Suppression of I_c and Fiske resonances in specially shaped Josephson junctions

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In some applications of Josephson junctions it is necessary to suppress the critical current and Fiske resonances with a relatively small magnetic field. The sidelobes of the Fraunhofer pattern can be suppressed by taking an appropriate shape for the junction. A suppression of the first sidelobe below 1% of the zero-field critical current is possible as was shown experimentally. However, Fiske resonances are still present. We investigated how an adaptation of the junction shape may suppress these resonances, still maintaining the suppression of the sidelobes of the Fraunhofer pattern. Measurements of the critical current and Fiske resonance heights as a function of the magnetic field for a junction with a special shape and an adapted specially shaped junction were performed. For both types of junctions, the sidelobes of the $I_c(B)$ patterns are suppressed. No extra suppression of the $I_F(B)$ patterns due to the adaptation of the shape is observed.

1. THEORY

In small Josephson junctions in a homogeneous magnetic field B_y , the tunnel current density J depends only on x . J is given by $J(x) = J_c \sin(kx + \phi_0)$, where $\phi = kx + \phi_0$ is the phase of the supercurrent, J_c is the maximum critical current density, $k = 2\pi B_y d / \Phi_0$, and the magnetic penetration depth $d = 2\lambda_L + t$. For a symmetric junction, described by the even function $f(x)$ for $y > 0$ and $-f(x)$ for $y < 0$, $I_c(B)$ is given by [1]:

$$I_c(B) = 2J_c \int_{-x_0}^{x_0} f(x) \cos(kx) dx. \quad (1)$$

The constant ϕ_0 was chosen to maximize I_c . The maximum dimensions are $L_x = 2x_0$ and $L_y = 2f(0)$. For a rectangular junction the well-known Fraunhofer pattern is obtained. If $f(x)$ is a properly chosen quartic polynomial, like the junction shown in fig.1a, an $I_c(B)$ pattern can be obtained with an envelope falling off as B^{-4} [2].

Fiske resonances in Josephson junctions arise from the interaction between standing electro-magnetic waves in the junction barrier and the ac Josephson current, giving rise to resonant modes, observed as current peaks in the I - V curve, when a magnetic field is applied. For a rectangular junction they occur at voltages $V_{nm} \sim [(n/L_x)^2 + (m/L_y)^2]^{1/2}$ (n, m are integers) [3]. The amplitude I_F of a Fiske step depends on the quality factor Q of the cavity for that resonant mode. The theoretical field dependence of Fiske resonances in high Q junctions has only been calculated in the rectangular case [4]. It has been

found experimentally that for Nb/Al junctions $I_F(B)$ roughly falls off as B^{-1} [5]. The junction geometry, that largely influences Q , may be used to reduce Q and thus $I_F(B)$. The junction shape is adapted such that the standing waves do fit less well in the cavity. Fig.1a shows that a quartic shape resembles a rectangle and quasi-rectangular cavity modes may exist. The quartic shape can be divided into smaller, non-rectangular sections, each having smaller dimensions and thus higher resonance frequencies, and may result in a lower Q due to the larger deviation from the rectangular shape. Therefore a reduction of the resonance amplitudes is expected. If all sub-sections are connected, the phase of the current in each section is locked to that of the neighbouring sections and eq.(1) is still applicable. Note that the function $f(x)$ in the integrand is changed into $f(x) = f(x) - a(x)$, $a(x)dx$ being the area at position x that can not carry any tunneling current. However, by changing the outer

Fig.1: Quartic shaped junction (Q1, left) and adapted quartic shaped junction (Q2, right).

Fig.2a: $I_c(B)/I_c(0)$ on two scales and $I_F(B)/I_c(0)$ for Q1 (exp. data, except $I_{c,th}$: theor. curve)

shape of the junction to $f(x)+a(x)$, the original $I_c(B)$ pattern is regained.

2. RESULTS

Josephson junctions with the quartic shape (type Q1; see fig.1a) and various adapted quartic shapes (e.g. Q2 in fig.1b, with the outer shape $f(x)+a(x)$) were fabricated in Nb/Al-technology, using the SNAP process. The structures inside the junction area of Q2 are fully anodized, so that they are not part of the tunneling area. For Q1 and Q2 $L_x=2x_0=40\mu\text{m}$, somewhat less than the Josephson penetration length. The measurements were performed at 4.2K.

In fig.2a and 2b the experimental $I_c(B)$ curves for these junctions are shown. In both cases I_c falls off far more rapidly than for rectangular junctions. Previously it was shown that for quartic junctions the decrease of I_c is even more drastic than eq.1 predicts, though at higher fields an $I_c(B)$ modulation with a very small amplitude remains [1]. The deviations from theory are mainly due to the large sensitivity of eq.(1) to small deviations from the ideal shape. Especially in the case of Q2 the fabrication process has rounded off all sharp edges of the beam-like structures inside the junction as well as the outer shape, giving rise to the foot and the extra lobe at 1.7mT, which is part of the remnant $I_c(B)$ modulation which is significantly larger than for Q1.

Fig.2 shows the $I_F(B)$ patterns of the resonances in junction Q1 and Q2 respectively. The main lobes have significant amplitudes up to

Fig.2b: idem for Q2.

30% of $I_c(0)$. But, whereas the $I_F(B)$ curves for a rectangular junction fall off only slowly, showing many lobes [5], here only one lobe is observed. For higher fields the peak amplitudes do not exceed the subgap current, and level off at about $0.06I_c$ as the field is increased. Because the resonance voltages are equal, F1 and F2 for Q1 and Q2 are assumed to have the same spatial modulation. No significant reduction of the resonances F1 and F2 in Q2 in comparison with Q1 is observed. One may expect this, because the corresponding wavelengths are large in comparison with the structures on Q2, and the reflection of e.m. waves at these places is small. At higher voltages the resonances are slightly suppressed, probably due to the smaller corresponding wavelengths.

3. CONCLUSIONS

A very strong suppression of the sidelobes of the $I_c(B)$ pattern and the Fiske resonances is possible in quartic shaped junctions. An adaptation of the structure only slightly improves the suppression of the higher mode resonances. The $I_c(B)$ sidelobe suppression is slightly deteriorated due to the deviation from the ideal structural shape.

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