IMAPS APPE/CICMT/HiTEC

THE UNIVERSITY OF UTAH

Memory Phenomenon of GaN pn Junction by Engineering Its Interface, Which is Stable at High Temperatures up to 500 C

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arpa·e U.S. DEPARTMENT OF ENERGY

NASA

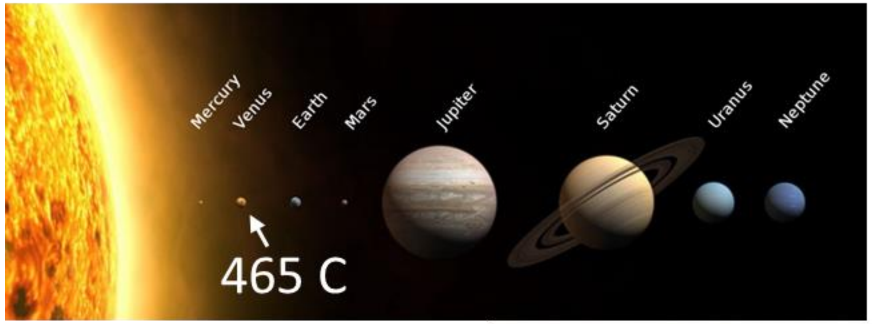
Outline

- GaN for High-temperature applications
- GaN resistive switching memory status
- **Discovery** of memory behavior in GaN p-n diodes
- **Mechanism** for the threshold switching behavior
- **Enhanced GaN memory behavior** up to 500 C
- Summary

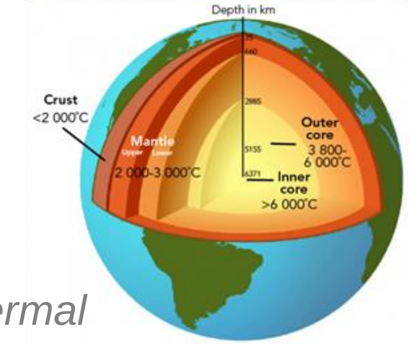
High Temperature Applications

automotive

aircraft engine



space exploration



Geothermal

TABLE 6.1 Semiconductor Technologies for Some Selected High-Temperature Electronics Applications

High-Temperature Electronics Application	Peak Ambient (°C)	Chip Power (kW)	Current Technology	Future Technology
Automotive				
Engine control electronics	150	<1	BS and SOI	BS and SOI
On-cylinder and exhaust pipe	600	<1	NA	WBG
Electric suspension and brakes	250	>10	BS	WBG
Electric/hybrid vehicle	150	>10	BS	WBG
Turbine engine				
Sensors, telemetry, control	300	<1	BS and SOI	SOI and WBG
	600	<1	NA	WBG
Electronic actuation	150	>10	BS and SOI	WBG
	600	>10	NA	WBG
Spacecraft				
Power management	150	>1	BS and SOI	WBG
	300	>10	NA	WBG
Venus and mercury exploration	550	~1	NA	WBG
Industrial				
High-temperature processing	300	<1	SOI	SOI
	600	<1	NA	WBG
Deep-well drilling telemetry				
Oil and gas	300	<1	SOI	SOI and WBG
Geothermal	600	<1	NA	WBG

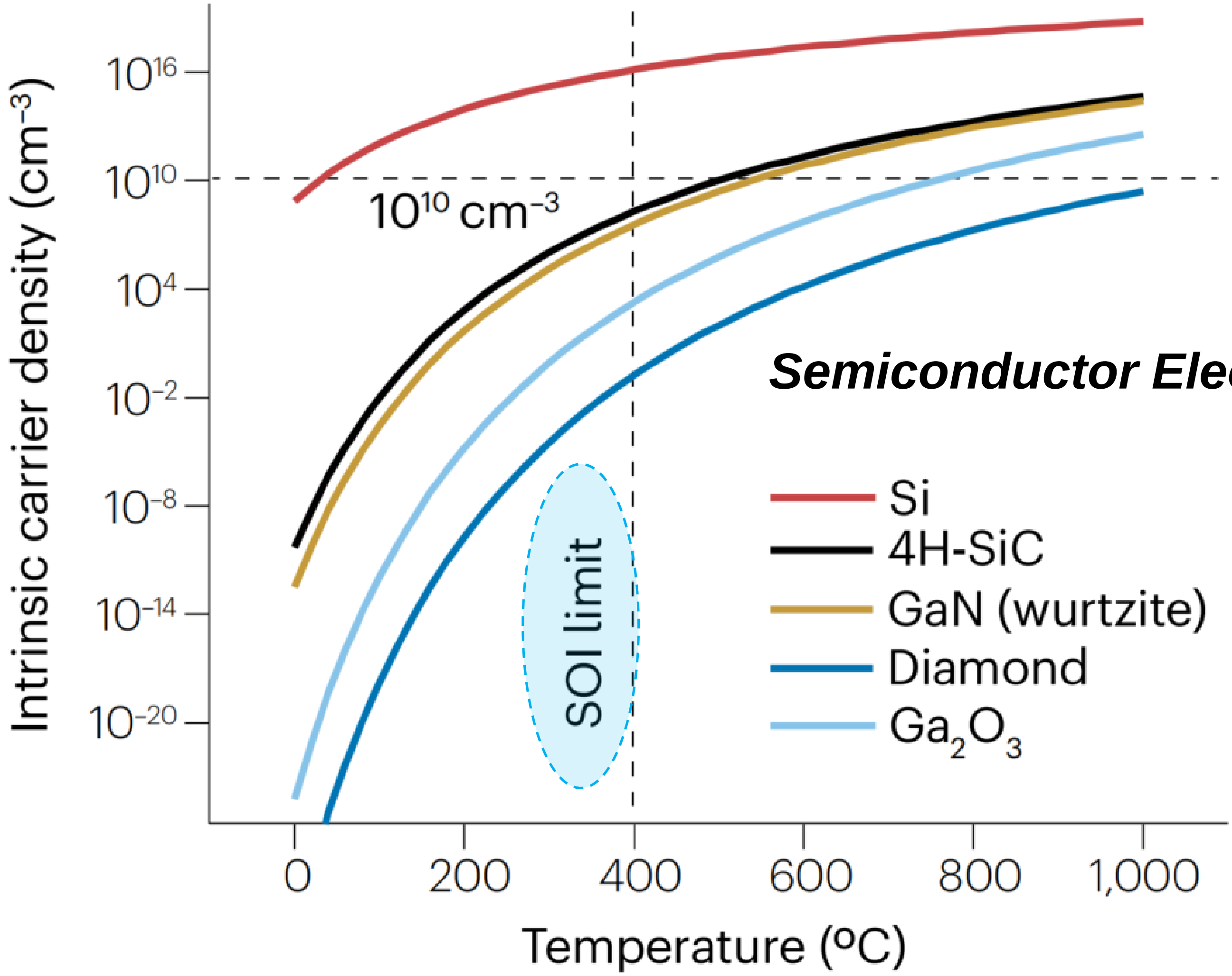
Source: Neudeck, P.G. et al., *Proc. IEEE*, 90(6), 1065. © 2002 IEEE.
BS, Bulk silicon; SOI, silicon-on-insulator; NA, not presently available; WBG, wide bandgap.

John D. Cressler, H. Alan Mantooth, Extreme Environment Electronics, 2013 by Taylor & Francis Group

GaN for High Temperature Applications

Intrinsic Carrier Density

$$n_i = \sqrt{N_c N_v}\, e^{-E_g / 2kT}$$



Semiconductor Electronics

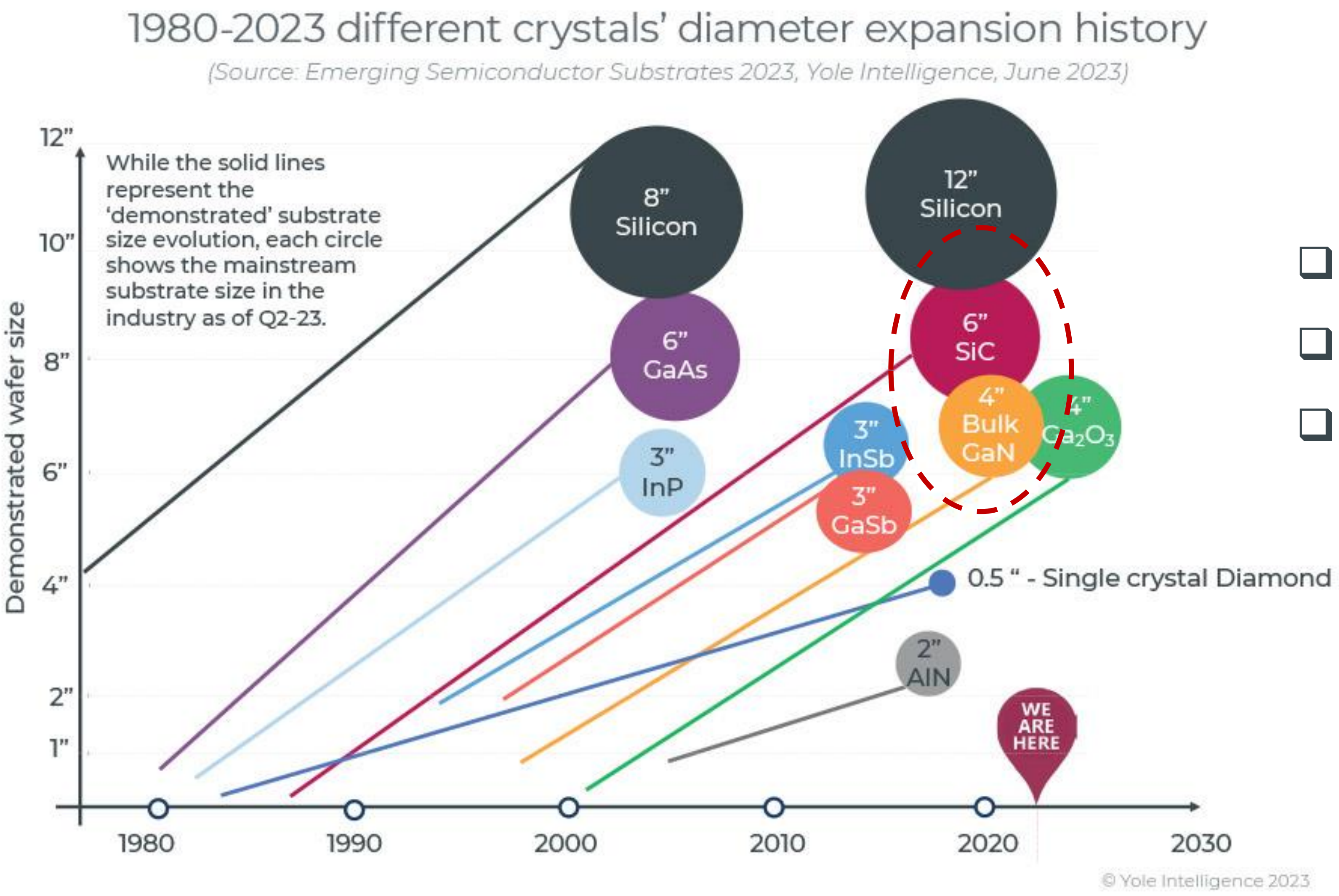
Pradhan, D.K., Moore, D.C., Francis, A.M. et al. Materials for high-temperature digital electronics. Nat Rev Mater 9, 790–807 (2024)

GaN for High Temperature Applications

Materials parameters	Si	GaAs	4H-SiC	GaN	Diamond	β-Ga_2O_3	Comments
Bandgap, E_g (eV)	1.1	1.43	3.25	3.4	5.5	4.85	Bandgap of Ga_2O_3 reported in range 4.6–4.9 eV
Dielectric constant, ε	11.8	12.9	9.7	9	5.5	10	
Breakdown field, E_C (MV/cm)	0.3	0.4	2.5	3.3	10	8	Experimental values for Ga_2O_3 have reached ~0.5 times the theoretical maximum
Electron mobility, μ (cm^2/Vs)	1480	8400	1000	1250	2000	300	
Saturation velocity, v_s (10^7 cm/s)	1	1.2	2	2.5	1	1.8-2	1.8 ⟨0 0 1⟩ and ⟨0 1 0⟩, 2.0 ⟨0 1 0⟩
Thermal conductivity λ (W/cm K)	1.5	0.5	4.9	2.3	20	0.1–0.3	0.13 ⟨1 0 0⟩, 0.23 ⟨0 1 0⟩
Figures of merit relative to Si							
Johnson $= E_c^2 \cdot V_s^2/4\pi^2$	1	1.8	278	1089	1110	2844	Power-frequency capability
Baliga $= \varepsilon \cdot \mu \cdot E_c^3$	1	14.7	317	846	24 660	3214	Specific on-resistance in (vertical) drift region
Combined $= \lambda \cdot \varepsilon \cdot \mu \cdot V_s \cdot E_c^2$	1	3.7	248.6	353.8	9331	37	Combined power/frequency/voltage
Baliga high frequency $= \mu \cdot E_c^2$	1	10.1	46.3	100.8	1501	142.2	Measure of switching losses
Keyes $= \lambda \cdot [(c \cdot V_s)/(4\pi \cdot \varepsilon)]^{1/2}$	1	0.3	3.6	1.8	41.5	0.2	Thermal capability for power density/speed
Huang HCAFOM, $\varepsilon \mu^{0.5} E_C^2$	1	5	48	85	619	279	Huang chip area manufacturing FOM

Pearton et al. , Appl. Phys. Rev. 5, 011301 (2018)

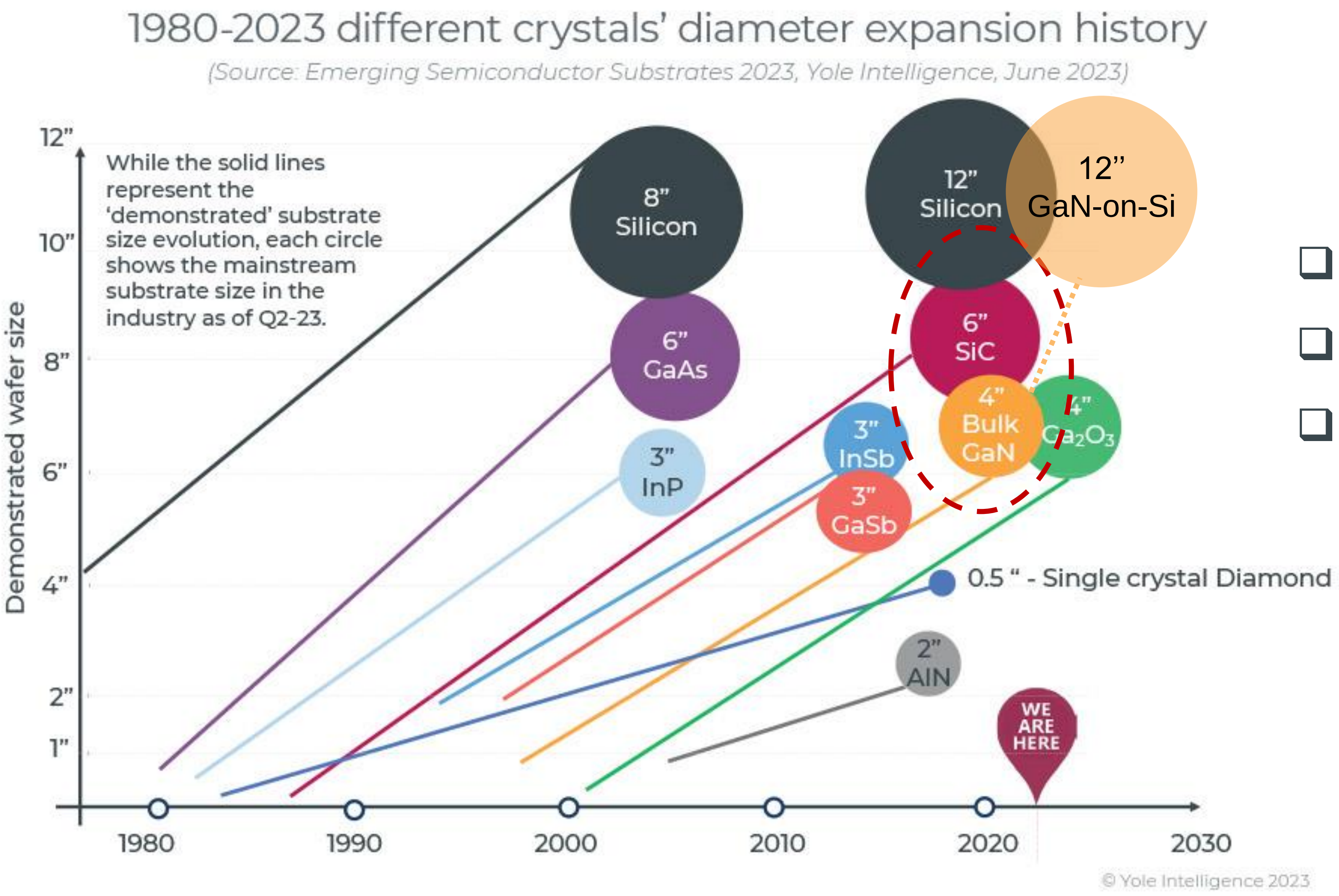
GaN for High Temperature Applications



- ❑ Size
- ❑ Cost
- ❑ Maturity

https://www.semiconductor-today.com/news_items/2023/jun/yole-210623.shtml

GaN for High Temperature Applications



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- ❑ Size
- ❑ Cost
- ❑ Maturity

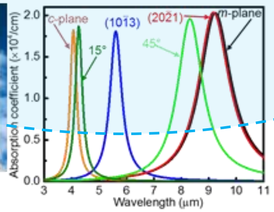
Unique Potential of GaN Electronics and Photonics

Photonics / Optoelectronics
- Lighting and Display
- Auto Headlights
- Photovoltaics
- Photodetectors


LED


Laser


Solar Cells



Detectors

Power Electronics
- AC/DC
- DC/DC
- inverter
- *EV*



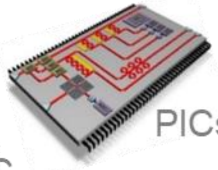

GaN
(Al, B, In, Ga)N

RF communication
- *5G, sub-THz*


Everything in one chip

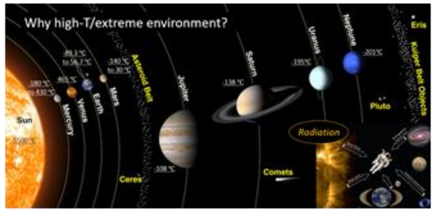
Processer / Computing
- Power **ICs**,
- *PICs, Sensing*


MMIC

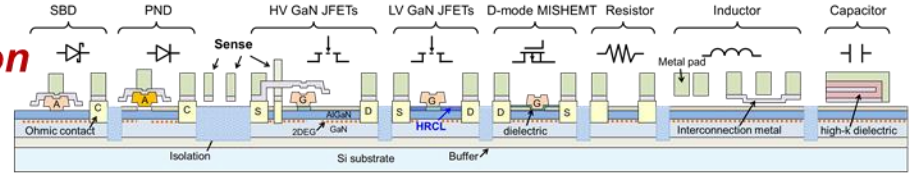

PICs

Smart Applications
- *Plant Growth*
- Visible Light Communication
- Biomedical


Li-Fi

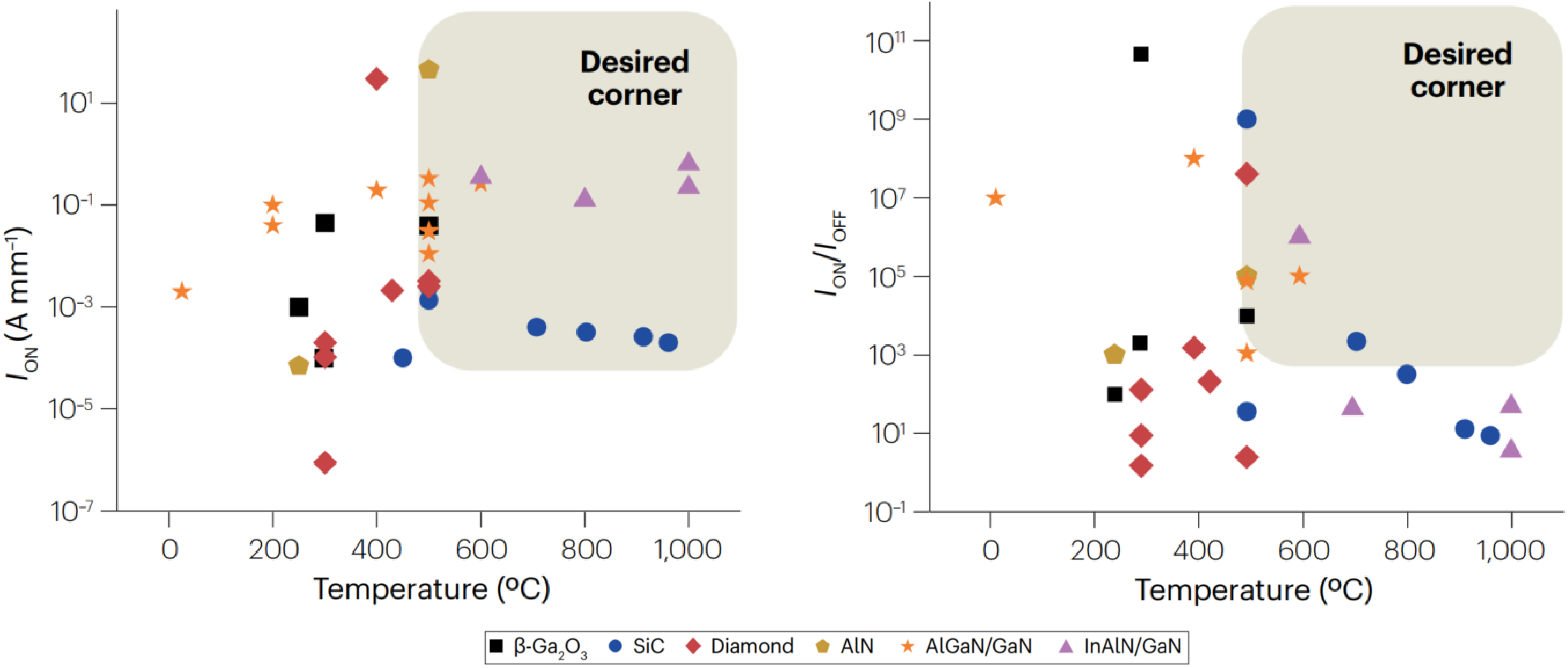


High Temperature, Radiation
- *Space exploration*
- turbine
- Deep-well drilling
- X-ay



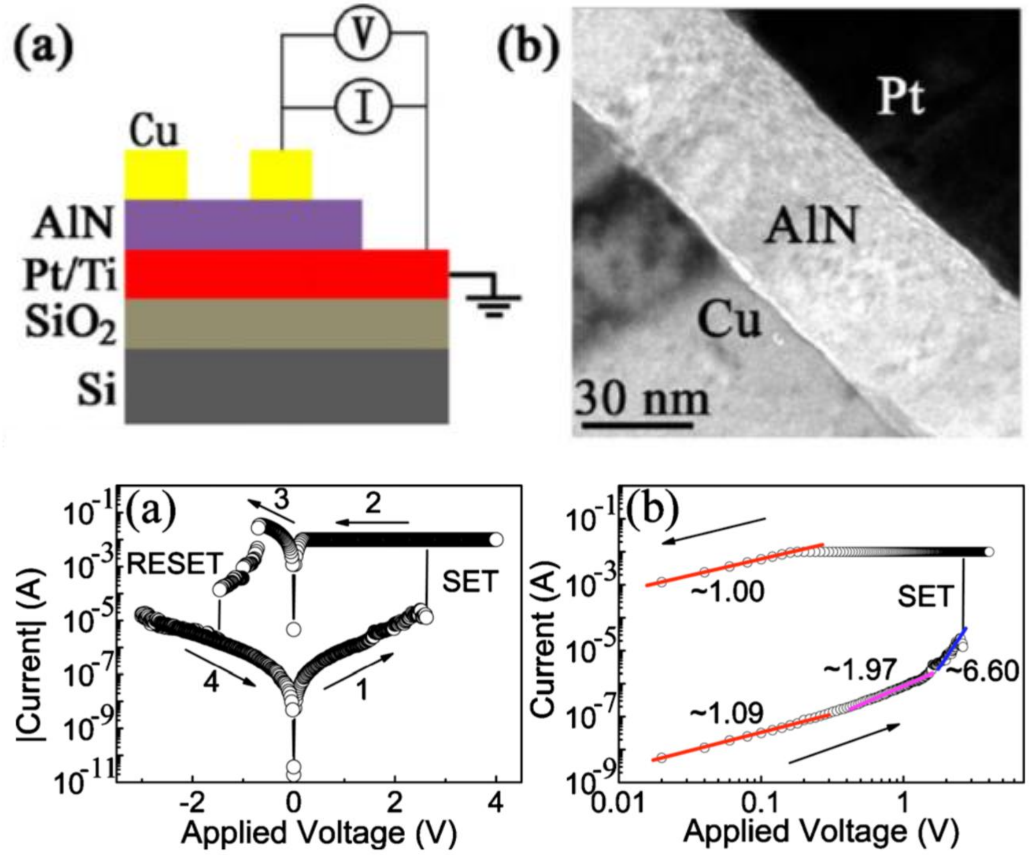
GaN: Discrete device → Integrated Circuits

Current Status of High-temperature Semiconductor Devices (Transistors)

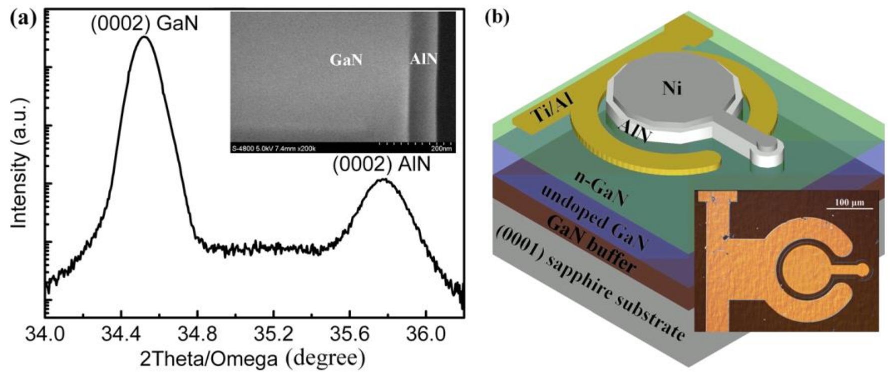


Pradhan, D.K., Moore, D.C., Francis, A.M. et al. Materials for high-temperature digital electronics. Nat Rev Mater 9, 790–807 (2024)

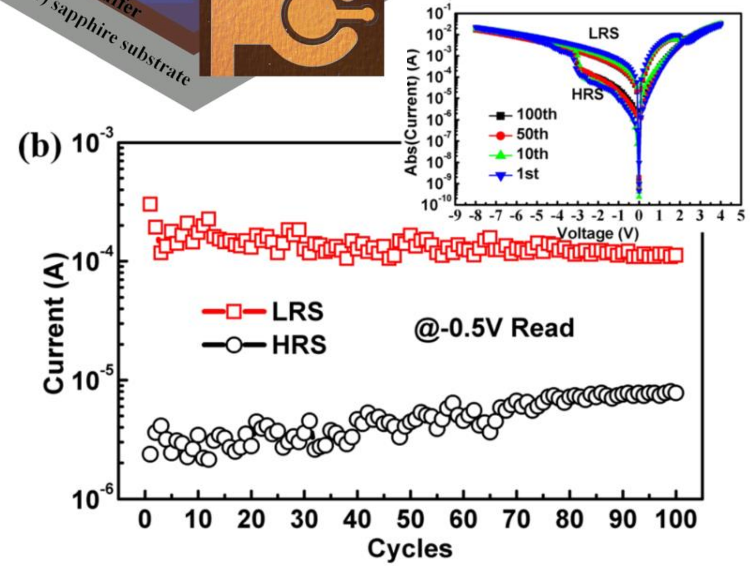
Topic: GaN Resistive Switching Memory



C. Chen, Y. C. Yang, F. Zeng, and F. Pan, "Bipolar resistive switching in Cu/AlN/Pt nonvolatile memory device," Appl. Phys. Lett., vol. 97, 2010.



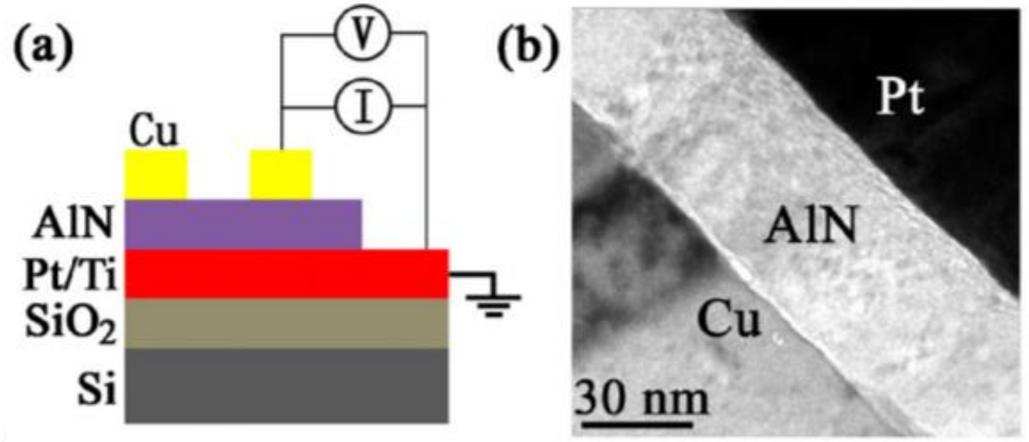
- *resistance-switching random access memory (RRAM)*
- *nonvolatile memory*
- *high response speed*
- *high scalability*
- *high density*

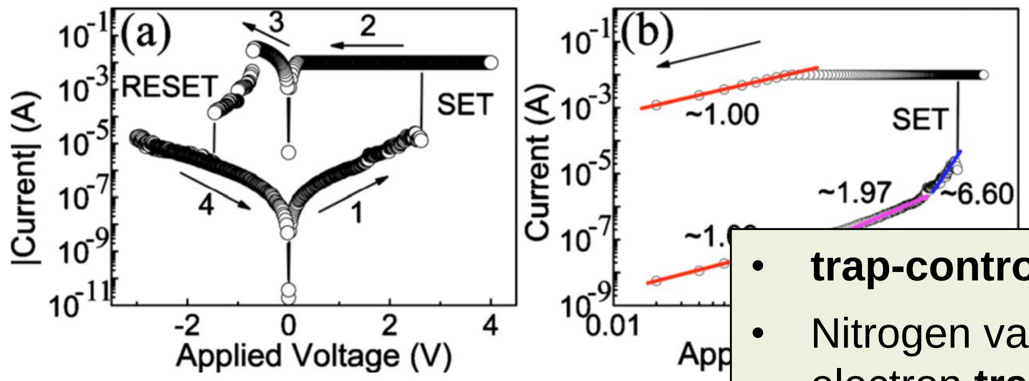


Y. Chen et al., "Reproducible bipolar resistive switching in entire nitride AlN/n-GaN metal-insulator-semiconductor device and its mechanism," Appl. Phys. Lett., vol. 105, 2014.

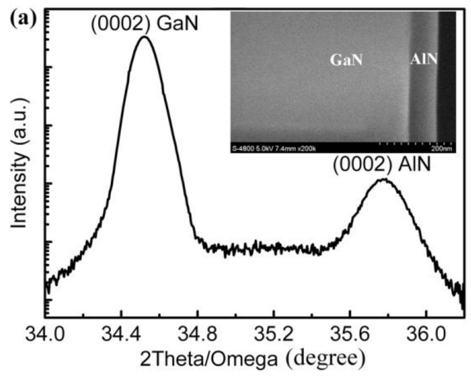
- ❑ Limited work on selector or memory before 2019: **<150 °C**, endurance problem

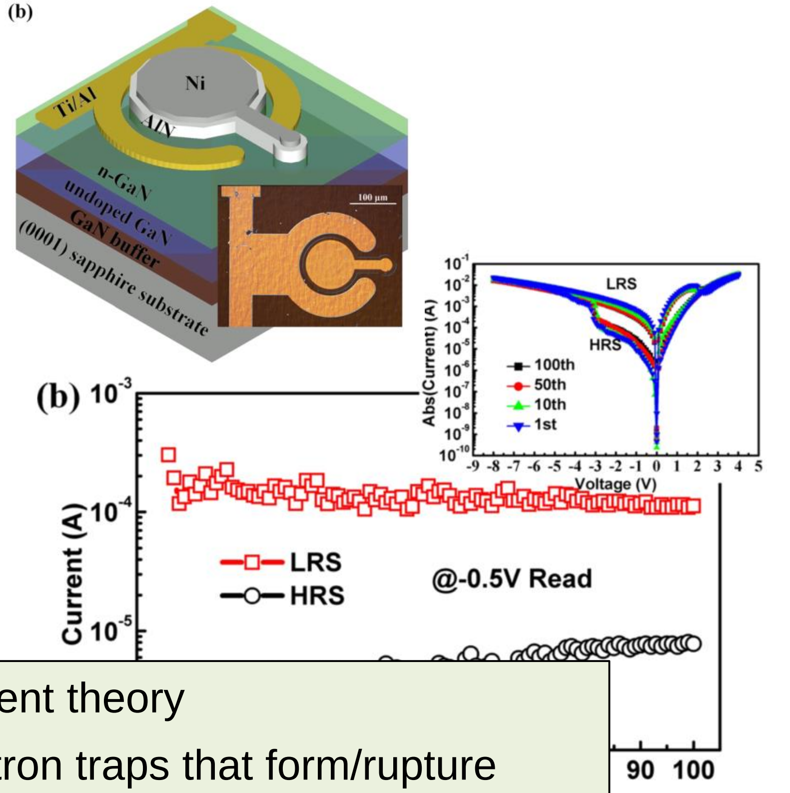
Topic: GaN Resistive Switching Memory





C. Chen, Y. C. Yang, F. Zeng, and F. Pan, "Bipolar resistive swit... nonvolatile memory device," Appl. Phys. Lett., vol. 97, 2010.





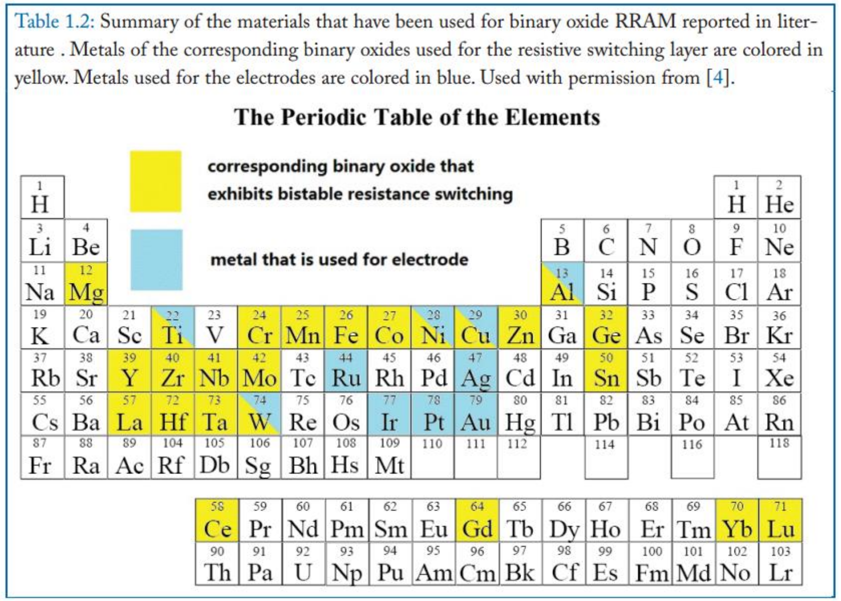
- *resistance-switching random access memory (RRAM)*
- *nonvolatile memory*

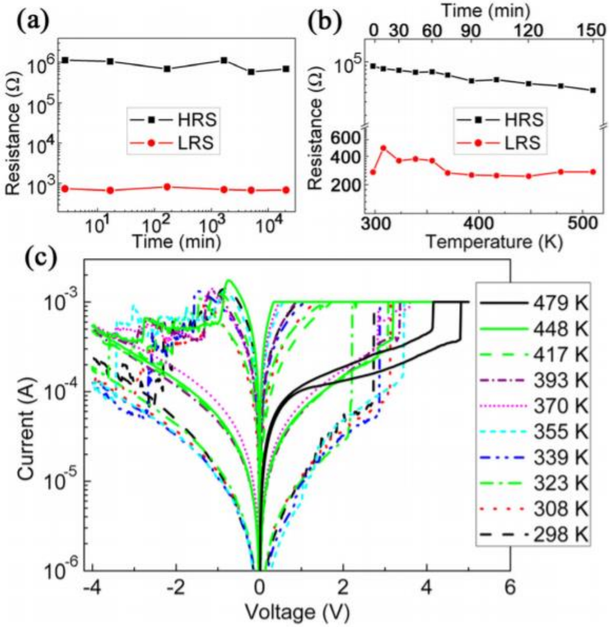
- **trap-controlled** space charge limited current theory
- Nitrogen vacancies of AlN serving as electron traps that form/rupture electron **transport channel** by **trapping/detrapping electrons**
- → high resistance state (**HRS**) and low resistance state (**LRS**)

...N/n-GaN metal-... , 2014.

❑ Limited work on selector or memory before 2019: <150 °C, endurance problem

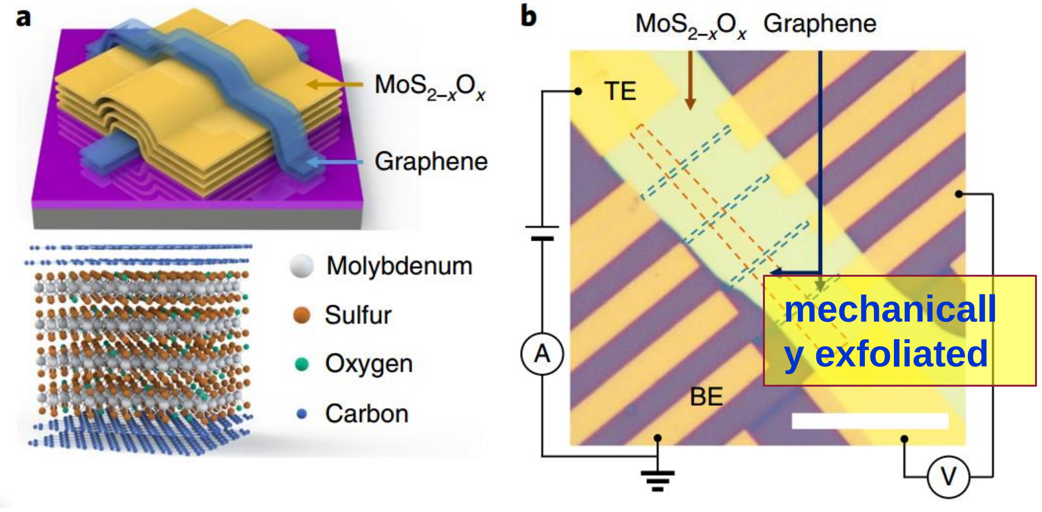
Other Materials

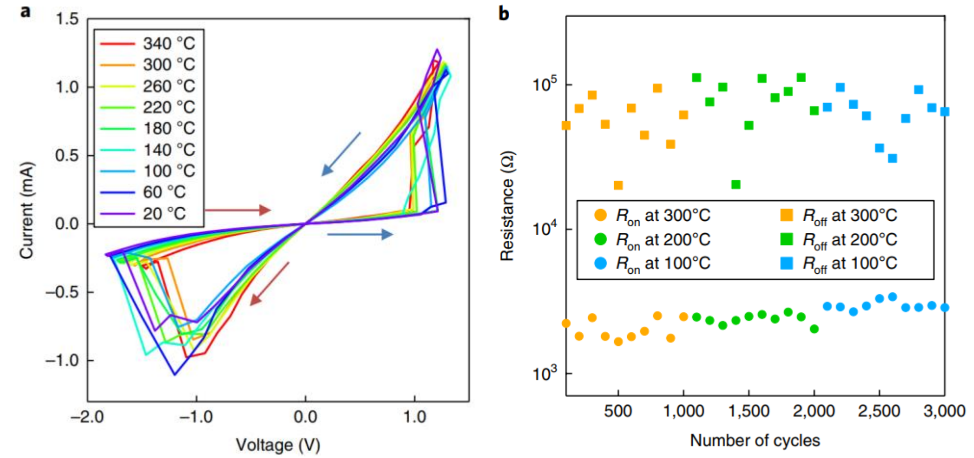




S. Yu, "Resistive Random Access Memory (RRAM): From Devices to Array Architectures," in Synthesis Lectures on Emerging Engineering Technologies. vol. 2, 2016.

C. Chen, C. Song, J. Yang, F. Zeng, and F. Pan, "Oxygen migration induced resistive switching effect and its thermal stability in W/TaOx/Pt structure," Appl. Phys. Lett., vol. 100, 2012



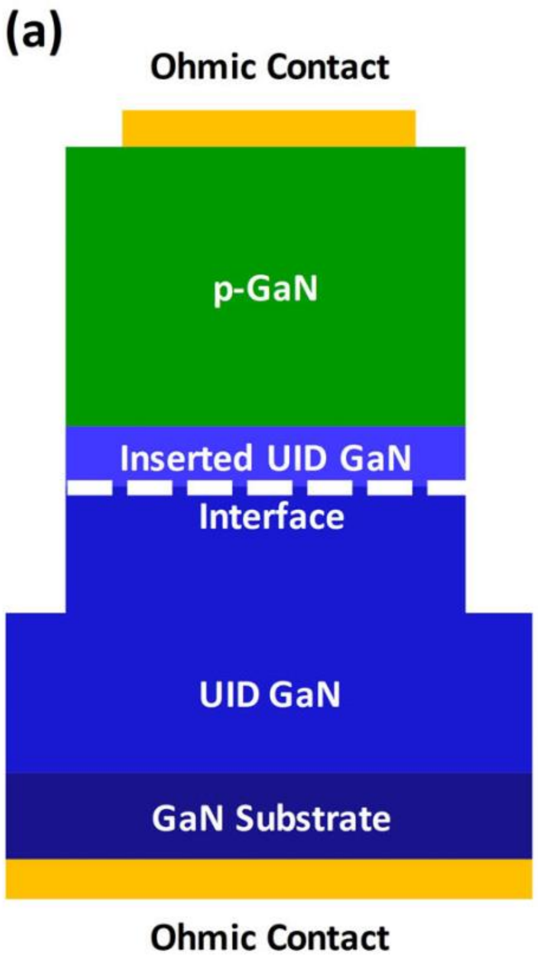


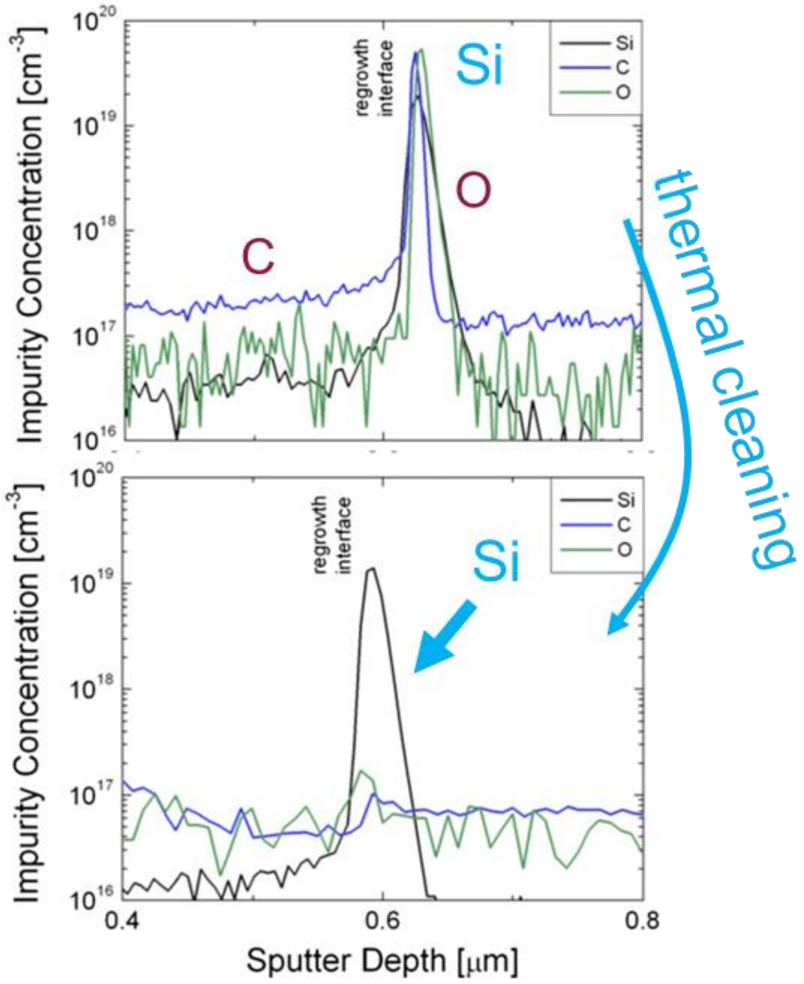
M. Wang et al., "Robust memristors based on layered two-dimensional materials," Nat. Electron., vol. 1, 2018.

- ❑ Wide variety of material systems for RRAM, such as NiO, TiOx, CuOx, ZrOx, ZnOx, HfOx, TaOx, AlOx…
- ❑ Almost all reported **< 200 °C**

- ❑ 2D graphene/$MoS_{2-x}O_x$/graphene → **340 °C**

Discovery of Memory Behavior in GaN p-n Diodes

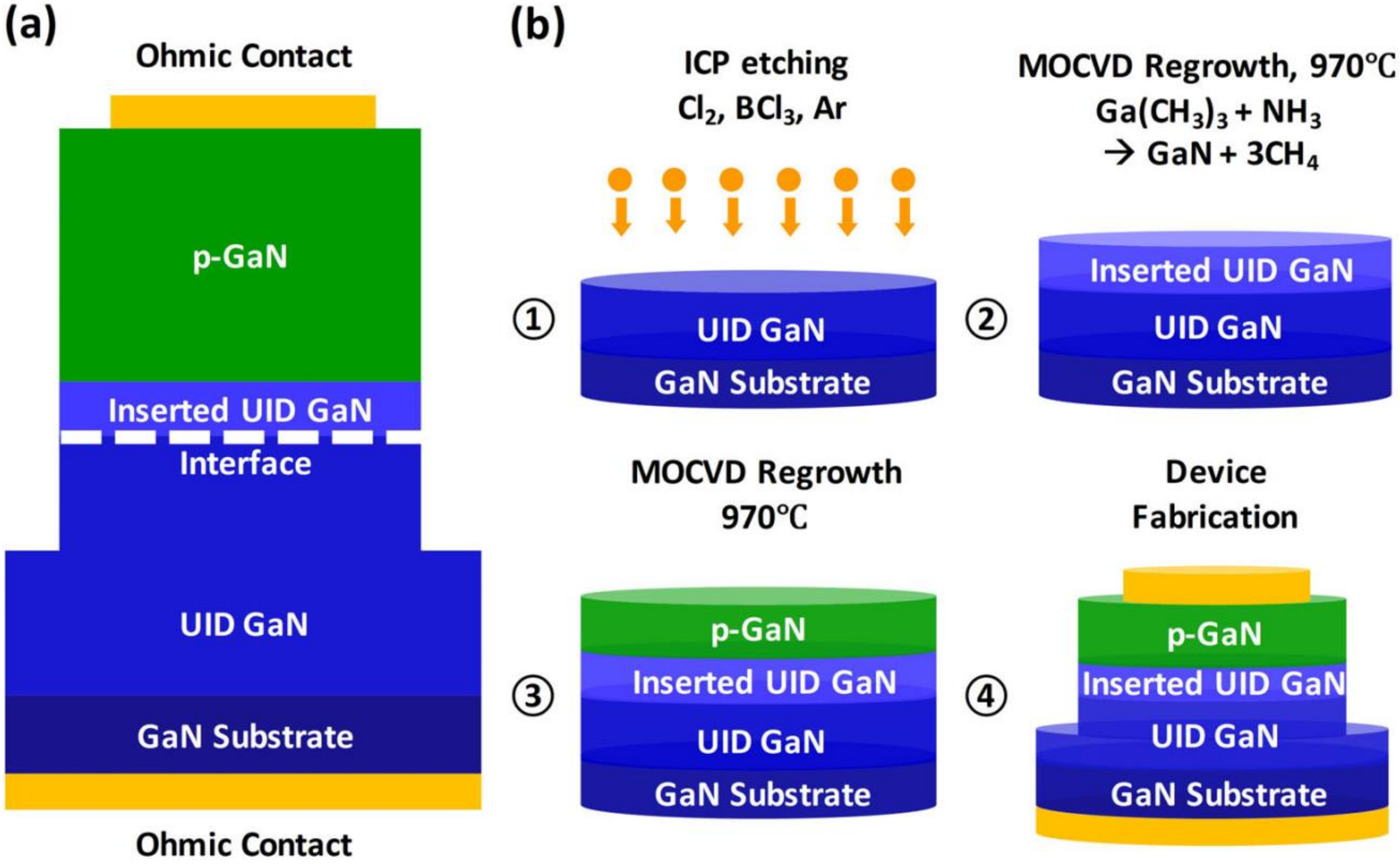




G. Koblmüller, J. S. Speck, et al., Journal of Applied Physics, 107, 043527 (2010)

K. Fu, et al., IEEE Transactions on Electron Devices 71.3 (2023): 1641-1645.

Discovery of Memory Behavior in GaN p-n Diodes



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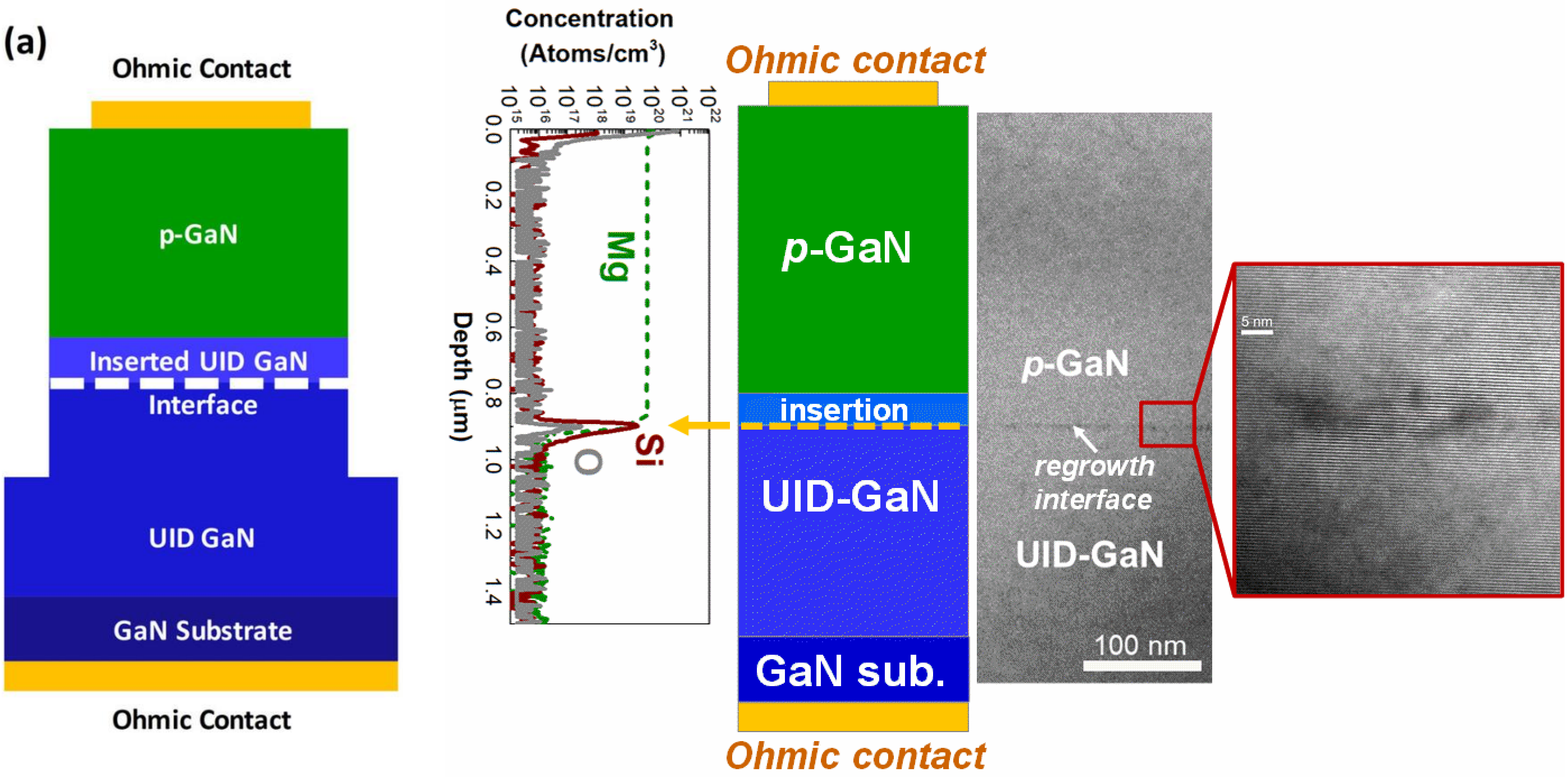

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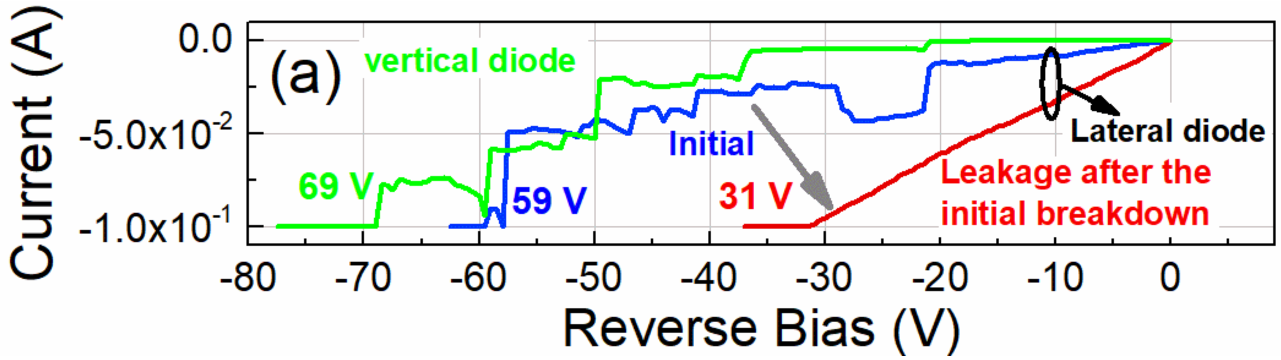

K. Fu et al., *IEEE Electron Device Letters*, vol. 40, 2019.

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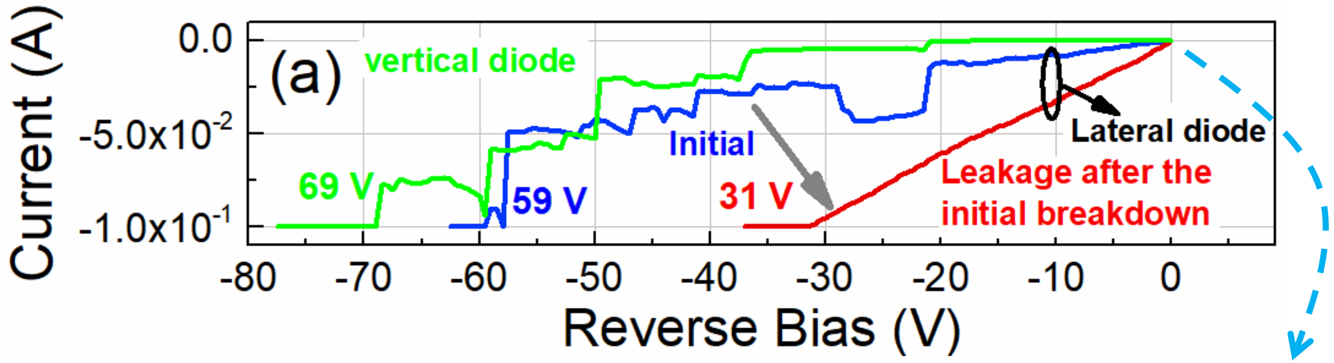
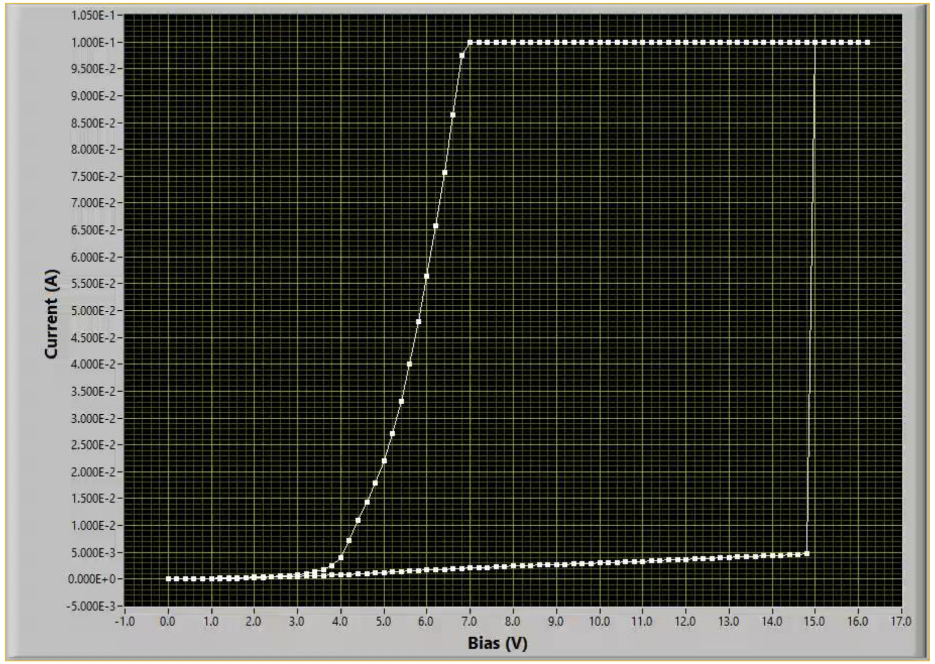
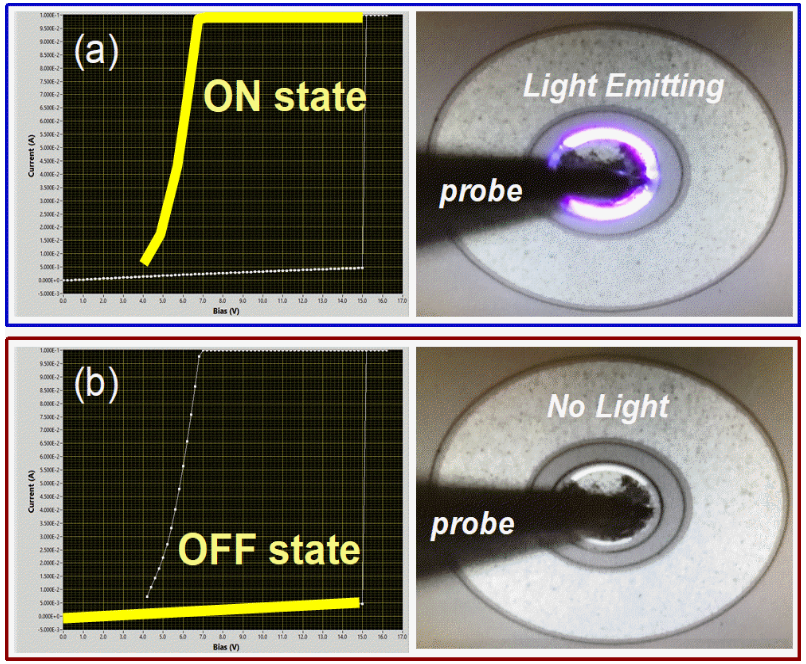




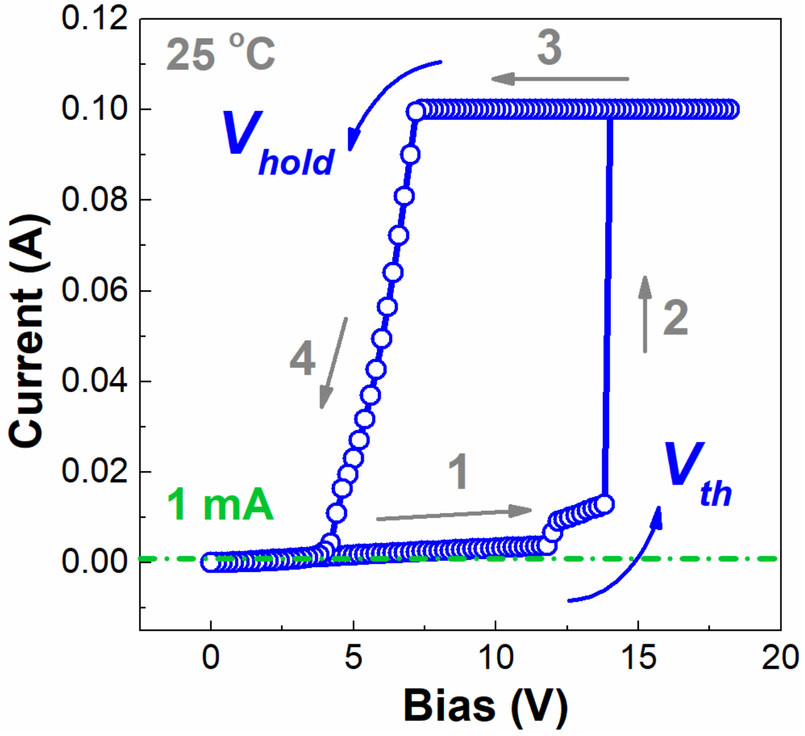


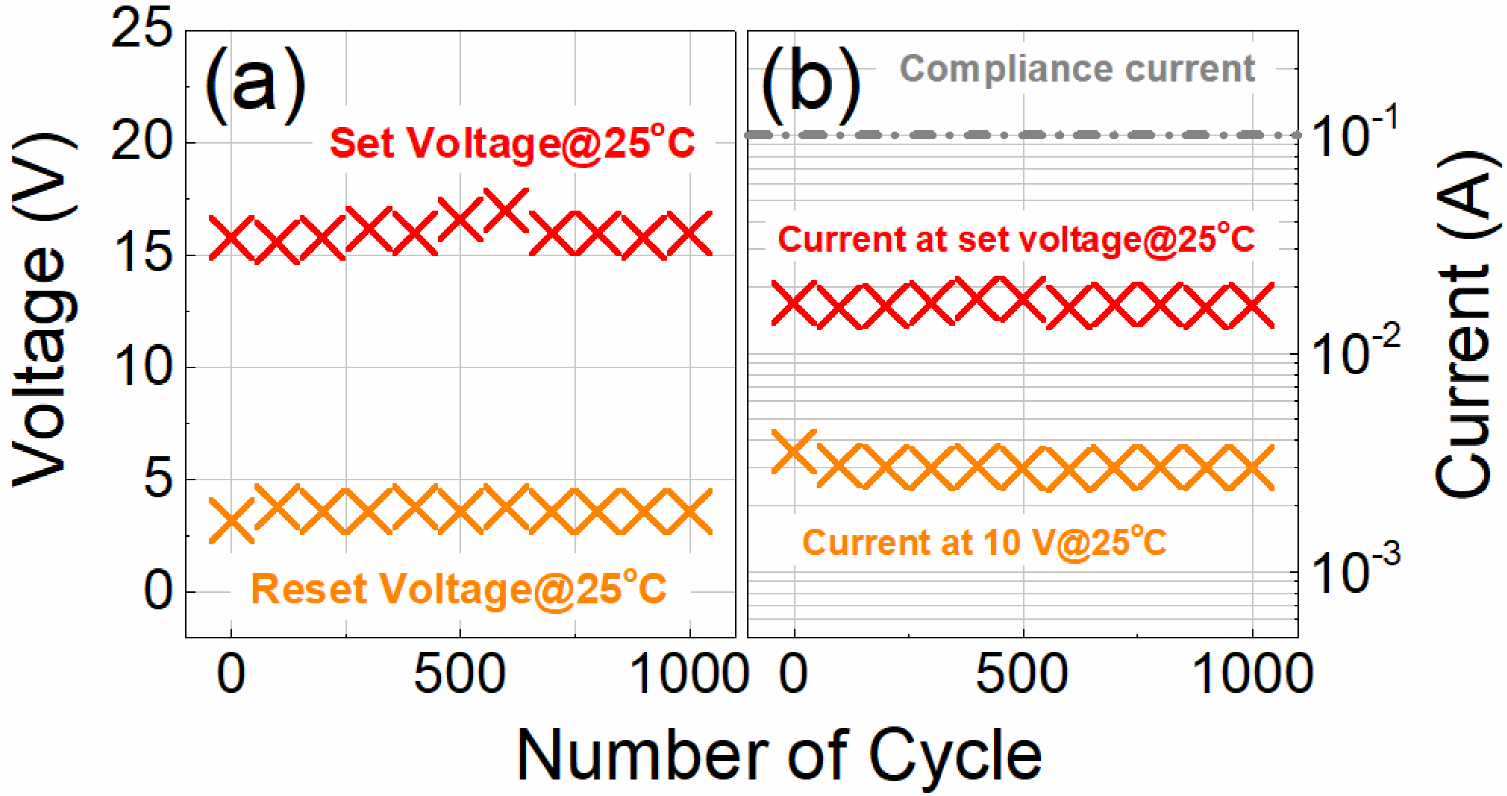
- ❑ **Reverse breakdown served as the forming process → resistive switching**

K. Fu et al., *IEEE Electron Device Letters*, vol. 40, 2019.

Discovery of Memory Behavior in GaN p-n Diodes

➢ *Room temperature performance*





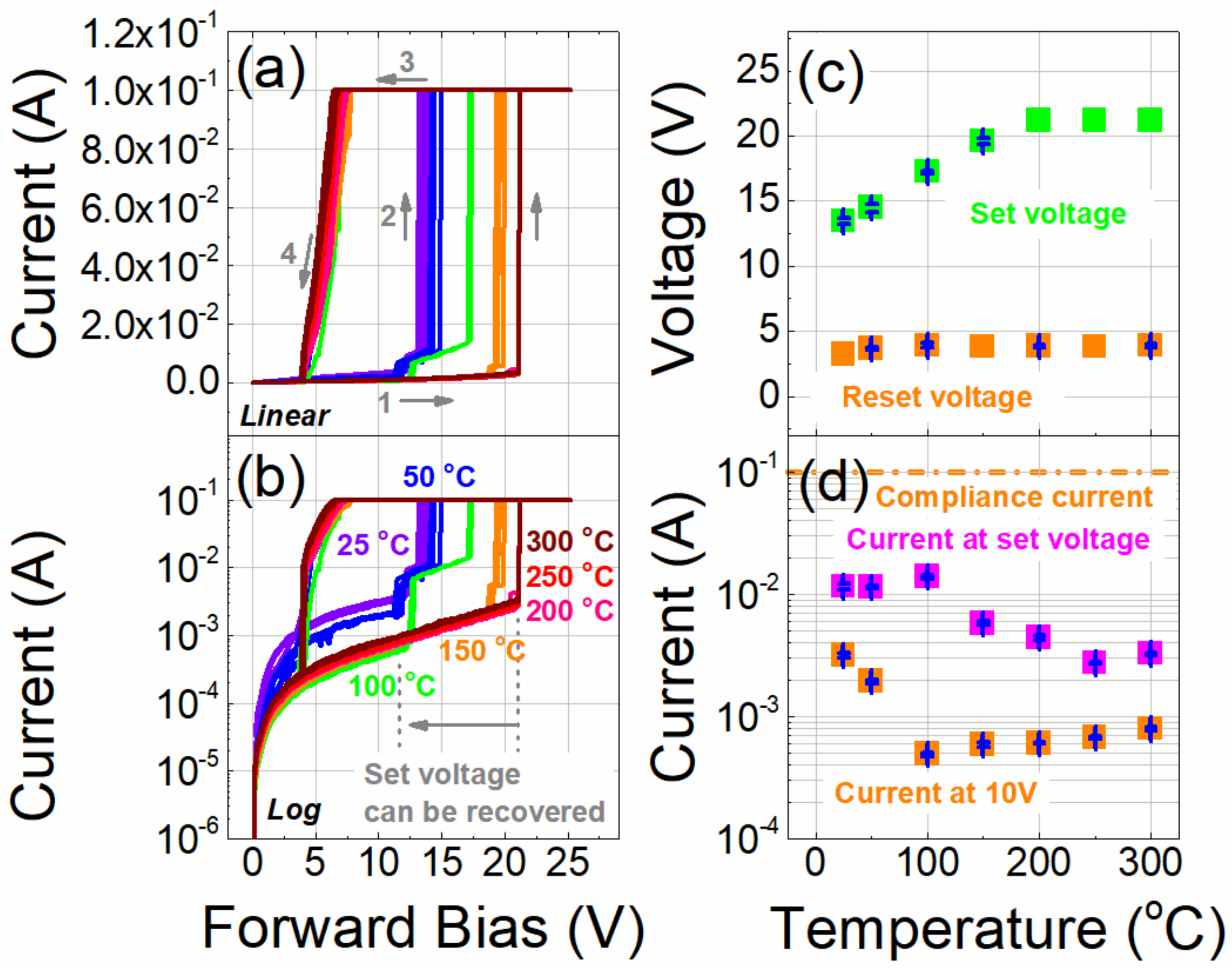
- ❑ Direct voltage scanning mode
- ❑ Reliably switched **more than 1000 cycles at room temperature** with **very small fluctuation** of the set voltage and the current at HRS

K. Fu et al., IEEE Electron Device Letters, vol. 40, 2019.

Discovery of Memory Behavior in GaN p-n Diodes

➢ ***High temperature performance***

- ❑ The set voltage increases with temperature
- ❑ The device performance **returns** to its initial values as the temperature decreases to room temperature.



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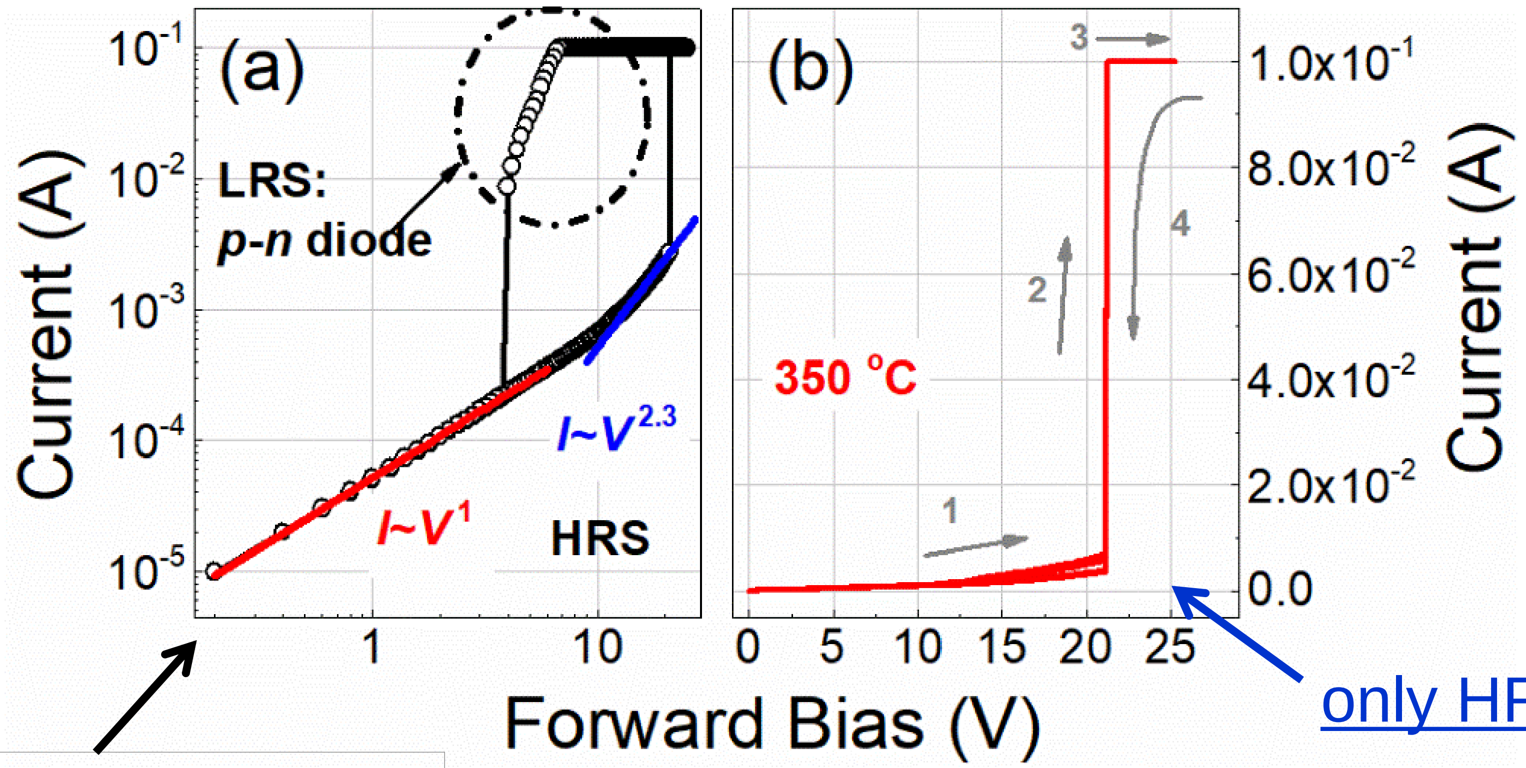
➢ ***High temperature performance***

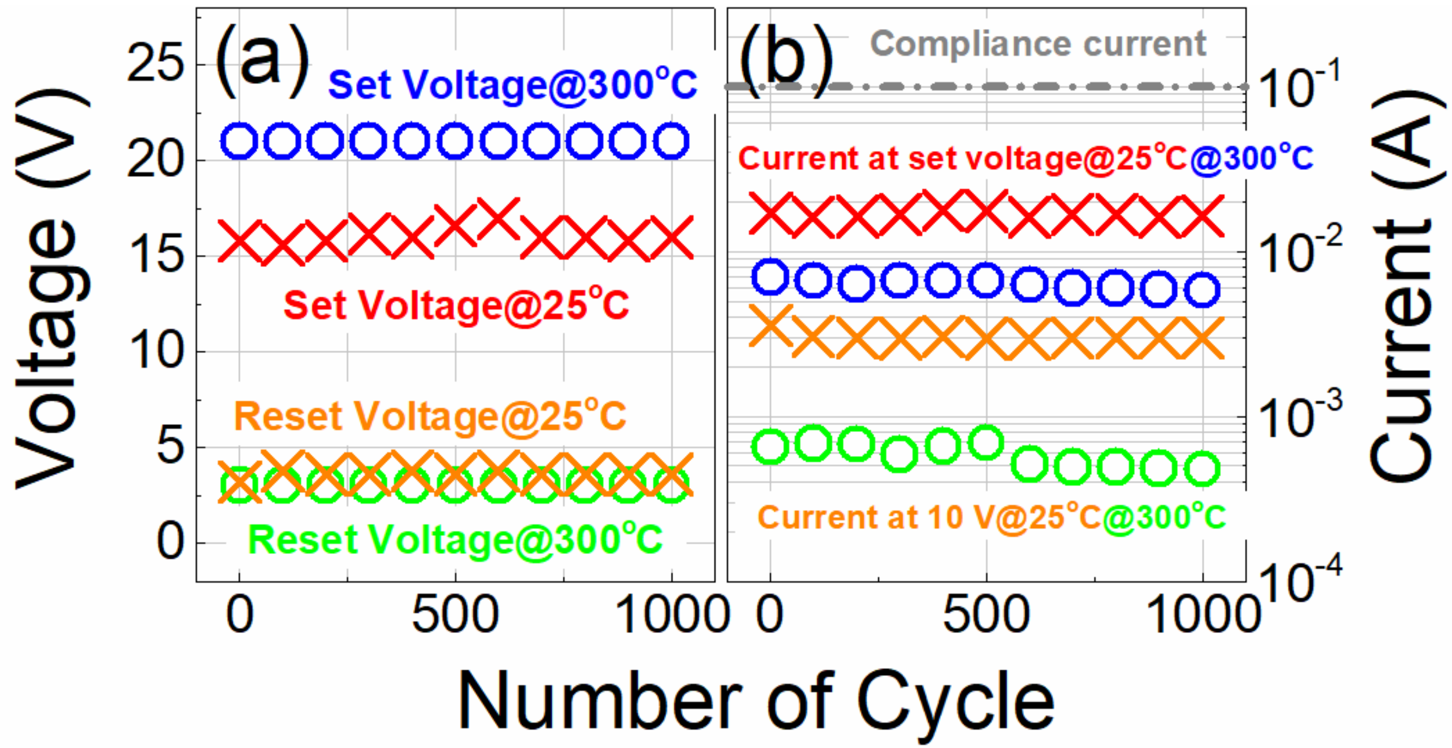


*HRS I-V curves: trap-assisted space charge limited current (**SCLC**) theory (the Ohmic region I~V, and the Child's square law region I~V^2 followed by a steep increase in current)*

K. Fu et al., IEEE Electron Device Letters, vol. 40, 2019.

Discovery of Memory Behavior in GaN p-n Diodes

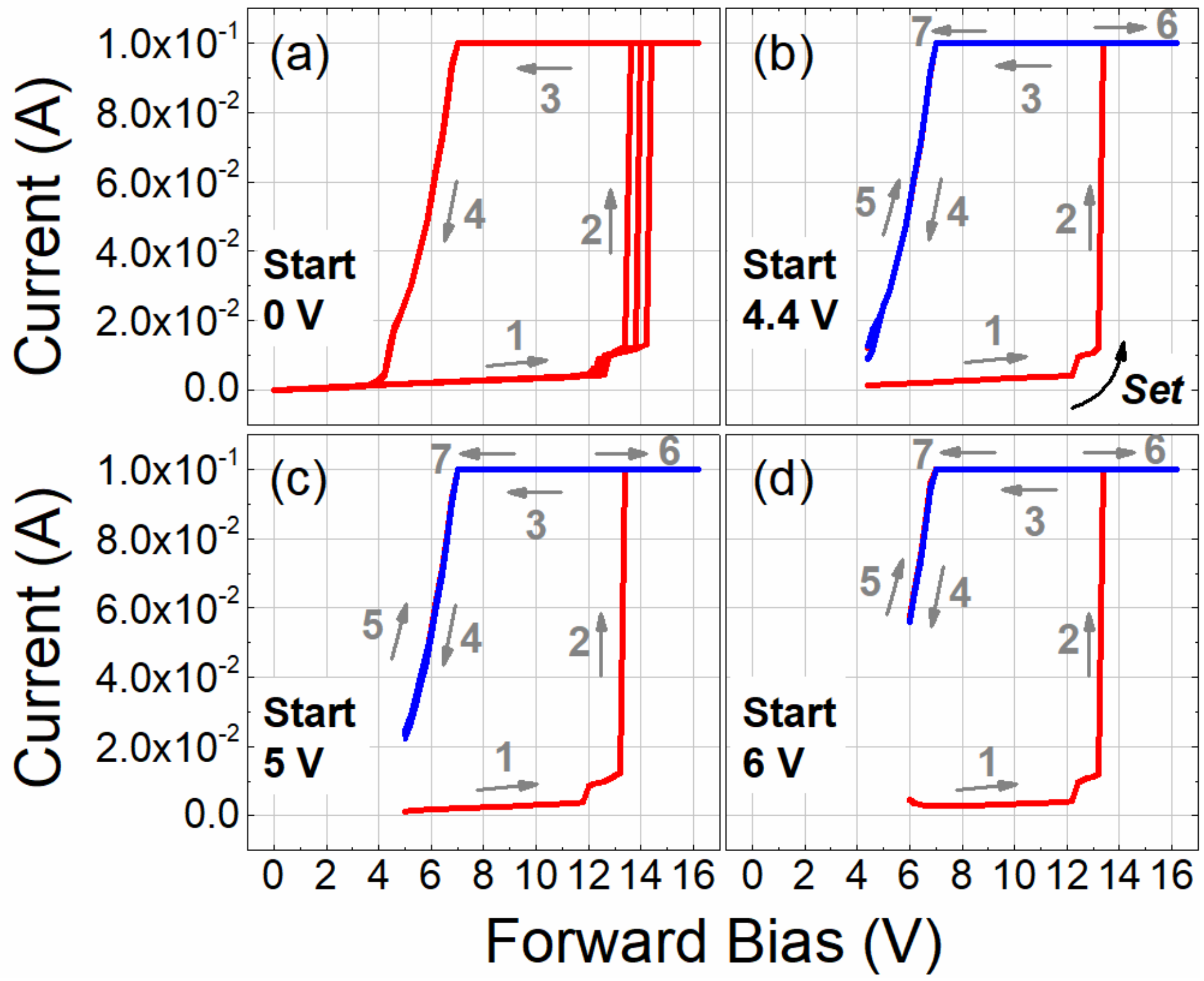
- ***High temperature performance***



- Reliably switched **more than 1000 cycles at 300 °C** with **very small fluctuation** of the set voltage and the current at HRS
- The fabrication is **repeatable**

Discovery of Memory Behavior in GaN p-n Diodes

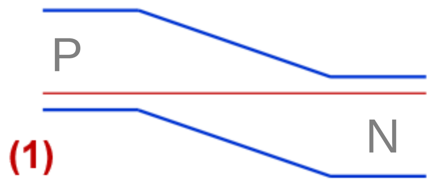
- The **traps-based conductive path could be maintained** when the **stop voltage** was a little higher than the turn-on voltage of the GaN p-n diode → Memory behavior, with high temperature stability!



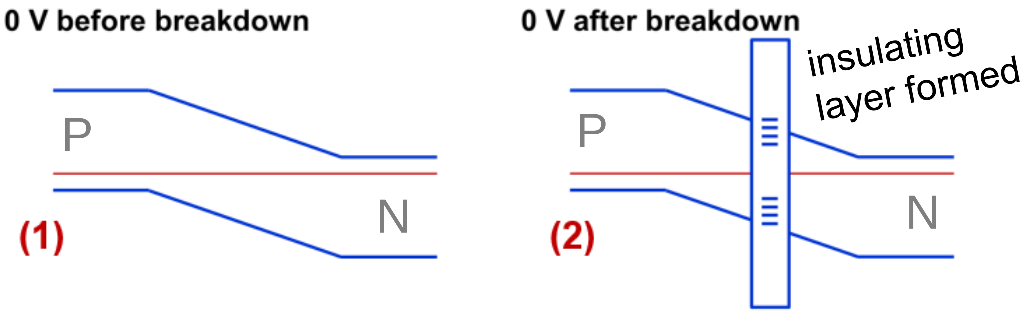
K. Fu et al., IEEE Electron Device Letters, vol. 40, 2019.

Mechanism for Resistive Switching Behavior

0 V before breakdown



Mechanism for Resistive Switching Behavior



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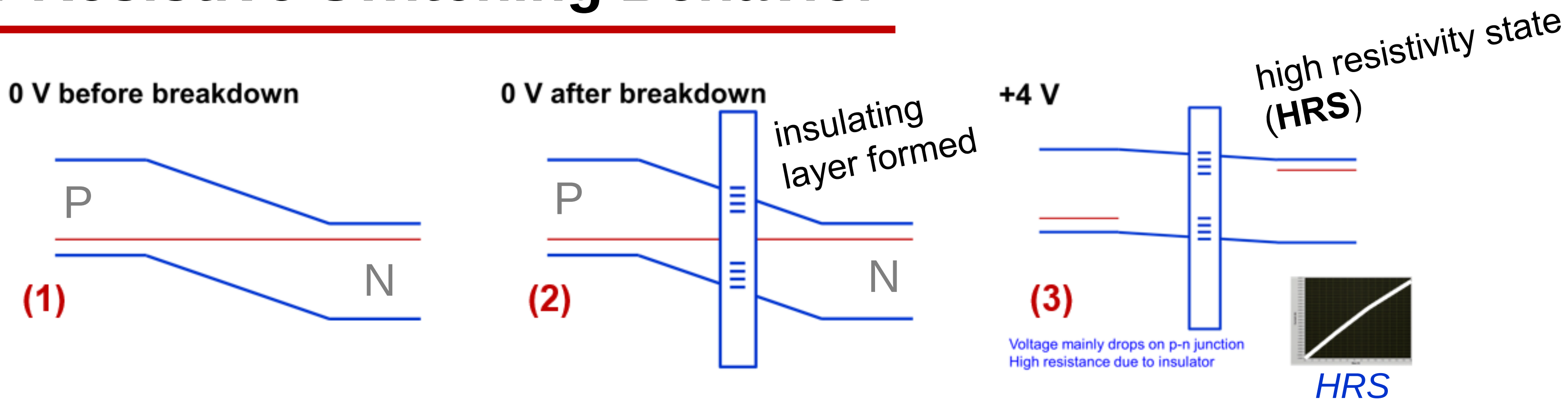

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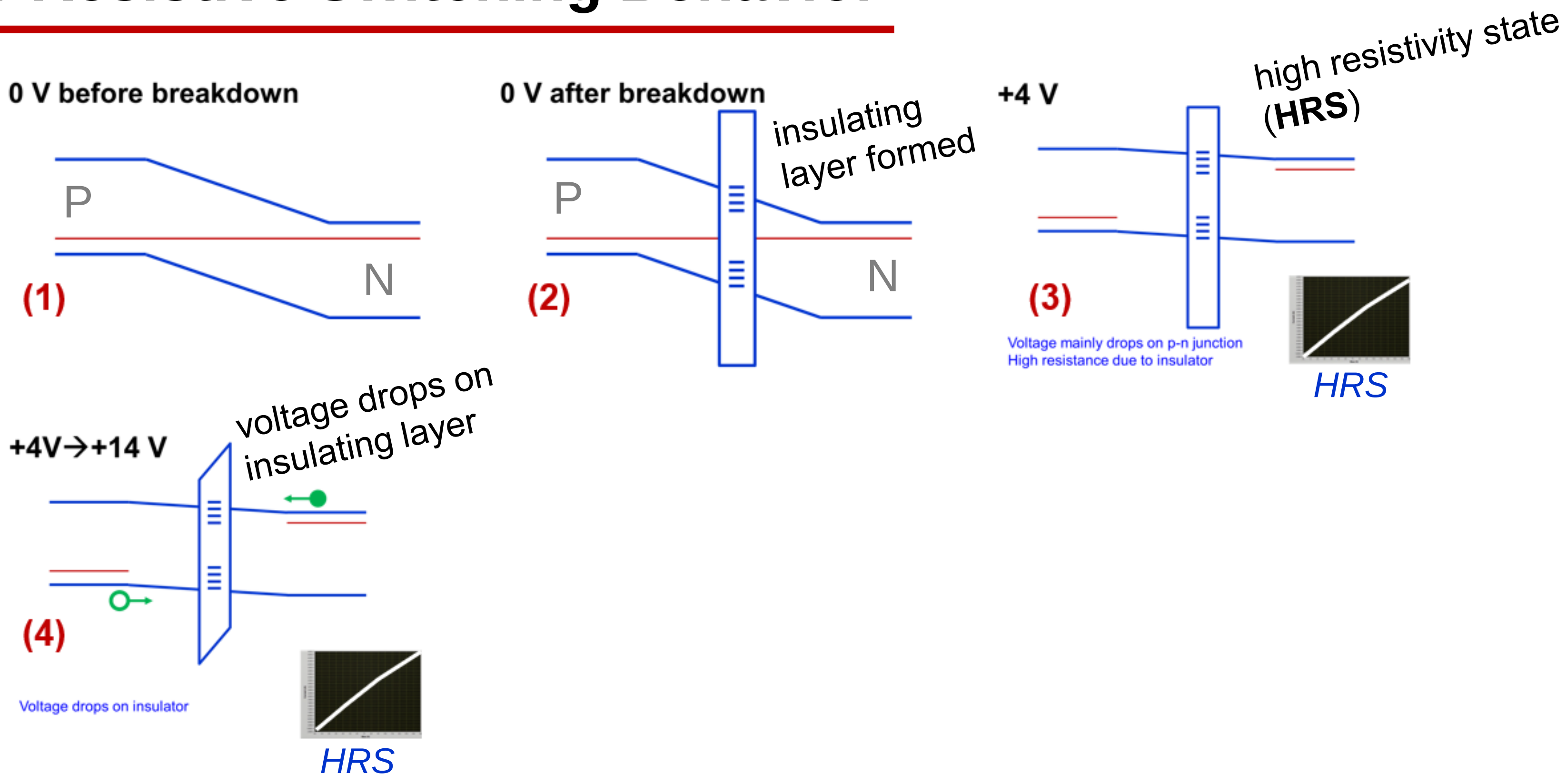

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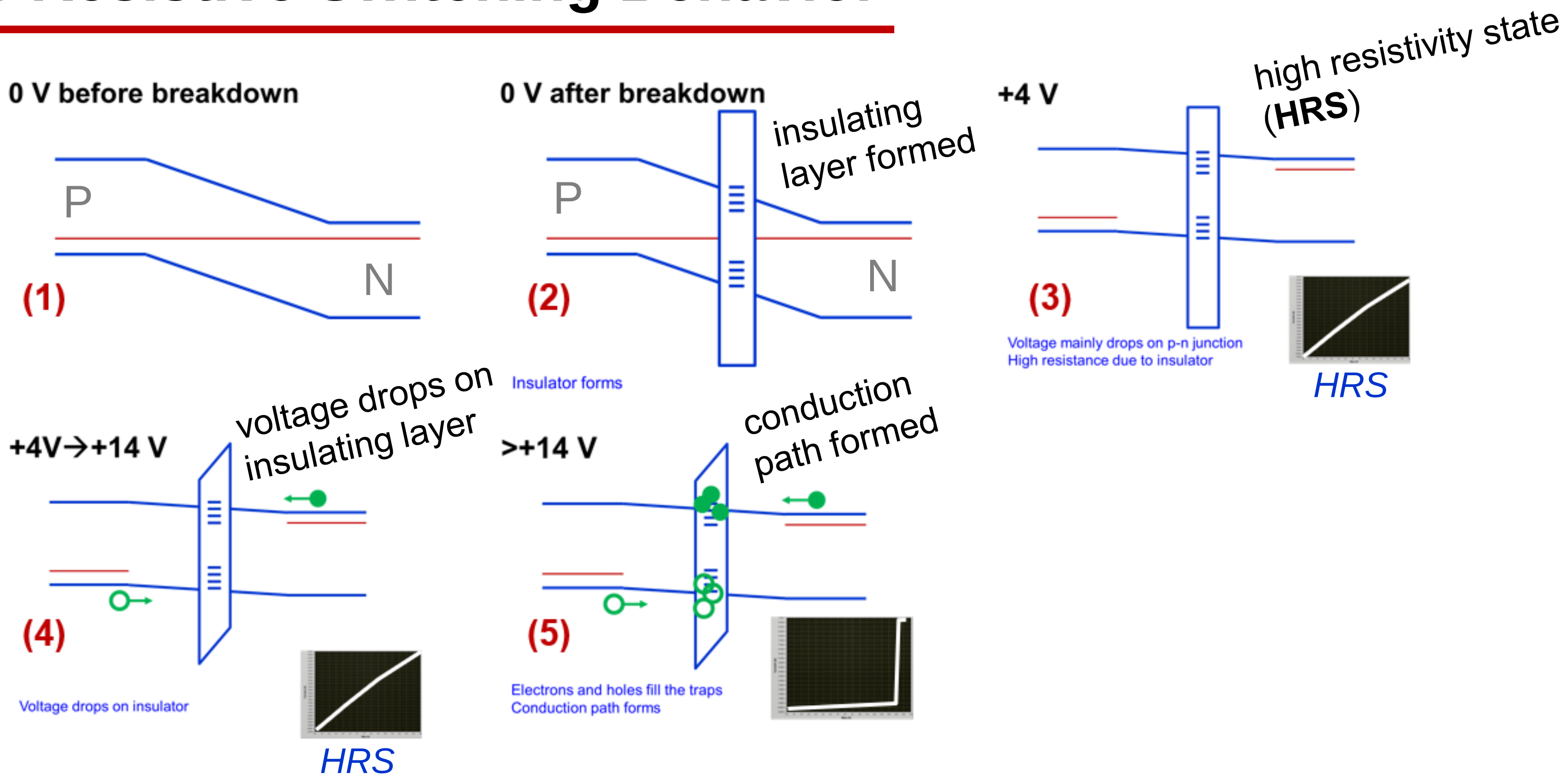

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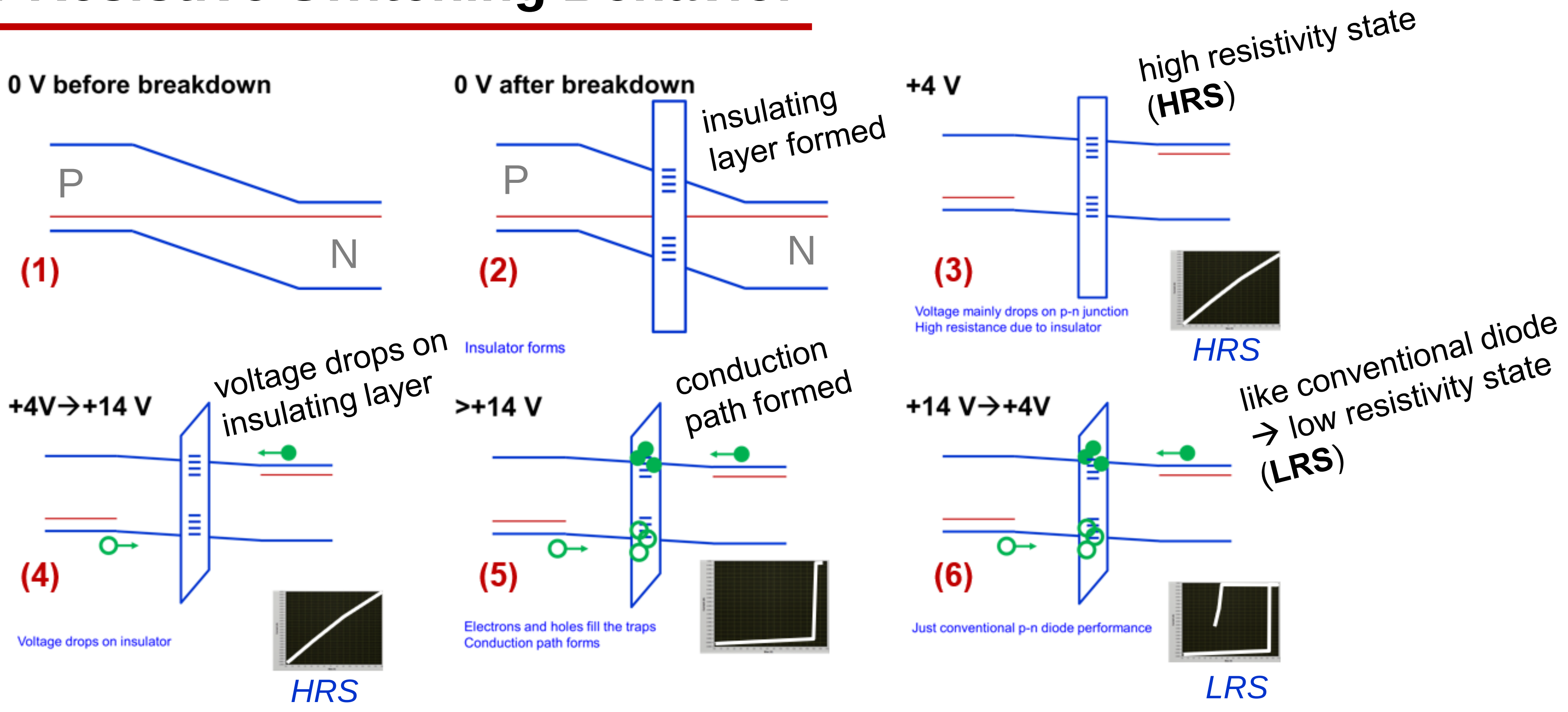

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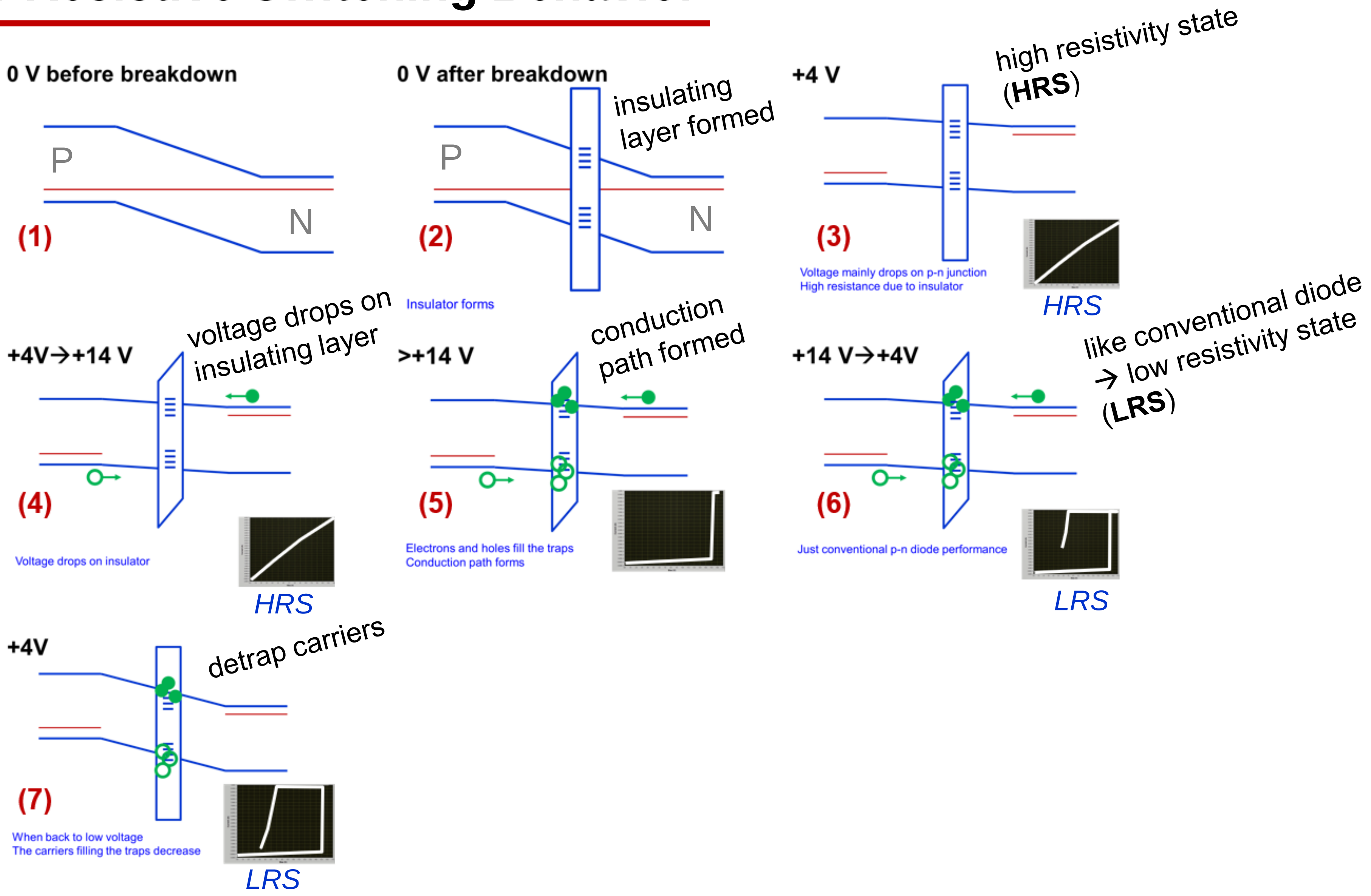

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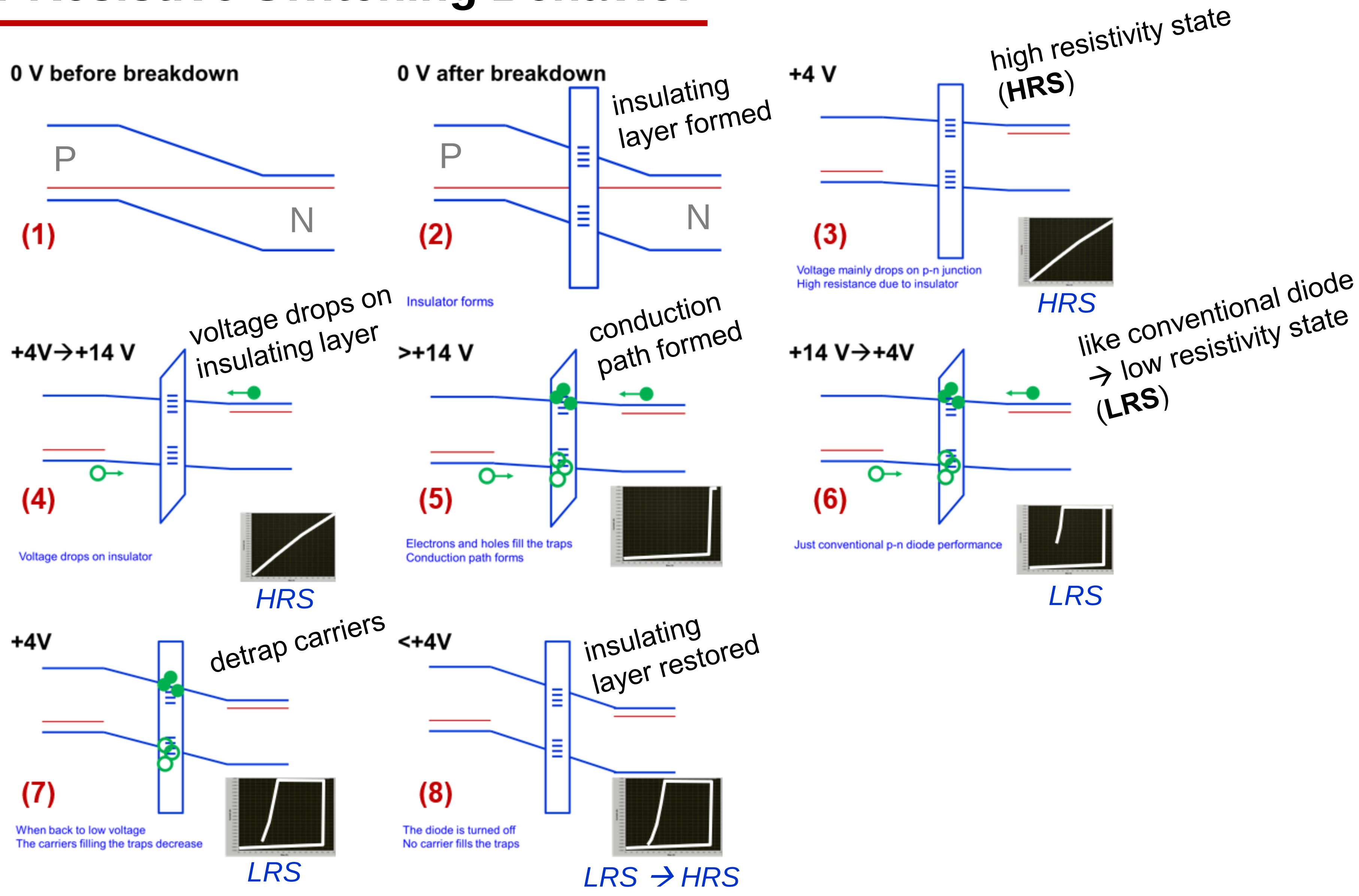

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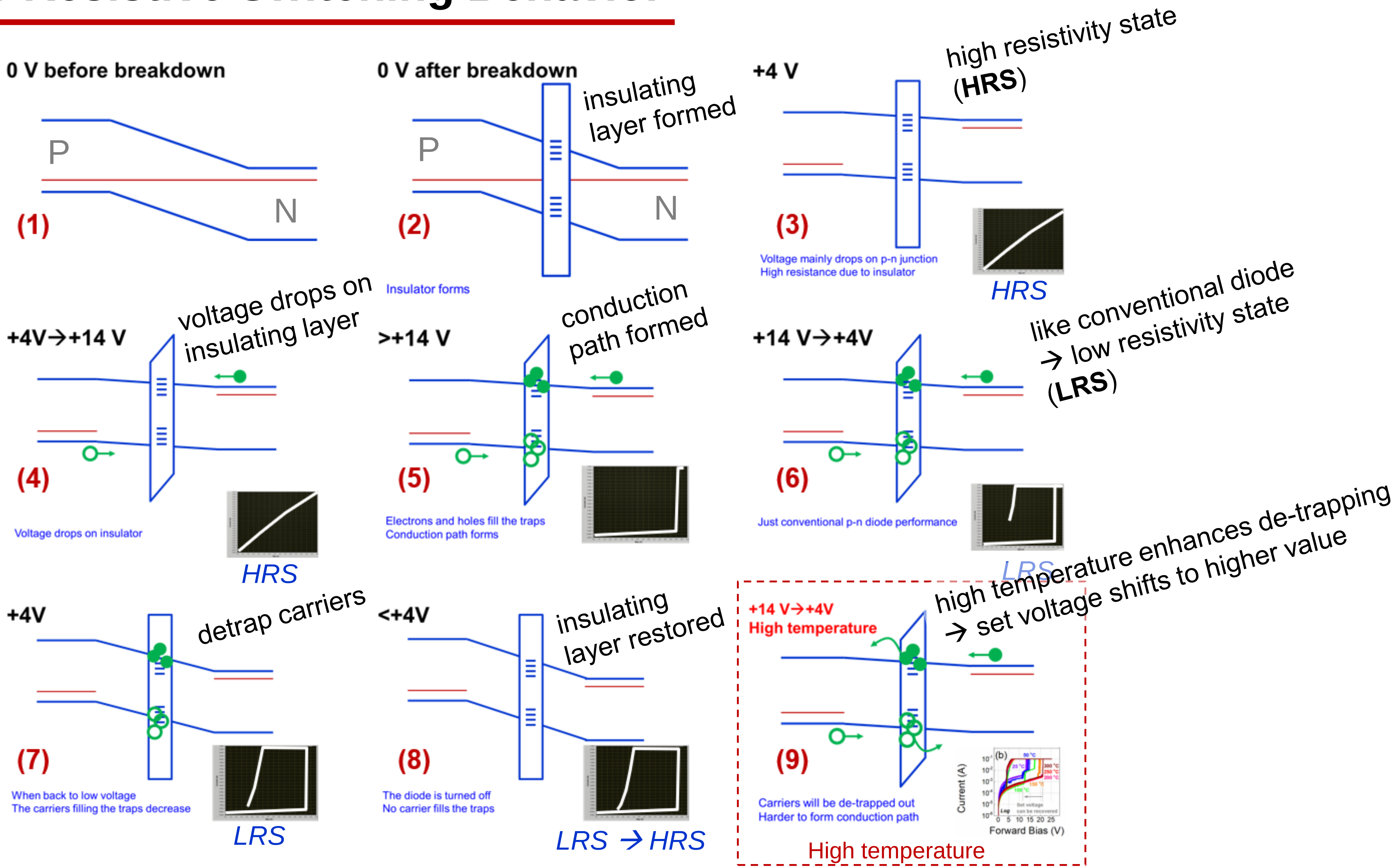

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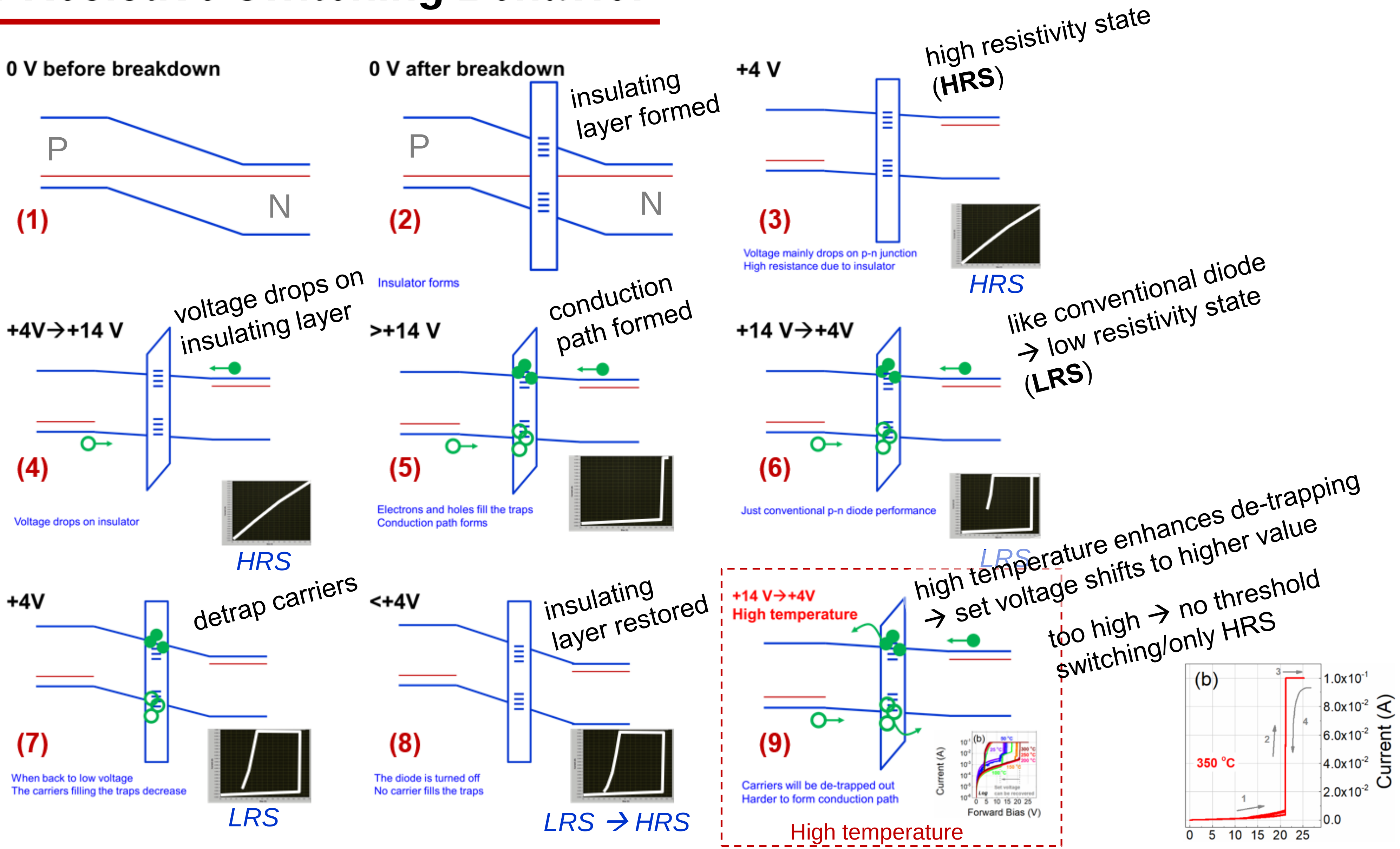
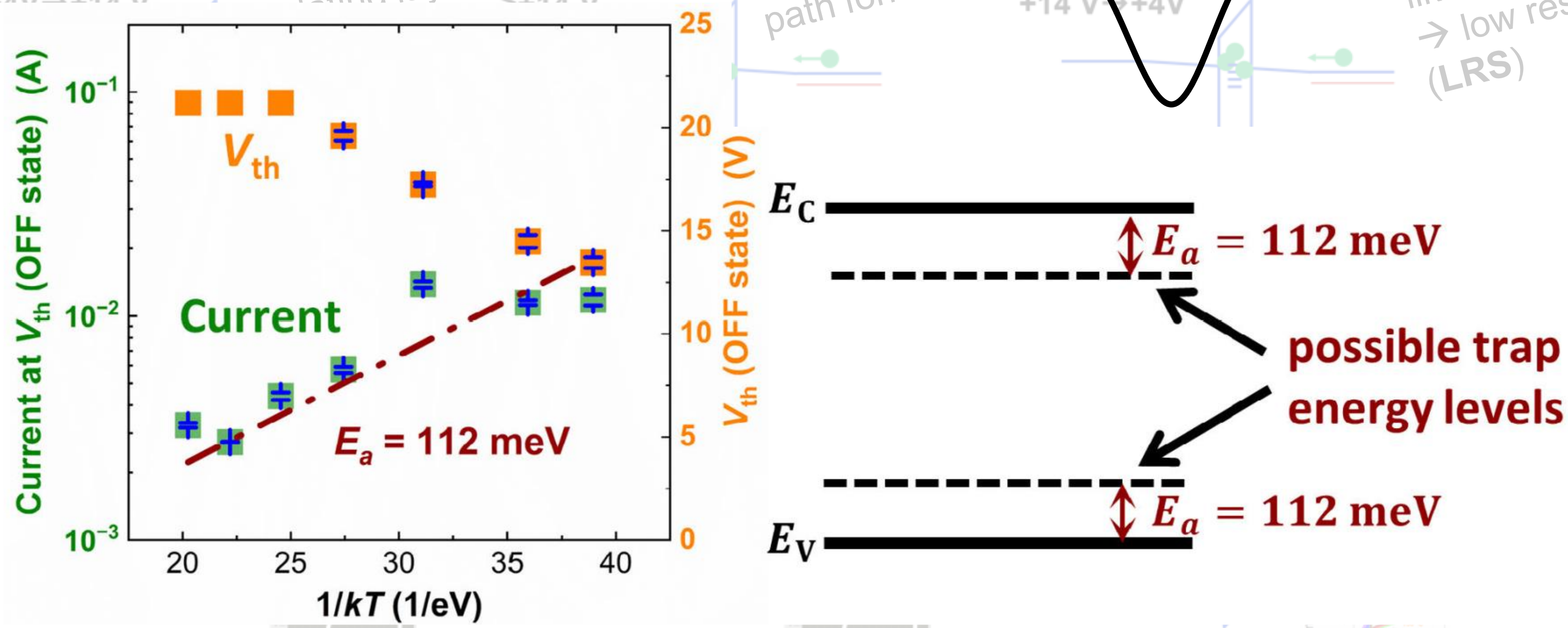


Mechanism for Resistive Switching Behavior

trapping vs de-trapping



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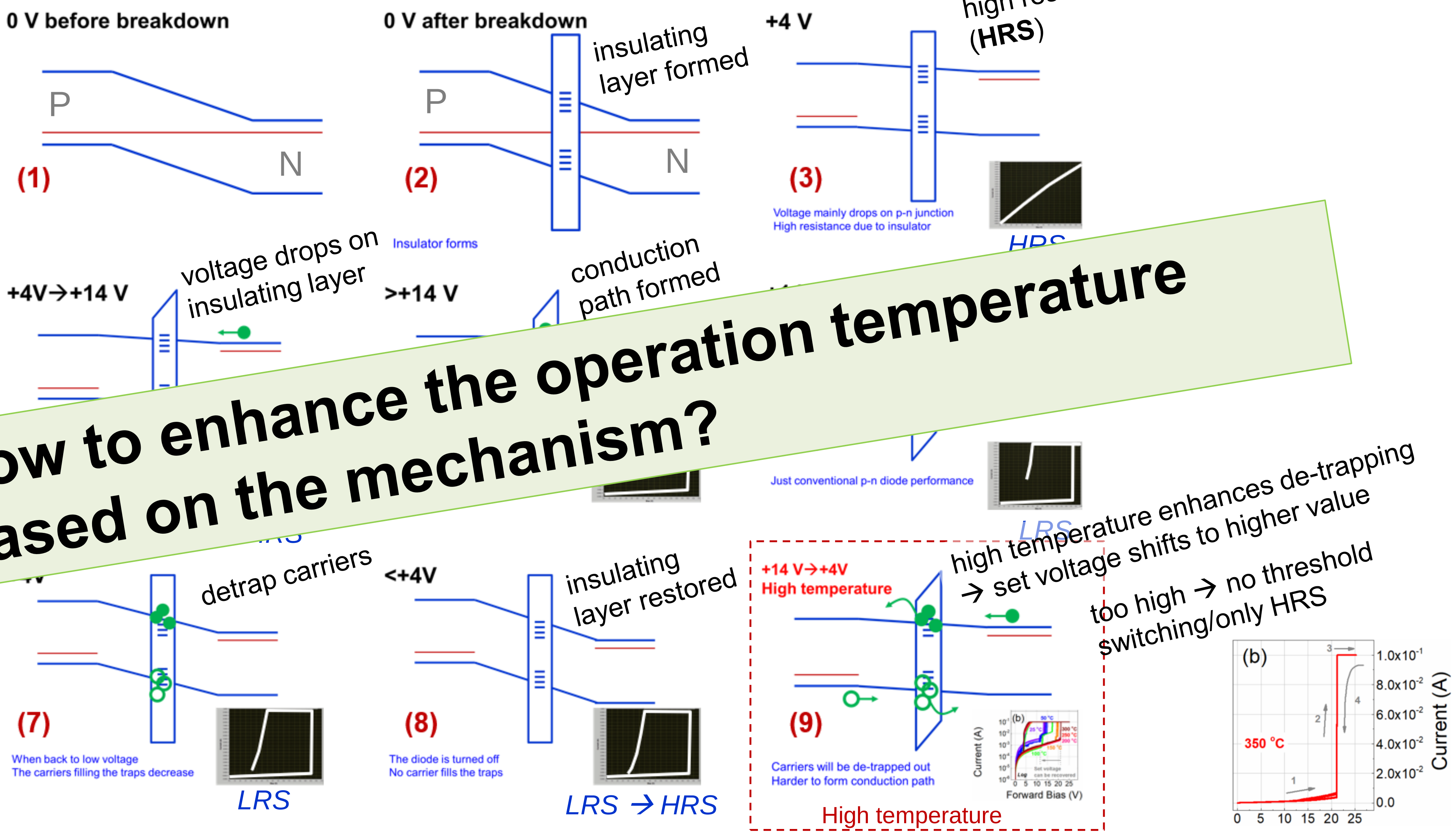
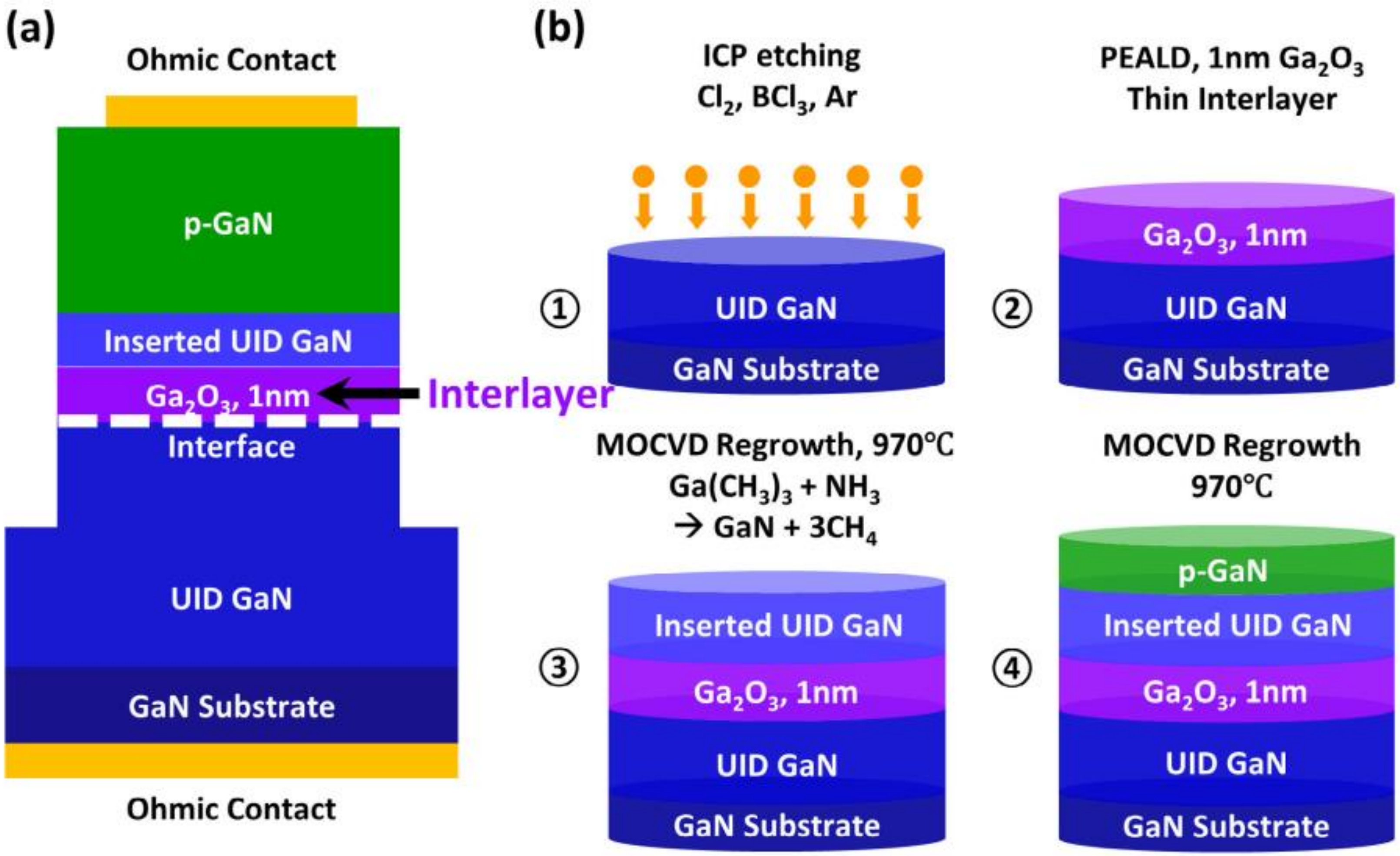


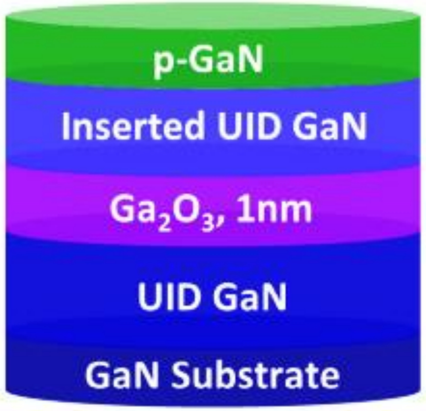
How to enhance the operation temperature based on the mechanism?

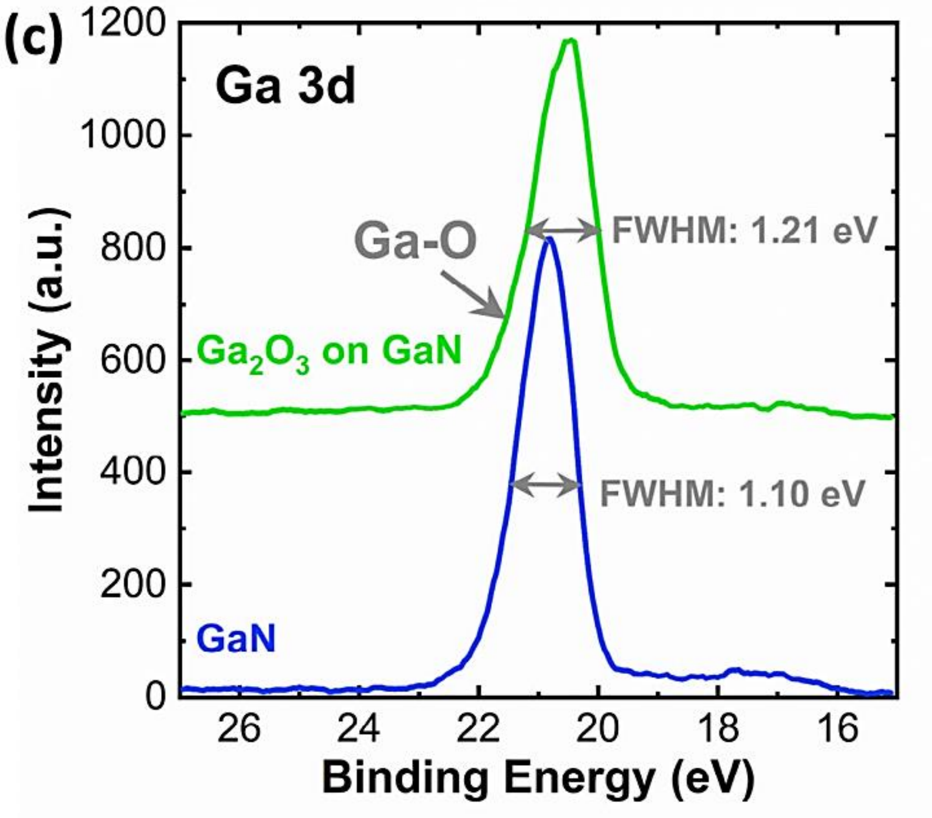
Enhanced GaN Memory Behavior up to 500 C

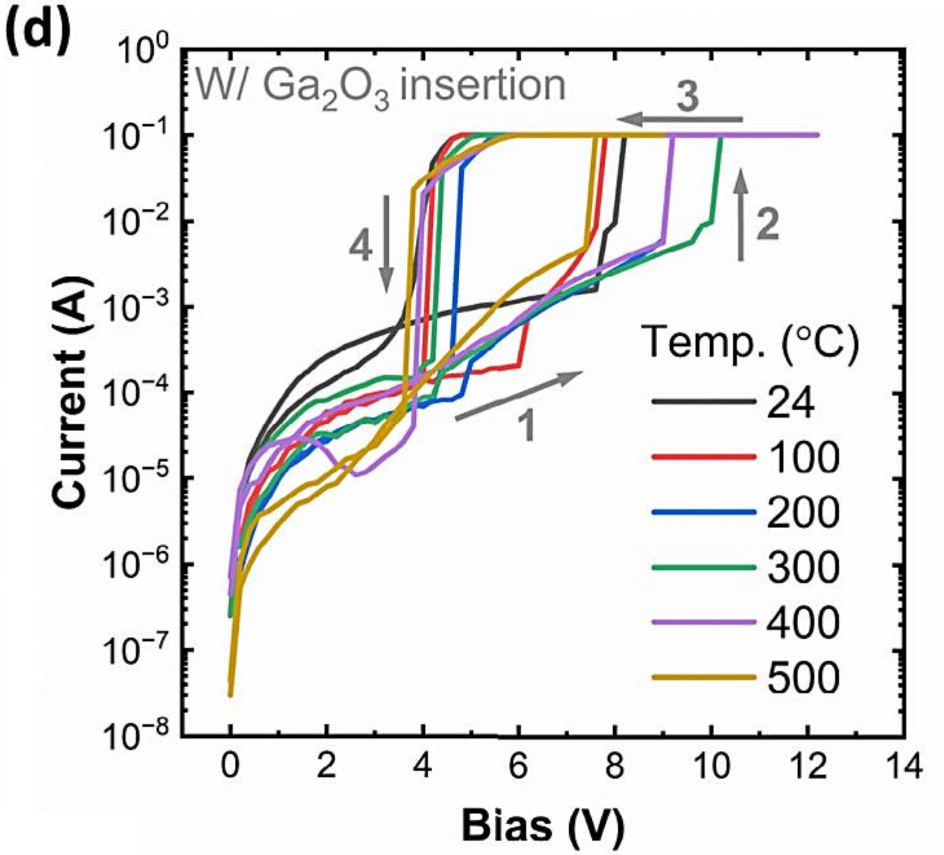


K. Fu, et al., IEEE Transactions on Electron Devices 71.3 (2023): 1641-1645.

Enhanced GaN Memory Behavior up to 500 C

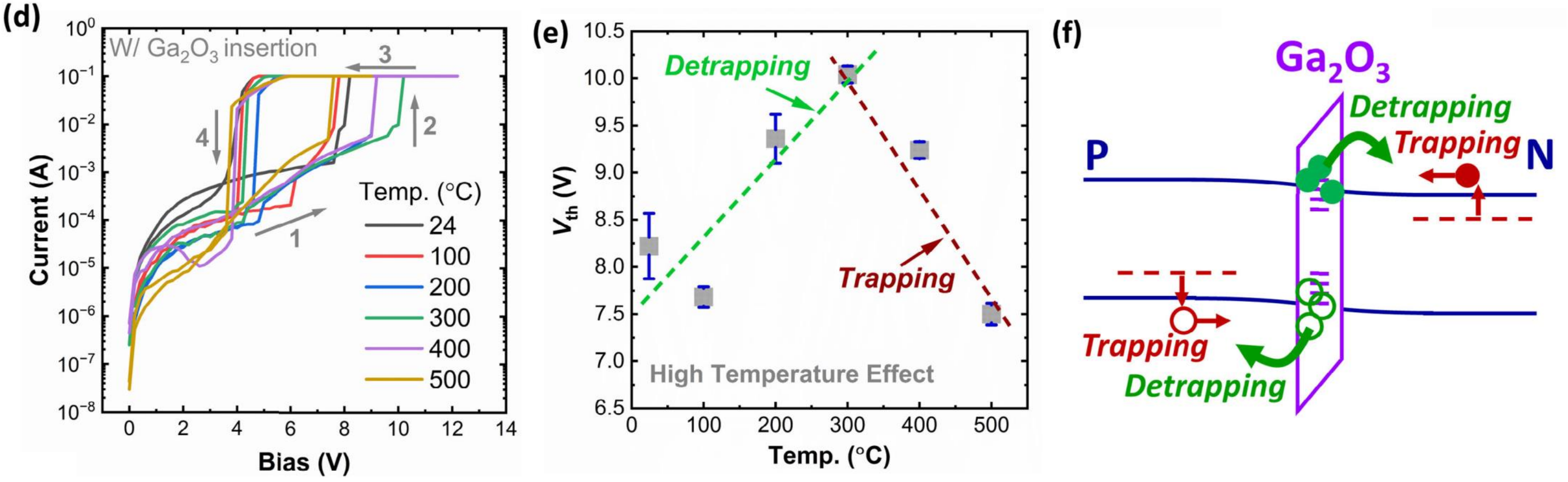






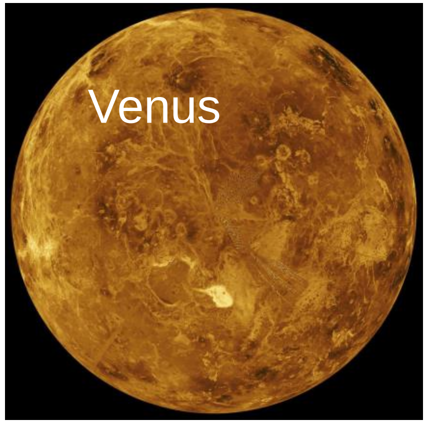
- ❑ The Ga_2O_3 interlayer was found to be effective in improving the high-temperature performance up to 500 C, but...

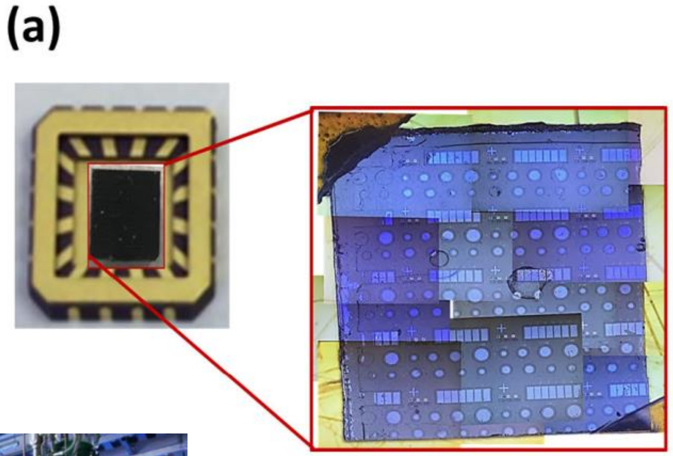
Enhanced GaN Memory Behavior up to 500 C



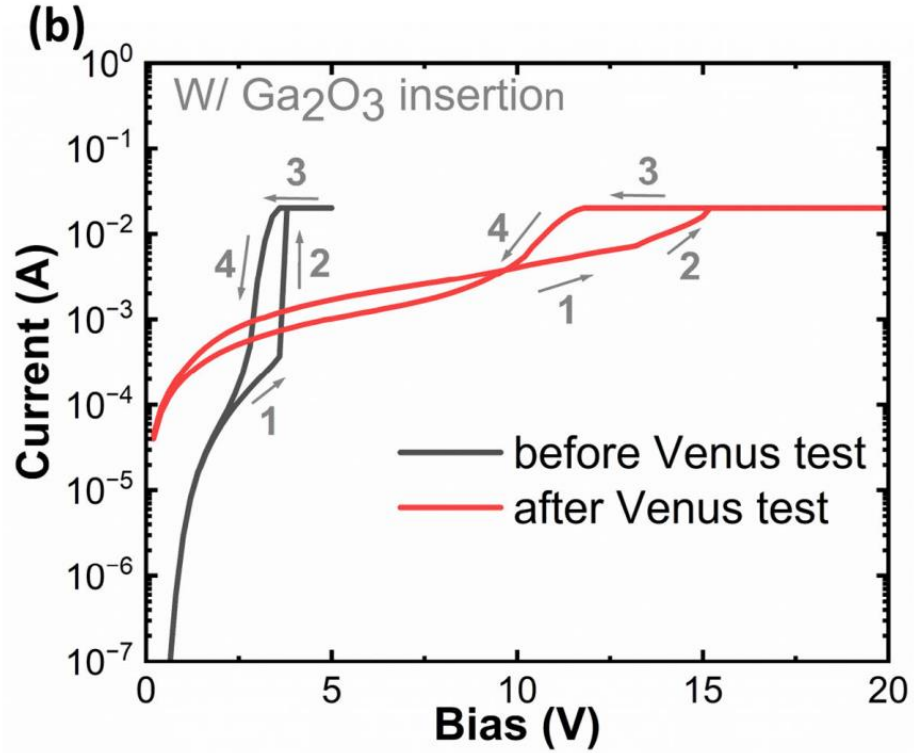
- 25 C–300 C: the detrapping from interfacial traps increased V_{th} at.
- 300 C–500 C: thermally activated intrinsic carrier densities in p-GaN and n-GaN increase. The **injection of thermal activation carriers** into traps could decrease the V_{th}
- The device performance **returns** to its initial values as the temperature decreases to room temperature.

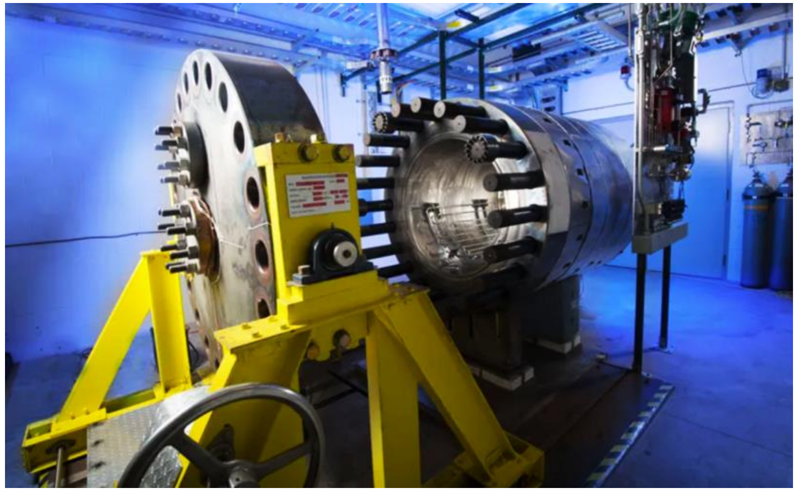
Enhanced GaN Memory Behavior up to 500 C





after 10 days





NASA Glenn Extreme Environments Rig (GEER) for Venus

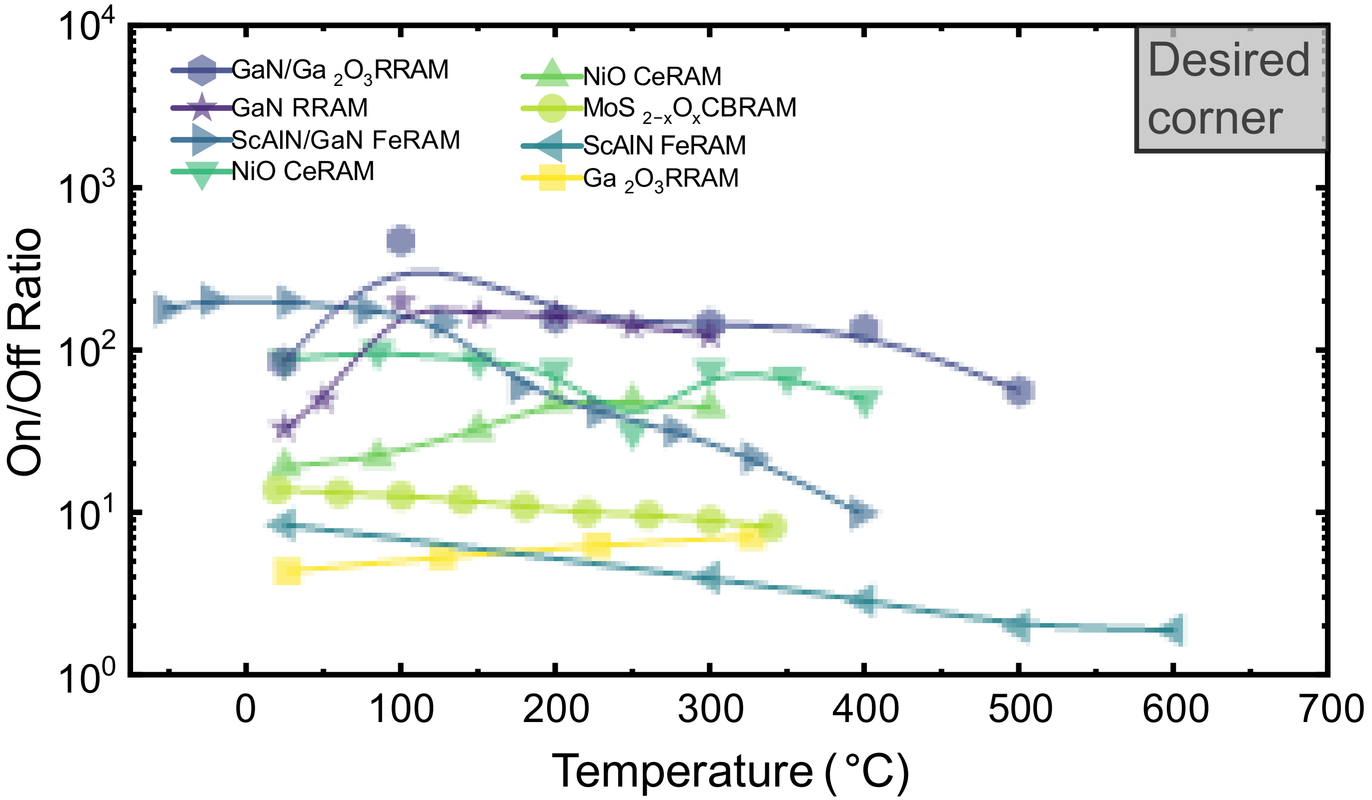
(460 C, ~ 92 atm., containing CO_2/N_2/SO_2 etc.)

- Memory behavior; V_{th} and V_{hold} are significantly increased
- Possible reasons (no passivation): p-GaN conductivity degradation, surface damage, increased trapping density at the regrown interface, and/or electrode metal degradation

https://science.nasa.gov/science-research/science-enabling-technology/hottech-attempts-to-tackle-venus/

Summary

- Observed resistive switching and memory behaviors in GaN p-n diodes with regrowth interface.
- Endurance and high temperature test: 1000 cycles; up to 300 C; small fluctuation.
- Mechanism: trapping vs de-trapping.
- Ga_2O_3 insertion is effective to enhance the operation temperature up to 500 C.
- The GaN/Ga_2O_3 memory survived in Venus environment for 10 days but shows severe degradation; passivation may improve the performance.
- New materials for high temperature...



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CHANGING WHAT'S POSSIBLE

ARPAe PNDIODES
(grant number DE-AR0000868)

THE UNIVERSITY OF UTAH

Looking forward to collaborating on UWBG