Abstract—We report on the first beta gallium oxide (β-Ga2O3) crystal feedback oscillator built by employing a vibrating β-Ga2O3 nanoresonator as the frequency reference for real-time middle ultraviolet (MUV) light detection. We fabricated suspended β-Ga2O3 nanodevices through synthesis of β-Ga2O3 nanoflakes using low-pressure chemical vapor deposition (LPCVD), and dry transfer of nanoflakes on microtrenches. Open-loop tests reveal a resonance of the β-Ga2O3 device at ~30 MHz. A closed-loop oscillator is then realized by using a combined optical-electrical feedback circuitry, to perform real-time resonant sensing of MUV irradiation. The oscillator exposed to cyclic MUV irradiation exhibits resonant frequency downshifts, with a measured responsivity of $\mathcal{R} \approx -3.1$ Hz/pW and a minimum detectable power of $\delta P_{\text{min}} \approx 0.53$ nW for MUV detection.

Index Terms—beta gallium oxide (β-Ga2O3), sensor, resonator, oscillator, middle ultraviolet (MUV) light detection.

I. INTRODUCTION

PHOTODETECTION in the solar-blind ultraviolet (UV) regime ($\lambda < 280$ nm) has received significant attention thanks to the absence of $\lambda < 280$ nm light in the earth’s atmosphere, providing a ‘null’ background in the solar-blind UV range, enabling ultrasensitive and selective illumination in missile tracking, fire detection, and environmental monitoring applications [1,2]. Beta gallium oxide (β-Ga2O3), 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. Endowed with the ideal bandgap and promising electronic properties, photodetectors (PDs) made of crystalline β-Ga2O3 could capitalize on optoelectronic interactions in the solar-blind UV range [6,7,8]. In addition, owing to its excellent mechanical properties (e.g., Young’s modulus, $E_Y \approx 260$ GPa) [9], β-Ga2O3 is an attractive and promising structural material for innovating nano/microelectromechanical systems (NEMS/MEMS) and new transducers, especially sensors that can benefit from its ultrawide bandgap. Given their ultrahigh responsivities to external stimuli, and enhanced by scaling, resonant-mode NEMS are engineered as novel physical sensors, e.g., infrared detectors [10]. To date, thin films of β-Ga2O3 have been mainly fashioned into electronic devices without any moving element, such as field effect transistors (FETs) [11,12,13] and diode UV PDs [6,7,8]. Transducers that exploit the mechanical properties of β-Ga2O3 are yet to be demonstrated and carefully studied.

In this Letter, we describe the construction and measurement of the first self-sustaining β-Ga2O3 crystal oscillator by using a β-Ga2O3 resonator and a feedback circuitry, for middle ultraviolet (MUV, 200–300 nm, strongly overlapping with the solar-blind UV range) light detection and real-time sensing. We first characterize the open-loop responses of the β-Ga2O3 resonator; we then devise and implement an optical-electrical feedback circuitry, to realize the oscillator operations, and demonstrate real-time sensing of cyclic MUV irradiation on the device. Fig. 1 illustrates the light sensing mechanism of the β-Ga2O3 nanomechanical resonator. The photothermal effect induced by the incident MUV light elevates the temperature and expands the suspended β-Ga2O3 crystal, leading to a resonance frequency downshift. By probing the resonance frequency shift of the β-Ga2O3 device, the intensity of the incident MUV light can be resolved to achieve MUV detection.

![Fig. 1. (a) Illustration of the MUV light sensing mechanism. (b) Signal transduction chain analysis. $P_{th}$: irradiation power on device; $R_w$: thermal resistance; $Q_{th}$: rate of heat flow; $\eta$: optical absorption coefficient; $T$: temperature; $\gamma$: surface tension; $\alpha$: thermal expansion coefficient; $E_Y$: Young’s modulus; $h$: thickness; $r$: radius; $\rho$: mass density; $(kr)^3$: eigenvalue; $f_0$: resonance frequency. (c) β-Ga2O3 nanomechanical device image. Insets: The structural crystal of β-Ga2O3 and a scanning electron microscopy (SEM) image of a β-Ga2O3 nanoflake on the growth substrate. Scale bars: 5 µm.](image-url)

II. DEVICE FABRICATION AND CHARACTERIZATION

Device fabrication consists of the synthesis and transfer of β-Ga2O3 nanoflakes for making suspended nanostructures. We
perform low-pressure chemical vapor deposition (LPCVD) using a 3C-SiC-on-Si substrate as a template for β-Ga2O3 nanoflake synthesis. Using high purity Ga pellets and O2 gas precursors in a 950 °C environment for 1.5 hours, the formation of β-Ga2O3 nanostructures proceeds, step by step, from β-Ga2O3 nanocrystals to nanorods, and then to nanoflakes via extrusion, without the need of any foreign catalyst [14]. We fabricate suspended β-Ga2O3 nanomechanical structures from β-Ga2O3 nanoflakes by using a dry transfer technique [9]. Fig. 1(c) shows a suspended β-Ga2O3 device made of a 73nm-thick β-Ga2O3 nanoflake. The flake is suspended over a ~5.2 μm-diameter circular microtrench. We use this device to build the β-Ga2O3 oscillator for MUV detection.

III. RESULTS AND DISCUSSIONS

Fig. 2 illustrates the real-time resonance tracking system utilizing the feedback oscillator built by using a β-Ga2O3 resonator as the frequency reference. PD: photodetector; LPA: long-pass filter; BS: beam splitter; LNA: low-noise amplifier; PS: phase shifter; BPF: band-pass filter.

To enable real-time MUV sensing, we build a self-sustaining oscillating by connecting the resonator to a combined optical-electrical feedback circuitry (Fig. 2, path ②) with the feedback switch on). We first characterize the oscillator in the frequency domain by using a spectrum analyzer. With the oscillator, the Q of the ~30MHz resonance is boosted from ~200 to an effective Qeff >15,000 (Fig. 4(a)), which is a >70-fold enhancement. We also measure the oscillator frequency fluctuations and compare the Allan deviation, to evaluate the frequency stability of the oscillator (Fig. 4(b)), which yields Allan deviation of σ(τ) ~3.9×10^-5 for τ = 10 ms.

With the Eg ≈ 4.5–4.9 eV bandgap of crystalline β-Ga2O3, photons with wavelength below 280 nm could be efficiently absorbed by β-Ga2O3. We investigate the MUV light detection characteristics of the β-Ga2O3 oscillator by illuminating light containing MUV photons onto the device. The power intensity from the aforementioned light source is adjusted to be ps = 0.5 and 1 W/cm². Therefore, the incident power of the light on device (PD) can be calculated using PD = ADP Tm(4d²/3c²) ps, where AD is the area of the chamber window, d5 and d6 are the diameters of the circular MUV light source and the light spot on device substrate, respectively. Thus, we have incident power levels of ~24 nW and ~49 nW on the suspended circular drumhead. The results of real-time tracking of the oscillator frequency show clear frequency downshifts upon cyclic illumination down to MUV range (Fig. 5). Using δf = P0/D, we obtain a responsivity of δf = -3.1 Hz/pW. Given the Allan deviation, the oscillator has a frequency fluctuation of δf = (2)^1/2σf0 ≈ 1.66 kHz. Thus, the minimum detectable
power (MDP) of the MUV sensing oscillator is \( \delta P_{\text{min}} = \delta \beta/\beta \approx 1.4 \text{nW at } \tau = 1 \text{s} \), and \( \delta P_{\text{min}} \approx 0.53 \text{nW at } \tau = 10 \text{ ms} \), i.e., better resolution in a higher speed detection. This clearly demonstrates an intrinsic advantage of feedback oscillators for real-time, high speed sensing.

![Fig. 4. Performance of the \( \beta\)-Ga\(_2\)O\(_3\) feedback oscillator. (a) The closed-loop oscillation spectrum. (b) Measured and intrinsic Allan deviation.](image)

Further, to analyze the fundamental limit of the \( \beta\)-Ga\(_2\)O\(_3\) resonator and oscillator for MUV detection, we calculate its thermomechanical noise limited Allan deviation, \( \sigma_{\lambda,\text{th}}(\tau) = (\pi k_B T(P_c T_Q^2))^{1/2} \), where \( k_B \) is the Boltzmann constant, \( T \) is temperature, and \( P_c \) is the operating power of the resonator [17]. We have \( P_c = 4\pi f_0^2 M_{\text{eff}}(0.745a_c)^2/Q \), where \( a_c \) is the critical amplitude, \( a_c = (1.54/(\beta Q))^{1/2} \) [18], \( \beta = (23-9\nu)(1+\nu)/(56\nu^2) \) [19], \( \nu = 0.2 \) is the Poisson’s ratio, and \( M_{\text{eff}} = 0.1828\rho\lambda\pi^2 \) is the effective mass for the first mode. Thus we get \( \sigma_{\lambda,\text{th}}(\tau = 10 \text{ ms}) = 1.5 \times 10^{-15} \text{ W/cm}^2 \), corresponding to a frequency noise of \( S_{\lambda}^1(\nu) = 2(\pi \nu)^{1/2} a_{\lambda} = 1.60 \text{ Hz/Hz}^{1/2} \) and a noise equivalent power \( \text{NEP} = S_{\lambda}^{1/2}(2\nu aR) = 8.2 \times 10^{-14} \text{ W/Hz}^{1/2} \). The much better intrinsic Allan deviation proves that the oscillator performance can be improved through future engineering. Table I shows metrics benchmarking of this work with previously reported resonant UV detectors, including thin film bulk acoustic resonators (FBAR) and surface acoustic wave (SAW) devices using ZnO or AlGaN [20,21,22]. The \( \beta\)-Ga\(_2\)O\(_3\) oscillator shows much better performance in both [\( \beta \)] and MDP. In addition (see Table II), the \( \beta\)-Ga\(_2\)O\(_3\) oscillator also exhibits similar NEP and better MDP compared to conventional \( \beta\)-Ga\(_2\)O\(_3\) UV PDs [6,7,8].

The measured frequency downshifts upon MUV irradiation could be explained by light absorption and photothermal effects. With the \( E_g \approx 4.5-4.9 \text{ eV bandgap} \), \( \beta\)-Ga\(_2\)O\(_3\) crystal will absorb MUV photons and elevates its lattice temperature. The suspended \( \beta\)-Ga\(_2\)O\(_3\) crystal, which has a positive thermal expansion coefficient \( (\alpha = 1.5-3.4 \times 10^{-6} \text{ K}^{-1}) \) [23], expands, thus ‘softening’ the resonator and causing a resonance frequency downshift. The substrate underneath the \( \beta\)-Ga\(_2\)O\(_3\) resonator consists of a \( \text{SiO}_2 \) layer on top of bulk Si. The bandgap of SiO\(_2\) (\( \sim 9 \text{ eV} \)) is too wide to contribute to photothermal absorption of the device structure. Rather, SiO\(_2\) layer serves as a mechanical isolator against the thermal expansion of the MUV-absorbing Si bulk. Further, the low thermal conductivity of SiO\(_2\) (\( k_{\text{SiO}_2} = 1.4 \text{ W/}(\text{m K}) \)) also makes it a good heat barrier between the \( \beta\)-Ga\(_2\)O\(_3\) device (\( k_{\beta\text{-Ga}_2\text{O}_3} = 10-27 \text{ W/(m K)} \)) and the Si substrate (\( k_{\text{Si}} = 148 \text{ W/(m K)} \)). With the relatively low thermal conductivity of \( \beta\)-Ga\(_2\)O\(_3\) and the considerable thermal resistance between \( \beta\)-Ga\(_2\)O\(_3\) and SiO\(_2\) due to van der Waals contact, the photothermal heating is efficiently confined in the \( \beta\)-Ga\(_2\)O\(_3\) suspended structure, ideally facilitating the MUV sensing. Accordingly, the \( \beta\)-Ga\(_2\)O\(_3\) nanomechanical feedback oscillator could provide excellent potential for future MUV, hence solar-blind UV (\( \lambda < 280 \text{ nm} \)), detection, and the performance can be enhanced by further engineering of device structure and integration with circuit.

### Table I. Comparison with UV Sensing Resonant Transducers

| Active Area (\( \mu \text{m}^2 \)) | Device Type | \( |\beta| \) (Hz/nW) | MDP, \( \delta P_{\text{min}} \) (nW) | Refs. |
|----------------------------------|-------------|------------------|-------------------------------|-------|
| 21.2 \( \mu \text{m}^2 \)       | \( \beta\)-Ga\(_2\)O\(_3\) NEMS | 3,100            | 0.53 nW                       | This Work |
| 0.026 \( \mu \text{m}^2 \)       | ZnO SAW     | 63               | 6.5 nW                        | [20]   |
| 1.6 \( \mu \text{m}^2 \)              | ZnO FBAR         | 2.3              | n/a                           | [21]   |
| n/a                               | AlGaN SAW     | 0.5              | n/a                           | [22]   |

| Active Area (\( \mu \text{m}^2 \)) | Device Type | \( |\beta| \) (Hz/nW) | MDP, \( \delta P_{\text{min}} \) (nW) | NEP (Ref.) |
|----------------------------------|-------------|------------------|-------------------------------|-----------|
| 21.2 \( \mu \text{m}^2 \)       | \( \beta\)-Ga\(_2\)O\(_3\) NEMS | 3,100            | 0.53 nW                       | This Work |
| 0.8 cm\(^2\)                     | 39.3 A/W     | 28.0 nW          | 1.5 \times 10^{-14} W/Hz\(^{1/2}\) | [6] |
| \(-7 \text{ mm}^2\) | 0.07 A/W   | 1–10 nW         | \~8 \times 10^{-14} W/Hz\(^{1/2}\) | [7] |
| \(-0.8 \text{ mm}^2\) | 8.7 A/W  | 1–10 nW       | \~7 \times 10^{-14} W/Hz\(^{1/2}\) | [8] |

### Table II. Comparison with \( \beta\)-Ga\(_2\)O\(_3\) Photodetectors

| Active Area (\( \mu \text{m}^2 \)) | Responsivity (\( \text{A} / \text{W} \)) | MDP, \( \delta P_{\text{min}} \) (nW) | NEP (Ref.) |
|----------------------------------|------------------|-------------------------------|-----------|
| 21.2 \( \mu \text{m}^2 \)       | 3.1 Hz/pW        | 0.53 nW                       | This Work |
| 0.8 \( \text{cm}^2\)           | 39.3 A/W         | 28.0 nW                      | 1.5 \times 10^{-14} W/Hz\(^{1/2}\) | [6] |
| \(-7 \text{ mm}^2\) | 0.07 A/W | 1–10 nW | \~8 \times 10^{-14} W/Hz\(^{1/2}\) | [7] |
| \(-0.8 \text{ mm}^2\) | 8.7 A/W | 1–10 nW | \~7 \times 10^{-14} W/Hz\(^{1/2}\) | [8] |

**Fig. 5.** Responses of the \( \beta\)-Ga\(_2\)O\(_3\) oscillator to photon irradiation. Note the base frequency has a slight drift between two separate measurements (1W/cm\(^2\) cyclic data taken ~30 mins earlier), likely due to adsorbates or other drifting effects.

**IV. CONCLUSION**

This Letter presents the first demonstration of a self-sustaining \( \beta\)-Ga\(_2\)O\(_3\) crystal feedback oscillator by employing a vibrating \( \beta\)-Ga\(_2\)O\(_3\) nanomechanical resonator (at \~30MHz) as its frequency reference. The feedback oscillator is further employed to demonstrate real-time sensing of cyclic MUV light irradiation onto the \( \beta\)-Ga\(_2\)O\(_3\) resonator. This study reveals the potential of using \( \beta\)-Ga\(_2\)O\(_3\) NEMS as ultrasensitive detectors for solar-blind UV (\( \lambda < 280 \text{ nm} \)), and using \( \beta\)-Ga\(_2\)O\(_3\) feedback NEMS oscillators for real-time MUV sensing, which could lead to future applications, including target acquisition, flame detection, and environmental monitoring.

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REFERENCES

[1] M. Razeghi, and A. Rogalski, “Semiconductor ultraviolet detectors,” J. Appl. Phys., vol. 79, no. 10, pp. 7433–7473, May 1996, doi: 10.1063/1.362677.

[2] M. Razeghi, “Short-wavelength solar-blind detectors—status, prospects, and markets,” Proc. IEEE, vol. 90, no. 6, pp. 1006–1014, Jun. 2002, doi: 10.1109/JPROC.2002.1021565.

[3] M. R. Lorenz, J. F. Woods, and R. J. Gambino, “Some electrical properties of the semiconductor β-Ga2O3,” J. Phys. Chem. Solids, vol. 28, pp. 403–404, Mar. 1967, doi: 10.1016/0022-3697(67)90305-8.

[4] N. Ueda, H. Hosono, R. Waseda, and H. Kawai, “Anisotropy of electrical and optical properties in β-Ga2O3 single crystals,” Appl. Phys. Lett., vol. 71, no. 7, pp. 933–935, Jun. 1997, doi: 10.1063/1.119693.

[5] M. Higashiwaki, K. Sasaki, H. Murakami, Y. Kuma-gai, A. Koukitu, A. Kuramata, T. Masui, and S. Yamakoshi, “Recent progress in Ga2O3 power devices,” Semicond. Sci. Technol., vol. 31, no. 3, p. 034001, Jan. 2016, doi: 10.1088/0268-1242/31/3/034001.

[6] W.-Y. Kong, G.-A. Wu, Y.-J. Wang, T.-F. Zhang, Y.-F. Zou, D.-D. Wang, and L.-B. Luo, “Graphene-β-Ga2O3 heterojunction for highly sensitive deep UV photodetector application,” Adv. Mater., vol. 28, no. 48, pp. 10725–10731, Dec. 2016, doi: 10.1002/adma.201604049.

[7] S. Nakagomi, T. Momoi, S. Takahashi, and Y. Kobukun, “Deep ultraviolet photodiodes based on β-Ga2O3/SiC heterojunction,” Appl. Phys. Lett., vol. 103, no. 7, p. 072105, Aug. 2013, doi: 10.1063/1.4818620.

[8] T. Oshima, T. Okuno, N. Arai, N. Suzuki, S. Ohira, and S. Fujita, “Spatial mapping of multimode Brownian motions in high-frequency silicon carbide microdisk resonators,” J. Appl. Phys., vol. 92, no. 5, pp. 2758–2769, Sep. 2002, doi: 10.1063/1.1499745.

[9] X. Qiu, J. Zhu, J. Oiler, C. Yu, Z. Wang, and H. Yu, “Film bulk acoustic-wave resonator based ultraviolet sensor,” Appl. Phys. Lett., vol. 94, no. 15, p. 151917, Mar. 2009, doi: 10.1063/1.3122342.

[10] X. L. He, J. Zhou, W. B. Wang, W. P. Xuan, X. Yang, H. Jin, and J. K. Luo, “High performance dual-wave mode flexible surface acoustic wave resonators for UV light sensing,” J. Micromech. Microeng., vol. 24, no. 5, p. 055014, Apr. 2014, doi: 10.1088/0960-1317/24/5/055014.

[11] W. S. Hwang, A. Verma, H. Peelaers, V. Protasenko, S. Rouvimov, H. Zhao, “Synthesis and characterization of Ga2O3 nanosheets on SiC-SiC-on-Si by low pressure chemical vapor deposition,” IEEE Electron Device Lett., vol. 39, no. 4, pp. 1050–1054, Dec. 1972, doi: 10.1115/1.442827.

[12] F. Orlandi, D. M. Shr, A. Sereika, R. Rimeika, R. Gaska, Q. Fareed, J. Zhang, X. Hu, A. Lunev, and Y. Bilenko, “Deep-UV LED controlled AlGaN-based SAW oscillator,” Phys. Sta. Sol. (a), vol. 203, no. 7, pp. 1834–1838, May 2006, doi: 10.1002/pssa.200565218.

[13] L. Kuramata, T. Masui, and S. Yamakoshi, “Recent progress in Ga2O3 power devices,” Proc. IEEE, vol. 71, no. 7, pp. 933–935, Jun. 1997, doi: 10.1109/1.119693.

[14] S. Nakagomi, T. Momoi, S. Takahashi, and Y. Kobukun, “Deep ultraviolet photodiodes based on β-Ga2O3/SiC heterojunction,” Appl. Phys. Lett., vol. 103, no. 7, p. 072105, Aug. 2013, doi: 10.1063/1.4818620.

[15] T. Oshima, T. Okuno, N. Arai, N. Suzuki, S. Ohira, and S. Fujita, “Vertical solar-blind deep-ultraviolet Schottky photodetectors based on β-Ga2O3 substrates,” Appl. Phys. Express, vol. 1, no. 1, p. 011202, Jan. 2008, doi: 10.1143/APEX.1.011202.

[16] X.-Q. Zheng, J. Lee, S. Rafique, L. Han, C. A. Zorman, H. Zhao, and P. X.-L. Feng, “Hexagonal boron nitride nanomechanical resonators with spatially visualized motion,” Microsys. Nanoengineering, vol. 3, no. 4, pp. 17038, Jul. 2017, doi: 10.1038/micronano.2017.38.

[17] A. N. Cleland, and M. L. Roukes, “Noise processes in nanomechanical resonators,” J. Appl. Phys., vol. 92, no. 5, pp. 2758–2769, Sep. 2002, doi: 10.1063/1.1499745.