Experiments Relating to the Theory of Magnetic Direct Generation of Ultrasound in Metals*

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Quantitative measurements of the temperature and frequency dependence of magnetic direct generation and the relative efficiency of generation in a number of metals are presented. These results are shown to be in substantial agreement with a description of the generation of ultrasound in terms of magnetic body forces on the eddy currents in the skin depth of the metal.

RECENT work has shown that, in the presence of a dc magnetic field, ultrasonic waves are generated by the direct action of electromagnetic fields at the surface of a metal.[1–4] This process of magnetic direct generation[5] results in a coherent ultrasonic wave, at the frequency of the electromagnetic field, which propagates into the metal with an amplitude proportional to the intensity of the dc magnetic field. The ion motion is parallel to the direction of the Lorentz force on the eddy currents in the skin depth. Thus, depending upon whether the dc magnetic field is perpendicular or parallel to the surface, either transverse or longitudinal waves are produced.[3] The inverse process also takes place; an ultrasonic wave incident upon a conducting surface from within a metal produces an external electromagnetic field with an amplitude proportional to the dc magnetic field strength. Ultrasonic waves at frequencies up to 500 MHz have been generated by this technique,[4] although most of the work to date has been at frequencies below 100 MHz. At these lower frequencies, magnetic direct generation has been observed in a number of metals in the temperature range of 2–300°K.[3,4] While the dependence of the ultrasonic amplitude upon magnetic field direction and intensity has been studied,[2–4] quantitative measurements of the ultrasonic amplitude as a function of temperature and frequency have not been reported.

In this article we present the results of quantitative measurements of the temperature and frequency dependence of magnetic direct generation and the relative efficiency of generation in a number of metals.[6] These experimental results are found to be in substantial agreement with a description of the generation of ultrasound in terms of magnetic body forces on the eddy currents in the skin depth of the metal.

From the self-consistent response of electrons and ions to both a static magnetic field and an electromagnetic field of frequency ω, Quinn[7] has shown that, under rather general conditions, an external electromagnetic field can generate an acoustic wave in a metal. He finds the Fourier transform of the resultant ion amplitude in terms of the dc magnetic field, the frequency and amplitude of the external electromagnetic field, and the various elastic and electrical parameters of the metal. For a semi-infinite metal with the dc magnetic field **B** normal to both the metal surface and the external electromagnetic field, a transverse acoustic wave is generated.[8] Under conditions of local conduction ($ql \ll 1$, q is the acoustic wave number and l the electronic mean free path) the ion amplitude is (in cgs units)

$$|u(r,t)| = \frac{BH_i}{4\pi\rho v_s \omega}\frac{1}{(1+\beta^2)^{1/2}}, \qquad (1)$$

where H_i is the amplitude of the incident rf magnetic field and $\beta = \frac{1}{2}(q\delta)^2$; $\delta = c/(2\pi\sigma_0\omega)^{1/2}$ is the classical skin depth; and σ_0, ρ, and $v_s = \omega/q$ are, respectively, the dc conductivity, mass density, and acoustic shear velocity of the metal. The ion motion is parallel to the direction of $\mathbf{H}_i$.

In the limit $ql \ll 1$, there is a simple physical argument which may be used to calculate the ultrasonic amplitude. Since (experimentally) the ion motion is parallel to the Lorentz force on the eddy currents in the skin depth of the metal, one might expect the driving force on the ions to be the body force $\mathbf{j}\times\mathbf{B}/c$, where $\mathbf{j}$ is the electronic current density. The equation of motion for the

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[5] We use the term "magnetic direct generation" to denote direct generation which arises because of the presence of a dc magnetic field. In very pure metals rf electromagnetic fields may generate transverse ultrasound at liquid-helium temperatures in the *absence* of a dc magnetic field. This latter means of direct generation is a process which is distinct from magnetic direct generation. See B. Abeles, Phys. Rev. Letters **19**, 1181 (1967); W. D. Wallace, M. R. Gaerttner, and B. W. Maxfield, Bull. Am. Phys. Soc. **14**, 64 (1969).
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ions is then simply

$$\frac{\partial^2 u}{\partial t^2} - v_s^2 \frac{\partial^2 u}{\partial x^2} = \frac{|\mathbf{j}\times\mathbf{B}|}{c}, \qquad (2)$$

where the coordinate x is taken normal to the metal surface (that is, parallel to **B**). In the classical skin-effect regime, the solution of Eq. (2) yields the ion amplitude given by Eq. (1) when the boundary condition of a free surface is used.

In the local limit, the major temperature dependence of magnetic direct generation comes from the conductivity in the parameter β. The frequency dependence and relative efficiency of generation in different metals also depend upon temperature through the parameter β.

In the present experiments, wire coils positioned near opposite faces of the samples were used to generate and detect the rf fields coupling to the ultrasound. In order to compare our experimental results with theory, it is necessary to consider the inverse process to magnetic direct generation, that is, the detection process. The signal from the receiver coil can be calculated as follows. The acoustic power generated in the sample is given by

$$P_s = GKI_T^2, \quad K = B^2/\rho v_s(1+\beta^2), \qquad (3)$$

where G is some geometrical factor and I_T is the transmitter coil current. Because the receiver and transmitter coils are components of a reciprocal network, one can show that the over-all power insertion loss is proportional to K^2. Hence we expect the receiver coil voltage to be proportional to K, that is,

$$V_R \propto \frac{B^2}{\rho v_s(1+\beta^2)}. \qquad (4)$$

Temperature- and frequency-dependence measurements of the combined generation-detection process were made from 77 to 300°K and from 10 to 70 MHz. All previous measurements of the temperature and frequency dependence of magnetic direct generation have been performed in the region $\beta^2 \ll 1$, and hence the experimental results were not sensitive to the details of the theory. Our measurements cover the range 0.1 $\beta^2 < 0.3$.

Small, flat-sided wire coils were used to generate and detect the ultrasound, using conventional pulse-echo techniques. An electromagnet provided a 10-kG field normal to the flat sample faces. In this geometry, transverse acoustic waves are produced. Each specimen was a single crystal cut with an abrasive string saw and hand-lapped to provide two faces flat and parallel to within 5×10^{-4} cm. The specimen faces were of irregular cross section and typically about twice the area of the coil faces. Specimens ranged in thickness from 0.7 to 0.9 cm. The sound propagation direction, normal to these faces, was either parallel to a ⟨100⟩ direction for cubic crystals, or parallel to the c axis for uniaxial crystals. In these directions the shear modes are degenerate and the velocity of sound is determined by the elastic constant c_{44}. Orientation was within 1° of the desired axis.

The temperature dependence of the signal amplitude in W and Al for several frequencies is shown in Fig. 1. At each frequency the input current to the transmitter coil was held constant and the temperature was varied over the desired range. Since different power levels were used at each frequency, these data have been arbitrarily normalized to the same amplitude at 77°K. In these as well as all other measurements reported in this article, we extrapolate the echo amplitudes so as to obtain the amplitude at the generating surface. This ensures that the experimental results are independent of the acoustic attenuation, which varies with temperature and frequency as well as from sample to sample.

With appropriate values of ρ and v_s, and on the assumption that the Grüneisen relation predicts the temperature dependence of the electrical conductivity in the range from 77°K to room temperature, Eq. (4) was used to calculate the temperature dependence of the receiver coil signal shown by the solid curves in Fig. 1.

Equation (4) predicts that for small β^2 the temperature dependence at a given frequency will be small. This is the case for Al, where $\beta^2 = 0.014$ at room temperature and at 10 MHz. Since β^2 remains small from 300 to 4.2°K, there is essentially no observable change in the Al signal at 10 MHz over this entire temperature range. Because β^2 is proportional to ω^2, there is an observable

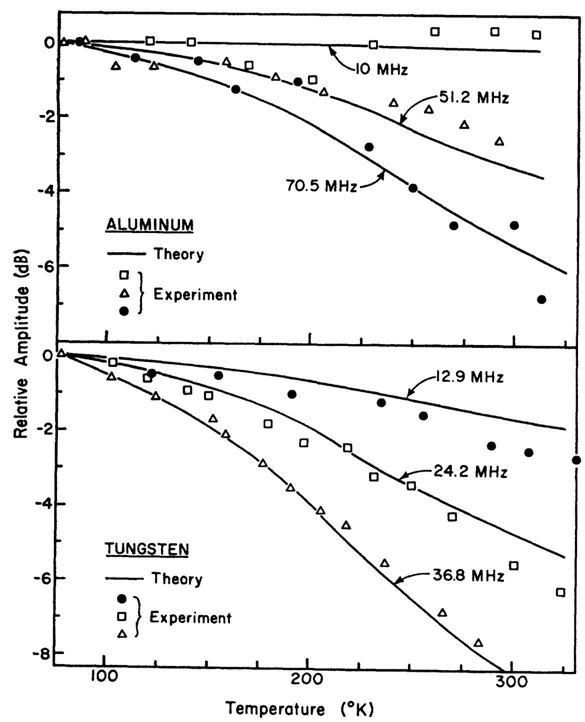

FIG. 1. Temperature dependence of signal amplitude in W and Al.

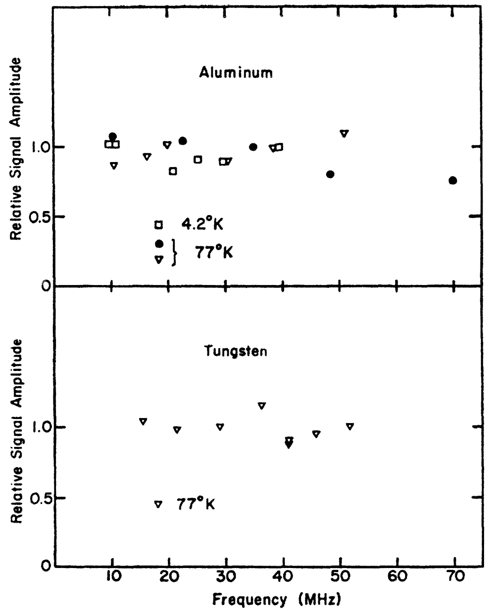

FIG. 2. Frequency dependence of combined generation-detection process in W and Al.

temperature dependence at higher frequencies, as is evident from the results shown in Fig. 1.

In the case of W, $\beta^2=0.10$ at room temperature and at 10 MHz; hence, at a given frequency, a greater temperature dependence is observed in W than in Al. Approximately the same change in amplitude between 77 and 300°K is found in W at 24 MHz and Al at 70 MHz. Within an estimated error of 1 dB, the experimental data are in agreement with the temperature dependence predicted by Eq. (4).

The frequency dependence of the combined generation-detection process in Al and W at 77°K is shown in Fig. 2. Because the experimental geometry was changed from run to run, the Al data has been normalized to 1.0 at 40 MHz. Each set of frequency measurements was made holding the transmitter coil current constant. Within the experimental error indicated by the scatter, we find that the signal at the receiving coil is independent of frequency between 10 and 70 MHz, which is in agreement with the prediction of Eq. (4) for the case of $\beta^2 \ll 1$.

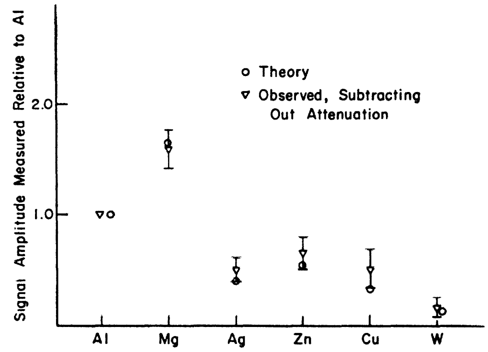

FIG. 3. Relative efficiencies of acoustic generation in a number of metals.

The relative efficiencies of acoustic generation have been measured in a number of metals at 25 MHz and 77°K. These data are given in Fig. 3, along with the efficiencies calculated from Eq. (4). The current in the transmitter coil was the same for each of these measurements. Within the indicated errors, the experimentally observed relative efficiencies are those predicted by the theory. The largest error in these measurements comes from the deviation of the echo patterns from true exponential behavior. At liquid-nitrogen temperatures, the major variation in generation efficiency from metal to to metal arises from the factor $(\rho v_s)^{-1}$ in Eq. (4).

In summary then, we find good agreement between the observed temperature and frequency dependence of magnetic direct generation of ultrasound and the theory proposed by Quinn[7] in the regime of local electrical conductivity. The observed relative efficiency of generation in a number of metals also agrees with this theory. We conclude that magnetic direct generation of ultrasound in the local regime arises from the magnetic body force on the eddy currents in the skin depth of the metal.

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