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DYNAMIC PHASE STRATIFICATION AND GENERATION OF ELECTROMAGNETIC WAVES IN THIN CURRENT-CARRYING SUPERCONDUCTING FILMS

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We have observed in [1] generation of electromagnetic waves by thin current-carrying tin films in the resistive state. In the present paper we report investigations of the current-voltage characteristics (CVC) of thin films, which may explain the generation mechanism.

We investigated films similar to those in [1] with respect to the preparation technology and dimensions. They were connected in a resonant circuit tunable from 30 to 230 MHz and the CVC and the amplitudes and frequencies of the generated oscillations were recorded simultaneously. The CVC of the films and the amplitudes of the generated oscillations had forms similar to those in [1]. No hysteresis was observed on the CVC at the point corresponding to generation at a given frequency. The agreement between the experimental temperature dependence of the critical current j_c with the Ginzburg-Landau theory [2] was checked for the investigated films.

Figure 1 shows the experimental temperature dependences of the current j_g at which a given frequency is generated, and the differential resistance $R_g = du/dj$ at the generation point. For convenience in comparison with the critical current, the ordinates represent the values of $j_g^{2/3}$ and the abscissas the values of $t = T/T_c$, where T_c is the critical temperature of the sample. Figure 2 shows the experimental frequency dependence of R_g, at which the given frequency is generated at a constant temperature. The presented experimental relations lead to the following conclusions:

1) A given frequency is generated at different temperatures with one and the same value of the relative current j_g/j_c, since the temperature dependences of j_g and j_c are identical [2]. Thus, the law of corresponding current states is satisfied for the frequency of the generated oscillations. At a fixed temperature, larger currents correspond to higher frequencies.

2) At different temperatures, a given generation frequency corresponds to a definite constant value of the differential resistance of the film. The differential resistance R_g is constant if the law of corresponding current states is satisfied.

3) At a fixed temperature, higher frequencies are generated at the CVC points corresponding to larger values of R_g. The relation between f and R_g is linear in the investigated frequency range.

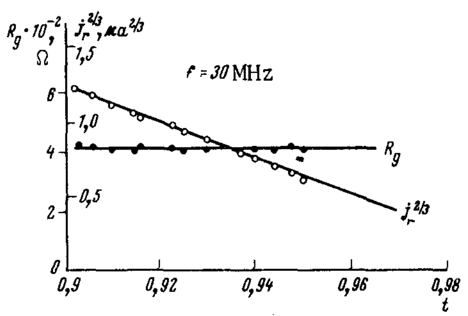

Fig. 1

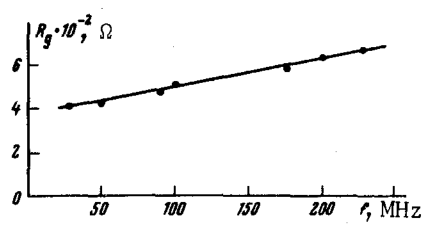

Fig. 2

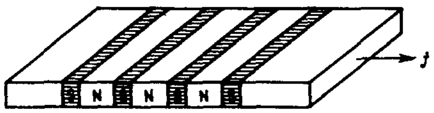

Fig. 3

As seen from the foregoing, the observed generation and the peculiarities of the CVC are most closely connected with the nature of the resistive current states in the superconducting channels. This enables us to advance definite hypotheses concerning the microscopic situation that leads to generation of the electromagnetic oscillations.

The fundamental fact of superconductivity is the absence of a dc component of the electric field in regions with nonzero superconducting order. The presence of such a component would lead to a constant gradient of the electrochemical potential or to constant acceleration of the superconducting condensate, and would move in either case the electron away from the Fermi surface in whose vicinity the superconducting pairing takes place. In our case there should therefore exist factors that lead to the appearance of a nonzero dc component of the electric field, i.e., resistivity. Since the resistivity of thin and narrow films cannot be attributed to the presence of an Abrikosov vortex structure [3, 4], the only possible explanation is to assume a dynamic phase stratification with alternation of normal and superconducting regions along the film (Fig. 3). Such a stratification should result from the normal current state when the current drops below a certain critical value j_{c2} because of the development of a Cooper instability, in analogy with the onset of a mixed state in type II superconductors in fields weaker than H_{c_2} [3]. Since the resistive state is not in equilibrium, it can be assumed that the resultant unstable structure is dynamic, and this should lead to the observed generation of electromagnetic waves.

We note that the experimental temperature dependence of the current j_{c_2} determined from that point on the CVC at which the deviation from Ohm's law begins, is linear, unlike the current j_c, which is proportional to $(T_c - T)^{3/2}$.

The described picture agrees qualitatively with the experimental data, primarily in that there is a direct connection between the generation frequency and the film resistance. Since the characteristic frequencies should be connected with the linear parameters of the stratification structure, the generation frequency should increase with the resistance, as is indeed observed in the experiments.

It should be emphasized that unlike the transition into the mixed state, in which the superconducting nuclei stem from a normal state that is in thermodynamic equilibrium, in the present situation the instabilities develop from the dissipative normal current state on going through the critical current j_{c_2}. This means that this instability is not described by the so-called time-dependent Ginzburg-Landau equation [5], since the latter describes the temporal behavior of the superconducting ordering parameter in the vicinity of the equilibrium normal state[1)]. Instructive from this point of view are the results of [7, 8], in which the nonlinear fluctuation correction to the conductivity of the superconductor in the normal state below the critical temperature was calculated. The calculation in [8] is based directly on the equation of [5] with addition of random forces. The results of the two papers coincide. The negative differential resistance obtained in these papers is thus evidence of the presence of a certain instability. The fluctuations, however, are finite for all currents and fields, and do not determine the value of the critical current j_{c_2}.[2)]

1) A detailed microscopic calculation of the phenomenon described in this communication, based on the kinetic theory of superconductivity [6], will be published later.

2) The explanation suggested in [7, 8] for the nonlinearity of the CVC of superconducting films by taking the fluctuation current into account does not agree with experiment. At the characteristic electric fields corresponding to the resistive section of the CVC, the fluctuation current is negligibly small.

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MAGNETOELECTRIC RESONANCE IN MAGNETIC SEMICONDUCTORS

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The appearance of a dc electromotive force (emf) was observed in magnetic semiconductors at ferromagnetic resonance (FMR). This emf exceeds by several time the emf previously observed in metallic magnetic films at FMR [1 - 3]. The emf previously observed in $HgCr_2Se_4$ [4] had a non-reproducible and complicated character, and at the author's own admission could not be uniquely interpreted.

The present investigations were made on disks of lithium spinel single crystals with resistivity $\rho \approx 10^3$ Ω-cm at 300°K, and on single-crystal $CdCr_2Se_4$ plates doped with silver ($\rho \approx 10^3$ Ω-cm at 77°K) with gold electrodes (Fig. 1). The current-voltage characteristic of the contacts was linear.

The samples were measured in a resonator and in a waveguide, using pulses of 9400 MHz frequency and 1 - 10 μsec duration, at a repetition frequency 40 Hz and a maximum pulse power 10 W. The sample was not heated under these conditions.

The emf of the lithium ferrospinel was measured at room temperature, and that of the $CdCr_2Se_4$ single crystals at 77°K.

Figure 1 shows plots of the resonant absorption (χ'') and of the emf (V) on the contacts as functions of the external magnetic field for a transversely magnetized disk of Li-ferrospinel. The sample was in a waveguide in the region of linear polarization of the microwave field. It is evident that the character of the variation of the emf with the external magnetic field is similar to the character of the variation of χ''.

A dc emf is produced not only in the case of homogeneous precession (H = 7400 Oe), but also for magnetostatic modes (H = 6900 Oe). The sign and magnitude of the emf remained the same when the direction of the external field was reversed (always positive at the center of the disk. Figure 2 shows a plot of the resonant emf against the microwave power. The transversely

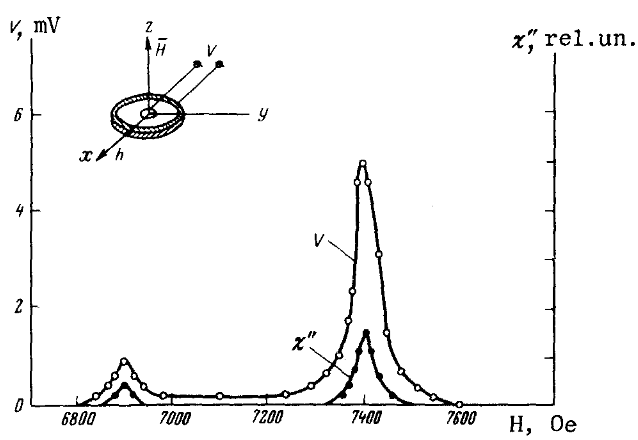

Fig. 1

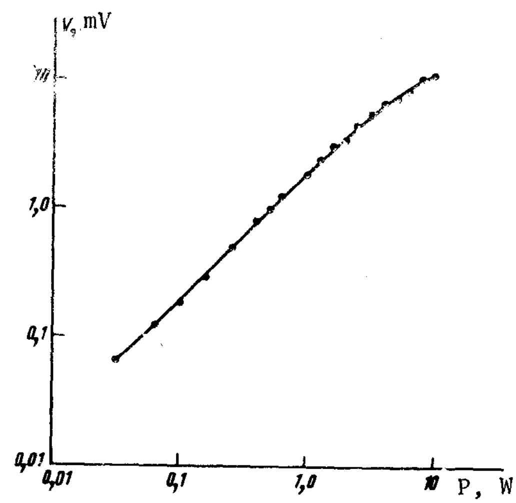

Fig. 2

Fig. 1. Resonant absorption (χ'') and dc emf (V) in waveguide vs the external magnetic field for transversely magnetized disk with [111] axis perpendicular to the plane of the disk. The construction of the sample with the electrodes is shown in the upper right.

Fig. 2. Resonant value of dc emf vs microwave signal power in short-circuited waveguide. The sample was in the antinode of the microwave magnetic field.