Gallium oxide power device technologies

Masataka Higashiwaki[1,2]

[1] *Department of Physics and Electronics, Osaka Metropolitan University, Japan*

[2] *National Institute of Information and Communications Technology, Japan*

Acknowledgement

This work was supported in part by MIC under a grant entitled “R&D of ICT Priority Technology (JPMI00316): Next-Generation Energy-Efficient Semiconductor Development and Demonstration Project (2nd period) (in collaboration with MOEJ)

Outline

1. Introduction
2. History of R&D on our Ga_2O_3 device technology
3. Nitrogen radical irradiation to recover Ga_2O_3 surface damage
4. Ga_2O_3 (010) FinFETs fabricated with N radical irradiation
5. Conclusion

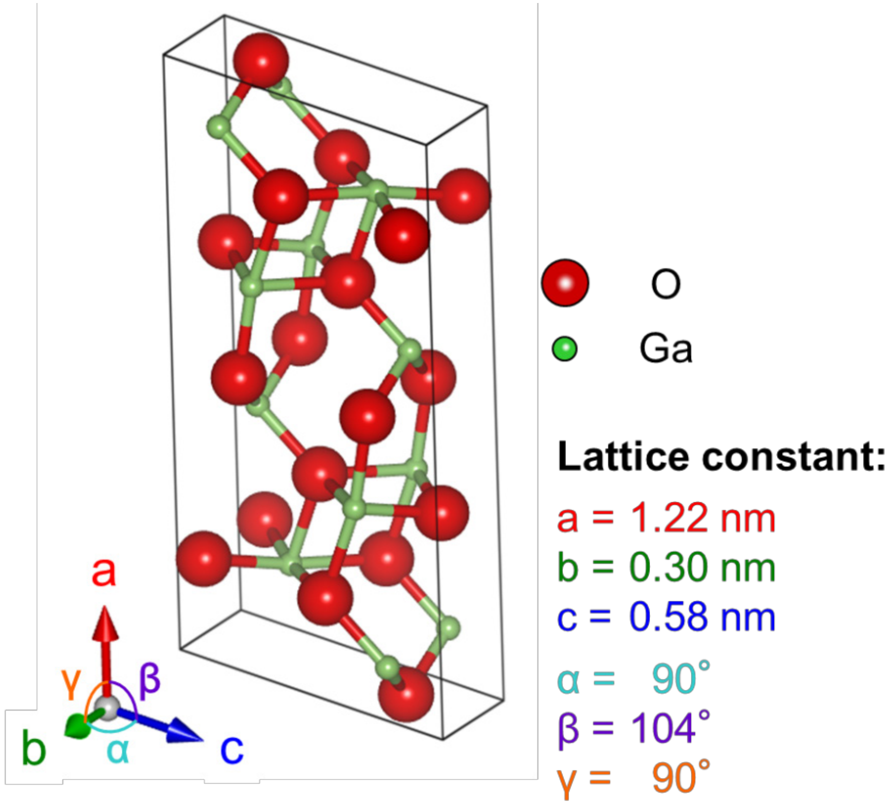
1. Introduction

What is gallium oxide (Ga_2O_3)??

Material properties of Ga_2O_3

- Polymorphs (α, β, γ, δ, ε)
- Most stable polymorph is β-Ga_2O_3
  - β-Ga_2O_3: monoclinic β-gallia structure
- Extremely large bandgap
  - β-Ga_2O_3 : 4.5 eV
  - α-Ga_2O_3 : 5.3 eV
- Controllable *n*-type conductivity
  - ($n = 10^{15} – 10^{19}$ cm^{-3}, $\rho = 10^{-3} – 10^{12}$ Ω·cm)
- No report on *p*-type doping and effective hole conductivity
- Poor thermal conductivity [1]
  - (0.27 W/cmK along [010], 0.11 W/cmK along [100])

Unit cell of β-Ga_2O_3

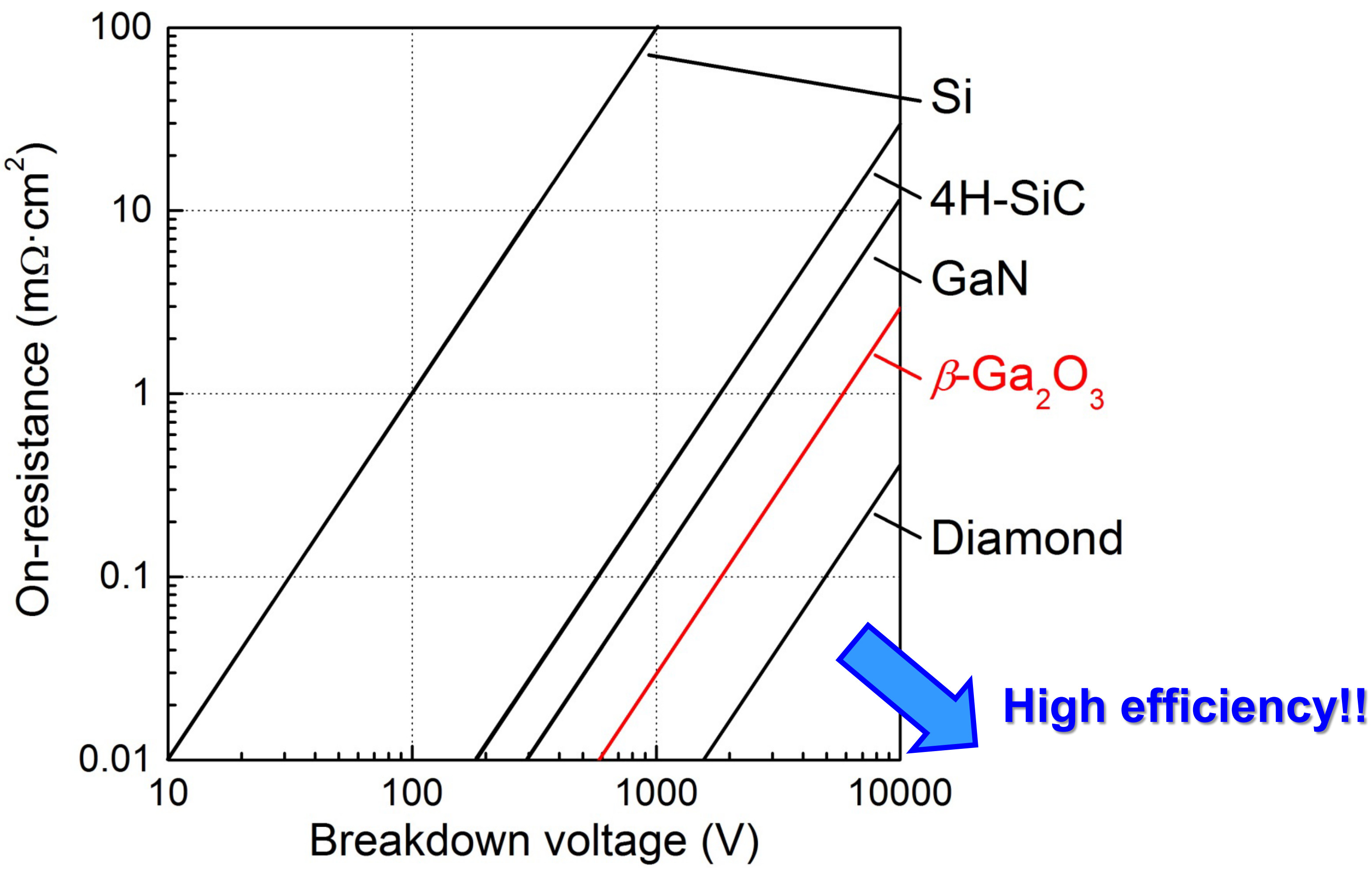


[1] Z. Guo *et al.*, Appl. Phys. Lett. **106**, 111909 (2015)

Comparisons of physical properties between major semiconductors and β-Ga_2O_3

	Si	4H-SiC	GaN	β-Ga_2O_3
Band gap (eV)	1.1	3.3	3.4	4.5
Relative dielectric constant	11.8	9.7	9.0	10.2 – 12.4
Electron mobility (cm^2/Vs)	1,400	1,000	1,200	200
Breakdown electric field (MV/cm)	0.3	2.5	3.3	> 7
Saturation electron velocity ($\times 10^7$ cm/s)	1.0	2.0	2.5	1.0 – 1.5
Thermal conductivity (W/cm·K)	1.5	2.7	2.1	0.27 [010]
Baliga's FOM ($\varepsilon\mu E_c^3$)	1	340	870	1,570 – 1,900
Johnson's FOM ($E_c^2 V_{sat}^2$)	1	280	760	540 – 1,200

On-resistance (R_{on}) vs breakdown voltage (V_{br})



Ga_2O_3 would be superior to SiC and GaN for power device applications

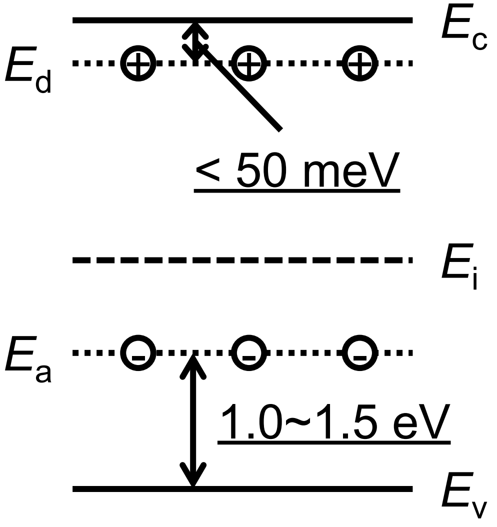
n-type, *p*-type Ga_2O_3

n-Ga_2O_3

- Shallow donors (Si, Sn, Ge)
  => 100% activation at RT
- Reasonable electron effective mass (m_e: $0.3m_0$)
- Room-temperature electron mobility: 200 cm^2/Vs

p-Ga_2O_3

- Deep acceptors (Mg, Zn, Be, N etc.)
  => Activation energy: > 1 eV
- Extremely large hole effective mass
- Localization of free holes due to lattice distortion



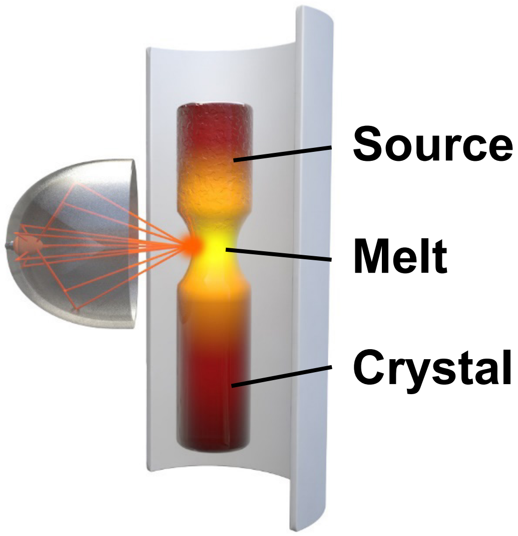
Band diagram of *n*-Ga_2O_3 and *p*-Ga_2O_3

Effective hole conduction is almost impossible;
however, it is possible to make an energy barrier by forming *p-n* junctions

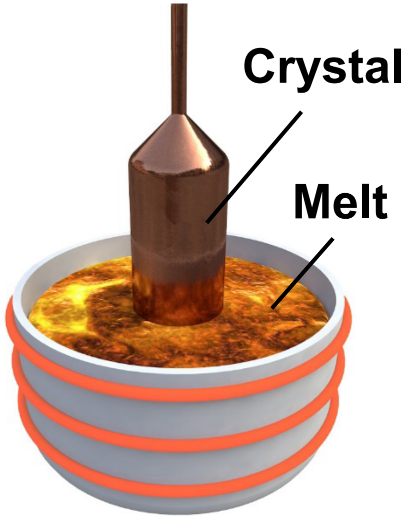
Ga_2O_3 bulk melt growth methods

β-Ga_2O_3 wafers can be produced from bulk single crystals synthesized by melt growth methods

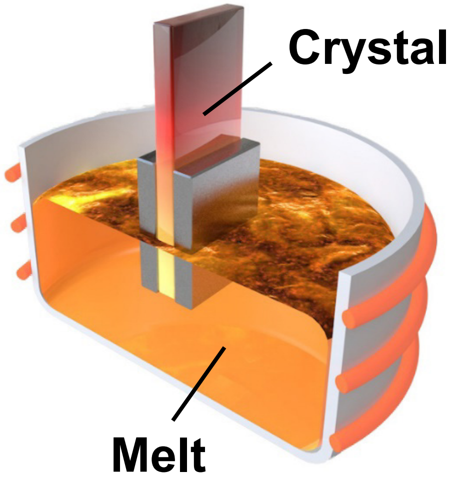
Floating zone



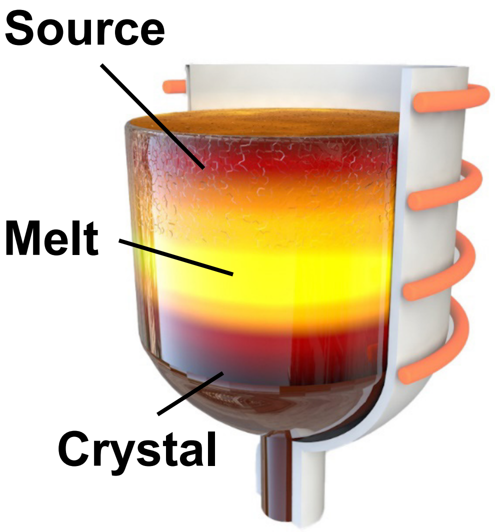
Czochralski



EFG



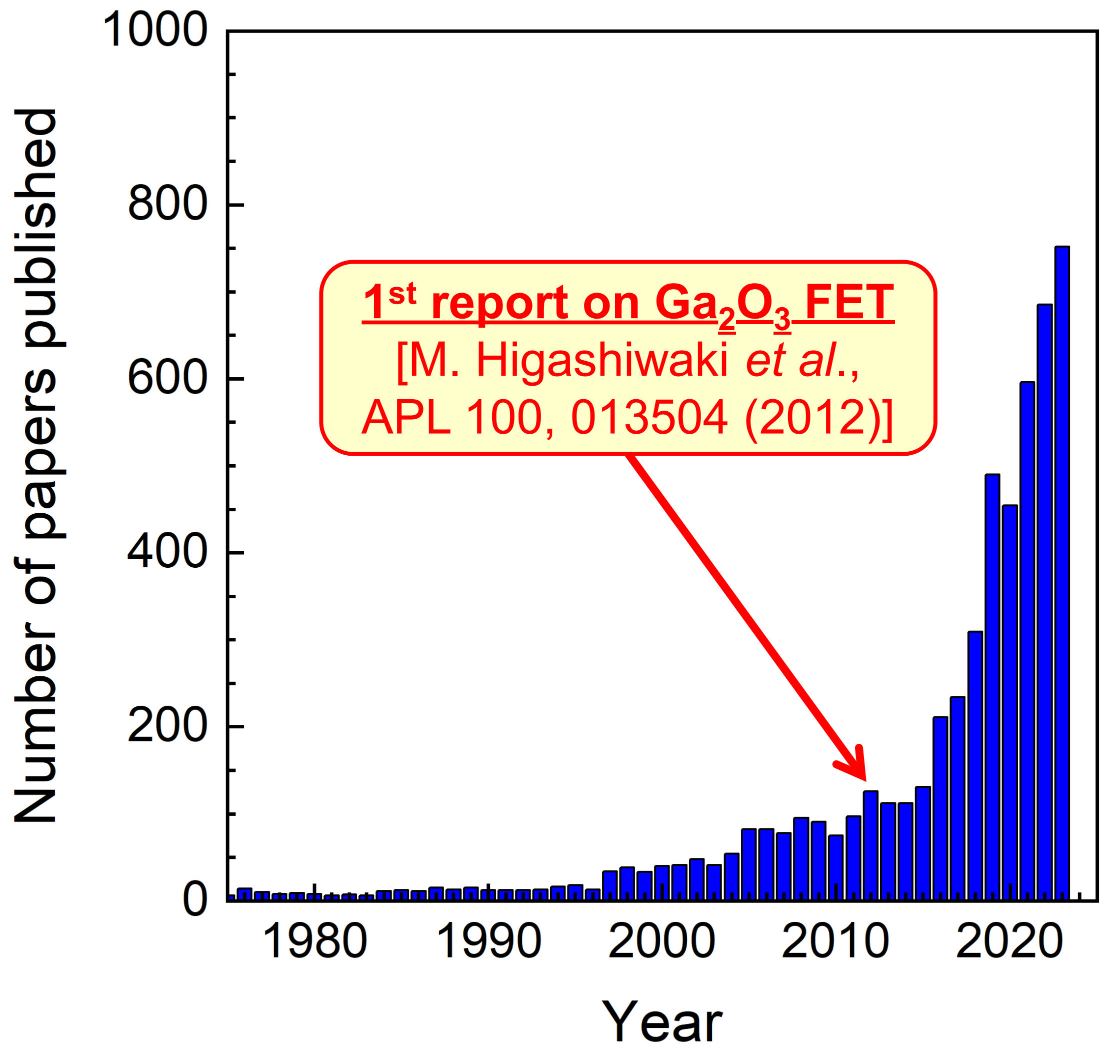
Bridgman



World-wide research activity of Ga_2O_3 initiated by the MESFET report

Web of Science (July 1st, 2024)

Search criteria: Keyword “Ga_2O_3” in “Title”



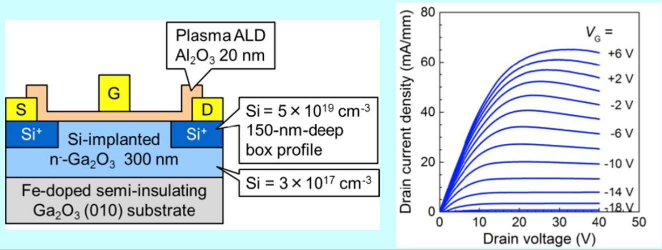
Ga_2O_3 has become a key material among compound semiconductors in the past ten years!!

2. History of R&D on our Ga_2O_3 device technology (2010 – present)

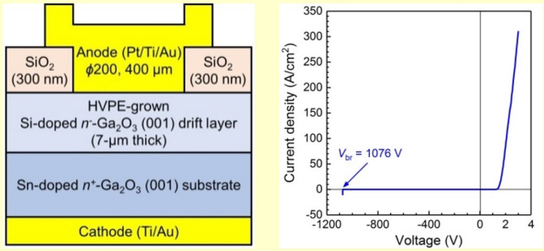
History of R&D on Ga_2O_3 power and high-frequency devices @ NICT (2010 – present)

R&D of Ga_2O_3 devices start!

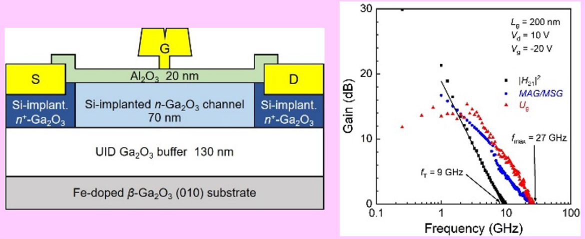
D-mode Ga_2O_3 MOSFET
(Si-ion implantation doping)



Ga_2O_3 field-plated SBD
(World's first V_{br}>1 kV)

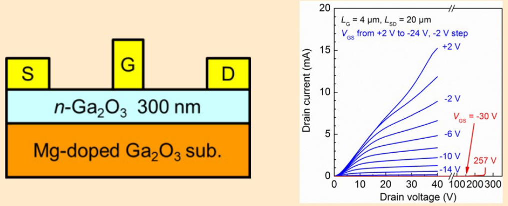


High-frequency Ga_2O_3 MOSFET (f_{max} = 27 GHz)

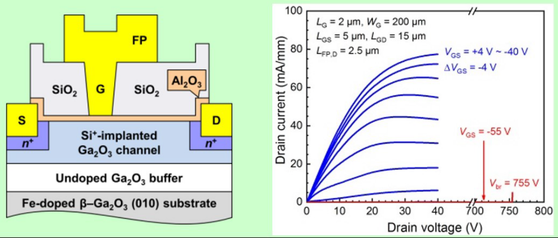


2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 (Year)

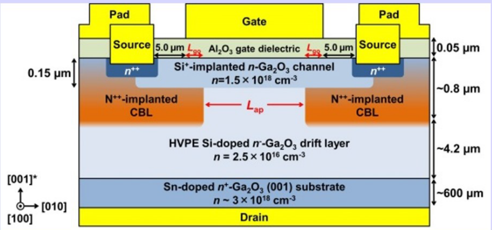
Ga_2O_3 MESFET
(World's first single-crystal Ga_2O_3 transistor)



Ga_2O_3 field-plated MOSFET
(V_{br}>750 V)



Vertical Ga_2O_3 MOSFET
(N-ion implantation doping)

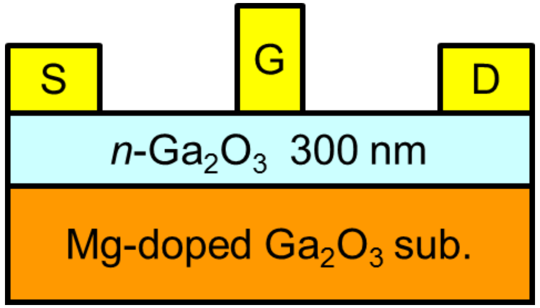


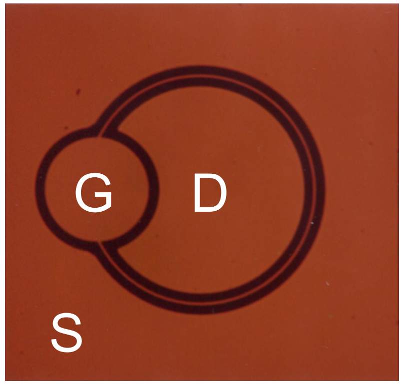
NICT and collaborators have been developing milestone technologies for Ga_2O_3 devices

Ga_2O_3 MESFETs (2011)

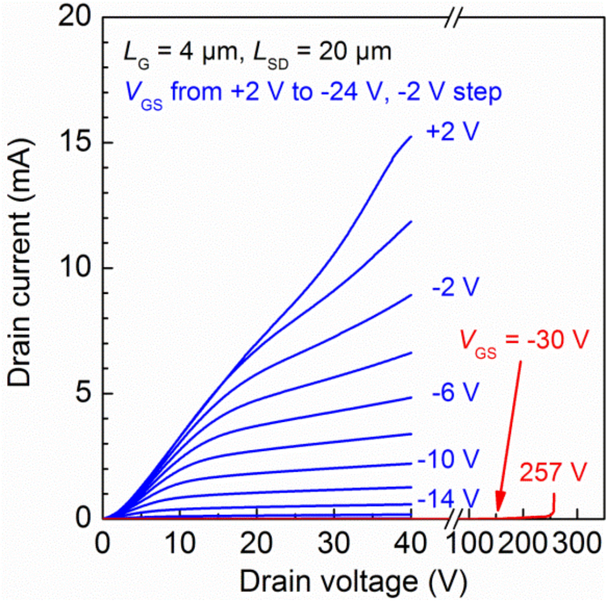
M. Higashiwaki *et al*., Appl. Phys. Lett. **100**, 013504 (2012)

Masataka Higashiwaki





(Left) Schematic cross section and
(right) optical micrograph of Ga_2O_3 MESFET structure



DC *I*–*V* characteristics

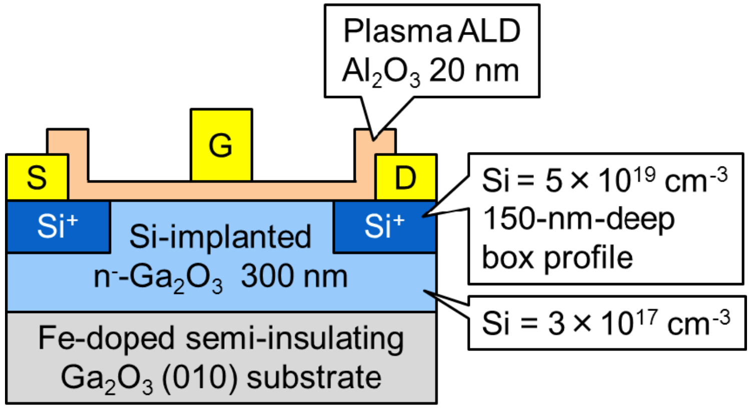
Breakthrough

- **First demonstration of Ga_2O_3 transistor**

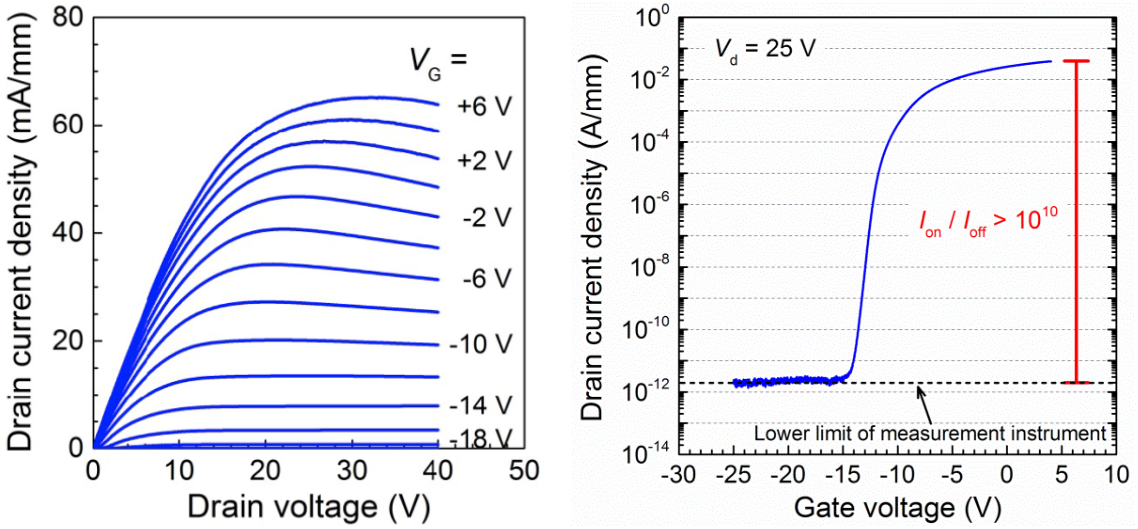
Depletion-mode Ga_2O_3 MOSFETs (2013)

M. Higashiwaki *et al.*, in *Tech. Dig. of the IEEE IEDM*, pp. 28.7.1, 2013

Masataka Higashiwaki



Schematic cross section of D-mode Ga_2O_3 MOSFET structure



(Left) *I*–*V* and (right) transfer characteristics

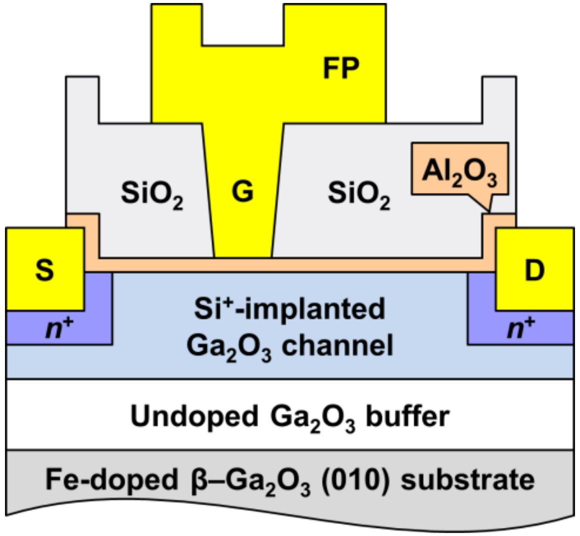
<u>Breakthrough</u>

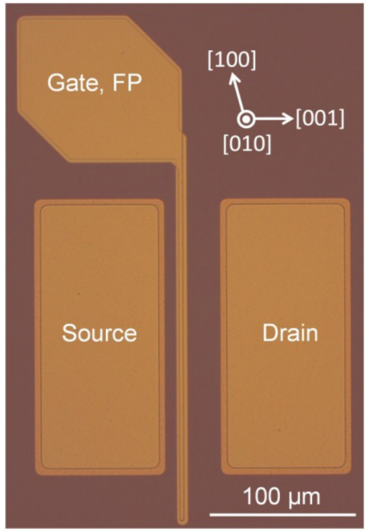
- **Si-ion implantation doping**
- **Good (normal) I_d–V_d characteristics**
- **Large I_d on/off ratio of > 10^9**
- **V_{br} > 400 V**

Depletion-mode Ga_2O_3 field-plated MOSFETs (2015)

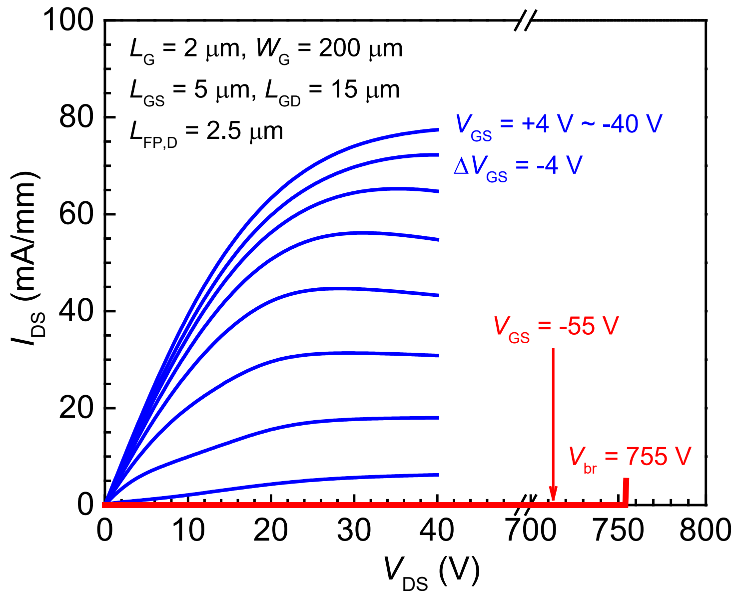
M. H. Wong, M. H. *et al.*, IEEE Electron Device Lett. **37**, 212 (2016)

Man Hoi Wong





(Left) Schematic cross section and
(right) optical micrograph of Ga_2O_3 FP-MOSFET structure



DC *I*–*V* characteristics

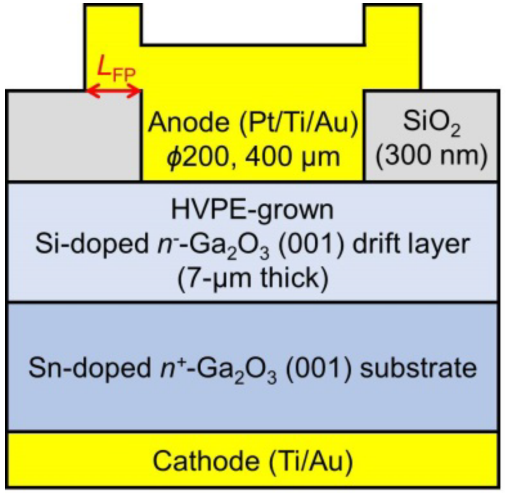
<u>Breakthrough</u>

- **V_{br} > 750 V by field-plate effect**

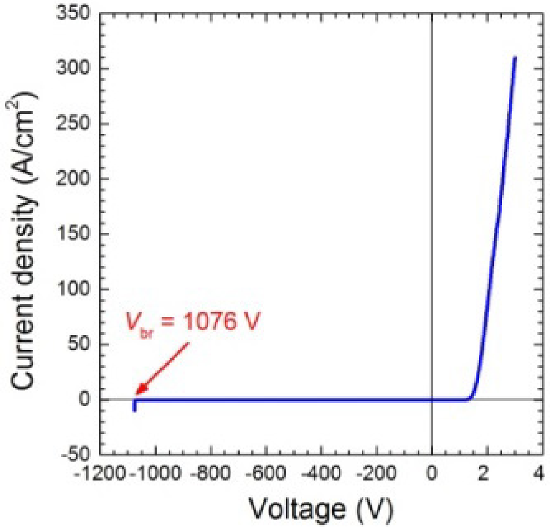
Vertical Ga_2O_3 field-plated Schottky barrier diodes (2016)

K. Konishi, M. H. *et al.*, Appl. Phys. Lett. **110**, 103506 (2017)

Keita Konishi



Schematic cross section of vertical Ga_2O_3 FP-SBD structure



DC *J*–*V* characteristics

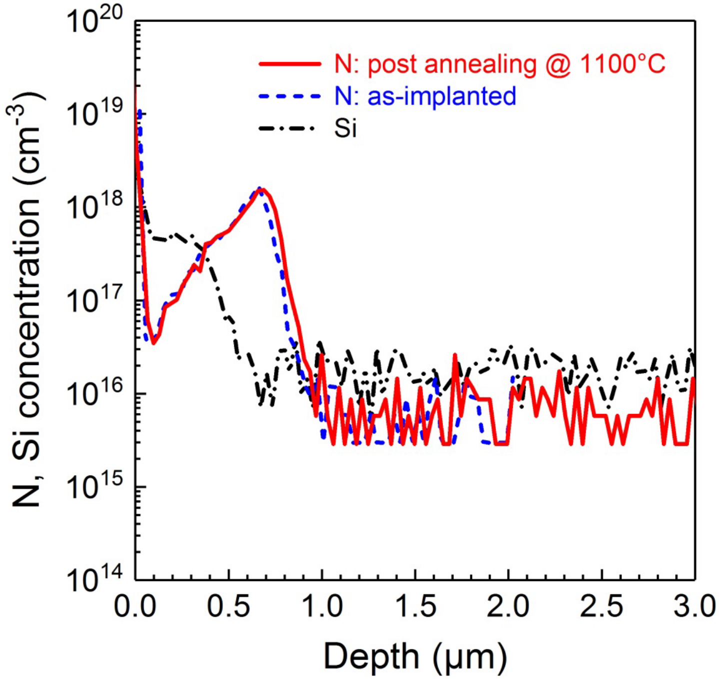
Breakthrough

- **HVPE growth technology**
- **First demonstration of V_{br} > 1,000 V for Ga_2O_3 devices**

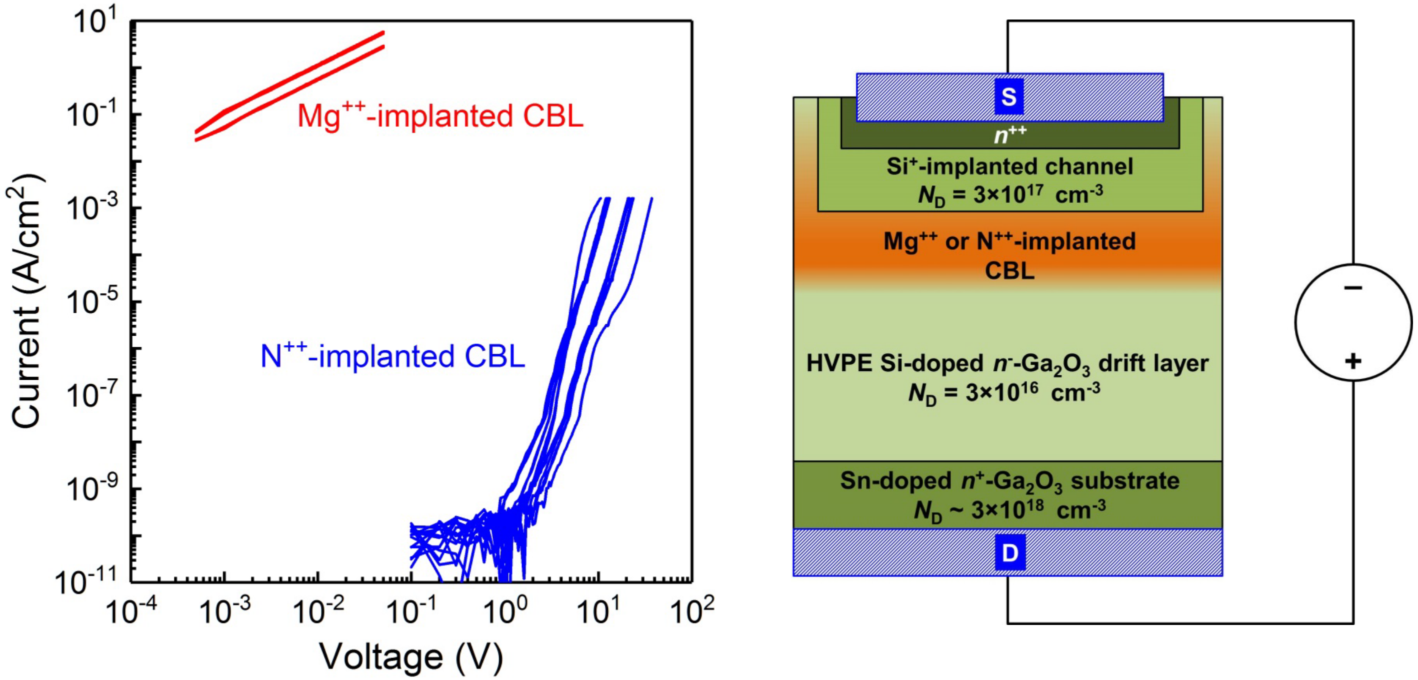
Nitrogen (N)-ion implantation doping (2017)

M. H. Wong, M. H. *et al.*, Appl. Phys. Lett. **113**, 102103 (2018)

Man Hoi Wong



SIMS depth profiles of N atoms



(Left) *J–V* characteristics, (right) cross section of test structure to characterize electrical properties of N-implanted current blocking layer

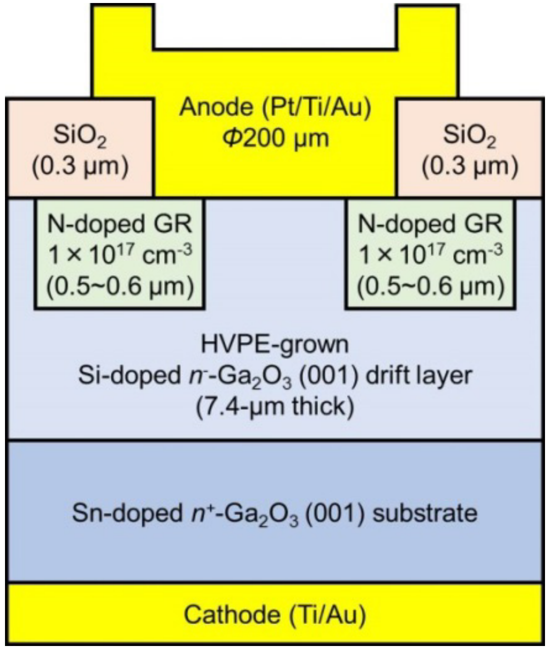
Breakthrough

- **N-ion implantation doping to form deep-acceptor *p*-type Ga_2O_3**

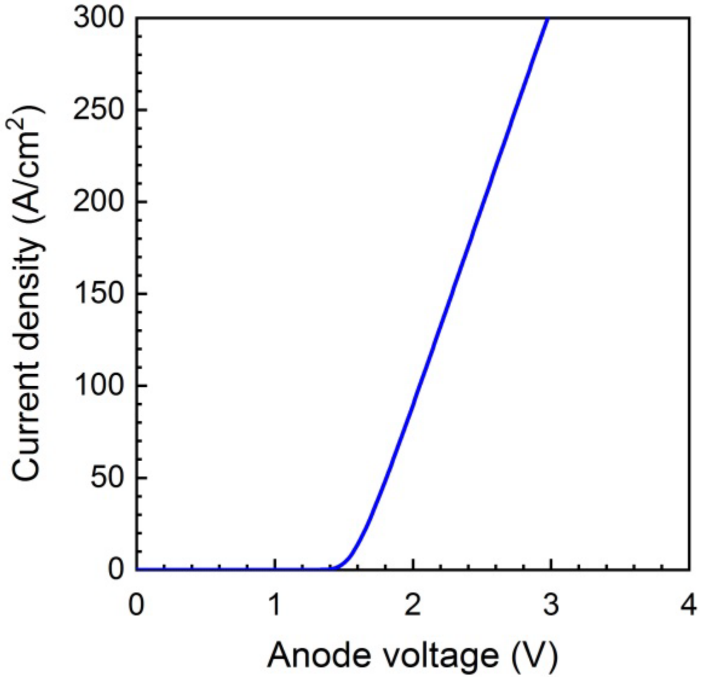
Device structure of Ga_2O_3 field-plated SBDs with nitrogen-implanted guard ring (2018)

C.-H. Lin, M. H. *et al.*, IEEE Electron Device Lett. **40**, 1487 (2019)

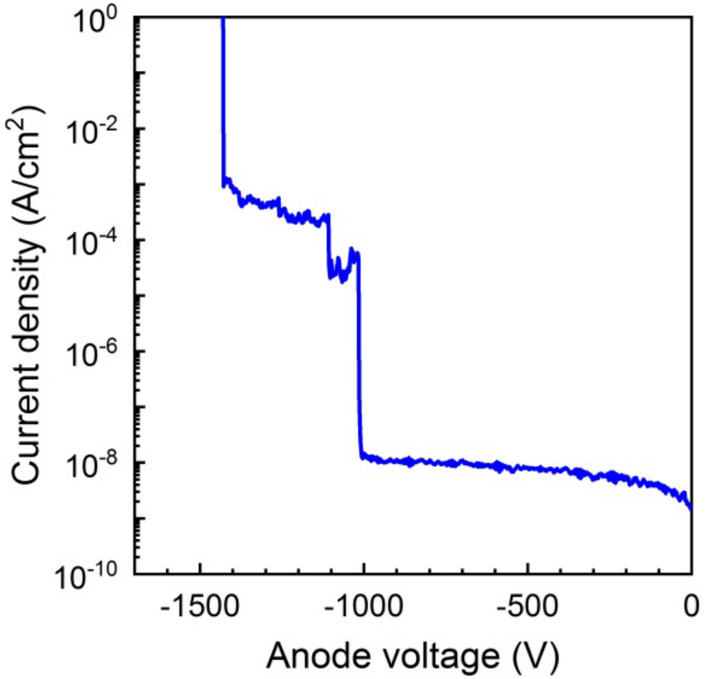
Chia-Hung Lin



Schematic cross section of vertical field-plated SBD with nitrogen-implanted guard ring



Forward *J*–*V* characteristics



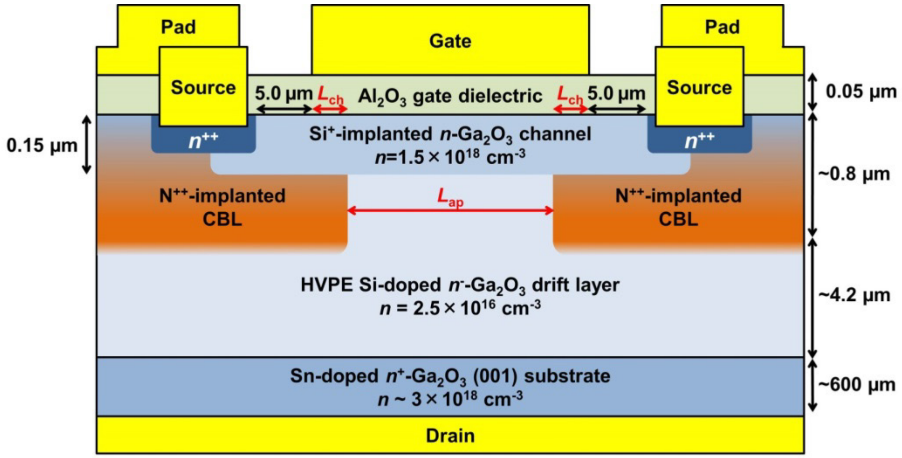
Reverse *J*–*V* characteristics

- **On-resistance**: R_{on} **= 4.7 mΩ·cm²**
- **Breakdown voltage**: V_{br} **= 1,430 V**

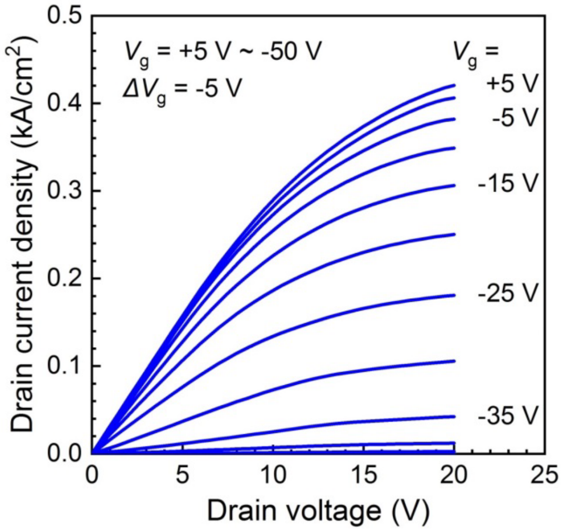
Vertical depletion- and enhancement-mode Ga_2O_3 MOSFETs (2018–2019)

M. H. Wong, M. H. *et al.*, IEEE Electron Device Lett. **40**, 431 (2019): D-mode
M. H. Wong, M. H. *et al.*, IEEE Electron Device Lett. **41**, 296 (2020): E-mode

Man Hoi Wong



Schematic cross section of
vertical D-mode Ga_2O_3 CAVET structure



DC *I*–*V* characteristics

Breakthrough

- **N-ion implantation doping to form current blocking layer**
- **Manufacturable all-ion-implanted process**

Trench staircase field-plated Ga_2O_3 Schottky barrier diodes (2021)

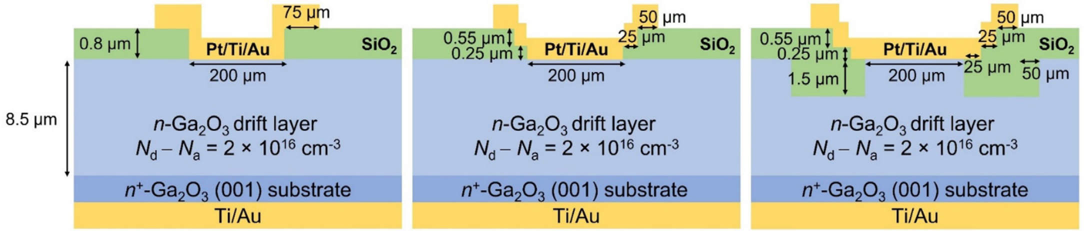
Ref. S. Kumar, M. H. *et al*. (NICT), Appl. Phys. Express **15**, 054001 (2022)

Sandeep Kumar

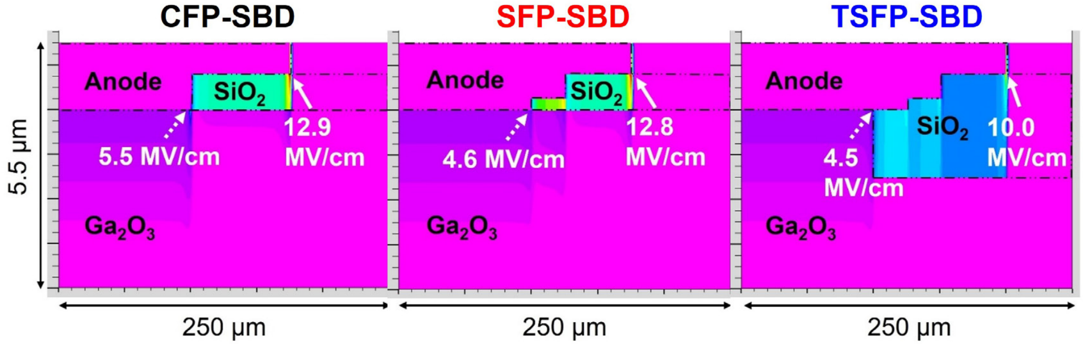
Conventional field-plated SBD (CFP-SBD)

Staircase field-plated SBD (SFP-SBD)

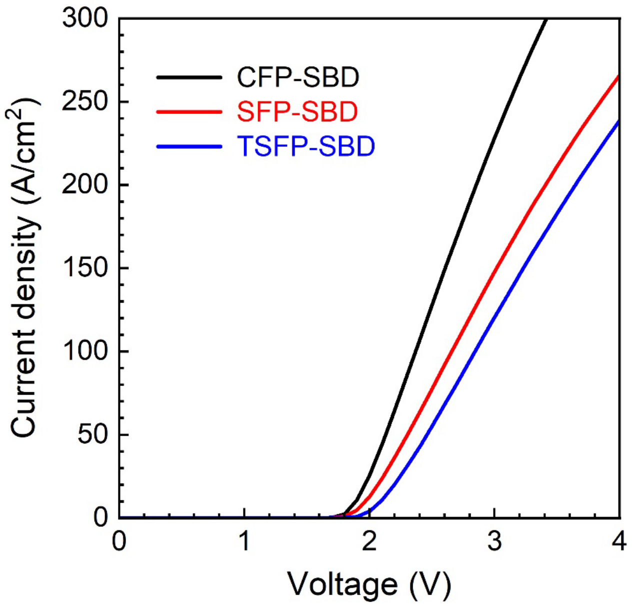
Trench staircase field-plated SBD (TSFP-SBD)



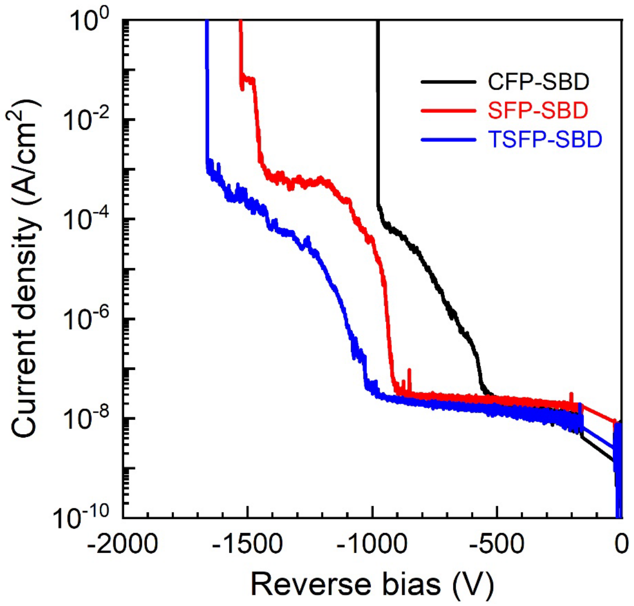
Electric field distributions @ V_{rev} = 2 kV



Forward *J–V* characteristics



Reverse *J–V* characteristics



CFP-SBD

- R_{on} = 4.7 mΩcm^2
- V_{br} = 980 V

SFP-SBD

- R_{on} = 7.0 mΩcm^2
- V_{br} = 1,530 V

TSFP-SBD

- R_{on} = 7.6 mΩcm^2
- V_{br} = 1,660 V

Zhenwei Wang
(NICT)

Shota Sato
(OMU)

Kura Nakaoka
(OMU)

Shoki Taniguchi
(OMU)

Kohki Eguchi
(OMU)

3. Nitrogen radical irradiation to recover Ga_2O_3 surface damage

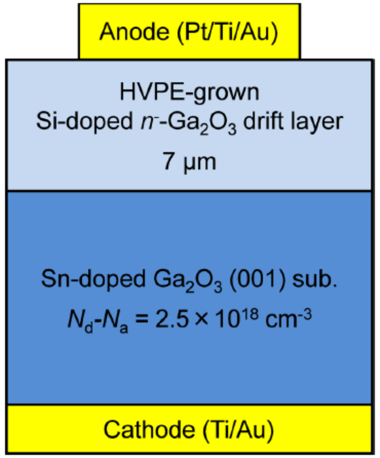
Ref. Z. Wang, M. H. *et al.*, EMC 2023
S. Sato, M. H. *et al.*, GOX 2023

Background

Question

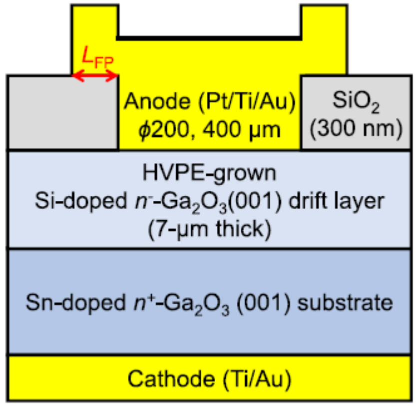
- **What is the origin of unstable Schottky barrier height on Ga_2O_3?**
- **Is there any technique to recover Ga_2O_3 surface damage?**

Higashiwaki *et al.*, APL 2016



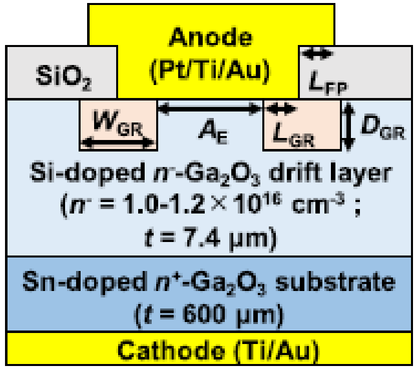
V_{on} = 1.2 V

Konishi *et al.*, APL 2017



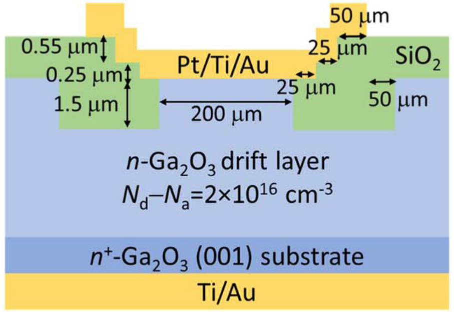
V_{on} = 1.5 V

Lin *et al.*, IEEE EDL 2019



V_{on} = 1.5 – 1.8 V

Kumar *et al.*, APEX 2022



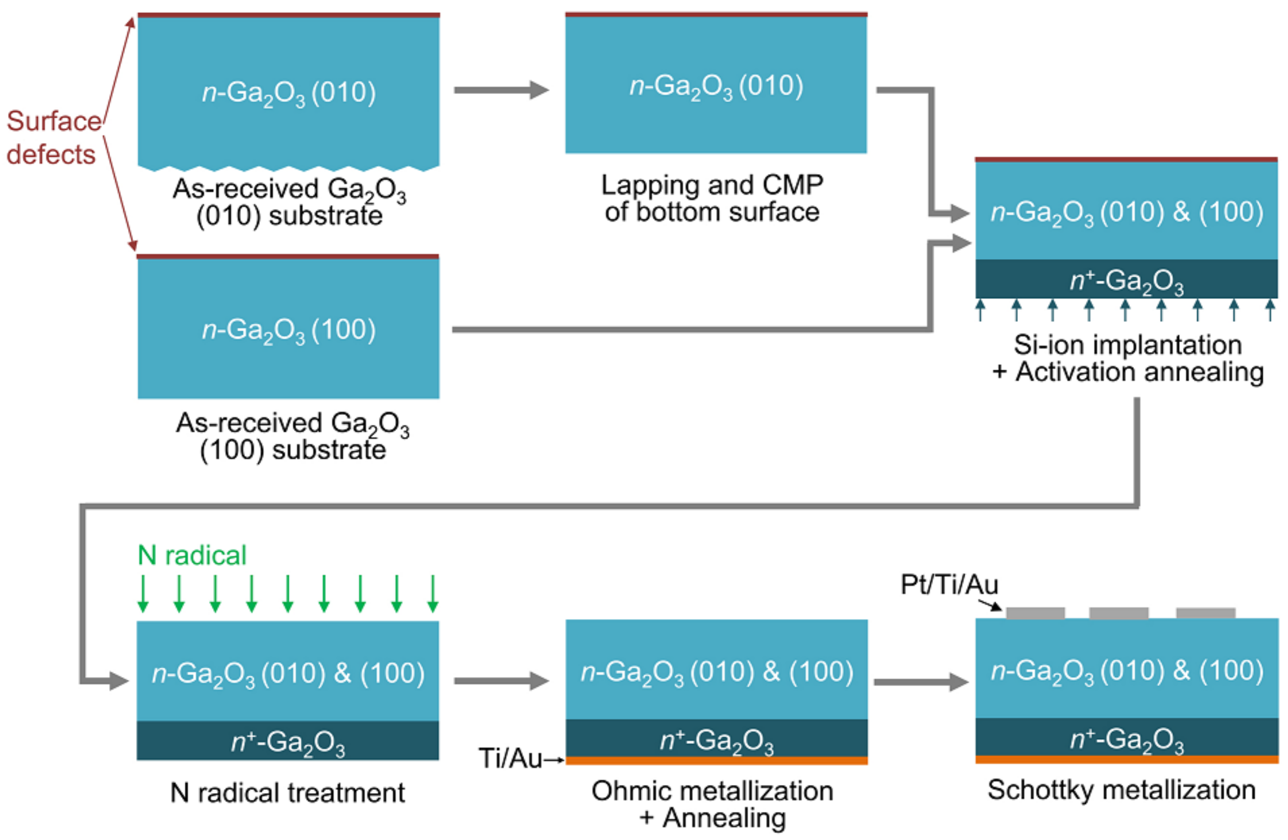
V_{on} = 1.9 – 2.1 V

This work

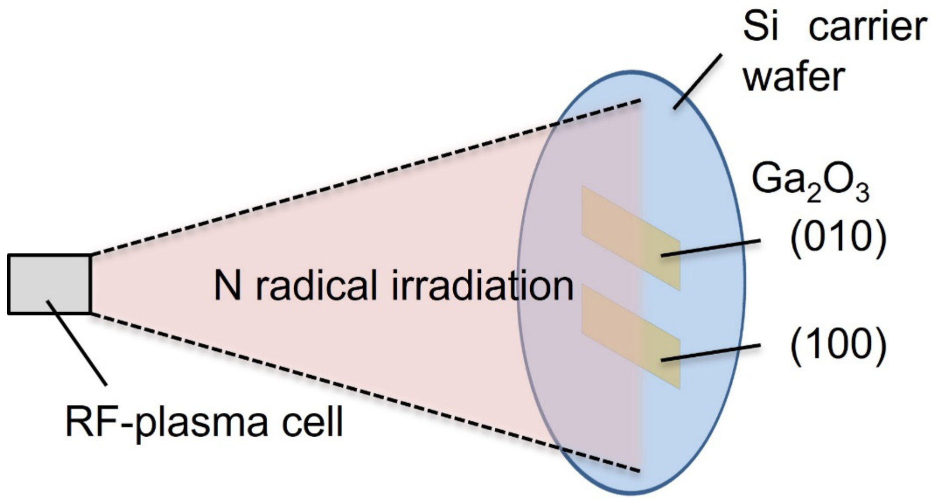
Investigation on effects of N radical treatment on Ga_2O_3 Schottky properties

Fabrication process of Ga_2O_3 (010) and (100) SBDs

Process flow of Ga_2O_3 (010) and (100) SBDs



N radical irradiation in MBE chamber



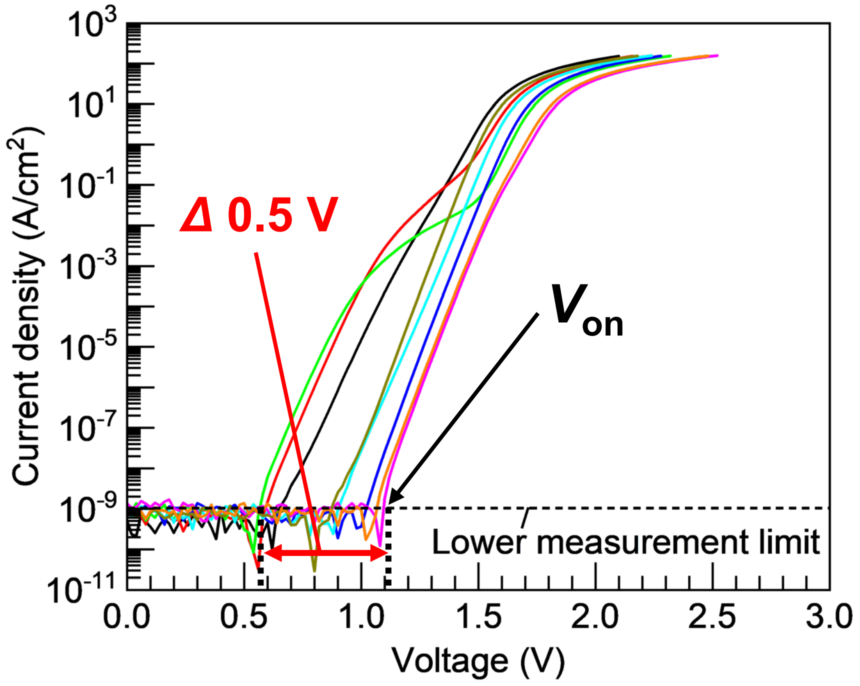
RF plasma: 500 W

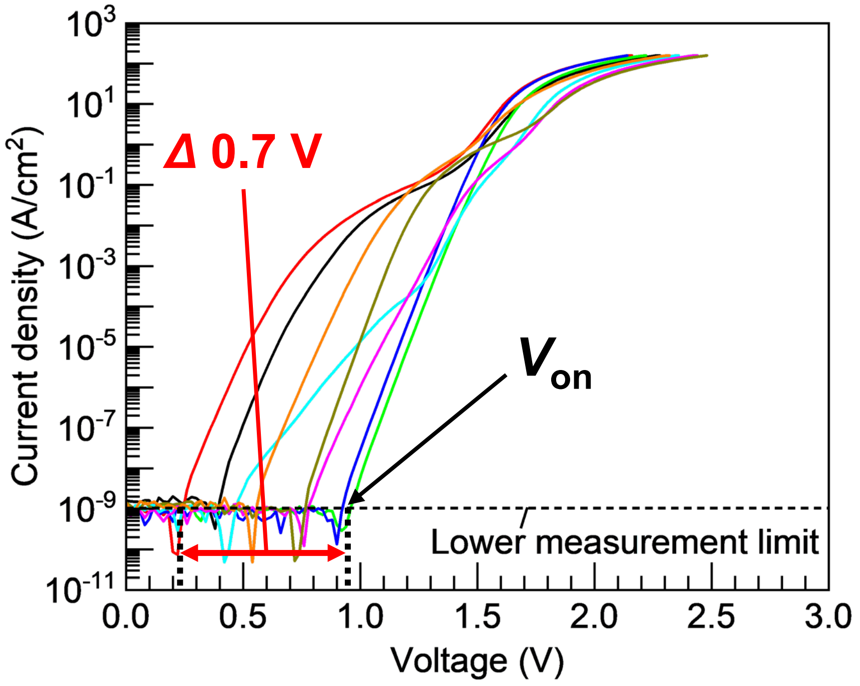
N_2 flow rate: 0.6 sccm

Substrate temp: 700^{o}C (pyrometer)

Duration: 120 min

Comparison of I–V characteristics of Ga_2O_3 (100) SBDs (1)



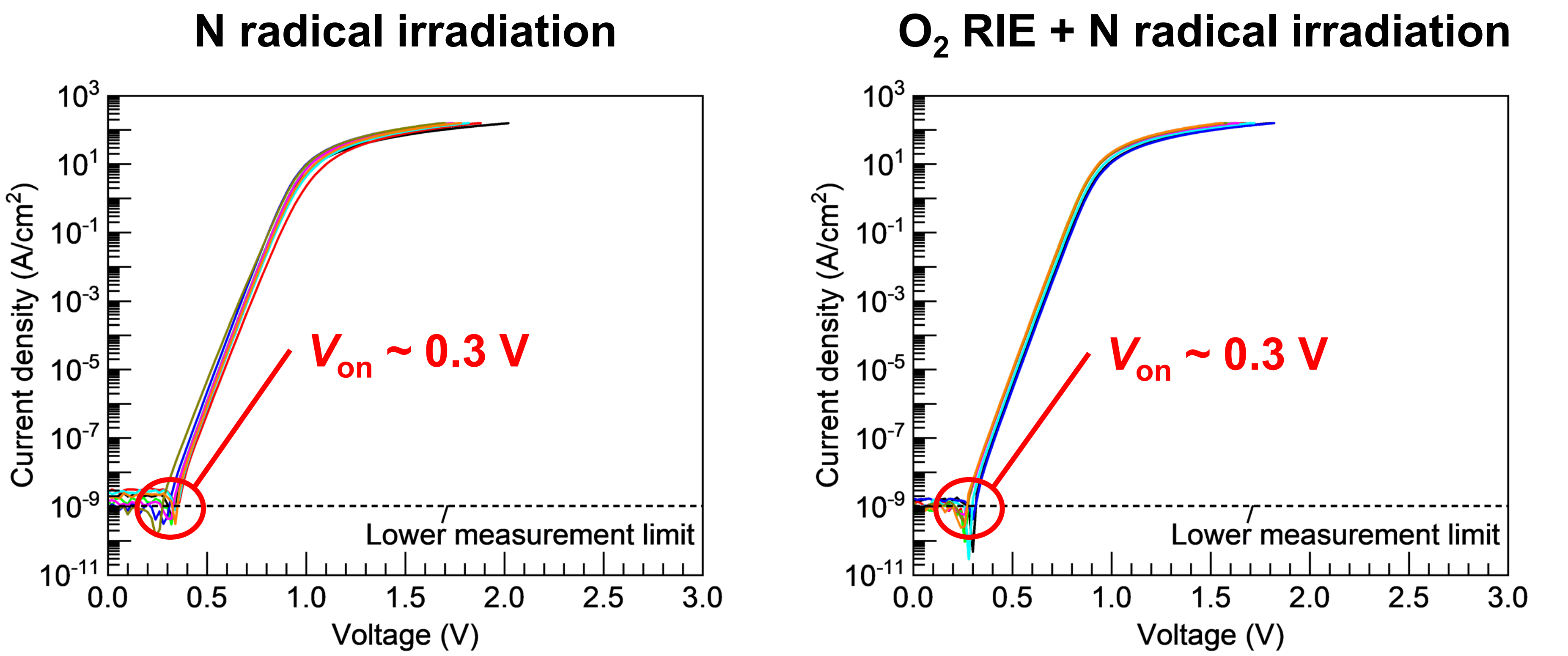


Effects of O_2 RIE

- **Increase in distribution of V_{on}**
- **Kinks in J–V curve for some devices** ➡

  Distribution of different Schottky barrier heights under an anode electrode

Comparison of *J*–*V* characteristics of Ga_2O_3 (100) SBDs (2)



Effects of N radical irradiation

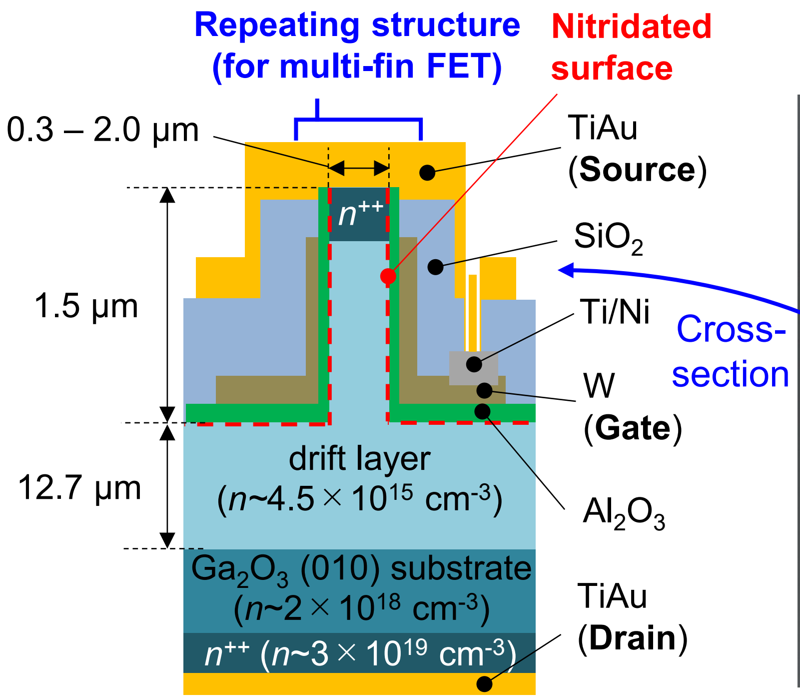
- **Constant V_{on} : 0.3 V**
- **Smaller Schottky barrier height than those of samples without N radical irradiation**
- **No kinks**

Zhenwei Wang
(NICT)

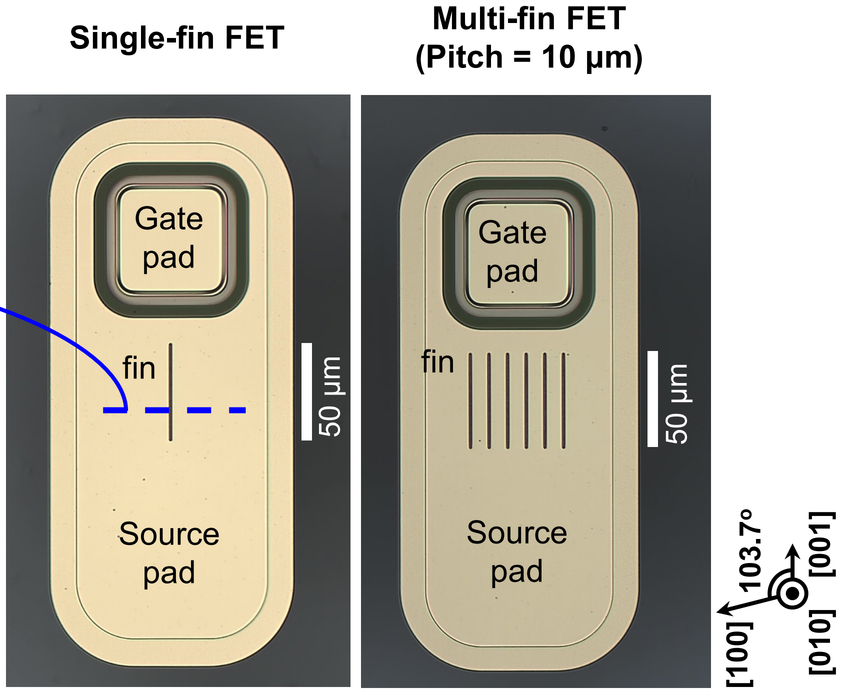
3. Ga_2O_3 (010) FinFETs fabricated with N radical irradiation

Ref. Z. Wang, M. H. *et al.*, *submitted to Appl. Phys. Lett.*

Ga_2O_3 (010) FinFETs processed with N radical irradiation



Schematic structure



Optical micrographs

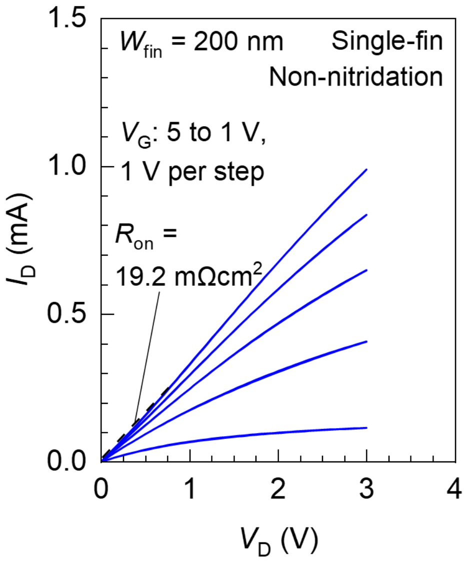
Orientation	Ga_2O_3 (010) substrate
Drift layer N_D-N_A	Si = 4.5×10^{15} cm^{-3}
Drift layer thickness	12.7 μm
Fin height	1.5 μm
Fin width	0.3 – 2.0 μm
Fin type	Single- and Multi-fin
Fin sidewall	On-axis (100) plane

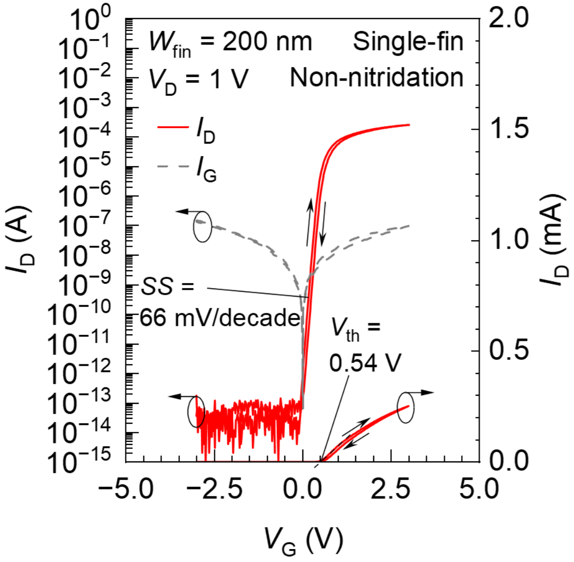
Details of FinFET Structure

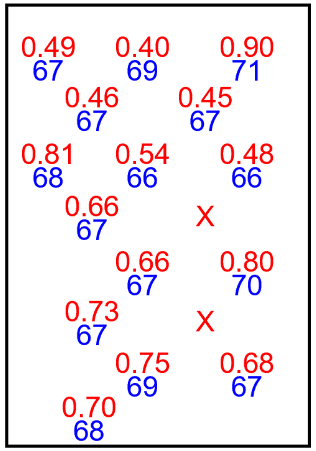
- **Ga_2O_3 (010) epitaxial layers** were grown by MOVPE at Kumagai lab at Tokyo University of Agriculture and Technology
- **Nitridation treatment** was performed at Higashiwaki lab at Osaka Metropolitan University
- **FinFET fabrication** was performed at NICT

Ga_2O_3 (010) single FinFETs processed with and without N radical irradiation (W_{fin} = 200 nm)

w/o nitridation



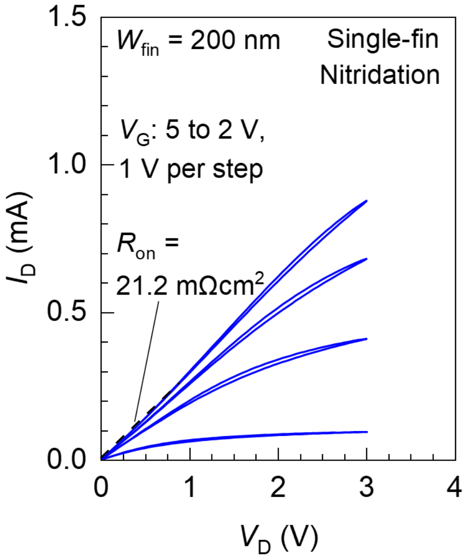


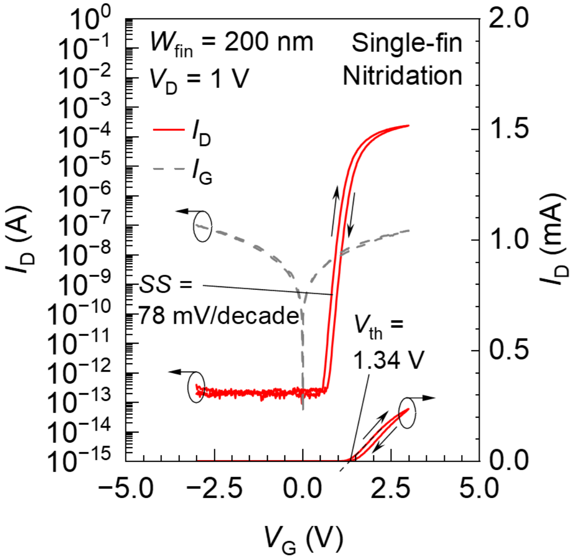


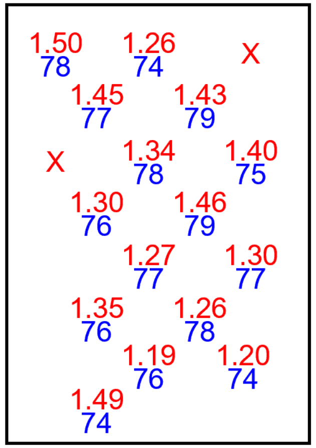
V_{th} (V)
SS (mV/decade)

Non-nitridated FinFETs:
V_{th} = 0.65 ± 0.25 V
SS = 68 ± 3 mV/decade

w/ nitridation





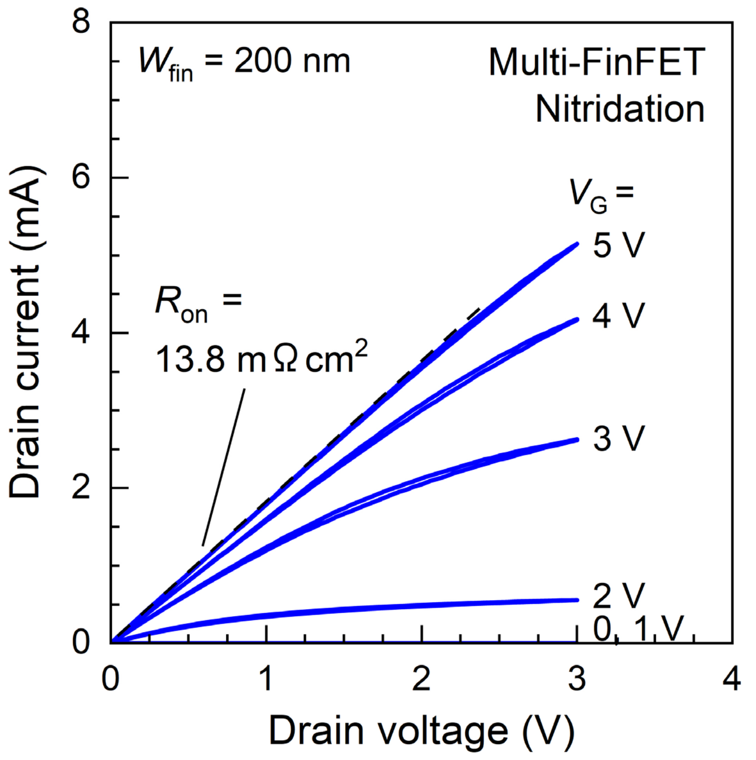


V_{th} (V)
SS (mV/decade)

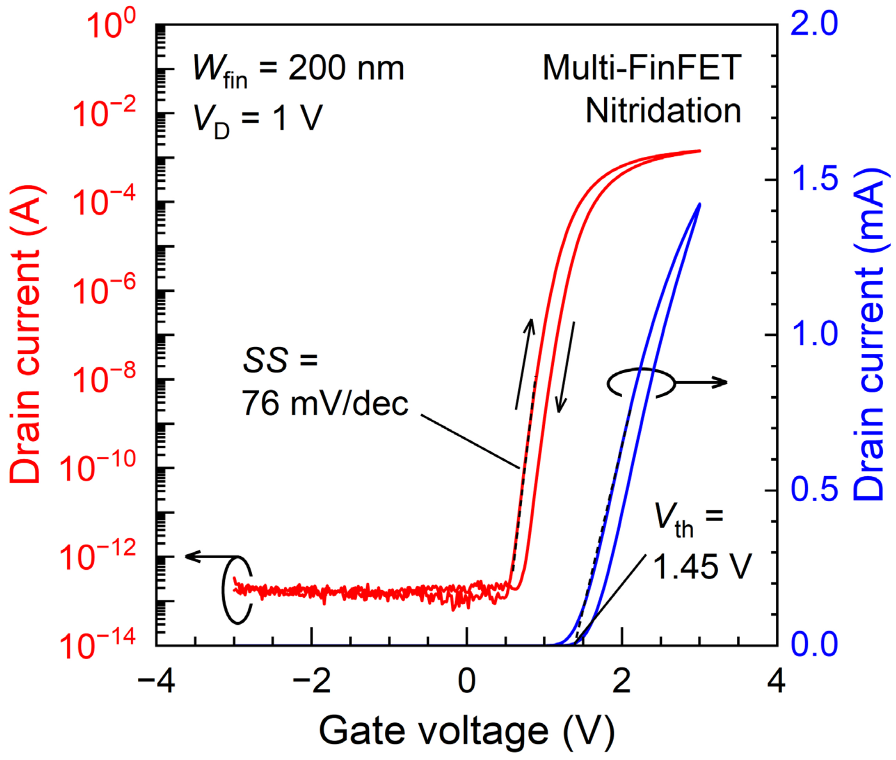
Nitridated FinFETs:
V_{th} = 1.35 ± 0.15 V
SS = 76 ± 3 mV/decade

Ga_2O_3 (010) multi FinFETs processed with and without N radical irradiation (W_{fin} = 200 nm)

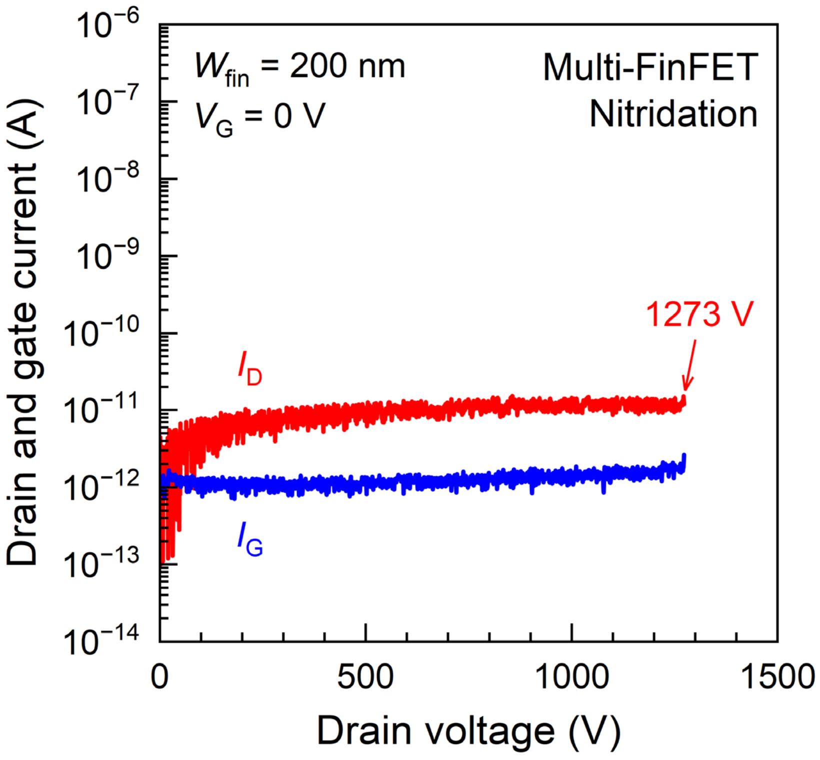
I_D–V_D



I_D–V_G



Reverse breakdown



W_{fin} = 200 nm

- R_{on} = 13.8 mΩcm^2
- *SS* = 76 mV/decade
- V_{br} = 1273 V

cf. W_{fin} = 300 nm

- R_{on} = 9.5 mΩcm^2
- *SS* = 73 mV/decade
- V_{br} = 1213 V

4. Conclusion

Summary and future prospect

Fifteen years have passed since I conceived the idea to develop Ga_2O_3 transistors and diodes in 2009

⬇

Developments in Ga_2O_3 technology have progressed significantly over the past decade, and Ga_2O_3 has established a solid position in compound semiconductor community

⬇

The next decade will be a critical one for Ga_2O_3, as it will either become a popular short-lived material, or be industrialized and become one of the fundamental semiconductors like Si, SiC, GaAs, and GaN