Photoinduced and thermal stress in silicon microcantilevers

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The photogeneration of free charge carriers in a semiconductor gives rise to mechanical strain. We measured the deflection of silicon microcantilevers resulting from photoinduced stress. The excess charge carriers responsible for the photoinduced stress, were produced via photon irradiation from a diode laser with wavelength $\lambda = 780$ nm. For Si microcantilevers, the photoinduced stress is of opposite direction and about four times larger than the stress resulting from only thermal excitation. In this letter we report on our study of the photoinduced stress in silicon microcantilevers and discuss their temporal and photometric response. © *1998 American Institute of Physics.* [S0003-6951(98)03742-5]

It is well known that absorption of photons by a solid results in temperature changes and thermal expansion. When the photon intensity is modulated, it can give rise to acoustic waves at frequencies corresponding to the modulation amplitude.[1,2] More recently, acoustic signals resulting from thermoelastic coupling have been used to obtain photoacoustic images of thin metallic films,[2] and the authors discussed the feasibility of a photoacoustic microscope. When photogenerated charge carriers are introduced in semiconductors, the photoacoustic generation is due primarily to the presence of excess carriers[3] and not due to thermoelastic effects.[4]

The photogeneration of free charge carriers (electrons and holes) in a semiconductor, results in the development of a local mechanical strain.[3,5] The heating and subsequent pressure buildup has been detected as acoustic waves with conventional photoacoustic techniques.[2,4,6]

For a semiconductor with a band gap energy ϵ_g, the change in total surface stress due to photogenerated excess charge carriers, Δn, and changes in temperature, ΔT, will be the sum of the photoinduced stress, Δs_{pi}, and thermal stress, Δs_{th}, given by,[3,5]

$$\Delta s = \Delta s_{\mathrm{pi}} + \Delta s_{\mathrm{th}} = \left(\frac{1}{3} \frac{d\epsilon_g}{dP} \Delta n \right) E + \alpha \Delta T E, \tag{1}$$

where, $d\epsilon_g/dP$ is the pressure dependence of the band gap energy, α is the thermal expansion coefficient, and E is the Young's modulus. A hole (in the valence band) decreases the energy of covalent bonds while an electron adds to the bonding (or antibonding) energy. Since $d\epsilon_g/dP$ can be either positive or negative there can be a competing effect between the photoinduced and thermal stress. For example, when $d\epsilon_g/dP$ is negative, the photoinduced stress is of opposite sign than that of the thermal stress which will tend to make the semiconductor crystal contract. On the other hand when $d\epsilon_g/dP$ is positive, the photoinduced stress will tend to make the semiconductor crystal expand.

Assuming a semiconductor cantilever of length l, width w, and thickness t, the maximum displacement $z_{\max}$ due to photoinduced and thermal stresses is given by[7]

$$z_{\max} \approx \frac{(1-\upsilon) l^2}{t} \frac{d\epsilon_g}{dP} \Delta n + \frac{3(1-\upsilon) l^2}{t} \alpha \Delta T, \tag{2}$$

where υ is the Poisson's ratio. An absorbed power, Φ_e^{abs}, of photons with wavelength $\lambda < \lambda_c (= hc/\epsilon_g)$ will produce a number density of excess charge carriers, Δn, given by

$$\Delta n = \eta \frac{\lambda}{hc} \frac{\tau_L}{lwt} \Phi_e^{\mathrm{abs}}, \tag{3}$$

where η is the quantum efficiency, h is Planck's constant, c is the speed of light, and τ_L is the lifetime of the carriers in the semiconductor. The maximum displacement $z_{\max}$ due to photogenerated carriers can then be written as

$$z_{\max} \approx \frac{(1-\upsilon) l^2}{t} \left(\eta \frac{\lambda}{hc} \frac{d\epsilon_g}{dP} \frac{1}{lwt} + \frac{3\alpha}{mc_p} \right) \tau_L \Phi_e. \tag{4}$$

Since the charge carriers can be generated in a very short time the photoinduced stress can manifest itself much faster than thermal stress. Of course, the overall change in $z_{\max}$ will depend on the physical and mechanical properties of the semiconductor. From Eq. (4) we can estimate the relative contribution of the photoinduced stress and thermal stress to the bending of Si ($\epsilon_g = 1.12$ eV)[8] microcantilevers such as the one used in the present studies having length $l = 100\ \mu$m, thickness $t = 0.5\ \mu$m, and width $w = 20\ \mu$m. The amount of photon energy needed to raise the temperature of a mass of Si equal to 2.3×10^{-9} g by 10^{-5} K is $\Phi_e^{\mathrm{abs}} \tau_d = (Nh\nu = c_p m \Delta T =) 1.62 \times 10^{-14}$ J where c_p for Si is 0.702 $\mathrm{Jg^{-1}\,K^{-1}}$. If the photon wavelength is $\lambda = 1.1\ \mu$m then 8.94×10^4 photons will be required. Therefore, the bending

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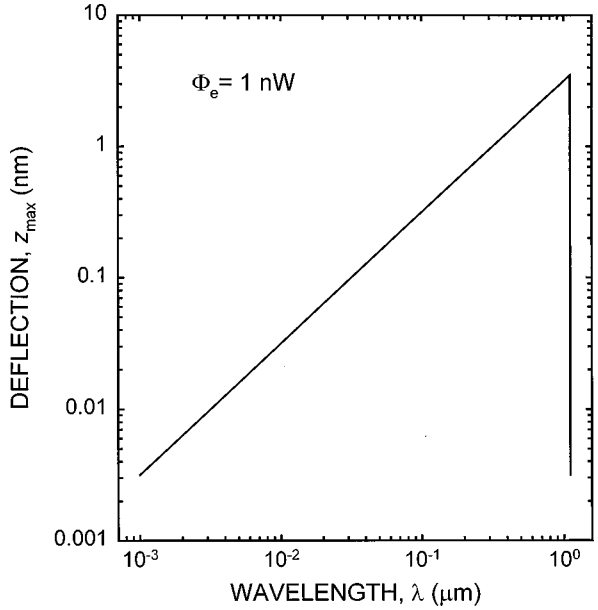

FIG. 1. Calculated deflection of a Si microcantilever due to photoinduced stress as a function of photon wavelength for an absorbed power of 1 nW.

due to thermal stress is $z_{max}^{th}=1.39\times10^{-10}$ cm. In order to estimate the bending due to the photoinduced stress we assume the quantum efficiency $\eta=1$ and that the charge carriers are uniformly distributed. Then, the carrier number density is $\Delta n=8.946\times10^{13}$ cm^{-3}. Using $d\epsilon_g/dP=-2.9\times10^{-24}$ cm^3 for Si (Ref. 9) we get $z_{max}^{pi}=5.19\times10^{-10}$ cm which is about 3.7 times larger than the bending due to thermal stress for the same power.

In Fig. 1 we calculated the photoinduced deflection of a Si microcantilever with length $l=100\ \mu$m, width $w=20\ \mu$m, and thickness $t=0.5\ \mu$m as a function of photon wavelength for an absorbed power of 1 nW. The bending due to photogenerated charges increases linearly with increasing wavelength up to the cutoff $\lambda_c=1.1\ \mu$m.

The bending of microcantilevers can be measured with high sensitivity using detection techniques commonly used in atomic force microscopy (AFM).[10] For example, Hansma[11] and Binnig[12] have demonstrated that changes in cantilever bending of 5×10^{-12} m can be measured. More recently even smaller microcantilever deflections were measured with a resolution of $\sim0.4\times10^{-12}$ m.[13] We have performed studies on the effect of photoinduced stress and thermal stress on silicon microcantilevers with dimensions of $l=100\ \mu$m, $w=20\ \mu$m, and $t=0.5\ \mu$m. The microcantilevers used had a 30 nm Al layer deposited on one side. The bending of such microcantilevers can readily be determined by a number of means, including optical, capacitive, piezoresistive, and electron tunneling. In the present studies we used an optical readout technique for observing the microcantilever bending. The experimental setup used is shown schematically in Fig. 2. The location of a probe laser beam (reflected off the tip of the microcantilever) is detected using a position sensitive photodiode in which the bending of the microcantilever depends linearly on the current output of the photodiode. A narrow bandpass optical filter is placed in front of the photodiode allowing the probe laser beam to be detected while preventing other wavelengths from reaching the photodiode.

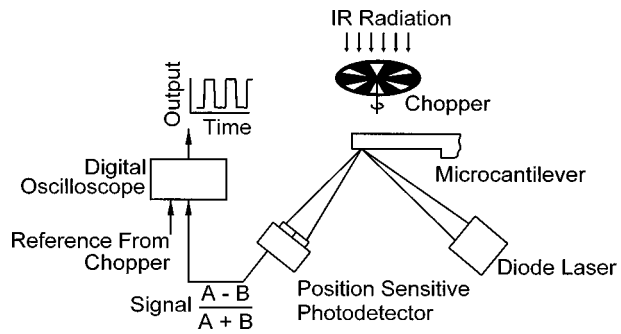

FIG. 2. Schematic diagram of the experimental setup used in the present studies.

The microcantilever was exposed to near infrared photons from a diode laser with wavelength $\lambda=780$ nm and using a mechanical chopper, the infrared radiation was modulated at a frequency of 1000 Hz. In Fig. 3 we show the temporal response of the Si microcantilever [curve (a)] to the modulator signal (b). The absorbed optical power was 3.9 nW and was calculated using $\Phi_e^{abs}=\alpha_{abs}\Phi_e^{inc}A_{cant}/A_{spot}$, where $\alpha_{abs}(\approx0.95)$ is the absorptivity of Si at 780 nm, A_{cant} is the cantilever area, and $A_{spot}(=1.53\ \text{mm}^2)$ is the area of the focused laser beam at the plane of the microcantilever. The observed bending is attributed to the fact that the irradiated side (Si part) of the microcantilever *contracts* due to photoinduced stress while the Al layer of the microcantilever will tend to *expand*. Because of the bimaterial nature of the microcantilever, after a steady state condition is reached the microstructure will remain bent while exposed to photons. As it can be seen from curve (a) in Fig. 3, the Si microcantilever responds rapidly to incoming photons that generate charge carriers which, in turn, cause a measurable mechanical bending. In these experiments, photons continued to im-

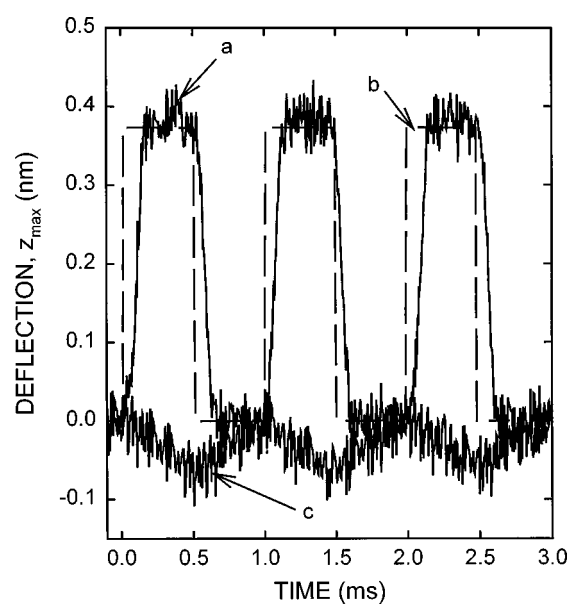

FIG. 3. Deflection of a Si microcantilever as a function of time [curve (a)] due to photogenerated charge carriers when exposed to photons with $\lambda=780$ nm and an absorbed power of 3.9 nW. The dashed curve (b) represents the signal from the modulator and shows the amount of time the detector was exposed to photons. Curve (c) corresponds to deflection of the microcantilever due to absorption of 2 nW power of photons with $\lambda=1300$ nm and is purely due to thermal effects.

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pinge on the detector surface for $\sim 5\times 10^{-4}$ s, while the bending reached its maximum value in $\sim 1\times 10^{-4}$ s. The time that the microcantilever reached its maximum bending corresponds nicely to the lifetime of photogenerated ''free'' charge carriers in Si.

In contrast to the photoinduced effects, thermal effects have been found to play a role in a slower time scale and have a time constant $>10^{-3}$ s.[14–16] In order to determine the effect of the thermal stress under our experimental conditions, we illuminated the Si microcantilever using photons with $\lambda = 1300$ nm. Since Si is transparent to these photons, we had deposited a thin aluminum coating of 30 nm along one side of the Si microcantilever. The absorbed power was estimated using $\Phi_e^{abs} = \alpha_{abs}\Phi_e^{inc} A_{Al}/A_{spot}$ where $\alpha_{abs} = 0.01$ is the absorptivity of Al and $A_{Al}(=2\times 10^{-5}\ \mathrm{cm}^2)$ is the area of the Al layer. We modulated the infrared radiation for the 1300 nm diode laser at a frequency of 1000 Hz. In Fig. 3 curve (c) we plotted the measured microcantilever response as a function of time due to absorption of 1300 nm photons for an absorbed power of 2 nW. Of course, the observed microcantilever bending depends on the difference between the coefficient of thermal expansion of Si and Al (bimaterial effect). Since Si is transparent to photons with $\lambda = 1300$ nm the Al layer heats up and the thermal stress causes the Al to expand forcing the microcantilever to bend in a direction opposite to that shown in curve (a) which is due to the photoinduced stress. From curve (c) in Fig. 3 it can be seen that for 1300 nm photons and 1000 Hz modulation frequency, the observed thermally induced bending of the microcantilever is smaller (over 2 times after correcting for the absorbed power) compared to the photoinduced bending [curve (a)]. Furthermore, the microcantilever response to the photoinduced stress [curve (a) in Fig. 3] is much faster than the response due to thermal effects [curve (c) in Fig. 3].

Since $d\epsilon_g/dP$ is negative for Si,[9] it is straightforward to separate the photoinduced from the thermal effects in Si by simply observing the direction of bending indicated by the phase shift of the signal waveform with respect to the reference signal. When photons with energies above the band gap are used to irradiate the Si microcantilever, Si contracts and deflects in one direction [curve (a) in Fig. 3]. However, when photons with energies below the band gap are used, both Al and Si will tend to expand and the microcantilever will deflect in the opposite direction [curve (c) in Fig. 3].

We also measured the microcantilever bending due to photoinduced stress as a function of absorbed power. In Fig. 4 we plotted the measured bending of a Si microcantilever as a function of absorbed power using a diode laser with $\lambda = 780$ nm. The microcantilever deflection was primarily due to photoinduced stress and was found to increase linearly with increasing power with a deflection sensitivity of 0.099 m/W.

Our present studies demonstrate that irradiating Si microcantilevers with photons having energies above the band gap results in a photoinduced mechanical stress. When the photon energy is below the Si band gap thermal effects dominate. The photoinduced stress in Si was found to depend linearly on the input optical power and exhibit a fast response. Such a mechanism can be used to detect near infrared photons using a Si microcantilever.

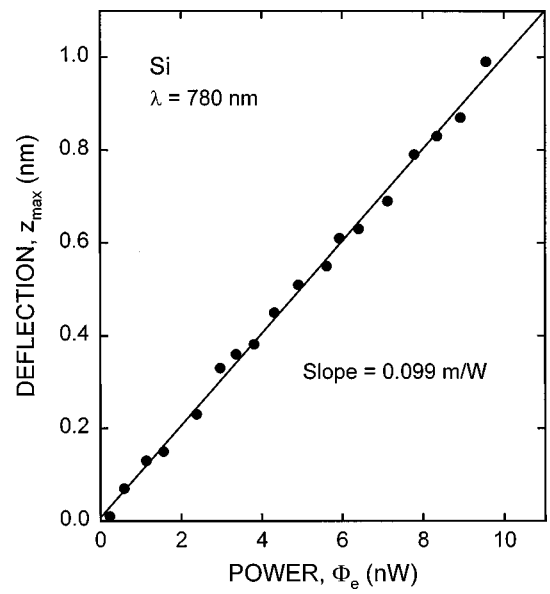

FIG. 4. Deflection of a Si microcantilever as a function of absorbed power due to photogenerated charge carrier when exposed to photons with $\lambda = 780$ nm.

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