Analysis of Silicon Nitride Trampoline Resonators for Ultrasensitive Infrared Detection

Yuncong Liu*, Connor A. Watkins, and Philip X.-L. Feng*
Department of Electrical & Computer Engineering, University of Florida, Gainesville, FL 32611, USA
*Emails: yuncong.liu@ufl.edu, philip.feng@ufl.edu

2023 IEEE Photonics Conference (IPC) | 979-8-3503-4722-7/23/$31.00 ©2023 IEEE | DOI: 10.1109/IPC57732.2023.10360553

Abstract—We theoretically assess the ability of ultrathin silicon nitride (SiN) trampoline nanomechanical resonators for ultrasensitive infrared light detection. Our findings indicate an order of magnitude improvement in normalized responsivity, achieving a level of 10^6/W. Absorptance optimization via patterned metamaterials could further enhance the resonance shift by two orders of magnitude.

Keywords—silicon nitride, thermal infrared (IR) detector, optomechanical resonator, trampoline resonator, responsivity.

I. Introduction

Thermal infrared (IR) detectors are instrumental in applications such as thermal imaging and IR spectroscopy [1]. Their operation relies on the absorption of incident photons which instigates photothermal heating. This results in an increase in the temperature of the detectors that can be electrically gauged via changes in resistance or through pyroelectric currents. Alternatively, micro/nanostructures that display strong temperature dependence can be exploited for mechanical IR sensing. This strategy has been effectively employed in structures like silicon nitride (SiN) nanomechanical strings [2], drumhead resonators [3], and trampoline resonators [4]. When such a resonant device is subject to incident light, the absorbed power induces a temperature rise, causing a reduction in tensile stress due to thermal expansion. This causes a downshift in the mechanical resonance frequency. With precise measurement of the frequency shift, the amount of light absorbed can be determined, thus enabling the resonator to function as a thermal IR detector (Fig. 1). In this work, we present a theoretical analysis on the mechanical resonance of a SiN trampoline and assess its responsivity towards thermal IR detection. Our calculations indicate that a 10^6/W normalized resonance shift per nanowatt absorbed power is attainable at 0.8MPa tensile stress. Furthermore, a metasurface-integrated SiN trampoline resonator could potentially enhance detectable frequency shifts by two orders of magnitude.

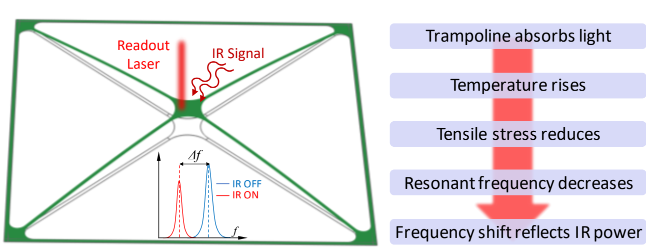

Fig. 1. Operating principle of the nano-optomechanical trampoline resonator. The readout laser reveals the resonant motion and frequency as it is modulated by the displacement of the trampoline. The IR radiation is partially absorbed by the resonator, causing a shift in the trampoline resonance frequency, which is used to measure the incident optical power.

II. Methods and Results

We utilize a probe beam to photothermally monitor the resonant motion of the trampoline, which in turn modulates the interference of reflected probe beams (Fig. 1). The proposed design of our SiN trampoline incorporates a 20μm×20μm inner square island, supported by four 5μm-wide, 260μm-long tethers (Fig. 2a). These tethers are connected to the Si substrate via four widened and rounded clamping points, which are designed with a radius of curvature to dilute dissipation by minimizing loss of coherent elastic energy. To thoroughly understand the mechanical characteristics of the structure, we calculate the mechanical eigenfrequencies via finite element method (FEM) analysis in COMSOL, implementing clamped boundary conditions on the overhanging outer edges. We simulate the resonance frequencies with the following SiN parameters: Young's modulus E_Y=250GPa, density ρ=2700kg/m^3, Poisson ratio ν=0.23, and built-in stress σ_0=0.8GPa. The resulting mode shapes are displayed in Fig. 2b–d.

Here we focus on the fundamental flexural mode of the trampoline which can be modeled by a crossed-string resonator with the equation:

$$f_0 = \frac{\pi}{8L_s^2}\sqrt{\frac{4E_Y h^2}{3\rho}}\sqrt{1+\frac{12\sigma_0 L_s^2}{E_Y h^2 \pi^2}} \qquad (1)$$

where L_s is the diagonal length of the resonator, E_Y is the Young's modulus, h is the thickness, ρ is the mass density, and σ_0 is the internal stress. As shown in Fig. 2e, we find very good agreement with the results from the FEM models. With an increase in temperature, the resonator's internal stress is reduced due to thermal expansion following the relationship $\Delta\sigma = -\alpha\Delta T E_Y$, where α denotes the thermal expansion coefficient and ΔT represents the temperature difference between the surrounding substrate and trampoline resonator.

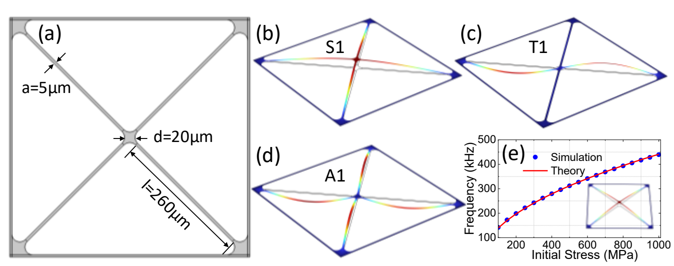

Fig. 2. (a) Geometric features of SiN resonator of a 50nm thick trampoline with a size of 30μm and a tether width of 5 μm. (b)–(d) Simulated displacement profiles of the first symmetric (S1), first torsional (T1), and fist asymmetric (A1) modes with frequencies at 311.43kHz, 642.10kHz, and 653.0kHz, respectively. (e) Resonant frequency of S1 calculated numerically (blue dots) is compared with resonant frequency calculated analytically using Eq. (1).

This work was supported in part by the NSF I/UCRC on Multi-functional Integrated System Technology (MIST) Center

The resonant frequency shift Δf can be described using the first order Taylor series approximation:

$$\Delta f \approx f_0 \left(\frac{-12 L_s^2 \alpha \Delta T E_Y}{24 L_s^2 \sigma_0 + 2 E_Y h^2 \pi^2} \right) \quad (2)$$

where the rising temperature change ΔT caused by IR light absorption is determined by a thermal RC circuit model:

$$\Delta T = P_{\text{in}} A(\lambda) \left(\frac{R_T}{\sqrt{1 + 4\pi^2 f_0^2 R_T^2 C^2}} \right) \quad (3)$$

where P_{in} is the incident power, $A(\lambda)$ is the absorptance at some wavelength λ, C represents the thermal capacitance, which is given by the heat capacity of the suspended SiN film, and $R_T = L_s/(\kappa a h)$ is the thermal resistance of the tether supports, where κ is the thermal conductivity of SiN. Plugging Eq. (3) into Eq. (2), Δf can be expressed as:

$$\Delta f \approx f_0 P_{\text{in}} A(\lambda) \frac{-12 L_s^2 \alpha E_Y}{24 L_s^2 \sigma_0 + 2 E_Y h^2 \pi^2} \frac{R_T}{\sqrt{1 + 4\pi^2 f_0^2 R_T^2 C^2}} \quad (4)$$

The normalized responsivity ($\Re_n$) of the IR detector is defined as the fractional frequency change $\delta f = \Delta f / f_0$ per power of the incident IR beam, which can be derived from Eq. (4) as:

$$\Re_n = \frac{-\delta f}{P_{\text{in}} A(\lambda)} \approx \frac{12 L_s^2 \alpha E_Y}{24 L_s^2 \sigma_0 + 2 E_Y h^2 \pi^2} R_T \quad (5)$$

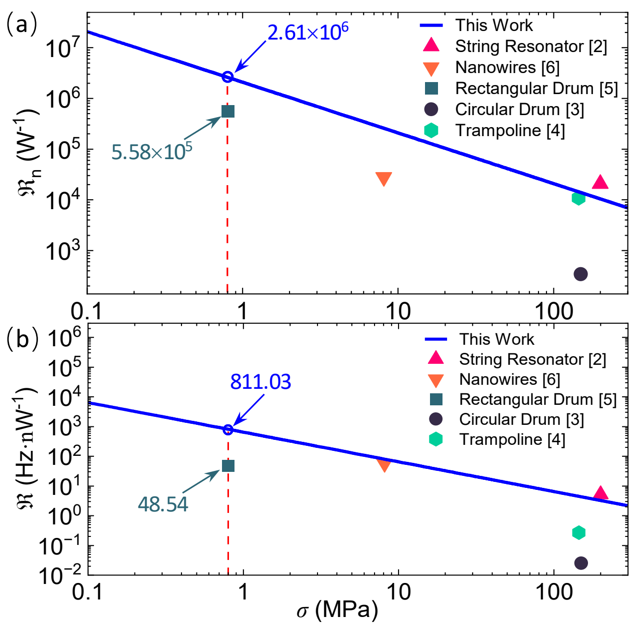

Fig. 3. (a) Comparison of $\Re_n$ calculated from Eq. (5) and reference values from previous studies under various amounts of tensile stresses. (b) Comparison of the responsivity $\Re$ assuming a unit nW power is absorbed by the device.

Figure 3a illustrates the variation of normalized $\Re_n$ with varying levels of tensile stresses ranging from 0.1–300MPa, as depicted by the solid blue curve plotted based on Eq. (5). Compared to reference values for $\Re_n$ reported from prior studies on SiN-based bolometers, our calculated $\Re_n$ is higher than most reference values given the same tensile stress. The $\Re_n$ is expected to be one order of magnitude greater than the highest reported $\Re_n$ in literature, to reach 10^6/W under 0.8MPa of stress (red dotted line). Figure 3b displays the absolute frequency shift per nanowatt absorbed power at different tensile stress levels.

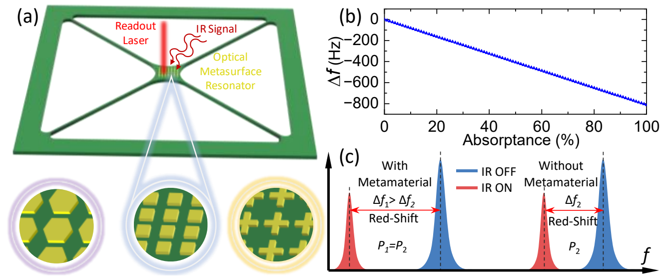

Fig. 4. (a) Schematic of optomechanical metamaterial IR detector. The metasurface atop the trampoline can be patterned with various shapes. (b) The Δf is calculated and plotted against different absorptance levels based on Eq. (4) with a P_{in}=1nW. (c) Illustration of the larger frequency shift of metamaterial-aid resonator than that in trampoline-only resonator.

To examine the performance of the detector for mid-IR absorption, we first calculate the absorptance of a 50nm-thick SiN film with 0.8MPa initial stress over the wavelength range of 3–5μm, and find a low, flat absorptance of ~0.2%. Putting this into Eq. (4) with an absorbed power of 1nW produces a $\Delta f \approx$-1.6Hz. One way to enhance the Δf is to increase the $A(\lambda)$ at the active area of the detector. We plot the impact of $A(\lambda)$ on Δf in Fig. 4b, showing a Δf improvement of two orders of magnitude (~769.96Hz) with an enhanced $A(\lambda)$≈95%. Such an $A(\lambda)$ could be realized by patterning a metasurface on the trampoline pad, creating an optomechanical metasurface IR detector (Fig. 4a). The metasurface can be optimized by modifying the shape, feature sizes, and/or spacing between adjacent unit cells. When exposed to an identical IR power, the metasurface-equipped detector shows a significantly larger Δf compared to the trampoline-only detector, a benefit for detecting ultralow radiation levels that could otherwise go unnoticed without the addition of the metasurface.

III. Conclusion

In summary, we have evaluated the potential of a SiN trampoline resonator for thermal IR detection. Our calculations indicate that a $\Re_n$ of 10^6/W can be achieved at a low tensile stress of 0.8MPa, marking an improvement by one order of magnitude over today's state-of-the-art. This $\Re_n$ translates into a Δf of 811Hz per nanowatt absorbed power. Moreover, by integrating metamaterials into the trampoline design, we foresee an enhancement in Δf by two orders of magnitude.

References

[1] J. T. Skidmore, *et al.*, "Superconducting bolometer for far-infrared Fourier transform spectroscopy", *Appl. Phys. Lett.*, vol. 82, pp. 469–471, 2003.

[2] S. Yamada, *et al.*, "Photothermal infrared spectroscopy of airborne samples with mechanical string resonators", *Anal. Chem.*, vol. 85, pp. 10531–10535, 2013.

[3] M. Piller, *et al.*, "Nanoelectromechanical infrared detector", in *Proc. SPIE*, pp. 9–15, 2019.

[4] M. Piller, *et al.*, "Thermal IR detection with nanoelectromechanical silicon nitride trampoline resonators", *IEEE Sens. J.*, vol. 23, pp. 1066–1071, 2023.

[5] M. H. Chien, *et al.*, "Single-molecule optical absorption imaging by nanomechanical photothermal sensing", *PNAS*, vol. 115, pp. 11150–11155, 2018.

[6] D. Papas, *et al.*, "Optomechanical metamaterial nanobolometer", *ACS Photonics*, vol. 6, Art. no. 126110, 2021.