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Sensitive detection of infrared photons using a high-Q microcantilever*

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Abstract: A new approach based on microcantilevers is presented to detect infrared photons with high sensitivity. Infrared photons are measured by monitoring the amplitude change of a vibrating microcantilever under light pressure force. The irradiating light is modulated into sinusoidal and pulsed waves, and to be in-phase and anti-phase with the cantilever driving signal. A linear relationship between the amplitude change of the cantilever and the light power distributing on the cantilever was observed. Under a vacuum of 10^{-4} Pa, an infrared light power of 7.4 nW was detected with the cantilever. The in-phase and anti-phase modulation to the cantilever vibration using a pulsed light results in an enhanced response of the cantilever.

Key words: infrared photon detection; light pressure force; cantilever
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1. Introduction

Photon detectors are used to sense the photon illumination based on the quantum effect of light. Now, infrared photon detectors have attracted extensive attention due to their distinguishing properties and versatile applications. The near-infrared (1310 nm and 1550 nm) are suitable for the remote optical fiber communication due to their low loss. The mid-infrared (3–5 μm) and the far-infrared (8–14 μm) are often employed to trace military objectives benefiting from the low loss in atmosphere. Moreover, infrared photon detectors are also required for applications such as thermal imaging, gas analysis for pollutant detection and numerous other applications[1].

Well-developed photon detectors, such as photomultiplier tubes (PMTs) and silicon avalanche photon diodes (Si-APDs), can not work at the infrared light range (> 1300 nm) despite their promising performances: such as large gain, fast response, low noise and high quantum efficiency[2,3]. InAsSb/GaSb heterojunction photon detectors and InGaAs photon detectors have extended their spectra response up to the mid-infrared range (3–5 μm) at room temperature[1,4]. The spectral response of photon detectors based on superconductors, quantum dots, quantum wells and super-lattices can even reach the far-infrared range[5–9]. Nevertheless, these photon detectors are made of expensive materials like niobium nitride and III–V group compounds, usually require complex fabrication processes and demand the low working temperatures.

Infrared photon detectors using microcantilevers provide a new alternative for detecting photons from the near-infrared to the far-infrared at room temperature. Two types of microcantilever-based infrared detectors have been reported[10,11]. Thermal detectors based on the photothermal effect have a broadband response and a detection accuracy of 10^{-10} W at room temperature but slow response (> ms). Photon detectors with a metal-semiconductor microcantilever structure utilize photon-induced electron stress and can work at room temperature with a high detection accuracy of 1 nW and fast response (< ms). However, the stress matching between the different structural layers is crucial since they are stress-sensitive elements and the photothermal effect should be minimized.

Above all, a new routine for infrared photon detection with high sensitivity and reliability at room temperature is in demand for extensive applications. Recently, we introduced a new infrared photon detection principle using a microcantilever as the sensing element to achieve a nanowatt detection accuracy at room temperature[12]. Now, this method is experimentally demonstrated here and a minimum light power of 7.4 nW is detected.

2. Experimental details

The cantilever fabrication process was introduced in detail in Ref. [12]. The cantilever fabrication process begins with ⟨100⟩ oriented silicon-on-insulator (SOI) wafers with a top silicon layer thickness of about 225 nm. The thickness of the cantilever is controlled by thermal oxidation of the SOI wafer. The cantilever is defined by reactive ion etching (RIE) on an SOI wafer using the photoresist as mask. The second photoresist mask is fabricated on the front side of the wafer for the final cantilever release. Subsequently a thick oxide layer is produced on the backside of the SOI wafer and is patterned to prepare the mask for deep anisotropic etching of the Si substrate. Finally the cantilever is released by anisotropic and isotropic etching

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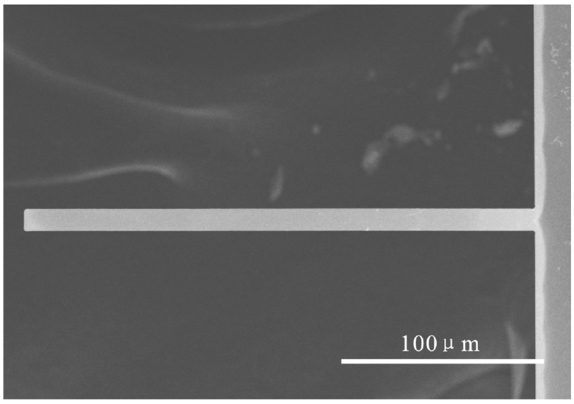
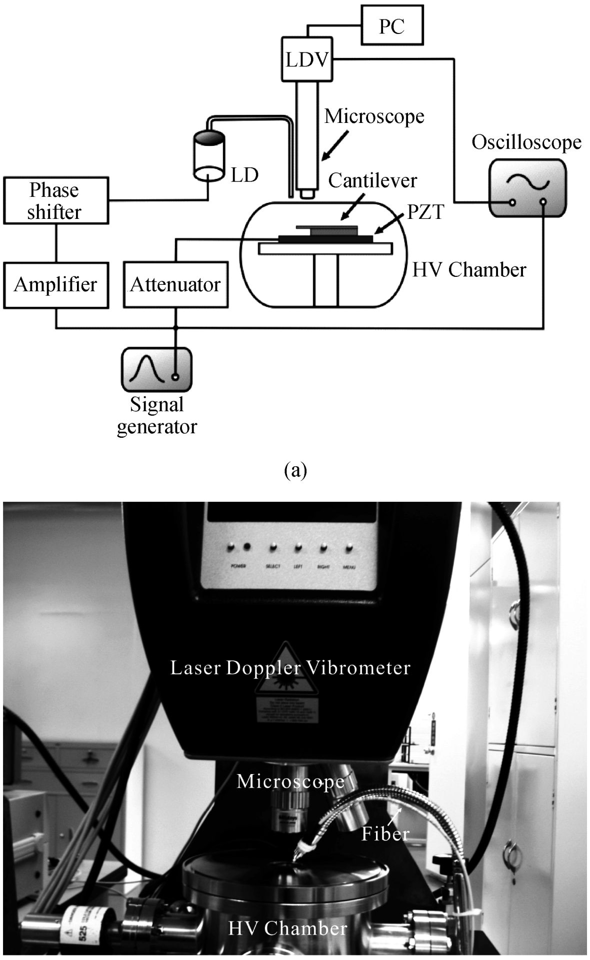


Fig. 1. SEM image of the single crystal silicon cantilever.



(a)

(b)

Fig. 2. (a) Schematic diagram of infrared photon detection system based on a microcantilever. (b) Image of experimental setup.

of Si from the front side of the wafer. Figure 1 is the SEM image of the fabricated single crystal silicon cantilever with a thickness of 116 nm to achieve high reflectivity for the infrared light under investigation.

The detailed measurement scheme and setup are given in Fig. 2. A single crystal silicon cantilever is employed as the sensing element and actuated to vibrate at its resonant frequency by a PZT under a vacuum of 10^{-4} Pa. The infrared light from an infrared source is modulated into a sinusoidal and pulsed wave, to be in-phase or anti-phase with cantilever driving signal, and irradiates on the cantilever through the optical window of the chamber. The infrared source can output the light power between 0 and 3.4 mW. The displacement change of the vibrating cantilever induced by the light pressure is monitored by the laser Doppler vibrometer (LDV) and the LDV (MSA-500) from Polytec has the resolution of 7 pm for displacement detection, which is good enough to meet the measurement requirements of this work.

3. Theoretical analysis

Considering the microcantilever as a damped harmonic oscillator, the equation of motion is

$$m\frac{\mathrm{d}^2x}{\mathrm{d}t^2}+(m\omega_0/Q)\frac{\mathrm{d}x}{\mathrm{d}t}+m\omega_0^2x=F_{\text{drive}}+F_{\text{photon}},\quad(1)$$

where x is the displacement of the cantilever free end, m is the cantilever effective mass, Q and ω_0 are the quality factor and resonance angular frequency of the cantilever, respectively; F_{drive} is the driving force provided by PZT, and F_{photon} is the light pressure force acting on the cantilever[12].

$$F_{\text{photon}}=\frac{2P}{c}R\cos\alpha,\quad(2)$$

where P is the light power irradiated on the cantilever, R is the reflectivity which will be up to 0.85 when the cantilever thickness is about $(2n-1)\lambda/4n_{\text{Si}}$ with n a positive integer and n_{Si} the refractive index of silicon[13], α is the light incidence angle, and c is the light velocity. When the signal generator outputs a sinusoidal signal, the cantilever driving force is $F_{\text{drive}}=F_{\text{D}}\cos(\omega_0t)$ with F_{D} the amplitude, and the light power irradiated on the cantilever is calculated as

$$P=P_0\cos\left(\omega_0t+\varphi_{\text{p}}\right)+P_{\text{c}},\quad(3)$$

where P_0 is the amplitude of the light power, φ_{p} is the initial phase and P_{c} is a constant light power. Inserting Eq. (3) into Eq. (2), the light pressure acting on the cantilever can be computed as

$$\begin{aligned}F_{\text{photon}}&=\frac{2R\cos\alpha}{c}\left[P_0\cos\left(\omega_0t+\varphi_{\text{p}}\right)+P_{\text{c}}\right]\\&=F_{\text{P}}\cos\left(\omega_0t+\varphi_{\text{p}}\right)+F_{\text{c}},\end{aligned}\quad(4)$$

where F_{P} is the amplitude of the light pressure and F_{c} is constant force. With the initial conditions: for $t=0$, $x=0$, the velocity $\mathrm{d}x/\mathrm{d}t=0$ as well as $F_{\text{drive}}=0$ and $F_{\text{photon}}=0$, Equation (1) can be solved as

$$x(t)=\frac{F_{\text{D}}Q}{m\omega_0^2}\sin(\omega_0t)+\frac{F_{\text{P}}Q}{m\omega_0^2}\sin\left(\omega_0t+\varphi_{\text{p}}\right)+\frac{F_{\text{c}}}{m\omega_0^2}.\quad(5)$$

Thus the amplitude of the microcantilever free end without light irradiation is

$$A=\frac{F_{\text{D}}Q}{m\omega_0^2}=\frac{F_{\text{D}}Q}{k},\quad(6)$$

where k is the cantilever spring constant. The sinusoidal light illumination results in a maximum displacement shift of the microcantilever free end

$$\Delta A=\frac{F_{\rm P}Q}{k}=\frac{8P_0QR\cos\alpha}{c}\frac{L^3}{EWH^3}, \tag{7}$$

where E is the Young's modulus of single crystal silicon, L, W and H are length, width, and thickness of the cantilever, respectively. ΔA can be obtained by monitoring the displacement shift of the cantilever with or without $F_{\rm photon}$.

Infrared light with wavelength of 1547 nm was used in our experiment. The core diameter of the optical fiber is 9 μm. The light field has Gauss distribution. So the light intensity distributes in the transverse direction as[14]

$$I\left(r,z\right)\propto\exp\left(-\frac{2r^2}{w^2\left(z\right)+a^2}\right), \tag{8}$$

where r is the radial coordinate with the origin at the output beam axis, $w(z)$ is the diameter of light spot with z the distance for the cantilever apart from the optical fiber end, and a is the optical mode radius. For a given distance z, $w(z)=w$ is a constant. When the light illuminates on the cantilever free end, the peak light power distributing on the cantilever P_0 can be computed from the peak infrared light power $P_{\rm source}$:

$$P_0=\frac{W}{\pi L}\frac{1-{\rm e}^{-2L^2/(w^2+a^2)}}{1-{\rm e}^{-2w^2(w^2+a^2)}}P_{\rm source}. \tag{9}$$

In this work, the diameter of the light spot w is 2.13 mm and the optical mode radius a is often just several micronmeters[14], much smaller than w, so it can be neglected. For a cantilever with $L=245$ μm, $W=4.56$ μm, and $H=116$ nm, $P_0=3.932\times10^{-4}P_{\rm source}$.

When a pulsed light illuminates the cantilever, $F_{\rm photon}$ can be expressed as

$$\begin{aligned}F_{\rm photon}=&\frac{4F_{\rm P}}{\pi}\sin\left(\omega_0t\right)\\&+\sum_{n=1}^{\infty}\frac{4F_{\rm P}}{\pi\left(2n+1\right)}\sin\left[\left(2n+1\right)\omega_0t\right]+F_{\rm c}.\end{aligned} \tag{10}$$

Only the first item on the right side of Eq. (10) contributes to the displacement amplitude shift. The maximum displacement change of the cantilever caused by the pulsed light is

$$\Delta A=\frac{4F_{\rm P}Q}{\pi k}=\frac{32P_0QR\cos\alpha}{\pi c}\frac{L^3}{EWH^3}. \tag{11}$$

4. Results and discussion

The amplitude of microcantilever free end with ($A_{\rm L}$) or without a light pressure (A) were recorded. The amplitude shift of the cantilever under a light pressure can be obtained $\Delta A_{\rm M}=A_{\rm L}-A$. The measured Q values are around 1600 under a vacuum of 10^{-4} Pa, not so high as expected due to the surface effect, more than one order of magnitude increase of the Q value can be achieved by annealing at ultra high vacuum (UHV)[15]. Figure 3 gives the light power P_0 dependence of $\Delta A_{\rm M}$ for a cantilever with $L=245$ μm, $W=4.56$ μm, and $H=116$ nm when $F_{\rm drive}$ and $F_{\rm photon}$ of a sinusoidal light are in-phase and anti-phase, respectively. Figure 4 depicts the relation between $\Delta A_{\rm M}$ and P_0, when the pulsed incident light and cantilever driving signal are in-phase or anti-phase.

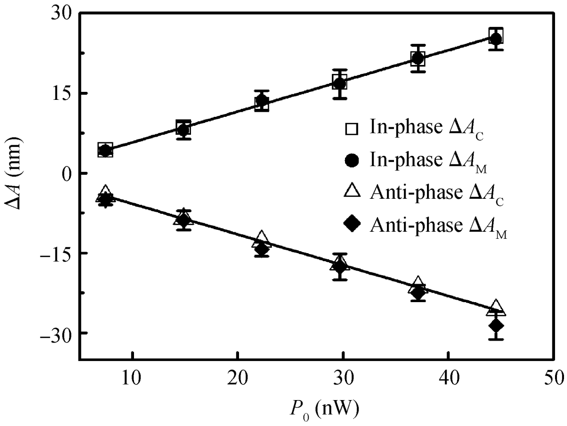


Fig. 3. P_0 dependence of $\Delta A_{\rm M}$ while $F_{\rm drive}$ and $F_{\rm photon}$ of sinusoidal light are in-phase and anti-phase.

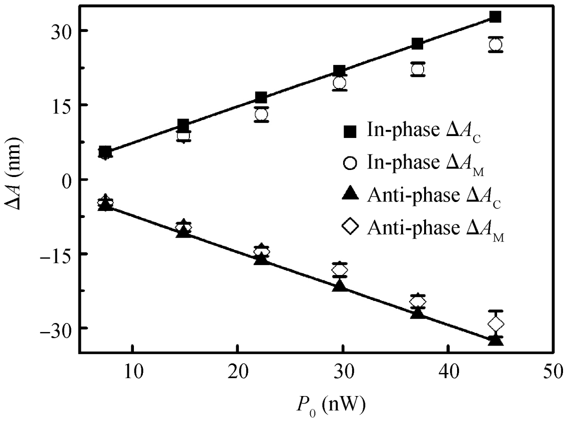


Fig. 4. P_0 dependence of $\Delta A_{\rm M}$ while the pulsed $F_{\rm drive}$ and $F_{\rm photon}$ are in-phase and anti-phase.

As is shown in Figs. 3 and 4, the in-phase sinusoidal and pulsed light enhance the cantilever displacement, and the amplitude shift $\Delta A_{\rm M}$ increases linearly with the light power. The anti-phase sinusoidal and pulsed light attenuates the cantilever vibration, and the vibration amplitude decreases linearly with the light power. These experimental results $\Delta A_{\rm M}$ are close to the corresponding theoretical values $\Delta A_{\rm C}$. With the measured Q values (around 1600), the detection sensitivity for in-phase sinusoidal infrared light is estimated about 0.570 m/W, one order of magnitude higher than the metal-semiconductor cantilever photon detector based on photon-induced electron stress with a detection sensitivity 0.0527 m/W[11]. The anti-phase light pressure leads to slightly higher sensitivity of 0.591 m/W.

A similar tendency was observed for pulsed light irradiation, which causes a larger amplitude change and a better detection sensitivity of 0.649 m/W due to the higher light intensity and stronger interaction between the photons and the cantilever, compared to the corresponding values for the sinusoidal light. Figure 5 compares the cantilever response to the sinusoidal and pulsed light, and further indicates that the

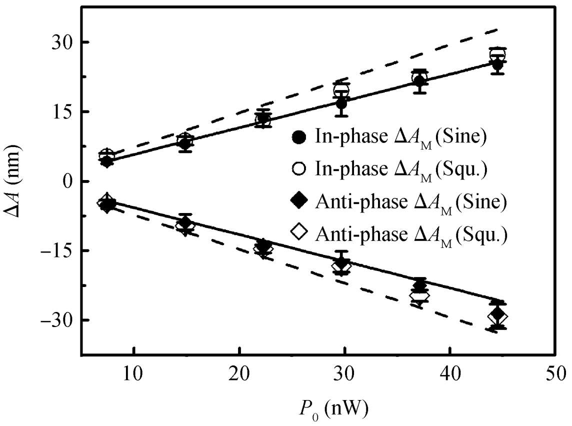


Fig. 5. P_0 dependence of ΔA_M. The "mark" denotes the measured data, and the solid and dashed lines are the corresponding theoretical data for the sinusoidal and pulsed light irradiation.

pulsed light could realize a better sensitivity. The minimum detectable displacement of the laser Doppler vibrometer is less than 7 pm, much smaller than the amplitude change of the lever used here. Therefore, the photon detection sensitivity is mainly determined by the performance of the cantilever, that is, the quality factor and resonance frequency. For the cantilever with a Q value of about 1600 at a vacuum level of 10^{-4} Pa, the minimum detectable power 7.4 nW of infrared light is achieved.

In this method, the minimum detectable power of infrared light is mainly determined by the thermo-mechanical noise of the microcantilever, as described in Ref. [12], the noise from other components of the measurement setup are negligible. Therefore, a high-end microcantilever with a high resonance frequency, high Q and a small spring constant is critical for the high-sensitive detection of infrared light.

5. Conclusions

A new infrared photon detection principle using a microcantilever as the sensing element to achieve nanowatt detection accuracy at room temperature is experimentally demonstrated and a minimum light power of 7.4 nW is detected.

The infrared photon is measured by monitoring the amplitude change of the cantilever under light pressure force. The infrared light irradiation, which is either in-phase or anti-phase to the cantilever driving force, leads to the displacement shift of the lever being distinguished. This effect has been applied to infrared light detection of high sensitivity. The pulsed light irradiation slightly increases the cantilever response compared to the sinusoidal light and thus improves the sensitivity of the detector.

When the cantilever is annealed in UHV, the Q value of the cantilever can reach 10^4 or even 10^5, thus the ultrahigh detection sensitivity can be realized.

References

[1] Sharabani Y, Paltiel Y, Sher A, et al. InAsSb/GaSb heterostructure based mid-wavelength-infrared detector for high temperature operation. Appl Phys Lett, 2007, 90: 232106
[2] Liu Y, Wu Q L, Han Z F, et al. Single photon detector at telecom wavelengths for quantum key distribution. Chin Phys Lett, 2006, 23(1): 252
[3] Zappa F, Lacaita A L, Cova S D, et al. Solid-state single-photon detectors. Opt Eng, 1996, 35(4): 938
[4] Tian Z B, Gu Y, Wang K, et al. Gas source MBE-grown metamorphic InGaAs photodetectors using InAlAs buffer and cap layers with cut-off wavelength up to 2.7 μm. Chin Phys Lett, 2008, 25(6): 2292
[5] Korneev A, Kouminov P, Matvienko V, et al. Sensitivity and gigahertz counting performance of NbN superconducting single-photon detectors. Appl Phys Lett, 2004, 84: 5338
[6] Komiyama S, Astafiev O, Antonov V, et al. A single-photon detector in the far-infrared range. Nature, 2000, 403: 405
[7] Kardynal B E, Hees S S, Shields A J, et al. Photon number resolving detector based on a quantum dot field effect transistor. Appl Phys Lett, 2007, 90: 181114
[8] Kong N, Liu J Q, Li L, et al. Strain-compensated InGaAs/InAlAs quantum cascade detector of 4.5 μm operating at room temperature. Chin Phys Lett, 2010, 27(3): 038501
[9] Razeghi M. Technology of quantum devices. New York: Springer, 2010
[10] Lai J, Perazzo T, Shi Z, et al. Optimization and performance of high-resolution micro-optomechanical thermal sensors. Sensors and Actuators A, 1997, 58: 113
[11] Datskos P G, Rajic S, Datskou I. Detection of infrared photons using the electronic stress in metal–semiconductor cantilever interfaces. Ultramicroscopy, 2000, 82: 49
[12] Cao L X, Zhang F X, Zhu Y F, et al. Ultrasensitive detection of infrared photon using microcantilever: theoretical analysis. Chin Phys Lett, 2010, 27(10): 108501
[13] Rugar D, Stipe B C, Mamin H J, et al. Adventures in Attonewton force detection. Appl Phys A, 2001, 72(Suppl): S3
[14] Liyama M, Kamiya T, Yanai H. Optical field mapping using single-mode optical fibers. Appl Opt, 1978, 17(12): 1965
[15] Yang J L, Ono T, Esashi M. Energy dissipation in submicrometer thick single-crystal silicon cantilevers. J Microelectromech Syst, 2002, 11(6): 775