Letters to the Editor

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Quenching-In of Lattice Vacancies in Pure Gold*

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PRELIMINARY data obtained by the quenching of 99.999 percent pure gold wires was reported in an earlier letter.[1] The quantities of interest are E_F, the energy required to produce a lattice vacancy; and E_M, the activation energy required for vacancy motion. The present letter reports on more accurate measurements.

E_F is measured by determining the increases in resistance produced by quenching a specimen from various temperatures in the range from 690°C to 900°C. One has $\Delta R = Ae^{-E_F/kT}$, where A is a constant and ΔR is the increase in the resistance at liquid nitrogen temperature produced by a quench from the high temperature T. Both 16-mil and 25-mil wires were used and the quench by a precooled jet of helium gas from the high temperature to room temperature occurred in about 10 milliseconds. The wire was then manually turned down into liquid nitrogen (time required, about a third of a second). In the case of the 25-mil wires we were unable to secure a sufficiently rapid cooling to retain all of the vacancies on quenching from temperatures above 800°C. The data from wires of both sizes showed the exponential increase in quenched in resistance but the data obtained with the 16-mil wires gave the more accurate values of E_F. The limiting low temperature which can be used for quenching appears to be determined by the amount of impurity present. The residual resistance of many of the specimens was measured at liquid helium temperature. The values obtained indicated that the wires were about 99.999 percent pure. It was noted that on specimens of rather low purity two difficulties arise: First, faster quenching rates are required to retain all of the imperfections. Second, on quenching from various temperatures below some temperature T_0 one finds that very nearly the same resistance ΔR_0 is introduced. Both T_0 and ΔR_0 increase with increasing amounts of impurity thus limiting the temperature range over which a determination of E_F can be made. No cold-work was introduced because all of the resistance increase could be annealed out by a 600°C anneal. Permanent changes in dimensions would be introduced by cold-work.

Since liquid nitrogen dissolves oxygen which changes the boiling temperature a similar dummy specimen was also measured to correct for changes in the bath temperature. R was measured to better than one part in thirty thousand.

It was found that $E_F = 1.28 \pm 0.03$ ev for gold. A quench from 816°C produced an increase of 0.21×10^{-8} ohm cm in the resistivity.

Annealing measurements were made to determine the activation energy of motion E_M for lattice vacancies in gold. Isothermal annealing measurements were made in which R was measured at liquid nitrogen temperature after various lengths of time in a constant temperature bath. At a certain stage in the annealing, the temperature of the annealing bath would be increased. The increase in the rate of annealing with increase in annealing temperature at constant R depends on E_M as follows:

$$\frac{dR_2}{dt} \Big/ \frac{dR_1}{dt} = \exp\left[-E_M\left(\frac{1}{kT_2} - \frac{1}{kT_1}\right)\right].$$

The annealing baths were operated between -30°C and $+15$°C. Their temperature was constant to ± 0.01°C. It was found that $E_M = 0.68 \pm 0.03$ ev. About half of the quenched-in resistivity recovered after 57 hours at 25°C.

If self diffusion in gold occurs by means of vacancies, then it can be shown that the activation energy for self diffusion, Q, should be given by: $Q = E_M + E_F$. The above data give $Q = 1.96 \pm 0.06$ ev. Gatos and Kurtz[2] have recently measured Q for gold, and find $Q = 1.965$ ev. The agreement is most satisfactory.

* This work is supported by the U. S. Atomic Energy Commission.

[1] J. W. Kauffman and J. S. Koehler, Phys. Rev. **88**, 149 (1952).
[2] H. C. Gatos and A. D. Kurtz, J. Metals **6**, 616 (1954).

Ferromagnetic Resonance in Nickel Ferrite Between One and Two Kilomegacycles

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DUE to limitations imposed by internal anisotropy fields, microwave resonance work in ferrites has largely been restricted to frequencies above 4 kMc/sec. This note describes special experimental arrangements, and observations on one of these, which make it possible to compound an applied field with the internal shape and crystalline anisotropy field to yield a particularly low effective field, and thus a low resonant frequency.

The method involved is best demonstrated for a (cubic) single-crystal, single-domain ferrite sphere, with cube axes and diagonals the hard and easy magnetization directions respectively. In zero applied field the

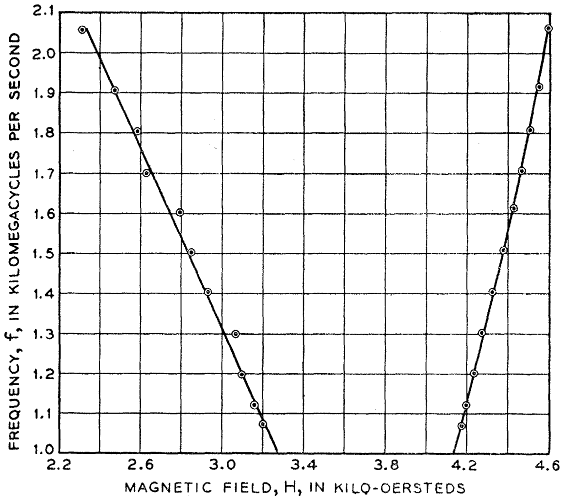

FIG. 1. Experimental curve of resonant frequency *vs* field, showing the characteristic two-arm structure.

magnetization M is aligned along 111, say, a minimum in the energy surface. Application of a dc field H in the (hard) 001 direction pulls the energy minimum towards 001 making it more shallow in the process. The natural precession frequency of M about the minimum is thus decreased. Finally at a certain critical field H_{crit}, the minimum reaches the maximum at 001, yielding a local "flat-spot" in the energy surface. M now has no "stiffness" at all, the natural precession frequency is zero. Further increase in H leaves M aligned along 001, and simply gives a resonance frequency $\gamma(H-H_{\mathrm{crit}})$, with γ the gyromagnetic ratio. H_{crit} for the sphere is $H_a=-2k_1/M$, where k_1 is the first anisotropy constant (here negative).

For the $\mathrm{Ni_{0.75}Fe_{2.25}O_4}$ crystal investigated,[1] ($H_a\sim 240$ oe, $M\sim 290$ gauss) spherical geometry is unsuitable. Single domain behavior results only if the effective field for domain wall motion [about $H-(4/3)\pi M$ in the sphere] exceeds zero, a condition which fails near $H=H_{\mathrm{crit}}$. However for a disk cut in the 001 plane, the same principles apply: at a certain critical field (now $4\pi M+H_a$) along 001 the resonant frequency goes to zero. The single domain condition (now $H-4\pi M>0$) is readily satisfied near H_{crit}. Measurements on a disk 0.2 in. in diameter and 0.005 in. thick are shown in Fig. 1.

More general arrangements are best examined by writing the total energy E (in external field, demagnetizing field, and anisotropy field) and the Landau-Lifschitz equations of motion in the polar coordinates θ, φ of the M vector. A small precession about equilibrium ($\partial E/\partial\theta=\partial E/\partial\varphi=0$) is then seen to have a natural frequency

$$\omega_{\mathrm{res}}=\frac{\gamma}{M\sin\theta}\left[\frac{\partial^2E}{\partial\theta^2}\frac{\partial^2E}{\partial\varphi^2}-\left(\frac{\partial^2E}{\partial\theta\partial\varphi}\right)^2\right]^{\frac{1}{2}}.$$

This expression goes to zero whenever the energy surface becomes "parabolic" near the minimum,[2] a condition attainable in many ways. In the disk just described, it is attained for example with H anywhere in the 010 or 100 planes; H_{crit}, and its inclination θ_H to 001 being given parametrically in terms of θ:

$$H_{\mathrm{crit}}^2=H_a^2\sin^6\theta+(H_d+H_a\cos^2\theta)^2\cos^2\theta,$$

$$\tan\theta_H=\frac{H_a\sin^2\theta}{H_d+H_a\cos^2\theta}\tan\theta,\quad H_d=4\pi M.$$

With H in the $1\bar{1}0$ plane, zero frequency is not always achieved. The curves computed in Fig. 2 have finite minima when H is inclined slightly into the octant occupied by M. Such misalignment is the more serious the greater M: with $H_d\sim 3000$ oe, it need only be 30′ to give $\omega_{\mathrm{min}}\sim 700$ Mc/sec. Similar considerations presumably apply to other low symmetry orientations of H. Thus crystal lineage may be responsible for the apparent failure of the two arms of the curve in Fig. 1 to extrapolate to zero frequency. Also, some residual domain structure (especially near the rim) may prevent uniform lineup of M.

Detailed theory predicts the following features of the line profile: On the high-field branch of the curve in Fig. 1, the line-strength should be independent of rf magnetic field orientation in the plane of the disk; but on

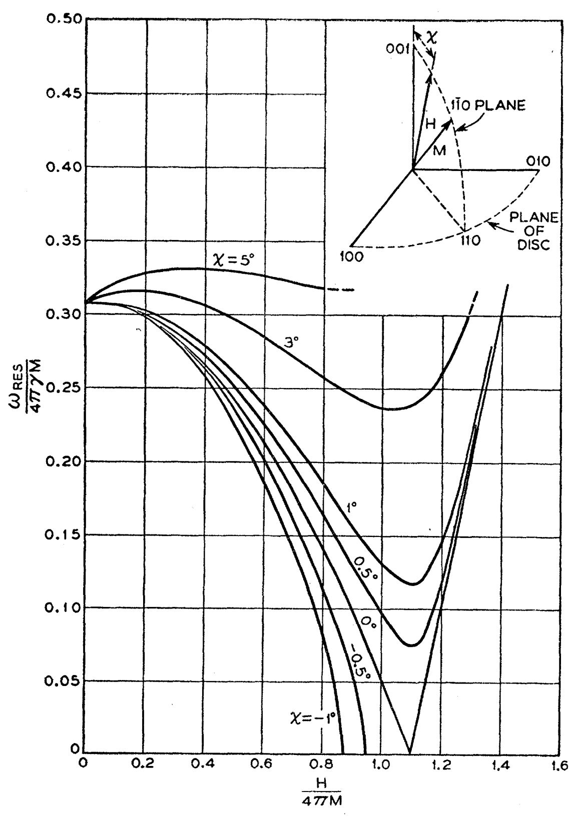

FIG. 2. Computed effect of misalignment of H in the 110 plane, for $H_a/H_d=0.1$. For $\chi<0$, the upper branch is unstable. k_2 has been neglected.

the lower branch the absorption should equal a constant term, plus a term varying as the sine squared of the angle between 110 and the rf field; thus as the disk is rotated in its own plane, there should be two absorption maxima 180° apart. The conclusions were well substantiated by experiment, except at the low-frequency end, where the upper branch also showed some sensitivity. The agreement indicates one, or at most two domains (in directions of equal latitude, with longitudes 180° apart), on the low field-branch. Four domains 90° apart in longitude would have given four absorption maxima.

The formula for linewidth (between points of $\frac{1}{2}$ maximum absorption on either side of resonance) is given by

$$\Delta H=\frac{\alpha}{|d\omega_{\text{res}}/dH|}\frac{\gamma}{M}\left(E_{\theta\theta}+\frac{1}{\sin^2\theta}E_{\varphi\varphi}\right),$$

in terms of the Landau-Lifschitz loss parameter α. The α measured at 1920 Mc/sec on the upper branch of the curve was about twice that found in similar material at 24 kMc/sec.[3] This increase is yet unaccounted for.

The author is indebted to Dr. A. M. Clogston for suggesting the experiment, to Dr. L. R. Walker for his continued interest in the theory, to Dr. J. F. Dillon, Jr. for supervising the sample preparation, to Mr. J. H. Rowen for valuable advice on instrumentation, to Mrs. A. Rebarber for the computations, and to Mr. J. Davis for assistance in the experiment. The single crystal was supplied by Dr. W. Clarke of Linde Air Products.

[1] Composition approximate.
[2] This formula was also derived, independently, by J. Smit, (Talk at Conference on Ferrimagnetism at the Naval Ordnance Laboratory, 11–12 Oct., 1954), and by P. Tannenwald and B. Lax (private communication). The latter have done theoretical work of the kind reported here.
[3] Galt, Yager, and Merritt, Phys. Rev. **93**, 1119 (1954).

Ultrasonic Attenuation Due to Lattice-Electron Interaction in Normal Conducting Metals

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In a recent letter to the editor,[1] Bömmel published some experimental results on the attenuation of sound waves at ultrasonic frequencies for single lead crystals, which showed that there was an increase in attenuation at very low temperatures for the normal conducting state which disappeared in the superconducting state. This attenuation difference occurred for both shear and longitudinal waves and increased in proportion to the square of the frequency. From 1.6°K to 4°K the difference was independent of the temperature and was 0.106 neper per cm for longitudinal waves of 26.65 Mc/sec and 0.061 neper per cm for shear waves of 9.5 Mc/sec. Figure 1 shows complete measurements for longitudinal waves. Bömmel has recently measured the same effect for a single tin crystal with the results shown by Fig. 2 for a longitudinal wave of 28.5 Mc/sec.

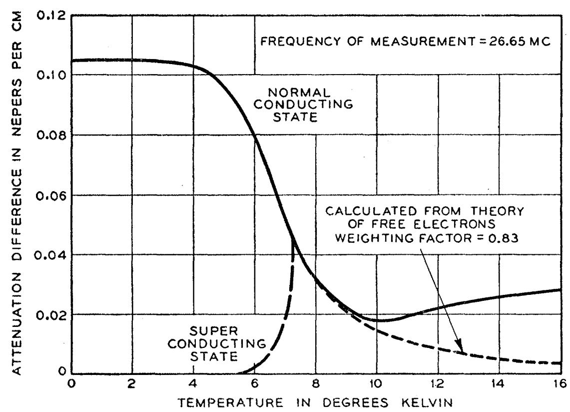

FIG. 1. Comparison of measured attenuation of a lead single crystal with that calculated from free electron theory.

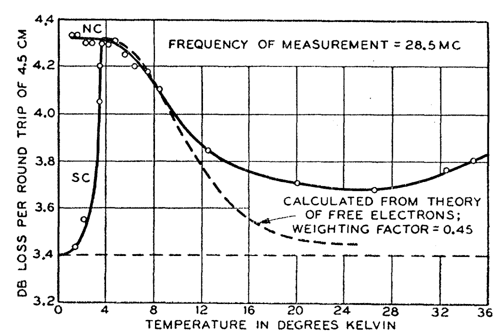

FIG. 2. Comparison of measured attenuation in tin with that calculated from free electron theory.

A curve of similar shape is obtained for shear waves with a value of 0.036 neper per cm at 17 Mc/sec and 1.5°K for the difference between normal and superconducting states.

It is the purpose of this note to point out that a simple phenomenological concept of the interaction between the lattice vibrations and the electron gas gives values of attenuations which agree well with the measured results. The concept considered is that in the normal state a lattice vibration can communicate energy to the electron gas by a viscous reaction, i.e., transfer of momentum, and is damped by the viscosity of the gas, while in the superconducting state the lattice is not able to transfer momentum to the electron gas and the damping disappears.

For the most general case the attenuations[2] caused by the energy loss due to the shear and compressional viscosities of the electron gas are for longitudinal and