Abstract

Superconductivity (S) and ferromagnetism (F) are competing phases whose coexistence is unlikely to occur. Exceptions require a non–uniform profile both for the pairing and the magnetization, as in the case of the FFLO state predicted independently by Fulde and Ferrell [1] and by Larkin and Ovchinnikov [2]. The coexistence of a superconducting and magnetic phase in a finite temperature range was first discovered in ternary rare earth compounds [3, 4]. Later on, other examples of coexistence of S and magnetic ordering were found [5–7] which motivated the investigation of alternative possibilities for the interplay of ferromagnetic and homogeneous superconducting order [8, 9]. Differently from the case of bulk systems, the coexistence may be easily achieved in artificial S/F hybrids, where the two antagonistic orderings are confined in spatially separated layers interacting via the proximity effect. Recently, these systems have been the subject of intensive theoretical and experimental studies and new concepts have been developed [10–14]. The improvement of the fabrication techniques has made possible the realization of heterostructures consisting of very thin layers of different materials coupled through high quality contacts. In this way, the reciprocal influence of the two opposite phases can be tuned by changing the materials, the layer thicknesses, and their configuration and topology. The analogy with the bulk situation is provided by the proximity effect: when a superconductor and a ferromagnet are brought into contact, Cooper pairs enter the F side and magnetic excitations leak into the S region across the S/F interface. As a result, superconductivity is suppressed in the superconductor within a distance ξ_S (the coherence length) from the interface, while S correlations are induced in the ferromagnet. The presence of the exchange field E_{ex} in F causes an energy shift between the electrons of the pairs entering in the ferromagnet and this results in the creation of Cooper pairs with non–zero momentum. Thus, the S order parameter does not simply decay in the F metal, as it would happen in a normal one, but it also oscillates in the direction perpendicular to the interface over a length scale given by ξ_F, the coherence length in F. This inhomogeneity of the order parameter may be interpreted as a manifestation of a FFLO phase in these structures [14–16].

In particular, in S/F hybrids, the inhomogeneous character of the S order parameter, caused by the proximity to the F side, leads to a non-monotonic behavior of all the physical quantities depending on the gap, as for instance for the transition temperature as a function of the F layer thickness, d_F [17]. In addition, re–entrant superconductivity has recently been experimentally observed as a function of d_F in Nb/CuNi bilayers [18, 19], as well as non-monotonic behavior of the anisotropy coefficient in S/F/S trilayers [20], negative critical current and reversed density of states in Josephson [21, 22] and tunnel [23] S/F/S π–junctions. Some peculiarities of the shape of the R(T) curves in S/F/S trilayers and multilayers have been analyzed and, in general, transport properties of these systems have been studied [24–28]. Very recently, experimental results were obtained on S/F structures when measuring the dynamic instabilities of the vortex lattice at high driving currents. The role played on the non-equilibrium properties of the hybrids by both the ferromagnetic and the superconducting materials has been analyzed with a special focus on the values and the temperature dependence of the quasiparticle relaxation times, τ_E. Knowledge of the relaxation

mechanisms in these systems is extremely important in view of possible applications since it can drive the optimal choice of both materials to realize, in particular, ultrafast superconducting single photon detectors based on S/F hybrid structures [29].

Another area of special interest in the field of the S/F structures concerns the investigation of spin triplet superconductivity [12]. In systems where the magnetization is spatially inhomogeneous, an equal spin pairing S component can be generated, that may survive over very long distances – of the order of the normal coherence length – inside F. In conventional spin–singlet S/F hybrids, superconductivity rapidly decays in the ferromagnet over distances of order of tenth of nanometers. However, the removal of the translational invariance due to the presence of interfaces leads, in clean systems, to a different mixed parity pairing, which can be responsible for the generation and the induction in the F side of a p–type spin–triplet component [30]. Such component can be induced in fully spin-polarized metals (half–metals) only in the presence of spin–active interfaces [31]. Recently it has been argued that in dirty systems even s–type spin–triplet superconductivity can survive in F over much longer distances [12, 32, 33]. Inhomogeneous magnetization in the F side [32, 33] or spin–active interfaces [34] can be responsible for the appearance of this triplet component. Some hints of the presence of odd–frequency spin–triplet correlations have been observed in S/F systems with half–metallic CrO2 [35, 36], metallic Co–PdNi–CuNi layers [37] and more exotic Ho ferromagnet [38, 39].

In this work we will analyze the effect of different ferromagnets on the superconducting transport properties of S/F hybrids. In particular, in chapter 1 and chapter 2 weak ferromagnets such as PdNi and CuNi will be used in conjunction with Nb to study the static and dynamic properties of the vortex lattice in Nb/PdNi and Nb/CuNi bilayers to obtain information on the quasiparticles relaxation processes in these systems. The last two chapters of the thesis will be dedicated to the influence of the inhomogeneous magnetization present in thick Py layers on the upper critical fields and critical temperature in Nb/Py/Nb trilayers.

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