See-Through Ga_2O_3 Solar-Blind Photodetectors for Use in Harsh Environments

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***Abstract*—This paper demonstrates the high-temperature operation of fully transparent solar-blind deep ultraviolet (DUV) metal–semiconductor–metal (MSM) photodetectors (PDs) employing β-Ga_2O_3 thin films with transmittance up to 80% from 400 to 900 nm without image blurring. Even at a bias up to 200 V, the β-Ga_2O_3 MSM PDs show dark current as low as $\sim$1 nA. The dark current of β-Ga_2O_3 MSM PDs under significantly different oxygen concentration in the ambiences are similar, indicating that the high inertness to surface effect. Moreover, the responsivity and the working temperature of β-Ga_2O_3 MSM PDs at 10 V bias are 0.32 mA/W and as high as 700 K, respectively. Full recovery after 700-K operation demonstrates reliability and robustness of β-Ga_2O_3 PDs. The superior see-through features, electrical tolerance, inertness to surface effect, thermal stability, and solar-blind DUV photoresponse of β-Ga_2O_3 MSM PDs support the use in next-generation DUV PDs applications under harsh environments.**

***Index Terms*—β-Ga_2O_3, solar-blind, photodetector, high temperature detection, harsh environment.**

I. Introduction

PHOTODETECTORS (PDs), particularly for solar-blind deep ultraviolet (DUV) detection (wavelength lower than 280 nm), have attracted a strong interest owing to their broad applications in solar observations, UV astronomy, missile tracking, automatization, short-range communication security, as well as environmental and biological researches [1]–[3]. As considering the requirements (such as high-temperature operation, high electrical tolerance, high spectral selectivity, and high thermal stability/reliability) for aforementioned practical applications, PDs capable of operation in harsh environments are inevitably required [4]. In some cases, for the studies of the Sun (*e*.g., the solar orbiter) in the next envisaged space missions of ESA and NASA, solar-blind PDs should be capable of operating at high temperatures [5].

Solar-blind DUV PDs based on BN [6], $AlxGa_{1-x}N$ [2], [3], diamond [7], $LaAlO_3$ [8], $In_2Ge_2O_7$ [9], and ZnMgO [10] exhibit intrinsic solar blindness and very low dark current because of their wide bandgap. The intrinsic nature enables the solar-blind photodetection without Wood's filters and heavy cooling systems required to be implanted in conventional Si-based PDs and photomultiplier tubes [11]–[13]. Compared to Si (1.5 W/cm °C and 0.3 MV/cm, respectively), which is the most widely used semiconductor material for the PDs, wide-bandgap materials are suitable for high-temperature and high-power applications due to their high thermal conductivity and breakdown field strength [14], [15]. However, only a few reports were discussed on the general suitability of aforementioned materials for extremely harsh environments although they have proved their selectivity and absorption ability in the DUV region (190–350 nm) [5]–[7]. Very recently, the solar-blind DUV PDs were carried out to work at the temperature as high as 300 °C (573 K) by employing AlN. Obviously, solar-blind DUV PDs for extremely harsh environments are still at their early stages of development; the operation temperature of solar-blind DUV PDs should be increased further to meet the requirements of extremely harsh environments.

Transparent electronics is an emerging technology employing "invisible" electronic circuitry and optoelectronic devices, such as building-integrated photovoltaics [16], [17]. Especially, the realization of transparent PDs is the crucial for next generation transparent electronics (such as mobile devices), since they can be integrated with already-demonstrated components such as transparent complementary inverters [18], transparent memories [16], and transparent display panels [19] and transparent battery [20]. In view of the integration toward see-through electronics, fully transparent PD devices consisting of transparent electrodes and active layers with a wide bandgap are indispensable and still deficient [21].

Monoclinic β-Ga_2O_3, the most stable phase in the polymorphism of Ga_2O_3, is one of the chemically stable oxide semiconductors with a large direct bandgap of 4.9 eV (DUV region), high dielectric constant (9.9–10.2), and high breakdown field (6.5–7.6 MV/cm) [22]–[24]. In this study, we fabricate fully transparent solar-blind DUV PD devices employing β-Ga_2O_3 as an active layer and indium zinc oxide (IZO) as the transparent electrodes, exhibiting the average transmittance

Manuscript received February 2, 2014; revised April 29, 2014; accepted April 30, 2014. This work was supported in part by the National Science Council of Taiwan (102-2628-M-002-006-MY3, 101-2221-E-002-115-MY2 and 102-2221-E005-072-MY3), National Taiwan University (103R7823 and 102R4000) and South Science Park and National Science Council of the Taiwan under Contract 102CE06. T.-C. Wei and D.-S. Tsai contributed equally to this work.

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Digital Object Identifier 10.1109/JSTQE.2014.2321517

up to 80% from visible to near IR wavelength region without image blurring. The β-Ga_2O_3 MSM PDs for the use in harsh environments show a very low dark current ($\sim$1 nA), no sign of breakdown even at a bias higher than 200 V, excellent thermal stability, and intrinsic solar blindness. The dark current of β-Ga_2O_3 MSM PDs under significantly different oxygen concentration in the ambiences is similar, indicating that the high inertness to surface effect due to superior crystallinity nature of β-Ga_2O_3. The working temperature is up to 700 K and the responsivity is 0.32 mA/W at 10 V bias under 185-nm illumination. β-Ga_2O_3 PDs can be fully recovered after 700-K operation, showing excellent thermal reliability and robustness. The intriguing optoelectronic and electrical properties of β-Ga_2O_3 promise a new generation of stable, solar-blind DUV PDs for the extremely harsh electronic applications, such as sensing, imaging, and intrachip optical interconnects in high-temperature environments.

II. Experiment

The 220-nm-thick β-Ga_2O_3 epilayers were grown on (0 0 0 1) sapphire substrates by using a modified Emcore D180 MOCVD system. The precursors of MOCVD system were the mixture of trimethylgallium (TEGa) and pure oxygen (99.999%). Ar (99.999%) was used as the carrier gas, passing through the TEGa bubbler to deliver the TEGa vapor to the reactor. To optimize β-Ga_2O_3 growth, the epilayers were grown under a relatively low pressure (15 torr) and temperature (500 °C) for 60 min. After the growth process of β-Ga_2O_3 epilayers, the microstructures were studied by a high-resolution transmission electron microscopy (HRTEM, model: JEM-2100 F). To further characterize β-Ga_2O_3 epilayers, confocal Raman microscopy systems (NT-MDT) with an excitation wavelength of 473 nm (2.63 eV) were used. In confocal Raman microscopy systems, the spot size of laser is $\sim$0.5 μm in diameter and the spectral resolution is 3 cm^{-1} (obtained with a 600 grooves per mm grating). To characterize the photoresponsivity of the β-Ga_2O_3 epilayers, the 100-nm-thick IZO finger electrodes were deposited on Ga_2O_3/sapphire substrates by RF sputtering deposition. The 100-nm-thick IZO finger-electrodes were designed to be 200-μm wide and 1.5-mm long with 30-μm wide spacing. A low-pressure mercury lamp was employed to act as the 185-nm light source to characterize β-Ga_2O_3 PDs. A Keithley 4200-SCS semiconductor characterization system was used to measure current–voltage (I–V) characteristics and time-dependent photoresponsivity of the β-Ga_2O_3 PDs under various measuring ambient (i.e., vacuum (10^{-5} Torr), air, and oxygen ambience). For high-temperature testing, the β-Ga_2O_3 PDs were heated on a high-temperature stage, and the device temperature was monitored with a calibrated thermocouple (K type).

III. Results and Discussion

The optimized growth process used here is able to produce homogeneous, large-area, and superior-quality β-Ga_2O_3 epilayers for PD applications. More details about the modified MOCVD process had been reported by P. Ravadgar *et al*. [25]. The cross-sectional HRTEM image of the β-Ga_2O_3 film and

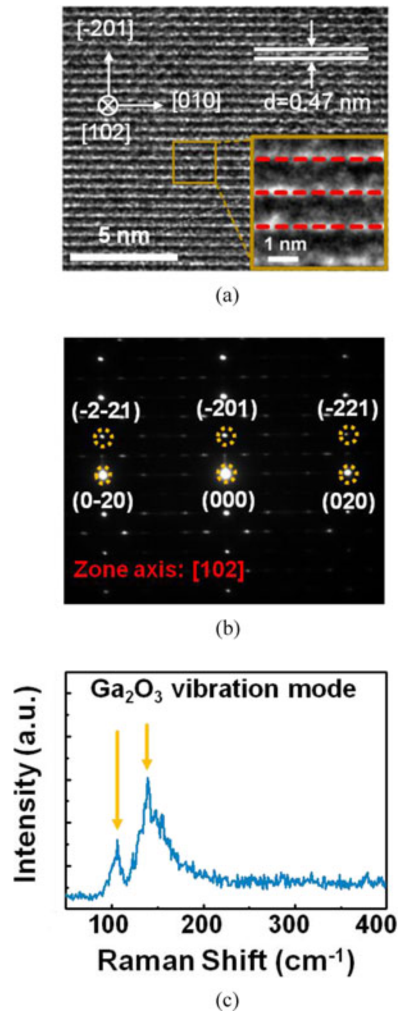

Fig. 1. (a) Cross-sectional HRTEM images of the β-Ga_2O_3 grown on a sapphire substrate. The inset shows an enlarged HRTEM image of the marked area in (a). (b) The ED patterns of the β-Ga_2O_3 films. (c) Raman spectrum of a 220-nm-thick β-Ga_2O_3 on sapphire measured at room temperature.

its corresponding electron diffraction (ED) pattern are shown in Fig. 1(a) and (b), respectively. In an enlarged HRTEM image shown in inset of Fig. 1(a), interplanar distances corresponding to the d-spacing of β-Ga_2O_3 (–201) plane of $\sim$0.47 nm are characterized [25]. No obvious structural defects and dumbbell-interstitials observed in β-Ga_2O_3 epitaxial thin films in the enlarged HRTEM image, indicating the superior crystal quality of the β-Ga_2O_3 films. The Raman characteristic peaks at 111 and 147 cm^{-1} correspond to A_g and B_g modes of β-Ga_2O_3 films in low-frequency libration and translation of tetrahedra–octahedra chains (below 200 cm cm^{-1}), respectively, as shown in Fig. 1(c) [26]. We note that the optical modes cannot be distinguished due to the strong adjacent sapphire peaks.

To highlight the fully transparent properties of IZO/β-Ga_2O_3 thin films, the optical transmittance/absorptance/reflectance spectra of IZO thin films, β-Ga_2O_3 thin films and IZO/β-Ga_2O_3 thin films are shown in Fig. 2(a), (b), and (c), respectively. All the average transmittance of IZO, β-Ga_2O_3 and IZO/β-Ga_2O_3 thin films are up to 80% from 400 to 900 nm (from visible to near IR wavelength regions) due to their wide bandgap nature.

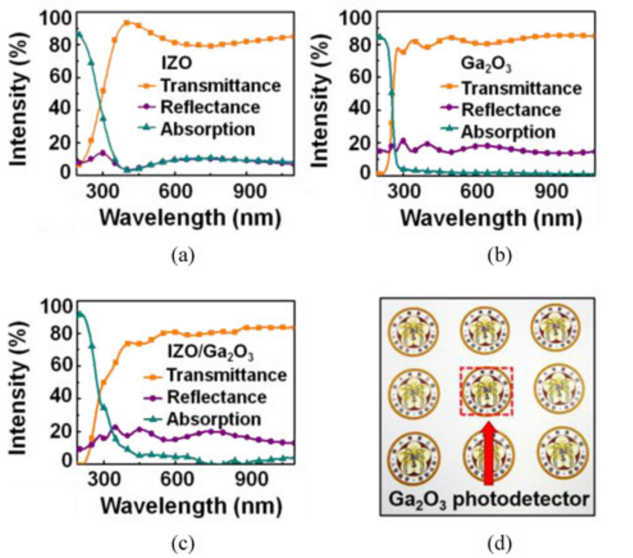

Fig. 2. Optical transmittance, absorptance, and reflectance spectra of (a) IZO thin films on sapphire substrates, (b) β-Ga_2O_3 thin films on sapphire substrates, and (c) IZO/β-Ga_2O_3 thin films on sapphire substrates. (d) Photographs of the fully transparent β-Ga_2O_3 MSM PDs on sapphire substrates.

In addition, the absorptance of IZO (bandgap: ∼3.9 eV) and β-Ga_2O_3 thin films rapidly increase at ∼320 and 250 nm, respectively, due to their wide bandgap absorption. Fig. 2(d) shows the see-through features of the β-Ga_2O_3 MSM PDs on the sapphire marked in a red dashed-line rectangle. The "NTU" emblem under the β-Ga_2O_3 MSM PDs can be observed clearly without image blurring because of the excellent transparency characteristics of β-Ga_2O_3 and IZO materials.

A schematic of the β-Ga_2O_3 MSM PDs is depicted in Fig. 3(a). Fig. 3(b) shows the I–V curves of β-Ga_2O_3 MSM PDs measured in the dark. To demonstrate the excellent electrical characteristics of β-Ga_2O_3 MSM PDs for high voltage operation, Si MSM PDs are compared. The β-Ga_2O_3 MSM PDs exhibit a dark current as low as ∼1 nA and no sign of breakdown at a bias up to 200 V. Note that 200 V is the measurement limit of our system. In contrast, the Si MSM PDs show the electrical breakdown at a bias of ∼50 V. These superior electrical characteristics are directly attributed to the outstanding material properties of β-Ga_2O_3, such as large energy bandgap, high breakdown electric field and excellent mechanical strength.

It has been known that surface defects of metal oxides, such as oxygen vacancies, function as chemisorption sites. O_2 molecules adsorbed at these sites act as electron acceptors to form chemisorbed O_2^- at room temperature. These chemisorbed O_2^- molecules deplete the surface electron states, and consequently, reduce the conductivity of metal oxide [16], [27], [28]. As shown in Fig. 3(c), the dark current of β-Ga_2O_3 MSM PDs under significantly different oxygen concentration in the ambiences (i.e., vacuum (10^{-5} Torr), air, and pure oxygen) are similar, indicating that the transport of β-Ga_2O_3 MSM PDs is not dominated by surface defects of metal oxides due to the superior crystal quality.

In order to demonstrate the solar-blind DUV photosensitivity of the β-Ga_2O_3 MSM PDs, the I–V characteristics of the

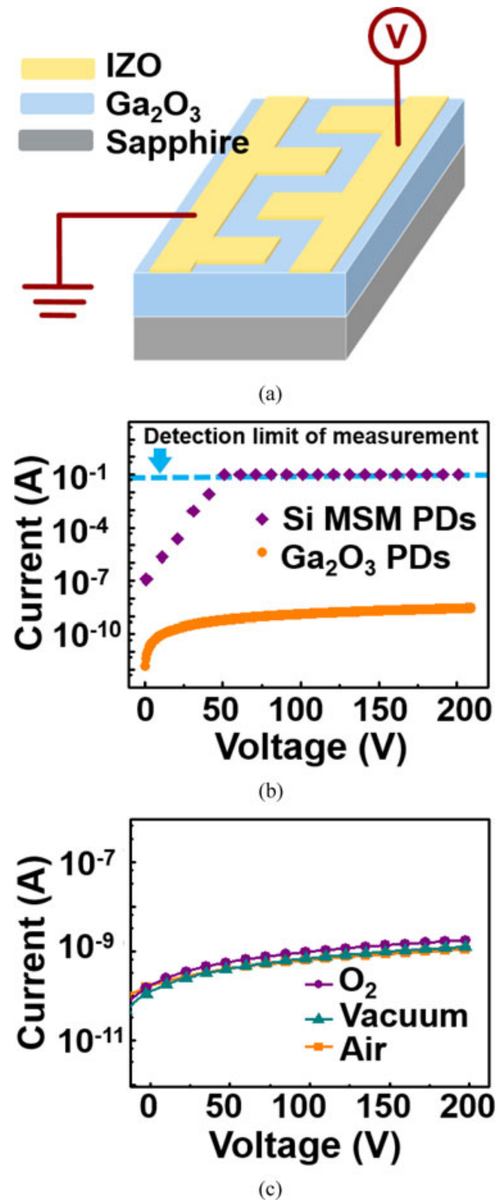

Fig. 3. (a) The schematic of the β-Ga_2O_3 MSM PDs. (b) I–V curves of β-Ga_2O_3 and Si MSM PDs in the dark. Note that 0.1 A is the detection limit of the electrical measurements. (c) I–V curves of β-Ga_2O_3 MSM PDs in the dark under vacuum (10^{-5} Torr), air, and oxygen ambience, respectively.

β-Ga_2O_3 MSM PDs (in air ambience) were measured in the dark, under air mass 1.5 global (AM 1.5G) illumination, and 185-nm light illumination, as shown in Fig. 4(a). One can see that there is no obvious solar light absorption in β-Ga_2O_3 films because the bandgap of β-Ga_2O_3 is larger than the energy (4.42 eV) of the shortest wavelength (280 nm) in AM 1.5G solar spectrum. The sensitivity factor of a PD, photo-to-dark current ratio (PDCR), is defined as $(I_{\mathrm{ph}}–I_{\mathrm{d}})/I_{\mathrm{d}}$, where I_{ph} is the photocurrent and I_{d} is the dark current [3], [29]. At 10 V bias, the PDCR value of β-Ga_2O_3 MSM PDs are 0 and 14 under AM 1.5G and 185-nm light illumination, respectively. The responsivity and the external quantum efficiency of the β-Ga_2O_3 MSM PDs can be also estimated to be 0.32 mA/W and 0.2% (assuming the photogain = 1), respectively, at room temperature

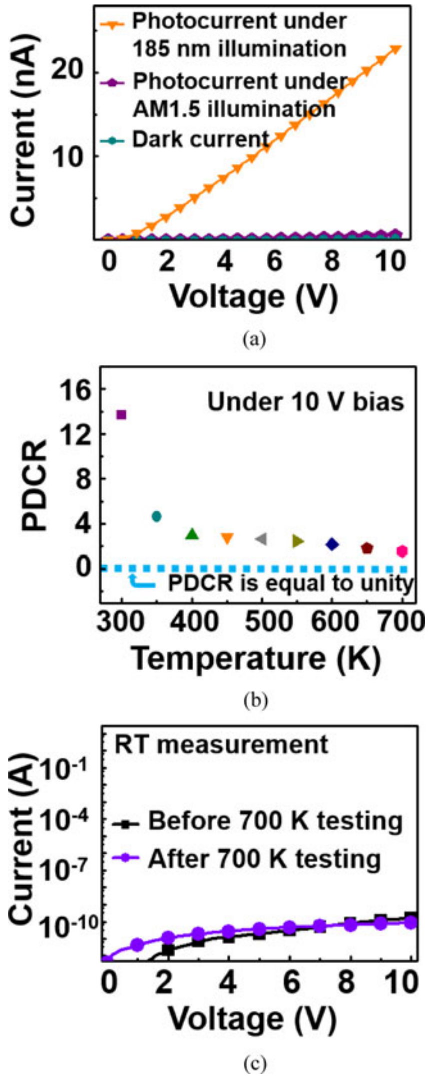

Fig. 4. (a) *I–V* curves of the β-Ga_2O_3 MSM PDs (in air ambience) measured in the dark, under AM 1.5G, and 185-nm light illumination ($I_{\rm light} = 140$ W/m^2). (b) PDCR of the β-Ga_2O_3 MSM PDs as function of temperature under a bias of 10 V and 185-nm light illumination ($I_{\rm light} = 140$ W/m^2). (c) *I–V* curves of the β-Ga_2O_3 MSM PDs measured in the dark at room temperature before and after 700-K testing.

under 10 V bias and 185-nm light illumination by $R = I_{\rm ph}/P = \eta_{\rm ext}$Gq/hv, where R is the responsivity, $I_{\rm ph}$ is the total generated photocurrent of the whole device, P is the total incident light power over the device, $\eta_{\rm ext}$ is the external quantum efficiency, G is the photogain, q is the electronic charge, h is Planck's constant, and ν is the frequency of the incident wavelength [30]. Moreover, the noise equivalent power (NEP) is an important parameter of a PD that is frequently quoted, i.e., the optical signal power required to generate a photocurrent signal $(I_{\rm ph})$ that is equal to the total noise current (I_n) in the PD at a given wavelength and within a bandwidth of 1 Hz [30]. It is apparent that NEP represents the required optical power to achieve a SNR (signal to noise ratio) of 1 with a bandwidth of 1 Hz. The detectivity (D^*) is the reciprocal of NEP, i.e., (D^*) = 1/ NEP [4]. According reviewer's suggestions, under a 10 V bias, the calculated NEP of our β-Ga_2O_3 PDs is 3.53×10^{-11} W/cm $Hz^{1/2}$ by NEP $= (2eJ_{\rm d})^{1/2}/R$, where R is responsivity, e is electronic charge, $J_{\rm d}$ is dark current density, leading to the detectivity (D^*) of $\sim 2.8 \times 10^{10}$ cm Hz$^{1/2}$/W [30].

To demonstrate photodetection under the high-temperature environments, the temperature-dependent PDCR under 185-nm illumination and 10-V bias was measured, as shown in Fig. 4(b). As the PDCR is above unity, it indicates that the PDs can work properly. One can see that the β-Ga_2O_3 MSM PDs are capable of photodetection up to 700 K (the PDCR value of 1.5) mainly due to small levels of leakage current and high thermal stability of β-Ga_2O_3 at high temperatures. A further increase in temperature lowers the PDCR of β-Ga_2O_3 MSM PDs due to the raise of dark current, which cannot be suppressed at higher temperatures [3], [29]. One possible explanation is that surface defects at the IZO contacts and the defects of IZO/β-Ga_2O_3 interfaces provide extra leakage current paths, which significantly increase the dark current at high temperatures, making the PDCR decrease to unity [31]. Therefore, in order to increase the working temperature of β-Ga_2O_3 PDs in harsh environments, the PDCR value might be increased by using the passivation layers, or the reinforcement of IZO/β-Ga_2O_3 interfaces [3], [30], [31]. As shown in Fig. 4(c), when the working temperature is decreased from 700 K back to 300 K (room temperature), the dark current decreases to its initial value. It demonstrates that β-Ga_2O_3 MSM PDs can be fully recovered after high-temperature operation, showing the reversibility of the β-Ga_2O_3 MSM PDs. We note that as compared to very low dark current ($\sim$0.1 nA under the bias of 10 V at room temperature), the high thermal noise of the probe tips used in the characterization setup should be considered when the β-Ga_2O_3 MSM PDs are characterized at high-temperature measurements. As a result, to further boost the operation temperature of the β-Ga_2O_3 MSM PDs, the thermal noise generated from the probe of characterization setups must be reduced by using either suitable high-temperature ceramic packages or a high-temperature probe station [3], [29].

IV. Conclusion

In summary, we demonstrate fully transparent solar-blind DUV PDs based on β-Ga_2O_3 thin films contacted by back-to-back IZO electrodes for use in harsh environments. Fully transparent solar-blind DUV PDs show the average transmittance up to 80% from 400 to 900 nm without image blurring, a dark current as low as $\sim$1 nA at a bias up to 200 V, a responsivity up to 0.32 mA/W at 10-V bias, and the working temperatures up to 700 K, indicating their outstanding see-through features, electrical tolerance and thermal stability, and photoresponse. Under significantly different oxygen concentration in the ambiences, the dark current characteristics of β-Ga_2O_3 MSM PDs are similar due to the superior crystallinity nature of β-Ga_2O_3. Moreover, full recovery after 700-K operation shows reliability and robustness of solar-blind DUV PDs. The results demonstrate the high promise of β-Ga_2O_3 as an active material for solar-blind DUV photodetection in extremely harsh environments.

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