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Universal resistance capacitance crossover in current-voltage characteristics for unshunted array of overdamped Nb–AlO₅–Nb Josephson junctions

S. Sergeenkov,²,³ V. A. G. Rivera,² E. Marega,² and F. M. Araujo-Moreira¹
¹Department of Physics and Physical Engineering, Materials and Devices Group, Universidade Federal de São Carlos, São Carlos 13565-905, Sao Paulo, Brazil
²Instituto de Física de São Carlos, USP, Caixa Postal 369, São Carlos 13560-970, Sao Paulo, Brazil

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We report on some unusual behavior of the measured current-voltage characteristics (CVC) in artificially prepared two-dimensional unshunted array of overdamped Nb–AlO₅–Nb Josephson junctions. The obtained nonlinear CVC are found to exhibit a pronounced (and practically temperature independent) crossover at some current $I_{cr}=(1/2\beta_{c}-1)I_C$ from a resistance $R$ dominated state with $V_R=R\sqrt{I-I_C}$ below $I_{cr}$ to a capacitance $C$ dominated state with $V_C=\sqrt{\hbar/4eC}\sqrt{I-I_C}$ above $I_{cr}$. The origin of the observed behavior is discussed within a single-plaquette approximation assuming the conventional resistively shunted junction model with a finite capacitance and the Ambegaokar–Baratoff relation for the critical current of the single junction. © 2010 American Institute of Physics. [doi:10.1063/1.3407566]

Among many different properties which can be studied using highly ordered two-dimensional (2D) arrays of Josephson junctions probably one of the most interesting (and important for their potential applications) is their transport behavior, reflecting manifestation of numerous dissipation mechanisms in the arrays (see, e.g., Refs. 1–3 and further references therein) via nonlinear current-voltage characteristics (CVC) of the general form $V \propto (I-I_C(T))^{\alpha(T)}$ with a power exponent $\alpha$ ranging from $\alpha<1$ to $\alpha>1$ depending on the particular mechanism and collateral effects (such as finite size of the single junction and/or the array, thermal fluctuations, quasiparticle contributions, etc.⁴⁻⁹). At the same time, recall that only sufficiently overdamped Josephson junctions (with nonhysteretic CVC) and their arrays can be effectively used in rapid single flux quantum logic circuits and programmable Josephson voltage standards (see, e.g., Refs. 10–13 and further references therein). In this paper we report our results on CVC for superconductor-insulator-superconductor (SIS) type array of strongly overdamped Nb–AlO₅–Nb junctions at different temperatures. We observed quite a pronounced crossover at some current $I_{cr}=(1/2\beta_{c}-1)I_C$ between a resistance $R$ dominated state (below $I_{cr}$) and a capacitance $C$ dominated state (above $I_{cr}$) which could be utilized as a versatile resistance-capacitance ($R$-$C$) switch within Josephson electronics. High quality ordered SIS type unshunted array of overdamped Nb–AlO₅–Nb junctions has been prepared by using a standard photolithography and sputtering technique.¹ It is formed by loops of niobium islands linked through 100×150 tunnel junctions. The unit cell of the array has square geometry with lattice spacing $a=46\ \mu$m and a single junction area of $5\times5\ \mu$m². The critical current for the junctions forming the arrays is $I_C(T)=150\ \mu$A at $T=1.7\ \text{K}$. Given the values of the junction quasiparticle resistance $R=10\ \Omega$ and capacitance $C=1.2\ \text{fF}$, the circuit frequency and dissipation measuring Stewart–McCumber parameter are estimated to be $\omega_{RC}=1/CR\approx 10^{14}\ \text{Hz}$ and $\beta_{c}(T)=\frac{2\pi CR(I_C(T))}{\Phi_0}\approx 0.05$ at $T=1.7\ \text{K}$, respectively. The parameters of the array are as follows, $I_C(1.7\ \text{K})=1.2\ \text{mA}$ and $R_A=25\ \Omega$. The measurements were made using homemade experimental technique with a high-precision nanovoltmeter.⁵ The temperature dependence of the normalized critical current of the array $I_C(T)/I_C(0)$ is shown in Fig. 1. Observe that it is very well fitted (solid line) to the Ambegaokar–Baratoff relation¹⁴ for the critical current of a single junction $I_C(T)=I_C(0)[\Delta(T)/\Delta(0)]\tanh[\Delta(T)/2k_BT]$, where $\Delta(T)$

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⁴Electronic mail: sergi@df.ufscar.br.

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FIG. 1. (Color online) The temperature dependence of the critical current for the array of overdamped Nb–AlO₅–Nb Josephson junctions. The solid line is the best fit using the single-junction Ambegaokar–Baratoff relation.
reported, because of the well-defined periodic structure of the array. However, as we have previously noted, the crossover behavior taking place around $I = I_c(T)$ is almost a universal phenomenon. According to Fig. 2, the crossover shows almost a universal behavior induced factors which seem to be of less importance for the plquettes used. This remarkable experimental fact suggests a rather strong coordinated response from all the junctions forming the array and allows us to substantially simplify the analysis of the obtained results by considering the properties of a single junction (plquettes, see below). For this purpose, the initial CVC data for array were rescaled by simply introducing the critical current of the single junction $I_c$. Some typical results of the normalized rescaled CVC taken at different temperatures are shown in Fig. 2. The solid lines through the data points are the best fits according to the following expressions: $V_R = V_0 \sqrt{(I-I_c)/I_0}$ for $I_c < I < I_c$, and $V_c = V_0 \sqrt{(I-I_c)/I_0}$ for $I > I_c$ with $V_0 = 30$ mV and $I_0 = 3$ mA. It is interesting to point out that, according to Fig. 2, the crossover shows almost a universal behavior taking place around $|I - I_c(T)|/I_0 = 0.4$ for all temperatures. To understand the observed behavior of the CVC in our array, in principle one would need to analyze in detail the dynamics of the array. However, as we have previously reported, because of the well-defined periodic structure of our array, it is reasonable to expect that our experimental results can be quite satisfactorily explained by analyzing the dynamics of a single unit cell of the array. In our calculations, the unit cell is a plquettes forming four identical Josephson junctions. By analogy with the resistively shunted junction (RSJ) model, the total current in the plquettes reads:

$$I = I_c(T) \sin \phi_i(t) + \left( \frac{\Phi_0}{2 \pi R} \right) (d\phi_i/dt) + \left( C \Phi_0/2 \pi \right) \times (d^2\phi_i/dt^2).$$

Here $\phi_i(t)$ is the gauge-invariant superconducting phase difference across the $i$th junction, and $\Phi_0$ is the magnetic flux quantum. For any particular solution $\phi_i(t)$ of this equation at $I = 0$, the resulting CVC of the RSJ model is given by the time average of the voltage ($\pi = 2 \pi / \omega$ is properly defined period) $V(I) = \hbar/2e \tau_0^2 dt (d\phi_i/dt)$. For the resistance dominated situation (when the capacitance related effects can be totally neglected), that is when $\phi_{RC} > 1$, the RSJ model has a well-known solution:

$$\phi_i(t) = 2 \tan^{-1} \left[ \left( h/2eR \right) \tan(\omega t/2) - (1/I_c) \right]$$

with $\omega = (2eR/h) \sqrt{I^2 - I_c^2}$, which brings about $V_R = (h/2e) \int_0^\infty dt (d\phi_i/dt) = R \sqrt{I^2 - I_c^2}$ for $R$-dominated CVC. As we can see, this dependence exactly corresponds to the fitting expression for the observed CVC below $I_c$, assuming the Ohmic relation $V_0 = RL_0$. Let us turn now to the opposite situation and consider the capacitance dominated regime when the resistance related effects can be totally neglected (that is when $\phi_{RC} < 1$). In this case, the first integral of the RSJ model reads:

$$\int_0^\infty dt \frac{d\phi_i}{dt} = \sqrt{2} \omega_p \left( C_1/I_c \right) + (1/I_c) \phi_i + \cos \phi_i$$

where $\omega_p = \sqrt{2eI_c/h} C$ is the plqueton frequency, and $C_1$ is the integration constant. Unfortunately, for $I = 0$, this equation cannot be solved exactly. Hence, let us consider its approximate solution as $\phi_i(t) = \left( \frac{2e}{h} \right) t + \theta(t)$ with $\theta(t) \equiv (\pi/2)$. By fixing the arbitrary constant as $C_1 = -\pi/2$, within this approximation, we obtain $\theta(t) = \sqrt{\omega_p^2 (I-c)/2I_c}$, which in turn results in the following explicit form of $C$-dominated CVC:

$$V_c = \left( h/2e \right) \int_0^\infty dt (d\phi_i/dt) = \sqrt{h/4eC} \sqrt{I-I_c}.$$  

As we can see, this dependence exactly corresponds to the fitting expression for the observed CVC above $I_c$, assuming $V_0 = \omega_p \sqrt{2eI_0} h = \hbar \omega_{RC}/2e$ and $I_0 = V_0/R = I_c/\beta C$ for the normalization parameters. Furthermore, given the experimental values for $R$ and $C$, we obtain $V_0 = 30$ mV and $I_0 = 3$ mA. In turn, from the obvious identity $V_0 = \sqrt{h/4eC} (I_c/I_c)$, we readily obtain $I_c = (1/2 \beta C - 1) I_c$ for the crossover temperature. Finally, a comment is in order regarding the employed here simplified model of 2D array. It should be noted that we completely ignored indurance (geometry) related effects which seem to be of less importance for the interpretation of the observed crossover than dissipation induced factors (resistance and capacitance). However, for more adequate description of the flux dynamics in truly 2D systems, these effects should be taken into account. Indeed, as accurate numerical simulations have revealed, both self-inductance and mutual inductance effects will have a significant impact on the array’s dynamic properties through creation of rather strong self-induced magnetic fields.

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