Tunable Field Induced Superconductivity

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We investigate the transport properties of a thin superconducting Al layer covering a square array of magnetic dots with out-of-plane magnetization. A thorough characterization of the magnetic properties of the dots allowed us to fine-tune their magnetic state at will, hereby changing the influence of the dots on the superconductor in a continuous way. We show that even though the number of vortex-antivortex pairs discretely increases with increasing the magnetization of the dots, no corresponding discontinuity is observed in the resistance of the sample. The evolution of the superconducting phase boundary as the magnetic state of the dots is swept permits one to devise a fully controllable and erasable field induced superconductor.

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The hallmark of superconductivity and the technological applications based on it is the possibility to carry electrical currents without resistance below the critical temperature $T_c$. This non-dissipative quantum state is however suppressed either by applying a magnetic field or by submitting the system to a high enough electrical current as to break the Cooper-pairs responsible for the superconducting condensate. In Type-II superconductors which are most interesting for practical applications, an applied magnetic field $H$ ($H_{c1} < H < H_{c2}$, with $H_{c1}$ and $H_{c2}$ the lower and upper critical fields) penetrates the superconductor in the form of flux quanta. Under the influence of an applied current these vortices start moving, hereby destroying the non-dissipative state. During the last decade enormous efforts have been devoted to prevent this drawback by anchoring vortices with different types of pinning potentials. Particular attention has been focused on magnetic pinning centres originally due to their promising enhancement of the critical current $I_c$. Interestingly, it was also found that in such superconductor/ferromagnet (S/F) hybrid systems field compensation effects between an applied magnetic field and the stray fields of the ferromagnets can drastically change the superconducting properties.

It has recently been shown that if an array of out-of-plane magnetized dots is deposited on top of a superconducting film, the $T_c(H)$ phase boundary can be shifted by exactly an integer number of flux quanta per unit cell. The occurrence of a maximum in $T_c$ at a non-zero magnetic field results from the compensation of the dots’ field by the applied field. The reason for the quantized character of field-induced superconductivity (FIS) lies in the ability of the superconductor to quantize the flux generated by a magnetic dot, whatever its value, by either compensating the field excess or generating the field deficiency with supercurrents. If the dots generate a small flux, supercurrents will counterbalance this flux and no compensation effects are present. However, if the flux crosses a certain critical value the field lines generated by the dot penetrate the superconductor in the form of vortex-antivortex (V-AV) pair(s) and hence and the maximum critical temperature will shift by exactly an integer number of flux quanta per unit cell. This picture suggests that for particular magnetization values the field locus of the maximum $T_c$ should undergo abrupt displacements from $n\phi_0$ to $(n+1)\phi_0$ with $n$ integer. So far, the detailed evolution of this shift by an integer number of flux quanta has remained unveiled, mostly due to the difficulties to control the magnetization of the dots in a continuous fashion. Here we explore the evolution of the superconducting properties of a thin film superconductor, now deposited on top of an array of tunable magnetic dots.

The sample under investigation is a superconducting Al film of thickness $d = 50$ nm evaporated on top of a square array of magnetic dots with 2 µm lattice constant. A 5 nm thick Si buffer layer was first evaporated on top of the dots to avoid proximity effects. In this way the interaction between the ferromagnet and the superconductor is purely electromagnetic in origin. An Atomic Force Microscopy picture of the dots’ array is shown in Fig. 1. The ferromagnetic dots have a diameter of 1.36 µm and consist of a 2.5 nm Pt buffer layer covered with a [0.4 nm Co/1.0 nm Pt]$_{10}$ multilayer with magnetization perpendicular to the sample surface.

The magnetic properties of the dots were investigated using a commercial Quantum Design SQUID magnetometer. The main panel of Fig. 1 presents the field dependence of the magnetization $M(H)$ for the Co/Pt dots at $T=5$ K, where the magnetization was determined by using the total volume of the dot. The broader magnetization loop (filled circles) was recorded after saturation in a field of $\mu_0 H_s=1$ T. After following a careful demagnetization procedure it is possible to reduce the remanent magnetization down to 0.5% of the saturation value. As a consequence of the large diameter of the dots, the demagnetized state microscopically corresponds to a magnetic multidomain state with very little stray field. Start-
ing from the demagnetized state minor loops can be built up by making field excursions \(H_m\) with \(H_m < H_s\) (open symbols). Every minor loop has a unique remanent magnetization value \(M_0\) associated with it. Repeating this procedure for several \(H_m\) we determined \(M_0\) as a function of \(H_m\) as shown in Fig. 1(b). It is important to note that the full control of the out-of-plane magnetization of the dots relies on the one to one correlation between the dots and samples with square arrays of antidots [10] and can be attributed to the change of dimensionally when \(\xi(T)\) exceeds the width \(w\) of the areas where superconductivity first nucleates. Within this regime the phase boundary can be approximated by \(T_c(H) / T_c(0) = 1 - (\alpha H)^2\), with \(\alpha = \xi(0)\pi w / 2\sqrt{3} \phi_0\). By using this expression to fit the data in Fig. 2(a) we estimate \(w\) as a function of \(M_0\) (as shown in Fig. 2(b)). Here a continuous decrease of \(w\) with \(M_0\) is observed which is consistent with the reduction of the available nucleation area due to the increasing strength of the magnetic template created by the dots.

The previous description of the evolution of \(T_c(H)\) with increasing \(M_0\) would remain incomplete without determining whether the transition from \(n\) to \(n+1\) V-AV pairs actually occurs as a sudden horizontal displacement. In order to address this issue we monitored the evolution of the resistance \(R(H)\) at a nearly constant reduced temperature \(t = 0.991\) as the magnetization of the dots \(M_0\) is increased. This procedure turns out to be far more sensitive than just following the evolution of the \(T_c(H)\) phase boundary itself. In Fig. 3(a) we present these measurements for the particular case of \(n=1\) although the complete spectrum of accessible magnetization values was experimentally spanned [12]. For the sake of clarity the curves in Fig. 3(a) have been displaced horizontally along the field axis. The leftmost curve exhibits a very symmetric shape with a minimum resistance centered at \(\phi = \phi_0\) and two local dips at \(\phi = 0\) and \(\phi = 2\phi_0\). This particular magnetization value corresponds to the generation of exactly one V-AV pair. As \(M_0\) is increased the central dip slowly moves upward whereas the satellite dip at \(\phi = 2\phi_0\) becomes deeper. Strikingly, at a certain critical magnetization \(M_{c2}\) both local minima reach the same level. From that point on the absolute minimum resistance is located at \(\phi = 2\phi_0\) and eventually a new symmetric configuration centered at \(\phi = 2\phi_0\) is obtained. The above described evolution shows that even though the absolute minimum of the \(R(H)\) jumps from \(\phi = \phi_0\) to \(\phi = 2\phi_0\) at \(M = M_{c2}\), at any field the resistance remains a continuous function of \(M_0\). A similar evolution is observed for switching from \(n\) to \(n+1\) with \(n < 7\) [12].

In order to explain the above described behavior it is crucial to take the screening supercurrents \(J\) into consideration, very much like in the Little-Parks effect [14] (see Fig. 3(b)). For \(M_0 = 1.67\) kA/cm, at \(\phi = \phi_0\) one flux line is located at the magnetic dot and no total currents are present since the flux of the vortex is provided by the field of the dot (black circle in Fig. 3(b)). Under these circumstances both vortices and anti-vortices feel the same interaction with the dot and thus the satellite dips at \(\phi = 0\) and \(\phi = 2\phi_0\) are equally deep. Upon increasing the magnetization, the excess of field generated by the dot is counteracted by the supercurrents (blue and red circles in Fig. 3(b)). These currents break the previous symmetry favoring the presence of vortices over anti-vortices thus accounting for the deepening of the mini-
num at $\phi = 2\phi_0$ and the rising of the minimum at $\phi = 0$. This unbalanced situation persists up to a certain magnetization $M_0$. Crossing this value (green circle in Fig. 2(b)) results in the creation of an extra V-AV pair, thus shifting the phase boundary to $\phi = 2\phi_0$. At the same time the currents circling the dots have reversed polarity, now favoring antivortices rather than vortices. This interaction is reflected in the reversal of the asymmetry with respect to the new minimum. Further increasing $M_0$ reduces the asymmetry as the current progressively approaches zero (cyan and magenta circles in Fig. 2(b)). Eventually a fully symmetric curve centered at $\phi = 2\phi_0$ is recovered (gold circle in Fig. 2(b)).

It is worth emphasizing that although the local minima in the resistance move up and down in a continuous manner as $M_0$ is swept, the field position of the absolute minimum of the $R(H)$ curves always undergoes a discrete jump every time a critical value $M_c$ is crossed. This situation becomes more evident in Fig. 4 where a contour plot of $R(H, M_0)$ at $t = 0.991$ is shown. The red islands in this graph indicate the location of the lower resistance. A clear stepwise structure associated with the discrete increase of V-AV pairs as $M_0$ rises, can be discerned. From this plot one can accurately determine the magnetization needed to generate the first, second, third, and fourth V-AV pairs.

It is interesting to note that the generation of the first vortex-antivortex pair appears delayed with respect to the subsequent steps. This finding is consistent with previous theoretical predictions by Milosevic et al. [6] based on the solution of the Ginzburg-Landau equations. In that work it is shown that for an analogous hybrid system with similar superconducting and magnetic properties to ours the induction of the first V-AV pair needs a larger flux than for the following transitions. The ultimate reason for this effect lies in the higher degree of symmetry of the $n=0$ V-AV state with respect to the $n \neq 0$ states. Our results represent the first experimental confirmation of this prediction. In a later report the same authors [13] have predicted that the $T_c(M_0)$ phase boundary corresponding to an array of tunable magnetic dots should exhibit cusp-like features associated with the generation of V-AV pairs superimposed on a global decrease of $T_c$ with increasing $M_0$. This global reduction of $T_c$ is clearly visible in Fig. 2(a). And since the critical temperature is determined by the lowest resistance, the crossing of the two minimal dips in the $R(H)$ curves at $M_c$ will result in a cusp-like feature in the $T_c(M_0)$ phase boundary as well.

As a last remark, we would like to point out that the observed similarities with the Little-Parks [14] effect should not be pushed too far. Although in both cases the currents adjust themselves to quantize the magnetic field, in our system the field is provided by the dots rather than by a homogeneous source giving rise to V-AV pairs. Also, the spatial coexistence of screening and vortex currents is not present in our system since vortices can move around in the two-dimensional lattice.

In conclusion, we have shown that the remanent magnetization $M_0$ of out-of-plane magnetized dots can be tuned from nearly zero (demagnetized) to a material dependent maximum value. This continuous degree of freedom allowed us to observe and investigate tunable field induced superconductivity and the progressive evolution of the superconducting phase boundary as a function of $M_0$ and thus reveal the microscopic mechanisms that lead to discrete jumps in $T^{\text{max}}$ without having discontinuities in the resistance at any point. The remarkable flexibility attainable with these magnetic field resistant superconductors makes them very attractive for practical applications.

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FIG. 1: (color online) Magnetization loops of the Co/Pt dots for three different excursion fields measured at 5 K. The insets show (a) an Atomic Force Microscopy-picture of the magnetic dots, and (b) the remanent magnetization $M_0$ as a function of the maximum applied field $H_m$ starting from the demagnetized state $\mu_0 H_m = 0$ mT.

FIG. 2: (color online) (a) Superconducting transition $T_c(H)$ of the Al film for different magnetic states of the dots. By increasing the magnetization a clear shift of $T_c(H)$ and a decrease of $T_{c\max}$ is observed. (b) Lateral dimension $w$ of the nucleation of superconductivity as a function of the magnetization of the dots.

FIG. 3: (color online) (a) Magnetoresistance measurements for different values of the magnetization $M_0$ of the magnetic dots at a constant reduced temperature $t = T/T_c$. The presented data corresponds to the transition of the location of the maximum $T_c$ from $\phi = \phi_0$ to $2\phi_0$. For clarity the curves have been displaced horizontally. (b) Illustration of the supercurrents encircling the magnetic dots as a function of the magnetization. Colored symbols correspond to the colored curves in panel (a). Starting from the black curve, the increase of the magnetization will result in increasing currents, counteracting the field of the dots and keeping the flux exactly equal to $\phi_0$. Crossing a critical value $M_{c2}$ the currents reverse polarity hereby generating an extra vortex-antivortex pair. Further increasing the magnetization will result in a decrease of the currents since the flux is increasingly carried by the dot itself.

FIG. 4: Contour plot of the resistance as a function of field and magnetization for $t = 0.991$. Red islands correspond to lowest resistance and hence highest critical temperature. The step-like profile is a consequence of the quantization of the magnetic field in an integer number of flux quanta by the superconductor.
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