Superconductor (SC)/ferromagnet (FM) Nb/Co multilayers have been produced with magnetron-sputtering with the 100 nm thickness of Nb and 5, 10, 20 nm of Co. The superconducting properties have been investigated by electric transport measurements. The magnetic properties show that with increase of the thickness of Co layers the superconducting transition temperature ($T_c$) significantly increases. In order to study the unusual behavior, cross-section samples have been prepared to investigate microstructures of the SC/FM interface by means of Transmission Electron Microscopy (TEM), Atomic Force Microscopy (AFM) and energy-dispersive X-ray spectroscopy line scan analyses in scanning TEM (STEM) mode.

Figure 1 (a) are the bright field TEM images showing a Nb – Co multilayer system with uniform thickness of the Nb and the Co layers. The individual Nb layers are polycrystalline and exhibit defects. The Co layers appear uniform in thickness and are interconnected on a larger scale. The dark filed images [figure 1 (b)] shows the size and shape of single crystallites and the texture-like lattice orientation of some of the Nb grains and dislocation contrast is visible in some of the grains. The transmission electron diffraction pattern (inset of figure 1) shows the polycrystalline nature of the Nb-Co multilayer. The surface profiles of two samples show that the sample with thinner Co layers [figure 2 (a)] has a much rough surface than the sample with a thicker Co layers [figure 2 (b)]. From our study we can conclude that the roughness of the SC/FM interfaces plays an important role in the effect of the magnetic layers on $T_c$: it first increases the area of the interface between the SC/FM layers, which gives stronger proximity effect and, second, enhances the effect of the stray field on $T_c$ based upon nano-scale observations of interfaces topography. It was found that the parameter which determines the effect of magnetic layers on the superconducting layers is not an absolute number of roughness only, but the ratio of the roughness and the thickness of the magnetic layers. On the other hand, these observations invite to elucidate the crystalline defect structure at the Nb/Co interfaces, namely misfit-compensating dislocations density, and the associated strain fields to allow localized coherency at the interfaces.

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Fig. 1: (a) Bright-field (BF) TEM micrograph of multilayer cross-section sample Co5; (b) Dark-field (DF) TEM image. Inset shows the transmission electron diffraction pattern. White circle: position and size of aperture chosen for TEM DF imaging. Dark arrow: beam stop blocking the central electron beam.

Fig. 2: AFM surface profile for (a) sample with 5 nm of Co and (b) sample with 10 nm of Co.