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NOTES

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A remote pressure sensing technique by using the photothermal bending effect

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Photothermal technique for sensing pressure in a cell is reported. The pressure is monitored from the frequency change of the vibration of the cell itself. The vibration is generated by the photothermal bending effect caused by the chopped laser irradiation, and it is sensed by the deflection of the probe laser beam. The proposed technique is noncontact, and thus it will be useful for remote pressure measurements in hostile environments.

Photoacoustic and photothermal effects by laser irradiation have been studied widely since they are useful for spectroscopic studies and nondestructive testing of several materials.[1] Nondestructive evaluation, subsurface imaging,[2] depth profiling of layered structures,[3] and measurement of thermal properties[4] have been successfully achieved. In the case of a thin-plate sample clamped at its circumference, the flexural vibration caused by the thermoelastic bending (the drum effect) becomes dominant for signal generation.[4,5] By using this type of vibration, a detection method for delamination in layered materials,[6] a probing technique for platelike samples,[7,8] and a noncontact inspection method for soldered connections[9] have been proposed recently. Moreover, since the resonant frequency of the flexural vibration of mechanical beams is sensitive to the external force, the mechanical vibration excited by laser irradiation can be used for tension sensing.[10] More recently, the optical activation of a silicon etched microresonator was reported for use as a microsensor of pressure.[11,12] The dimensions of the resonator were less than 1 mm.

Here, we report a photothermal technique for sensing cell pressure. The pressure is monitored from the frequency change of the vibration of the cell itself. The dimensions of the cell are of the order of one centimeter. The vibration of the cell is generated by the thermoelastic bending effect caused by the chopped laser irradiation and it is simultaneously sensed by the deflection of the probe laser beam. Therefore, the sensing technique is noncontact, and thus it will be useful for remote measurements of the pressure in hostile environments.

Light irradiation on the solid surface produces a temperature rise in the solid and the surrounding gas. The periodic absorption of laser light at the surface produces a periodic thermal diffusion (thermal wave) into the solid.[13] In the case of a platelike structure fixed partially at its circumference, the thermal wave causes the vibrational bending of the plate itself. The source that generates the flexural vibration of the plate is the bending moment due to the thermal wave. For a one-dimensional temperature distribution under quasistationary condition, the bending moment (temperature moment) of the uniform plate is given by[14]

$$M_T=\frac{3}{2h^3}\int_{-h}^{h} T(z)z\,dz, \tag{1}$$

where $T(z)$ is the temperature distribution across the thickness (z axis) and $2h$ denotes the sample thickness.

When the chopping frequency of the heating laser is coincident with the flexural resonant frequency inherent in the plate, the vibration amplitude becomes considerably larger within the narrow frequency region. From the peak value of the vibration amplitude, the resonant frequency can be determined precisely. In addition, the value of the resonant frequency is highly sensitive to the tension acting on the plate. Conversely, the tensile condition of the plate can be deduced from the value of the resonant frequency. In our experiment (Fig. 1), the pressure difference between the inside and the outside of the cell is converted to the tension acting on the platelike structure, and the tensile condition is sensed from the resonant frequency. Thus, the pressure is sensed from the shift in the resonant frequency of the flexural vibration of the platelike structure excited by the laser irradiation.

Figure 1 shows the schematic diagram of the experimental setup. Two types of pressure cells as shown in Fig. 1 were made to demonstrate the sensing technique. In our first experiment, the pressure sensing was carried out by using a simple sphere glass cell (3 cm in diameter) shown in Fig. 1 [type (a)]. The upper part of the cell is made to be the flat diaphragm coated with 30-nm-thick aluminum. The thickness and the diameter of the diaphragm are 0.2

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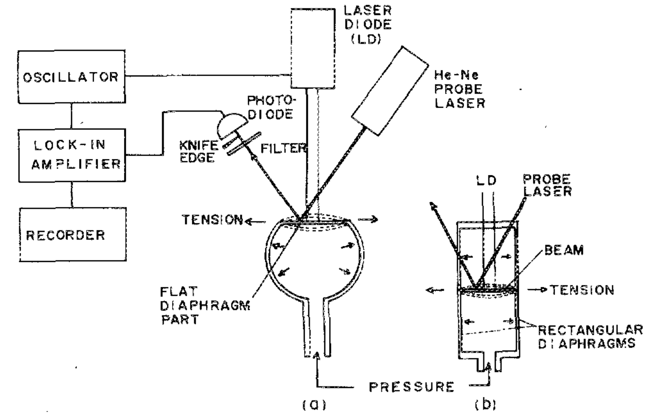

FIG. 1. Schematic diagrams of the sensing technique and the pressure cells.

mm and 2 cm, respectively. The internal pressure produces the membrane stress on the shell of the cell. Therefore, when the pressure inside is higher than the outside, the tension acts on the flat diaphragm part of the cell. The flexural vibrational resonance of the flat diaphragm is generated by the irradiation of the chopped laser light.

For the second experiment, another sample denoted by type (b) in Fig. 1 has been used, which has a beam structure (0.09 mm thick, 1 mm wide, 1 cm long) between the two rectangular diaphragms (0.1 mm thick, 1 cm × 2 cm wide). The pressure applied to the diaphragms is converted more efficiently than the sample of type (a) into the axial force acting on the beam. The front surface of the beam is coated with 30-nm-thick aluminum to absorb the laser light uniformly. The flexural vibrational resonance of the beam is generated by the chopped laser irradiation. The value of the resonant frequency is measured with increasing pressure. The sample is made of borosilicate glass, and its density and modulus of elasticity are 2.53 g/cm^3 and 7.09×10^{10} N/m^2, respectively, which are used for calculating the theoretical values.

A laser diode (Sharp, LT015MD0) is used as a light source to generate the flexural vibrations of the plate and the beam. The power of the laser diode used in the experiments is ~20 mW and the wavelength of the light is 830 nm.

In order to detect the photoacoustic effects from a distance, two methods can be used. The first uses the deflection of a laser beam reflected from the surface,[15,16] whereas the second technique uses the beam bending due to changes in refractive index.[17,18] We employ here the beam deflection method as shown in Fig. 1 since the method can also be used for vacuum.

The light intensity of the He-Ne probe laser (Uniphase, 1107P) is detected by a silicon photodiode (Hamamatsu Photonics, S2386-8K, internal capacitance of 3.2 nF, rise time of 7 μs) after passing through the knife edge. The photocurrent is converted into a voltage through a negative feedback amplifier using an opamp (LF356). The knife edge is placed at the position of the beam axis, where the change of the light intensity for a small beam deflection becomes maximum.

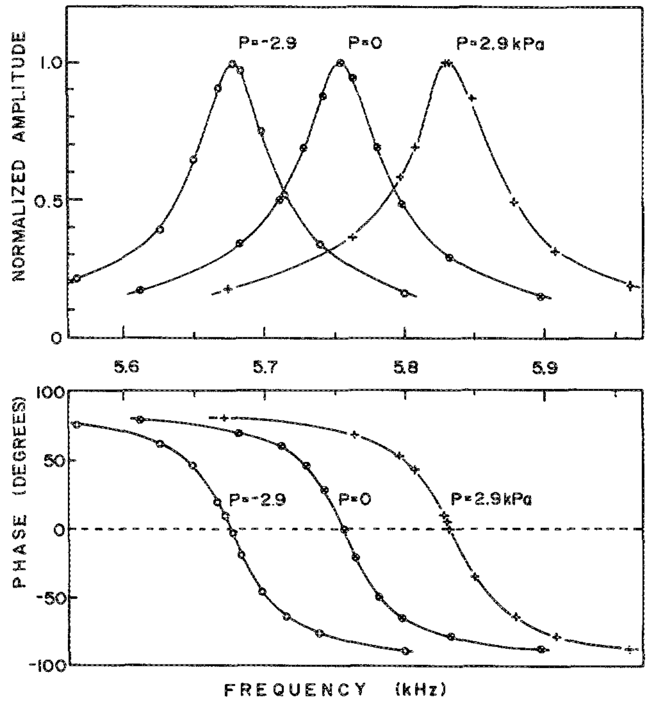

FIG. 2. Amplitude and phase signals as a function of the chopping frequency around the first resonance for the respective pressures (P).

The value of the resonant frequency is determined from the amplitude peak of the resonance curves or from the phase signal of zero degree. The electric signals are measured by a phase tracked lock-in amplifier (NF-LI575).

The pressure is applied to the cell by sliding mechanically a piston in the cylinder (4 cm in diameter) which is connected with the cell. The pressure is measured by the U-type manometers filled with water or mercury.

Using the sample of type (a), the first resonant frequency of the flat diaphragm was 5.75 kHz without pressure difference (P) between the inside and the outside of the cell. Figure 2 shows the amplitude and phase signals as a function of the chopping frequency around the resonant frequencies for the pressure differences $P = 2.9$, 0, and -2.9 kPa, respectively. The Q value of the resonance curve for $P = 0$ is 70 ± 5 and those for $P = \pm2.9$ kPa are equal to that for $P = 0$ within the uncertainty. The increase of the pressure causes the resonance curves to shift to the high frequency region. The phase signals change from 90° to $-90°$. In particular, the phase signal changes sensitively around the zero degree region, where the amplitude signal takes a peak value. Therefore, the resonant frequency can also be monitored by using the phase signal instead of the amplitude signal.

Since the resonance mode was the lowest order mode possible, the maximum vibration of the diaphragm was at its center, with the vibration amplitude decreasing gradually from the center to the edge of the diaphragm. The maximum efficiency to sense the vibration with the He-Ne probe beam was obtained under the condition that the spot of the probe beam was located between the center and the

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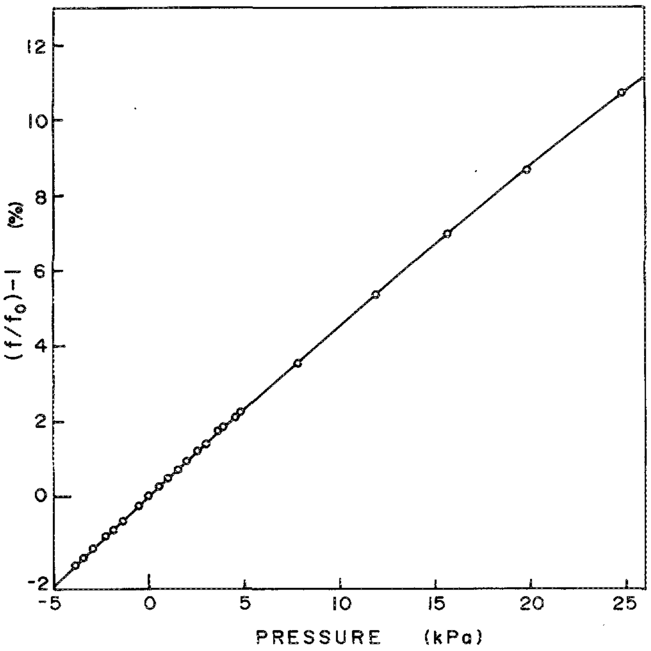

FIG. 3. Change in resonant frequency as a function of pressure for the cell of type (a).

edge of the diaphragm part because the displacement of the spot on the photodiode was proportional to the slope of the diaphragm deformation. When the radial spot position of the heating laser coincided with a maximum of the resonance, the vibration amplitude became larger. Therefore, the maximum efficiency to excite the resonant vibration for the first-order mode was obtained when the center of the diaphragm was irradiated by the chopped laser.

The beam deflection was calibrated to be 16 mV/μrad by translating the knife edge perpendicularly to the laser beam axis with a micrometer screw. From the measured value of the beam deflection, the slope of the vibrational deformation of the diaphragm was obtained. Assuming the shape of the vibration of the diaphragm, the amplitude of the vibration was roughly estimated. The maximum displacement of the diaphragm was approximately 0.5 nm.

Using the calibrated value of the beam deflection, static deformation of the diaphragm due to changes in pressure can also be obtained. Thus, from the static deformation, the pressure inside can be evaluated for the cell of type (a). The value of the beam deflection, however, is likely to be affected by the drift of dc signal which is often caused by a slight change of relative position between cell and detection apparatus. In the proposed method, since the pressure is obtained from the frequency, the measured value is not affected by the drift in signal intensity.

Figure 3 shows the frequency change at resonance $(f/f_0) - 1$ as a function of the applied pressure using the sample of type (a), where f_0 denotes the resonant frequency without pressure difference. The resonant frequency f was measured for the first-order mode in the range of -5 to 25 kPa. The negative sign of the pressure corresponds to the conditions that the pressure inside is lower than the outside atmospheric pressure. The frequency change $(f/f_0) - 1$ increases almost linearly in the region of -5 to 5 kPa and the rate of the increase is approximately 0.5%/kPa (30 Hz/kPa). From experiments using the sample of type (a), it has been shown that window and shell of the gas container can also be used to sense the inside pressure without contact.

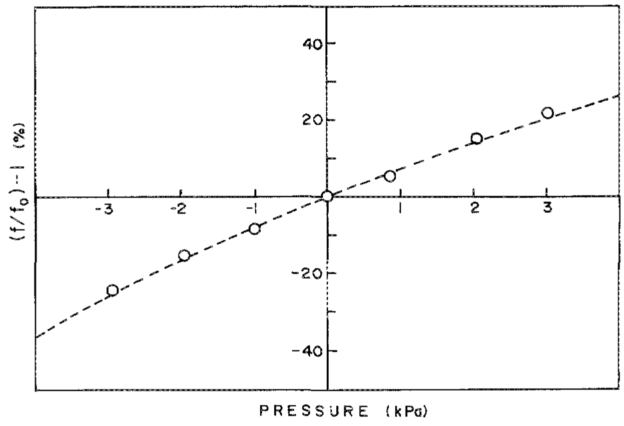

FIG. 4. Change in resonant frequency as a function of the pressure for the cell of type (b). The dashed curve shows the calculated result.

Using the sample of type (b), the resonance curves of the beam were obtained for the first order mode. The first resonant frequency of the beam was 7.59 kHz without pressure difference between the inside and the outside of the cell. The vibration amplitude at the resonance was of the order of nanometer, similar to that obtained during the experiment using the sample of type (a). The change of the resonant frequency $(f/f_0) - 1$ is shown in Fig. 4 as a function of the applied pressure in the range of -3 to 3 kPa. Increase of the pressure inside causes the resonance curve to shift to the higher-frequency region. The Q values of the resonance curves are approximately 100. The rate of the frequency change is 7%/kPa (500 Hz/kPa) in the measured region, which is higher than that obtained by using the sample of type (a). The dashed curve in Fig. 4 shows the result calculated numerically by using Eq. (3) in Ref. 10 after obtaining the axial force acting on the beam from the applied pressure. The calculated result explains the experimental result well in the measured region. From the theoretical calculations, the resonant frequency increased monotonously with a slight decrease of the increase rate. The increase rate becomes larger with decreasing the thickness of the beam although the absolute frequency of resonance decreases. Since the bending moment calculated by the Eq. (1) is kept almost constant below the characteristic frequency f_c, and decreases as f^{-1} with the increase of the frequency in the region higher than f_c,[7] the frequency lower than f_c is effective to generate the high bending moment. The value of f_c approaches to the resonant frequency of the beam when the thickness of the beam decreases. Therefore, a thinner beam is preferable for measuring the pressure with a higher sensitivity, and for generating the vibration effectively.

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In summary, we have proposed a photothermal technique for sensing the cell pressure. The pressure was monitored from the frequency change of the vibration of the cell itself. The vibration was generated by the photothermal bending effect. Since the output signal is obtained from the frequency change, this technique is suited for the digital signal processing and is not affected by the signal intensity fluctuation. Furthermore the technique is optical and noncontact. Therefore, the technique should be valuable for remote measurements of the pressure in high temperature and hostile environments.

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