LARGE STEPS IN LONG JOSEPHSON JUNCTIONS

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ABSTRACT

Large constant voltage current-steps were observed in the IV-characteristics of long NbN-MgO-NbN Josephson junctions in the presence of external magnetic fields of a few Gauss. The steps are separated by a voltage ΔV corresponding roughly to 3 to 5 times the voltage spacing expected between adjacent Fiske-steps. Models discussing the origin of such steps are presented. Simultaneous nucleation of fluxons at several sites along the junction with thin electrodes, favored by the large London penetration depth of NbN, would introduce a large amount of magnetic flux into the junction at once which would lead to large steps. A new model is presented here; involves pinning of fluxons in the junction. Due to the granularity of NbN and its very small coherence length there will be pinning sites in the junction preventing single fluxons to move at low bias currents. At particular junction parameter values the steps become very regular and sharp. Such characteristics are well suited for a voltage standard and oscillators.

INTRODUCTION

Long Josephson junctions have attracted increased interest in recent years because they are highly nonlinear, modeled by a perturbed sine-Gordon equation, where the dynamics of solitons can be investigated in great detail experimentally and in numerical simulations. Furthermore applications of these junctions to superconducting electronics, especially microwave oscillators, are promising.

A junction is considered long if one of its dimensions (length L) is larger than the Josephson penetration depth λ_J, while the other one (width W) is much smaller than λ_J. When an external magnetic field is applied parallel to the plane of the junction barrier and parallel to the short dimension of the junction, the magnetic flux is initially screened from the interior of the junction; the screening persists up to the Josephson critical field $H_{c1,J} = 2\lambda_J j_c$, where j_c is the critical current density of the junction. Then, at $H > H_{c1,J}$, magnetic flux enters the junction in quantized units of flux $\Phi_0 = 2.07 \cdot 10^{-7}$ G$\cdot$cm^2; such vortices are known as Josephson fluxons and are in fact solitons.

A bias current through the junction exerts a Lorentz-force on the fluxons and causes them to move in the junction. The speed of the fluxons is determined by a balance between energy input from the bias current and losses caused by normal currents in the junction barrier and in the electrodes; the terminal speed is typically a few percent of the speed of light in vacuum. At the edges of the junction the fluxons are reflected as plasma waves or antifluxons; this leads to resonant motion of fluxons. The motion of fluxons manifests itself as constant voltage current-steps in the IV-characteristics of the junction. Steps (Fiske-steps) appear at fixed voltages given by

$$V_n = n\Phi_0 \bar{c}/2L,$$

where n is the number of fluxons present in the junction and c is the fluxon speed. At each reflection of a fluxon at one of its ends, electromagnetic radiation with a frequency determined by the fluxon speed is emitted from the junction. This is known as the resonant mode oscillator.

In this paper we present data on large steps, which have been observed in many of our NbN long Josephson junctions. The model presented above applies to homogeneous junctions; inhomogeneities in the junction barrier or in the electrodes will influence the fluxon motion and may cause changes in the IV-characteristics. Possible models describing the origin of such steps will be discussed and finally possible applications will be presented.

EXPERIMENT

The long junctions are fabricated from NbN-MgO-NbN tri-layers reactively sputtered in a dc magnetron sputtering system, by using photolithography and plasma etching. The junctions are of the overlap type, with eight equally spaced current injection fingers on each electrode, Fig. 1. The NbN electrodes are approximately 3000 Å thick, while the thermally oxidized MgO barrier is 20 to 30 Å thick. Due to the large London penetration depth λ_L of NbN thin films, the film thickness is comparable to λ_L. Important parameters of two junctions used here are listed in Table 1.

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Table 1: Parameters of two junctions

Junction	LxW [μmxμm]	R_n [Ω]	j_c [Acm^{-2}]	λ_J [μm]
2/1 #1-2	130 x 6	0.75	154	12-15
11/29 #21	100 x 6	0.68-0.70	217	11-13

The junctions were mounted in a cryostat and cooled to temperatures between 1 K and 4 K. A superconducting coil operating in the persistent mode produces a magnetic field at the junctions. IV-characteristics of the current-biased junctions were measured by means of a conventional 4-point technique at variable magnetic fields. Low-pass filters on the leads and a lead shield around the junction reduced effects of external noise.

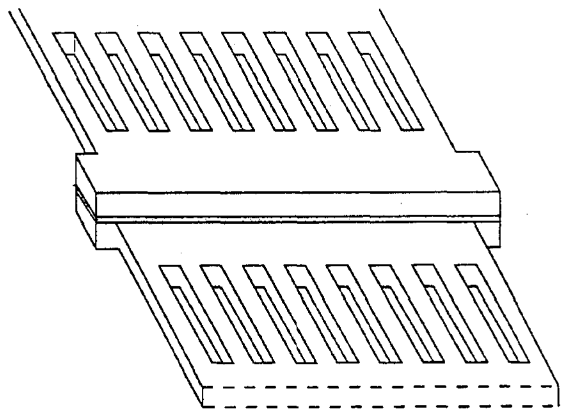

Fig. 1: Schematic of a long josephson junction.

RESULTS

IV-characteristics at several temperatures and at many values of magnetic field were measured for two junctions. ΔV is typically a few hundred μV, roughly corresponding to multiples of the Fiske-step spacing. There are no current steps present at voltages below $300\mu V$, where regular Fiske-steps are expected in low magnetic fields. As the magnetic field is increased, the behavior of the two junctions becomes different. In junction 11/29 #21 the steps collapse to smaller steps; in junction 2/1 #1-2, however, the large steps persist up to rather high magnetic fields and, in addition, some small steps are superposed on the large ones. Fig. 2 presents IV-curves of junction 11/29 #21 in three different magnetic fields. Fig. 3 shows the voltage of junction 2/1 #1-2 measured at the top of large current steps, as a function of magnetic field. The large steps are very sharp. At certain magnetic fields, they become almost regular in size. Such large steps have been observed in many of our junctions; they persist to very low temperatures (as low as 15 mK). There is some hysteresis in the current return to zero.

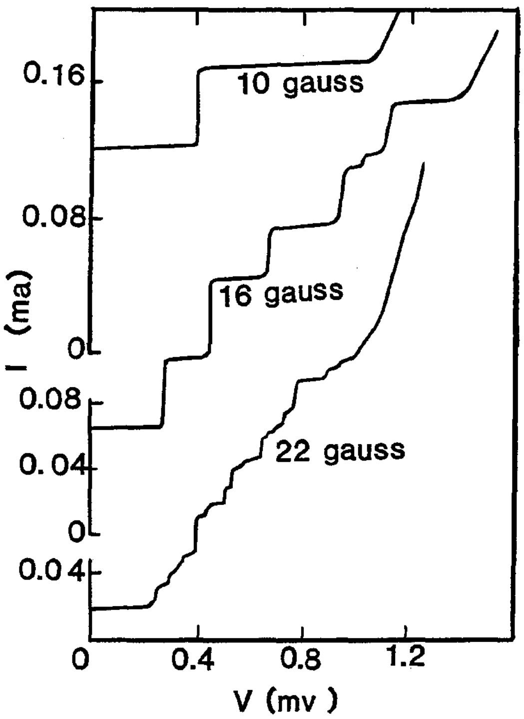

Fig. 2: IV-curves of junction 11/29 #21 in external magnetic fields of 10,16, and 22 gauss. Note persistence of large steps for wide range of fields.

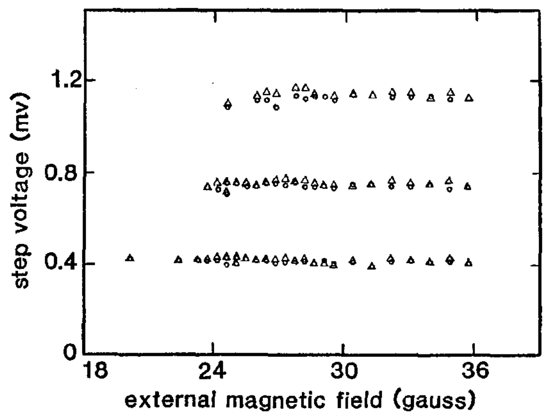

Fig. 3: Step voltages at large steps of junction 2/1 #1-2. The circle data were measured at the top of the current steps when the current is increased. The triangle data were measured when the current is reduced to zero.

DISCUSSION

There are several models which could possibly explain the origin of such large steps. Here we will present evidence for a model involving pinning and collective motion of magnetic flux.

Large steps have been observed [1] in specially designed long Josephson junctions where the barrier contains several, equally spaced, inhomogeneities. Due to the interaction of the fluxons with the periodic lattice of inhomogeneities, the step spacing ΔV is increased by a factor L/a where L is the length of the junction and a is the distance between the inhomogeneities. Thus, a reduction of the characteristic length of the junction leads to large voltage separation between steps.

In our junctions, the fingers on each electrode could act as a lattice of inhomogeneities. However, in a previous paper [2] we presented results on two junctions, one with and the other without fingers, both showing large steps in their IV-curves. This was enough evidence to dismiss this model.

Another approach, also discussed in ref. [2] proposes simultaneous nucleation of several fluxons; this is likely to occur because of the large magnetic penetration depth λ_L of NbN thin films. To investigate this in more detail, junctions with Nb/NbN bilayer electrodes were fabricated with the purpose to reduce λ_L. These junctions also show large steps in their IV-characteristics.

Our model for large steps presented here is based on pinning of fluxons in long junctions. When a magnetic field is applied to the junction, a fluxon enters the junction at one of its edges; increasing the magnetic field will nucleate another fluxon and push the first one inside the junction. This continues until several fluxons, determined by the strength of magnetic field, have entered the junction. By applying a bias current, a Lorentz force is exerted on the fluxons. Pinning of the fluxons inside the junction prevents them from moving until the bias Lorentz force overcomes the pinning force. In addition, the pinned fluxons do not move individually, but rather in bunches of several fluxons. In a one-dimensional array of fluxons, as is the case here, it is energetically more favorable for fluxons to move collectively due to interaction forces between them. The motion of bunches of several fluxons then leads to large steps, as observed in our junctions.

Pinning of flux and collective flux motion are well known phenomena in type II superconductors [3]. The static behavior of a long junction in a magnetic field is similar in some respects to that of a type II superconductor; for example, it shows magnetic flux screening, the Meissner effect, and quantized flux, known as Josephson fluxons, which have some similarity to the Abrikosov fluxons. The influence of pinning in long junctions on its static behavior has been investigated by Yamashita and Rinderer [4] and more recently by Fehrenbacher et al [5]. Except for ref. [1] and [6], which treat a periodic lattice of inhomogeneities, we are not aware of investigations on the influence of defects on IV-curves.

NbN films are known to be inhomogeneous; they have columnar structure on the scale of a few hundred Å and other defects of larger length scales. Such defects, which cause variations in the current density, are able to pin flux. The presence of defects is further consistent with the frequent trapping of flux, well known in NbN junctions. The nature of these defects, which ultimately determines the size of the large steps, can vary from junction to junction as it depends on details of the film fabrication. This might explain the differences in behavior of the two junctions presented in this paper.

In our junctions, no zero-field steps were observed. This is consistent with our pinning model where a small number of fluxons do not move; zero-field steps, however, require fluxons to move resonantly. From this point of view, pinning of fluxons explains the absence of zero-field steps.
Further evidence for our model is found in the sharpness of the large steps; when the bias overcomes the pinning a bundle of fluxons is released and set in motion.

CONCLUSIONS

We have presented a model based on fluxon pinning and collective flux motion to explain large current steps observed in our long NbN Josephson junctions. The model uses the similarities between long junctions and type II superconductors. The sharp steps observed here can be used as a voltage standard without external rf bias or as high-power oscillator when the device is suitably biased.

ACKNOWLEDGEMENTS

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