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Mechanical and thermal effects of laser irradiation on force microscope cantilevers

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In an optical lever set-up one or two modulated laser beams of 0.1 to 6 mW modulation amplitude at a wavelength of 670 nm were focused at uncoated and gold-coated microfabricated cantilevers. The motion of the levers was analyzed by an optical lever set-up. The mechanical resonance (30 to 60 kHz) of the cantilevers was excited by the modulated light both in air and under vacuum conditions (10^{-6} mbar). The measured resonance frequencies and the width of the resonances were identical to the values found by exciting the cantilevers by piezo ceramics. At low frequencies under vacuum conditions, we found an increase of the oscillation amplitude with decreasing frequency. The time constant of this increase is of the order of 5 ms. At the resonance frequency of uncoated cantilevers light pressure effects dominate thermal effects; the resonance is thus excited by light pressure. Gold-coated cantilevers, however, are driven by the bimetal effect, even above 10 kHz. A possible application of the light pressure effects is the use of a modulated light beam in the attractive mode operation of a scanning force microscope to excite the cantilever oscillation.

1. Introduction

Scanning force microscopy (SEM) [1–3] has proved to be a valuable tool for investigation of a vast array of different systems, such as biological samples [4], magnetic structures [5] and local charges [6]. Many scanning force microscopes today use some kind of optical detection for the deflection of force sensing cantilevers [2,3]. Optical detection is simple and efficient for both static and dynamic measurements of forces. The investigation of samples by weak forces is often limited by the noise in the detection system. The interaction of light with force sensing cantilevers is usually neglected, although a report on the photothermal excitation of a cantilever resonance has been published [7]. A better understanding of the physics of the force detection will help to improve the accuracy and usefulness of scanning force microscopes.

2. Theoretical considerations

The interaction of light with the cantilever is through mechanical and thermal processes. The input power I_{in} is partially reflected ($I_{\text{ref}} = rI_{\text{in}}$), where r is the reflectance coefficient and partially absorbed according to

$$I(z) = (1-r) I_{\text{in}} e^{-\gamma z}, \qquad (1)$$

where γ is the absorption coefficient. Since the thickness of the cantilevers is of the order of the wavelength of the light part of the light (I_{trans}) is transmitted; this intensity also includes the light which was diffracted by the cantilever. The mechanical momentum transferred by reflected photons to the cantilever is given by

$$p = 2\hbar k \cos \alpha, \qquad (2)$$

where α is the angle of incidence of the light. The momentum transfer of absorbed photons is half this value. Transmitted photons do not transfer momentum to the cantilever. Using the reflectance coefficient r and the transmittance coefficient t and neglecting multiple reflectance, the light pressure force on the cantilever is given by

$$F = (2r + (1 - r - t))n \cos(\alpha)\hbar k$$
$$= (1 + r - t)\frac{I_{\text{in}}}{c}\cos\alpha, \qquad (3)$$

where n is the number of photons per second in the light beam and c is the velocity of light. $(1 - r - t)$ is the absorbed fraction of the intensity in the cantilever.

The absorbed power raises the local temperature $T(x, y, z, t)$ until the steady state situation is reached, where the power transferred to the cantilever is balanced by the radiated thermal power and the heat power conducted to the base acting as a heat sink. The temperature distribution in the cantilever is the solution of the heat diffusion equation [8]

$$\rho c_p \frac{\partial T(x, y, z, t)}{\partial t} = \lambda \nabla^2 T(x, y, z, t) + p(x, y, z, t), \qquad (4)$$

where ρ is the density of the material, c_p the heat capacity at constant pressure, λ the thermal conductivity and $p(x, y, z, t) = i(x, y, t)(1 - r)(\partial/\partial z)\exp(-\gamma z)$ the power density of the absorbed light. $i(x, y, z, t)$ is the time-dependent intensity distribution of the light perpendicular to the direction of propagation. The boundary condition on the cantilever is given by the Stefan–Boltzmann law

$$\boldsymbol{n} \cdot (-\lambda \nabla T) = \sigma(T^4 - T_0^4), \qquad (5)$$

where $\boldsymbol{n}$ is the surface normal unit vector and $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}. The boundary condition implies, that the temperature increase decreases with increasing input power.

Using Sommerfeld's Ansatz [9] for an oscillatory heat input we can solve eqs. (4) and (5) for a cantilever with a uniform temperature in y and z:

$$T(x, t) = C_0 + 2\sum_{n=1}^{\infty} |C_n| e^{-q_n x} \times \cos\left(2\pi n \frac{t}{\tau} + \gamma_n - q_n x\right), \qquad (6)$$

where the C_n are the Fourier coefficients determined at the end of the lever, γ_n the relative phases, τ the period of the signal, and $q_n = \sqrt{|n| \pi c_p \rho / \lambda\tau}$. The exponential term in eq. (6) shows, that at high frequencies ($> 1/\tau$) the cantilever is subject only to an averaged temperature for most of its length.

3. Experiment

Fig. 1 shows the experimental set-up. A microfabricated silicon nitride [11] cantilever is mounted in the centre of a small vacuum chamber evacuated by a turbo-molecular pump to 10^{-6} mbar. The laser diode modules LD1 and LD3 [10] (670 nm) are focused on the cantilever (40 μm spot diameter). Their output power is adjustable from 0.3 to 2 mW with a modulation depth from 2 to 70%. The modulation frequency can be controlled by an external oscillator and the relative phase of the modulation of the laser diodes is set to 0° (in phase) or 180° (out of phase). Laser diode LD2 (0.7 to 7 mW, 670 nm) supplies the light for the optical lever detection of the cantilever deflection [10]. Both uncoated cantilevers with a thickness of 0.3 μm and gold coated (30 nm) cantilevers with a thickness of 0.6 μm were used with spring constants ranging from 0.02 to 0.37 N/m. The cantilevers were mounted on a piezo slab to have independent means for the excitation of their resonance frequency.

4. Results and discussion

The cantilever can be excited either by one of the laser diodes LD1 and LD3 or by both either in phase or out of phase. Fig. 2 displays the

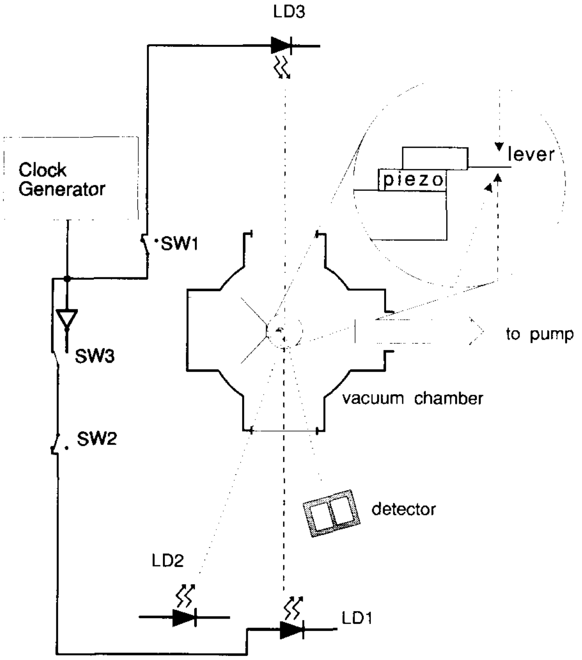

Fig. 1. Schematic view of the experimental set-up. The cantilever mounted on a piezo slab (see inset) is positioned in the centre of a vacuum chamber. The light of laser diodes LD1 and LD3 is focused on two sides of the cantilever. Laser diode LD2 is the source of the readout beam analyzed by the quadrant detector. Laser diodes LD1 and LD3 are driven by the same clock generator, either in phase or out of phase, depending on the position of SW3. SW1 and SW2 allow one to disable part of the driving laser diodes.

resonance curves of uncoated Si_3N_4 cantilevers. The curves "circles" and "triangles" result from driving the cantilever with the respective laser diodes; curve "squares" shows the combined action of the two laser diodes in a push–pull arrangement. The resulting amplitude is 1.95 times that of a single laser diode. Modulating the light of the laser diodes in phase (curve "diamonds") yielded a reduction of the amplitude. The amplitude relationships are as expected for light pressure. The resonance curves were fitted with equation

$$A(\omega)=A(0)\left[\left\{1-\left(\frac{\omega}{\omega_0}\right)^2\right\}^2+\left(\frac{\omega}{Q\omega_0}\right)^2\right]^{-1/2}, \tag{7}$$

where ω_0 is the resonance frequency and Q the quality factor of the resonance. From fig. 2 we calculate a resonance frequency of $\omega_0 = 32490.5$ Hz and a quality factor $Q = 12000$. The calculated excitation amplitudes for uncoated cantilevers (force constant = 0.02 N/m) are 0.1 pN away from the resonance for single laser diode excitation with a power modulation of 100 μW. A variation of the input power revealed a linear relation between intensity and resulting force. This behaviour and the size of the effect agree well with the hypothesis that light pressure is the dominating effect. The values of the resonance

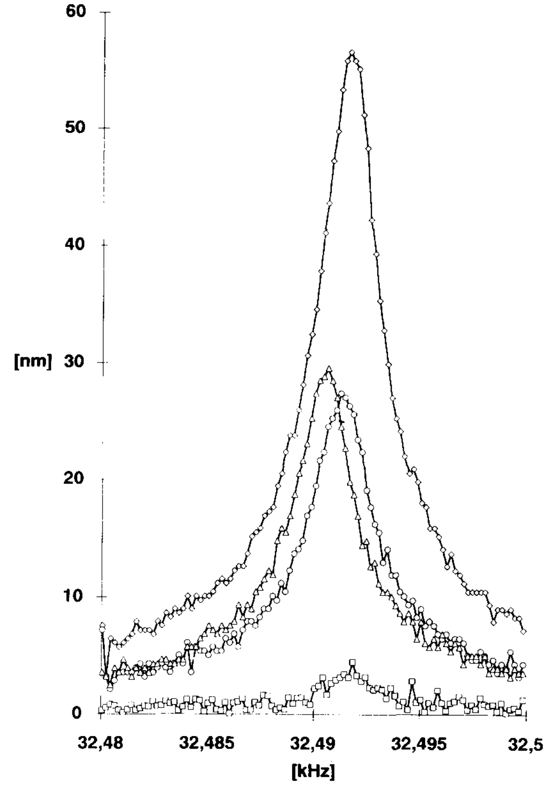

Fig. 2. Resonance curves of uncoated silicon nitride cantilevers at 10^{-6} mbar. Curves "circles" (LD1) and "triangles" (LD2) refer to excitations with the respective diodes alone. Curve "diamonds" shows the doubling of the amplitude by the push–pull action of the two counter-propagating laser beams modulated out of phase. Curve "squares" shows the cancellation of the light pressure induced motion by two counter-propagating light beams with equal intensity modulated in phase. The intensity modulation amplitude of both laser diodes was 100 μW.

frequency and the quality factor were equal for light pressure and piezo driven excitation. Due to the increased damping in air and the disturbance by air currents no resonance curve could be measured at ambient conditions with uncoated cantilevers.

Gold-coated cantilevers, on the other hand, could be excited at ambient conditions, although at a very low level. The relative size of the amplitudes for the different excitation modes were different (see fig. 3) from the results obtained for uncoated cantilevers. Curves "circles" and "triangles" excited by the respective laser diodes show again a similar amplitude. The amplitude of curve "diamonds" however is decreased below the single diode excitation value. This fact can be explained by assuming a bimetal action due to heating. The out-of-phase illumination represents an almost constant power input to the cantilever suppressing the oscillation of the lever. Curve "squares" shows a larger amplitude because of the heating is pulsed at twice the power of a single laser diode. The slight shift to a lower resonance frequency might be understood as a softening of the cantilever due to the higher temperature. Gold-coated cantilevers showed at low frequencies in vacuum a giant excitation of up to 10 nN (excitation power: 100 μW). A dominant time constant of (1.5 ± 0.5) ms was observed. Increasing the laser diode power above 1 mW resulted in damage to the cantilever (fig. 4). Under ambient conditions the bimetal effect is reduced due to the efficient cooling of the cantilever by air.

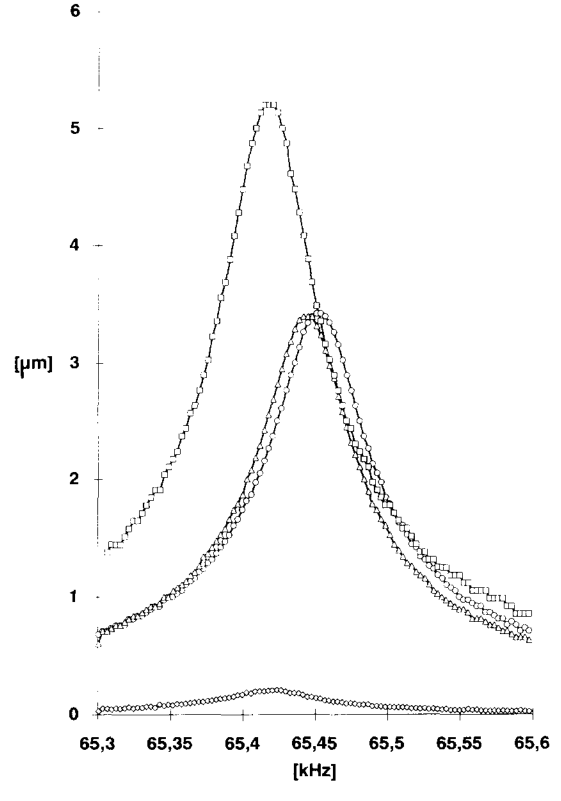

Fig. 3. Resonance curves of gold-coated silicon nitride cantilevers at 10^{-6} mbar, dominated by the bimetal effect. Curves "circles" (LD1) and "triangles" (LD3) refer to excitations with the respective diodes alone. Curve "diamonds" shows the reduction of the amplitude when LD1 and LD3 are modulated out of phase. The amplitude of the curve "squares" is enhanced due to the chopped heat input by the two diodes modulated in phase. The intensity modulation amplitude of both laser diodes was 100 μW.

When exciting uncoated cantilevers by single diodes or in the out-of-phase scheme, the light always incident on one side, is causing a temperature gradient, which will induce a bending away from the light source according to equation

$$z(L) = -\alpha \frac{\Delta T}{h} \frac{L^2}{2}, \tag{8}$$

where α is the thermal expansion coefficient, L the length of the cantilever, h its thickness and ΔT the temperature gradient from top to bottom [17]. To estimate the size of the effect, we assume that all the light is absorbed at the surface of the cantilever. The heat transport to the other side compensates the power loss by blackbody radiation.The size of the heat current is given by the actual temperature of the cantilever, and not by the temperature gradient ΔT. The actual temperature can be found solving eqs. (4) and (5). The main difficulties solving this partial differential equation stem from the nonlinearities in the boundary conditions and the excitations. We note that the absorption constant for silicon nitride is $\gamma = 10^5$/m [14], i.e. the light intensity is reduced to 0.97 times the input intensity upon traversing a cantilever of 0.3 μm thickness. Therefore we assume a constant light intensity across the uncoated cantilever. This argument does not apply to gold-coated cantilevers, since a gold layer of 30 nm thickness absorbs > 10% of the incoming light at 670 nm [12]! We furthermore neglect the loss of energy due to thermal radiation and will justify this assumption in a moment. Since the focal spot of our laser diodes is at least a factor of 2 bigger than the width of the cantilevers, the intensity distribution of the laser beam is assumed to be constant.

Eq. (4) can then be solved and yields

$$T(x)=\begin{cases} T_0+\dfrac{p_0 d(L-x)}{\lambda hb}, & x>d, \\ T_0+\dfrac{p_0 dL}{\lambda hb}-\dfrac{p_0(d^2+x^2)}{2\lambda hb}, & x\le d, \end{cases} \tag{9}$$

where d is the diameter of the light beam, b the width of the cantilever, h its height and L its length. $p_0=I_{\mathrm{in}}(1-r)/d$ is the line density of power.

Substituting the dimensions and physical properties of uncoated cantilevers (L = 100 μm, b = 20 μm, h = 0.3 μm, $\gamma = 10^5$/m, λ = 32 W/Km [15], p_0 = 1 mW (taking into account reflectance and spot size) and d = 40 μm) we calculate a temperature rise of 25 K and a total emitted power of 0.4 μW, assuming an emissivity of 1. Compared to the total absorbed power of 30 μW we can neglect this heat leakage. Using Wien's law we find that the temperature difference from top to bottom of a 0.3 μm thick silicon nitride cantilever is 1.4 μK. Substitution of this result into eq. (8) yields an upper limit for the transversal bending of 0.64 fm for a cantilever with a force constant of 0.1 N/m, equivalent to a force of 0.064 fN. Since this effect is negligible for uncoated cantilevers, they ar driven by light pressure at the resonance frequency.

The increased temperature causes the cantilevers to bend due to inhomogeneities, such as a metal coating. Since it can be assumed that the temperature distribution is homogeneous over the cross section, this effect can be directly measured with two light beams of equal intensity (and hence equal light pressure) which are turned on and off in phase (see fig. 3). Using Young's modulus for gold (E = 80 GPa [13]) and silicon nitride (E =

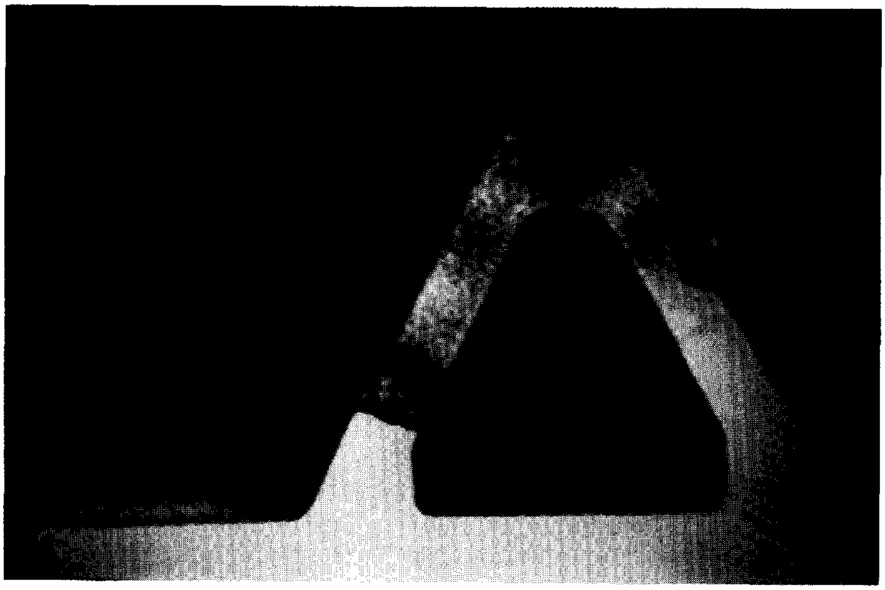

Fig. 4. Image of a gold-coated cantilever damaged by ≤ 1 mW of laser radiation at 670 nm in a vacuum of 10^{-6} mbar.

180 GPa [15]) and the respective thermal expansion coefficients ($\alpha = 14.2 \times 10^{-6}$/K [13] and $\alpha = 3.0 \times 10^{-6}$/K [15]) we calculate a deflection of the cantilever of 0.3024 nm/K [16] because of the bimetal effect.

5. Conclusions

We have demonstrated that mechanical and thermal effects are present in scanning force microscopy with optical readout, be it interferometric or of the optical lever type. We have shown that uncoated silicon nitride cantilevers, due to their low absorption of laser light at 670 nm, are driven by light pressure. The largest amplitudes obtained with 2 mW modulation amplitude are 35 pm (spring constant $k = 0.02$) away from resonance and Q times more at resonance. In our case, we reached amplitudes as high as 420 nm at resonance. These amplitudes are sufficient to perform scanning force microscopy with vibrating cantilevers to detect, for instance, magnetic fields or electric charges. We used a three-beam set-up to be able to distinguish mechanical from thermal light effects, but a single-beam set-up is sufficient to excite the cantilever and as an optical lever detection beam. Another possible application is for local stiffness measurement, where the well defined impulse of photons will lead to more accurate measurements.

The data on the light-induced forces on the cantilever can be used to estimate the uncertainty of the force due to intensity fluctuations of the light source. Taking a 1 mW laser diode with a power stability of 1%, we estimate a fluctuation of up to 1 nm for gold-coated cantilevers in vacuum and 6 pm for uncoated cantilevers.

Our results show that gold-coated cantilevers are not suitable for work in UHV. The gold coating absorbs enough power to melt the cantilever. A better choice would be silver, which has a higher reflectance and a lower absorbance for 30 nm films [12].

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