BROADBAND LONG-WAVELENGTH INFRARED MICROMECHANICAL PHOTOSWITCH FOR ZERO-POWER HUMAN DETECTION

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ABSTRACT

This paper reports on the first demonstration of a long-wavelength infrared (LWIR) micromechanical photoswitch (MP) suitable for human detection with zero-power consumption in standby. The proposed MP employs a highly-efficient broadband IR absorber (η~80%, λ=8-12μm), spectrally matching with the IR radiance of a human body. An ultra-low detection threshold of ~140 nW is experimentally demonstrated for the first time thanks to the high thermal sensitivity (~1.44 nm/nW) and stiffness (~0.033 nN/nm) of the optimized bimaterial actuating beams and the aggressively scaled nanoscale contact gap (<200 nm) maintained by the built-in temperature and stress compensation mechanisms. Such low threshold potentially enables human detection with a lens at a projected distance of 5.7 m.

INTRODUCTION

IR-based human detection technologies have been extensively used in motion-triggered automation, indoor/outdoor security, search-and-rescue and many other applications [1]. However, the relatively high-power consumption of state-of-the-art motion detectors limits their battery life and increases the maintenance cost of sensor networks deployed in remote or hazardous locations. For instance, commercial off-the-shelf motion detectors based on a pyroelectric IR sensor consume about 200 μW continuously in standby [2]. Their lifetime is limited to less than one year (powered by a coin battery) when deployed in regions where energy harvesting is not available. The constant power consumption is attributed to the use of active electronics for signal conditioning and processing which accounts for the great majority of total consumed power. The high maintenance cost associated with limited sensor lifetime has been a major limiting factor for the implementation of high capacity sensor networks for security monitoring in regions such as tunnels, underground facilities and national borders. Driven by the growing need for persistent monitoring with long sensor lifetime, significant efforts have been devoted into developing completely-passive switch-based sensors capable of digitizing the signal of interests without using active electronics [3-4].

Recently, our group has demonstrated zero-power IR sensors based on plasmonically-enhanced micromechanical photoswitches (MPs) [4-7]. MPs exploit IR signature emissions from targets of interests to form an electrical channel between the device terminals via thermomechanical coupling. An MP can be placed in between a battery and active electronics, such as shown in Figure 1(a), to eliminate power consumption when there is no event of interests. In other words, it is only when the absorbed IR power exceeds the designed threshold level (~500 nW) that the mechanical switch is closed to supply power to the active electronics. A large ON/OFF conduction ratio (>10^{12}) and near-infinite subthreshold slope are measured to demonstrate the zero-standby-power consumption [4]. One of the crucial components in the previously demonstrated MPs is the narrowband plasmonic absorbers tailored for near-unity absorption in mid-wavelength IR (MWIR) spectral range specifically for detection of hot exhaust plumes [8]. Nevertheless, the reported narrowband absorption of the plasmonic absorbers in MWIR and the relatively high detection threshold of ~ 500 nW prevents the use of such previously-demonstrated MPs for the detection of objects with a temperature significantly lower than that of exhaust plumes, such as the one of a human body.

In this work, a long-wavelength infrared (LWIR) MP with a reduced IR threshold (~140 nW) is demonstrated for the first time, suitable for human detection with zero-power consumption in standby. Differently from state-of-the-art human detectors that rely on pyroelectric IR sensors and active digitizing electronics, the device proposed here exploits the energy contained in the LWIR radiation emitted from a warm object to trigger a micromechanical switch. The first-of-its-kind prototype presented here is selectively activated by a broadband LWIR radiation (λ = 8-14 μm) closely matching the spectral content of IR radiation emitted by a human body (Figure 1a). The proposed technology therefore demonstrates the great potential for the realization of persistent zero-power human detection to be deployed in remote regions where high maintenance cost is to be avoided.

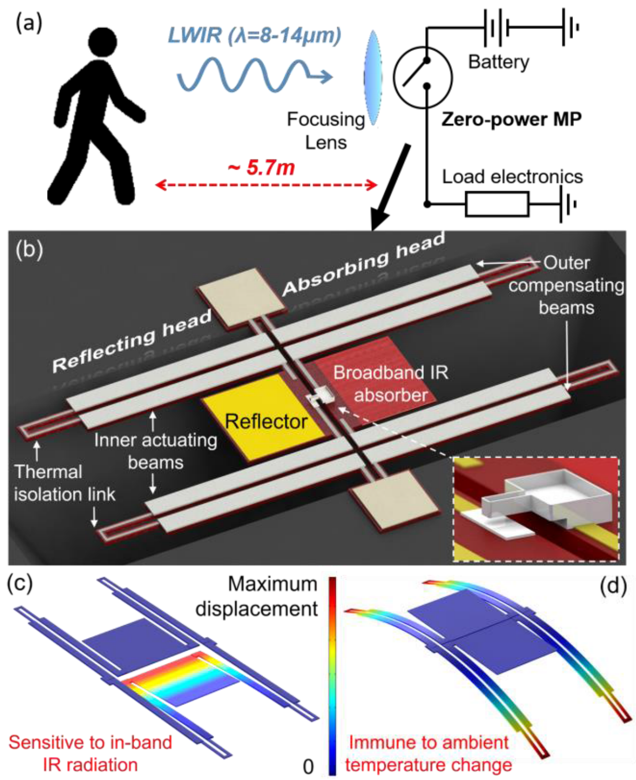

Figure 1: (a) The near-zero power broadband MP used for human detection. (b) The 3-dimensional schematic of the broadband MP. The inset shows a zoomed-in schematic highlighting the bowl-shaped platinum (Pt) contact tip. (c) Finite Element Method (FEM) simulation result showing the downward bending of MP in response to in-band (LWIR) IR absorption. (d) FEM simulation result showing the complete immunity to the ambient temperature change.

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DEVICE DESIGN

The MP proposed here consists of a pair of symmetric released cantilevers, each composed of an absorbing (or reflecting) head and an inner and outer pair of thermally sensitive bimaterial legs separated by a thermal isolation link as shown in Figure 1b. The broadband absorbing head can selectively convert impinging optical power in LWIR regime. Upon the absorption of broadband LWIR radiation in the absorbing head, a large and fast increase of temperature in the corresponding inner pair of legs results in a downward displacement of the cantilever, bringing a high-stiffness platinum (Pt) tip into contact with the opposite terminal (Figure 1c). It is worth noting that the switch remains open until it absorbs LWIR radiance (e.g. from a human nearby) regardless of the change in ambient temperature, thanks to the symmetric design of the two cantilevers (Figure 1(d)). The sub-micron air-gap maintained in standby translates directly into essentially zero leakage current and zero-standby power IR sensing.

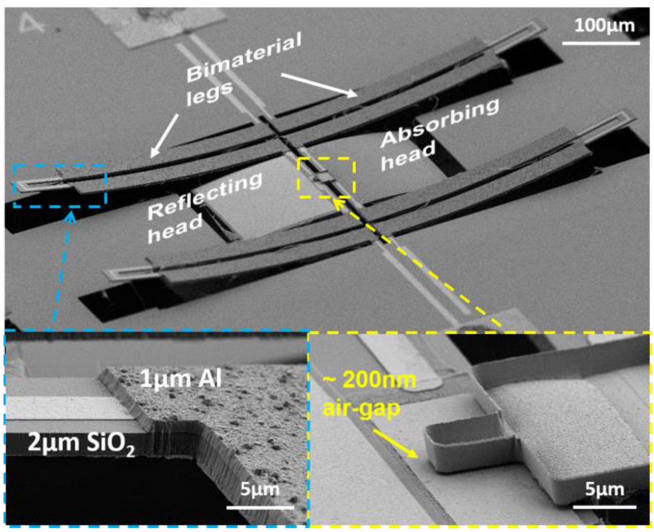

Figure 2: Scanning electron microscope (SEM) image of the fabricated device. The insets show close-up images of the bi-material leg and the Pt contact-tip, highlighting the increased Al thickness and the aggressively scaled contact gap of ~200nm.

Low Detection Threshold MP for LWIR Sensing

In this work, a 2-µm silicon dioxide (SiO_2) slab backed by a metal reflector is employed as the IR absorbing element in an optimized micromechanical photoswitch for ultra-low threshold IR detection in the LWIR range (Figure 2). Replacing the plasmonic absorber used in previous demonstration for narrowband mid-IR absorption, this broadband dielectric absorber exploits the intrinsic absorption of the SiO_2 layer. The intrinsically high loss of SiO_2 slab due to vibrational modes of longitudinal-optical (LO) phonons leads to a consistently high broadband absorption in LWIR specifically suitable for human detection applications [9].

To improve the detection threshold, two approaches were adopted. First, the thermal sensitivity of the bimaterial actuating beams is increased by optimizing thickness ratio of aluminum (Al) and SiO_2. Differently from the previous demonstrations, the device in this paper employs 1-µm Al on a 2-µm SiO_2 as shown in the bottom left inset of Figure 2. This ratio in fact corresponds to the maximum thermal sensitivity (1.44 nm/nW, corresponding to more than 15% increase compared to previous demonstrations) for a fixed 2-µm SiO_2 layer (Figure 3).

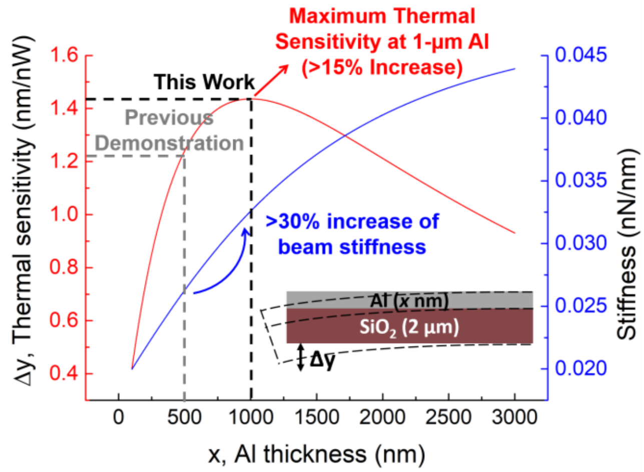

Figure 3: Thermal sensitivity (left y-axis) and beam stiffness (right y-axis) of the bimaterial legs as a function of the Al thickness for a fixed SiO2 thickness of 2-µm. The vertical displacement, Δy, per unit absorbed IR power is maximum for an Al thickness of 1-um.

Second, the contact-gap is scaled down to reduce the actuation threshold. The smaller contact-gap was defined by the thickness of amorphous silicon layer, which serves as a sacrificial layer between the Pt contact and the electrical terminal on the opposite head [4]. It is worth noting that, although the contact gap can be in principle arbitrarily scaled within fabrication limits, a small gap inevitably yields an insufficient restoring force causing stiction of the contacts. In the device presented here, however, stiction-free contacts are achieved, despite the aggressive gap scaling, thanks to the optimization of the bimaterial beams, which not only increased the thermal sensitivity but also the overall stiffness of the folded beam structure (~ 0.033 nN/nm). Compared to the previous demonstration of narrowband MPs in [4], the optimized bimaterial design led to more than 15% increase in maximum thermal sensitivity and at the same time, the beam stiffness increased by more than 30% (Figure 4).

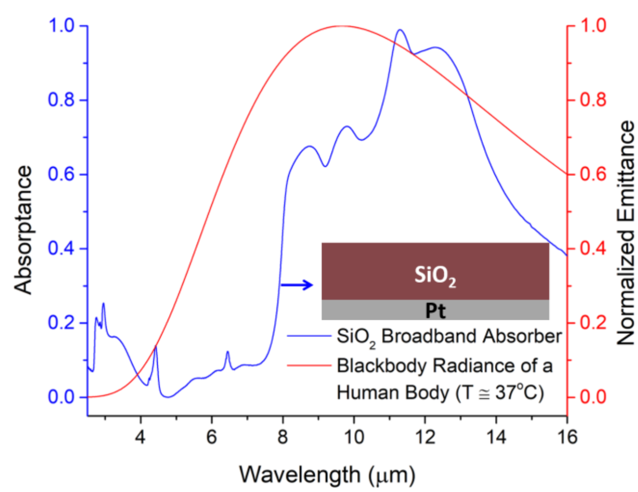

Figure 4: The spectral response of the broadband SiO2 absorber in LWIR (blue curve, left y-axis) and the normalized blackbody emission at 37°C (red curve, right y-axis). The inset shows the cross-section schematic of the broadband SiO2 absorber.

EXPERIMENTAL RESULTS

The spectral response of the fabricated device was characterized using a Fourier Transform Infrared Spectroscopy (FTIR) microscope. The reference was first measured on the gold reflecting head, then the reflection (*R*) of the SiO_2 dielectric absorber on the absorbing head was measured. Since the optically-thick (~100 nm) continuous Pt plate underneath efficiently suppress the transmitted power (transmittance, *T*), the absorptance (*A*) can be calculated as follows assuming negligible transmittance: $A = 1\text{-}R\text{-}T \approx 1\text{-}R$. The fabricated dielectric absorber exhibits the absorption as high as $\eta \sim 98.8\%$ at $\lambda = 11.3$ μm and consistently high absorption ($\eta > 80\%$) in the wide LWIR regime ($\lambda = 8\text{-}14$ μm) (Figure 4). The measured absorption shows a good spectral overlap with the emission spectrum of a blackbody at 37°C (closely representing a human body), which guarantees an effective sampling of the emitted IR power from a human body.

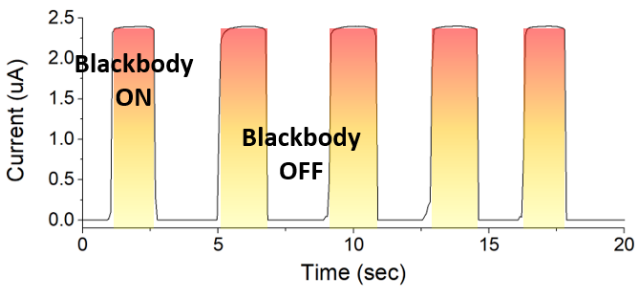

Figure 5: Measured current (using sourcemeter with a 10mV bias) through the MP in response to chopped IR radiation emitted by the calibrated blackbody source.

The function of the device was tested in a vacuum chamber using a calibrated blackbody IR source. The current through the device was monitored using a sourcemeter with a constant bias of 10 mV, while the blackbody radiation is manually chopped. Several consecutive ON/OFF cycles were recorded when the device was exposed to chopped broadband IR radiation (Figure 5). The minimum absorbed power to trigger the device ON was estimated based on the measured absorption spectrum and the calibrated power density, and found to be ~140 nW. The achieved detection threshold corresponds to a minimum detectable IR power density of ~6.2W/m^2, which is equivalent to the IR radiation collected from a human body at 5.7m distance, with a 25mm focal length lens. The same high-stiffness bowl-shaped Pt contact demonstrated in [4] is employed in the LWIR MPs, which guarantees the outstanding reliability with numerous consecutive ON/OFF cycles (up to 8000 cycles measured). It is worth noting that a blackbody temperature of 300°C had to be used to deliver to the sensor a power density equivalent to the one that would be received from a 37°C human body without the attenuation of the vacuum chamber window. That is, the inherent absorption in CaF_2 optics limits the transmission and allows only a fraction of the available power from the blackbody in LWIR regime.

CONCLUSION

An ultra-low detection threshold of ~140 nW is experimentally demonstrated for the first time thanks to the high absorption (η~80%) of the SiO_2 broadband absorber, the high thermal sensitivity (~1.44 nm/nW) of the optimized bimaterial actuating beams, and the aggressively scaled nanoscale contact-gap (<200 nm) maintained by the built-in temperature and stress compensation mechanisms. These results demonstrate the great potential of the proposed technology for the realization of persistent zero-power human detection. The drastically increased sensor lifetime with the MPs will enable the unprecedented zero-power IR sensor network that can be deployed virtually anywhere.

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