TOWARD REAL-TIME MIDDLE ULTRAVIOLET (MUV) LIGHT DETECTION BY BETA GALLIUM OXIDE (β -Ga₂O₃) NEMS OSCILLATOR

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ABSTRACT

We report on the first beta gallium oxide (β -Ga₂O₃) feedback oscillator built by using a β -Ga₂O₃ nanoresonator as the frequency reference for real-time middle ultraviolet (MUV) light detection. We fabricate suspended β -Ga₂O₃ nanodevices through growth of β -Ga₂O₃ nanoflakes using low-pressure chemical vapor deposition (LPCVD), and all-dry transfer of nanoflakes onto microtrenches. Open-loop tests reveal multimode resonances of the β -Ga₂O₃ devices in the ~20 to 50 MHz range. A closed-loop oscillator is then realized by using a combined optical-electrical feedback circuitry, 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 power sensitivity of 0.9 nW.

INTRODUCTION

β -Ga₂O₃, a semiconductor with a monoclinic crystal structure (Fig. 1a), is rapidly emerging as a promising candidate for future power electronics, due to its ultrawide bandgap, $E_g \approx 4.5\text{--}4.9$ eV, and other excellent electronic properties [1]. In optoelectronics, crystalline β -Ga₂O₃ is suited for making photodetectors in the MUV range (200–300 nm). In addition, owing to its excellent mechanical properties (e.g., measured Young's modulus, $E_Y \approx 250\text{--}300$ GPa) [2], β -Ga₂O₃ 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 -Ga₂O₃ crystal has been mainly focused on electronic devices without any moving component, such as field effect transistors (FETs) [1] and electronic UV photodetectors [3]. Transducers exploiting mechanical properties of β -Ga₂O₃ are yet to be shown and carefully studied. In this digest paper, we describe the construction and measurement of the first self-sustaining β -Ga₂O₃ oscillator by using a β -Ga₂O₃ nanoresonator and a feedback circuitry, for MUV light detection and real-time sensing.

DEVICE FABRICATION

The device fabrication process consists of chemical synthesis and direct transfer of β -Ga₂O₃ nanoflakes for making suspended nanostructures. We perform LPCVD to grow β -Ga₂O₃ nanoflakes on a 3C-SiC-on-Si substrate. Using high purity Ga pellets and O₂ gas precursor in a 950 °C LPCVD chamber for 1.5 hours, the formation of β -Ga₂O₃ nanostructures proceeds, step by step, from β -Ga₂O₃ nanocrystals to nanorods, and then to nanoflakes, without the need of any foreign catalyst (Fig. 1b).

We use an all-dry transfer technique to fabricate suspended β -Ga₂O₃ nanomechanical structures (Fig. 2). We secure and harvest the β -Ga₂O₃ nanoflakes from the growth substrate by using a polydimethylsiloxane (PDMS) stamp. Under an optical microscope, we align a selected β -Ga₂O₃ nanoflake to a predefined microtrench. By pressing down and detaching the PDMS stamp, the nanoflake is transferred onto the microtrench, thus creating a suspended device structure. Both doubly clamped beams/ribbons (Fig. 2d) and circular drumheads (*insets* in Fig. 4b and Fig. 5) have been realized.

Figure 1: (a) The crystal structure of β -Ga₂O₃. (b) Formation of β -Ga₂O₃ nanoflakes in LPCVD. (c) A scanning electron microscopy (SEM) image of a β -Ga₂O₃ nanoflake on the growth substrate.

Figure 2: Fabrication of β -Ga₂O₃ nanomechanical structures. (a) Aligning the β -Ga₂O₃ nanoflake to a microtrench. (b) Pressing down the nanoflake. (c) Lifting the stamp, leaving nanoflake on substrate. (d) 3D illustration of the fabricated β -Ga₂O₃ device.

EXPERIMENTAL RESULTS AND DISCUSSIONS

We use a home-built ultrasensitive laser interferometry system [4] to measure both the undriven thermomechanical noise spectra and the photothermally driven resonances of the β -Ga₂O₃ devices in vacuum. We employ a 633nm laser to read out the device motion interferometrically and a 405nm laser to photothermally drive the device. A photodetector (PD) is used to measure the intensity of the device-motion-modulated laser light. A measurement scan captures three thermomechanical resonance modes (here only 633nm laser is used) in the range of 20 to 50 MHz, with quality factors (Q s) in the range of ~320 to ~550, for a doubly clamped, 28nm-thick β -Ga₂O₃ resonator suspended over a 2.2 μ m-wide microtrench (Fig. 3). Similarly, a 73nm-thick β -Ga₂O₃ nanoflake drumhead on a circular microtrench with a diameter of ~5.2 μ m exhibits a measured thermomechanical resonance at ~30 MHz with a $Q \sim 200$ (Fig. 4a). Further, by adding the 405nm laser as the driving source, we measure an open-loop, photothermally driven resonance of the same device, also at ~30 MHz with a $Q \sim 150$ (Fig. 4b).

Figure 3: Undriven thermomechanical resonances of a doubly clamped β -Ga₂O₃ device. (a) Wide resonance spectrum. Inset: device optical image. (b)-(d) Zoomed-in spectra of the 3 modes.

Figure 4: (a) Thermomechanical noise spectrum of a circular drumhead β -Ga₂O₃ resonator. (b) Photothermally driven response of the resonator. Inset: device SEM image. Scale bar is 10 μ m.

Figure 5: Scheme for demonstrating real-time MUV detection via a self-sustaining β -Ga₂O₃ oscillator. Inset: device optical image.

Figure 6: Performance of the β -Ga₂O₃ feedback oscillator. (a) The closed-loop oscillation spectrum. (b) Measured Allan deviation.

Further, we build a closed-loop oscillator by adding a feedback circuit to the β -Ga₂O₃ resonator (Fig. 5). 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 feedback oscillators. The modified signal is then fed back to the device using the amplitude-modulated 405nm laser. A self-sustaining β -Ga₂O₃ oscillator is therefore achieved without external ac source. The Q of the ~ 30 MHz resonance is boosted from ~ 200 to an effective Q_{eff}

$>15,000$ (Fig. 6a), with a >70 -fold enhancement. We also measure the frequency stability of the oscillator (Fig. 6b), which yields Allan deviation of $\sigma(\tau) \sim 10^{-4}$ for $\tau = 0.1-10$ s.

To demonstrate MUV sensing with the β -Ga₂O₃ oscillator, we employ a light source to illuminate the ~ 30 MHz device with wavelengths of 200 to 600 nm (Fig. 5). We introduce periodic light irradiation to the device with power intensity adjusted to be 1 W/cm^2 , corresponding to an incident power of ~ 49 nW on the circular device. The results of real-time tracking of the oscillator frequency show clear frequency downshifts (~ 0.13 MHz) upon cyclic illumination (Fig. 7), yielding an average responsivity of -3.3 Hz/pW. Given the frequency stability (Allan deviation of $\sim 10^{-4}$), the oscillator exhibits a light power sensitivity of 0.9 nW.

Figure 7: Responses of β -Ga₂O₃ oscillator to photon irradiation.

In analysis, β -Ga₂O₃ crystal absorbs photons with wavelengths <280 nm (because of the ultrawide bandgap) and generates heat. The resulting temperature elevation expands the β -Ga₂O₃ device, softens the resonator, and causes resonance frequency downshift. The SiO₂ (with bandgap ~ 9 eV) layer beneath β -Ga₂O₃ has minimal photothermal effect and acts as an isolator of mechanical deformation and a heat barrier between the β -Ga₂O₃ nanoflake and the Si substrate. The photothermal effect in the β -Ga₂O₃ crystal is the main contributor to the observed resonance frequency downshift of the oscillator upon MUV irradiation.

CONCLUSION

In summary, the demonstration of MUV light detection by the β -Ga₂O₃ nanostructure-enabled self-sustaining oscillator opens new possibilities of using resonant β -Ga₂O₃ MEMS/NEMS transducers for solar-blind UV (<280 nm) detection and real-time sensing.

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