MULTI-FLUXON STEPS IN LONG JOSEPHSON JUNCTIONS
AND THEIR APPLICATION TO OSCILLATORS

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Abstract

Studies of long NbN Josephson junctions of the overlap type in the presence of an external magnetic field show constant voltage steps, of the Fiske type, and large voltage steps. The latter are attributed to multifluxon resonances within the cavity of the junction. The multifluxon steps correspond to bunches of fluxons introduced in the junction because the junction electrode thicknesses are comparable to the penetration depth. These steps are very sharp and they have large current amplitudes. When biased at such constant voltage steps the device can be a resonant mode oscillator. The power and frequency will be determined by the mode of fluxon motion inside the junction.

Introduction

Long Josephson junctions[1] present a wide range of interesting phenomena because of their highly non-linear properties; their high speed can be used in many applications. A junction is long when $L > \lambda_J$, where λ_J is the Josephson penetration depth. A localized phase change of $\pm 2\pi$ in the phase differences across the junction can be associated with a fluxon or antifluxon. A current bias through the junction will exert a Lorentz force on the fluxon causing it to travel along the junction. The dynamics of the fluxon are well described by a perturbed sine-Gordon equation where the attained fluxon speed is determined by the bias and the losses. When the fluxon is reflected from the ends of the junction, electromagnetic radiation is emitted. This leads to an important application of this type of junction, a high frequency oscillator[2]. We present here studies of all NbN long junctions for use as a source of microwave radiation. Because of the relatively high T_c (~15 K) and its stable mechanical properties, NbN is an attractive material for fluxon oscillators.

Direct evidence of fluxon dynamics in a long junction is presented by a series of current steps at fixed voltages in the I-V curve of the junction. They are called zero field steps and they correspond to the resonant behavior of an integral number of fluxons within the junction. In the presence of a magnetic field, another series of current-steps, Fiske steps, is produced due to the interaction of fluxon motion with the cavity resonances of the junction. When current-biased at such steps, the junction emits microwaves. The voltage steps occur at $V_n = \frac{n\phi_o}{2} f$ where ϕ_o is the flux quantum and f the fundamental frequency of the fluxon motion. This frequency depends on the fluxon speed $\bar{c}$ inside the junction and

hence $f = \bar{c}/2L$ where L is the length of the junction. Here n is the number of fluxons moving independently of each other in the junction. Thus electromagnetic radiation is emitted every time a fluxon interacts with the end of the junction; this is the principle of the resonant mode oscillator. Since the linewidth[3] of the emitted radiation is limited by the internal thermal noise set by the dynamic resistance at the current steps, very narrow linewidths can be achieved with this type of oscillator. Because of the large difference of impedance inside and outside the junction, there are problems in coupling to this device. The behavior of such oscillators has been demonstrated and analyzed[4]. Our interest is in the application of NbN to such devices. In this paper we report large constant voltage steps found in the I-V curves of NbN junctions and we discuss the implications for a resonant mode oscillator.

Experimental Details

Long Josephson junctions were fabricated from NbN–MgO–NbN films deposited on silicon wafers by reactive dc magnetron sputtering. Photolithographic methods were used to pattern the junctions. The barrier consists of thermally oxidized Mg, ~25 Å thick. The junction is of the overlap type, 100 μm long and 6 μm wide. Two different types of current injection were used, as shown in Fig. 1. In one type, 8 injection fingers were used to achieve a more uniform bias current distribution across the junction, while in the other type wide electrodes with no fingers were used. Both had similar characteristics with a critical current of 0.9 mA and a current
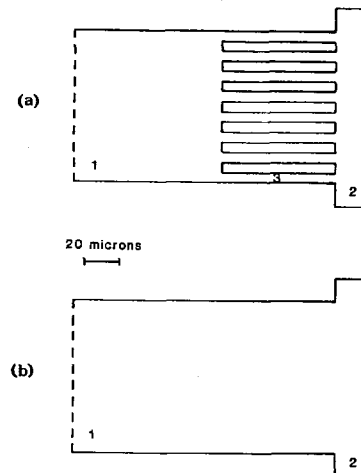

20 microns

Fig. 1. Electrode masks for long junctions (a) with fingers (b) no fingers. Electrode 1, Junction area 2, Equally spaced fingers 3.

density of 150 A/cm^2. A Josephson penetration depth λ_J = 17 μm classifies the junction as long since L/λ_J = 5.8. The McCumber parameter β_c is in the range of 60-80 and hence the junctions are in the low damping regime allowing resonant motion of fluxons. The speed of electromagnetic waves in the junction is 6 × 10^6 m/sec but it could be lower due to the large penetration depth λ_L in NbN. The junctions were cooled from 4 K to 1 K and measurements of the I-V curve were performed in an external magnetic field produced by a superconducting solenoid in the persistent mode.

Results

I-V curves for a wide range of fixed magnetic fields were obtained by sweeping the bias current. As the fixed magnetic field was increased, current steps at large voltage intervals started to appear, eventually becoming almost regular in size. This is shown in Fig. 2 where the I-V curve is measured in a field of 16 Gauss at 1.2 K on an 8-finger junction. The large steps collapsed into smaller steps as the field was increased. The fundamental Fiske step for our junctions is ~60 μvolts. The large steps that we observed have typically ΔV = 180, 240, and 300 μvolts corresponding to 3, 4 and 5 fluxons in the junction at once. The current step height reaches 0.12 I_c for the

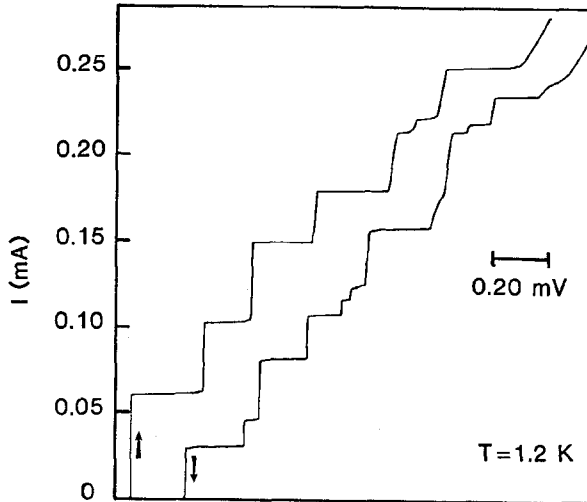Fig. 3. I-V characteristics of Nb junction with fingers in a magnetic field of 12.8 gauss. For this junction I_c = 21 mA, L/λ_J = 16, β_c = 16, ΔV = 50 μvolts.

Fig. 2. I-V characteristics of NbN junction with 8 injection fingers in an external magnetic field of 16 gauss.

Fig. 4. I-V characteristics of a NbN junction without fingers in a magnetic field.

highest step which is lower than the predicted value of 0.34 I_c for Fiske steps. The steps are very sharp with no rounding of the corners up to 4 K. They persist down to 250 mK where small steps start to become stable. The dynamic resistance, R_D = dV/dI, at the large steps ranges from 100 m Ω for the first step to 1 Ω for steps at higher voltages. This is comparable to the dynamic resistance at Fiske steps in Nb-Aℓ_2O$_3$-Nb junctions of comparable geometry as obtained from the I-V curve in Fig. 3. The large voltage steps appear for the two types of NbN-junctions studied, with and without fingers. Fig. 4 shows the results obtained with a junction of same dimensions as for Fig. 2 but without fingers. There was much more flux trapping in this junction than in the one with fingers.
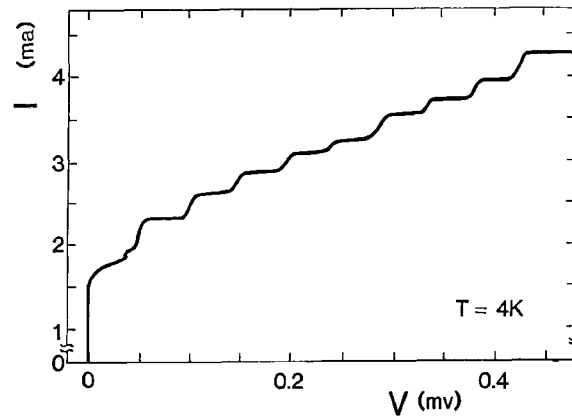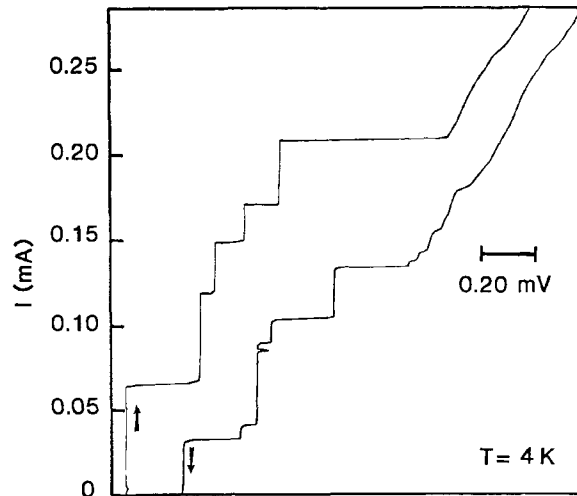
Discussion

The large constant voltage steps that we observed in NbN junctions raise questions as to their origin and as to applications to oscillators. Such large steps were not observed in Nb junctions of similar geometry. We attribute the behavior in NbN to the large penetration depth λ_L. Because the electrode thicknesses are 3000 Å while λ_L for NbN is in the range 2500 Å - 5000 Å, we expect much more flux penetration than in Nb junctions where λ_L ~ 450 Å.

Usually, fluxons in long junctions are nucleated at the edges, one by one. However, when flux can enter the barrier at other locations as well, multifluxon effects can be observed. Another explanation could be attributed to the creation of artificial barriers in

the junctions[5]. The evenly-spaced injection fingers
can be viewed by the fluxons, because the electrode
thickness is comparable to λ_L, as plasma wave
excitation centers leading to resonances at $\Delta V' = \Delta V(L/\ell)$, with ℓ being the spacing between fingers.
Similar effects were demonstrated in references 6,7.
However, the junction without fingers showing also
multifluxon steps dismisses this explanation in our
case.

The large magnitude of the current-step height
at these voltage steps suggests that there might be
high power available from this type of resonant
oscillator. Should the n fluxons present in a
junction biased on a step at V_n move as independent
fluxons, then indeed a large power would be expected
at the frequency n times that of the fundamental step,
i.e. at 242 MHz/μV. However, because of surface
dissipation in the electrodes and bias, n fluxons can
be bunched in various configurations[8,9]. These
multifluxon modes lead to subharmonics in the power
spectra of the emitted radiation. If only few modes
were excited, we would expect high power emitted at
the corresponding frequencies.

Acknowledgements

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