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Nanooscillators based on carbon whiskers for detectors of optomechanical effects

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Abstract. A new mechanical resonance method for determining the effect of photoinduced heating from laser radiation on mechanical systems based on carbon whiskers was developed. We demonstrate a fast and universal approach for manufacturing the resonant nanooscillator detecting the effect of optical radiation on the properties of nanoobjects. The nanomechanical whisker-based resonator was grown on at the end of the tungsten needle using an electron beam induced deposition approach implemented in a scanning electron microscope. The influence of laser radiation on the mechanical properties of nanoresonators was experimentally revealed, and the trajectory of their movement at the first mechanical mode was visualized. The demonstrated approach for detecting the influence of optical radiation on the vibrational characteristics of nanooscillators paves the way for new photothermal and optomechanical sensors.

Keywords: nanowhiskers oscillations, optical heating, optical power sensing

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Нанооциляторы на основе углеродных вискеров в качестве детекторов оптомеханических эффектов

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Аннотация. Разработан новый резонансный метод для определения влияния фотоиндуцированного нагрева лазерным излучением на механические системы на основе углеродных вискеров. Мы демонстрируем быстрый и универсальный подход к созданию резонансных нанооциляторов, в качестве детекторов влияния оптического излучения на свойства нанообъектов. Углеродный вискер был выращен на конце вольфрамовой иглы с использованием метода осаждения, индуцированного электронным лучом, реализованного в сканирующем электронном микроскопе. Экспериментально выявлено влияние лазерного излучения на механические свойства нанорезонаторов и визуализирована траектория их движения на первой резонансной частоте. Продемонстрированный подход к обнаружению влияния оптического излучения на колебательные характеристики наноосцилляторов прокладывает путь к новым фототермическим и оптомеханическим датчикам.

Ключевые слова: углеродные нановискеры, оптический нагрев, детектор оптической силы

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Introduction

The study of the effect of optical radiation on micro- and nanoobjects is of particular interest for the development of optomechanical, chemical, and biological applications [1]. In particular, the study of the effect of laser radiation on the mechanical properties of nanooscillators based on single carbon whiskers (CNWs) can be employed to develop various types of sensors [2, 3]. The mechanical oscillations of CNWs can be visualized in a scanning electron or optical microscope, which distinguishes them from the existing sensors, requiring rather complex optical, mechanical or electronic systems.

In our study CNWs were grown from the residual atmosphere in a scanning electron microscope (SEM) chamber by focusing an electron beam on a tungsten tip. The clamped from one side CNWs had a small mass and eigen frequencies in the MHz range, which provides high sensitivity in detecting forces of the order of pN. In our setup, a whisker and lensed fiber for inputting laser radiation were located inside the vacuum chamber. This approach allows to operate without deterioration of vacuum, which is of great importance for detecting small forces. This method does not require any additional specific equipment other than nanomanipulation tools inside the microscope [4]. To detect the influence of optical radiation on nanomechanical oscillations, the laser beam was focused on free end of CNW and the change of amplitude-frequency characteristic (AFC) was registered. Such approach enables the study of new optomechanical and photoinduced effects under intense optical radiation.

Fabrication of the optomechanical effects sensor

The resonant detector consists of carbon nanowhiskers grown at the end of a tungsten needle. A tubular piezoelectric transducer connected to a signal generator of a special form “AKIP - 3413/3” was used as an oscillation generator. A sharp tungsten needle was fabricated by electrochemical etching in a 5% KOH solution, as schematically shown in Fig. 1, *a*. Carbon whiskers were grown by means of the electron beam induced deposition using hydrocarbon groups from the residual atmosphere in the chamber of the SEM FEI Quanta Inspect (Fig. 1, *b*). In this case, the trajectory of the electron beam movement determines the shape of the deposited carbon nanoobject, which allows us to control the geometry of the whisker. The sensor consists of a tungsten needle placed in a piezotube vibration transducer with a CNW (Fig. 2, *a*).

To obtain the AFC of the whisker, we used the simple method, based on the SEM visualization of oscillations. When the oscillator frequency coincides with the resonant frequency of the nanoresonator, the SEM image of the whiskers is blurred and takes the form of a fan (see scheme in Fig. 2, *b*). To study the optical effect on the vibrational characteristics of the nanooscillator, we used a laser diode with a wavelength of 658 nm, equipped with a voltage regulator for adjusting

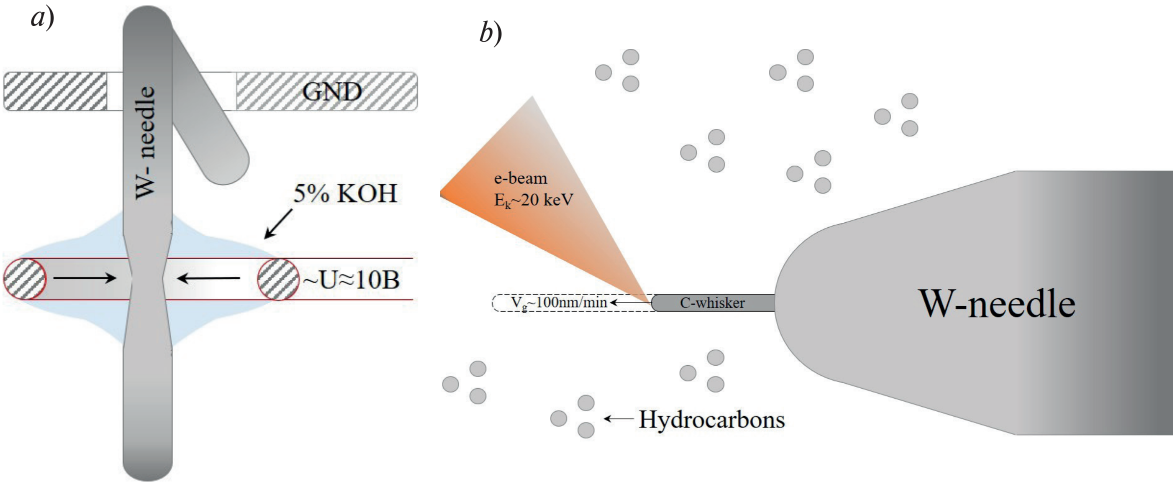

Fig.1. Electrochemical etching of the W-needle (GND denotes the ground electrode) (*a*); CNW fabrication process in the SEM chamber (E_k is the e-beam accelerating voltage) (*b*)

the radiation power. To input laser radiation into the SEM chamber, we used a lens fiber with a maximum output power of 3 mW and a focal length (*F*) of ~ 6 μm, spot diameter (ds) of ~ 3 μm, and aperture of 0.385 (see scheme in Fig. 3). The positioning of the lensed fiber for the localization of laser radiation on the nanooscillator at the focal length was carried out using a kleindiek nanomanipulator inside the SEM chamber. To avoid the charge of fiber under electron beam, the end fiber was covered with an ITO film (approximately 100 nm thickness).

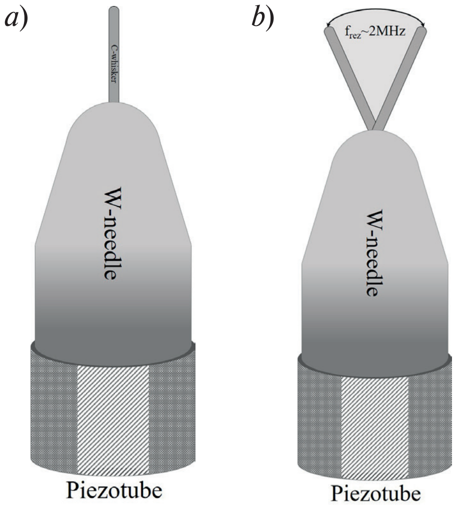

Fig. 2. CNW at rest (*a*) and resonance (*b*)

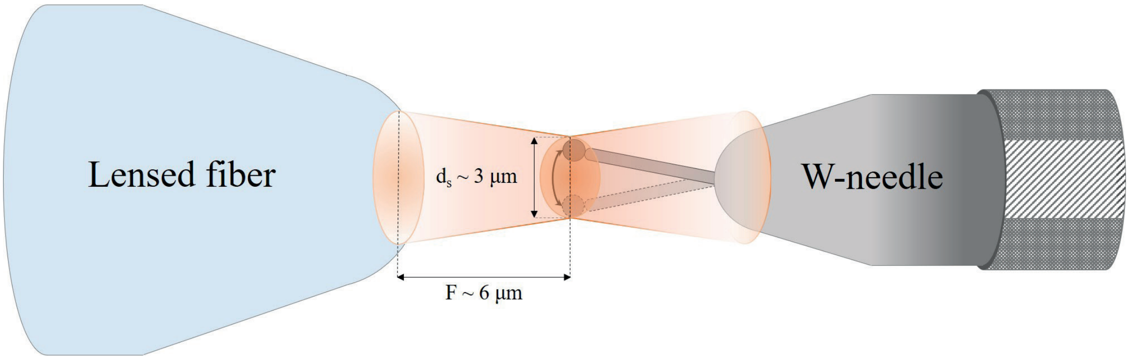

Fig. 3. Focusing the laser beam through a lensed fiber on a nanooscillator

Results and Discussion

Amorphous CNW with a length of 5.38 μm and an average diameter of 142 nm was grown on a tungsten needle with a sharpening radius of 2.1 μm (see insert in Fig. 4, *b*). The measured resonant frequency (the first eigen mode) was 2346 kHz, while the oscillation amplitude was 1714 nm. Fig. 4 shows the acquired AFC of the whisker.

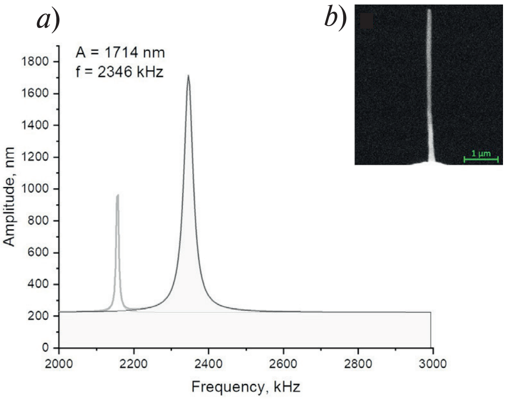

Fig. 4. AFC of the whisker (*a*). The insert demonstrates an SEM image of whisker (*b*)

We present a method for studying the influence of optical effects on the vibrational characteristics of a nanoresonator. When the carbon whisker is positioned at the focus of the laser beam, a change in the amplitude and resonant frequency is observed (Fig. 5).

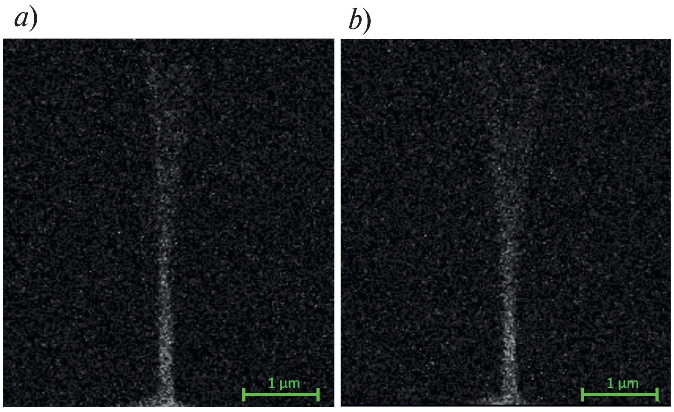

Fig. 5. Whisker mechanical resonance with laser off (*a*) and on (*b*)

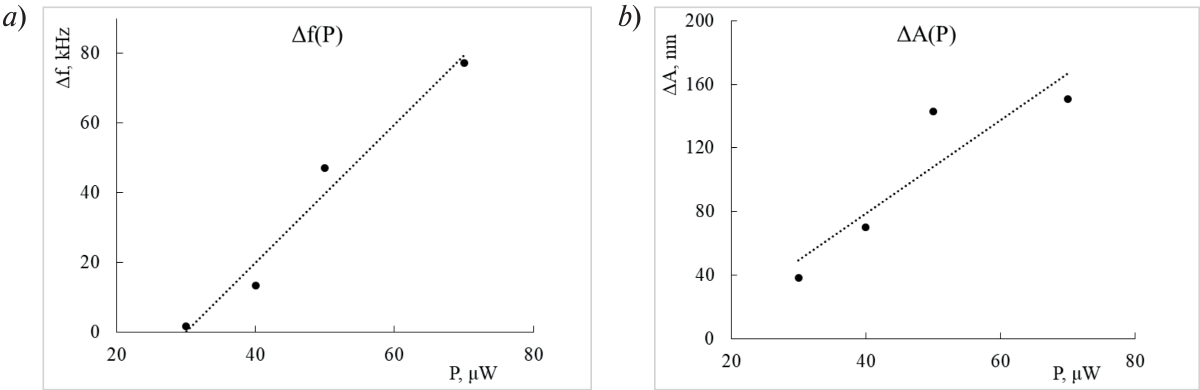

Fig. 6. Dependencies of the frequency shift (*a*) and amplitude change (*b*) on laser power

The resonant frequency of the nanooscillator decreases and the amplitude increases when the laser is on. In this case, an increase in the shift of the resonant frequency up to 77 kHz (3%), and the amplitude up to 151 nm (20%), is observed with an increase in the laser radiation power from 30 to 70 μW (Fig. 6).

Conclusion

This study presents a new method for detecting optomechanical effects based on the shift of the resonant frequency and amplitude of the nanooscillator when a carbon whisker is positioned at the focus of a laser beam. This approach for sensing the effect of laser radiation on the vibrational characteristics of nanoobjects is efficient and fast. The use of a CNW as a detector of optomechanical effects does not require additional specific equipment for its manufacture and is eficient due to its high sensitivity to laser radiation. The observed change in the resonant frequency and amplitude of the nanooscillator under laser radiation can be due to the action of the optical forces, induced by the laser beam, or the effect of thermoparametric resonance.

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