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Manifestation of π-contacts in magnetic field dependence of I–V characteristics for proximity-type 2D Josephson junction array

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ABSTRACT

Results on the temperature and magnetic field dependence of current–voltage characteristics (CVC) are presented for SNS-type 2D ordered array of Nb–$Cu_{0.95}Al_{0.05}$–Nb junctions. The critical current $I_C(T,H)$ and the power exponent $a(T,H) = 1 + \Phi_0 I_C(T,H)/2k_B T$ of the nonlinear CVC law $V = R[I - I_C(T,H)]^{a(T,H)}$ are found to have a maximum at non-zero value of applied magnetic field $H_p = 225$ Oe, which is attributed to manifestation of π-type Josephson contacts in our sample.

1. Introduction

Among many different properties which can be studied using highly ordered 2D arrays of Josephson (or proximity) junctions probably one of the most interesting (and important for their potential applications) is their magnetotransport behavior, reflecting evolution of numerous dissipation mechanisms in the arrays under applied magnetic field [1–3]. One of such mechanisms, known as Berezinskii–Kosterlitz–Thouless (BKT) topological transition, is related to creation (destruction) of bound vortex–antivortex pairs below (above) some temperature T_{BKT} [4–6]. In zero magnetic field, this transition is expected to manifest itself in two-dimensional (2D) systems (including thin films and Josephson arrays) via nonlinear current–voltage characteristics (CVC) of the form $V = RI^{a(T)}$ with the power exponent $a = 3$ at $T = T_{BKT}$. However, the observation of a rather delicate BKT transition in real materials is quite a formidable task because it requires fulfilling of some strict experimental conditions. Besides, it can be easily masked by other competing mechanisms, such as finite size effects, extrinsic and intrinsic weak links, thermal fluctuations, quasi-particle contributions, etc. [7–14].

In this Letter we report recent results regarding the influence of magnetic field on critical current of the ordered SNS type arrays of unshunted Nb–$Cu_{0.95}Al_{0.05}$–Nb junctions through measurements of their current–voltage characteristics. The obtained experimental results and their theoretical interpretation suggest a possible manifestation of π type contacts in our array resulting in a pronounced peak in the field behavior of both the critical current and power exponent at non-zero value of applied magnetic field.

2. Results and discussion

High quality ordered SNS type array of Nb–$Cu_{0.95}Al_{0.05}$–Nb junctions has been prepared by using a standard photolithography and sputtering technique [1]. Fig. 1 shows the scanning electron microscopy (SEM) photography of the square array ($L_x = L_y = 300a_s$) formed by loops of niobium islands (critical temperature $T_{CS} = 9.25$ K) with a lattice parameter $a_s = 8.4$ μm (producing the inductance $L = \mu_0 a_s = 10.6$ pH for each loop), a single junction width $w = 1.4$ μm, the normal metal layer of $d_N = 310$ nm, the normal state resistance $R_N = 0.4$ Ω, and the junction capacitance $C = 0.18$ fF. The measurements were made using homemade experimental technique with a high-precision nanovoltmeter [14].

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Some typical results for CVC taken at different temperatures in zero magnetic field are shown in Fig. 2. Below the critical temperature of the array $T_C = 8$ K (which is lower than the corresponding temperature $T_{CS} = 9.25$ K for Nb due to proximity mediated effects between the junctions), the CVC show a nonlinear behavior:

$$V = R(I - I_C)^a. \tag{1}$$

In order to relate the observed power-like dependence of the CVC to dissipation processes, we adopt the BKT type expression for the power exponent in terms of the critical current $I_C(T, H)$ in our array [1–5]:

$$a(T, H) = 1 + \frac{\Phi_0 I_C(T, H)}{2k_B T}. \tag{2}$$

The data for zero-field $V(I)$ curves is fitted to the following temperature dependence of the zero-field critical current $I_C(T, 0) = I_C(0, 0)(1 - T/T_C)^2 e^{-\beta(T,0)}$ and the proximity mediated resistance $R(T, 0) = R_N \exp[\beta(T, 0) - \beta(T_{CS}, 0)]$. Here, $\beta(T, 0) = \gamma(T/T_C)^{1/2}$ with $\gamma = 2.9$, $I_C(0, 0) = 0.5$ μA, $R_N = R(T_{CS}, 0) = 0.4$ Ω, $T_{CS} = 9.25$ K and $T_C = 8$ K.

The best fits for the critical current and the power exponent are shown in Fig. 3. Notice that we did not observe the BKT transition most probably because even the highest value of the critical current in our array, $I_C(1.7\text{ K}, 0) = 38$ nA, is too small to meet the necessary conditions [11]. As a result, the transition region is shifted to very low temperatures which are beyond the range used in our experiments (in other words, T_{BKT} lies below $T = 1.7$ K). Besides, the obtained value of the critical current also suggests quite pronounced finite size effects in our array (since $L_x < \Phi_0/2\pi\mu_0 I_C(1.7\text{ K}, 0)$), which will further decrease T_{BKT} [11].

At the same time, some unusual magnetic field behavior was observed in our array. By treating the measured $V(I)$ curves in applied magnetic field (shown in Fig. 4 for $T = 1.7$ K) using the same Eqs. (1) and (2), both the critical current $I_C(T, H)$ and the power exponent $a(T, H)$ (shown in Fig. 5) are found to

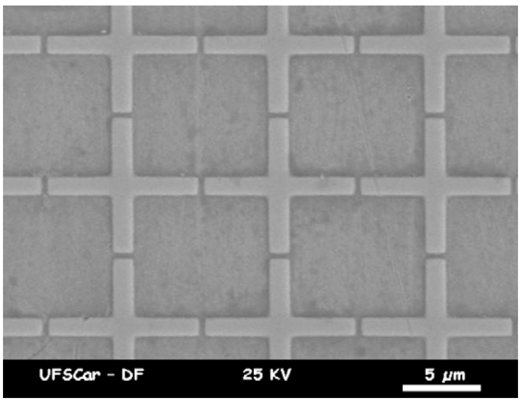

Fig. 1. SEM photography of 2D array of Nb–$Cu_{0.95}Al_{0.05}$–Nb junctions.

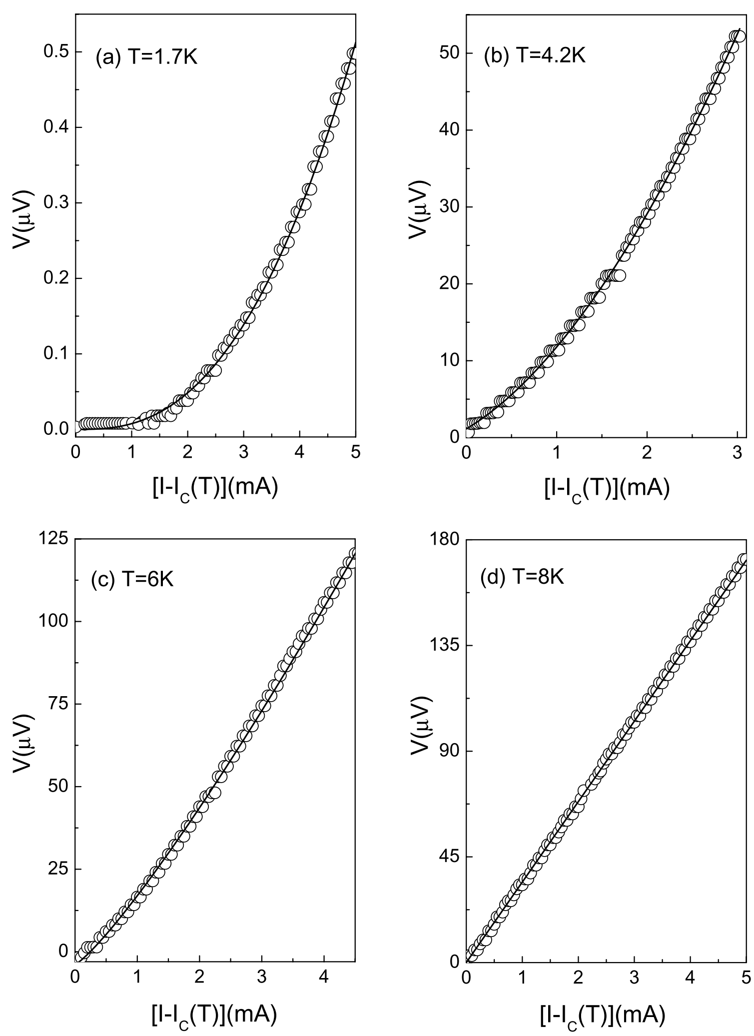

Fig. 2. Zero-field current–voltage characteristics for array of Nb–$Cu_{0.95}Al_{0.05}$–Nb junctions taken at various temperatures along with the best fits (solid lines) using Eqs. (1) and (2).

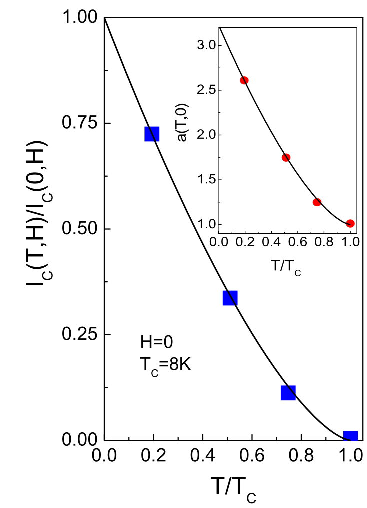

Fig. 3. Temperature dependence of the experimental points along with theoretical fits (solid lines) for zero-field values of the critical current $I_C(T,0)$ and the power law exponent $a(T,0)$ deduced from the $I \times V$ data (see Fig. 2) using Eqs. (1) and (2).

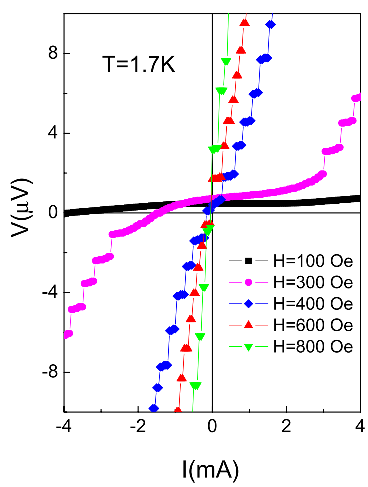

Fig. 4. The evolution of current–voltage characteristics for 2D array of Nb–$Cu_{0.95}Al_{0.05}$–Nb junctions with applied magnetic field (at $T = 1.7$ K).

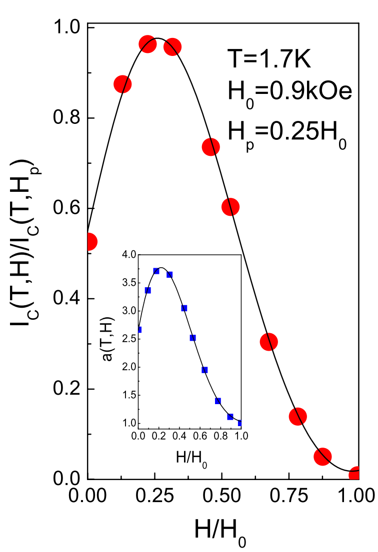

Fig. 5. Magnetic field dependence of the experimental points along with theoretical fits (solid lines) for the critical current $I_C(T,H)$ and the power law exponent $a(T,H)$ deduced from the $I \times V$ data (taken at $T = 1.7$ K, see Fig. 4) using Eqs. (1)–(4).

exhibit a pronounced peak at non-zero value of magnetic field $H_p = 0.25H_0 = 225$ Oe. To understand the origin of this peak, recall [15,16] that the magnetic field dependence of the critical current $I_C(T,H) = I_C(T,0)\exp\{-K_N(T,H)d_N\}$ for a single SNS type junction is governed by the inverse decaying length $K_N(T,H) = K_N(T,0)(1 + H/H_d)^{1/2}$, where $K_N(T,0) = (2\pi k_B T/hD_N)^{1/2}$ with diffusion coefficient $D_N = (1/3)v_F l$ for normal electrons (with Fermi velocity v_F and mean free path l), and $H_d = \Phi_0/4\pi\xi_N^2$ is the so-called [15] breakdown field with $\xi_N(T,0) = 1/K_N(T,0)$ being the characteristic length of the normal metal barrier. Apparently, the proximity induced exponential field dependence is not enough to explain the observed maximum of $I_C(T,H)$ in our case. As we shall show, to understand the origin of this maximum, the field dependence of the phase difference ϕ across the barrier should be taken into account as well. By analogy with the Josephson effect, we have [15] $\Delta\phi(T,H) = 2\pi HS(T)/\Phi_0$ for the field induced phase variation in SNS type junction, where $S(T) = d(T)w$ is an effective contact area with the length w and width $d(T) = d_N + 2\lambda_L(T)$ of a single contact (with $d_N = 310$ nm being a thickness of the normal metal barrier and $\lambda_L = 85$ nm the penetration depth for Nb).

For our analytical calculations, the so-called single-loop approximation [17–22] was employed which proved to be quite a reliable simplification for describing magnetic and transport properties in the well-defined periodic structure with no visible distribution of junction sizes and critical currents. Within this approximation, the unit cell is a loop containing four identical junctions with $\phi(x)$ being the gauge-invariant superconducting phase difference across the proximity type barrier. Since in our experiments $d_N > 2\lambda_L$, the true magnetic field dependence of the critical current in each loop can be presented as

$$I_C(T,H) = I_0 \int_0^{d_N} dx\, e^{-K_N(T,H)x} \sin\bigl[\varphi(0) + k(H)x\bigr] \tag{3}$$

and is defined by two contributions: the field induced variations of the proximity mediated inverse decaying length $K_N(T,H)$ and the Josephson mediated phase difference $\phi(x) = \phi(0) + k(H)x$, where $\phi(0)$ is the initial (zero-field) value and $k(H) = 2\pi Hw/\Phi_0$.

It can be easily verified that the above expression for $I_C(T,H)$ has a maximum at non-zero values of magnetic field only assuming $\phi(0) = \pi$ for the initial value of the phase difference (which signifies the presence of the so-called [23–27] π-type contacts in our array). The result of integration in this case readily produces

$$I_C(T,H) = I_C(T,H_p)\left\{\frac{1}{2} + \frac{e^{-\beta(T,H)}[h\cos(h) + \beta(T,H)\sin(h)] - h}{h^2 + \beta^2(T,H)}\right\} \tag{4}$$

for explicit field dependence of (normalized to the peak value) critical current in our array, where $h = HS(T)/\Phi_0$ and $\beta(T,H) = K_N(T,H)d_N = \beta(T,0)(1 + H/H_d)^{1/2}$, with $\beta(T,0) = \gamma(T/T_C)^{1/2}$. Notice that, in line with the observations, $I_C(T,0) = 0.5I_C(T,H_p)$. The data for $V(I)$ curves in applied magnetic field is fitted to Eq. (4) and the proximity mediated expression for magnetoresistance $R(T,H) = R(T,0)\exp[\beta(T,H) - \beta(T,0)]$ with $R(T,0)$ defined earlier, $H_d(T = 1.7\text{ K}) = 30$ Oe, and $\gamma = d_N/\xi_N(T_C,0) = 2.9$. The latter produces $D_N = 0.01$ m^2/s and $l = 40$ nm for estimates of the normal electrons diffusion coefficient and mean free path, respectively (assuming $v_F = 7 \times 10^5$ m/s for the Fermi velocity). A careful analysis of Eq. (4) revealed that the absolute value of the peak field H_p is defined by the competition between the proximity (β) and phase (h) mediated effects via the implicit expression, $h_p = h_p(\beta_p)$ with $\beta_p = \beta(1.7\ \mathrm{K}, H_p)$, leading to $\gamma_p = d_N/\xi_N(1.7\ \mathrm{K}, H_p) = 4$. Given the explicit field dependence of $\beta(T, H)$ and the value of the normal metal layer thickness $d_N = 310$ nm, the values of the decaying length at different temperatures and magnetic fields can be estimated from the fitting parameter γ. In particular, we obtain $\xi_N(T = 1.7\ \mathrm{K}, 0) = 232$ nm, $\xi_N(T = 4.2\ \mathrm{K}, 0) = 147$ nm, $\xi_N(T = 6\ \mathrm{K}, 0) = 125$ nm, $\xi_N(T_C = 8\ \mathrm{K}, 0) = 107$ nm; $\xi_N(T = 1.7\ \mathrm{K}, 0.1\ \mathrm{kOe}) = 111$ nm, and $\xi_N(T = 1.7\ \mathrm{K}, 0.9\ \mathrm{kOe}) = 41$ nm. Notice also that the field induced variation of the decaying length at the peak field $\xi_N(T = 1.7\ \mathrm{K}, H_p) = 80$ nm is equivalent to the breakdown field $H_d(T = 1.7\ \mathrm{K}, H_p) = 230$ Oe which remarkably correlates with the observed value of the peak field $H_p = 225$ Oe.

3. Summary

In summary, by treating the measured current–voltage characteristics for SNS type array of ordered Nb–$Cu_{0.95}Al_{0.05}$–Nb junctions within standard dissipation scenario, the critical current of the array was found to exhibit a maximum at non-zero value of applied magnetic field which was attributed to manifestation of π-type contacts in our sample.

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