Acoustoelectric effect at a Josephson *SNS* junction

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A nonlinear acoustoelectric effect has been observed at a Ta-Cu-Ta *SNS* Josephson junction as a low-frequency traveling acoustic wave passes through it. A periodic amplitude modulation of the acoustic wave gives rise to constant-voltage steps on the current-voltage characteristic of the junction.

As a traveling acoustic wave interacts with normal excitations of a superconductor, it transfers momentum to them, giving rise to a current of the normal component, I_n. This acoustoelectric effect is related to the thermoelectric effects which are caused in metals by the phonon drag of electrons.[1,2] A normal current should be canceled everywhere in the volume by the current of the superconducting component, I_s (Ref. 3). When sound passes through a Josephson *SNS* junction, the current I_s that arises may exceed the critical current of the junction, I_c; if it does, then one should observe, as in the thermoelectric case,[4–6] a Josephson generation and a nonlinear increase in the time average of the voltage across the junction with increasing power of the acoustic flux through it. In the present letter we report a study carried out to observe effects of this sort.

The acoustoelectric effect in metal was first studied by Parmenter.[7] Zavaritskiĭ[2] observed an acoustic drag of electrons in normal metals. Gal'perin *et al.*[3] studied acoustoelectric phenomena in superconducting rings. Shmidt *et al.*[4–6] carried some experimental observations, similar to those which we are discussing here, of the thermoelectric effect at a Josephson junction.

As the Josephson *SNS* junctions in the present experiments we used Ta-Cu-Ta sandwiches fabricated by joint hot rolling.[4] The thicknesses of tantalum plates of the sandwich exceeded 0.03 cm; the thickness of the copper interlayer was 4–5 μm. The area of the junction was ~ 0.04 cm^2.

At the experimental temperature $T \approx 0.9\ T_c^s$ the typical parameter values of the junction were a critical current $I_c \approx 100\ \mu$A, a normal resistance $R_n \approx 10^{-8}\ \Omega$, a characteristic Josephson voltage $V_c = I_c R_n \approx 10^{-12}$, and a characteristic Josephson frequency $f_c \approx 500$ Hz. To record current-voltage and "voltage-acoustic" characteristics of the junctions, we used an rf-SQUID voltmeter with feedback in the magnetic flux. Experiments were carried out in a magnetically shielded cryostat with a residual field $\lesssim 10^{-3}$ G.

A traveling acoustic wave was sent through the junction between the quartz and copper regions of an acoustic line. The sound source was a magnetostrictive transducer with a working frequency ≈ 43 kHz, mounted on the quartz part of the acoustic line, outside the cryostat. Behind the sample on the copper part of the acoustic line, was a piezoelectric transducer made of the piezoelectric ceramic TsTS-19, which was

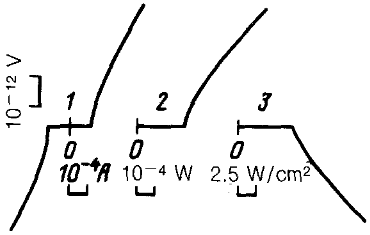

FIG. 1. Characteristics of a Josephson *SNS* junction recorded at $T/T_c^s \approx 0.9$. 1—Current-voltage characteristic (the critical current of the junction is $I_c \approx 100$ μA); 2—"voltage-thermal" characteristic (the critical heat flux is $P_c \approx 0.3$ mW); 3—"voltage-acoustic" characteristic (the critical acoustic flux is $S_c \approx 5$ W/cm^2).

used to monitor the transmitted acoustic power. This power lay in the range 0.01–0.5 W. The acoustic system with a long acoustic line minimized the electromagnetic stray pickup at the *SNS* junction.

Figure 1 shows three characteristics of one of the junctions, recorded at the same sample temperature, $T \approx 0.9\ T_c^s$. Curve 1 shows the ordinary I-V characteristic of the *SNS* junction; curve 2 is the "voltage-thermal" characteristic of the junction, which was discussed in detail in Refs. 4 and 6; and curve 3 is a plot of the acoustoelectric voltage across the junction versus the transmitted acoustic power *S*, in which we are interested here. We quickly see that all the curves are similar in shape, but the acoustoelectric and thermoelectric voltages have opposite signs for the case in which the heat and acoustic fluxes across the junction are in the same direction. During the flow of an auxiliary alternating current with a frequency $f \cong 0.5$ kHz, all three curves exhibit constant-voltage steps at $V_n = nf\Phi_0$ (Φ_0 is the quantum of magnetic flux, and n is an integer).

We also observe the appearance of constant-voltage steps on the ordinary I-V characteristic of the junction, in the absence of an alternating external current, during amplitude modulation, at frequencies $f \lesssim 1.2$ kHz, of the acoustic wave that propagates through the junction. Figure 2 shows a series of I-V characteristics of the junction which were recorded during the passage of acoustic fluxes of fixed power ~ 0.1 W with different modulation frequencies, $f \cong 520$ Hz, 670 Hz, 970 Hz, and 1100 Hz. The arrows mark the step positions V_n calculated from the Josephson relation. Figure 3 shows I-V characteristics of the same junction recorded during the passage of an

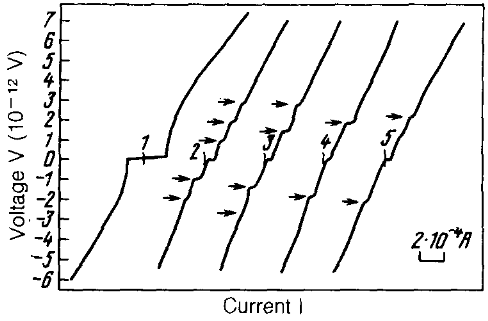

FIG. 2. Series of current-voltage characteristics of a junction being traversed by an acoustic flux with a power $S \approx 0.1$ W, amplitude-modulated at various frequencies: 1—$f \cong 520$ Hz; 2—$f \cong 670$ Hz; 3—$f \cong 970$ Hz; 4—$f \cong 1100$ Hz.

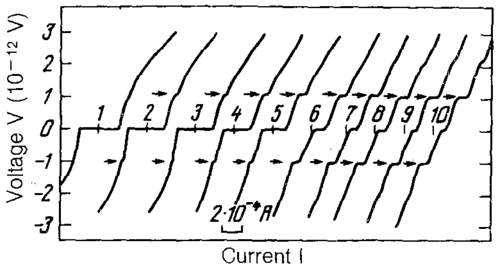

FIG. 3. Series of I-V characteristics of a junction being traversed by an acoustic flux with a fixed modulation frequency $f\cong510$ Hz, with various power levels: 1—0 W/cm^2; 2—0.42 W/cm^2; 3—1.69 W/cm^2; 4—2.4 W/cm^2; 5—2.6 W/cm^2; 6—2.9 W/cm^2; 7—4.5 W/cm^2; 8—6.2 W/cm^2; 9—7.4 W/cm^2; 10—9.5 W/cm^2.

acoustic flux with a fixed modulation frequency $f\cong510$ Hz but various power levels through the junction.

These experimental results can be described in a consistent way by assuming that the copper interlayer contributes most of the acoustoelectric voltage of the *SNS* Ta-Cu-Ta sandwich which we studied. Specifically, when we extrapolate the data in the literature[8] to frequencies in the kilohertz range,[9] we find that the acoustic attenuation Γ_{Ta} cannot exceed Γ_{Cu}. Even if these quantities were equal, however, the contribution of the superconductor which results from the nonequilibrium electric field in it[10] would be considerably smaller than the contribution of the normal interlayer, according to our estimates. The observed effect (curve 3 in Fig. 1) is accordingly due to the appearance of an acoustoelectric current in the copper interlayer[3]:

$$I_n = -\frac{A\Gamma_{\mathrm{Cu}}}{\rho Nec}S.$$

Here A is the area of the junction, e is the charge of an electron, N and ρ are the density of conduction electrons and the resistivity of copper, and c is the sound velocity. Knowing the critical current of the junction (curve 1 in Fig. 1) and the critical acoustic power S_c (curve 3 in Fig. 1), we can estimate the attenuation of low-frequency sound in copper: $\Gamma_{\mathrm{Cu}}\approx10^{-2}$ cm^{-1}. This figure agrees with data in the literature.[9]

We wish to stress that parasitic thermoelectric contributions to the observed effect are negligible. The evolution of thermal power during the propagation of the acoustic flux S_c creates a heat flux through the junction which is considerably smaller than P_c, according to our estimates (curve 2 in Fig. 1). Direct proof of the acoustoelectric origin of the observed effect is the fact that the signs of the thermoelectric and acoustoelectric voltages are different, while the directions of the heat flux and the sound flux in the junction are the same (curves 2 and 3 in Fig. 1). According to the experimental data of Ref. 6, the thermoelectric effect in a Ta-Cu-Ta sandwich at a temperature $T\approx0.9\ T_c^s$ is dominated by the contribution from the superconducting tantalum; the sign of the thermal emf of the tantalum determines the sign of the thermoelectric effect.

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