# Science Talks

## Exfoliated and Bulk β-Gallium Oxide Electronic and Photonic Devices

--Manuscript Draft--

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| **Abstract:** | Monoclinic gallium oxide (β-$Ga_2O_3$) has recently attracted increasing attention due to the availability of high quality, large diameter single crystals from mature melt growth methods and its attractive material properties of wide $E_G$ of 4.6–4.9 eV, good electron mobility (>200 $cm^2$/Vs) and estimated $E_c$ of~ 8 MV/cm. Compared to other ultra-wide bandgap materials, the inexpensive substrates lower the manufacturing cost for β-$Ga_2O_3$ power devices. Applications of deep-UV detectors with solar blindness include inspection of high voltage transmission lines for corona and partial discharges, detection of fires and various defense systems. Si- and GaAsbased UV PDs are not truly solar-blind, as additional, bulky visible-light blocking filters are required. In this short review we discuss the use of bulk and exfoliated β-$Ga_2O_3$ for these applications and relate this to the basic surface and response of the material to high temperatures, radiation exposure and typical semiconductor processing steps. The material can easily be cleaved along the (100) surface and layers with (100)A surface termination have higher energy than the (100)B termination. The (100)B cleavage plane is the favorable one, observed experimentally. |
| **Additional Information:** | |
| **Question** | **Response** |

*Exfoliated and Bulk β-Gallium Oxide Electronic and Photonic Devices*

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**Abstract**
*Monoclinic gallium oxide (β-$Ga_2O_3$) has recently attracted increasing attention due to the availability of high quality, large diameter single crystals from mature melt growth methods and its attractive material properties of wide $E_G$ of 4.6–4.9 eV, good electron mobility (>200 $cm^2$/Vs) and estimated $E_c$ of~ 8 MV/cm. Compared to other ultra-wide bandgap materials, the inexpensive substrates lower the manufacturing cost for β-$Ga_2O_3$ power devices. Applications of deep-UV detectors with solar blindness include inspection of high voltage transmission lines for corona and partial discharges, detection of fires and various defense systems. Si- and GaAs-based UV PDs are not truly solar-blind, as additional, bulky visible-light blocking filters are required. In this short review we discuss the use of bulk and exfoliated β-$Ga_2O_3$ for these applications and relate this to the basic surface and response of the material to high temperatures, radiation exposure and typical semiconductor processing steps. The material can easily be cleaved along the (100) surface and layers with (100)A surface termination have higher energy than the (100)B termination. The (100)B cleavage plane is the favorable one, observed experimentally.*

**Figures and tables**

*Ultra-wide bandgap semiconductors with bandgaps > 4eV are being developed for more efficient power electronic switching systems and for truly solar-blind UV detection. The development of power electronics based on wide bandgap semiconductors is attracting much interest because of the potential for significantly higher switching efficiency and ability to operate at higher powers and temperatures. Within the next decade, about 80% of all US electricity is expected to flow through power electronics. These include power distribution systems, electric vehicle fast chargers, data center power supplies, ship power systems, and renewable wind/solar energy integration. SiC and GaN power electronics are now commercialized and provide more efficient performance than conventional Si-based devices. The combination of high breakdown voltage, low on-state resistance and lower switching losses is improved in the ultra-wide bandgap semiconductors, such as $Ga_2O_3$, diamond, and AlN [1-6]. This leads to their high Baliga's figure of merit (BFOM), defined as $\varepsilon.\mu.E_c^3$, where ε, μ, and $E_c$ are the dielectric constant, carrier mobility, and critical breakdown field strength, respectively [7-11].*

*Among these ultra-wide bandgap semiconductors, monoclinic gallium oxide (β-$Ga_2O_3$)is attractive because of its large breakdown field, shown in Figure 1.*

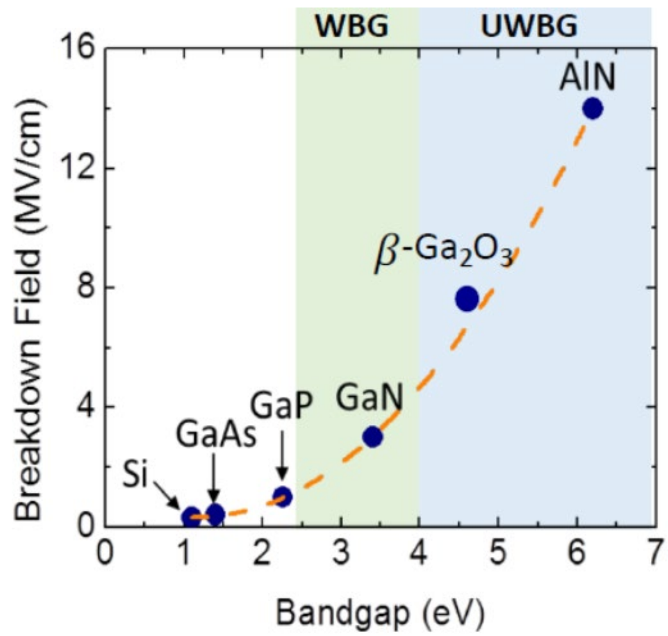


Figure 1. **Breakdown field versus bandgap for various semiconductors.** The monoclinic polytype of $Ga_2O_3$ provides higher voltage capability than either of the commercialized semiconductors GaN and SiC. This allows high voltage capability, efficient switching (low on-state resistance, Ron), high temperature operation and low cost of production due to the ability to grow large melt grown crystals. The α-polytype of $Ga_2O_3$ has even larger bandgap (5.1 eV) and is almost lattice matched to sapphire [12,13]. It is also possible to grow $(Al_xGa_{1-x})_2O_3$ , $(In_xGa_{1-x})_2O_3$ alloys, spanning a bandgap rage of 3-8.5 eV. Disadvantages include the low thermal conductivity of $Ga_2O_3$ and the absence of practical p-type doping.

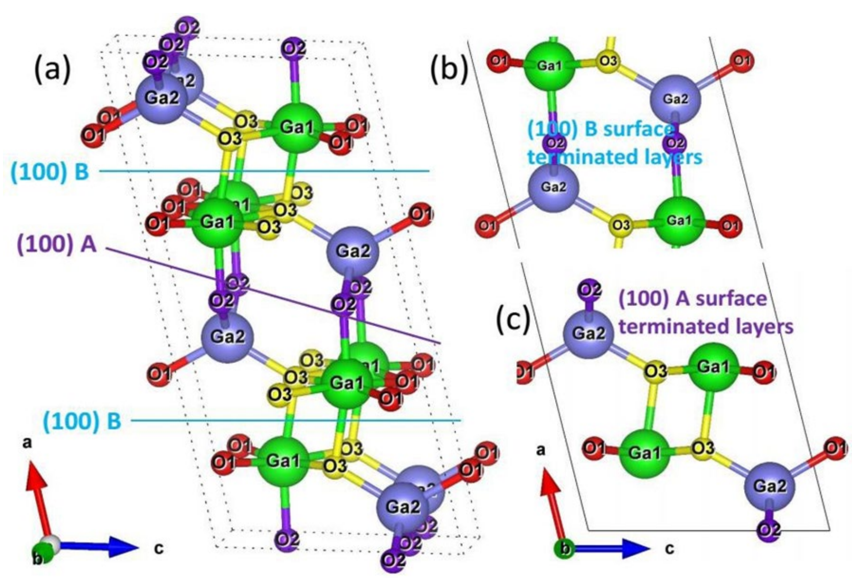


Figure 2. **Gallium Oxide surface and cleaving.** (a) Conventional unit cell of β - $Ga_2O_3$ with (b) (100)B and (c)(100)A surface terminated bilayers. In this polytype there are two symmetrically inequivalent Ga atoms indicated as Ga1 and Ga2, which have octahedral and tetrahedral coordination, respectively. There are three inequivalent O atoms indicated as O1, O2 and O3.

The material can easily be cleaved along (100) surface and layers with (100)A surface termination having higher energy than the (100)B termination. The (100)B cleavage plane is the favorable one, observed experimentally. Both bulk and exfoliated devices can be fabricated.

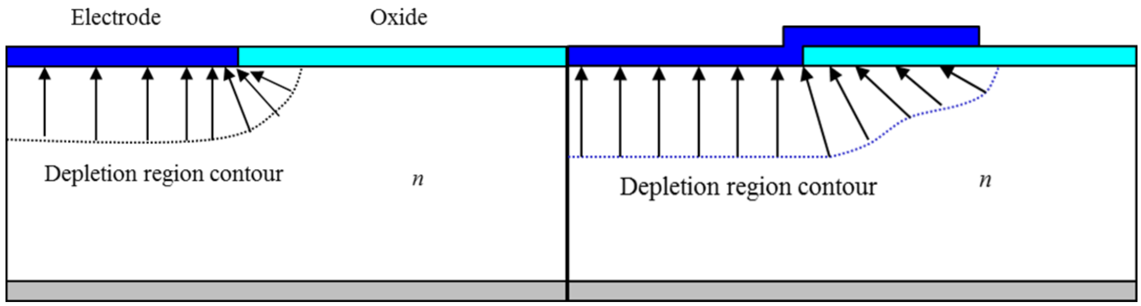


Figure 3. **Mitigation of field crowding by edge termination methods.** To prevent electric field breakdown at the edge of Schottky contacts on rectifier structures, various edge termination methods such as extending the electrode over a dielectric layer, called a field plate (illustrated) [7-11].

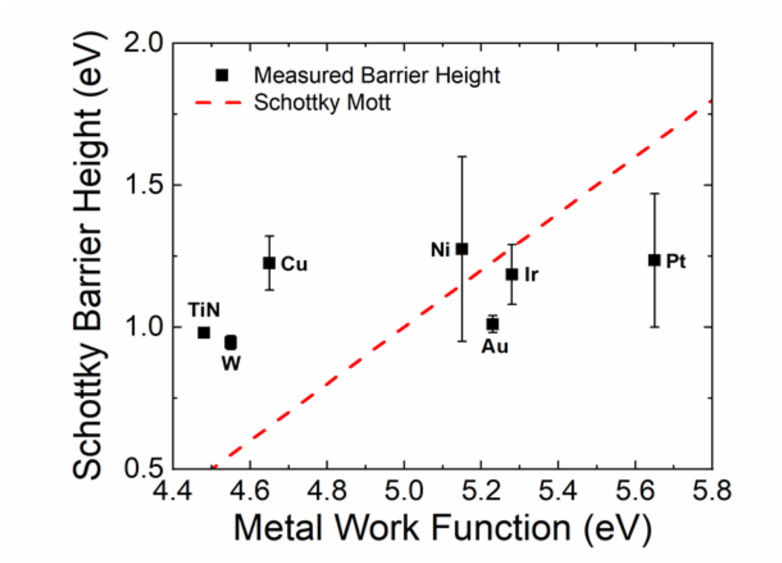


Figure 4.**Metal contacts on $Ga_2O_3$ show some Fermi level pinning.** The Schottky–Mott theory for ideal metal-semiconductor contacts shows barrier height should be given by ΦB = ΦM- Xs where ΦB is the Schottky barrier height, ΦM is the work function of the metal Xs is the electron affinity of semiconductor. Experimentally it is observed that (100) β-$Ga_2O_3$ shows a strong positive correlation between barrier heights and work function, while (-201) β-$Ga_2O_3$ shows no discernable correlation. The (010) β-$Ga_2O_3$ orientation shows a mixed correlation. Fermi level pinning on (-201) surface is due to its higher oxygen dangling bond density and oxygen vacancy concentration.

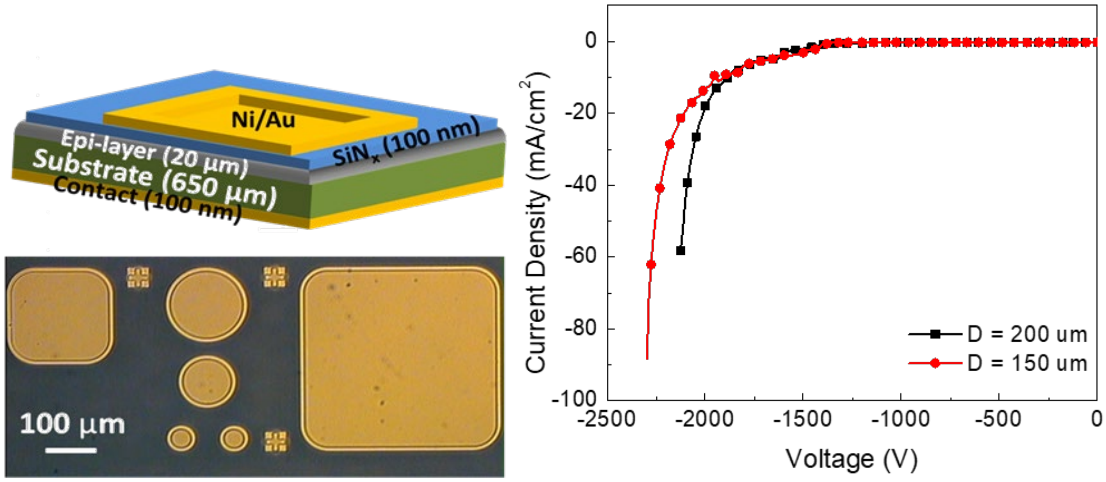


Figure 5. **$Ga_2O_3$ Field-Plated Diode with $V_{BD}$ of 2300 V.** There have been a variety of high voltage, large area vertical rectifiers and MOSFETs demonstrated, with voltages up to ~4kV and separately, currents in single scan mode up to 135A [6-11]. Schottky barrier diodes of corundum-structured gallium oxide have shown on-resistance of 0.1 mΩ $cm^2$ grown by mist epitaxy. Heterojunctions have been demonstrated using $Cu_2O$, NiO or $IrO_2$ as the p-type oxide [14-17]. Lateral field effect transistors are also promising for rf applications, with high Ecrit for ultra-low total dynamic switch power losses, chip-size reduction and fast switching frequency with reduced passive energy storage requirements at circuit level. It is promising that experimentally over half of predicted mobility and Ecrit has already been achieved, with an average Ecrit of ~ 4 MV $cm^{-1}$ achieved by multiple groups for lateral $Ga_2O_3$ FETs [1,4,6].

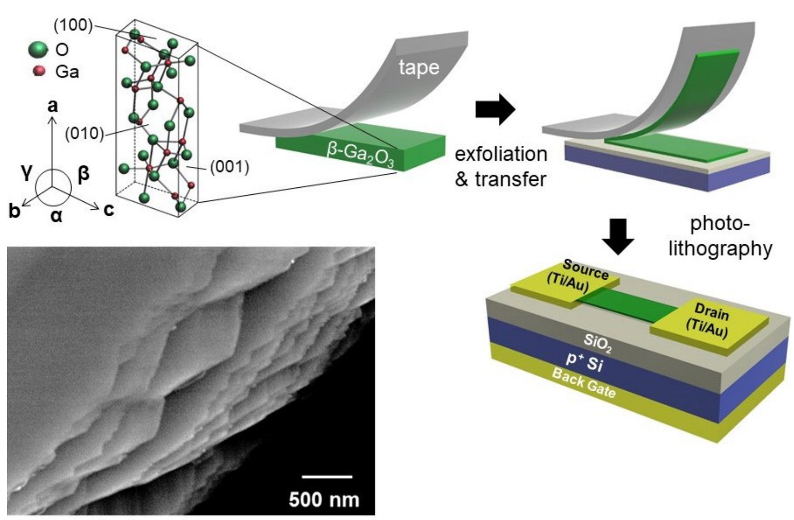


Figure 6. **Exfoliation process for $Ga_2O_3$.** It is also possible to make devices on mechanically exfoliated flakes [18-28].

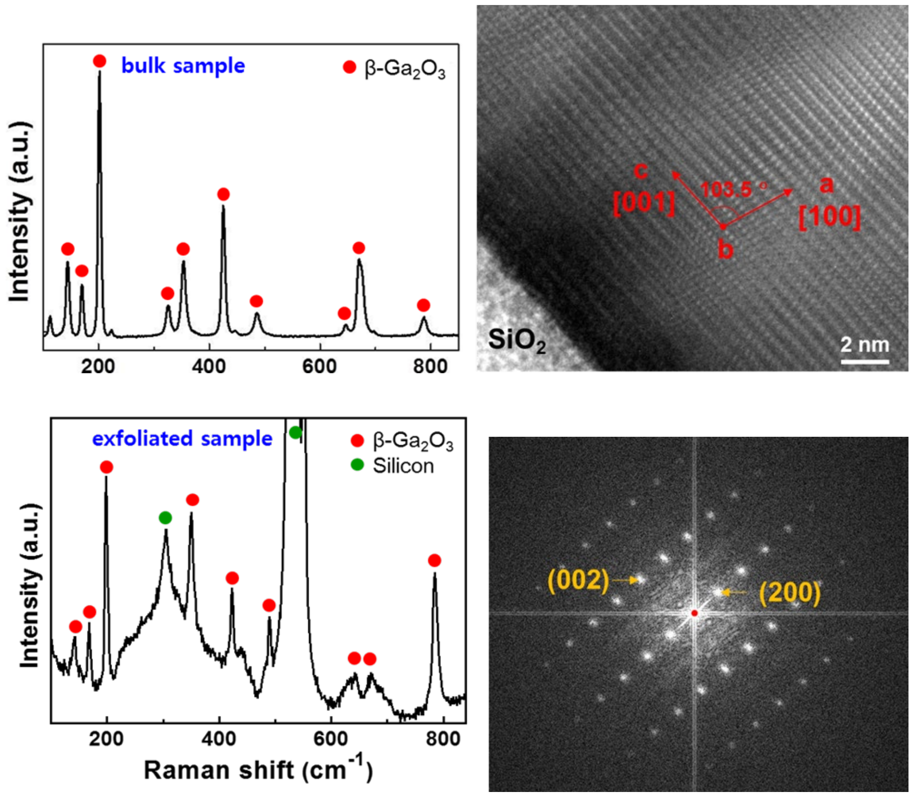


Figure 7.**Exfoliated layers retain excellent crystalline properties.** Raman spectra show no perturbation by the exfoliation process, while TEM shows good crystal quality. The angle between the [001] and [100] was 103.5° and the distances between the (200) and between the (002) were consistent with literature values. The flakes were exfoliated along the (100) plane.

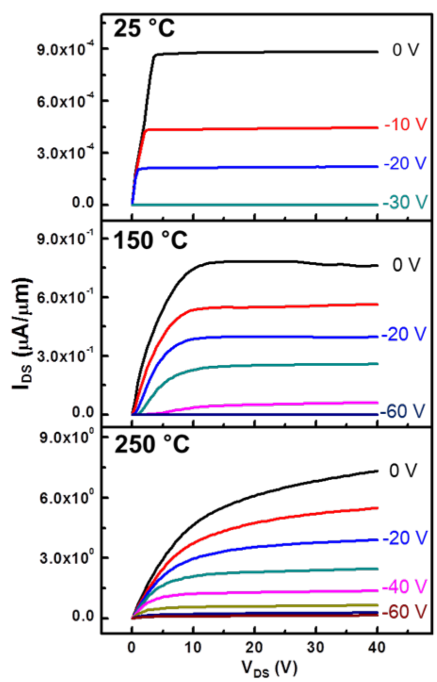

Figure 8. **Back-gated field effect transistors at high temperature.** I-Vs of the TFTs at the elevated operating temp. $I_{DS}$ was modulated by $V_{GS}$ with good saturation and sharp pinch-off characteristics**.** n-type channel. No electrical breakdown up to 250 °C. These devices can deliver high powers at elevated temperatures, which has not been demonstrated in low-dimensional devices. After a month of storage in air ambient there no degradation, with excellent air-stability [18].

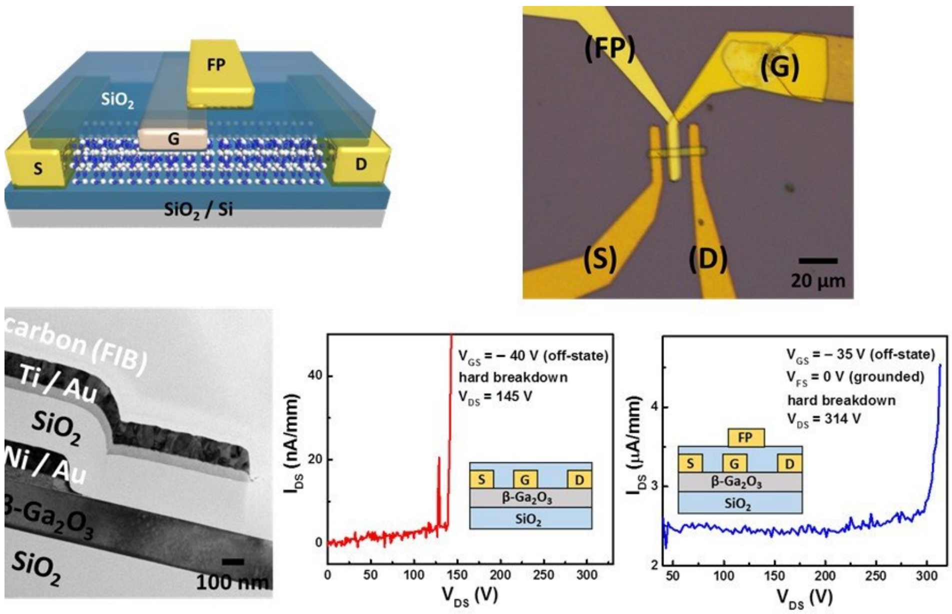


Figure 9. **Gate field plated flake field effect transistors.** Employing a field plate enables a significantly larger breakdown voltages to be achieved in these lateral devices.

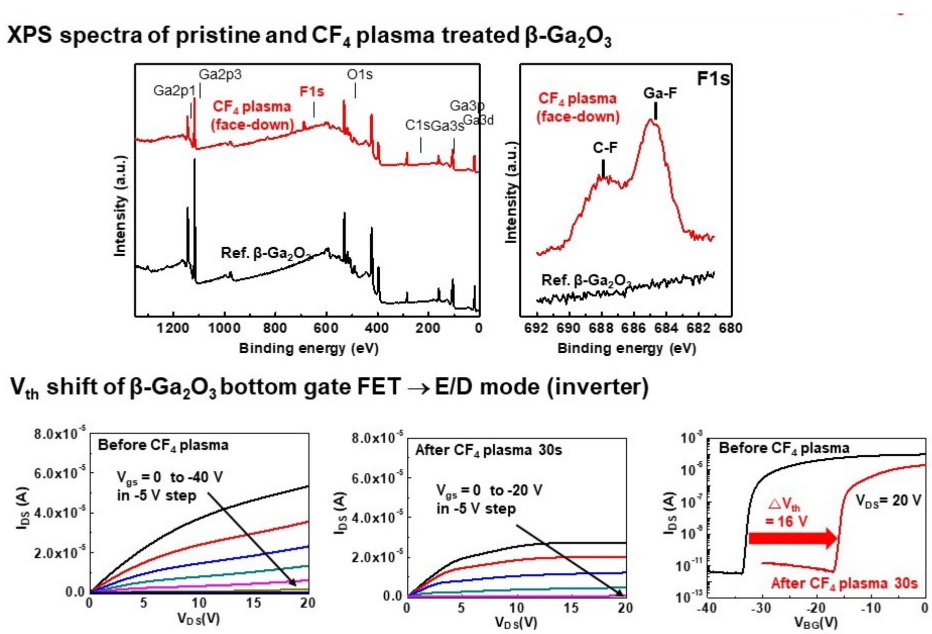


Figure 10. **Exposure to F-based plasmas can tune the thickness of the flake and the threshold voltage of transistors [22,23]**.

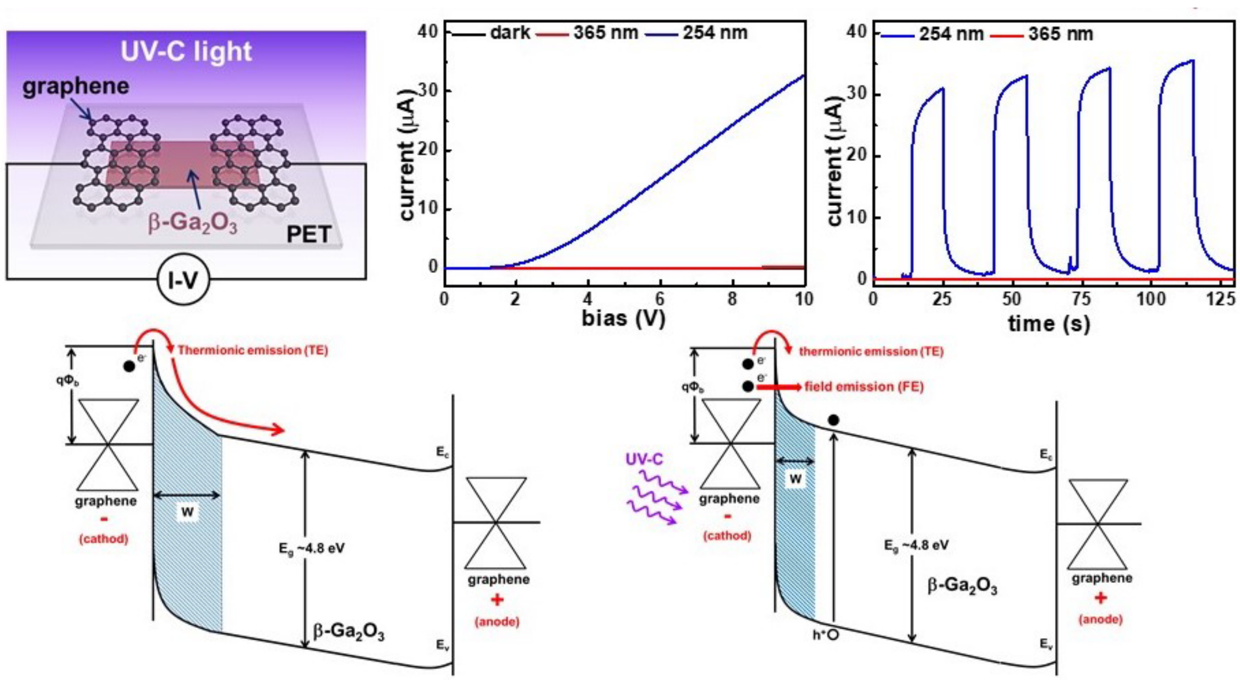


Figure 11. **Solar-blind photodetectors with graphene electrodes.** MSM photodetectors (PD) can suffer from low responsivity. The MSM PDs with graphene electrodes exhibited excellent operating characteristics including responsivity (~29.8 A/W), PDCR (~$10^6$%), rejection ratio (R254 nm/R365 nm, ~$9.4 \times 10^3$), detectivity (~$10^{12}$ Jones), and operating speed, compared with MSM PDs with opaque Ni/Au metal electrodes. Minimization of shading by the graphene electrode allows maximum exposure to the incident photons, suggesting potential for UV applications. Transition between MSM-type (dark  low leakage current by SBH) and photoconductive-type (UV-C  photocurrent + injected current) because graphene is UV-transparent [29].

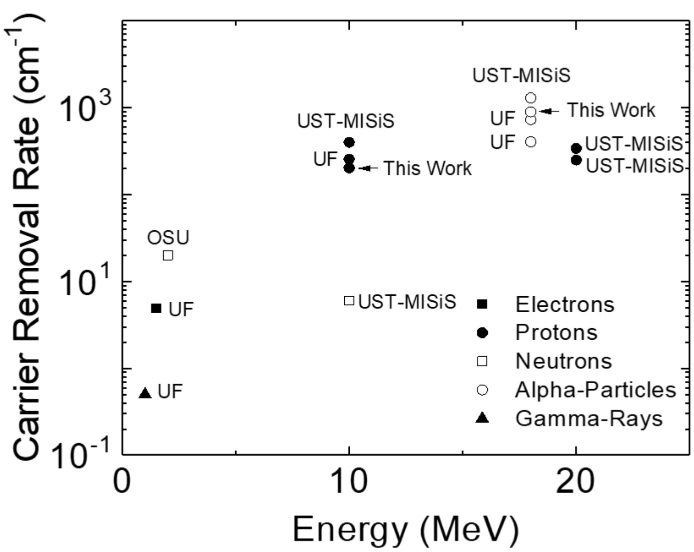


Figure 12.**Comparison of carrier loss by different forms of radiation.** Alpha particles are the most damaging, followed by protons, neutrons, electrons and gamma rays [30]. The main

conclusions are that useful devices can be made from bulk crystals, epi and mechanical exfoliation of β-$Ga_2O_3$ The main devices are rectifiers, rf transistors, UV photodetectors. For power devices, edge termination design is improving, with premature breakdown still occurring at the contact edge. Over 4kV $V_B$ demonstrated with a >30 μm drift layer. Other demonstrations of forward currents as high as135 A achieved in single-sweep voltage mode. Thermal management also needs to be incorporated. Quasi-2D β-$Ga_2O_3$ is an appropriate candidate for solar-blind PDs and high voltage nano electronics. initial data on p, e, n, α and γ- irradiation show similar or higher radiation resistance to GaN devices under the same conditions. All the initial work on $Ga_2O_3$ indicates its application to high power nano-electronic devices for harsh environments and deep-UV photodetectors as well as the miniaturization of power circuits and cooling systems in nano-electronics.

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**Declaration of interests**

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☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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