Superconductivity in S/F hybrids:

a Scanning Probe Microscopy study of orbital interaction

Abstract

In the framework of the Ginzburg-Landau (G-L) theory [1], conventional superconductors are classified in type I and type II, based on the value the G-L parameter $k = \frac{\xi}{\lambda}$, $k > \frac{1}{\sqrt{2}}$ and $k < \frac{1}{\sqrt{2}}$ respectively. The coherence length ξ defines the length scale on which the local density of the superconducting Cooper pairs varies whereas the penetration depth λ is the distance at which the external magnetic field is exponentially screened from the interior of the superconducting sample (Meissner effect). In type II superconductors the nucleation of quantized magnetic flux tubes, Abrikosov vortices [2], in a field range $H_{c1} < H < H_{c2}$, where H_{c1} and H_{c2} are the lower and upper critical field respectively, enables the persistence of the superconducting state in high applied magnetic fields, enhancing their technological relevance. However, all the technological applications are still dealing with the capability to control and prevent vortex motion, which causes energy dissipation, eventually introducing artificial pinning sites.

In such a scenario, the nanoscale investigation of the superconducting vortex dynamics holds the potential of understanding macroscopic behaviors in terms of microscopic mechanism. Among all the techniques able to perform experiments at the nanoscale, Magnetic Force Microscopy (MFM) and Scanning Tunneling Microscopy and Spectroscopy (STM/STS) allow the investigation of the superconducting vortex arrangement with individual vortex resolution, keeping track of the magnetic polarity and in high applied magnetic field respectively.

Planar Superconductor/Ferromagnet (S/F) heterostructures, magnetically coupled, i.e. having an insulating thin layer between the S and F films to suppress the proximity effect [3], have been proposed to increase the vortex pinning, due to the

interaction between superconducting vortices and magnetic template. However, being the vortex physics highly sensitive to the nano-variation in size and geometry of the constituting materials, the investigation of such systems requires preliminary efforts in:

1. modeling the magnetostatic interaction between the S layer in the mixed state and the F film;

2. identifying the proper superconductor, insulator and ferromagnet;

3. rescaling S and F thickness in order to make thin film based heterostructures.

In the past, a lot of effort has been spent to experimentally probe and theoretically model many of the exciting effects that can occur in magnetically coupled S/F hybrids having artificial, litographically defined, magnetic nanotextures as well as on planar S/F bilayers. Such works focused primarily on the effects of the underlying magnetic template on vortex nucleation, vortex dynamics, and on the nucleation of localized superconductivity above domains and domain walls [4-22]. This remarkable and solid background, very briefly reviewed in Chapter 1, guided the experiments discussed in this dissertation and helped in the interpretation of the data.

The focus of the presented thesis is on the study of vortex nucleation, pinning and dynamics in planar S/F hybrids, made by thin films of Nb/Py and Pb/[Co/Pd]multilayers. The fabrication of the constituting superconductors (Nb and Pb), insulators (SiO2 and Al2O3) and ferromagnets (Py and [Co/Pd]multilayers) as well as the deposition procedures are beyond the goal of this dissertation. Shortly, Nb/SiO2/Py hybrids were made by sputtering deposition at Argonne National Laboratory (Chicago, IL (USA)) by Dr. V. Novosad, Dr. V. Yefremenko and Dr. S.A. Moore, [Co/Pd]multilayers /Al2O3 were fabricated by Dr. V. Novosad, whereas Pb thin films were made by electron beam deposition at Temple University (Philadelphia, PA (USA)) by Dr. S.A. Moore. The choice of the materials is strongly dependent on the investigating technique. The ferromagnetic domain size as well as the weakness of the out-of-plane magnetic stray field of Py are suitable for MFM experiments, whereas, on the contrary, [Co/Pd]multilayers, having a relatively high out-of-plane stray field, would cause a magnetic overlapping of superconducting vortices, eventually not individually resolvable by MFM. On the contrary, the vortex-vortex separation induced by the Py magnetic template as well as the domain size would be too big for STM/STS investigation. In addition to this, while Nb is not a good material for STM measurements, due to the ease in oxidation, Pb, with a Tc=7.2K, is not suitable for the presented MFM experiments, performed in an Omicron-Scanning Force Microscope, limited by a base temperature of 5K.

The working principle of MFM and STM/STS is presented in Chapter 2, followed by the description of the cryogenic Ultra-High Vacuum systems used in performing the scanning probe microscopy experiments.

In Chapter 3, low temperature MFM experiments on Nb/Py hybrids are presented with the aim of investigating the conditions of spontaneous vortex nucleation as well as their in-field behavior. Being Nb a conventional low-temperature superconductor and Py a room temperature ferromagnet with a peculiar stripe-like configuration of the out-of-plane magnetic domains, a field cooling of Nb in the spatially non-uniform Py stray field occurs every time the S film is cooled down below its critical temperature (Ts=9K). In such a way, depending on the intensity of the out-of-plane component M0 of the Py magnetization vector, alternating up and down, spontaneous quantum fluxes with opposite polarities, vortex-antivortex (V-AV) pairs, can be nucleated in Nb film and guided along the magnetic channels. As a consequence, the nucleation of spontaneous V-AV can be indirectly tuned, by increasing the intensity of M0, by making thicker F films or by decreasing the S thickness. In addition to this, MFM measurements in external (static and dynamic) magnetic field are presented, with the aim of studying vortex dynamics.

In Chapter 4, peculiar vortex distribution in presence of strong, randomly distributed, pinning sites, called bifurcations of the magnetic template, have been studied in Nb/Py by low temperature MFM as well as in Pb/[Co/Pd]multilayers by low temperature STM/STS. It has been shown how the enhancement of the stray field at the bifurcation core as well as the topology of the bifurcation itself definitely affect vortex arrangement, bringing to the formation of strongly confined vortex cluster. The complementarily of MFM and STM/STS has been successfully used to get insights into the vortex confinement matter.

Finally, in Chapter 5, a new method to perform quantitative MFM experiments is developed and presented. The main idea is to extract a magnetic characterization of the MFM tip by probing a sample with well known magnetic signal. The superconducting vortex, always supporting a flux quantum $\Phi_0 = \frac{hc}{2e}$, is thus a perfect object to use in developing such a characterization procedure. Moreover, an example of quantitative MFM experiment on Nb/Py is presented, bringing to the estimate of the out-of-plane magnetization component M0 of (1µm)-Py film.

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