Nonlinear rf electromagnetic excitation of sound in tungsten

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A nonlinear electromagnetic generation of the second harmonic of longitudinal sound under the conditions of anomalous skin effect has been detected. A nonmonotonic "suppression" of nonlinear generation of sound in a magnetic field normal to the surface of the sample has been observed.

Nonlinear electromagnetic generation of longitudinal sound in the presence of anomalous skin effect in metals, when $\delta \ll l$ (δ is the depth of the skin layer, and l is the mean free path of electrons), was first analyzed theoretically by Vasil'ev *et al.*[1] This nonlinearity, which is of an electrodynamic nature and which occurs as a result of the self-effect of the alternating magnetic field **H** in the skin layer on the current, is embodied in the Lorentz force. There are two distinct cases of nonlinearity which have been analyzed theoretically by Makarov *et al.*[2] from a common standpoint. The effectiveness of a nonlinearity is characterized by the parameter[2] b

$$b \sim (H/\delta)^{1/2} l \ . \tag{1}$$

If the nonlinearity is weak ($b \ll 1$), the frequency of the lattice vibration amplitude is doubled $U \propto H^2$ (Ref. 1) and $H \ll 0.1$–0.5 Oe. If the nonlinearity is strong ($b \gg 1$), $H \gg 0.1$–0.5 Oe, a group of trapped electrons appears in the skin layer, and $U \sim H^{6/5}$ (Ref. 2) Since the conversion is nonlocal ($\mathbf{q}l \gg 1$, where $\mathbf{q}$ is the wave vector of sound), the source of nonlinearity in each case is the deformation mechanism responsible for the conversion of electromagnetic and acoustic waves.

We report in this letter the results of the first experimental study of nonlinear electromagnetic generation of the second harmonic of sound in tungsten. In the experiment we used a pulsed method in the transmission regime. The low-temperature device is described elsewhere.[3] The thickness of the parallel-plane tungsten plates was $d = 1.95$ mm and $\rho_{300}/\rho_{4.2} = 4 \times 10^4$. The experiment was carried out at a temperature $T = 4.2$–1.7 K in the $\mathbf{q} \parallel [001]$ geometry. In one of the experiments the vector of the exciting electromagnetic field, $\mathbf{E}(0)$, at the surface of the sample could be oriented in an arbitrary direction in the inveral $\mathbf{E}(0) \parallel [010]$ and $\mathbf{E}(0) \parallel [100]$. The transmission system generated rf pulses of lengths $\tau = 2$–10 μs with a repetition frequency $\nu \sim 10^2$ Hz and a carrier frequency $\omega_1/2\pi = 173$ MHz (the "long"-pulse method, $s = 5.2 \times 10^5$ cm/s is the velocity of the longitudinal sound). The receiving system detected the sound waves transmitted by the carrier $\omega_2/2\pi = 346$ MHz, which correspond to the third harmonic of the longitudinal piezoelectric transducer. The bandwidth of the transmitting channel was $\omega_1/2\pi \pm 2$MHz. By using this bandwidth we were able to prevent parasitic penetration of the oscillator's second harmonic into the receiving channel. The pulsed electromagnetic power level did not exceed 75–100 W/

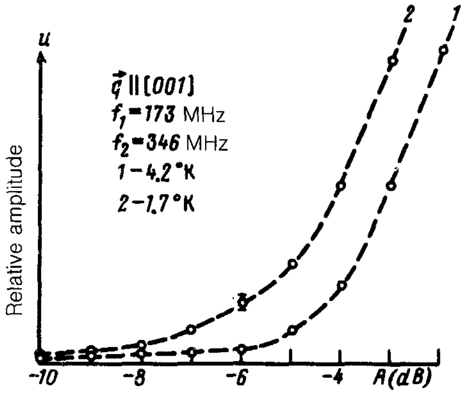

FIG. 1. The amplitude of the signal showing the efficiency of nonlinear electromagnetic excitation of sound versus the pumping amplitude.

cm^2. This amounted for $H \sim 5$–10 Oe. The component of the earth's magnetic field parallel to the sample's surface was screened by superconducting and Permalloy shields. At peak pumping the superheating of the sample did not exceed 0.1–0.2 K.

The relations among the parameters of the experiment are: $l_s \lesssim l$, $ql \gg 1$, and $\omega_{1,2}\tau \gtrsim 1$ (l_s is the attenuation length of sound, and τ is the relaxation time.) The plot of the amplitude of the signal U vs the pumping amplitude A is shown in Fig. 1. Curve 1 corresponds to $T = 4.2$ K, curve 2 corresponds to $T = 1.7$ K, $\tau = 5$ μs, and $\nu = 300$ Hz., Each curve has two characteristic sections where U vs A is nearly linear. We are assuming that there is a change in the nonlinear regimes and that there is a transition region in which the nonlinearity parameter $b \sim 1$. According to Fig. 1, a lowering of the temperature causes a change of the nonlinear regimes to occur at lower pumping levels. This conclusion is in agreement with Eq. (1). It should be noted that a detailed comparison of the experimental curves in Fig. 1 with the theoretical predictions of Refs. 1 and 2 is not entirely correct, since the inverse relations among the parameters were assumed to hold in Refs. 1 and 2: $l_s > l$, $\omega_{1,2}\tau \ll 1$. We studied the efficiency of nonlinear generation as function of the external static magnetic field $\mathbf{H}_0$ normal to the sample's surface ($\mathbf{H}_0 \sim 0$–4 kOe). The field dependences for different pumping levels are shown in Fig. 2. We observed a nonmonotonic "suppression" of the signal by the field $\mathbf{H}_0$. At maximum pumping levels the signal decreased to the noise level measured in >3-kOe fields. The field dependences in Fig. 2 exhibit two "step-like" features. The first feature is localized in a ~ 200-Oe field and the second one exists only at high pumping levels and is localized in fields ~ 1–2 kOe. Earlier we have detected a linear electromagnetic generation of longitudinal sound in W upon pumping with a transverse electromagnetic wave.[4] This sound stems from the presence of anisotropy of the Fermi surface and is absent in an isotropic model. The specific features of the field dependence of this effect observed in Ref. 4 will be discussed in detail in a separate paper. We note, however, that a comparison of the field dependence of $U(H_0)$ of a linear and nonlinear conversion shows that the behavior of the signal is fundamentally different in a magnetic field. On the other hand, a monotonic decrease in the efficiency of nonlinear generation in a field H_0 below the noise level and its minimum in fields, where $R < l < d$ for all groups of charge carriers (R is the radius of the Larmor orbit of

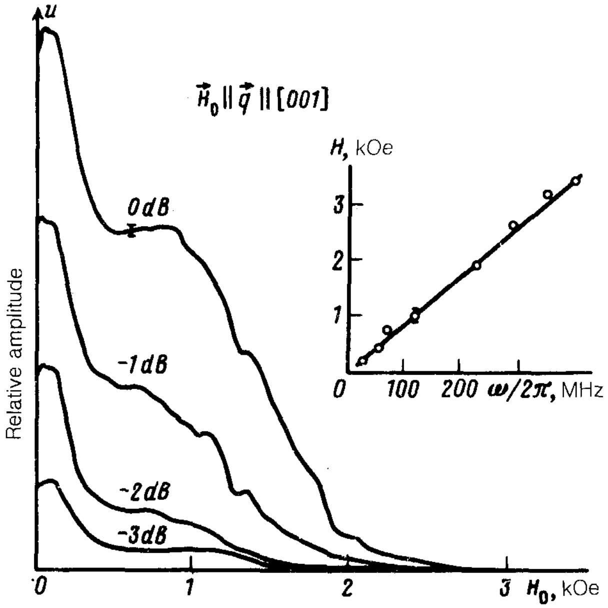

FIG. 2. Field dependence of the efficiency of nonlinear electromagnetic excitation of sound at different pumping levels. Inset—Frequency dependence of the "suppression" of the linear conversion of the electromagnetic wave to a transverse sound.

the electron in a field $\mathbf{H}_0$), are similar to the field dependence for a linear generation of transverse sound in tungsten at a frequency ω_2 in our experimental geometry. The inset in Fig. 2 shows the frequency dependence of the field which suppresses the conversion efficiency of the transverse linear sound. This dependence implies that the field H_0, which corresponds to the minimum signal, is of the same order of magnitude as that in the nonlinear case. We can assume, therefore, that the mechanism which leads to the suppression of the nonlinearity is associated with the appearance of a secondary linear Lorentz force in a field $\mathbf{H}_0$ and with its competition with the nonlinear skin wave in the field H. Further study of the frequency dependence of the nonlinear generation of sound and the determination of the physical nature of the characteristic features of the field dependence (Fig. 2) would thus be of considerable interest.

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