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Optomechanical coupling between AFM cantilever and semiconductor laser

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Abstract. Optomechanical coupling between cantilever of the atomic force microscope (AFM) and a semiconductor laser was studied. When an AFM cantilever is oriented parallel to the surface of the emitting semiconductor laser, the system forms an optomechanical resonator. The optomechanical coupling due to photothermal effect was shown in room conditions. By optomechanical cooling the effective temperature of Si_3N_4 cantilever was reduced down to 80 K. Amplitude-to-phase conversion in the studied cavity was demonstrated.

1. Introduction

In a system consisting of optical cavity and mechanical resonator an optomechanical coupling can be realized [1]. Usually, optomechanical resonator is formed by optical cavity with movable mirror clamped by the spring. Light stored in the optical cavity due to a radiation pressure moves the mirror. Then the mirror is shifted and the cavity will be detuned with simultaneous reducing of the radiation pressure, which returns the mirror to the initial position.

Detuning of the laser from the cavity resonance allows one to control the damping rate of the mirror oscillations. For the red-detuned case (laser frequency lower than the cavity resonance) mechanical oscillations of the mirror will be damped, in other words the mirror will be "cooled" [2]. For the blue-detuned case the damping will be negative and the mirror will be "heated" with arising of parametric self-oscillations. Optomechanical coupling opens the way to cool the macroscopic mirror down to its ground state, where the quantum mechanics describes the motion of the mirror [3]. Besides the cooling, the optomechanical resonators increase the sensitivity in displacement and mass measurements and find a place in a plenty of other novel devices [4].

In atomic force microscopy (AFM), optomechanical coupling can be implemented in quality factor "Q" control of the cantilever oscillations. The cooling of the cantilever down to 18 K was achieved [5]. The cantilever served as a movable mirror and a semi-reflecting cleavage of the optical fiber – as the counterpart mirror. The optomechanical coupling was realized due to photothermal (bolometric) effect. Recently, we have studied Fabri-Perot resonances between AFM cantilever and semiconductor laser cleavage [6]. The cantilever was inclined by 20 degrees with respect to the cleavage plane and the optomechanical coupling was not observed. The strongest photothermal effect was observed on Si_3N_4 cantilever due to its low thermal conductivity.

The aim of this work was to study an optomechanical coupling between AFM cantilever and semiconductor laser in room conditions. In addition, the influence of the cantilever material was studied.

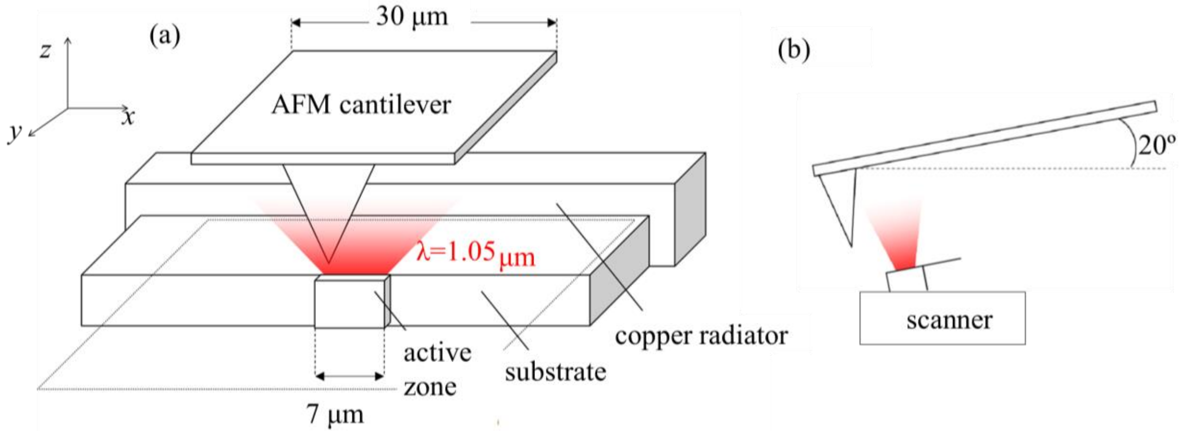

Figure 1. (a) Scheme of experimental setup for the measurements. (b) Scheme of optical cavity formed by cantilever and laser surface.

2. Experimental section

Measurements were performed using Ntegra-AURA (NT-MDT) scanning probe microscope in room conditions. We tested AFM probes fabricated of different materials: (1) silicon "Nanosensors" PPP-FMAu probes without tip coating and (2) silicon nitride "Bruker" ORC-8 probes with 30 nm thick Au tip coating. Both rectangular shaped cantilevers had the first resonance frequency f_1 ~70 kHz.

Figure 1 shows a scheme of experimental setup. The cantilever was oriented parallel to the cleavage surface of a semiconductor laser. For this purpose, the laser was mounted on a special holder with inclined surface. The inclination angle (20 degrees) was equal to that of cantilever with respect of *xy* scanning plane. This setup forms optical cavity with parallel mirrors: the laser surface and the cantilever surface on the tip side.

We have used semiconductor stripe laser with Fabry-Perot resonator radiating at λ=1.05 μm. Width of the laser stripe was 7 μm and the laser operated in the single mode regime. Optical power was varied in 10-100 mW range depending on the electrical pumping current (threshold current I_{th}=25 mA). During the measurements, AFM cantilever was moved with respect to laser surface by *xyz* scanner and a phase shift of the cantilever oscillations was recorded.

3. Results and discussion

3.1. Optomechanical coupling due to photothermal effect

In the optomechanical cavities, the optomechanical coupling can be realized by either light radiation pressure or photothermal effect. These effects have different characteristic times [7]. For the photothermal effect, the whole cantilever should be heated by laser radiation. Heated cantilever changes its stiffness due to temperature-sensitive Young's modulus [6]. Since the thermal diffusivity coefficient of silicon is of ~1 cm^2/s, the characteristic time for the silicon cantilever heating will be of 1 msec. For the light radiation pressure such a time is many orders shorter ~1 ns. Therefore, the mechanism of optomechanical coupling can be distinguished by time resolved experiment.

Figure 2 shows an absolute phase shift of the silicon cantilever oscillations during the increasing of a z-distance between cantilever and laser surface (mirrors in the optical cavity). For cantilever velocity of 7 μm/s, the phase shift dependence exhibited a sinusoidal curve specific for Fabry-Perot resonances with period corresponding to λ/2 (Fig. 2a). Such behavior has been observed earlier even when the cantilever was not parallel to the laser surface [6]. However, velocity decreasing down to 1.4 μm/s transforms the phase curve shape from "sinusoidal" to asymmetrical one, but still with periodical z-dependence (Fig. 2b). The similar curve shape was observed earlier [5] as a clear signature of the optomechanical coupling. Since the optomechanical coupling arises only for relatively slow change of the distance between mirrors, one can declare a photothermal effect responsible for the coupling.

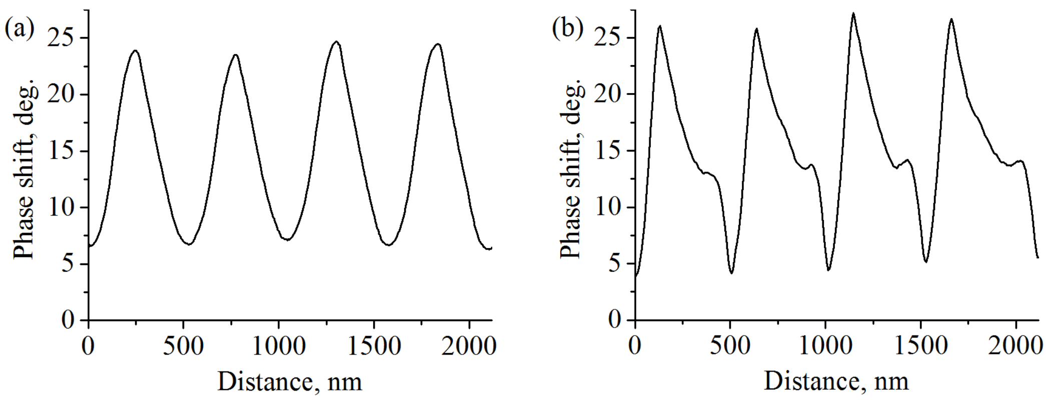

Figure 2. Dependence of the phase shift of cantilever oscillations on cantilever-laser surface z-distance for different velocities of cantilever motion along z-axis: (a) 7 μm/s, (b) 1.4 μm/s.

3.2. Optomechanical cooling of silicon and silicon nitride cantilevers

The optomechanical cooling of the cantilever was studied. For this purpose, the optical cavity was red-detuned by *z*-moving of cantilever to a proper position. Experiment was performed as follows: thermal noise spectrum of the cantilever was measured with and without laser pumping. From the obtained spectra, the resonance frequencies ω, ω_{eff}, and damping factors Γ, Γ_{eff} were extracted for non-lasing and lasing cases, respectively. The effective temperature of the "cooled" cantilever T_{eff} can be expressed as follows [5]:

$$T_{eff} = T\frac{\omega^2}{\omega_{eff}^2}\frac{\Gamma}{\Gamma_{eff}} \tag{1}$$

where *T* is the room temperature.

The calculated values of T_{eff} thermal noise and spectra obtained with different laser pumping for Si and Si_3N_4 cantilevers are presented in Figures 3a and 3b, respectively. It is seen that the cooling of Si_3N_4 cantilever is more effective than Si one. For the Si_3N_4 cantilever, effective temperature decreases down to 80 K at 40 mA pumping current, while for the Si one even at 100 mA pumping the temperature decreases only to 170 K. Such a distinction is connected with different impacts of the photothermal effect on Si and Si_3N_4 cantilevers. Previously, we have shown a better photosensitivity of Si_3N_4 cantilever. Interestingly, in spite of the effective absorption of laser radiation by silicon, Si_3N_4 showed better results due to its lower thermal conductivity [6]. The lower thermal conductivity leads to effective optomechanical cooling; however, increasing of laser pumping current above 40 mA heated the Si_3N_4 cantilever to more than 80 K. Thus, the minimum reachable temperature of cooling at our setup was 80 K for Si_3N_4 cantilever.

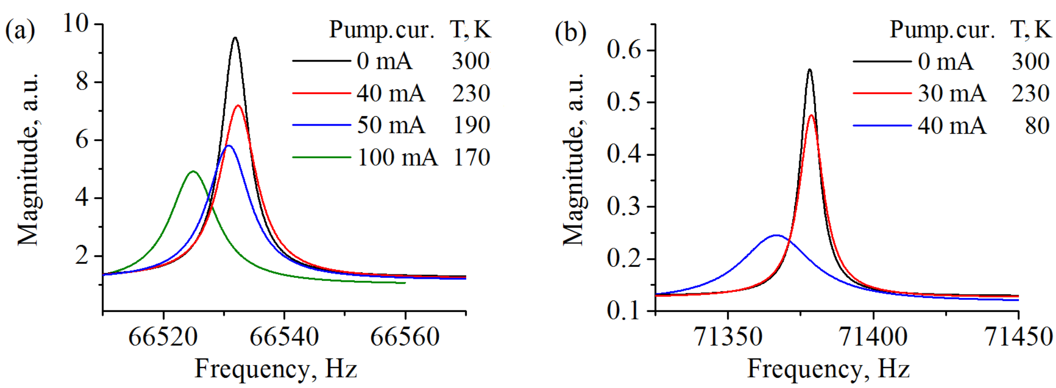

Figure 3. Thermal noise spectra of cantilever oscillations obtained with different laser pumping for (a) silicon cantilever, (b) Si_3N_4 cantilever.

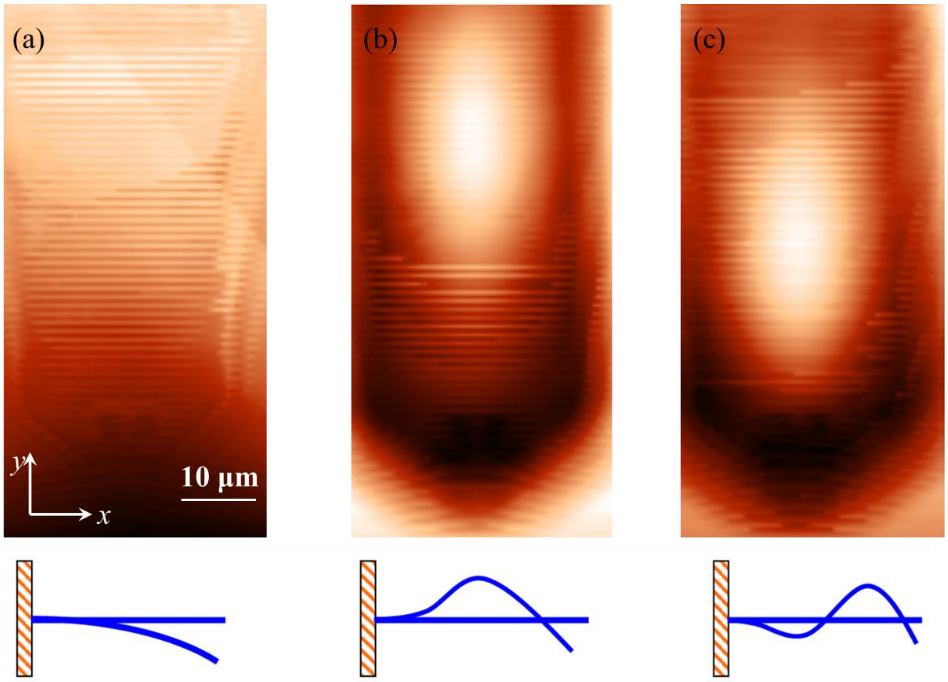

Figure 4. Phase images of the Si_3N_4 cantilever oscillations obtained while scanning semiconductor laser at various resonance frequencies: (a) f_1, (b) f_2, (c) f_3. At the bottom – flexural cantilever modes at the correspondent resonance frequencies.

3.3. XY scanning of the optomechanical cavity

In the previous section, the cantilever was moved only in *z*-direction. However, AFM provides a cantilever movement in *xy* directions (100x100 μm^2). Figure 4 shows phase images obtained while scanning a semiconductor laser in *xy* directions. The scanning was performed at different resonance frequencies of cantilever (f_1, f_2, f_3 – Figs. 4(a)-(c), respectively).

For various resonance frequencies, the bending profiles of the oscillating cantilever are different. For example, at the first resonance frequency an unclamped end of the cantilever moves up and down, and the bending profile changes monotonically. For the higher resonances the bending profiles become more complex (see bottom part of the Figure 4). It should be noted that such a bending profile can be obtained by measuring a magnitude of oscillations across the cantilever length.

Optomechanical cavity is a convenient tool of optical modulation and phase-to-amplitude conversion [4, 8]. Oscillation amplitude of a movable mirror changes the phase of optical oscillations in the cavity and vice versa. In the Figure 4, phase images of the mirror (cantilever) oscillations correlate with corresponding bending profiles. Thus, the bending profiles at different resonance frequencies can be obtained by measuring the phase image of the cantilever oscillations. Apparently, this effect can be used for measuring the bending profiles of different 1D and 2D flexural nanostructures.

4. Conclusions

To conclude, an AFM cantilever placed parallel to the surface of the mirror of the semiconductor laser forms an optomechanical cavity in room conditions. It was shown that optomechanical coupling arised due to photothermal effect. The optomechanical cooling of the AFM cantilever was studied for Si and Si_3N_4 cantilevers. The effective temperature of the Si_3N_4 cantilever was reduced down to 80 K; apparently, this value is close to the minimum reachable in our experimental setup. Scanning in the *xy* directions revealed the similarity of the phase images of cantilever oscillations at different resonance frequencies with the corresponding bending profiles of the cantilever.

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