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Interfacial roughness and proximity effects in superconductor/ferromagnet CuNi/Nb heterostructures

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We report an investigation of the structural and electronic properties of hybrid superconductor/ferromagnet (S/F) bilayers of composition Nb/$Cu_{60}Ni_{40}$ prepared by magnetron sputtering. X-ray and neutron reflectometry show that both the overall interfacial roughness and vertical correlations of the roughness of different interfaces are lower for heterostructures deposited on $Al_2O_3(1\bar{1}02)$ substrates than for those deposited on Si(111). Mutual inductance experiments were then used to study the influence of the interfacial roughness on the superconducting transition temperature, T_C. These measurements revealed a $\sim$4% higher T_C in heterostructures deposited on Al_2O_3, compared to those on Si. We attribute this effect to a higher mean-free path of electrons in the S layer, caused by a suppression of diffusive scattering at the interfaces. However, the dependence of the T_C on the thickness of the ferromagnetic layer is not significantly different in the two systems, indicating a weak influence of the interfacial roughness on the transparency for Cooper pairs.

I. INTRODUCTION

The interplay of two antagonistic states - superconductivity (S) and ferromagnetism (F) - at interfaces has been in the focus of experimental and theoretical investigation for the past two decades[1–3]. Theoretical work describes and predicts numerous manifestations of the mutual influence between the superconducting and ferromagnetic order parameters. These effects appear due to the oscillating nature of the decaying superconducting correlations in ferromagnetic materials that are proximity-coupled with the superconductor. One of the most striking manifestations of the interaction between both order parameters is a non-monotonic dependence of the critical temperature for superconductivity, T_C, in S/F heterostructures on the thickness of the ferromagnetic layer, d_F[2,4,5]. The key parameter controlling the shape of the $T_C(d_F)$ dependence is the S/F interface transparency[6,7], T_{SF}. For highly transparent ($T_{SF} \to 1$) S/F interfaces, the $T_C(d_F)$ curve oscillates, whereas for low ($T_{SF} \to 0$) or moderate ($T_{SF} \lesssim 0.5$) transparency it decays monotonically. To date, experimental research on S/F hybrids has mainly focused on the dependence of parameters characterizing the superconducting state (including T_C and the critical current) on the thickness of the ferromagnetic layer, whereas the effect of the interfacial structure has remained practically unexplored. However, the characteristics of the interface may well be crucial for a detailed comparison with theoretical predictions and for the performance of functional S/F devices.

In the present paper, we address this issue by studying how the roughness of standard substrates used in modern vacuum technology (silicon and sapphire) influences the electronic proximity effect in S/F bilayers. We have used neutron and X-ray reflectometry as effective characterization methods of the structural properties of the layers and interfaces. Whereas specular reflectometry is a widely used method to determine the thicknesses of F and S layers and the root-mean-square (rms) roughness of the S/F interface[8–14], off-specular (diffuse) X-ray and neutron scattering is only rarely applied to S/F hybrid structures[15–17]. Off-specular scattering reveals further important characteristics of the interfaces, including the in-plane and vertical correlation lengths of the roughness profiles. In Nb/Cu systems prepared by molecular beam epitaxy (MBE) and by sputtering, X-ray off-specular reflectometry showed that the statistical properties of the roughness strongly depend on the deposition technique[15]. In particular, samples grown by sputtering are characterized by roughness with high vertical correlation. Vertical roughness correlations were also reported for magnetron-sputtered $[Nb/PdNi]_{5-9}$ multilayers grown on Si(100) substrates[17]. This work demonstrated growth of the rms roughness with increasing number of deposited layers.

In present work, we used X-ray (XRR) and neutron (NR) reflectometry to characterize the structural properties of CuNi/Nb bilayers fabricated on silicon and sapphire substrates in a single deposition run. The resulting information yields important insights into the electronic properties. In particular, the rms height and in-plane