High resolution photothermal laser probe

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At frequencies near 1 GHz, the acoustic wavelength in argon gas becomes half that of visible light, making possible collinear Bragg scattering of laser light by the sound. This acousto-optic interaction has been used to detect photothermally generated acoustic power at the surface of solids. This new technique provides a noncontacting probe for the detection of 100–1000-Å thermal waves with optical resolution. The essential features of the theory behind this new photothermal probe are presented along with a description of the experimental implementation. High resolution images of implanted silicon are included which clearly demonstrate the sensitivity of the probe to variations in the thermal characteristics of solids.

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There have been many photothermal detection schemes reported in the literature. Piezoelectric transducers,[1] optical beam deflection,[2] interferometry,[3] acoustic lenses,[4] and other techniques have been used to measure the photothermal and photoacoustic responses to periodic heating. In this letter, a new acousto-optic probe is presented which exploits the photoelastic coupling between optical and acoustical fields in a high pressure gas under collinear Bragg scattering conditions. The probe has several features which look attractive. It is a noncontacting, optical technique which does not require acoustic transducers. Its operating frequency is near 1 GHz, constrained there by the collinear Bragg resonance. At this frequency, the thermal wavelength in most solids is less than 1000 Å. The resolution therefore is determined only by the the probe beam spot size. The probe can be used to measure both the amplitude and the phase of the high-frequency thermal waves generated by the absorbed optical power.

When an intensity modulated laser is focused onto the surface of an absorbing solid, the region of absorption is periodically heated. The magnitude and phase of the temperature fluctuation are determined by the thermal characteristics of the material as well as the frequency of the modulation and the absorbed power distribution. When the surface of the solid is in contact with a gas, the temperature fluctuation at the surface of the solid generates an acoustic wave in the gas, as shown in Fig. 1. The acoustic power in the gas is generated in two ways. First, the surface of the solid is periodically displaced by the thermal expansion of the solid. This surface displacement acoustically drives the gas, generating a sound wave which propagates away from the solid. Second, the temperature of the gas is also driven by the temperature of the solid. This fluctuation of the gas temperature also generates a sound wave in the gas due to the thermal expansion of the gas itself. One dimensional theory[5] predicts that when the modulated pump beam is highly absorbed near the surface of the solid, the contribution of the surface displacement is small compared to the contribution due to the expansion of the gas. Therefore, a measurement of the acoustic wave amplitude in the gas gives information about the surface temperature, rather than the acoustical characteristics of the solid.

The detection of the photothermally generated acoustic wave is accomplished by using the acousto-optic coupling between light and sound in the gas. As shown in Fig. 1, a second "probe" beam is focused to the same location as the modulated "pump" beam. As the generated sound propagates through the high density gas, the local density fluctuations cause a perturbation of the index of refraction. When the wavelength of the sound in the gas is one-half the wavelength of the probe, Bragg scattering takes place for the counterpropagating light and sound fields. Under these conditions, a portion of the probe beam is back reflected from the sound wave in the gas, see Fig. 2.

The Bragg scattered light contains the desired information about the magnitude and phase of the acoustic power in the gas. Because the Bragg interaction upshifts the frequency of the scattered light, it is possible to mix in an optical detector the light scattered from the sound in the gas with the unshifted light which is reflected from the surface of the solid. The optical heterodyne power is proportional to the product of the two reflected electric field strengths.

The efficiency of the scattering can be called a "reflectivity." The power reflectivity Γ can be shown to be[6]

$$\Gamma = \left(\frac{\pi(\epsilon - 1)S_0}{2\lambda_0}\right)^2 \left(\frac{1}{\alpha^2 + \Delta k^2}\right), \tag{1}$$

where ϵ is the relative dielectric constant of the gas, $S_0 = (\rho - \rho_0)/\rho_0$ is the peak acoustic condensation in the gas, α is the acoustic attenuation constant of the gas, λ_0 is the wavelength of the incident light in the gas, $\Delta k = (\omega - \omega_0)/V_a$ is the k-vector mismatch, ω_0 is the acoustic frequency at which Δk is zero, and V_a is the velocity of sound in the gas. There is a Fourier transform relationship between the spatial

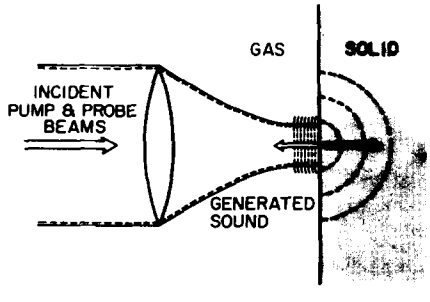

FIG. 1. Generation of sound at the surface of a solid.

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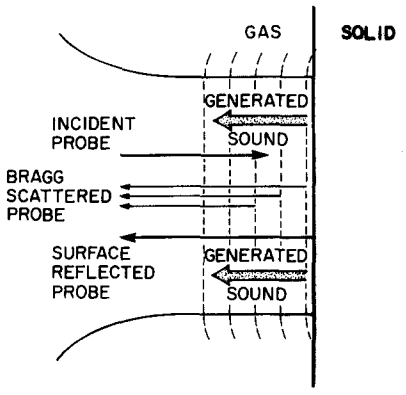

FIG. 2. Illustration of the two reflected probe beam components. One component is reflected from the solid surface, the other from the sound wave in the gas.

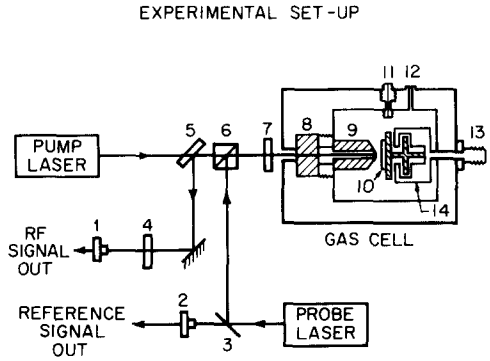

FIG. 4. Experimental arrangement. (1), (2) fast silicon photodiodes; (3) beamsplitter; (4) spike filter; (5) dicroic miror; (6) polarizing beamsplitter; (7) quarter wave plate; (8) optical window; (9) focusing objective; (10) sample; (11) electrical feed through; (12) gas input; (13) focusing micrometer; (14) electromechanical scanner.

dependence of the acoustic wave and the frequency dependence of the Bragg interaction. Because the acoustic wave is exponentially damped, the frequency dependence is Lorentzian. The theoretically expected frequency dependence, along with some experimental data, is shown in Fig. 3.

Under reasonable experimental conditions, including shot, amplifier, and Johnson noise in the heterodyne detection system, the signal to noise ratio is given by[7]

$$S/N = (1.2\times 10^{7}/B)\theta_0^2, \tag{2}$$

where B is the detection bandwidth, and θ_0 is the peak ac temperature fluctuation of the surface of the solid. The minimum detectable sinusoidal temperature variation over a 1-μm spot size is less than 3×10^{-4} °C in a 1-Hz bandwidth. The acoustic power generated by this temperature fluctuation over this area is less than 10^{-16} W. The corresponding surface displacement is less than 10^{-4} Å.

A schematic diagram of the photothermal surface probe is shown in Fig. 4. A pump laser, modulated at 1.03 GHz, is focused by an optical microscope objective (9) inside the gas cell to a diffraction limited spot on the sample surface (10). The absorbed optical power photothermally generates sound which propagates away from the solid. The probe laser is directed through a quarter wave plate (7) into the cell by a partial mirror (3), and a polarizing beam splitter (6),

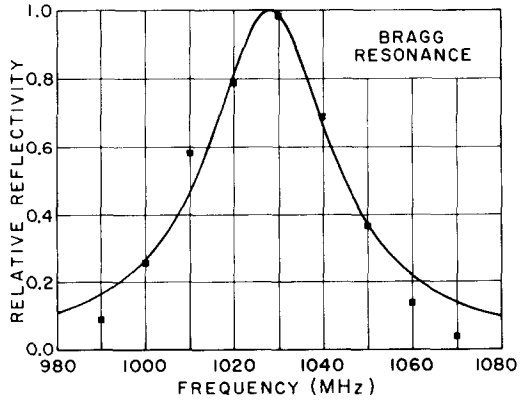

FIG. 3. Theoretically predicted collinear Bragg scattering efficiency as a function of the frequency of the generated sound in the gas, with some experimental data.

where it is focused to the same location as the pump beam. There, it is reflected at the sample surface as well as by the sound wave propagating in the gas. These two reflected components are then recollimated by the optical objective, and pass through the quarter wave plate a second time. The two passes through the quarter wave plate cause a 90° rotation of the polarization. The reflected probe therefore propagates through the polarizing beam splitter. It is then reflected by a dicroic mirror (5) and finally passes through a narrow band interference filter (4) to a fast photodiode (1). The interference filter isolates the photodiode from the pump laser power. The cell is pressurized to 50–100 atmospheres by simply connecting it through a high pressure regulator to a standard argon gas cylinder. The sample is positioned for focus by a micrometer (13) from outside the gas cell. An electromechanical scanner[8] (14) inside the gas cell makes possible two-dimensional scanning of the sample with respect to the pump and probe beams. A reference signal at the frequency of the axial mode spacing of the probe laser (ω_r) is detected in a second photodetector (2).

To avoid the problems of rf interference that occurs when detecting at the modulation frequency of the pump laser (ω_a), the two longitudinal modes of the He-Ne probe laser are used to optically mix the heterodyne signal to a frequency other than that of the acoustic wave. This is accomplished by optically mixing the Bragg shifted signal from one axial mode ($\omega_0 + \omega_a$) with the unshifted second axial mode ($\omega_0 + \omega_r$). The result is a heterodyne signal out of the optical detector at the difference between the acoustic frequency and the axial mode spacing ($\omega_a - \omega_r$).

To demonstrate the sensitivity of the probe to variations in the thermal properties of materials, a silicon wafer was implanted with $\approx$150 keV boron through a resist pattern.[9] After implantation, the patterned resist was plasma etched, leaving only a thin oxide. This oxide was then removed, exposing a clean silicon surface. Thus, the silicon was left uniformly implanted, except in the regions where the resist had isolated the silicon from the boron implant. In these regions, the silicon was intrinsic. The implant density was calculated to be 10^{18}/cm^3 at the surface, increasing to 10^{21}/cm^3 at a depth of 5000 Å.

The sample was imaged with the photothermal probe,

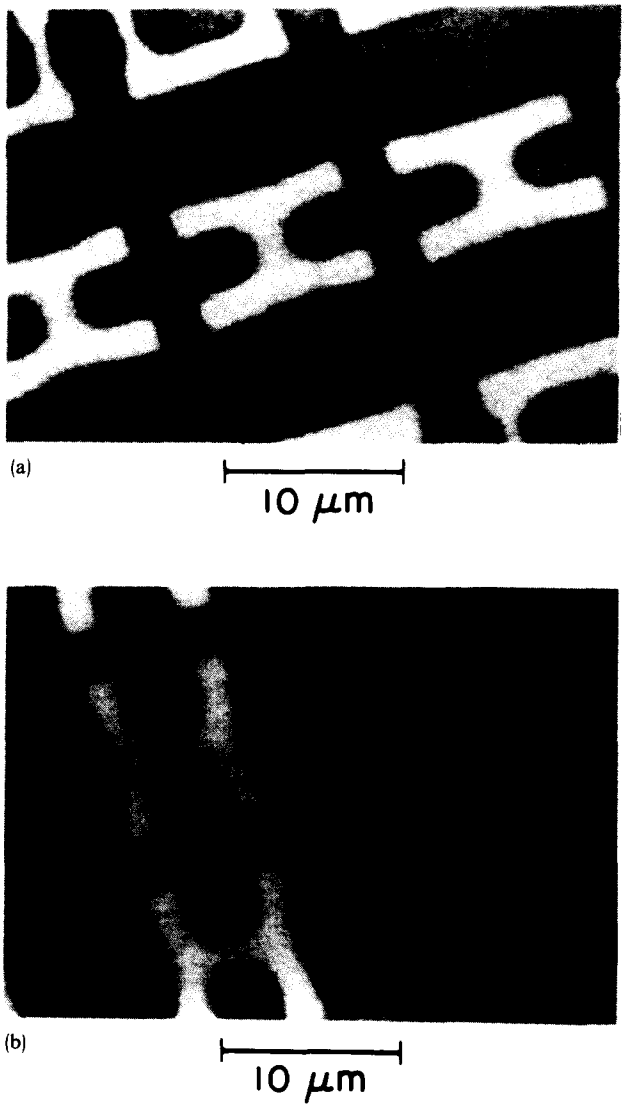

FIG. 5. (a) Photothermal image of boron-implanted silicon. The darker area is the implanted region; the lighter region is not implanted. (b) Photothermal image of implanted silicon with 300 Å of titanium deposited on the silicon in the left half of the image.

and there was found a variation in the thermal response of the implanted region (darker) relative to the unimplanted region (lighter). The photothermal image is shown in Fig. 5 (a) below. The spacing of the H-like characters from center to center is approximately 15 μm. A 3% variation in the optical reflection was measured from region to region due to the effects of the implantation. This optical variation is much too small to account for the photothermal contrast seen in Fig. 5. However, to eliminate any optical variation, 300 Å of titanium were deposited on the silicon surface and the sample was imaged again. Figure 5(b) again shows the thermal contrast due to the boron implant. The titanium covered silicon region (left) actually generates a larger photothermal signal than the silicon alone. This is mainly due to the larger optical attenuation constant of the titanium. The signal from the uncoated silicon region (right) is not apparent in the image because the bias level and gain of the signal were adjusted to allow for maximum contrast in the titanium/silicon region. The source of contrast in the titanium covered silicon region is the variation in the thermal wave reflectance at the interface between the titanium and silicon. The images in Fig. 5 demonstrate the sensitivity of the probe to changes in the thermal properties of the silicon created by the boron implantation.

In amorphous materials, which have thermal conductivities that are much smaller than that found in silicon, the thermal wavelength for a 1-GHz modulation frequency is on the order of 100 Å. When imaging these materials with a pump beam which is highly absorbed at the surface, only the region located within one thermal wavelength ($\approx$100 Å) of the surface will significantly contribute to the signal. This provides a discrimination against the bulk properties of materials, and may be useful for surface studies. Inhomogeneities with dimensions on the order of tens of angstroms will be significant scatterers of the high-frequency thermal waves. This gives the probe a materials characterization capability. The phase sensitivity to the thermal waves should also make possible the measurement of the thickness of films in the range of 20–500 Å with high resolution. Further investigation is planned in these areas.

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