Adjustable superconducting anisotropy in MoGe-Permalloy hybrids

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Abstract. We studied the magneto-transport properties of magnetically coupled superconductor-ferromagnet MoGe/Permalloy bilayers. The rotatable anisotropy Permalloy ferromagnet with stripe domain structure induces in-plane anisotropy in superconducting order parameter. Superconducting phase diagram shows that near the superconductor-normal state phase boundary the superconductivity is localized in narrow mesoscopic channels just above the magnetic domain walls. By changing the in-plane direction of magnetic stripe domains it is possible to re-configure the direction of the superconducting channels and controllably rotate the direction of the in-plane anisotropy axis in the superconductor.

1. Introduction
Interaction of two (or more) systems with strongly correlated electrons leads to a wealth of new physical phenomena. Magnetism and superconductivity are an excellent example as their interaction has been studied for decades (for review see [1, 2, 3, 4]). With the advent of local scanning probes and nanofabrication, this area of research has experienced a renaissance with the objective to engineer systems that can mimic the behavior of complex single phase compounds exhibiting coexistence of superconductivity and magnetism [5, 6, 7]. The fundamental premise is the engineering of model systems to tailor the dominant interaction between two correlated systems and test the existing theoretical predictions. Recent explorations of the magnetic interaction between a superconductor and a ferromagnet have led to the discovery of intriguing phenomena associated with domain-wall superconductivity and magnetic domain pinning [8, 9, 10, 11, 12]. Depending on the characteristic correlation lengths in both magnetic and superconducting subsystems, these hybrid materials can have very different behavior [13, 14, 15].

In this paper we explore the magnetic interaction between a macroscopically well-ordered magnetic domain state in a ferromagnet and a type-II superconductor with a very small coherence length and negligible intrinsic pinning. We show that a re-configurable stripe domain pattern could provide a modulation template in the superconducting condensate. This hybrid system could be a potential playground for testing superconductivity on mesoscopic scale without the need to employ nanoscale lithography techniques.
2. Sample preparation
Eighty nanometers thick MoGe thin film (Mo 79% and Ge 21%) was sputtered under Ar pressure using DC magnetron at a rate of 2.7 Å/s on patterned Si substrate with native oxide. The MoGe thin films have critical temperature $T_c = 6.1\, \text{K}$, normal state residual resistivity $\rho_0 = 160\, \mu\Omega\, \text{cm}$ and critical field slope $\left( \frac{dH_c}{dT} \right) |_{T_c} = 2.3\, \text{T/K}$. Due to amorphous nature of MoGe dirty-limit expressions [16] can be applied to calculate superconductor parameters, yielding $\lambda(0) = 530\, \text{nm}$ and $\xi(0) = 5\, \text{nm}$. The transport was measured in a four-terminal geometry on a conventional bridge pattern with bridge width of 100 $\mu\text{m}$. The MoGe bridge was patterned using conventional optical photolithography methods and lift-off technique. After covering the sample with a 30nm SiO$_2$ insulator we sputtered a 2 $\mu\text{m}$ thick permalloy (Fe$_{20}$Ni$_{80}$) overlayer through a shadow mask. The magnetic film covered the area between the voltage contacts.

3. Results and discussion
Thick permalloy film forms narrow magnetic stripe domain pattern with a period comparable to the film thickness [17, 18]. The magnetic stripe domains arise from a weak perpendicular anisotropy induced by internal stress in sputtered films. A negative magnetostriiction constant and planar tensile stress lead to a perpendicular easy axis that, in turn, generates dense stripe domains above a critical film thickness. The best way to image such magnetic domain structure is by using scanning magnetic force microscopy (Fig. 1). The stripe domains are nucleated along the direction of an in-plane applied magnetic field and they can be subsequently rotated in the plane of the film by applying external in-plane magnetic field exceeding the in-plane saturation field. This class of materials thus earned its nickname “rotatable anisotropy” materials [19]. Our films have in-plane and out-of-plane saturation fields of 30 mT and 1.8 T, respectively, which results in saturation magnetization $M_s = 1455\, \text{G}$ and anisotropy constant $K_u = 2.6 \times 10^5\, \text{erg/cm}^3$. The common value for the exchange anisotropy in this material is $10^{-6}\, \text{erg/cm}$. We demonstrate that by combining the well known properties of a Permalloy thick film with a superconductor, we can control the conductance anisotropy in our hybrid material. In our experiment we limit ourselves with purely magnetic interaction between Permalloy and the superconductor by separating them with SiO$_2$ insulating film. The specific magnetic domain structure of Permalloy (weak perpendicular anisotropy combined with stripe domain structure) leads to a spatial modulation of the superconducting properties in MoGe including the critical temperature $T_c$. Since the magnetic material forms continuous stripe domains the spatial modulation of the critical temperature would also lead to stripe symmetry and therefore define well resolved channels along which the supercurrent can flow.

We measured the magnetotransport properties of the MoGe bridge covered with Permalloy thick film in a Quantum Design MPMS system equipped with external device control option using DC current (Keithley 2182/220). The magnetic stripe domains, oriented either parallel or perpendicular to the supercurrent flow in the bridge, were prepared at room temperature by intermittently applying strong (approximately 0.5 T) magnetic field in the plane of the film. The preferred stripe direction remained fixed after reducing the in-plane field to zero. Subsequently, the sample was transferred into the MPMS chamber and cooled down to the desired temperature. The magnetoresistance measurements were performed in magnetic fields applied perpendicular to the film surface.

The appearance of localized superconducting channels along the supercurrent direction is observed in Fig. 2. When the applied current is parallel to the domain walls the superconducting current flows through parallel channels that are defined by the magnetic domain structure. In this geometry the modulation of the superconducting order parameter due to underlying magnetic structure vanishes along the current flow, but it is strongly modulated perpendicular to the current. Thus the current flows along the paths where superconductivity is most robust i.e. where the magnitude of the local magnetic field is minimal. According to the parameters of our
Figure 1. Magnetic force microscope image of 20 × 20 µm² area of the surface of a Permalloy film grown over MoGe/SiO₂ bilayer on a silicon wafer. The thickness of the film is 2 µ.

Figure 2. Superconducting phase diagram of the MoGe/Permalloy bilayer for two magnetic stripe domain orientations (for supercurrent parallel to the stripe domains (■) and when they are perpendicular to each other (□)). The diagram was obtained from R(T) curves by defining the critical temperature as R(T_c)=0.1×R_n, where R_n is the normal state resistivity at 6.1 K.

system (short coherence length and large effective penetration depth $\lambda_\perp(0) = \lambda^2(0)/t_s \approx 3.5\mu$m with respect to the magnetic stripe width) the supercurrent should be most robust above the domain wall boundary [20]. Here, $\lambda(0)$ is the London penetration depth, and $t_s$ is the thickness of the MoGe thin film.

On the other hand, when the current is directed perpendicular to the magnetic domain walls, the superconductivity is strongly modulated along the current flow and the current carrying properties are limited by the weakly superconducting areas. As a result, in low applied magnetic fields the superconducting transition is much broader and the transition temperature is lower than in the case when the supercurrent is parallel to the stripe domains (Fig. 2). The difference in critical temperature for the two orientations of the magnetic stripe domains is 30mK or 0.5% of $T_c$. This is related to the spatial modulation of the critical temperature in MoGe due to magnetic coupling with the Permalloy in absence of applied magnetic field.

At higher magnetic fields the local induction in the superconductor becomes more isotropic as a consequence of the change in stripe domains to form pockets of bubble domains. Formation of bubble domains reduces the in-plane superconducting anisotropy and the superconducting transition becomes independent on the stripe orientation at higher fields, as seen from the phase diagram. The superconducting phase diagram of this hybrid system shows that in sufficiently small external magnetic fields there exist clearly defined supercurrent pathways that could be re-oriented by an in-plane rotation of the magnetic domain walls.

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