The effect of optical cooling of the SPM probe in the optomechanical resonator

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Abstract. Optomechanical resonators formed by the surface of an emitting semiconductor laser and the reflective surface of the probe of scanning probe microscope (SPM) were studied. The use of scanning probe microscopy techniques allowed studying the properties of such optomechanical resonators in details. The effect of optical cooling of an SPM probe in an optomechanical resonator was investigated by measuring the spectra of thermal vibrations of an SPM probe. Minimal achievable temperatures of SPM probe cooling were experimentally established.

1. Introduction

The optomechanical resonator is a connected system consisting of an optical resonator and a mechanical resonator. The simplest example of an optomechanical resonator is a Fabry-Perot resonator, in which one mirror is stationary, and the second one is attached to a spring and can oscillate. However, there is a huge number of other various designs of optomechanical resonators. Optomechanical resonators have been studied since the 1970s, one of the first ideas in this area was proposed by Braginskii [1]. In the last decade, studies of processes in optomechanical resonators were actively carried out [2,3]. Ongoing studies indicate the possibility of substantial optical cooling of microscopic mirrors in optomechanical resonators down to the ground state [4,5]. This opens up a number of new research opportunities in the field of precision measurements of ultra-small forces [6], quantum computing [7], as well as in other areas. The ability to detect ultra-small forces is extremely important, for example, in scanning probe microscopy (SPM) measurements. It is worth noting the work [8] proposing a method for creating a special SPM-probe, which is connected to a high-Q optical resonator and forms an optomechanical resonator, which allows: (i) increasing the sensitivity of motion detection to values ~ 1 fm/(Hz)^1/2 and (ii) tuning the stiffness coefficient of the SPM-probe in a wide range from 0.01 N/m up to 290 N/m. It is worth noting that such an optomechanical SPM-probe is quite difficult to manufacture, extremely expensive, and, therefore, cannot be widely used in SPM research.

In this paper, we study the optomechanical resonators formed by the surface of an emitting semiconductor laser and the reflective surface of SPM-probe. The use of SPM techniques allows studying the properties of such optomechanical resonators in details. In this paper, we study the effect of optical cooling of the SPM probe. The optical cooling effect can be used to increase significantly the sensitivity of the SPM during the detection of small forces.
2. Experimental details

Recently, the authors of this work have discovered the effect of a shift in the resonant frequency $\Delta \omega$ of an atomic force microscope (AFM) probe under illumination [9]. This effect is related with the light absorption in the probe. Based on this effect, a new probe method was developed to measure light-induced frequency shifts (LIFS) for the near-field mapping of the intensity distribution $J(x,y,z)$ of the radiation of semiconductor laser structures [9]. In addition, the authors discovered the interference effect between the light wave emerging from a laser and the wave reflected from the SPM probe [10]. In this case, the laser surface and the reflecting surface of the SPM-probe form an optomechanical resonator. As a result, when the SPM-probe was placed at a distance (from the laser surface) equal to an integer number of half-waves, multiple amplification of the detected signal occurred. This allows one to use this effect for (i) increasing sensitivity when detecting light emission, (ii) performing LIFS-spectroscopy experiments, and (iii) performing optical cooling experiments.

It is worth noting that the SPM-probe is usually inclined at an angle of 15 degrees to the surface under study, which does not allow creating a high-Q resonator. To improve the quality factor, we placed the SPM-probe surface parallel to the light-emitting surface of the semiconductor laser (Fig. 1). Such a plane-parallel optical resonator, in which one mirror is stationary and the second one can oscillate (the SPM-cantilever is a mechanical oscillator), is a classic example of an optomechanical resonator. A feature of such optomechanical resonators is that when light interacts with the SPM-probe, an additional force arises, which can either suppress the thermal vibrations of the SPM-probe (optical cooling), or vice versa, significantly increase them (optical heating). In this work, for the experimental detection of the effect of optical cooling, we will use the standard technique for measuring the spectrum of thermal vibrations of the SPM-probe.

The SPM measurements were carried out using Ntegra-Aura (NT MDT, Russia) device. Silicon PPP-FMAu (Nanosensors) and silicon nitride ORC-8 (Bruker) probes were used to study the optical cooling effect. We used semiconductor stripe laser emitting on 1.05 $\mu$m (threshold current $I_{th}=30$ mA) as a part of the optomechanical resonator. This laser is based on the AlGaAs/InGaAs/GaAs heterostructure grown by metalorganic chemical vapour deposition.

3. Results and discussion

Figure 2 shows the measured spectrum of thermal vibrations of the silicon PPP-FMAu probe (in the dark) and the result of its fitting by the Lorentzian function. In further analysis, we will give only the smoothed spectra of thermal vibrations that are already free from noise. Figure 3 shows the measured spectra of thermal vibrations of the silicon PPP-FMAu probe (i) in the dark and (ii) when the laser is turned on and pumped with a current above the laser generation threshold. It can be seen that at certain probe-surface distances, increase in the power of the laser radiation leads to a multiple attenuation of the thermal noise amplitude, which corresponds to a multiple decrease in temperature.

![Figure 1. The scheme of the optomechanical resonator “semiconductor laser - SPM probe”.](image)
Figure 2. The spectrum of thermal vibrations of the silicon PPP-FMAu probe (black curve) and its fitting (red curve) by the Lorentzian function.

Figure 3. The fitted spectra of thermal vibrations of the silicon PPP-FMAu probe in the dark and with increase of light intensity in the optomechanical resonator.

It should be noted that with a further increase in the power of the light entering into the optomechanical resonator, the temperature increase was observed. That is a certain limiting value of the achieved cooling temperature ($T_{\text{min}}$). In our experiments, it was possible (i) to cool silicon PPP-FMAu probes down to 100 K and (ii) to cool silicon nitride probes down to 80 K. It can be assumed that heating is associated with an increase in light absorption in the probe. In order to decrease $T_{\text{min}}$ during optical cooling, probes with a bottom reflective coating can be used. This will reduce absorption in the probe and allow the probe to be cooled down to $T_{\text{min}}$.

4. Conclusion
The formation of optomechanical “probe-laser” resonators using silicon and silicon nitride probes was investigated using scanning probe microscopy methods. The possibilities of optical cooling of probes in an optomechanical resonator were investigated. It is shown that the minimum achievable optical cooling temperatures are 80-100 K. To improve the optical cooling process, it is necessary to deposit a bottom reflective coating to the probes thus decreasing absorption in the probes.
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