Fluxon pinning by an array of Abrikosov vortices in a long Josephson junction

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(Submitted 12 March 1993)
Pis'ma Zh. Eksp. Teor. Fiz. **57**, No. 8, 468–472 (25 April 1993)

Peaks have been observed on the plot of the Josephson critical current against the external magnetic field in a long Josephson tunnel junction with an array of mismatched Abrikosov vortices. An increase in the maximum critical current with increasing number of Abrikosov vortices localized in the junction has also been observed. The observed effects prove that there is a pinning of Josephson vortices by mismatched Abrikosov vortices.

It has been shown theoretically[1,2] that Abrikosov vortices introduced in a long Josephson junction can be thought of as local magnetic inhomogeneities which interact with Josephson vortices. ("Long" here means that the maximum dimension of the junction is greater than the Josephson penetration depth λ_j.) The introduction of a regular chain of Abrikosov vortices (A-vortices), which serve as pinning centers for Josephson vortices (such A-vortices are called "effective" vortices) should raise the maximum Josephson critical current $I_c^{\max}$ on the plot of the Josephson critical current I_c versus the magnetic field parallel to both the plane of the junction and its short side ($H_\parallel$).[3] Furthermore, by analogy with long Josephson junctions with periodic insulating inhomogeneities,[4] we might expect that a regular chain of effective A-vortices would give rise to a series of regular peaks of the critical current I_c on the plot of $I_c(H_\parallel)$ at certain fields $H_\parallel > |H_{c1}|$. These fields would satisfy the condition that the period in the chain of Josephson vortices (J-vortices) must be spatially commensurate with the period of the array of A-vortices. (H_{c1} is that value of the magnetic field $H_\parallel$, parallel to the plane of the junction, at which the first J-vortex penetrates into the junction.)

In this letter we are reporting an observation of effects stemming from the pinning of J-vortices by a chain of mismatched A-vortices, for which the axes passing through the centers of the normal cores do not coincide.[5,6] We used long Nb–AlO$_x$–Nb Josephson junctions with an "overlap" geometry,[7] with a length $L \approx 500\ \mu$m and a width $W \approx 20\ \mu$m. The value of λ_j was $\simeq 11\ \mu$m. The A-vortices were introduced in the junction by cooling the sample from $T > T_c$ to $T < T_c$ ($T = 4.2$ K) in a magnetic field directed perpendicular to the plane of the junction ($H_\perp$). After the cooling, the field $H_\perp$ was turned off, and $I_c(H_\parallel)$ was measured. The experimental conditions (the procedure for preparing the samples, the experimental apparatus, and the procedure for introducing the A-vortices) were identical to those of Refs. 5 and 6. It was possible

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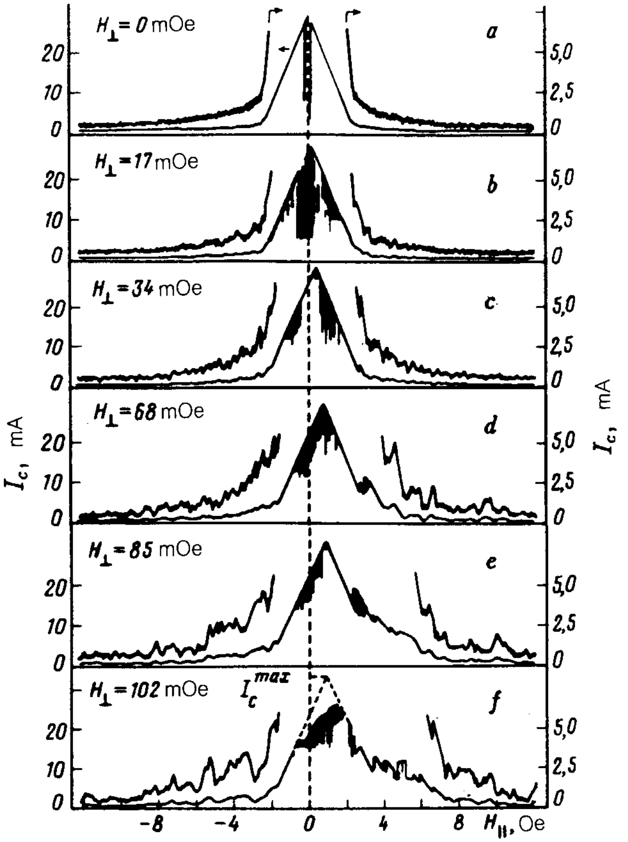

FIG. 1. Curves of $I_c(H_\parallel)$ measured after the cooling of the long Josephson junction in perpendicular magnetic fields $H_\perp$ of various strengths. The values of $H_\perp$ are specified in the figure. Two current scales are used for each $I_c(H_\parallel)$ plot.

to introduce in the film of the junction a disordered array of mismatched A-vortices separated by an average distance

$$l \approx \Phi_0 (H_\perp W)^{-1}, \quad l \gg W,$$
$$l \approx \sqrt{\Phi_0 / H_\perp}, \quad l \ll W. \tag{1}$$

The curve of $I_c(H_\parallel)$ measured after the cooling of the junction in a background magnetic field (1–5 mOe) had a shape similar to that of the curve for a quasi-1D tunnel junction with a maximum dimension[8] $L \gg \lambda_j$ (Fig. 1a). The field H_{c1} was ≈ 2.5 Oe.

Figure 1, b–f, shows some illustrative plots of $I_c(H_\parallel)$ measured after the junction was cooled in fields of identical polarity from the interval 8 mOe $\leqslant H_\perp \leqslant$ 102 mOe. It was found that I_c peaks appear at fields $H_\parallel > |H_{c1}|$. As the field $H_\perp$ is increased, the

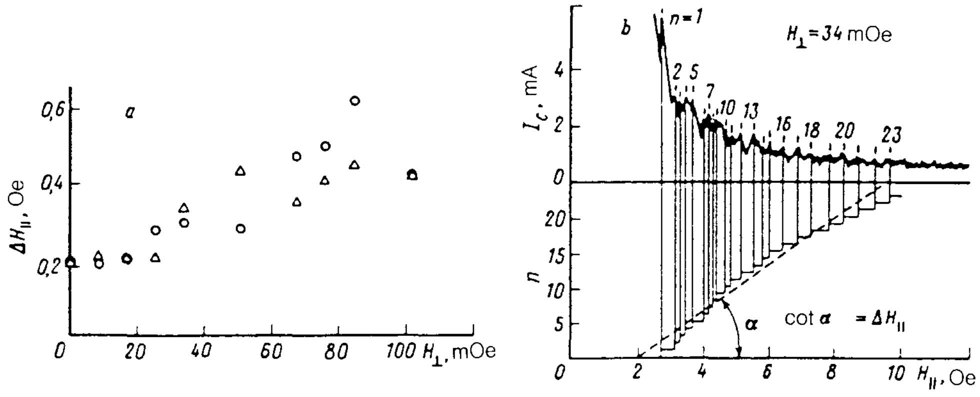

FIG. 2. a: Average distance between I_c peaks, $\Delta H_{\parallel}$, versus the cooling magnetic field $H_{\perp}$. The circles and triangles correspond to opposite directions of $H_{\parallel}$. b: Procedure for determining $\Delta H_{\parallel}$ from the $I_c(H_{\parallel})$ curve; n is the number of observed peaks.

structure of the peaks becomes progressively more obvious, and the average distance between peaks ($\Delta H_{\parallel}$) increases. The latter effect can be seen clearly on the experimental curve of $\Delta H_{\parallel}$ ($H_{\perp}$) in Fig. 2a (Fig. 2b illustrates the procedure for determining $\Delta H_{\parallel}$). In addition to the appearance of I_c peaks, the increase in $H_{\perp}$ causes the main peak on the $I_c(H_{\parallel})$ curve to shift along the $H_{\parallel}$ axis. It also causes a change in the Josephson critical current in the main peak on the $I_c(H_{\parallel})$ curve ($I_c^{\max}$). Figure 3a shows a plot of $I_c^{\max}$ versus $H_{\perp}$. On the curve of $I_c(H_{\parallel})$ corresponding to the field $H_{\perp} = 102$ mOe (Fig. 1f) the value of $I_c^{\max}$ cannot be detected directly. It was found by an extrapolation method. The plot of $I_c^{\max}(H_{\perp})$ shows an increase in $I_c^{\max}$ in the field interval 8 mOe$\leqslant H_{\perp} \leqslant$ 34 mOe, a sharp decrease in $I_c^{\max}$ at $H_{\perp} = 51$ mOe, and a renewed increase in $I_c^{\max}$ in the field interval 51 mOe$< H_{\perp} \leqslant$ 102 mOe. The instabilities of the critical current I_c, which are observed in certain intervals of the field $H_{\parallel}$ on the curves of $I_c(H_{\parallel})$ (Fig. 1), are not due to stray pickup or noise. At these values of $H_{\parallel}$, the current-voltage characteristic of the long junction measured at the frequency 10–90 Hz has several values of the critical current I_c and also some soliton branches.

Let us examine the results. At those fields $H_{\perp}$ which we used in these experiments, an array of A-vortices separated by an average distance $l > W$ was produced in the films of the long Josephson junctions [the value of l was estimated from expression (1)]. In these experiments, an array of A-vortices consisting of one or two rows of vortices was introduced in the long Josephson junction. These rows were oriented along the long dimension of the junction. The peaks on the $I_c(H_{\parallel})$ curve detected after the mismatched A-vortices were introduced in the junction should appear when the distance between the effective A-vortices, l_{eff}, and the period in the chain of J-vortices, $l_f \approx \Phi_0/2\lambda_L H_{\parallel}^*$, become commensurable[4] (λ_L is the London depth, and $H_{\parallel}^*$ is the magnetic field at which the peak in I_c is observed). It follows from the condition for commensurability[4] that the spacing of the I_c peaks, $\Delta H_{\parallel}$, and the distance l_{eff} must satisfy

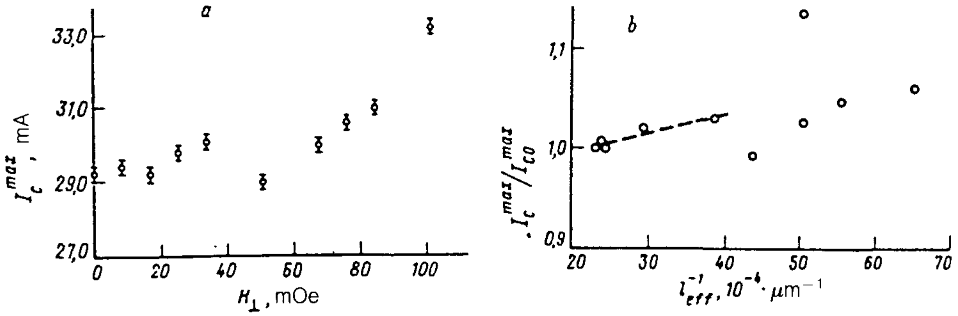

FIG. 3. a: $I_c^{\max}$ versus the cooling magnetic field $H_\perp$. b: $I_c^{\max}/I_{c0}^{\max}$ versus the average distance between effective A-vortices, l_{eff}.

$$\Delta H_\parallel = \Phi_0 (2\lambda_L l_{\text{eff}})^{-1}. \tag{2}$$

The experimental $\Delta H_\parallel$ ($H_\perp$) curve (Fig. 2a) agrees qualitatively with relation (2), since l_{eff} decreases with increasing $H_\perp$. Using the experimental values of $\Delta H_\parallel$ and (2), we can estimate l_{eff} for each field $H_\perp$ (for the particular Josephson junction used[5] we have $\lambda_L \simeq 0.12$ μm). The value of l_{eff} for all values of the field $H_\perp$ used in these experiments is greater than the average distance between vortices, l. For a maximum field $H_\perp = 102$ mOe, for example, we have $l_{\text{eff}} \simeq 20$ μm, and the average distance between vortices, l, is found from (1) to be $\simeq 14$ μm.

We know that the value of $I_c^{\max}$ is approximately proportional to the force which must be applied in order to put a J-vortex in motion.[9] Accordingly, the observed increase in the maximum Josephson critical current $I_c^{\max}$ with increasing field $H_\perp$ (Fig. 3a) reflects a pinning of J-vortices which have entered the junction; they are pinned by the array of effective mismatched A-vortices. Using the theoretical method of Refs. 5 and 6 to analyze the modified sine-Gordon equation with captured mismatched A-vortices,[1] one can show that the presence of one row of effective mismatched A-vortices with an average period $l_{\text{eff}} \gg \lambda_j$ causes an increase in $I_c^{\max}$ in accordance with

$$I_c^{\max}/I_{c0}^{\max} = 1 + a(W^{-1})\overline{\cos\theta}(L - 2\lambda_j)(l_{\text{eff}})^{-1}, \tag{3}$$

where $I_{c0}^{\max}$ is the critical current at the main peak on the $I_c(H_\parallel)$ curve measured after the junction was cooled in the background magnetic field, a is the average mismatch parameter of the A-vortices,[5,6] the term $\overline{\cos\theta}$ determines the average direction of the axes of the A-vortices with respect to the axis of the J-vortex (the axis of an A-vortex lies in the plane of the junction and passes through the points of entry into and exit from the magnetic field of the A-vortex). Expression (3) was derived under the condition $l_{\text{eff}} \gg W$ ($\lambda_j \simeq W$), which corresponds to the case in which the A-vortices interact independently with the J-vortex (the range of the interaction between A-vortices is[2] $\sim W$). The force of the interaction of one mismatched A-vortex with a J-vortex is proportional to $a(W^{-1})\overline{\cos\theta}$. For the junctions used in these experiments[5, 6] we have $a \simeq 1\ \mu$m. Using the $\Delta H_{\parallel}\ (H_{\perp})$ dependence (Fig. 2a) along with relation (2), we can calculate l_{eff} for each value of the field $H_{\perp}$. We can use the $I_c^{\max}(H_{\perp})$ dependence (Fig. 3a) to plot $I_c^{\max}/I_{c0}^{\max}[(l_{\text{eff}})^{-1}]$ (Fig. 3b). The dashed line in this figure is a least-squares fit of the points corresponding to fields $H_{\perp} \leqslant 34$ mOe, for which the average distance between vortices, l, as calculated from (1), exceeds the width of the junction, W. This case corresponds to the capture of one row of effective mismatched A-vortices. Comparing the slope of this dashed line with the coefficient of l/l_{eff} in (3), we find $\overline{\cos\theta} \approx 0.83$. We can thus conclude that only those mismatched A-vortices whose axes are directed approximately along the axis of the J-vortex are effective in pinning a J-vortex.

Note the abrupt decrease in $I_c^{\max}$ at $H_{\perp} = 51$ mOe (Fig. 3a). It is possible that this experimental result is associated with the entry of two rows of effective mismatched A-vortices into the junction.

The shift of the main peak on the $I_c(H_{\parallel})$ curve (Fig. 1, b–f) can probably be attributed to the presence of an effective magnetic field in the junction. This field would be produced by the captured mismatched A-vortices and would have a component parallel to $H_{\parallel}$.

In summary, in a long Josephson junction in which one or two rows of mismatched A-vortices have been captured, we have observed a pinning of J-vortices by effective A-vortices. The results indicate that the effective mismatched A-vortices are those vortices whose axes are directed nearly along the axes of the J-vortices.

We wish to thank V. V. Lyubimov for assistance in the measurements of the weak magnetic fields. We also thank L. Ya. Vinnikov and A. F. Volkov for a discussion of the results.

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Translated by D. Parsons