Giant Josephson generation in wide superconducting films

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Josephson generation of huge amplitude has been observed to occur in shunted granular films with a distinct channel in which the magnetic field is concentrated. The particular features of this generation are explained on the basis of a mechanism of a synchronized motion of multiquantum flux tubes with $\Phi = (10^5\text{–}10^6)\Phi_0$.

1. In thin films of type II superconductors loaded by a current, a synchronized nucleation and motion of multiquantum magnetic-flux tubes can occur.[1,2] The time-averaged voltage $\overline{U}$ that arises can be related to the nucleation frequency ν by the Josephson relation

$$\overline{U} = Nh\nu/2e = \frac{N\nu}{c}\,\Phi_0\,, \tag{1}$$

where N is the number of quanta in the tube, h is Planck's constant, e is the electron charge, c is the velocity of light, and Φ_0 is the quantum of magnetic flux.

In the present letter we describe some oscillations which have been observed in films, whose magnetic properties qualify them as typical type II superconductors, since their second critical field exceeds the critical field of bulk indium by more than two orders of magnitude.

2. Two types of indium samples were studied: variable-thickness bridges and bridges with a neck. The typical dimensions of the weakened regions of the superconductor in the directions parallel to (l) and perpendicular to (w) the current satisfy the relations $l \approx \lambda_T \sim 10^{-2}$ cm and $\lambda_T \ll w \gtrsim 10^{-1}$ cm, where λ_T is the temperature decay length in the superconductor.

The initial part of the current-voltage characteristic of the samples corresponds to the motion of rows of vortices. In certain intervals of the current and the voltage (Fig. 1), an abrupt transition occurs to a state of a synchronized motion of large groups of flux quanta (flux spots). A Josephson generation of huge amplitude arises; the instantaneous value of the voltage reaches several millivolts (see the oscilloscope trace of the voltage in the inset in Fig. 1).

The pulse repetition frequency increases with increasing voltage across the sample in a linear fashion between a few kilohertz and hundreds of kilohertz (Fig. 2). The number of quanta in a spot is calculated from (1) to lie between 10^5 and 5×10^6.

Interestingly, the generation frequency can be tuned over a wide dynamic range (a factor of more than 100) for films with small values of N and with a sizable average voltage across the sample at large values of N, amounting to hundreds of microvolts

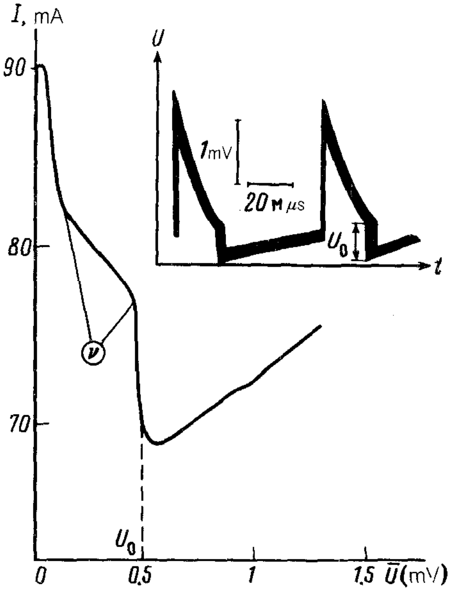

FIG. 1. Typical current-voltage characteristic of a film in which a regime of giant generation is achieved. The arrows mark the region in which oscillations occur. The limiting voltage at which these oscillations still occur, U_0, is $2\Delta(T')/e$, where Δ is the order parameter of the superconductor, and T' is the temperature in the flux concentration region. The inset is an oscilloscope trace of the voltage pulses.

(in the samples studied in Refs. 1 and 2, the value of $\bar{U}$ at $N \sim 10$ was $\sim 10^{-7}$ V).

3. A necessary condition for the onset of the observed generation is the presence of a descending region on the I-V characteristic of the film. This region may be of a purely electromagnetic nature, or it may be determined by a heating of the film in the

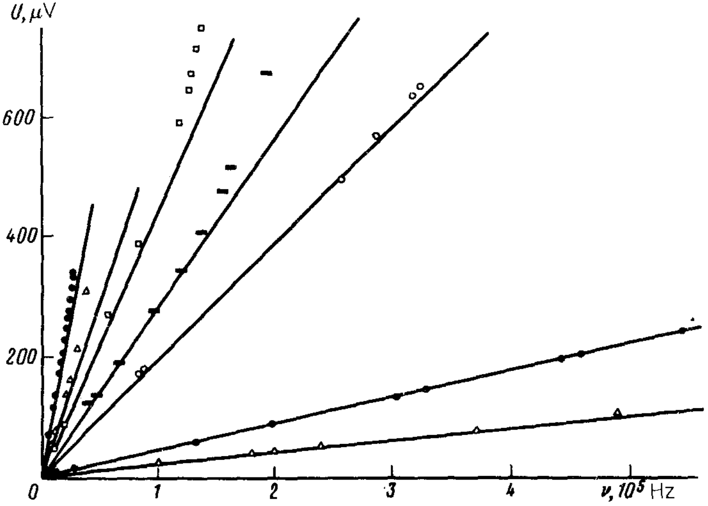

FIG. 2. Average voltage across the film during generation versus the frequency of the generation. This figure illustrates the Josephson nature of the oscillations.

flux flow region. In the samples studied, the inclination of the descending region varied substantially near the λ-point of helium; in some samples it converted into an ascending region in superfluid helium, implying a governing influence of heated effects.

We wish to emphasize that the size of these samples along the direction perpendicular to the current was much greater than λ_T. In the films studied in Refs. 3 and 4, with l, $w \ll \lambda_T$, relaxation oscillations of a Josephson type were observed. Those oscillations were associated with a periodic destruction and restoration of superconductivity of the entire sample as a whole. In contrast with those oscillations, the giant Josephson generation is caused by a motion of spatially separate flux spots.

From the observed dependence of the characteristics of the generation on the heat-removal conditions, e.g., at the transition through the λ-point of helium, we can conclude that the force responsible for the attraction of vortices in a spot is related to a relative heating of the spot with respect to the rest of the film. Further evidence in favor of this suggestion comes from an estimate of the dimensions of the spot based on the number of flux quanta in it and the magnetic-field penetration depth. This estimate puts the diameter of the spot on the order of 10^{-2} cm or $\sim\lambda_T$.

The origin of a force associated with a local heating of the sample can be understood by noting that an isolated vortex in a thin film tends to move into a region in which the order parameter is suppressed. A multiquantum spot of flux, which is stable as a result of a local heating of the film, might be called a "thermomagnetic soliton."

4. Experimental confirmation that the giant generation is caused by a motion of a thermomagnetic soliton comes from the following facts.

For each sample studied, at a fixed temperature, we observed a lowest frequency of stable generation, ν_{min}, which is inversely proportional to w, and also a maximum frequency $\nu_{\max}$, which does not depend on w. These properties of the generation can be understood easily by noting that the stability of this generation requires a synchronization of the process by which a thermomagnetic soliton is created on one side of the sample and by which a soliton formed previously leaves from the opposite side. The minimum frequency is evidently determined by the expression $\nu_{\min} = (v/w)$, where v is the soliton velocity.

The maximum generation frequency, according to this model, is determined by the circumstance that the distance between the separate thermomagnetic solitons in a row cannot be smaller than the thermal length scale: $\nu_{\max} = v/\lambda_T$. Assuming that the velocity of the soliton does not depend on ν, we find

$$\nu_{max}/\nu_{min} = w/\lambda_T . \qquad (2)$$

Experimentally, the ratio $\nu_{\max}/\nu_{\min}$ ranged from ten to several tens and corresponded to (2) with a value of λ_T agreeing with an estimate for samples of this type. In films of greater width, the ratio $\nu_{\max}/\nu_{\min}$ exceeded 10^2.

We observe a typical Josephson behavior of the sample in a weak magnetic field H. Figure 3 shows the dependence $\overline{U}(H)$, which has the appearance of a diffraction pattern. The oscillatory nature of the dependence is preserved when the parameter values are varied slightly (see the dotted curve). The observed periods satisfy the

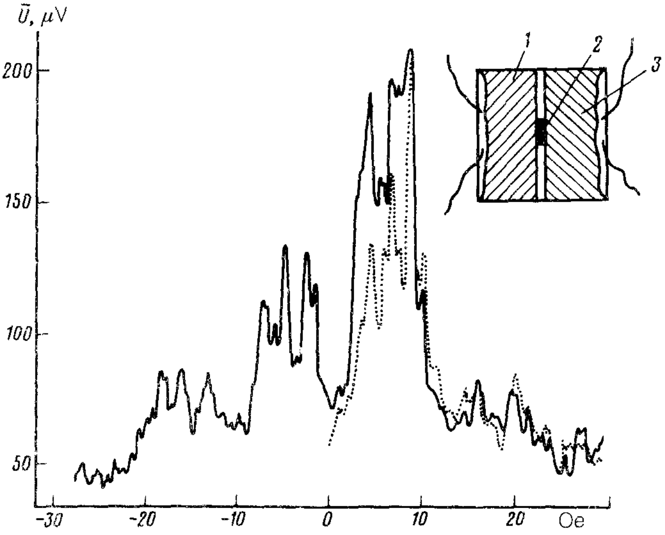

FIG. 3. The average voltage induced by the moving flux spots versus the external magnetic field. The inset is a sketch of the sample. The numbers specify the regions which determine the oscillation periods of $\overline{U}(H)$.

relation $\Delta H = N\Phi_0/S_i$, where S_i are the areas of the special regions of the sample (the hatched regions in the inset in Fig. 3). When the regime of coherent motion of the thermomagnetic soliton is disrupted, the oscillatory dependence $\overline{U}(H)$ disappears.

[1] R. P. Huebener, Struktury magnitnykh potokov v sverkhprovodnikakh (Magnetic Flux Structures in Superconductors), Mashinostroenie, Moscow, 1984, p. 244.
[2] K. Penner, J. Parisi, B. Mühlemeier, and R. P. Huebener, J. Low Temp. Phys. **62**, 177 (1986).
[3] Y. Taur and P. L. Richards, J. Appl. Phys. **46**, 1793 (1975).
[4] S. A. Peskovatskiĭ and L. P. Strizhko, Fiz. Tverd. Tela (Leningrad) **19**, 3442 (1977) [Sov. Phys. Solid State **19**, 2011 (1977)].

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