Photoacoustic detection of ferromagnetic resonance in films
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yields local fluctuation of the Mn concentration which produces different separations of Mn-Mn atoms.

The characteristics of hysteresis loop shown above are similar to those of micromagnetic behavior, which arises from the coexistence of short-range ferromagnetic and antiferromagnetic spin alignments observed by Kouvel for Cu-Mn alloys.

The sign of the exchange interaction between two Mn atoms depends very sensitively on their separation. It is proposed by Kouvel that the statistical fluctuations of composition and the coexistence of ferromagnetic and antiferromagnetic interaction between Mn atoms of different separation are together responsible for small regions of ferromagnetic and antiferromagnetic order in the Cu-Mn alloy.\(^3,4\)

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We report on the detection of the ferromagnetic resonance of Ni and Fe films through the photoacoustic effect. The photoacoustic signal dependence on both the magnetic field and the chopping frequency is also discussed in light of existing theoretical models for the production of the photoacoustic signals.

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Recently the photoacoustic (PA) effect was revived by Rosencwaig\(^1\) to measure the light absorption spectra of highly absorbing solids. Since then the photoacoustic technique has proved useful not only as a spectroscopic tool\(^1\) but also for measuring the thermal properties of condensed matter.\(^2,3\) Even though photoacoustic spectroscopy in the visible has been an extremely active field, to our knowledge, no study has been reported in the microwave region. In this letter we present our preliminary study using the photoacoustic effect of a well-known phenomenon in solids in the microwave region, the ferromagnetic resonance (FMR) of the metals Ni and Fe.

Several workers\(^4,6\) using microwave reflection measurements, have already studied the FMR of metals. However, the PA technique, by virtue of its main characteristic (i.e., it measures directly the heat generated in a sample by incident radiation), has special significance for measuring the absorptive part of the permeability of the ferromagnetic metals.

The microwave rig for exciting our samples consisted of a klystron (2K25) which provided 20 mW at 9 GHz, followed by an isolator, a wavemeter, a directional coupler, a screw tuner, and a short, upon which was mounted the PA cell. With the screw tuner we could match the impedance of the waveguide to that of the microwave short. The reflected power from the short was monitored with the directional coupler. The microwave power was chopped at frequency \(f_M\) by applying square pulses to the klystron reflector.

The acoustic detection system was a Helmholtz resonator\(^7\) coupled to a electret microphone. The sample chamber was made of Lucite—a low-loss material in the microwave region—and has the dimensions \(2 \times 6 \times 17 \text{ mm}^3\); the micro-
The microwave heating power per unit of volume can be expressed as the divergence of the microwave Poynting vector $S$ in the metallic sample. Using the expression for the electric and magnetic fields inside of the metallic sample\(^6\) we can get the Poynting vector.

The modulated heating power per unit of volume can then be written as

$$P(x,t) = \frac{1}{2} \beta I_0 e^{-\alpha x} [1 + \cos(2\pi f_m t)],$$

where $I_0 = c |H_0|^2/\Sigma\sigma (H_0)$ is the intensity of the microwave magnetic field on the surface and

$$\beta = 2k_e^2(1/c)(2\pi\Sigma_0\mu_n)^{1/2},$$

$$\mu = (\mu_1^2 + 4\pi^2\alpha^2 + \mu_2)$$

(\(\sigma\) is the Ni conductivity, \(\omega\) is the frequency of the microwave, and \(\mu\) is the complex transverse permeability of Ni: \(\mu = \mu_1 + j\mu_2\)).

The theoretical analysis of the photoacoustic effect was carried out by Rosencwaig and Gersho (RG)\(^9\). These authors considered the problem of a sample periodically heated by a chopped light beam. The heating power per unit of volume, $P$, as a function of the penetration $x$ in the sample is given by

$$P(x,t) = \frac{1}{2} \beta I_0 e^{-\alpha x} [1 + \cos(2\pi f_m t)],$$

where $\beta$ is the optical absorption coefficient and $I_0$ is the average incident power.

Using the prescription

$$I_0 \beta = (cI_0/8\pi\sigma)^{1/2},$$

we can translate all the RG results for our problem. More important for us is Eq. (21) of the RG paper for the variable $Q$, the pressure-fluctuation amplitude in the acoustic cell.

Since our sample is metallic, its thermal conductivity is much bigger than the respective quantities for the backing (glass)—on which the sample is glued—and for the gas. The expression for $Q$ reduces, then, to

$$Q = \frac{P_0}{2\sqrt{2}T_0} \frac{1}{a_s} \frac{cI_0}{8\pi\sigma} \frac{\beta}{\sinh(\sigma t)} \left( \coth(\sigma t) - \exp(-\beta t) \right),$$

where $P_0$ is the ambient pressure in the sample chamber, $T_0$ is the ambient temperature, $I_p$ is the dimension of the gas chamber parallel to the direction of microwave beam propagation, $a_s = (\Pi f_m/\alpha_2)^{1/2}, \alpha_2$ is the thermal diffusion constant of the gas, $\sigma = (1 + j)(\Pi f_m/\alpha_2)$, $\alpha_2$ is the thermal diffusion constant of the sample, $t$ is the sample thickness, and $k_s$ is the sample thermal conductivity.

Qualitatively the dependence of the PA signal on the external magnetic field can be explained by the above expression. The increase of the PA signal at the resonance corresponds to the resonant absorptive behavior of $\beta$ through its dependence on $\mu_n$ [see Eq. (3)]. Assuming that the transport properties—electrical and thermal conductivity—do not vary with the magnetic field, we can, with help of Eq. (6), determine the relation $\delta P_M/\delta P_B$ for each Ni film thickness $t$. The theoretical values for $\delta P_M/\delta P_B$ vs. $t$ are plotted in Fig. 2. We note that the RG model cannot explain quantitatively our experimental observations. The same disagreement is also found if one uses the recently reported theory of Cesar et

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**Figure 2:** Variation of the ratio $\delta P_M/\delta P_B$, defined in the text, vs film thickness $t$ of Ni films. The two points around $5 \times 10^5 \AA$ correspond to two different films, one prepared by electrodeposition, the other by cold rolling.
which is essentially an improved version of the RG model.

The $f_M$ dependence of the PAS signal is not explained by the above theories. In the limit of thermally thin samples ($\tau a_1 < 1$) both theories predict a PAS signal proportional to $f_M^{-1}$. For samples of Ni $5 \times 10^5$ Å (thermally thin) the experimental results show PAS $\propto f_M^{1.3}$.

We believe that reason for the inability of these theories to explain quantitatively our findings is due to the fact that they both assume only thermal diffusion as the mechanism for production of the PA signal. A more complete model should include the elastic waves in the solid as well thermal diffusion as the sources of the PA signals, as suggested by McDonald and Wetsel. The analysis of our data based upon this more complete description of the PA-signal production mechanism is currently in progress.

In conclusion we thank Professor L. C. Miranda for stimulating discussion on the PA theory and for critical reading of the manuscript.