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How to make 10,000 V power devices in GaN and Ga_2O_3?

Yuhao Zhang, Professor
University of Hong Kong
Email: yuhzhang@hku.hk

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Power semiconductors as pathways to carbon neutrality

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Wide-bandgap semiconductors and power electronics as pathways to carbon neutrality

Yuhao Zhang, Dong Dong, Qiang Li, Richard Zhang, Florin Udrea & Han Wang

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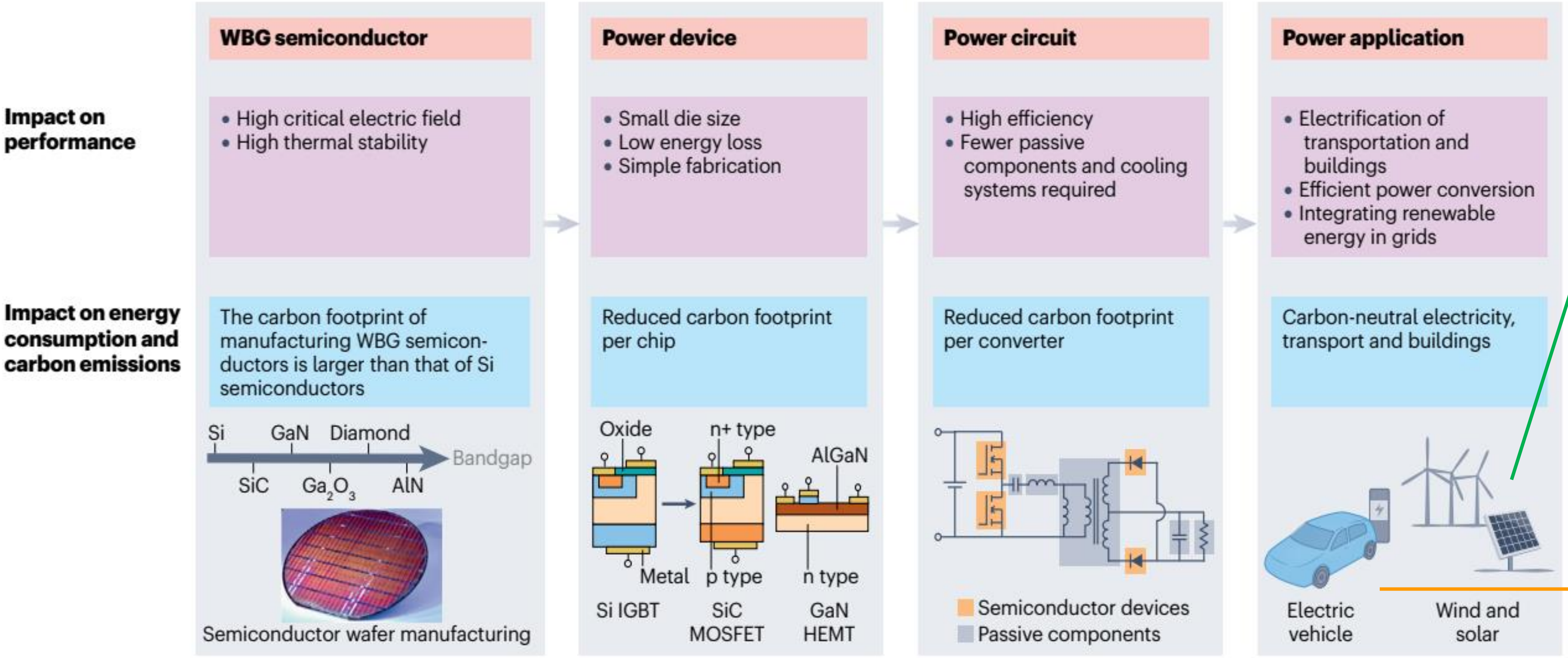
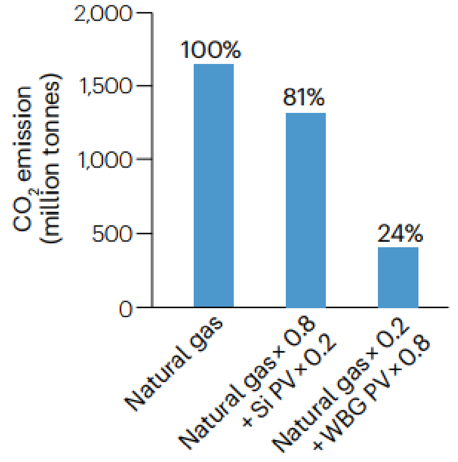
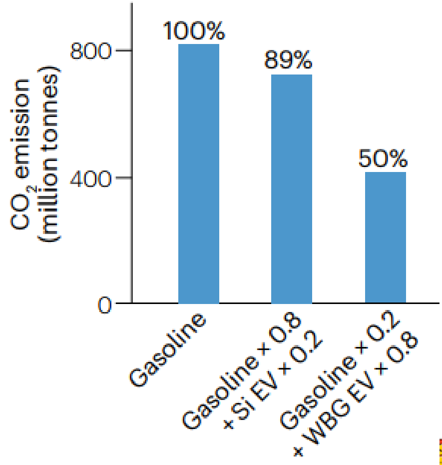
WGB replacing Si can enable an annual carbon saving of at least 20 million tonnes in the USA – annual emissions of 4 million gasoline passenger vehicles



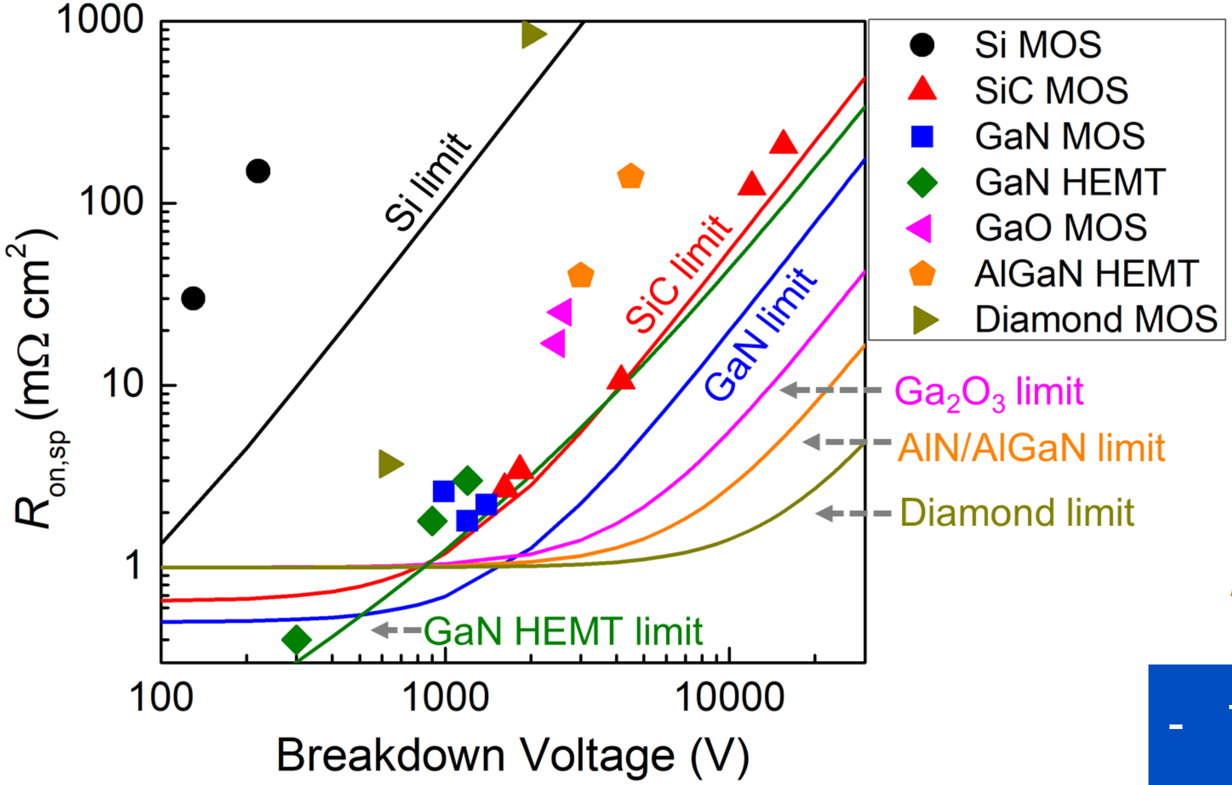
electricity generation



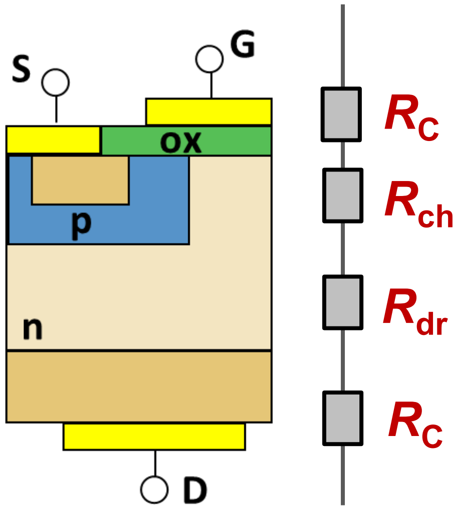
electric vehicles



Challenges for WBG devices going up



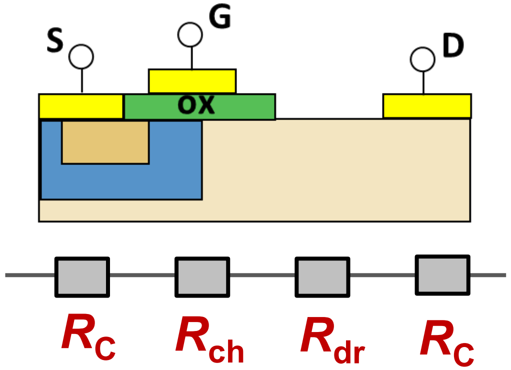
Vertical FET



$$R_{ON,SP} = R_C + R_{ch} + \frac{4BV^2}{\varepsilon \mu E_C^3}$$

- Thick lowly-doped drift region
- Low material/device yield
- High material cost

Lateral FET



$$R_{ON,SP} = R_C + R_{CH}\frac{BV}{\eta E_C} + \frac{BV^2}{q n_{2D} \mu_{2D} \eta^2 E_C^2}$$

- Non-uniform E-field
- Difficult *BV* upscaling
- High $R_{DS,ON}$

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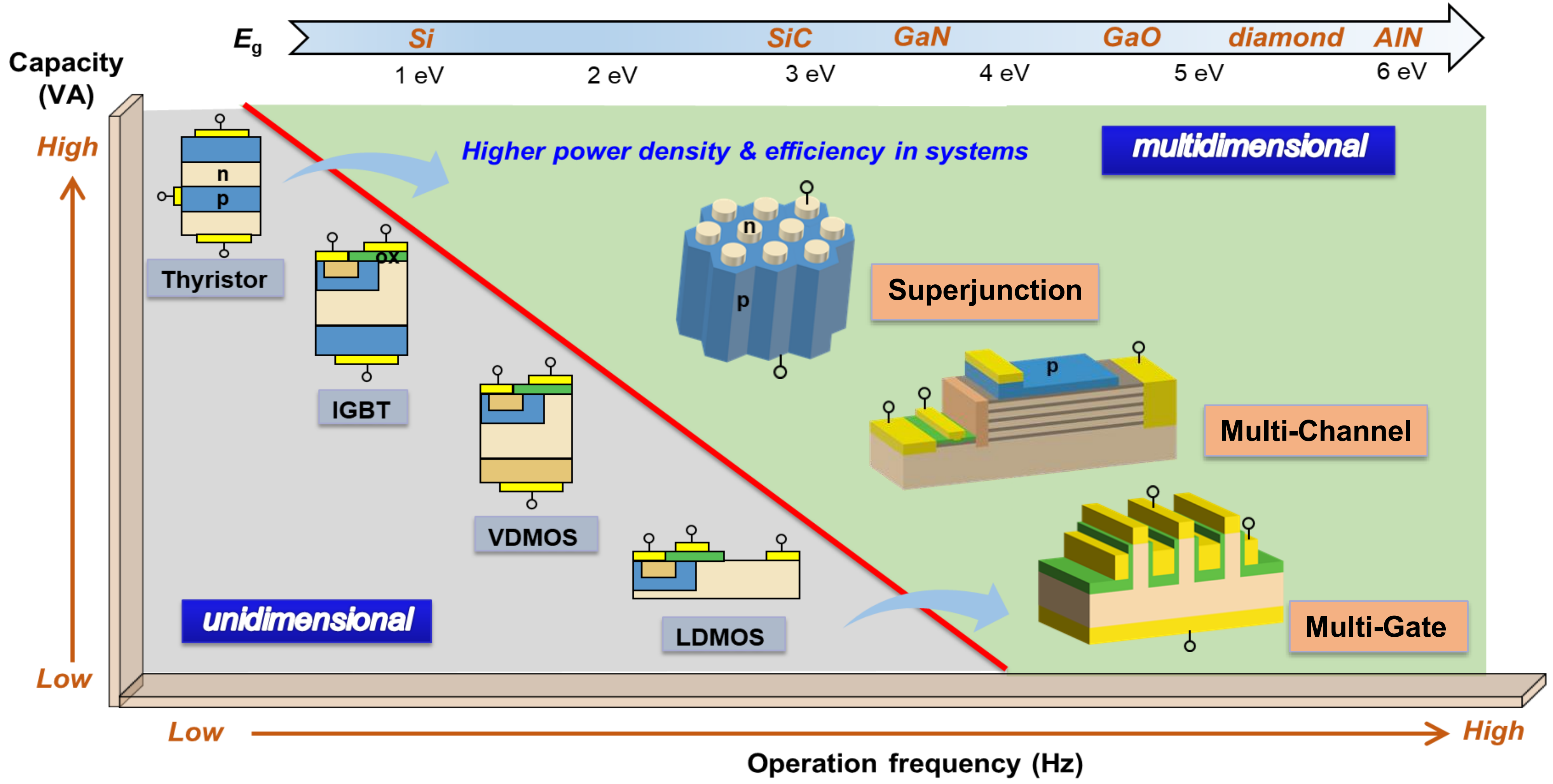
Solution – Multidimensional power devices



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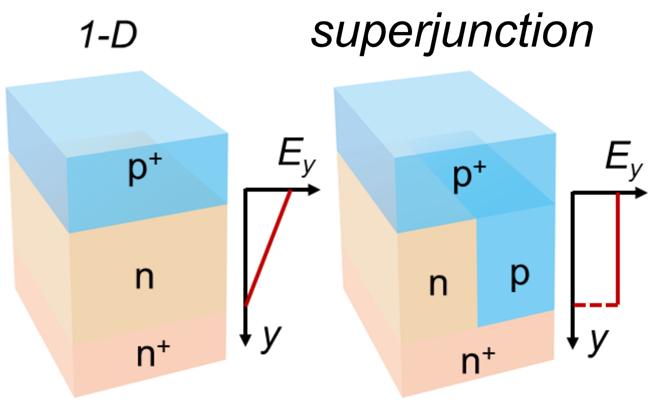
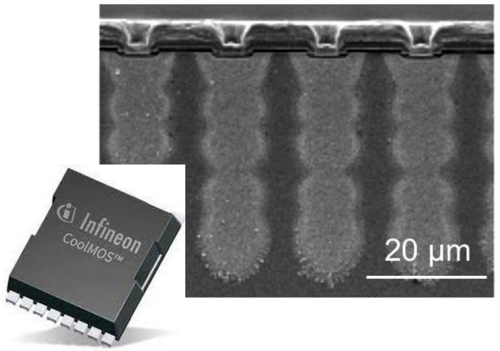
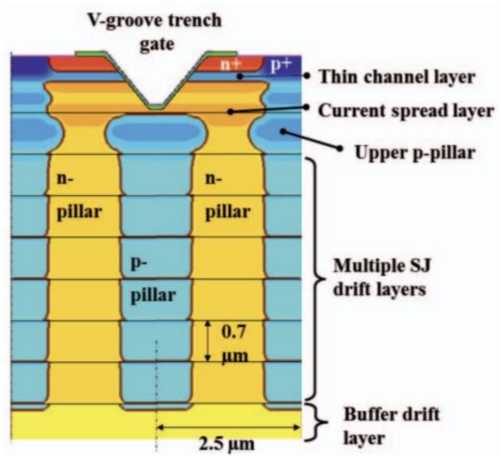
- electrostatic engineering in at least one additional geometrical dimension
- break the capacity-frequency and $R_{ON,SP}$~BV trade-off

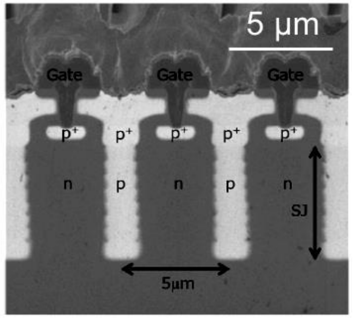
Vertical superjunction: from Si to WBG and UWBG



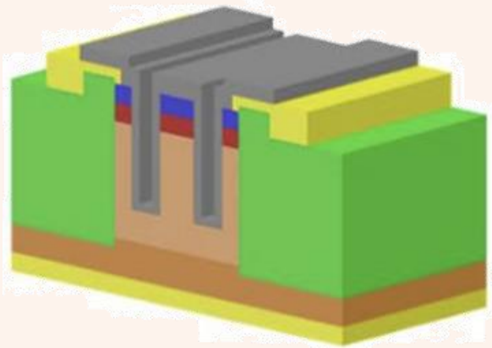


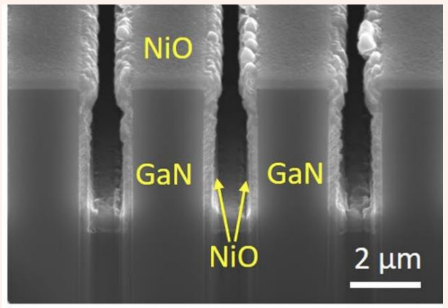
Si superjuction
commercial since 1998
~$1billion market



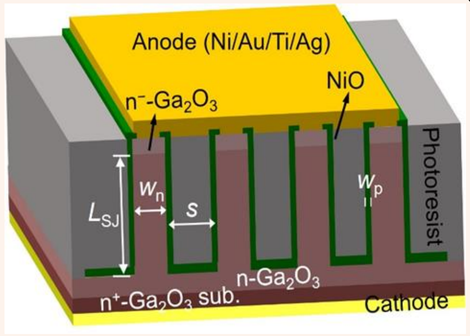


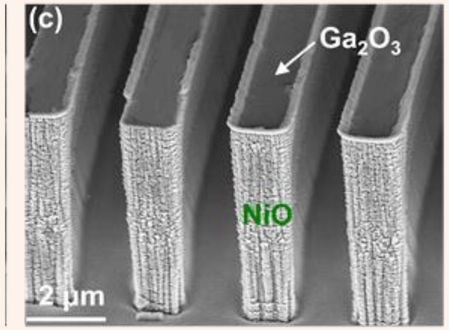
SiC superjuction
1^{st} demo in 2016-2018
1.2kV, 0.63mΩ·cm²





GaN superjuction
1^{st} demo (IEDM2022)
1.1kV, 0.3mΩ·cm²

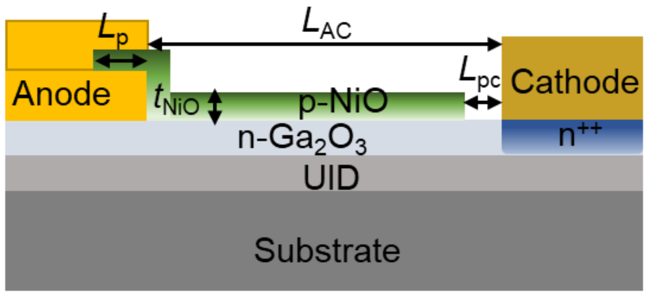


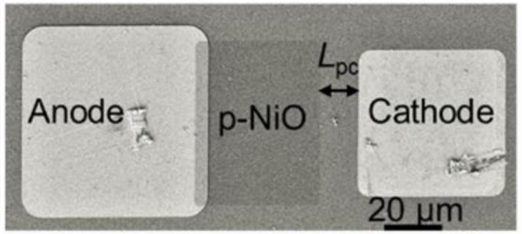


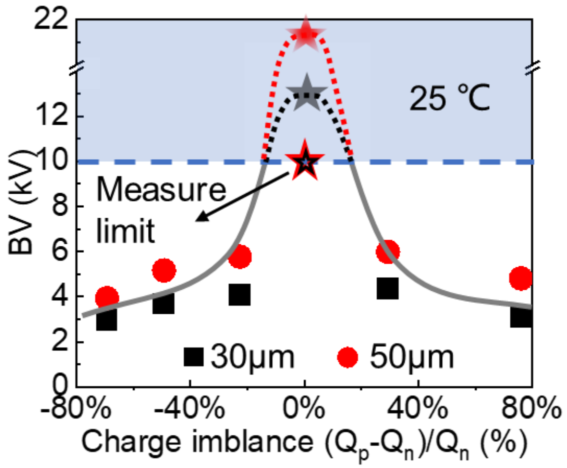
Ga_2O_3 superjuction
1^{st} demo (IEDM2023)
2kV, 0.7mΩ·cm²

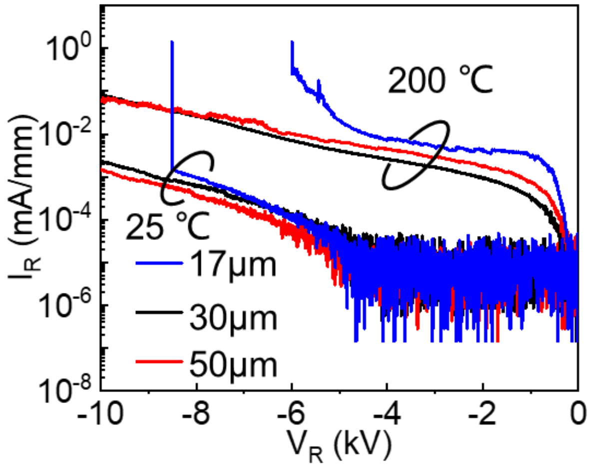
[1[T. Masuda et al., "0.63 mΩ·cm², 1170 V 4H-SiC Super Junction V-Groove Trench MOSFETM," IEDM, 2018. [2] M. Xiao *et al.*, "First demonstration of vertical sueprjunction diode in GaN", IEDM, 2022. [3] Y. Qin *et al.*, "2 kV, 0.7 mΩ·cm² vertical Ga_2O_3 superjunction Schottky rectifier with dynamic robustness," IEDM 2023.

Lateral superjunction: first 10kV Ga_2O_3 device







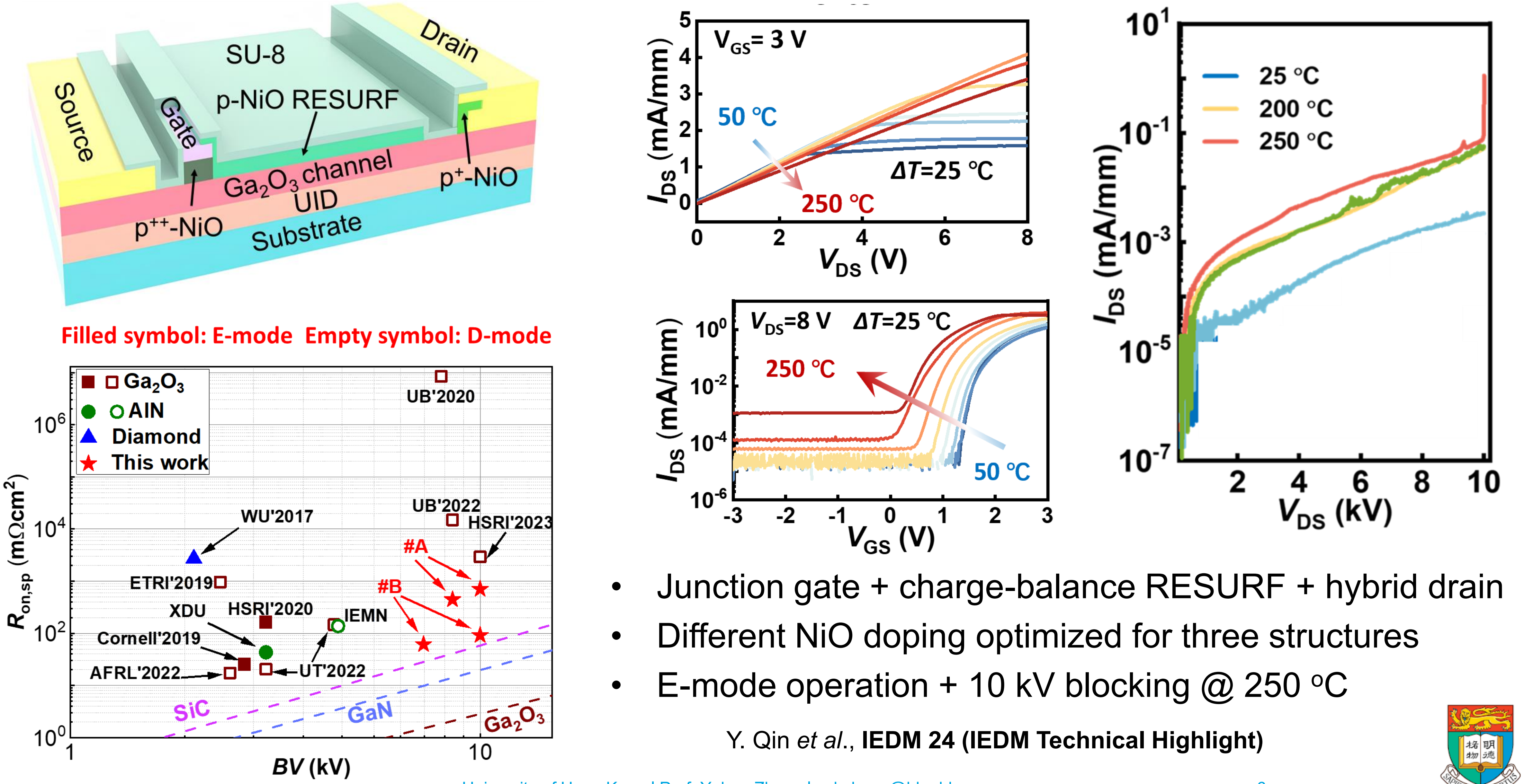


Device	Ave. E-field (MV/cm)
Ga_2O_3 RESURF SBD	**4.7**
Ga_2O_3 SBD	1.1
AlGaO/NiO PND	0.5
Ga_2O_3 MOSFET	1-1.4
GaN SBD	0.94
GaN HEMT	1.1
AlGaN HEMT	1.1
Diamond SBD	0.57

- 10 kV Ga_2O_3 SBD operational at 200 ^{o}C
- NiO superjunction: *BV* shows strong modulation by charge balance
- Record high lateral E-field in kilovolts devices

[1] Y. Qin *et al*., **EDL**, 2023; [2] Y. Ma, Y. Qin, M. Porter *et al*., **Adv. Electron. Mater**. 2023.

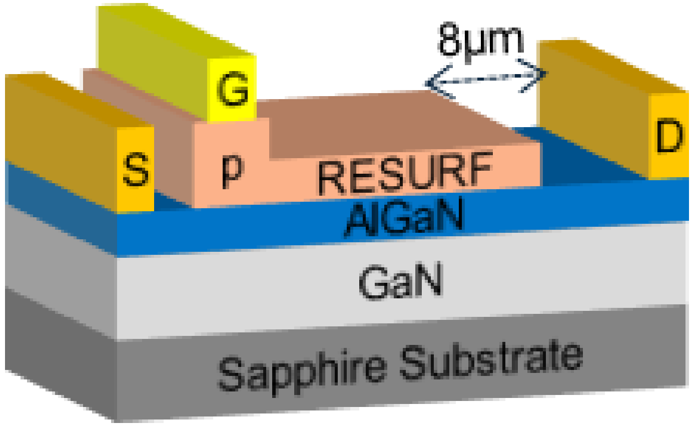
10 kV Ga_2O_3 E-mode superjunction JFET operational up to 250 °C

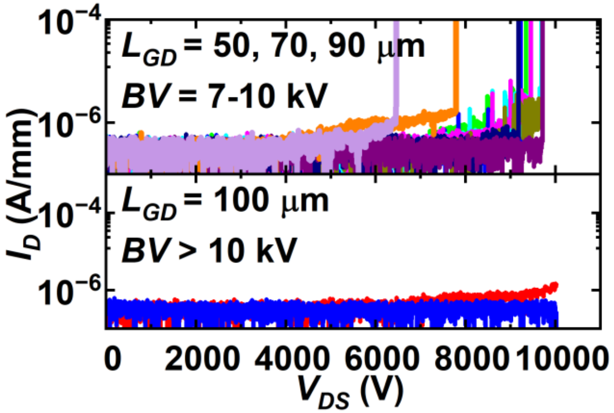


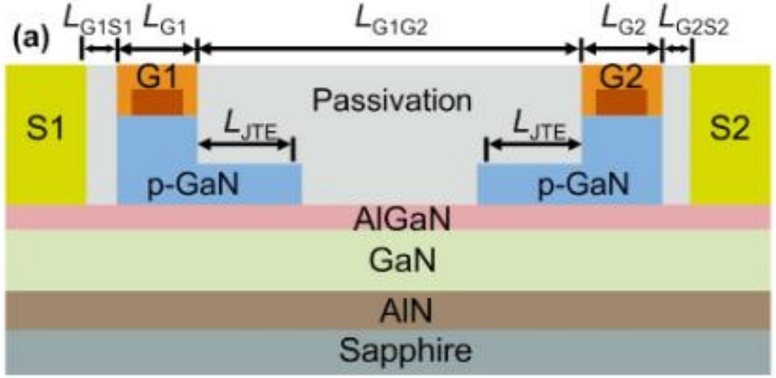
- Junction gate + charge-balance RESURF + hybrid drain
- Different NiO doping optimized for three structures
- E-mode operation + 10 kV blocking @ 250 °C

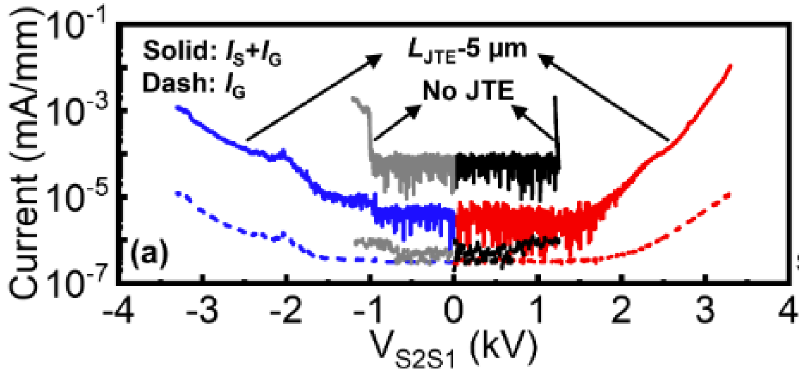
Y. Qin *et al.*, **IEDM 24 (IEDM Technical Highlight)**

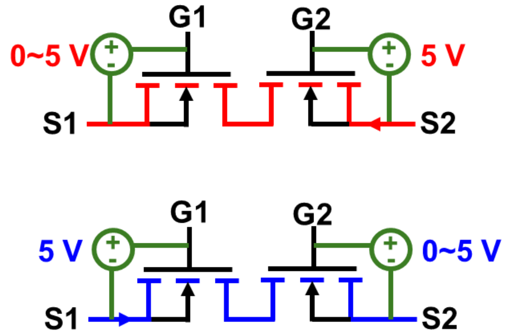
10 kV GaN superjunction HEMT and Monolithic Bidirectional Switch

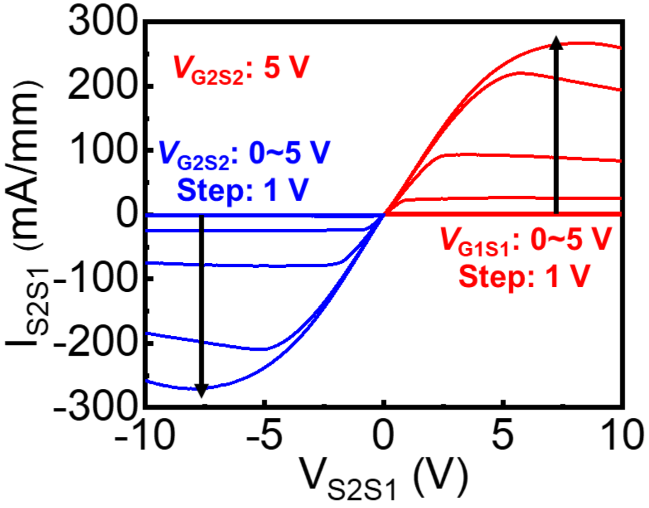












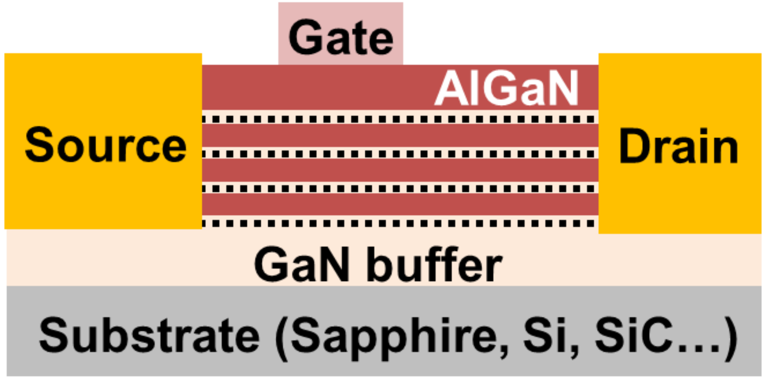
- BV upscaling enabled by charge-balance between p-GaN and AlGaN/GaN
- 10 kV, 70 mΩ·cm^2 E-mode GaN HEMT

Y. Guo *et al.*, under review

- Dual p-GaN JFET improves E-field management
- 3.3 kV, 5.6 mΩ·cm^2 E-mode GaN monolithic bidirectional HEMT

Y. Guo *et al.*, EDL 2025

Multi-channel: lateral polarization superjunction



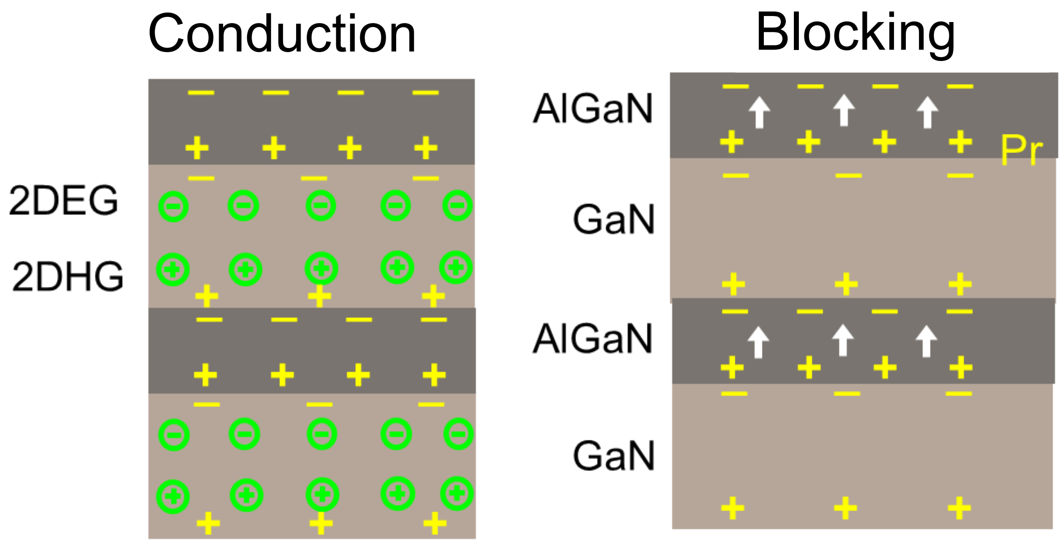
√ High current capability

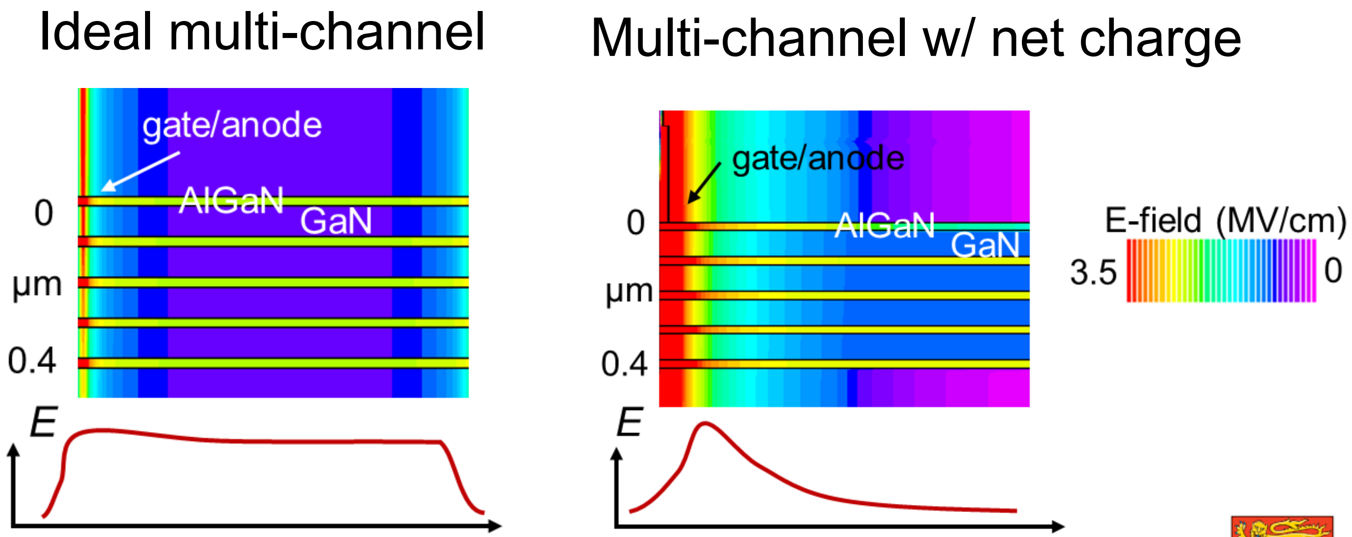
√ Low R_{on} for HV

√ Ideally, a natural superjunction

New challenges:

- **(non-ideal) E-field management**
- **E-mode gate**

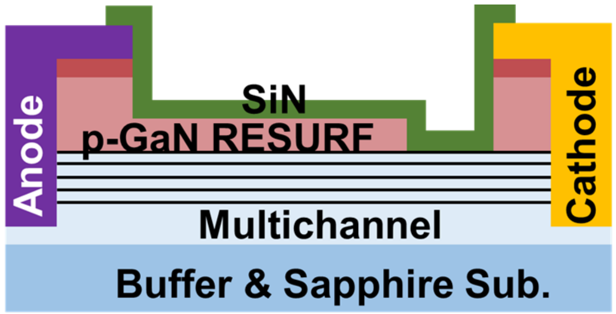


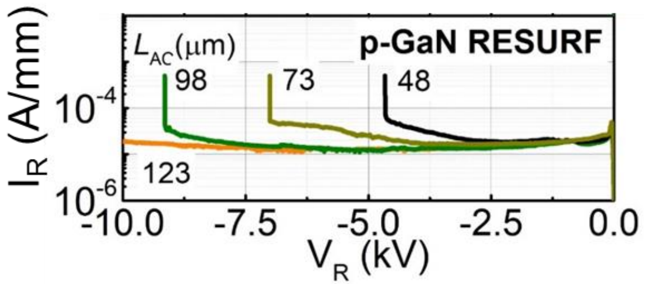


Y. Zhang, F. Udrea, H. Wang, **Nature Electronics**, 5, 723, Nov. 2022

Multi-channel: enabling 10kV GaN with $R_{ON,SP}$ 2.5x lower than SiC

- 4-inch wafer, five channels, R_{SH} 120 Ω/sq
- p-GaN charge balance with multi-channel (superjunction design)
- *BV* > 10 kV, $R_{ON,SP}$ = 39 mΩ·cm²

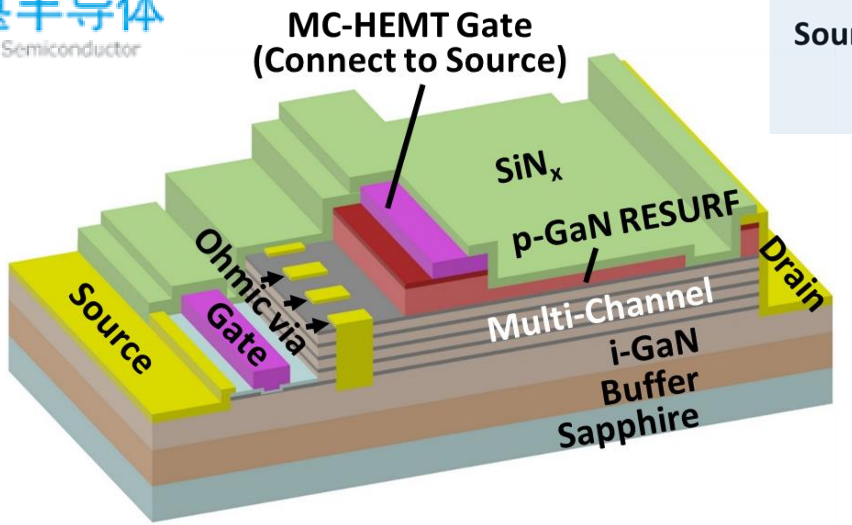


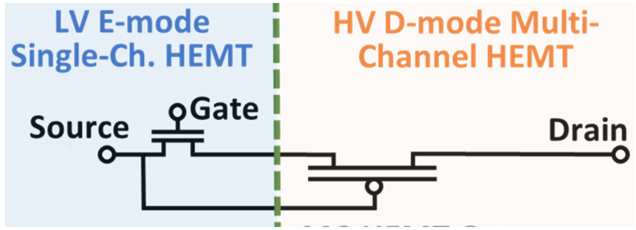


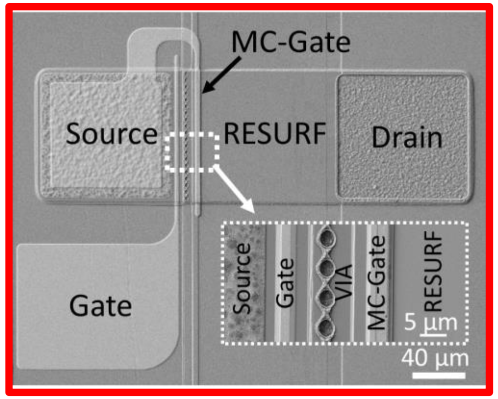
M. Xiao *et al*., "10 kV, 39 mΩ·cm² Multi-channel AlGaN/GaN Schottky barrier diodes," *IEEE Electron Device Letters*, 2021.

- Multi-Channel Monolithic-Cascode HEMT (MC²-HEMT)
- V_{TH} > 1.5 V; I_{SAT} > 300 mA/mm; $R_{ON,SP}$ of 40 mΩ·cm²
- Best FOM in 6.5kV+ power transistors

晶湛半导体
Enkris Semiconductor

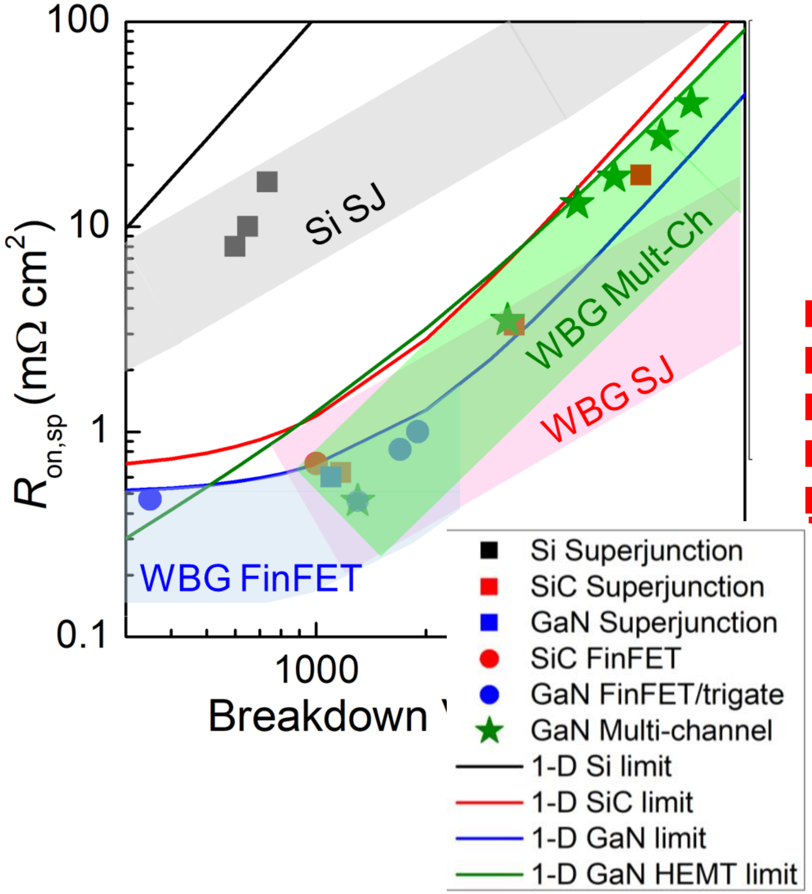






M. Xiao *et al*., "Multi-Channel Monolithic-Cascode HEMT (MC2-HEMT): A New GaN Power Switch up to 10 kV," *IEDM*, 2021.
(**IEDM Technical Highlights**, Nature Electronics Coverage)

Multidimensional devices: new limits and new scaling laws



Drift region design	1D	2D superjunction	Multi-channel (PSJ)
Structure	S G D	n p … ←d→	… N channels
Performance limit	$R_{ON,SP} = \frac{4}{\varepsilon\mu E_C^3} BV^2$	$R_{ON,SP} = \frac{4d}{\varepsilon\mu E_C^2} BV$	$R_{ON,SP} = \frac{BV^2}{NqE_C^2 n_{2D} \sum_{e,h} \mu_{2D}}$
Scaling parameter	NA	Cell pitch (*d*)	Channel number (*N*)
Scaling limit	NA	$d = \frac{50E_g}{9qE_C}$	Process and technology related
Minimum specific on-resistance	$\frac{4BV^2}{\varepsilon\mu E_C^3}$	$\frac{20E_g BV}{q\varepsilon\mu E_C^3}$	–
Material FOM	$\varepsilon\mu E_C^3$	$\varepsilon\mu E_C^{2.5}$	$E_C^2 n_{2D} \sum_{e,h} \mu_{2D}$

- Allow geometrical scaling in power devices (limit: line -> band)
- Baliga's FOM is no longer suitable for benchmarking multidimensional power devices

Y. Zhang, F. Udrea, H. Wang, "Multidimensional device architectures for efficient power electronics," ***Nature Electronics***, 2022

Key takeaway

- The renaissance of lateral devices for high-voltage applications (significant cost reduction)
- Multidimensional architectures – such as superjunction and multichannel – are essential; e.g., multichannel GaN HEMT enables $R_{on,sp}$ 2.5x lower than SiC MOSFET at 10 kV
- UWBG can enable high E-field and high-temperature operation