# Reflections on the state of ultra-wide-bandgap $Ga_2O_3$ MOSFETs

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**Abstract**

Gallium oxide ($Ga_2O_3$) is an emerging ultra-wide-bandgap (4.5–4.9 eV) semiconductor for high power and high voltage electronics with potential applications in harsh environments. Since the first report of a $Ga_2O_3$ field-effect transistor (FET) in 2012, $Ga_2O_3$ power devices have undergone tremendous technological advancement. This talk reviews the progress we have made and the lessons we have learnt on both lateral and vertical $Ga_2O_3$ metal-oxide-semiconductor (MOS) FETs. Future development directions will also be discussed.

## 1. Introduction

There have been strong interests in developing electronic devices based on wide bandgap compound semiconductors since Si technology is approaching fundamental performance limits. The past few years witnessed an enormous upsurge in research activities on ultra-wide-bandgap $Ga_2O_3$ for next-generation power electronics with high efficiency and compact size owing to the material's astounding Baliga's figure of merit and low substrate cost [1]. $Ga_2O_3$ is also thermally stable and radiation hard, thus rendering it suitable for devices and systems that demand stable operations in harsh environments. In this talk, we introduce the design principles and engineering strategies of lateral depletion-mode (D-mode) and enhancement-mode (E-mode) $Ga_2O_3$ MOSFETs. Progress toward vertical $Ga_2O_3$ MOSFETs will also be presented.

## 2. Experimental

Lateral $Ga_2O_3$ MOSFETs were fabricated on unintentionally-doped (UID) $Ga_2O_3$ (010) grown by molecular beam epitaxy. D-mode devices consisted of an *n*-type channel and ohmic contacts doped by Si-ion ($Si^+$) implantations [Fig. 1(a)] [2]. E-mode devices consisted of a UID channel for accumulation-mode operation and $Si^+$-implanted access regions overlapped by the gate electrode [Fig. 2(a)] [3]. Vertical D-mode $Ga_2O_3$ (001) MOSFETs [Fig. 3(a)] [4], which had a drift layer grown by halide vapor phase epitaxy, featured a planar-gate architecture wherein an Mg-ion-implanted current blocking layer (CBL) provided electrical isolation between source and drain except at an aperture opening through which drain current ($I_{DS}$) was conducted. Transistor action was realized by gating a $Si^+$-implanted channel above the CBL. All MOSFETs incorporated an $Al_2O_3$ gate insulator formed by plasma-assisted atomic layer deposition.

## 3. Results and Discussion

Field-plated lateral D-mode $Ga_2O_3$ MOSFETs with $SiO_2$ surface passivation achieved a high off-state breakdown voltage of 755 V [Fig. 1(b)], a large $I_{DS}$ on/off ratio ($I_{ON}/I_{OFF}$) of over $10^9$, stable high temperature operation at 300°C, and dispersion-free output characteristics [2]. The bulk $Ga_2O_3$ channel exhibited strong gamma-ray tolerance, yet radiation-induced dielectric damage and interface charge trapping limited the total-dose radiation hardness of these devices [Fig. 4] [5]. E-mode operation was enabled by a low maximum background carrier density of ~$10^{14}$ $cm^{-3}$ in UID $Ga_2O_3$ that enabled full channel depletion at zero gate bias. Despite hysteretic effects associated with an unoptimized gate dielectric, a decent $I_{ON}$ of 1.4 mA/mm and a large $I_{ON}/I_{OFF}$ near $10^6$ were obtained [Fig. 2(b)] [3]. The vertical MOSFETs demonstrated clear $I_{DS}$ modulation [Fig. 3(b)]; however, Mg diffusion during activation annealing led to residual *n*-type conductivity in the CBL and consequently large off-state source–drain leakage [4]. Future work on vertical MOSFETs will focus on investigating thermally-stable deep acceptor species (e.g. nitrogen) for the CBL (Fig. 5) [6].

## 4. Conclusion

The rapid development of $Ga_2O_3$ MOSFETs in recent years has affirmed their prospects for next-generation power switches. Advanced device architectures, notably normally-off vertical transistors, will further enhance the impact of this technology.

## References

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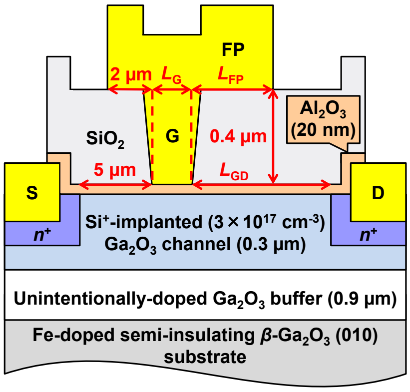
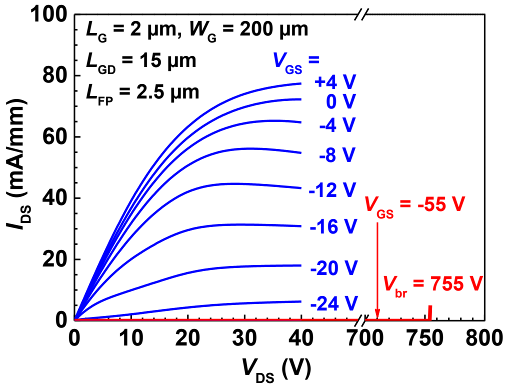
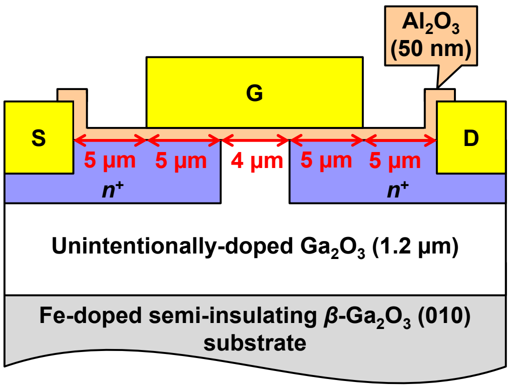



(a)

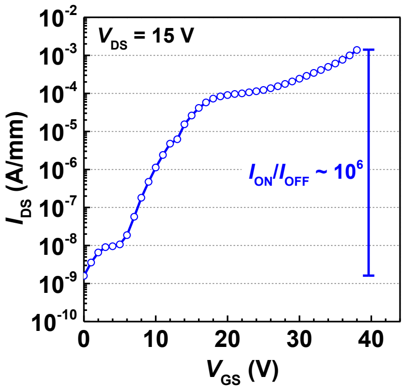



(b)

*Fig.1: (a) Cross-sectional schematic and (b) DC output characteristics of field-plated lateral D-mode $Ga_2O_3$ MOSFET [2].*

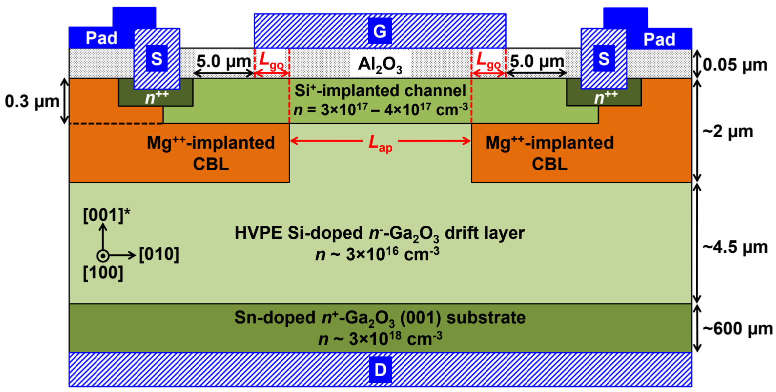



(a)

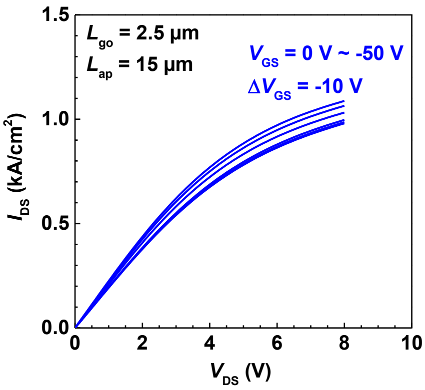



(b)

*Fig.2: (a) Cross-sectional schematic and (b) DC transfer characteristic of lateral E-mode $Ga_2O_3$ MOSFET [3].*




(a)




(b)

*Fig.3: (a) Cross-sectional schematic and (b) DC output characteristics of vertical D-mode $Ga_2O_3$ MOSFET [4].*

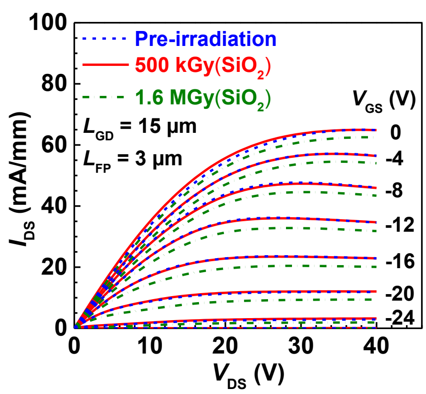



*Fig.4: DC output characteristics of field-plated lateral D-mode $Ga_2O_3$ MOSFET before and after gamma-ray irradiations [5].*

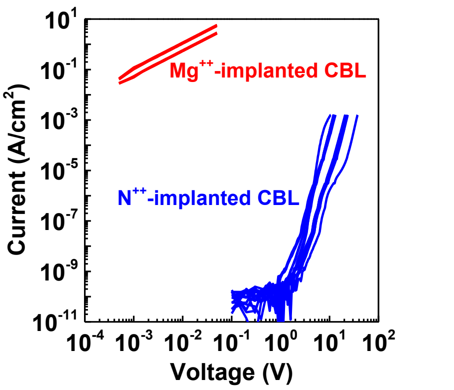



*Fig.5: Comparison between leakage currents through N-ion-implanted and Mg-ion-implanted CBLs [6].*