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Anomalous T_c behavior in NbTi/Nb superconducting multilayer

Y. Obi[a], M. Ikebe[b], H. Fujishiro[b] and H. Fujimori[a]

[a]Institute for Materials Research, Tohoku University, Sendai 980, Japan.
[b]Faculty of Engineering, Iwate University, Morioka 020, Japan

The sputter deposited NbTi/Nb multilayers are found to show anomalies in T_c vs λ curves. These anomalies seem to be associated to the Anderson localization and/or the reduction of Debye temperature related to a lattice parameter anomaly.

1. INTRODUCTION

In superconductor(S)/normal metal(N) multilayers where S and N metals are in close contact each other, the proximity effect plays a vital role to determine the fundamental superconducting properties. According to the theories based on the proximity effect T_c of multilayers always decreases with the decrease of the structural modulation wavelength λ ($\lambda=d_S+d_N$, where d_S and d_N is the layer thickness of S and N layer) and finally reaches Cooper limit. Even in superconductor/superconductor S/S multilayers, the proximity effect leads to only the monotonic change in T_c vs. λ curve. The present sputter deposited S/S multilayers NbTi/Nb, however, were found not to show monotonic change in T_c but to show an anomalous minimum in T_c vs. λ curve. We discuss about the possible origins for this anomaly.

2. SAMPLE PREPARATION AND EXPERIMENT

NbTi/Nb have been fabricated by a sputter deposition technique. The starting target materials were $Nb_{65}Ti_{35}$, $Nb_{28}Ti_{72}$, $Nb_{51}Ti_{49}$ and Nb. NbTi targets were prepared from Nb and Ti both with purity 99.95%. Prior to deposition the chamber was evacuated to below 5×10^{-7}Torr. All the samples were arranged to have an equal sublayer thickness ($d_S=d_N=(1/2)\lambda$). λ ranged from about 20Å to 2000Å with total thickness about 5000Å. Quartz glasses were used for the substrates. The values of λ was checked by the low angle X-ray diffraction. The deviation of λ of the nominal values from the analyzed values were less than 10%. We denote these λ values by the nominal ones, for convenience.

The T_c and the resistivity ρ_0 just above T_c were determined by the four probe electric resistivity measurement. The lattice parameter a was determined by the [110] peak of bcc lines from the X-ray diffraction using CuKα radiation.

3. RESULTS AND DISCUSSION

Fig. 1 shows the λ dependence of T_c for $Nb_{65}Ti_{35}$/Nb (NTN1), $Nb_{28}Ti_{72}$/Nb (NTN2) and $Nb_{51}Ti_{49}$/Nb (NTN3). These T_c vs λ curves show two kinds of anomalies. The first is that T_c takes a minimum around $\lambda\sim$200Å for all the NbTi/Nb series. The second is that for both NTN1 and NTN2, curves show the rapid decrease of T_c with decreasing λ in small λ region. For NTN3, however, the behavior of T_c for the small λ region is not confirmed for lack of the experimental data. In this figure we also show the result of calculation based on the improved new formalism[1, 2] using several parameters such as the density of states N, BCS interaction coefficients V, electron diffusion constants D, critical temperatures for single layers T_c, GL coherence lengths $\xi_{GL}(0)$, and Debye temperature θ_D. The calculated curves are monotonic function of λ and never take lower T_c values than those of NbTi and Nb.

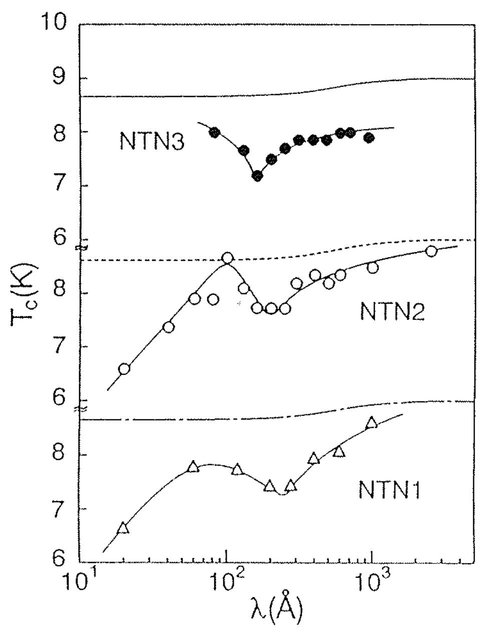

Fig. 1. T_c vs λ for present samples together with calculated curves.

Fig. 2 shows the residual resistivity ρ_0 as a function of λ for the three multilayer series. In all the present multilayers, ρ_0 increases drastically for the small λ region. We also notice a slight peak of ρ_0 around $\lambda\sim$200Å. Fig. 3 shows the X-ray [110] diffraction

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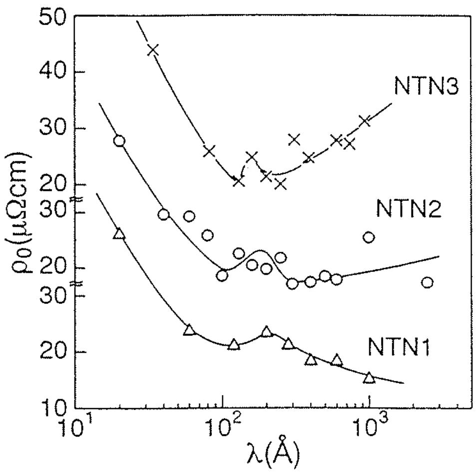

Fig. 2. ρ_0 vs λ for present samples.

line profile for NTN1 series. With decreasing λ value the peak intensity becomes smaller and FWHM (full width at half maximum) becomes broader, which suggests that structural inhomogeneity or distortion occurs in this small λ region. This inhomogeneous crystal structure may cause the increase of ρ_0 in Fig. 2.

The T_c degradation for the small λ region which were confirmed in NTN1 and NTN2 may be related to the observed high ρ_0 values through the influence of the Anderson localization. Fukuyama and Maekawa pointed out that T_c of thin films with high sheet resistance $R_\square$ is depressed through the influence of the Anderson localization and roughly follows the

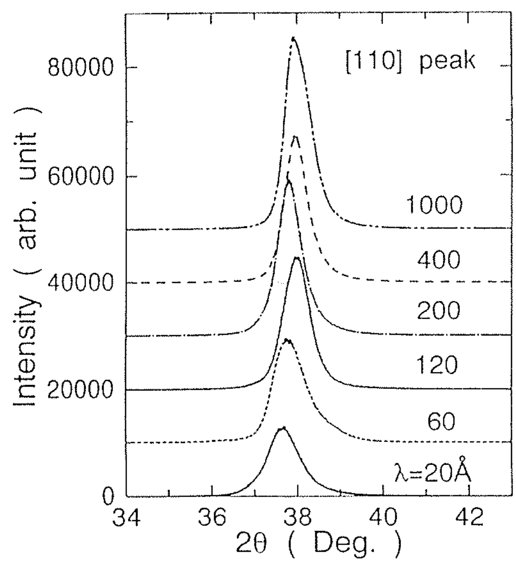

Fig. 3. X-ray [110] diffraction line profile for NTN1.

relation, $T_c \sim -pR_\square + q$ (p and q are positive coefficients). So the increase of $R_\square$, i.e., that of ρ_0 yields the decrease of T_c.

Fig. 4 shows the lattice constant a determined from the bcc [110] peak position in Fig. 3. Because the lattice constants of Nb and NbTi are very close each other, the [110] does not split. The noticeable fact is that for all the three series the lattice parameter a takes a maximum around $\lambda \sim 200$Å. As already noticed, T_c and ρ_0 show anomalies in the vicinity of this λ value.

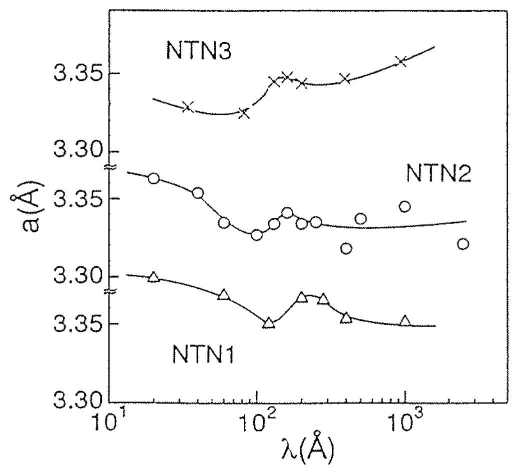

Fig. 4. Lattice constant a vs λ for present samples.

Based on the BCS theory, T_c is expressed as $T_c = 1.14\,\theta_D \exp(-1/NV)$. Therefore, the decrease of θ_D or NV is a possible origin of the T_c anomaly near $\lambda = 200$Å. The Debye temperature θ_D is related to the elastic stiffness constant and the anomalous increase of the crystal lattice may cause the reduction of θ_D and the resultant reduction of T_c. Of course, if the expansion of the crystal lattice leads to the decrease of the density of state N, this is also a possible mechanism for the T_c reduction as well as the ρ_0 maximum at near $\lambda = 200$Å.

In summary, two types of anomaly in the T_c vs λ curves were observed for the NbTi/Nb multilayer systems. One is the anomalous minimum of T_c at near $\lambda = 200$Å, which seems to be associated with the anomalous maximum of the lattice constant a. The other is the anomalous reduction of T_c in small λ regions, for which high values of the residual resistivity ρ_0 are probably responsible through the effect of the Anderson localization.

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