A NOVEL TRANSDUCER FOR PHOTON ENERGY DETECTION VIA NEAR-FIELD CAVITY OPTOMECHANICS

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ABSTRACT
This paper reports an optomechanical transducer for photon energy detection on the silicon-photonics platform. The photon energy is enhanced by a ring resonator and converted into mechanical energy via optical gradient force. An integrated electron tunneling displacement sensor is used to detect the photon-induced mechanical deformation on-chip. Compared with the traditional photon energy detection based on photon absorption, this optomechanical transducer has more compact size (60 μm × 230 μm), low thermal noise (0.03 V/˚C) and low cost. And it is a silicon based device, compatible with CMOS process and easier to be integrated with silicon-photonics.

KEYWORDS
Optomechanics, photon energy detection, electron tunneling displacement sensor, resonator cavity, NEMS

INTRODUCTION
Traditional on-chip photon energy detection, also known as photodiode, is based on photon absorption via a p-n junction or p-i-n structure made of semiconductor materials. Their wavelength response is determined by the materials’ bandgap, for example Si working in 190 nm – 1100 nm while Ge working in 400 nm – 1700 nm [1]. In communication wavelength (~ 1550 nm) region, all of the photodiodes are mostly fabricated by InGaAs material. Unfortunately, its fabrication process is not compatible with CMOS process, and it is also difficult to integrate with silicon-photonics, which is the most important direction for future fiber communication system [2-3]. Although SiGe based photodiodes are proposed by some researchers, its fabrication process is complex and the thickness of Ge-layer is greatly limited by the strain resulting from lattice mismatch between Ge and Si [4-5]. To solve these problems, a novel approach to detect the photon energy by Si material at 1550 nm wavelength by optomechanical effect is proposed.

The detection principle based on optomechanical effect is relative to the energy transfer between photon and mechanics which is different from the photon absorption phenomena [6]. In the device, the photo energy is converted into the mechanical energy through optical gradient force, and then stored in a deformable suspended Si nano-beam. The deformation is measured by a highly precise electron tunneling displacement sensor, which is also on-chip integrated [7]. A ring resonator cavity structure is employed in the detection system to enhance the light intensity, and subsequently to improve the optomechanical coupling coefficient ($g_{OM}$), which is approximately 30-fold higher than previous report [8].

DESIGN AND THEORY
Figure 1 shows the working principle of the proposed photon energy transducer. It consists of a micro-ring resonator cavity and a double clamped suspended nano-waveguide as shown in Fig. 1(a). The micro-ring cavity enhances the light intensity according to resonance. The enhanced optical field can excite dipoles in the adjacent nano-waveguide and generate an attractive optical force [9]. It can be explained by the optical tweezers model, in which the force attracts the dielectric object to the center of the light beam due to the gradient of the optical field as shown in Fig. 1(b). Therefore, the input photon energy is transferred into the mechanical energy and indicated by the waveguide bending value.

Figure 1: (a) Schematic of the proposed transducer for photon energy detection via a micro-ring resonator with a suspended nano-waveguide. (b) Generic cavity system for particle manipulation by using gradient optical force.

In the nano-waveguide structure system, the optical gradient force generated by one photon can be expressed as [10]
The total optical gradient force in the coupling system is

$$f_o = \frac{d(h\omega)}{d\xi} |_{k}$$  \hspace{1cm} (1)

where $h$ is the reduced Planck constant, $\omega$ is the light frequency, $k$ is the wave vector, $\xi$ is the gap between the ring resonator and the suspended beam. The frequency $\omega$ is related to the effective refractive index of the waveguide as $\omega = \omega_0 n_{ef}$, where $\omega_0$ is the free space frequency. The total optical gradient force in the coupling system is

$$F = N f_o$$  \hspace{1cm} (2)

where $N$ is the total photons number in the coupling part, and can be expressed as

$$N = \frac{U}{\hbar \omega_0}$$  \hspace{1cm} (3)

Assuming that the energy in the coupling part is given by $U = PL_n g/c$, where $P$ is the optical power, $L$ is the length of the coupling part and $n_g$ is the group index of the mode. Since the coupling part is generated between the ring resonator and the suspension beam, the optical power is enhanced compared with the input power as expressed

$$P = BP_{in}$$  \hspace{1cm} (4)

where $B$ is the buildup factor of the ring resonator, which is determined by the coupling efficiency, waveguide loss and optical wavelength [11]. Therefore, the total optical gradient force in the coupling part can be expressed as

$$F = \frac{BP_{in} L n_g}{c \omega_0} \frac{d\omega}{d\xi}$$  \hspace{1cm} (5)

It shows the total force is proportional to the buildup factor $B$, and the length of the coupling part $L$. For a typical ring resonator, its buildup factor is up to ~ 100 [11], which means that the optical power can be enhanced by 100-fold as compared to that without resonator. Moreover, increasing the coupling length can also increase the optical force.

Figure 2: Calculated optical gradient force between the ring resonator cavity and the nano-waveguide.

Figure 2 shows the simulated optical gradient force with cavity and without cavity. The magnitude of the optical gradient force is up to 0.12 nN/μm/mW when the gap is 150 nm. This large optical gradient force can generate obvious displacement when the force is loading on the suspended structure.

In the displacement detection part, we use an electron tunneling displacement sensor to detect the deformation value of the suspended beam. The tunneling tip is fixed at the center of another suspension beam. It has a dimension of 300 nm × 220 nm × 300 μm (Width × Height × Length). The gap between the suspension beam and the deflection electrodes is around 500 nm. The calculated displacement varies with the deflection voltage is shown in Fig. 3. The electron tunneling tip can be steadily actuated between 0 to 100 nm when the deflection voltage is within 45 V. The deflection voltage is high due to the small interaction. The tunneling gap in the design is set as zero since it will be separated (around ~ 10 nm) in the fabrication according to our previous results in fabrication [8].

Figure 3: Actuation of the electron tunneling part via electrostatic force. Insert shows finite element simulation showing the mechanical shape of the suspension beam, with the strain distribution displayed in colour.

FABRICATION

All structures are fabricated on an SOI-wafer with a structure layer of 220 nm, and a buried-oxide (BOX) layer of 2 μm. Fig. 4 shows the SEM images of the photon energy transducer. The fabrication steps include: 1) silicon etching to form waveguide structures and suspended beams; 2) 2-μm cladding HDP SiO$_2$ deposition to cover the optical waveguide; 3) 2-kÅ a-Si deposition and etching for the release of region selection; 4) 5-kÅ contact pad deposition and etching; 5) release of BOX and cladding oxide by using VHF process; 6) 100-Å gold coating on the suspended beams and the tunneling tips to improve the electrical conductivity and reduce the tunneling barrier.

Fig. 4(a) is the overview of the photon energy transducer with a footprint size of 60 μm × 230 μm. The optical gradient force interaction region is highlighted by the red rectangle. The optical coupling length and gap are ~ 4 μm and ~ 150 nm, respectively. The ring resonator is designed as a racetrack-shape resonator to increase the optical coupling region, since the total optical gradient force is proportional with the coupling length as depicted in Eq. 5. The ring has a radius of 10 μm and a coupling length of 4 μm. In the design, the electrical part and the
optical part are separated to reduce the undesired interaction between the electrostatic force and optical gradient force. Fig. 4(b) shows the zoom view of the electron-tunneling displacement sensing part, which is marked by the yellow color. The dimensions of all suspended beams are 300 nm × 220 nm × 30 μm (Width × Height × Length). In order to increase the electrical conductivity, the suspended beams are firstly doped, and then coated with 100-Å thickness of Au by using shadow mask technology [12].

MEASUREMENTAL RESULTS

First, the transmission spectrum of the ring resonator is measured to characterize the light intensity in the optomechanical coupling as shown in Fig. 5. The optical power loss after the release process is mainly induced by the increased coupling loss between the lensed-fiber and the end of waveguide, but the quality factor (Q-factor) has no obvious reduction. For example, the 3-dB bandwidth (Δλ) of the marked resonance wavelength (1568.08 nm) is 0.083 nm. The Q-factor is up to 18, 900 with an on-resonance extinction of 11.8 dB while the Q-factor is approximately 19, 500 before the release process. The measured free spectral range (FSR) is 8.1 nm, and the estimated finesse (F) is 97.6 (F = FSR / Δλ) and the buildup factor (B) of the ring resonator is approximately 31 (F/π) [13]. It means that the light intensity in the ring resonator is 31-fold stronger than the input light.

![Figure 5: Transmission spectrum for the ring resonator cavity before and after the release process.](image)

To verify tunneling the relationship between the deflection voltage and the tip displacement is firstly measured. A deflection voltage (V₀ + VP) is applied to deflect the suspended beam and decrease the gap between the tips. The total electrostatic is proportional to (V₀ + VP(Pin, t))², and the resulting force is proportional to V₀² + 2V₀VP(Pin, t) + VP²(Pin, t). As V₀ >> VP, only the second term is important for dynamic control and this term is linearly depending on V₀. The tunneling current matches with the relationship of Iᵣ ∝ Vᵣ exp (−α√(Φx)), where Φ is the effective barrier height, α = 1.025 for Φ in eV, x in Å. Fig. 6 shows the tested tunneling at different deflection voltages. When the deflection voltage is kept within 28.30 – 28.58 V, the tunneling current is changed between 0 – 0.6 nA. Thus, the effective barrier height is 0.172 eV.

![Figure 6: Tested tunneling current vs. deflection voltage. The detected effective barrier height is 0.172 eV.](image)
the resonant condition of the ring resonator. Fig. 7 shows the photon energy measurement results. A feedback control circuit is used to maintain a constant tunneling current (0.4 nA) by adjusting the deflection voltage to balance the electrostatic force and the optical gradient force. The system obtains a stable detection performance in 0 - 1 mW. The detected sensitivity is up to 14.2 V/mW. During operation, a feedback circuit compares the tunneling current to a reference value and adjusts the deflection voltage as needed to keep the current constant.

**CONCLUSIONS**

In conclusions, a high-performance silicon-based photon energy transducer has been demonstrated by using the optomechanical technology. As it possesses the advantages of small size (60 μm × 230 μm), high sensitivity (14.2 V/mW), and COMS fabrication compatibility, it has potential applications in silicon- photonics integration chips and lab-on-chip analytical systems.

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