Two-dimensional imaging of trapped magnetic flux quanta in Josephson tunnel junctions

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(Received 29 October 1986)

Using low-temperature scanning-electron microscopy we have observed, with high-spatial resolution, magnetic flux quanta trapped in a Josephson tunnel junction. The observed influence of the trapped vortices on the distribution of the Josephson current density agrees well with theoretical calculations.

Trapped magnetic flux quanta in Josephson tunnel junctions have been the subject of strong theoretical[1-3] and experimental[4-8] interest during the last decade because of their degrading effects on the performance of Josephson junction devices. By employing low-temperature scanning-electron microscopy,[9] for the first time we were able to obtain detailed information on the position of trapped flux quanta in Josephson tunnel junctions, on their orientation, and on their influence on the spatial distribution of the Josephson current density.

The measurements presented here were performed with a lead-alloy junction evaporated on a single-crystal sapphire substrate of 1 mm thickness. A PbIn film (11-wt.% In) of 1300 Å thickness served as the base electrode. A 2000-Å SiO layer was deposited upon this film to define the tunneling area as indicated in Fig. 1. The tunnel barrier, grown by thermal oxidation, was covered by a 2800-Å-thick PbIn film (5-wt.% In) forming the top electrode. The value of the Josephson penetration depth was 15 μm, as determined by evaluation of the I-V characteristic. During the experiments the back side of the sapphire substrate was immersed in liquid He held at 4.2 K, whereas the top side carrying the junction was exposed to the vacuum of the electron microscope.[9]

As described in more detail elsewhere,[10] the spatial variation of the maximum Josephson current of the junction was measured by scanning the junction surface with the electron beam (26 keV and typically 100 pA) and by recording the beam-induced change $\delta I_{\max}(x,y)$ of the maximum Josephson current as a function of the coordinates x and y of the beam focus. In this way we obtained the result presented in Fig. 2. The beam-induced change $-\delta I_{\max}(x,y)$ is plotted vertically for a series of horizontal line scans (y modulation), the maximum value of $|\delta I_{\max}|$ being about 10% of the total Josephson current. The boundaries of the tunneling area are indicated by the triangles. In the following, we focus our attention on the two depressions of the Josephson current density seen in Fig. 2 in the upper left and in the lower right part of the junction.

During the experiments we noticed that these depressions could be displaced by an electric current flowing in the top electrode and that they could be completely removed by heating the junction with the electron beam. These observations suggested to us that we are dealing possibly with transverse magnetic flux quanta trapped in the junction.

Taking up this idea we have calculated the spatial variation of the density of the critical Josephson current, assum-

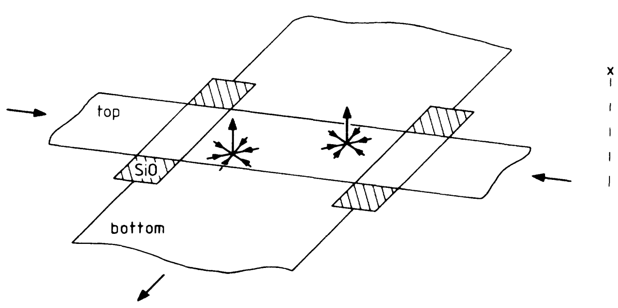

FIG. 1. Geometry of the investigated Josephson junction. The supercurrent enters the junction by the top electrode and leaves it via the bottom electrode, as indicated by the arrows. The two starlike objects drawn in the tunneling barrier indicate trapped transverse magnetic flux quanta. The two SiO layers along the boundaries of the bottom junction (hatched areas) serve for strengthening the electric insulation between both junction electrodes in these regions. The x at the right shows the viewpoint of the perspective presentations given in Figs. 3 and 4.

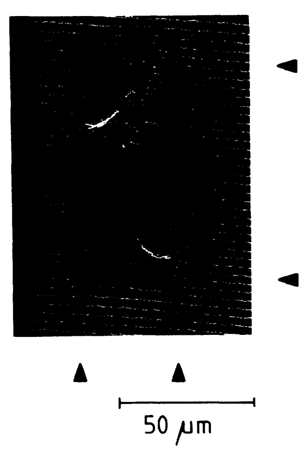

FIG. 2. Measured spatial variation of the Josephson current density in the cross-line junction sketched in Fig. 1. The beam-induced change $-\delta I_{\max}(x,y)$ of the maximum Josephson current is plotted vertically in arbitrary units for a series of horizontal line scans (y modulation). The triangles indicate the location of the boundaries of the junction.

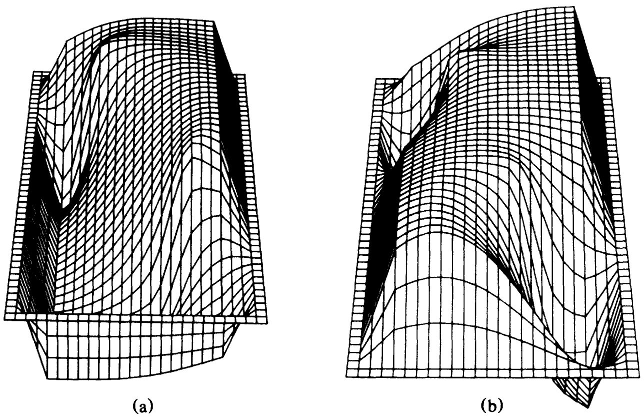

FIG. 3. Calculated spatial variation of the Josephson current density (in arbitrary units) for the junction shown in Fig. 1 and for $\lambda_J = 15$ μm. The figure depicts an area of 37×85 μm^2. The spatial resolution of the calculation was artificially lowered to 3 μm for a direct comparison with the experimental result. (a) One misaligned vortex penetrating the total junction from the lower right to the upper left is presumed. (b) Vortex configuration as shown in Fig. 1 is assumed.

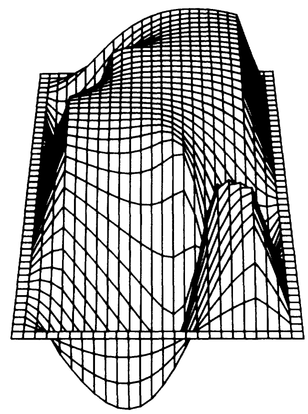

FIG. 4. Calculated spatial variation of the Josephson current density (in arbitrary units) for the junction shown in Fig. 1 with $\lambda_J = 15$ μm and a spatial resolution of 3 μm, assuming that the vortex located in the lower right carries two flux quanta. The figure depicts an area of 37×85 μm^2.

ing that magnetic flux is penetrating the junction transversely. For these calculations we used a numerical iteration method that starts with an evaluation of the magnetic flux density in a Josephson junction carrying an arbitrarily chosen distribution of the supercurrent. Next, from this flux density the phase difference function of the junction was calculated. In the following step, the Josephson current distribution was computed, representing the starting point of the next iteration step. A more detailed description of this method can be found elsewhere.[11] Transverse magnetic vortices were taken into account by adding their magnetic field to the magnetic field of the Josephson current in the course of the iteration procedure. For the evaluation of the magnetic flux density of the vortices we followed the ideas of Miller, Biagi, Clem, and Finnemore.[2]

The calculated spatial variation of the density of the critical Josephson current is shown in Fig. 3 for two cases. Figure 3(a) displays the current density expected if a single vortex penetrates the base electrode in the lower right of the junction, follows the barrier to the upper left, and leaves the junction through the top electrode. We see that there is a striking deviation from the measured current density. On the other hand, excellent agreement between experiment and theory can be found if one assumes that two separate vortices enter the junction via the barrier and leave the sample piercing through the top or the bottom electrode. The calculated result is shown in Fig. 3(b) for this case.

It is easily verified by comparison with numerical calculations that the vortices we have observed experimentally carried single flux quanta. Figure 4 shows, for example, the theoretical prediction for the spatial variation of the current density one obtains with the assumption that the vortex located in the lower right part of Fig. 3(b) carries two flux quanta. The perspective of the graphic presentations in Figs. 3 and 4 is approximately indicated by the position of the point marked x in Fig. 1.

Having found the spatial dependence of the phase difference function we are now able to determine the local magnetic flux density with an accuracy of a few percent and with a spatial resolution of a few μm. The magnetic field lines corresponding to the case of Fig. 3(b) are shown in Fig. 5.

The mechanism determining the location of the trapped vortices represents an interesting and important question. We have observed the preferential formation of hillocks near the boundaries of the SiO layers. It may be these stressed film regions which act as trapping centers for the vortices. On the other hand, the two trapped flux quanta tend to position themselves at maximum available distance

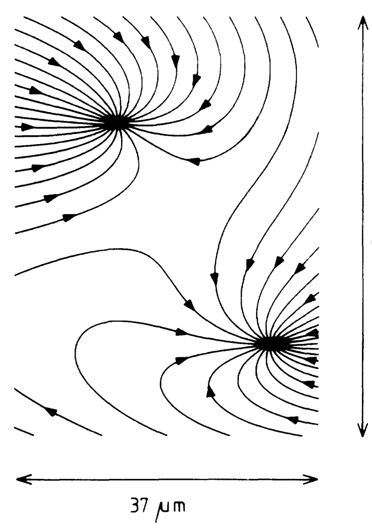

FIG. 5. Field lines representing the magnetic flux density within the barrier of the junction for the case indicated in Figs. 1 and 2.

due to their repulsive interaction.

Summarizing our results, we conclude that low-temperature scanning-electron microscopy combined with appropriate theoretical calculations provides a powerful tool for investigating the phenomena in Josephson tunnel junctions associated with the spatial distribution of the pair current. In particular, we expect from further applications of this technique a wealth of information concerning trapped flux quanta. Pinning of trapped flux quanta can be studied by observing the influence of an applied force such as the Lorentz force upon the vortex behavior.

Financial support of this work by the Stiftung Volkswagenwerk is gratefully acknowledged. The authors benefited from stimulating conversations with John R. Clem.

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