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SUPERCONDUCTING MICROPHONE FOR PHOTOACOUSTIC SPECTROSCOPY*

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ABSTRACT. A superconducting microphone has been developed for photoacoustic spectroscopy at low temperatures. The microphone consists of a thin mylar membrane coated with a film of lead whose motion is detected by a SQUID magnetometer. For the simple set-up presented here, the limiting pressure sensitivity is 7.5×10^{-14} atmospheres/$\sqrt{Hz}$.

RESUMO. Foi desenvolvido um microfone supercondutor para espectroscopia fotoacústica a baixas temperaturas. O microfone consiste de uma fina membrana de mylar com uma camada de chumbo evaporado. O movimento de membrana é detetado por um magnetômetro SQUID. Para a montagem simples aqui apresentada, a sensibilidade limite é de 7.5×10^{-14} atmosferas/$\sqrt{Hz}$.

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1. INTRODUCTION

This paper presents a new type of detector, a superconducting microphone, for use in photoacoustic spectroscopy at low temperatures[1]. In this type of spectroscopy[2], resonant absorption is detected by the effect of the non-radiative transitions resulting from the absorbed energy: these transitions heat up the sample. When the incident photons have their intensity modulated at an audio frequency and when the sample is in contact with a gas, the periodic heat flow from the sample will cause pressure changes in the gas, i.e., sound. This can be detected with a sensitive microphone.

We have extended this type of spectroscopy to low temperature for two reason: to investigate energy levels in certain systems and to use very sensitive instrumentation which results from reduced thermal fluctuations. Hence we have developed the superconducting microphone which is monitored by a SQUID magnetometer; this combination offers the possibility of detecting very small pressure changes. The very high sensitivity of this device makes it useful for the detection of weak photoacoustic signals which can occur in certain systems.

2. PRINCIPLE OF THE MICROPHONE

Pressure variations Δp of a sound wave in a gas can produce corresponding displacements of a very thin and light membrane. The displacement Δz of the membrane at a distance r from its center is given by[3]

$$\Delta z = \frac{(a^2-r^2)\Delta p}{4S} \qquad (1)$$

where S is the tension per unit length and a is the radius of the membrane. This relation is valid for displacements much less than the radius. The ultimate sensitivity of such a membrane is governed by the Johnson noise of the membrane which places a limit on the pressure variations Δp that can be detected at a temperature T. The mean square equivalent noise pressure for a frequency interval Δf is[4]

$$\langle \Delta p^2 \rangle = \frac{(8kT\sigma)}{A\tau}\,\Delta f \qquad (2)$$

where τ is the membrane damping time, σ is its mass per unit area, and A its area. Thus a large membrane area and low temperature will improve the sensitivity to small pressure changes.

For a 1.3cm diameter membrane with a $\sigma=1.8\times10^{-3}$ gm/cm^2, the pressure noise at room temperature is 1.6×10^{-13} atmospheres/$\sqrt{Hz}$. Of course the electrical circuits connected to the pressure-sensing membrane also introduce noise. Both of these noise figures can be reduced by operating at low temperatures and using detection electronics based on the SQUID magnetometer; this is achieved with the superconducting microphone.

At 4K, the above thermal noise pressure becomes $\Delta p = \approx 2\times10^{-14}$ atmospheres/$\sqrt{Hz}$; this can be detected with a SQUID magnetometer.

A SQUID magnetometer can detect very small magnetic flux changes down to flux noise levels of

$$\phi_N \sim 10^{-4}\ \phi_0/\sqrt{H_z}$$

where $\phi_0=2.07\times10^{-7}$ gauss cm^2 is the flux quantum. Whe, a superconducting membrane is placed in a magnetic field H, its diamagnetic contribution to the magnetization M produces a flux ϕ,

$$\phi = 4\pi M A_e \tag{3}$$

where A_e is the effective area of the membrane. Motion of this membrane by sound waves will cause a flux change which is detected by a SQUID magnetometer[5].

In order to obtain the largest signal and to operate in a linear region of the pressure sensor, the membrane's motion is detected by a pair of coils in a gradiometer configuration coupled to a SQUID. This is shown in figure 1. In that case, a displacement of the membrane by Δz will produce a flux change

$$\Delta\phi = \frac{(\partial\phi)}{\partial z} \Delta z \tag{4}$$

where $\partial\phi/\partial z$ is the flux gradient in the gradiometer coils In terms of the parameters of the membrane, a flux change $\Delta\phi$ results from a pressure change Δp,

$$\Delta\phi = \frac{(\Delta p)\pi H a^4}{4S\ell(1-D)} \tag{5}$$

ℓ being the distance between the coils of the gradiometer and D is the demagnetization factor. For a flat plate perpendicular to a field, $D=1-t/2a$ where t is the thickness of the superconducting material on the membrane. Because of the demagnetization factor for the membrane, the magnetization in a field H is

$$M = -\frac{1}{4\pi}\frac{(H)}{1-D} \tag{6}$$

attaining its maximum values $M= -H_c/4\pi$ at $H'=(1-D)H_c$. Here H_c is the critical field for the superconductor (H_c=803 Oe for lead).

Above this field H' the membrane is in the intermediate state and the magnetization is then $M=-(1/4\pi D)(H_c-H)$ decreasing with field to zero at H_c. As equation (5) shows, we have an enhancement of the magnetization at low field due to D.

For our membrane under a tension S of 100 dynes/cm and coil spacing of 4mm in a field of 10 Oe, this gives a limiting sensitivity of $\Delta p=7.5\times10^{-16}$ atmospheres/$\sqrt{Hz}$. It is interesting to note that for this limiting pressure sensitivity the corresponding displacement of the membrane is $\approx 10^{-18}$ cm/$\sqrt{Hz}$. This calculation is based on a demagnetization factor of 0.999 for our superconducting microphone.

3. RESULTS

The superconducting microphone consists of a thin mylar sheet, 1.25×10^{-3} cm thick and 1.3cm in diameter. A thin layer of lead is evaporated onto this mylar sheet. The membrane is glued at its rim to an epoxy resin support which forms part of the photoacoustic cell.

The pickup coil is wound out of niobium-titanium wire, 0.011cm diameter, with 9 turns in each coil of the gradiometer, the spacing between the coils being 4mm. This coil is coupled to a SQUID magnetometer. The external field H is trapped in a superconducting lead tube surrounding the microphone. This tube also acts as a shield to the gradiometer coils.

For proper operation of the microphone, it is kept in a leak-tight chamber with He gas at atmospheric pressure on both sides of the membrane. The whole unit is surrounded by liquid helium at 4.2K and hence in good thermal contact with the bath.

The sound frequency is determined by the chopping frequency of the light beam falling on the sample to be studied.

The output of the SQUID magnetometer is fed to a phase-sensitive detector locked to the chopping frequency.

Because the sensitivity of the microphone is so high, it picks up noise form th boiling liquid helium, outside noises, and vibrations of the cryostat. These disturbances caused the noise of the magnetometer with the superconducting microphone to be as high as 10^{-2} $\phi_0/\sqrt{Hz}$. Hence the measured noise of the system corresponded to pressure variations Δp=7.5 10^{-14} atmospheres/$\sqrt{Hz}$, which is still adequate for many experiments.

The performance of the microphone was investigated from 100 Hz down to a few hertz. With a SQUID magnetometer, the detection of the membrane's motion is excellent at low frequencies and it is limited at high frequencies by the modulation frequency in the magnetometer. The sensitivity was sufficient to detect in a preliminary experiment[1] the photoacoustic signal from lampblack at 4.2K.

4. CONCLUSIONS

A very sensitive microphone was developed for studies of photoacoustic spectroscopy at low temperatures. Although no special effort was made to optimize the device, it is sensitive enough for many experiments. The geometry could be modifiel so as to get a larger signal and the microphone could be used at its natural frequency (in this case approximately 200 Hz) for optimum signal to noise ratio, and higher H_c superconductors could be used for the membrane.

The application of the device to photoacoustic spectroscopy promises a variety of interesting studies on samples that are difficult to study by conventional methods. The sensitivity is very impressive.

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FIGURE CAPTION

Fig.1 - Superconducting microphone with SQUID detection.

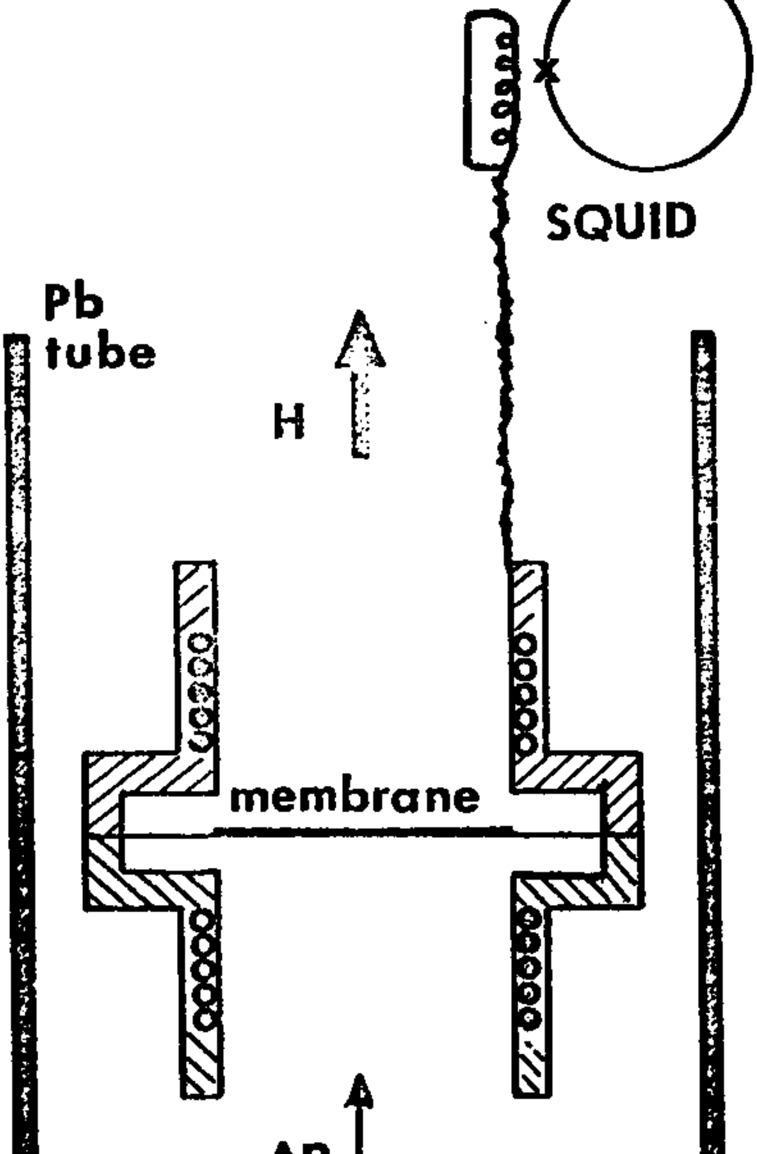

Fig.1