Letters

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Letter

Peculiar interference pattern of Josephson junctions involving periodic ferromagnet-normal metal structure

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Abstract

We report the observation of an oscillatory behavior of the critical current versus magnetic field dependence in $Nb/(Al/Py)_5/Al/AlO_x/(Al/Py)_6/Al/Nb$ Josephson tunnel junctions at 4.2 K. The oscillations resemble those that occur in superconducting quantum interference devices. Since the oscillations occur in the junctions without any superconducting loop, and therefore are suitable for sub-micrometer miniaturization, we believe they are promising for the development of a new generation of field-sensitive nanodevices.

Keywords: superconductivity, Josephson effect, SQUID, tunneling in superconductors, periodic multilayers, superconducting-ferromagnetic structures

(Some figures may appear in colour only in the online journal)

1. Introduction

In recent years, there has been growing interest in the development of nano-SQUIDs (superconducting quantum interference devices) capable of measuring single atomic spins (see, e.g., review articles [1, 2] and references therein). The standard approach to fabricating nano-SQUIDs is to reduce both the size of the involved Josephson junctions and the superconducting loop connecting the two junctions (in DC geometry). Such lateral geometry is hard to scale down to deep sub-micrometer dimensions. It is therefore interesting to build a lumped device easily scalable down and having SQUID-like properties. Such a device should obviously be based on new physical principles of operation.

Here we report the observation of an oscillatory $I_c(H)$ dependence in single Josephson tunnel junctions whose electrodes comprise periodic N/F multilayers (here N and F denote a normal metal and a ferromagnetic metal, respectively) proximitized by adjacent superconducting (S) layers. We present a particular case of such $S(NF_m)NI(NF)_nNS$ junctions with $m = 5$ and $n = 6$ (here I is an insulator), specifically, $Nb/(Al/Py)_5/Al/AlO_x/(Al/Py)_6/Al/Nb$ Josephson tunnel junctions involving aluminum/permalloy periodic multilayers situated on both sides of the AlO_x tunnel barrier.

2. Experimental

A schematic view of the junctions and their biasing is shown in figure 1(a). Figure 1(b) shows a transmission electron microscopy (TEM) image of the cross-section of real junction. The thickness of the bottom and top Nb layers is 125 nm and 68 nm, respectively (the latter figure excludes about 490 nm of the wiring layer). The thickness of the Al and Py (80% Ni – 20% Fe) layers, d_{Al} and d_{Py}, composing the periodic Al/Py structure, is nominally $d_{Al} = 6.2$ nm and $d_{Py} = 1.3$ nm. The thickness of the bottom and top Al layers adjacent to Nb layers, as well as the thickness of the Al layer on top of the Al/AlO_x barrier, is 3.1 nm each (the Al layer used to make the AlO_x barrier is 6.2 nm thick). The cross-type junctions with lateral dimensions of 10 μm × 10 μm were fabricated using optical lithography. The junction area was formed by reactive ion etching of the top Nb electrode and ion milling of the Al/Py multilayer down to the bottom Nb layer.

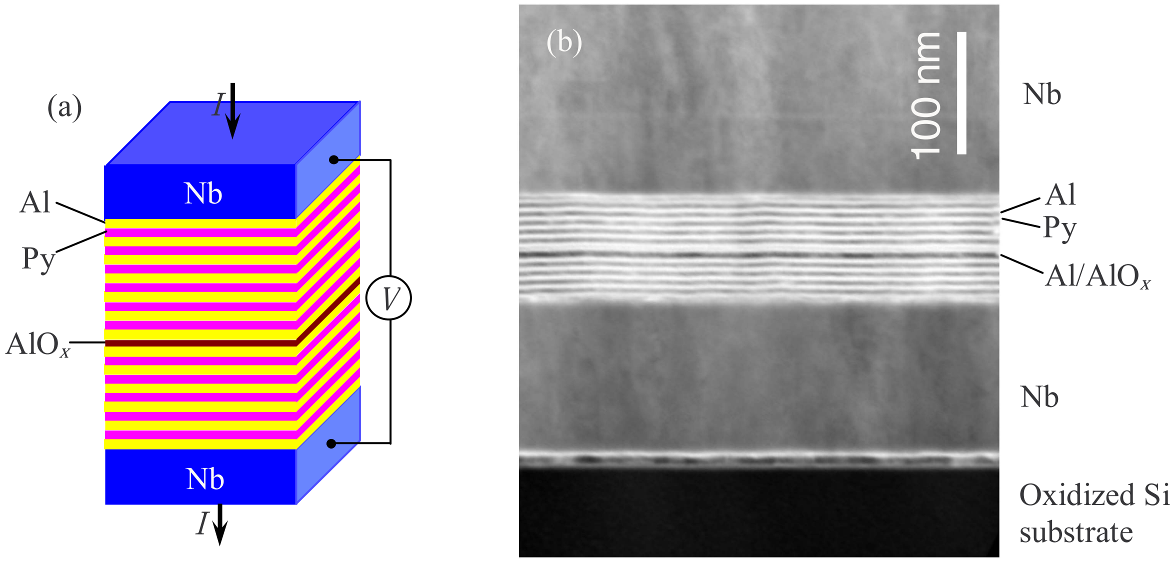

Figure 1. (a) Schematic of the multilayer Nb/(Al/Py)$_5$/Al/AlO$_x$/(Al/Py)$_6$/Al/Nb Josephson junction and biasing. (b) TEM image of the cross-section of an actual junction. In the periodic structure, lighter and darker layers are from Py and Al, respectively.

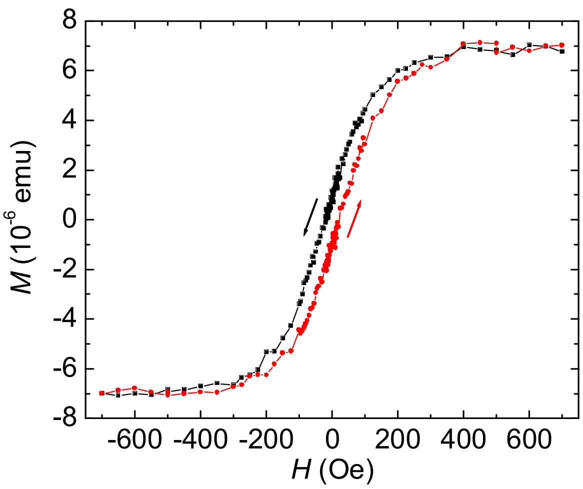

Figure 2. The magnetic moment as a function of magnetic field applied parallel to the structure plain for an unpatterned Nb/(Al/Py)$_5$/Al/AlO$_x$/(Al/Py)$_6$/Al/Nb structure with an area of 5 mm × 12 mm, taken at 10 K. Black and red curves are for opposite directions of magnetic field sweeping. Arrows show directions of field sweeping.

Then, using the same photoresist mask, anodization was done to 20 V; additionally, about 20 nm of SiO_2 was deposited for better insulation of the pillars. The wiring layer was deposited after the cleaning of the top Nb layer by etching about 5 nm of the material using ion milling.

The junctions were characterized at 4.2 K, well above the superconducting transition temperature, T_c, of Al films. The T_c of Al films, 2.3 K, was evaluated in an independent experiment [3].

In figure 2, we show the dependence of the magnetic moment as a function of magnetic field applied parallel to the structure plain ($M(H)$ dependence) for an unpatterned Nb/(Al/Py)$_5$/Al/AlO$_x$/(Al/Py)$_6$/Al/Nb structure with an area of 5 mm × 12 mm, taken at 10 K (i.e., above the superconducting transition temperature of Nb film, which was about 9 K). It demonstrates that the Al/Py multilayer structure is soft magnetic with a small hysteresis.

In order to estimate the induced superconducting coherence length in Py films at 4.2 K, ξ_{Py}, we fabricated and tested Nb/Al/AlO$_x$/Al/Py/Al/Nb junctions with various d_{Py} thicknesses. The thickness of Nb electrodes is the same as that for the junctions involving Al/Py multilayers. The thickness of the Al overlayer used to thermally grow AlO$_x$ barrier was nominally 9.3 nm, and the thickness of the other two Al layers was 3.1 nm. The respective I_cR dependence on d_{Py} obtained for such junctions is shown in figure 3(a). Here, the resistance R is the junction resistance at a voltage above $2\Delta/e$, where Δ is the Nb energy gap; it is close but not equal to the normal state resistance, R_N. One can see from figure 3(a) that I_cR falls to zero at d_{Py} of about 2 nm. Therefore, the total thickness of Py in the (Al/Py)$_5$Al/AlO$_x$/(Al/Py)$_6$ multilayer, $d_{\Sigma F} = 13.9$ nm, considerably exceeds $\xi_{Py} \sim 2$ nm, which constitutes a long-range proximity effect in N/F periodic multilayers [4].

An example of an I–V curve and $I_c(H)$ dependence for a Nb/Al/AlO$_x$/Al/Py/Al/Nb junction with $d_{Py} = 1.4$ nm is shown in figure 3(b).

The I–V curve for a typical Nb/(Al/Py)$_5$/Al/AlO$_x$/(Al/Py)$_6$/Al/Nb junction is shown in figure 4(a). The I–V curve has shape more typical for an SNS junction rather than SIS junction. The $I_c(H)$ dependence for the same junction is shown in figure 4(b) (blue curve). The latter curve is obtained as a result of magnetic field sweeping in two directions, starting from the maximum 'negative' field; there is a small hysteresis in the $I_c(H)$ dependence.

For comparison, we also show in figure 4(b) the $I_c(H)$ dependence for an ordinary Nb/Al/AlO$_x$/Al/Nb junction with the same size, 10 μm × 10 μm, and the same thickness of Nb electrodes (red curve). One can see a striking difference between the two dependences. In comparison with the SIS junction, the S(NF)$_5$I(NF)$_6$S junction (*i*) displays a

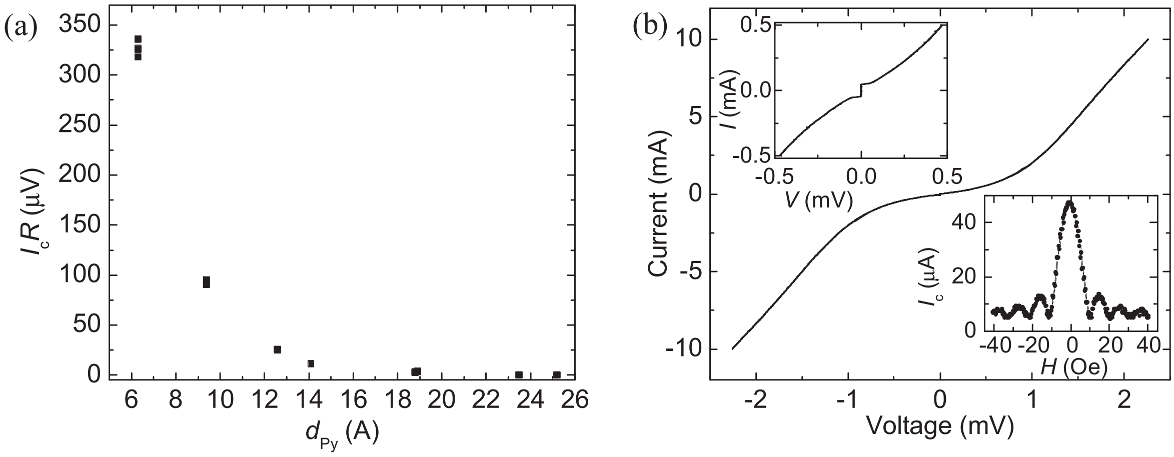

Figure 3. (a) The I_cR dependence on the thickness of Py layer, d_{Py}, for Nb/Al/AlO$_x$/Al/Py/Al/Nb junctions ($T = 4.2$ K). (b) *I–V* curve of an Nb/Al/AlO$_x$/Al/Py/Al/Nb junction with $d_{\text{Py}} = 1.4$ nm. Top inset shows the initial portion of the same *I–V* curve on a magnified scale. Bottom inset shows $I_c(H)$ dependence for the same junction.

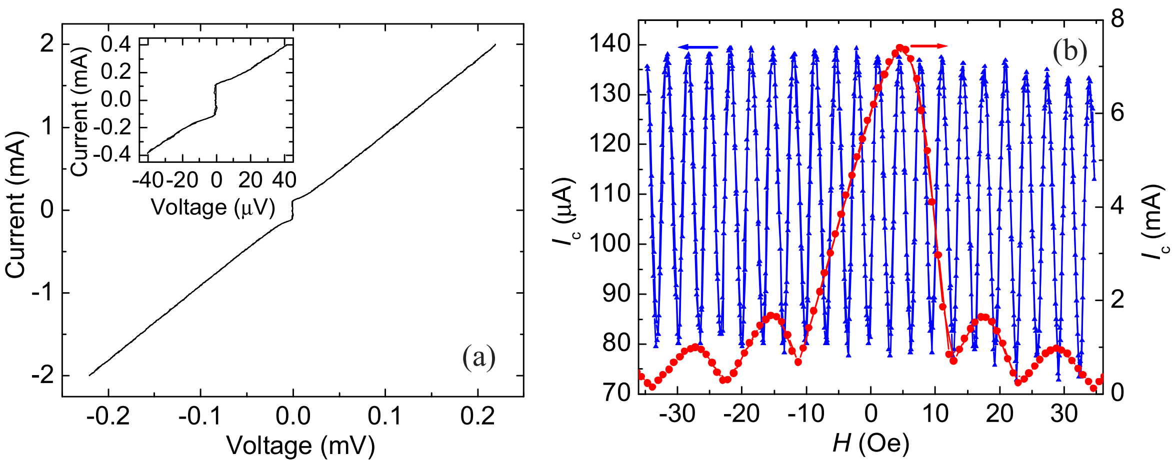

Figure 4. (a) Typical *I–V* curve of a Nb/(Al/Py)$_5$/Al/AlO$_x$/(Al/Py)$_6$/Al/Nb junction at 4.2 K. Inset shows the initial portion of the *I–V* curve on a magnified scale. (b) $I_c(H)$ dependence of the same junction (blue curve). Red curve is the $I_c(H)$ dependence for a reference Nb/Al/AlO$_x$/Al/Nb junction with the lateral dimensions of 10 μm × 10 μm.

considerably smaller oscillation period in H; (*ii*) I_c decays with H much more slowly; and (*iii*) all lobes are equivalent: there is no difference between the central and side lobes (note that the width of the central lobe in the $I_c(H)$ Fraunhofer-like dependence for the SIS junction, ideally, is twice that of the rest of the lobes). In fact, it is hard to determine where the central lobe in the $I_c(H)$ dependence for the S(NF)$_5$I(NF)$_6$S junction is: the measurement was carried out without any magnetic shielding; a small background field may be present, so that the entire pattern may be slightly shifted. In any case, one can see that the $I_c(H)$ dependence for the S(NF)$_5$I(NF)$_6$S junction is very similar to the $I_c(H)$ dependence of SQUID [5].

3. Discussion

Using the parameters of our junctions and the periods of the $I_c(H)$ patterns in figure 4(b), we estimate an effective magnetic spacing, λ_m, in our S(NF)$_5$I(NF)$_6$S and SIS junctions to be 629 nm and 181 nm, respectively, which yields corresponding Josephson penetration depths, λ_J, to be 17.3 μm and 4.4 μm. Therefore, the SIS junction is a 'distributed' junction, because its size $a > \lambda_J$, whereas the S(NF)$_5$I(NF)$_6$S junction is a 'lumped' junction ($a < \lambda_J$). In the latter case, we assumed that the period of the oscillations (blue curve in figure 4(b)) corresponds to the flux quantum, $\Phi_0 = 2.068 \times 10^{-7}\,\text{G}\cdot\text{cm}^2$.

The value $\lambda_m = 629$ nm obtained for the S(NF)$_5$I(NF)$_6$S junction does not correspond to that inferred from the device geometry (cf figure 1). Indeed, the magnetic field penetrates the central (NF)$_5$I(NF)$_6$ part of the device with the total thickness of about $d_{\text{NF}} = 85$ nm, and each of the adjacent Nb electrodes to the depth of λ_L (London penetration depth). It follows from the above estimate that $2\lambda_L \approx 180$ nm; therefore, the total magnetic depth for the S(NF)$_5$I(NF)$_6$S junction should be about 265 nm. One reason for an overestimated $\lambda_m = 629$ nm obtained from the period of $I_c(H)$ dependence may be that the effective flux penetrating the junction has a contribution from the magnetization of the F layers: $\Phi = \Phi_H + \Phi_M = Ha \cdot (2\lambda_L + d_{\text{NF}}) + 4\pi Ma \cdot d_{\Sigma\text{F}}$. Using the data for $M(H)$ in figure 2, we can estimate this contribution. For example, for the blue curve in figure 4(b), ten periods are achieved in an external field $H \approx 34$ Oe. For this field, the average (between black and red curves in figure 2) magnetization value is about 1.5×10^{-6} emu, which (taking into account the sample volume of 8.34×10^{-7} cm^3) is equivalent to the field B of 22.6 G. Then, using the above formula for Φ, we obtain that, in an external field of 34 Oe, the S(NF)$_5$I(NF)$_6$S junction experiences the flux $\Phi = 4.5\Phi_0$, which is less than the apparent experimental value of $10\Phi_0$. We conclude that the 'contraction' of the Fraunhofer pattern with increasing magnetization in the F layers [6], is not likely to be the main mechanism responsible for a short period observed in the oscillatory $I_c(H)$ dependence. Furthermore, this dependence is qualitatively different from a standard Fraunhofer pattern, as noted above. Also, we exclude the possibility that such $I_c(H)$ dependence may be due to parasitic effects like Abrikosov vortex trapping [7]. In the latter case, one obtains an irregular pattern but not a regular one with a small period.

Considering possible mechanisms, we suggest that F layers cause some shifts of the phase of the superconducting wave function, and there is interference between the N/F elements of the periodic structure, leading to a pattern with small-period oscillations. At the same time, since the overall coherence in the periodic N/F structure is obviously preserved, the Fraunhofer-type diffraction between the outer S electrodes also takes place. The combination of the two types of diffraction may lead to the observed interference pattern. A similar type of behavior is also observed for structures without any tunnel barrier and with different F material [3]; in that case, a theoretical model is developed based on the theory proposed by Bakurskiy *et al* [4]. Further study is needed to better understand the physical mechanisms of the observed effect and to optimize device parameters.

4. Conclusion

In conclusion, we have observed quantum interference in Josephson tunnel junctions in which the N/F periodic multilayers are constituents of the weak link. We suggest that the interference is intrinsic to the periodic N/F structure, so that no external superconducting loop is required to obtain oscillatory behavior of the Josephson critical current in an external magnetic field. Such a property is important for device miniaturization and may open new prospects in nanoscale quantum magnetometry.

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