3.3%. The thickness of FeN films was fixed at 20 nm, while the thickness of NbN films was varied from 3 nm to 90 nm. Four different layer-structures were employed: a single NbN layer of Si/SiO₂/NbN (S), two bilayer structures of Si/SiO₂/FeN/NbN (F/S) and Si/SiO₂/NbN/FeN (S/F), and trilayer of Si/SiO₂/FeN/NbN/FeN (F/S/F). In order to minimize possible run-to-run variations of the detail deposition conditions, we fabricated 12 samples of different NbN thickness in series for each structure in a

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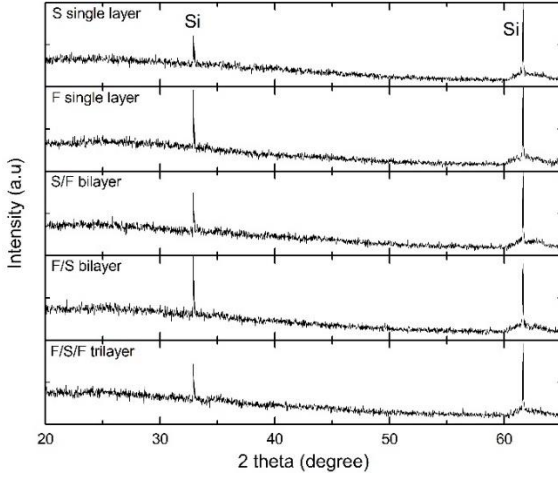


Fig. 1. X-ray diffraction patterns of five different NbN and FeN single layers and multilayers. The sharp peaks are from Si substrates. No discernable peak was observed for all the structures, implying that all NbN and FeN layers are amorphous in phase.

single run by using a linear motion shutter and rotating sample holder platform.

The film structure was characterized by X-ray diffraction (XRD) through θ - 2θ scan using Cu K_α source. The temperature dependence of resistance was measured by using a conventional dc four-probe method in a closed-cycle refrigerator down to 3.0 K. Mid-point temperature of the superconducting transition was defined as T_c of a given sample.

3. RESULTS AND DISCUSSION

Fig. 1 shows the XRD scans of single NbN and FeN layers, NbN/FeN (S/F) and FeN/NbN (F/S) bilayers, and FeN/NbN/FeN (F/S/F) trilayers. The thickness of NbN layers were 40 nm and that of FeN layers were 20 nm, respectively. The above thicknesses were chosen because those thickness range corresponds to a condition where suppression of T_c due to proximity effect starts to exhibit a notable change.

Two sharp peaks at 33° and 62° are from Si substrate. Except those peaks, no other discernable peak was observed in all samples. NbN (200) and (111) peaks used to be detected at 41° and 35° , and (110) peak of α -Fe used to exist at around 44° when polycrystalline phases were formed [13,14]. The present results of the XRD scans state that all NbN and FeN layers prepared with the current deposition conditions are amorphous in phase.

Fig. 2 shows T_c of all four structures as a function of NbN layer thickness (d_s). One can observe monotonically decreasing T_c as d_s is decreased. In general, the effects of boundary scattering and reduced dimensionality compared to the superconducting coherence length cause T_c to fall with decreasing d_s . For a reference, the Ginzburg-Landau coherence length at 0 K estimated from the upper critical field was ~ 4.5 nm for similarly prepared NbN films [13].

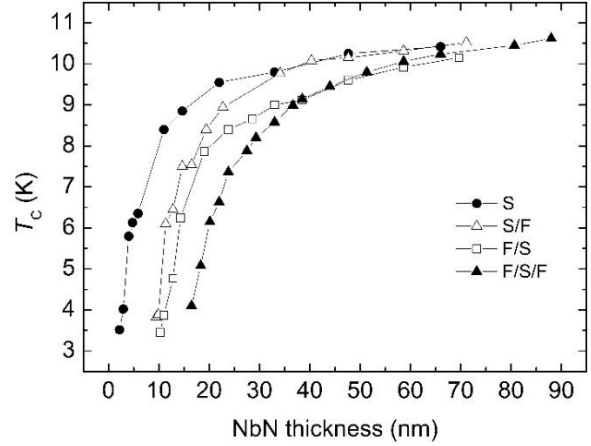


Fig. 2. The superconducting transition temperature (T_c) of all four structures as a function of NbN layer thickness. As the thickness was decreased, T_c was monotonically decreased. The magnitude of the T_c suppression was increased in order of S, F/S, S/F, and F/S/F structure for a given NbN thickness.

This agrees with a very steep fall of T_c of single NbN layer below 10 nm. The free NbN layers had the highest T_c at given NbN thickness, and F/S, S/F, and F/S/F in order of higher T_c .

The largest T_c suppression has been observed in the F/S/F structure for a given d_s . It is expected since the proximity effect influences the superconductivity of NbN layer from both ferromagnetic sides, therefore, the pair breaking effect in the F/S/F structure should be larger than the bilayer structures. For the F/S/F trilayer, T_c suppression relative to the S layer persists up to $d_s \sim 70$ nm. On the other hand, T_c difference between the S and F/S layer disappears at $d_s \sim 35$ nm and that between the S/F and F/S/F layer does at similar d_s . An interesting result is the dissimilar T_c suppression between the F/S and S/F layers compared to T_c of the S layer. It implies that although microstructure of each layer is same amorphous phase, the interfacial properties between the S and F layers depends on the order of layer deposition. T_c suppression is larger in the S/F structure. If we interpret the dissimilar T_c suppression between the F/S and S/F layers in terms of the interface transparency, the S/F structure has higher transparency than the F/S structure, in other words, the transmission probability of finite momentum state of the Cooper pairs coming out from the F layer is larger in the S/F structure. The destructive interference between the transmitted and incident wave functions gives rise to a suppression of superconductivity.

Because of the suppression of superconductivity, the effective thickness of the superconducting layer will be significantly reduced. Fig. 3(a) shows two $T_c - d_s^{\text{eff}}$ curves of the S and the F/S structure, respectively. Here d_s^{eff} is the effective thickness of the superconducting layer. For single Nb layer, $d_s^{\text{eff}} = d_s$, but for the F/S structure, $d_s^{\text{eff}} = d_s - 7$ nm was used. One can find that the two $T_c - d_s^{\text{eff}}$ curves coincide very well. It implies that the superconducting thickness has been reduced by ~ 7 nm due to the proximity

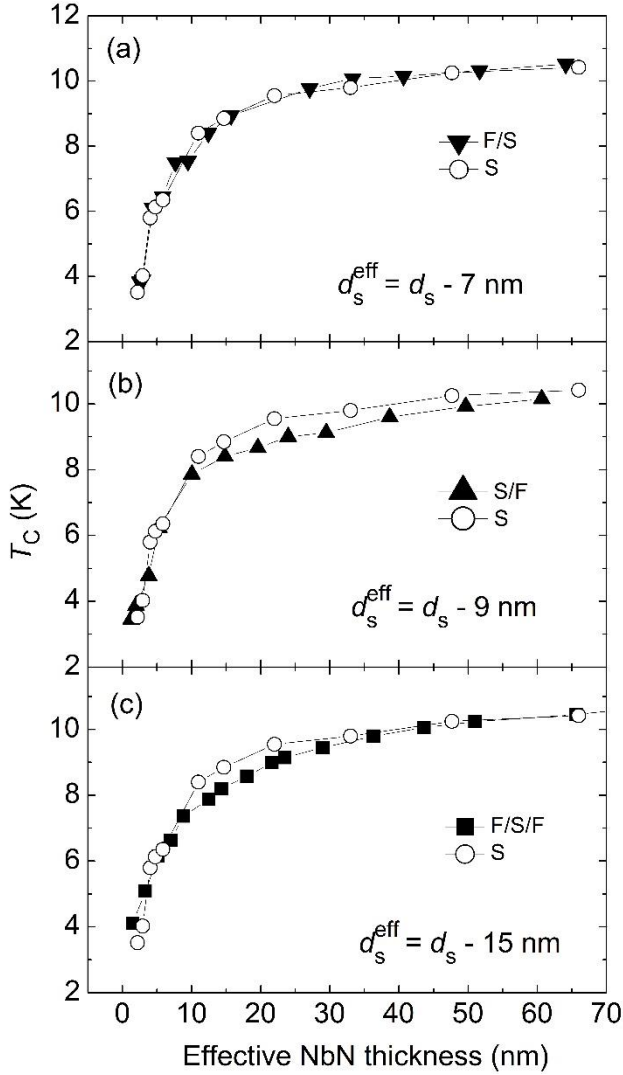


Fig. 3. Comparison of T_c 's of the multilayers and the single NbN layer after adjusting the nominal thickness (d_s) of the multilayers to effective superconducting thickness (d_s^{eff}). (a) F/S and S, (b) S/F and S, and (c) F/S/F and S. After adjustment to d_s^{eff} , agreement of T_c 's between the S and the multilayers is quite good.

effect, in other words, 7 nm deep layer in proximity with FeN layer is effectively normal and the remnant part is superconducting. One may regard this normal layer thickness as the decay length of the exchange driven pair breaking.

Fig. 3(b) is two $T_c - d_s^{\text{eff}}$ curves for the S and the S/F structures, respectively, with $d_s^{\text{eff}} = d_s - 9 \text{ nm}$. The agreement between the two curves is still good. The larger decay length in the S/F structure than in the F/S structure is thought to be related to the larger T_c suppression in the S/F structure.

Fig. 3(c) displays two $T_c - d_s^{\text{eff}}$ curves for the S and the F/S/F structure, respectively. Here $d_s^{\text{eff}} = d_s - 15 \text{ nm}$ was used for the trilayer. Two curves agree with each other well for entire range of d_s^{eff} . We note that the induced normal layer thickness of 15 nm in the F/S/F structure is very close to the sum of each normal layer thickness of two bilayers, 7 nm for the F/S and 9 nm for the S/F structure. This fact

supports that in the F/S/F trilayer, the proximity effect suppresses the superconductivity in NbN layer from each ferromagnetic side: $\sim 7 \text{ nm}$ from bottom FeN layer and $\sim 9 \text{ nm}$ from the top FeN layer, respectively. So far the obtained information provides the low and upper limit of d_s , that is, $16 \text{ nm} < d_s < 40 \text{ nm}$, in order to observe spin switching effect in FeN/NbN/FeN trilayers.

As shown above, a small asymmetry exists in T_c suppression as well as in the decay length of the exchange driven pair breaking between the two F/S and S/F structures. This is somewhat anticipated because the growth conditions for the bottom and top FeN layer are essentially different: The bottom FeN layer is on a substrate and the top FeN layer is on the NbN layer. When asymmetric effect is strong, T_c of a multilayer is determined by the F layer with the larger influence on the superconductor. However, T_c difference between two magnetic states of the F layers, parallel and antiparallel alignment, is determined by the F layer with smaller influence, which is the most important operation parameter for the implementation of a spin switch based on the F/S/F trilayers. Thus, reducing asymmetry from the present magnitudes needs more consideration in the future. Another future task is the estimation of the interface transparency. The estimation by using the $T_c - d_s$ curves is not straightforward. It requires additional experimental data of T_c with variation of the F layer thickness, instead of the S layer thickness, as well as intensive numerical calculations. This formidable task will be next step of the ongoing research.

4. SUMMARY

NbN/FeN multilayers have been prepared while varying the thickness of the superconducting NbN layer. Relative T_c suppression among different multilayer structures were analyzed in order to obtain optimum condition for NbN thickness for the fabrication of spin switch.

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