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GENERATION AND DETECTION OF INCOHERENT HYPERSONIC VIBRATIONS USING SUPERCONDUCTING TUNNEL JUNCTIONS

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The investigations of superconducting tunnel junctions as phonon generators and detectors are reported. Theoretical predictions and the published results of the experimental research on such devices are briefly reviewed. The experimental results of the investigations of the current-voltage characteristics of fabricated tin tunnel junctions are presented and discussed, and then the measured current-signal transmission characteristics of pairs of identical tunnel junctions deposited on the corundum sample are analyzed and interpreted. The results obtained are compared with the results o similar investigations reported in the literature.

1. Introduction

The process of the generation and detection of phonons in superconducting devices is based on the production of nonequilibrium (quasi-equilibrium) states in thin superconducting layers. In general, the nonequilibrium states of the superconducting layer can be produced by the injection of electrons, phonons or photons.

In the case of a detector, the nonequilibrium state is produced by a flux of incident phonons, while in the case of a generator the external source of energy produces an excess population of quasiparticles. Of the various methods for producing nonequilibrium population of quasiparticles in superconducting layers, superconducting tunnel junctions [1, 2], the a.c. Josephson effect [3], and the "phonon fluorescence" effect [4, 5], (i.e. the effect of thermal pulses) have been used to generate phonons, while the possibility of using laser light was noted in [6].

Since a conversion of the energy of the external source into the energy of the phonons occurs in a superconducting generator, it is possible to obtain the similar intensity of the flux of phonons generated for each of the methods, because it is limited by the possibility of destruction of the superconducting state. The superconducting devices used for phonon detection are superconducting tunnel junctions [2] and bolometers [1]. The general model and the related quantitative description of the performance of detectors and generators with superconducting elements must therefore be based on the equations of dynamic equilibrium of the kinetic processes occurring in a nonequilibrium superconductor. It is assumed that the time scale of the action of the external source, which produces the nonequilibrium is several orders of magnitude greater than the time scale of the kinetic processes in the superconductor itself — and thus it can be assumed that we are concerned here only with the steady states of the nonequilibrium superconductor. The general equations of dynamic equilibrium balance of the superconductor were derived in [7] and developed in [8]. These equations are valid for macroscopic densities of phonons and quasiparticles and they do not determine the energy distributions of these excitations.

In order, however, to determine the spectrum and possibly also the intensity of the flux of phonons generated, or the variation of the detector current caused by a given incident flux of phonons, it is necessary to know the distributions of the quasiparticles and phonons and the characteristic times of the kinetic processes in the layer of the nonequilibrium superconductor under investigation. These quantities can be calculated from solutions of the coupled balance and kinetic equations and from the gap equation of a nonequilibrium superconductor. Such equations were derived in [9], with the assumption that the processes of scattering and recombination of quasiparticles and phonon trapping are equally significant in the nonequilibrium superconductor [10].

In previous models of a nonequilibrium superconductor [11, 12] it was assumed that scattering is the main mechanism of the relaxation processes. In [9], however, only a linearized form of these equations was derived, with the assumption of relatively low energy of the injected excitations i.e. weak nonequilibrium and, thus ignoring electron – electron interactions, which are essential for quasiparticles of large energies, and also assuming that the superconducting layer is "thin" i.e. phonon escope time is independent of phonon energy. Thus the applicability of [9] for actual generators and detectors of phonons depends on the satisfaction of these assumptions.

The problem of a nonequilibrium superconductor has not yet been solved for the general case, and it is not therefore possible to present a general model for a superconducting generator and detector of phonons.

Application of superconducting tunnel junctions for the generation and detection of incoherent phonons was developed in early 1970's [5, 12, 14-20]. In this paper we present the results of the experimental investigations related to the technique of manufacturing superconducting tunnel junctions and the results of the observations of the current-signal characteristics of two identical junctions on a sample of Al_2O_3 (corundum) operated with low modulation of the generator current [5]. These results are compared with the published experimental investigations and with the theoretical predictions.

2. The superconducting tunnel junction as a generator and detector of phonons

The papers concerning the application of superconducting tunnel junctions for the generation and detection of phonons, in addition to the results of experimental investigations, have also presented same attempts to build a theoretical model of such devices in order to calculate the spectrum of the emitted phonons and the transmission characteristics. The calculations of the spectrum of the emitted phonons [13, 14], and of the transmission characteristics of tunnel generator—tunnel detector system [16] were performed on the basis of a model of a equilibrium superconductor at zero temperature [21]. This required the assumption of a negligibly low density of injected excitations compared to the equilibrium density, and also that the phonons produced in the relaxation and recombination of the excess quasiparticles are not trapped.

In [19] and subsequently in [5], a quantitative description of the generator detector system was based on the balance equations [7] and on a simplified model of the generator and detector, assuming three possible energy levels for the quasiparticles and the same functions for the density of the quasiparticles and phonons as for an equilibrium superconductor, which in consequence gave an "artificial" root singularity in the "theoretical curves".

In the case of moderate quasiparticle injection generator current and relatively low temperatures good agreement of the calculated and experimental results was achieved for Al—I—Al [15] and Pb—I—Pb [19] junctions, while in the case of Sn—I—Sn junctions the discreponcy was significant [5].

A description of a nonequilibrium superconductor was attempted in [18], using discrete levels for the states of the quasiparticles and phonons, and on the basis of detailed balances of the velocities of escape and scattering of phonons and of pair breaking by phonons the energy spectrum, i.e. the width of the recombination peak of the phonons emitted by a tunnel generator operated in the low intensity range $V < 4\Delta/e$ (where 2Δ is the width of energy gap, and e is the charge of the electron) was found by numerical calculation.

The calculated results were compared with the experimental results for a Sn—I—Sn junction and gave good agreement.

The phenomenon of resonance absorption of phonons by the donor levels of Sb in a uniaxially stressed smaple of Ge: Sb was used in [5, 16] for an experimental determination of the spectrum of the phonons emitted by the superconducting tunnel junctions.

The problem of an appropriate and full theoretical model for superconducting generator and detector of phonons has not yet been solved to the authors knowledge and thus the first stage of the investigations undertaken was limited to an experimental investigation. It seems, however, that the approach proposed in [9, 22] may prove fruitful in theoretical analyses.

3. The experimental investigation of a system of tunnel junctions

The superconducting tunnel junctions used for the generation and detection of phonons are usually made of tin (Sn) [2, 5, 13, 18], lead (Pb) [16] or aluminium (Al) [15]. The use of aluminium, requires a working temperature below 1K, because of its relatively low critical temperature and this causes some technical difficulties. Junctions made of tin and lead can work effectively at slightly higher temperatures, with the former giving a better signal to noise ratio in the measurements, because of the lower recombination velocity, compared to that of lead. Tin tunnel junctions were therefore used in the present investigations. The junctions had the form of two thin layers, 2000 A thick, between which there was a dielectric barrier of tin oxides (Sn_x0_y) approximately 20 Å thick. The surface area of the junction was 1 mm². The sample was a single corundum crystal (Al_2O_3) of dimensions 7 ×7 ×4 mm³. Thin layers of Sn were deposited successively in a vaccuum apparatus, and the oxide barrier was obtained by oxidining the first (bottom) layer of Sn in the atmosphere, with the barrier thickness being controlled by varying the time of oxidation. In the normal state, the resistances of the junctions prepared did not exceed 0.3 Ω. The junctions were placed on the largest opposite sides of the sample perpendicular to the c-axis of the single crystal. The sample with the junctions is shown in Fig. 1. The sample with the junctions was clamped, providing electrical connections, and the whole was placed in a metal container immersed in liquid helium. A typical cryostat equipped with a booster pump was used, in which temperatures from 4.2 K to 1.8 K were obtained by helium evaporation.

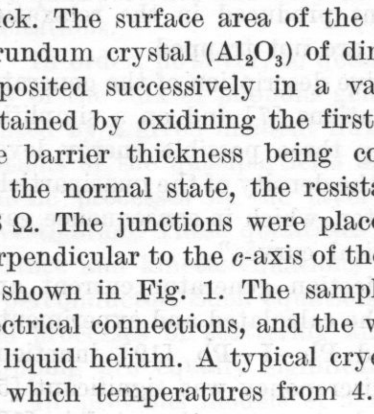

Fig. 1. AnAl_2O_3 single crystal sample with $Sn-(Sn_xO_y)-Sn$ junctions

Investigation of the tunnel junctions

The investigations of the current-voltage characteristics of the manufactured junctions were performed by the four point method using an X-Y recorder. The aim of these measurements was to examine the correctness of the junction fabrication and to find the point on the characteristic at which the junction would be operated as phonon detector, i.e. the voltage $V < 2\Delta/e$ in the vicinity of which the $I(V)$ characteristic is approximately most linear.

An example of the $I(V)$ characteristic of a junction operated at a temperature of 1.8 K used for both phonon detection and generation is shown in Fig. 2.

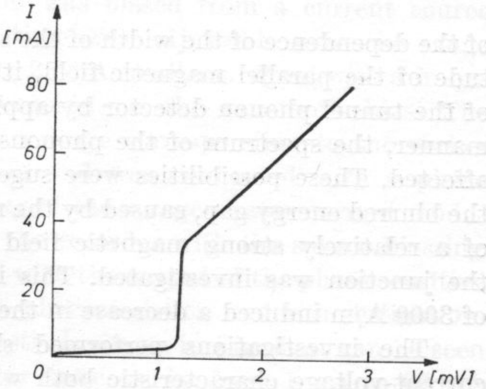

Fig. 2. The current-voltage characteristic of the $\mathrm{Sn}-(\mathrm{Sn}_x\mathrm{O}_y)-\mathrm{Sn}$ junction at a temperature $T = 1.8$ K

From the current-voltage characteristic of a junction the width of the energy gap can be evaluated and for the characteristic shown in Fig. 2, $2\Delta = 1.2$ meV. Since all the Josephson effects occurring in a superconducting tunnel junction can be suppressed by the application of a low magnetic field parallel to the superconducting layers, thus reducing the "zero current" of the detecting junction, the influence of a low magnetic field on the current-voltage characteristic of fabricated junctions was determined. The results of these investigations are shown in Fig. 3. It can be seen in the figure that for $H = 40$ A/m the "zero current" decreases more than three times. As a result

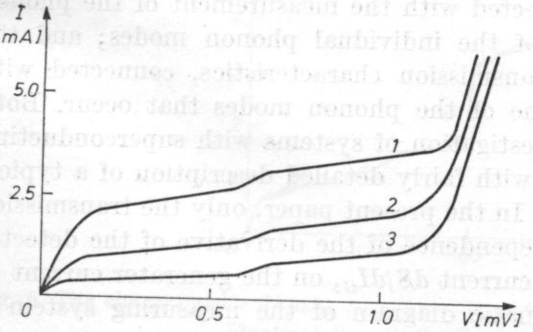

Fig. 3. The current-voltage characteristics of the $\mathrm{Sn}-\mathrm{SnO}-\mathrm{Sn}$ junction for weak magnetic fields

$1 - H = 0$, $2 - H = 20$ A/m, $3 - H = 40$ A/m. The magnetic field H was paralell to the plane of the junction; $T = 1.8$ K

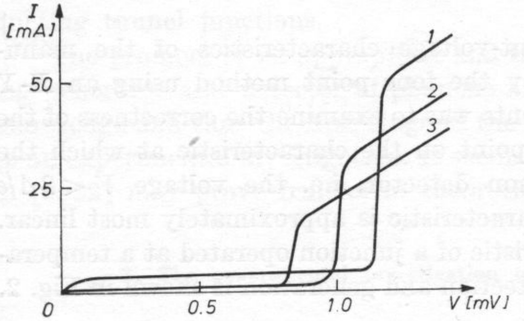

Fig. 4. The current-voltage characteristics of the junction for strong magnetic fields $1 - H = 0$, $2 - H = 2000$ A/m, $3 - H = 3000$ A/m; $T = 1.8$ K

of the dependence of the width of the superconduction energy gap on the magnitude of the parallel magnetic field, it is possible to tune the energy threshold of the tunnel phonon detector by applying the magnetic field. In an analogous manner, the spectrum of the phonons emitted by the tunnel generator can be affected. These possibilities were sugested in [14], although it was noted that the blurred energy gap, caused by the magnetic field occurs. Thus, the influence of a relatively strong magnetic field on the current-voltage characteristic of the junction was investigated. This is illustrated in Fig. 4. A magnetic field of 3000 A/m induced a decrease in the energy gap of approximately 30 percent.

The investigations performed show that the junctions had "correct" current-voltage characteristic both without an external magnetic field and in the presence of a magnetic field. The "zero current" of these junctions (i.e. the current for $V < 2\Delta/e$) was, however, much higher than the "zero current" of the similar junctions used, for example, in [5, 23]. This may have been caused by a slightly higher working temperature, and also by the possible existance of "point" breakdowns of the isolating barrier.

Investigation of the transmission characteristics

In the investigation of a superconducting phonon generator – material sample – superconducting phonon detector system, two basic methods have been used: the pulse method, connected with the measurement of the phonon arrival times and the separation of the individual phonon modes; and the method of the measurement of transmission characteristics, connected with the integration with respect to time of the phonon modes that occur. Both methods have been used in the investigation of systems with superconducting tunnel junctions [2, 13, 14, 18, 20], with fairly detailed description of a typical measurement set being given in [5]. In the present paper, only the transmission characteristics in the form of the dependence of the derivative of the detector signal with respect to the generator current dS/dI_G, on the generator current I_G have been investigated. The schematic diagram of the measuring system is

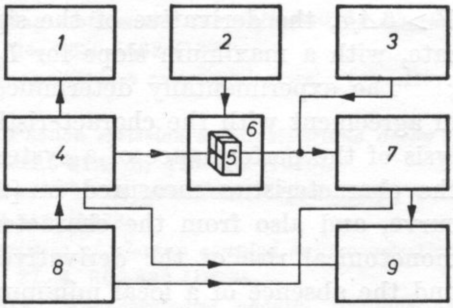

Fig. 5. A block diagram of the measuring system

1 – digital voltage indicator, *2* – electromagnet supply, *3* – bias source, *4* – saw-tooth voltage generator, *5* – the sample with junctions, *6* – electromagnet, *7* – phase sensitive detector, *8* – low-frequency generator, *9* – *X-Y* recorder

shown in Fig. 5. The generating junction was biased from a current source with a saw-tooth waveform, whose rise time was adjustable over the range 5 to 50 s, and amplitude over the range 0 to 2 A. A small a.c. signal with a frequency of approximately 130 Hz was superposed on the saw-tooth bias. The detecting junction was biassed by a d.c. voltage corresponding to the earlier determined working point of the junction and was connected with a phase sensitive detector adjusted to the frequency of the a.c. generator current modulation. The connection of the input X of the recorder with the source biassing the generating junction and of the input Y with the output of the phase sensitive detector permits direct recording of the characteristics under investigation. An example of the transmission characteristic is shown in Fig. 6. It can be seen from Fig. 6 that over the range of generator currents, I_G, from 1 mA to 60 mA corresponding to voltages $2\Delta/e < V < 4\Delta/e$ the derivative of the signal rises slightly, nearly linearly with increasing current. The jump in the derivative, whose slope depends on the magnitude of the modulation of the generator current and corresponding to a generator voltage $V = 4\Delta/e$, occurs at a current $I_G = 60$ mA. For currents I_G between 60 mA and 90 mA corresponding to voltages $4\Delta/e < V < 6\Delta/e$ the derivative of the signal is nearly constant. As the current increases above 90 mA, which corresponds to the voltage range

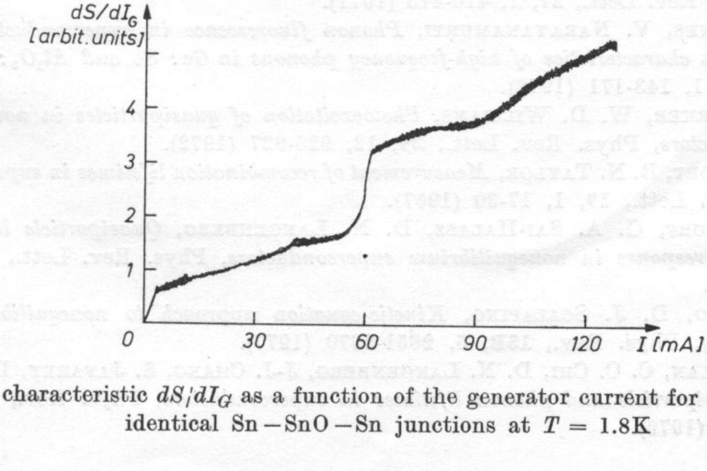

Fig. 6. The characteristic dS/dI_G as a function of the generator current for a system of two identical Sn – SnO – Sn junctions at $T = 1.8$K

$V > 6\Delta/e$, the derivative of the signal increases monotonically at a varying rate, with a maximum slope for I_G −90 mA, i.e. $V = 6\Delta/e$.

The experimentally determined transmission characteristics are basically in agreement with the characteristics expected from a rather qualitative analysis of the performance of a system of junctions, and also in agreement with the characteristics measured in [2, 5]. Some differences from the expected curve, and also from the characteristic measured in [18], involving a slight monotonical rise of the derivative for generator voltages $2\Delta/e < V < 4\Delta/e$, and the absence of a local minimum of the derivative over the voltage range $4\Delta/e < V < 6\Delta/e$ most probably results from the resistance of the junctions in the normal state being much higher than in [18], and from a much higher "zero current" of the junctions used, which in turn is connected with the much higher working temperature of the system compared to that in [18] and to undamped Josephson effects. The sensitivity of the measuring apparatus used, the magnitude of the signal modulating the current of the junction and the electrical matching of the individual elements of the measuring system may also be of some significance.

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