β-Ga_2O_3 NEMS Oscillator for Real-Time Middle Ultraviolet (MUV) Light Detection

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***Abstract*—We report on the first beta gallium oxide (β-Ga_2O_3) feedback oscillator built by using a β-Ga_2O_3 nanoresonator as the frequency reference for real-time middle ultraviolet (MUV) light detection. We fabricate suspended β-Ga_2O_3 nanodevices through growth of β-Ga_2O_3 nanoflakes using low-pressure chemical vapor deposition (LPCVD), and all-dry transfer of nanoflakes onto microtrenches. Open-loop tests reveal a resonance of the β-Ga_2O_3 nanomechanical resonator at ~30 MHz frequency with a quality factor (*Q*) of ~150–200. A closed-loop oscillator is then realized by using a combined optical-electrical feedback circuitry boosting an >70-fold enhancement to *Q*, to perform real-time MUV sensing. The oscillator exposed to cyclic MUV irradiation exhibits resonant frequency downshifts, with a responsivity of -3.3 Hz/pW and a minimal detectable power of 0.9 nW, showing great promise of β-Ga_2O_3 transducers for resonant-frequency-based MUV detection.**

***Index Terms*—Beta gallium oxide (β-Ga_2O_3), NEMS, oscillator, ultraviolet light detection.**

I. Introduction

PHOTODETECTION in solar-blind range (<280 nm) has received significant attention thanks to the absence of <280 nm light irradiation in earth atmosphere, providing a "black" background in solar-blind ultraviolet (UV) regime for ultrasensitive and selective illumination detection in missile tracking, fire detection, and environmental monitoring applications [1,2]. Beta gallium oxide (β-Ga_2O_3), a semiconductor with a monoclinic crystal structure, has an ultrawide bandgap, $E_g \approx 4.5$–4.9 eV [3,4,5], perfectly aligned with the cutoff wavelength of the solar-blind range. Various optoelectronic photodetectors (PDs) made of β-Ga_2O_3 crystal have been demonstrated utilizing the ideal bandgap and promising electronic properties of the material [6,7,8]. In addition, owing to its excellent mechanical properties (*e.g.*, measured Young's modulus, $E_Y = 261$ GPa) [9], β-Ga_2O_3 can be an appealing structural material for building micro/nanoelectromechanical systems (MEMS/NEMS) and new transducers, especially sensors that can capitalize on its ultrawide bandgap embedded in the MEMS/NEMS device platforms. To date, engineering of β-Ga_2O_3 crystal has been mainly focused on electronic devices without any moving parts, such as field effect transistors (FETs) [10,11,12] and electronic ultraviolet photodetectors [6,7,8]. Transducers exploiting mechanical properties of β-Ga_2O_3 for light sensing are yet to be shown and carefully studied.

In this letter, we describe the construction and measurement of the first self-sustaining β-Ga_2O_3 oscillator by using a β-Ga_2O_3 nanoresonator and a feedback circuitry, for middle UV (MUV, 200–300 nm, strongly overlapped with solar-blind range) light detection and real-time sensing. Fig. 1(a) illustrates the light sensing mechanism of the β-Ga_2O_3 nanomechanical device. The photothermal effect induced by the incident MUV light will elevate the temperature and expand the suspended β-Ga_2O_3 crystal, causing a resonance frequency downshift. By probing the resonance frequency shift of the β-Ga_2O_3 resonator, the intensity of the incident MUV light can be resolved to achieve MUV light detection and real-time sensing.

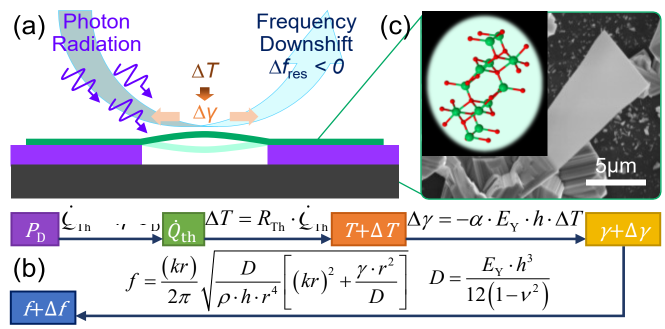

Fig. 1. (a) Transduction scheme of MUV light sensing. (b) Signal transduction chain. P_D: radiation power on device; $\dot{Q}_{th}$: rate of heat flow; *T*: device temperature; *γ*: surface tension; E_Y: Young's modulus of β-Ga_2O_3; *h*: device thickness; *r*: device radius; *ν*: Poisson's ratio of β-Ga_2O_3; *ρ*: mass density of β-Ga_2O_3; $(kr)^2$: eigenvalue; *f*: resonance frequency; (c) A scanning electron microscopy (SEM) image of a β-Ga_2O_3 nanoflake on the growth substrate. *Inset*: The crystal structure of β-Ga_2O_3.

II. Device Fabrication

The device fabrication process consists of chemical synthesis and direct transfer of β-Ga_2O_3 nanoflakes for making suspended nanostructures. We perform low-pressure chemical vapor deposition (LPCVD) to grow β-Ga_2O_3 nanoflakes on a 3C-SiC-on-Si substrate. Using high purity Ga pellets and O_2 gas precursor in a 950 °C LPCVD chamber for 1.5 hours, the formation of β-Ga_2O_3 nanostructures proceeds, step by step,

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from β-Ga_2O_3 nanocrystals to nanorods, and then to nanoflakes, without the need of any foreign catalyst [13]. Fig. 1(b) shows an as-grown β-Ga_2O_3 nanoflake on the growth substrate.

We use an all-dry transfer technique to fabricate suspended β-Ga_2O_3 nanomechanical structures (Fig. 2). We secure and harvest the β-Ga_2O_3 nanoflakes from the growth substrate by using a thermal release tape. We apply the harvested β-Ga_2O_3 nanoflakes to a substrate with predefined circular microtrenches. By heating up the substrate to 90 °C and detaching the thermal release tape, the nanoflakes are transferred onto the substrate, thus creating circular β-Ga_2O_3 drumheads on microtrench locations. Fig. 2(b) shows a nanomechanical resonator made of a 73nm-thick β-Ga_2O_3 nanoflake suspended over a ~5.2 μm-diameter circular microtrench. We use this resonator to build the β-Ga_2O_3 oscillator for MUV light detection.

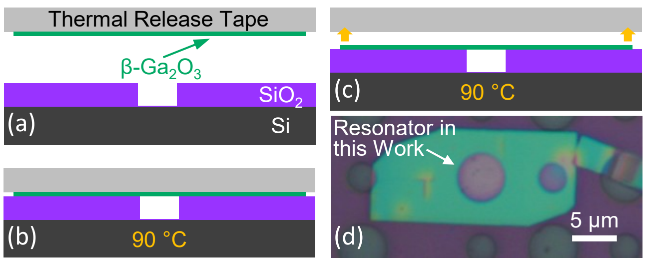

Fig. 2. Fabrication of β-Ga_2O_3 nanomechanical structures. (a) β-Ga_2O_3 nanoflake picked up by thermal release tape. (b) Pressing down the nanoflake and heating the substrate to 90 °C. (c) Lifting the tape in 90 °C temperature, leaving nanoflake on substrate. (d) Image of the fabricated β-Ga_2O_3 device.

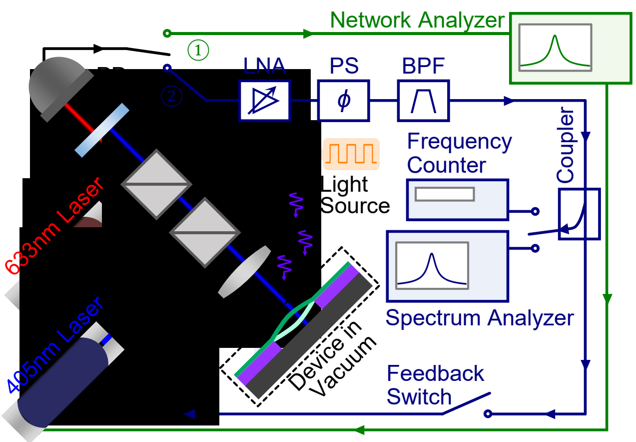

Fig. 3. Schematic of the apparatus for resonance measurement of a β-Ga_2O_3 nanoresonator and the demonstration of MUV detection via a self-sustaining β-Ga_2O_3 oscillator. PD: photodetector; LPF: long-pass filter; BS: beam splitter; LNA: low-noise amplifier; PS: phase shifter; BPF: band-pass filter.

III. Results and Discussion

Fig. 3 illustrates the system for measuring the resonances of the β-Ga_2O_3 nanomechanical resonator and the self-sustaining β-Ga_2O_3 oscillator for MUV detection. We use a home-built ultrasensitive laser interferometry system [9,14,15] to measure both the undriven thermomechanical noise spectrum and the photothermally driven resonance of the β-Ga_2O_3 nanomechanical resonator in vacuum. We employ a 633nm laser to read out the device motion interferometrically and a 405nm laser to photothermally drive the device. A PD is used to measure the intensity of the device-motion-modulated laser light. Loop #1 of the system is used for measuring the photothermally driven resonance of the β-Ga_2O_3 nanoresonator. Further, we build a closed-loop oscillator by adding a feedback circuit to the β-Ga_2O_3 resonator (Loop #2 with feedback switched on). The amplitude and phase of the signal from the PD are adjusted by an amplifier and a phase shifter, respectively, to satisfy the Barkhausen criterion for a feedback oscillator. The modified signal is then fed back to the device using the amplitude-modulated 405nm laser. A self-sustaining β-Ga_2O_3 oscillator is therefore achieved without external ac source. For demonstration of MUV light detection using the oscillator, we employ a light source with wavelengths of 200–600 nm to periodically illuminate the resonator. We measure its frequency response using the feedback oscillator.

We first measure the resonance frequency of the β-Ga_2O_3 nanomechanical resonator. Using Loop #1, we measure an open-loop, photothermally driven resonance of the β-Ga_2O_3 resonator at ~30 MHz with a quality factor (Q) ~ 150 (Fig. 4(a)). From Loop #2 without feedback, the resonator also exhibits a measured thermomechanical resonance at ~30 MHz with a Q ~ 200 (Fig. 4(b)), readout by the spectrum analyzer.

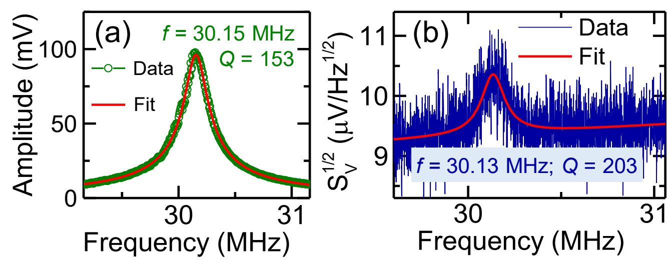

Fig. 4. (a) Photothermally driven response of a circular drumhead β-Ga_2O_3 resonator. (b) Thermomechanical noise spectrum of the resonator.

By closing the feedback switch in Loop #2, an oscillator is built. The Q of the ~30MHz resonance is boosted from ~200 to an effective Q_{eff} >15,000 (Fig. 5(a)), which corresponds to a >70-fold enhancement. Using the frequency counter, we also measure the frequency stability of the oscillator (Fig. 5(b)), which yields an Allan deviation of $\sigma_A(\tau)$ ~10^{-4} for τ = 0.1–10 s.

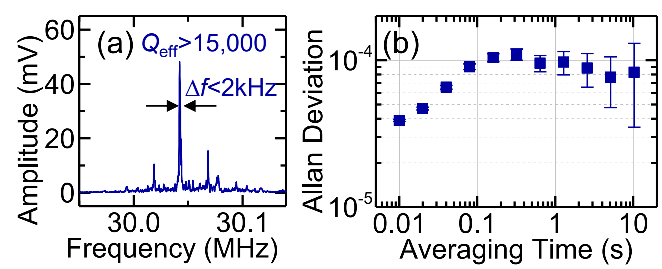

Fig. 5. Performance of the β-Ga_2O_3 feedback oscillator. (a) The closed-loop oscillation spectrum. (b) Measured Allan deviation.

To demonstrate MUV sensing using the β-Ga_2O_3 oscillator, we introduce periodic light irradiation to the device with power intensity adjusted to be p_S = 1W/cm^2. Therefore, the incident power of the light on device (P_D) can be calculated using $P_D = A_D \cdot T_{Op} \cdot \left(d_S^2 / d_C^2\right) p_S$, where A_D (≈ 21.2 μm^2) is the suspended area of the resonator, T_{Op} (= 0.92) is the optical transmission coefficient of the fused silica optical window of the vacuum chamber, d_S (= 5 mm) and d_C (≈ 10 mm) are the diameters of the circular MUV light source and the light spot on device substrate, respectively. Thus, an incident power of ~24 nW and ~49 nW on the circular resonator, for 0.5 W/cm^2 and 1W/cm^2 intensity, respectively, can be calculated. The results of real-time tracking of the oscillator frequency show clear frequency downshifts upon cyclic illumination (Fig. 6). Using $\Re = \Delta f / P_D$, we can get an average responsivity of -3.3 Hz/pW. Given the Allan deviation, the oscillator has a frequency fluctuation of $\delta f = \sigma_A f \approx 3$ kHz at the ~30 MHz resonance for $\tau = 0.1$–10 s. So we can get a minimal detectable power (MDP) of the oscillator, $\delta P_D = \delta f / \Re \approx 0.9$ nW.

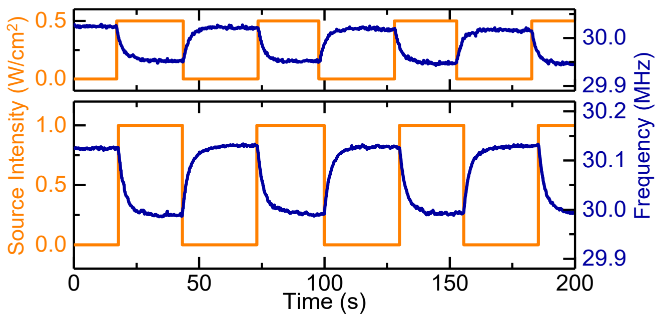

Fig. 6. Responses of the β-Ga_2O_3 oscillator to photon irradiation.

In analysis, β-Ga_2O_3 crystal absorbs photons with wavelengths <280 nm (because of the 4.5–4.9 eV ultrawide bandgap) and generates heat. The resulting temperature elevation expands the β-Ga_2O_3 device, softens the resonator, and causes resonance frequency downshift. The SiO_2 (with bandgap ~9 eV) layer beneath β-Ga_2O_3 has minimal photothermal effect and acts as an isolator of mechanical deformation and a heat barrier between the β-Ga_2O_3 nanoflake and the Si substrate. The photothermal effect in the β-Ga_2O_3 crystal is the main contributor to the observed resonance frequency downshift of the oscillator upon MUV irradiation.

IV. Conclusion

We summarize the sensing performance of the β-Ga_2O_3 oscillator and compare it with performance of the β-Ga_2O_3 PDs made in conventional ways (see Table I). With a different photon detection mechanism, the oscillator made by using a β-Ga_2O_3 nanomechanical resonator already show promising performance compared to conventional PDs.

TABLE I
Summary and Comparison for MUV Sensing β-Ga_2O_3 Oscillator

Active Area	Responsivity ($\Re$)	Frequency Fluctuation (δf) / Dark Current (I_D)	MDP (δP_D) / NEP[a]	Refs.
21 μm^2	–3.3 Hz/pW	~3 kHz	0.9 nW	This work
0.8 cm^2	39.3 A/W	1.1 μA	1.5×10^{-14} W/Hz$^{1/2}$	[6]
~7 mm^2	0.07 A/W	~10^{-10} A	~8×10^{-14} W/Hz$^{1/2}$	[7]
~0.8 mm^2	8.7 A/W	~10^{-8} A	~7×10^{-15} W/Hz$^{1/2}$	[8]

[a]Noise equivalent power (NEP) = $(2qI_D)/\Re$, q: electronic charge, I_D: dark current, $\Re$: responsivity.

In conclusion, the demonstration of MUV light detection by the β-Ga_2O_3 nanostructure-enabled self-sustaining oscillator reveals the potential of using resonant β-Ga_2O_3 nanostructures as ultrasensitive solar-blind UV (<280 nm) sensing transducers. The demonstrated β-Ga_2O_3 oscillator could pave the way for future solar-blind UV detection using β-Ga_2O_3 nanomechanical transducers for applications including target detection and acquisition, flame detection, and environmental monitoring.

Acknowledgment

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