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Gallium Nitride HEMTs: advantages, opportunities and challenges

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Outline

- Introduction & GaN properties
- Applications opportunities
- Open issues
  - Materials
  - Technology (E-Mode, Breakdown, Vertical vs lateral, ...)
  - Parasitic & Reliability
- GaN Activities within IU.NET
- Conclusions

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Introduction to the GaN-HEMTs

Back to the material properties:

	GaN	InN	AlN	Si
Bandgap (eV)	3.4 eV	0.6 eV	6.4 eV	1.1 eV
Mobility ($cm^2V^{-1}s^{-1}$)	1500	3000	300	1000
Breakdown Field (MV/cm)	3	Low	11	0.3
Effective Mass	0.21 m_e	0.09 m_e	0.4 m_e	0.19 m_e
Velocity (cm/s)	2 x 10^7	2 x 10^8	-	1.0 x 10^7
Polarization	High charge, carrier confinement			

[1] U. K. Mishra, P. Parikh, Y.F. Wu, "AlGaN/GaN HEMTs—An Overview of Device Operation and Applications" IEEE Proc. Vol. 90, No. 6, p. 1022, June 2002.
[2] U. K. Mishra, L. Shen, T. E. Kazior, Y. F. Wu, "GaN-Based RF Power Devices and Amplifiers" IEEE Proceedings, Vol. 96, No. 2, p. 287, February 2008.

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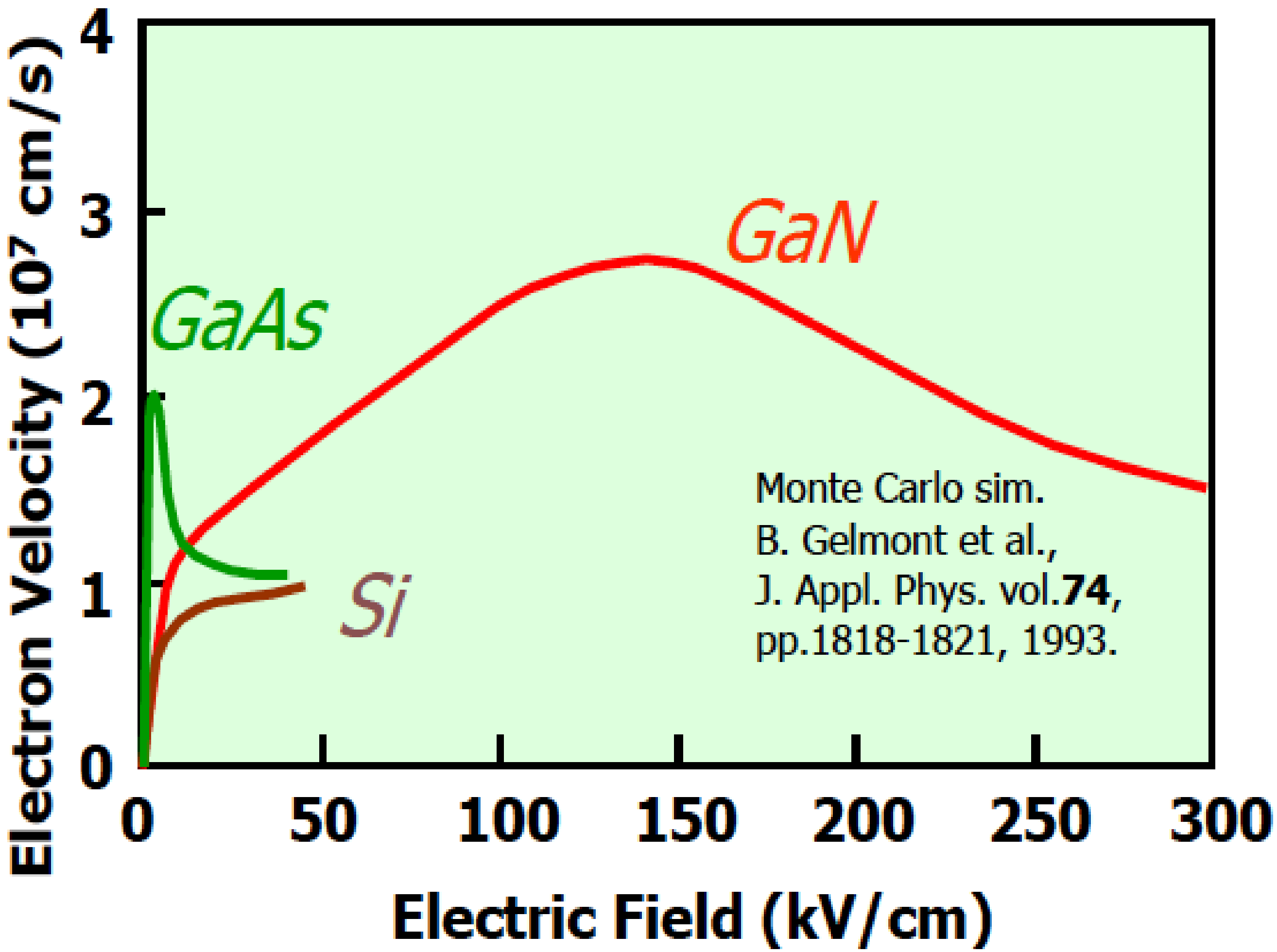
Introduction to the GaN-HEMTs



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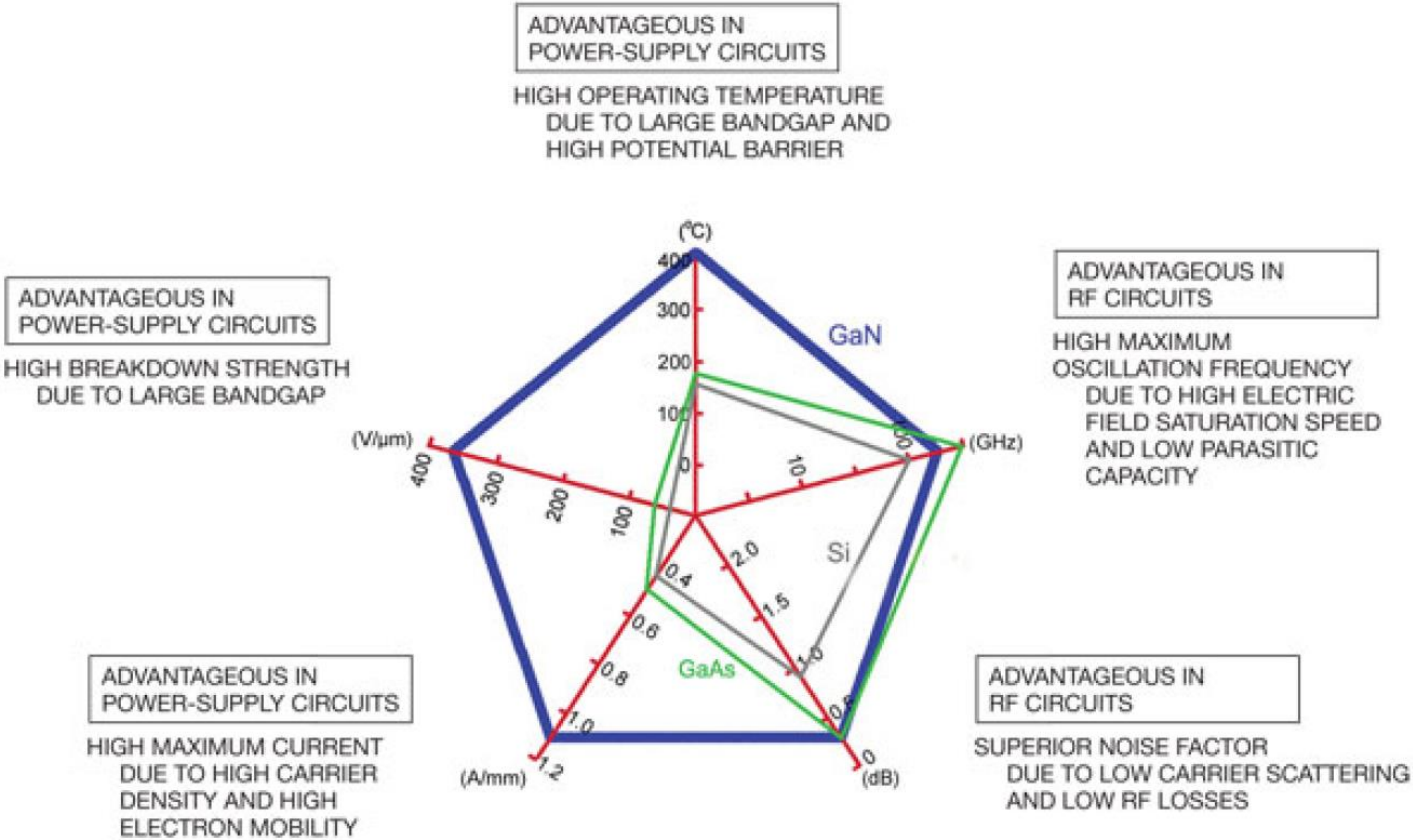
Introduction & Motivations



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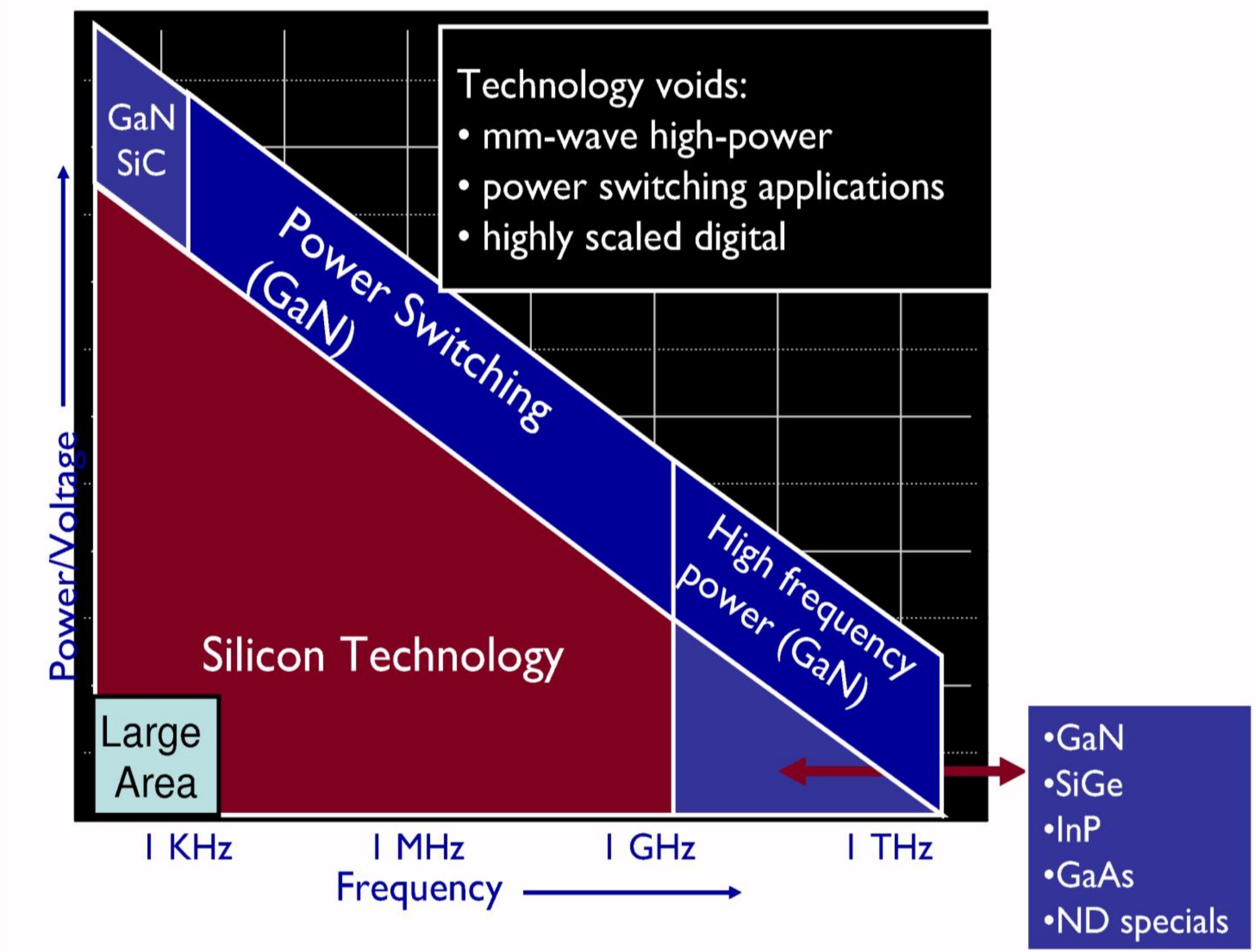
Introduction to the GaN-HEMTs



courtesy: Umesh Mishra, UCSB

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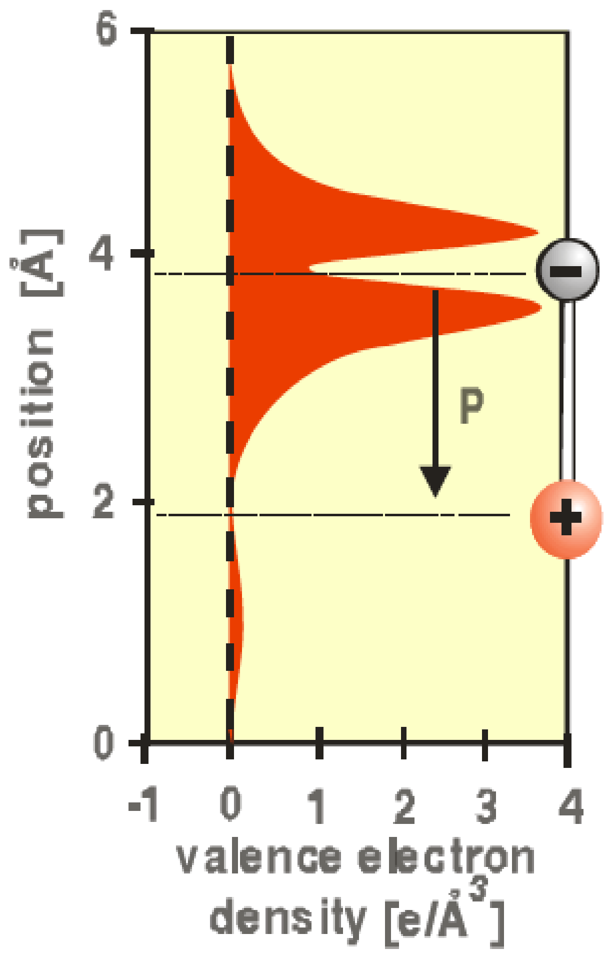
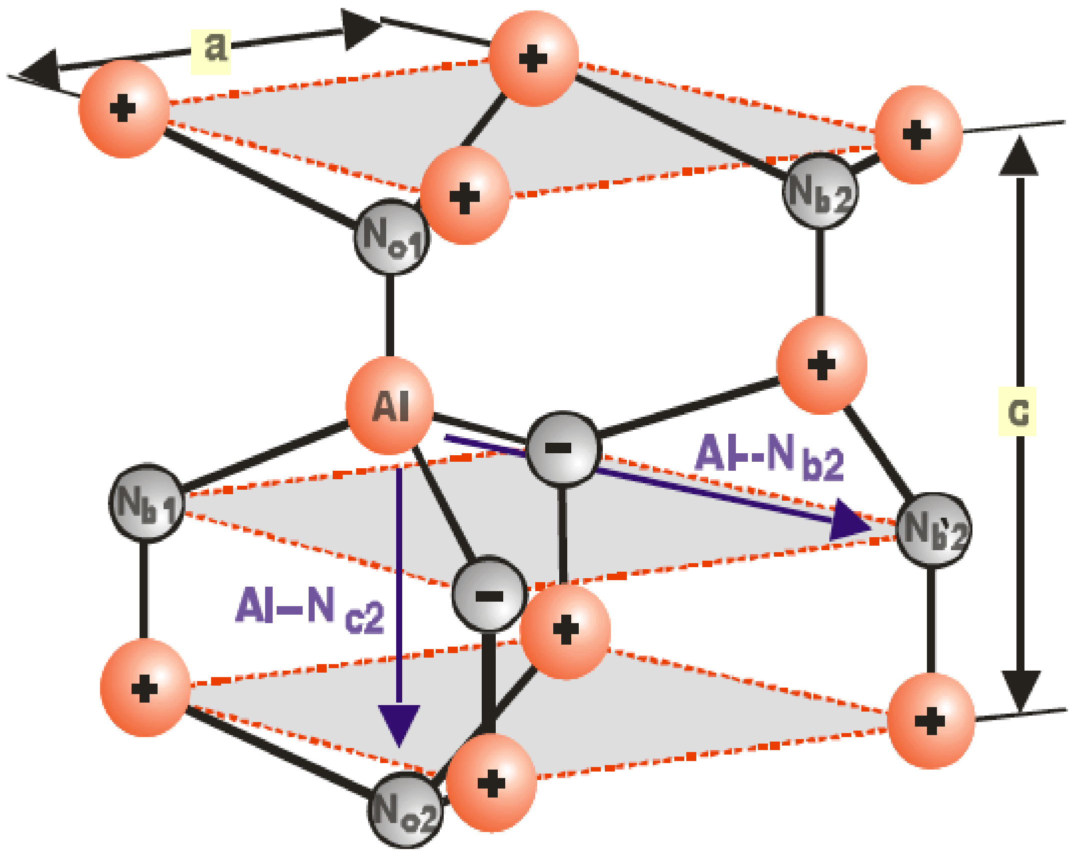
GaN: Polar material





O. Ambacher et al JAP 87, 334 (2000)
O. Ambacher et al. J.Appl. Phys. 85, 3222 (1999)

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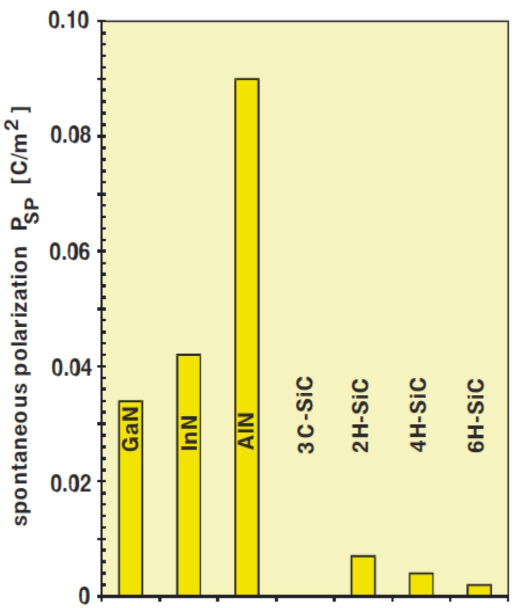
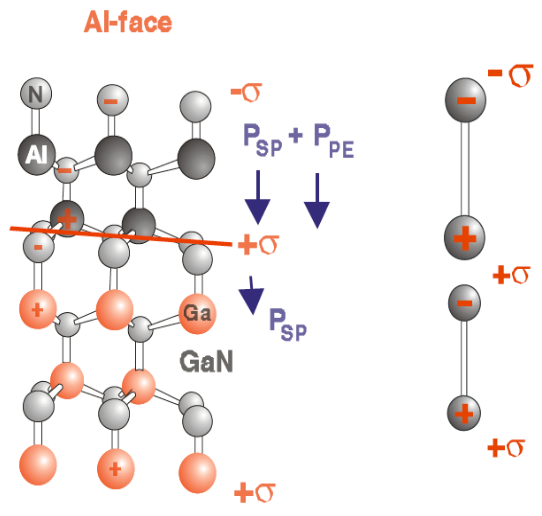
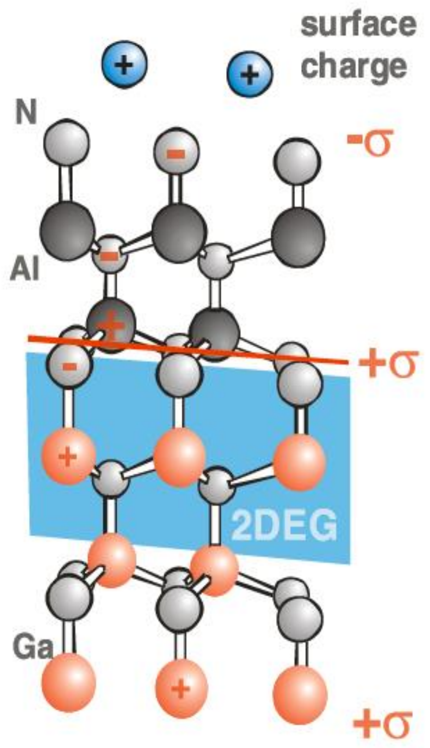
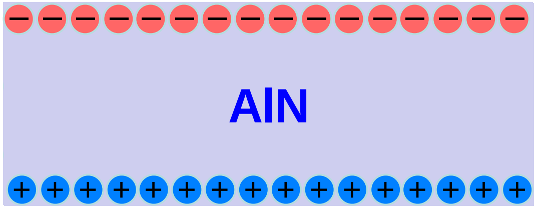
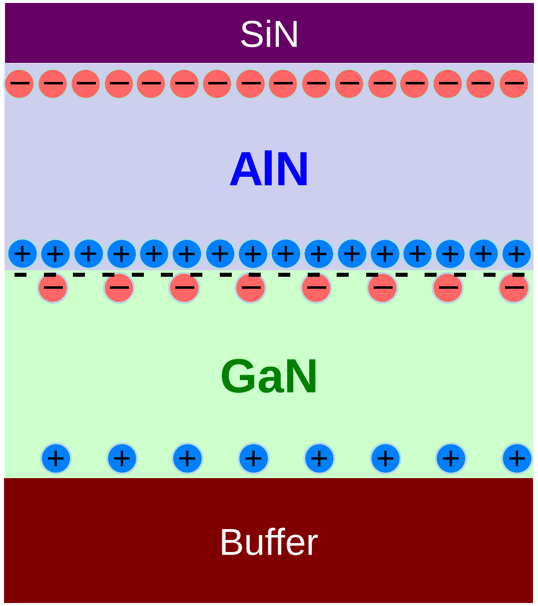
GaN: Polar material











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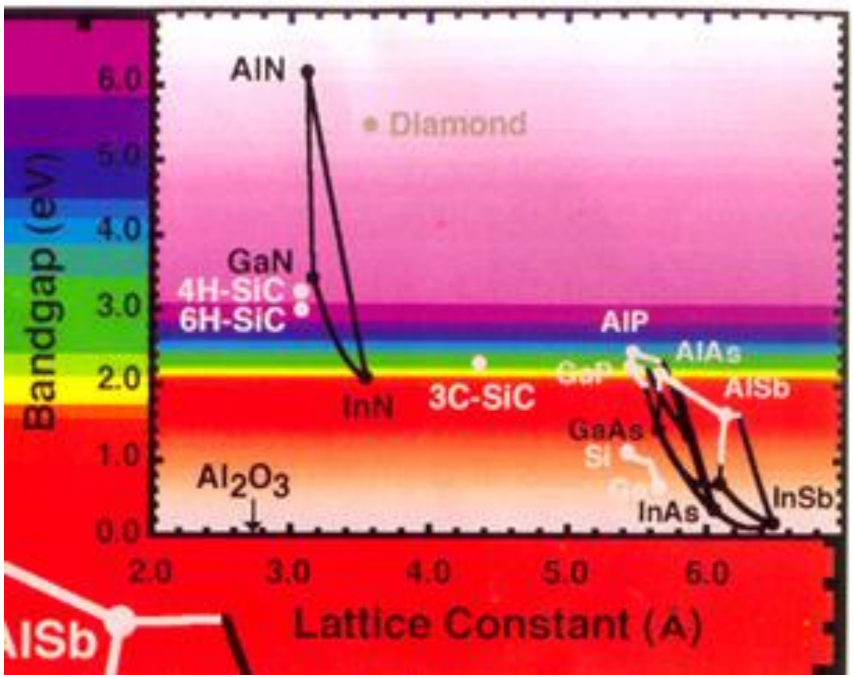
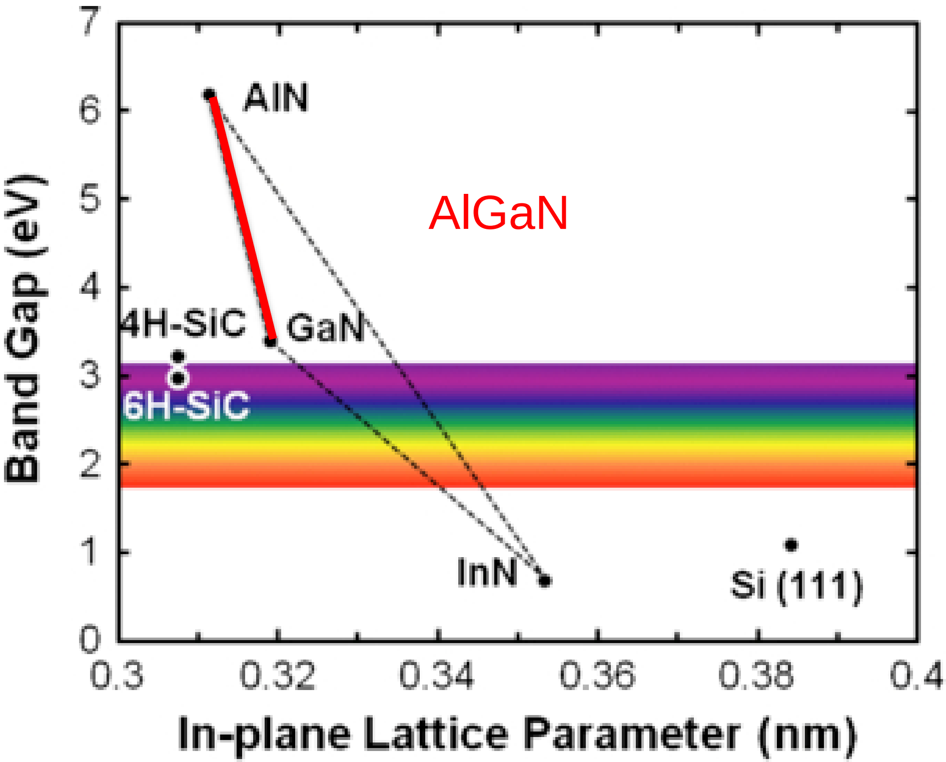
GaN: Polar material

GaN/AlGaN

OK the lattice constant





Typically 20-25% Al composition

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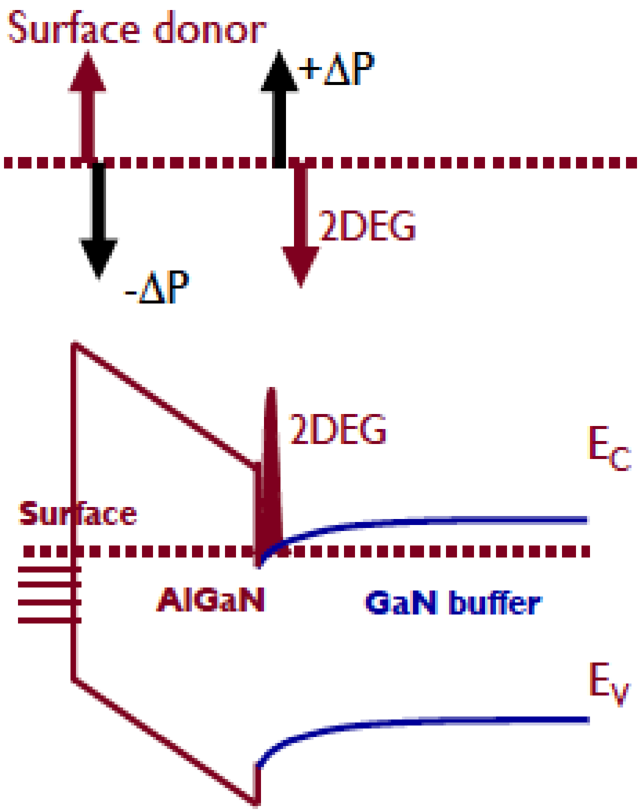
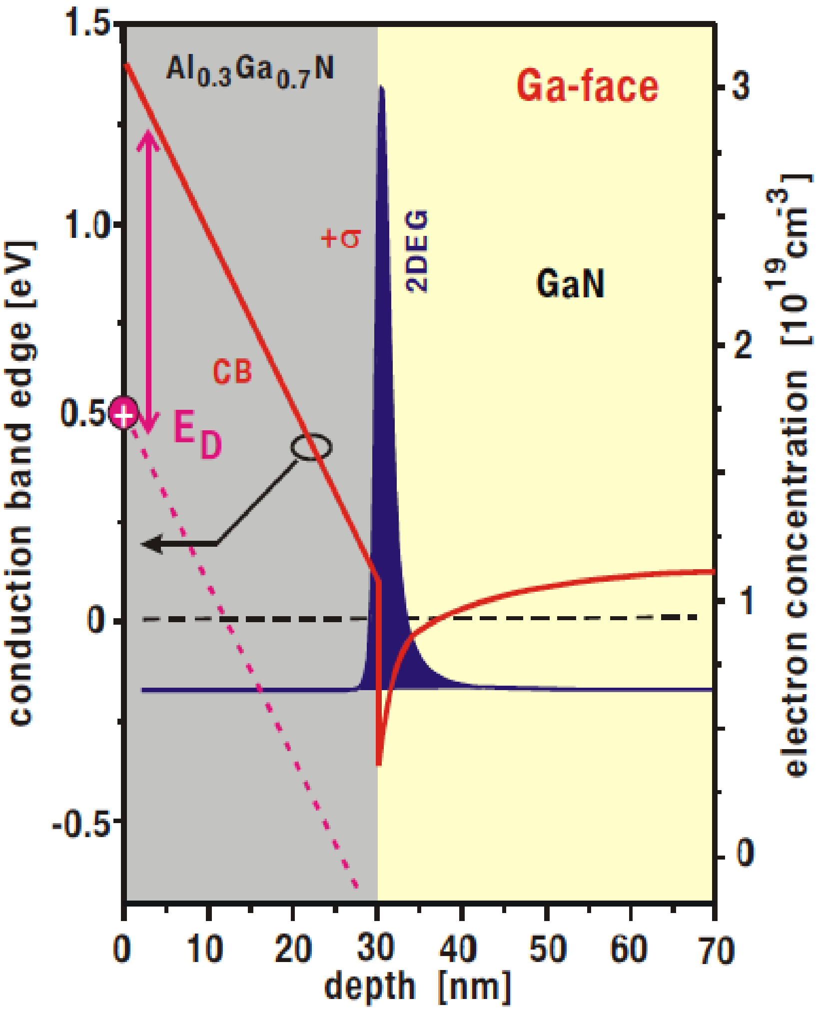
GaN HEMTs: 2DEG w/o doping!





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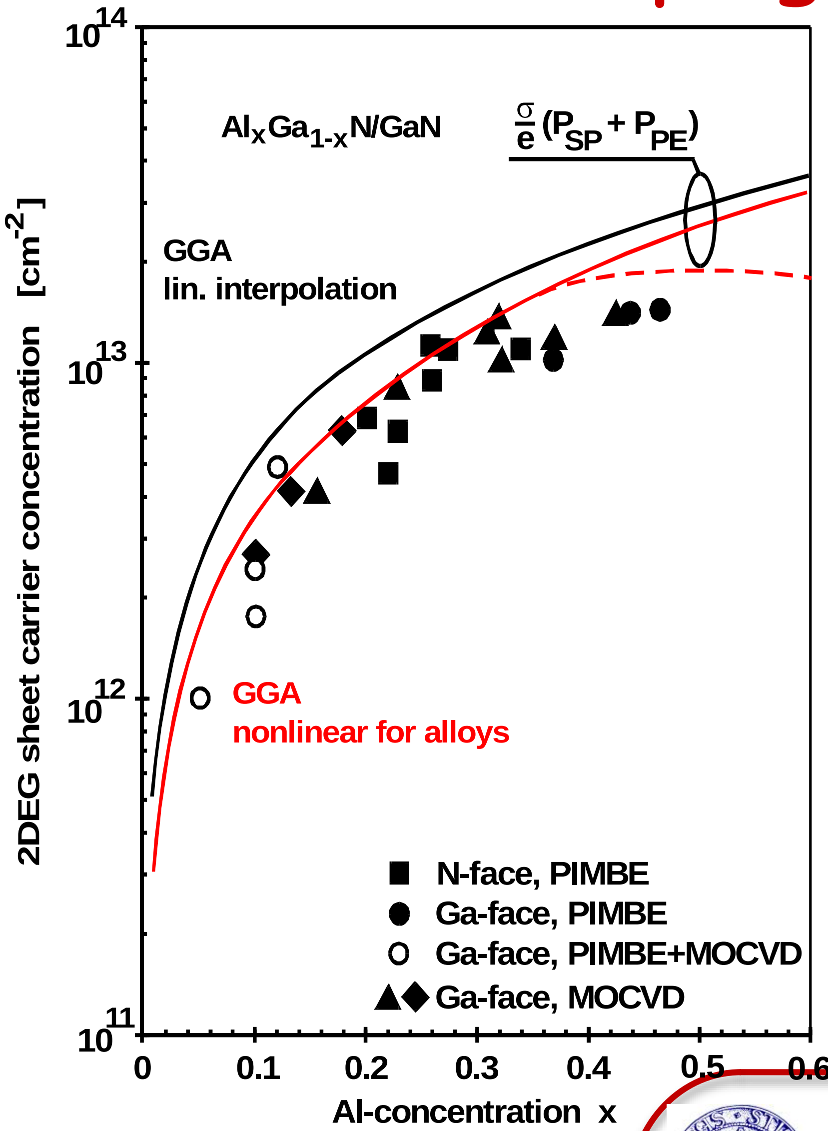
GaN HEMTs: 2DEG w/o doping!

O. Ambacher et al JAP 87, 334 (2000)
O. Ambacher et al. J.Appl. Phys. 85, 3222 (1999)

generalized gradient approximation (GGA)
plasma-induced molecular beam epitaxy (PIMBE)



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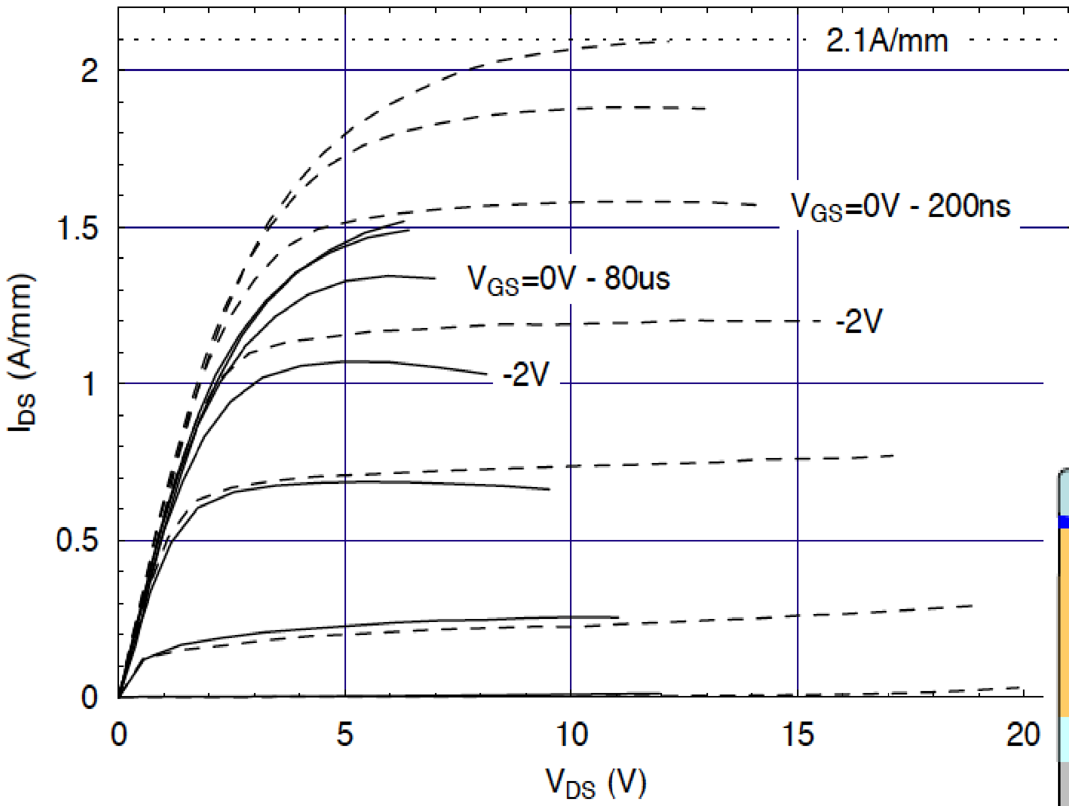
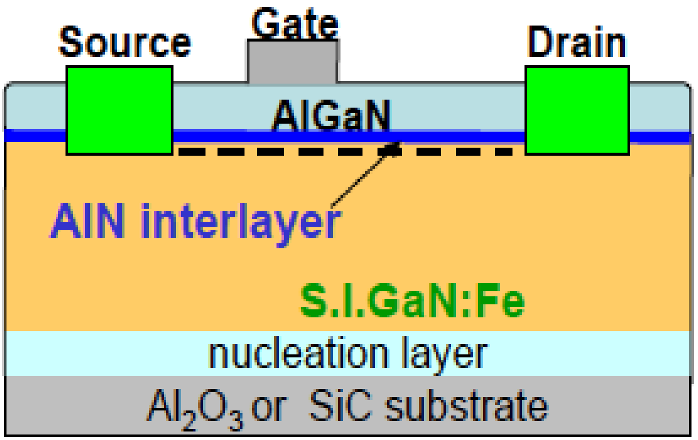
Basic HEMTs design I_{Dmax}= 2.1 A/mm





A. Chini, R. Coffie, G. Meneghesso, E. Zanoni, D. Buttari, S. Heikman, S. Keller, and U. K. Mishra
"A 2.1A/mm Current Density AlGaN/GaN HEMT"
IEE Electronics Letters, vol. 39, N. 7, April 2003, pp. 625-626

Figure of Merit in semiconductors

Table 1 Figures of merit of various semiconductors

	Si	GaAs	4H-SiC	GaN
JFM	1	11	410	790
KFM	1	0.45	5.1	1.8
BFM	1	28	290	910
BHFM	1	16	34	100

JFM : Johnson's figure of merit for high frequncy devices = $(EbVs/2\pi)^2$

KFM : Keyes's figure of merit considering thermal limitation= $\kappa(EbVs/4\pi\varepsilon)^{1/2}$

BFM : Baliga's figure of merit for power switching = $\varepsilon\mu Eg^3$

BHFM : Baliga's figure of merit for high frequency power switching = μEb^2

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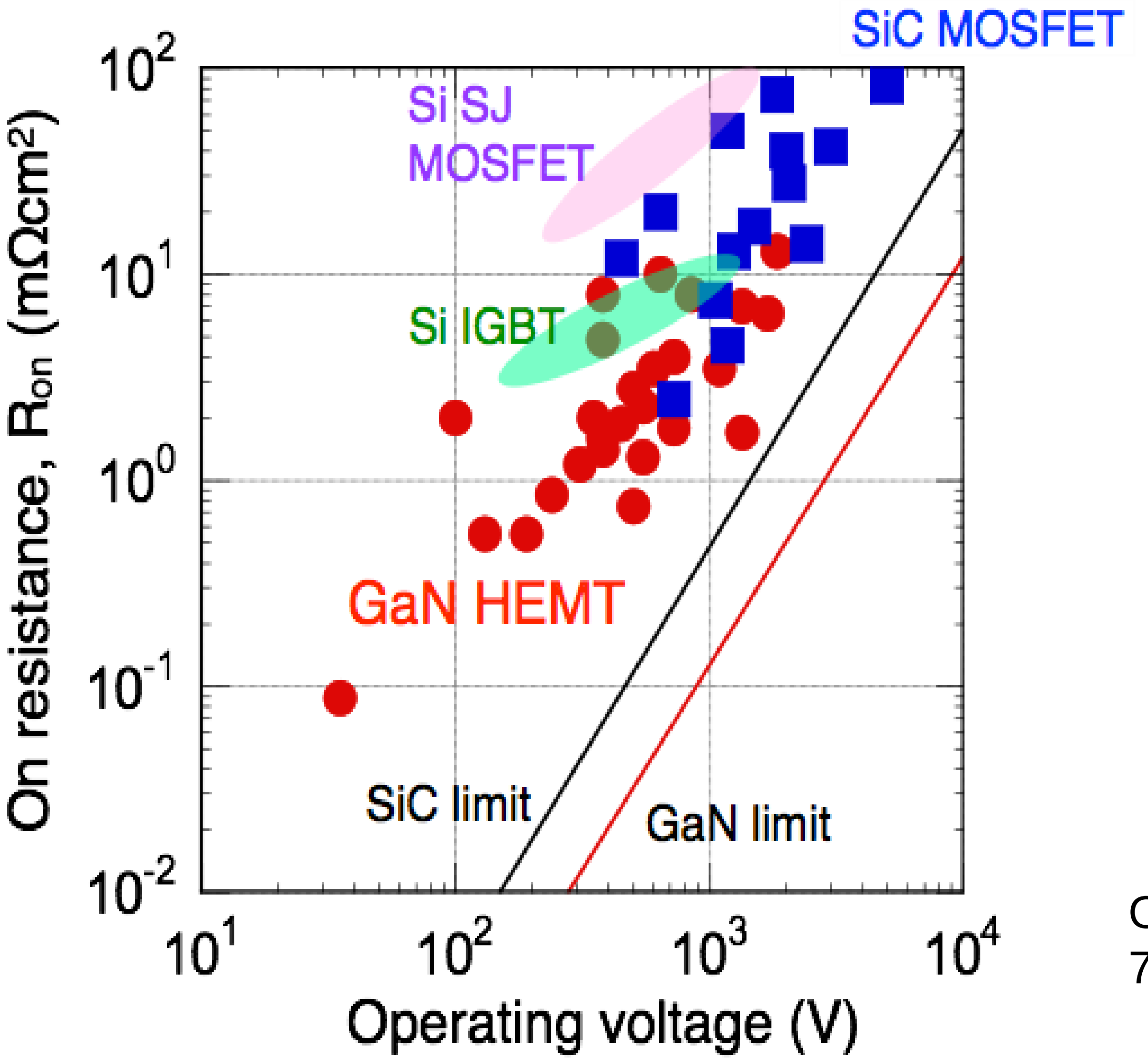
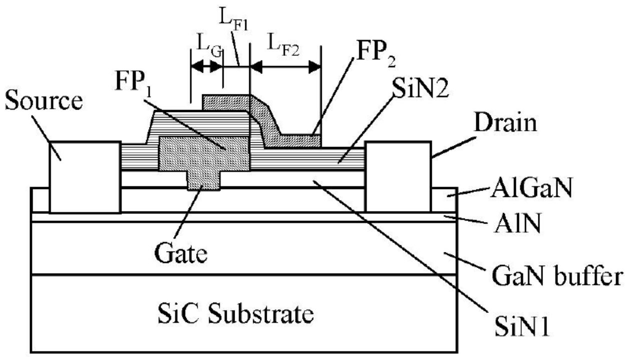
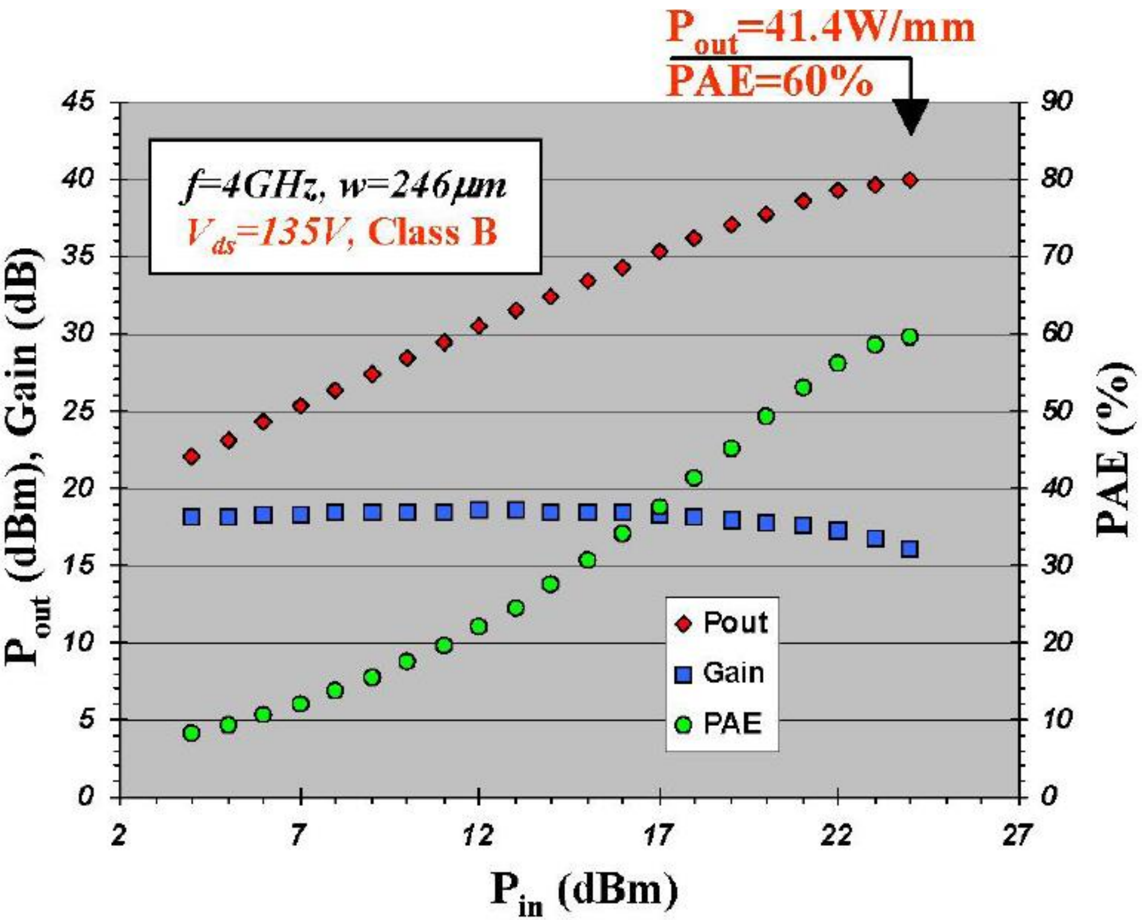
Comparison of R_{on} for Si, SiC and GaN



Okumura, JJAP 45, 7565(2006)

GaN-HEMTs capabilities: proven!





[3] Y.-F. Wu, M. Moore, A. Saxler, T. Wisleder and P. Parikh "**40-W/mm** Double Field-plated GaN HEMTs", Device Research Conference, . 151, 2006

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GaN-HEMTs capabilities: proven!

40 W Gallium-Nitride Microwave Doherty Power Amplifier

Kyoung-Joon Cho, Wan-Jong Kim, Jong-Heon Kim*, and Shawn P. Stapleton

School of Engineering Science, Simon Fraser University
*Department of Radio Science & Engineering, Kwangwoon University

the GaN Doherty amplifier yielded a power gain over 12 dB from 1.8 GHz to 2.5 GHz, and 65 % power added efficiency at 40 W peak power. A good linearity of - 55 dBc ACPR was

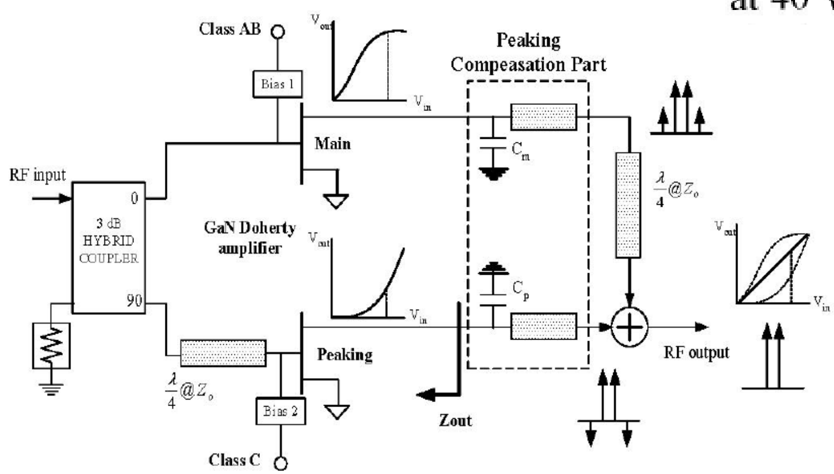


Fig. 1. Simplified diagram for linearity and efficiency of Doherty amplifier

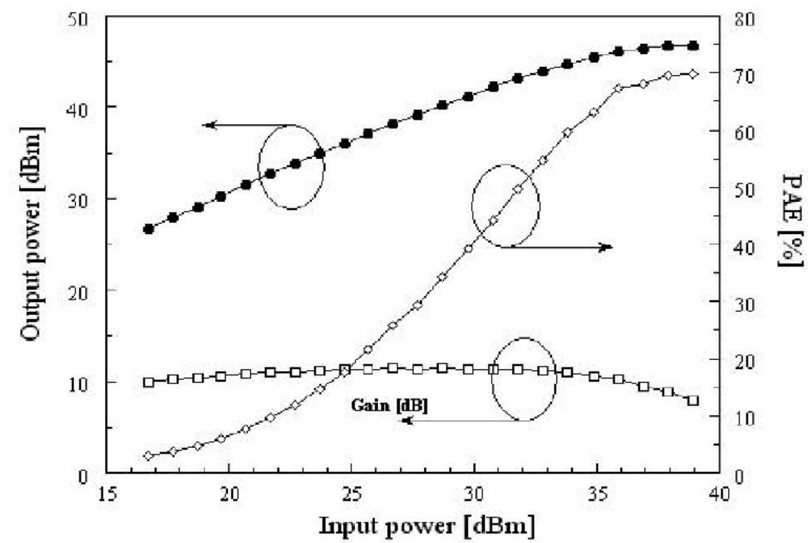


Fig. 6. Measured output power, gain and PAE of a GaN HEMT Doherty power amplifier

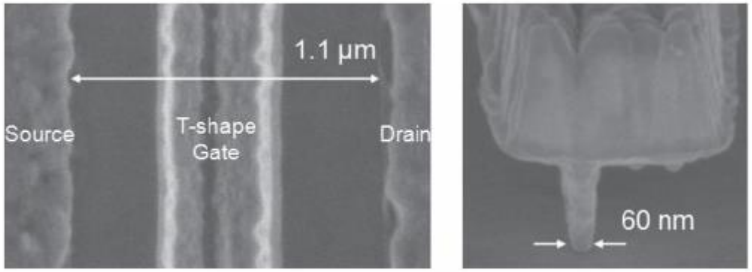
[5] IEEE MTT-S Dig., 2006, pp. 1895–1898.

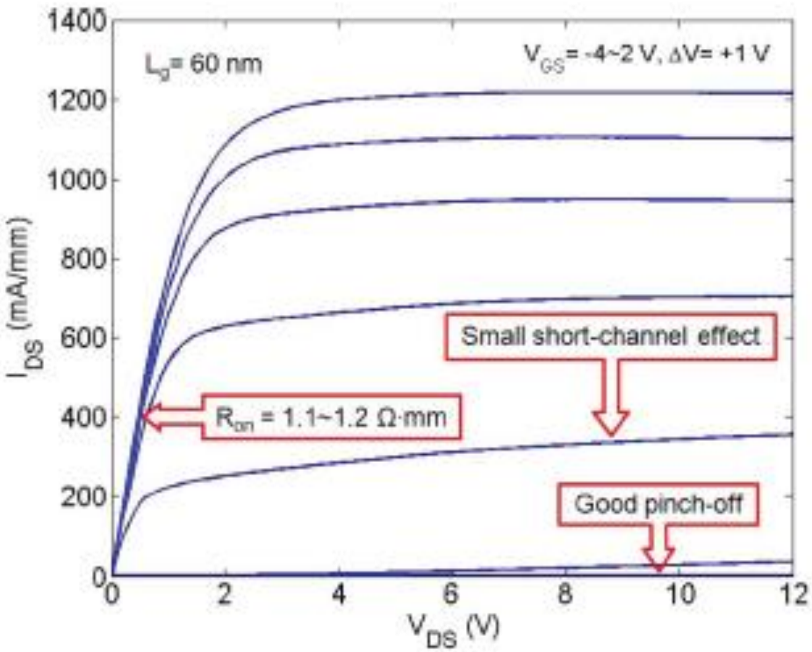
GaN-HEMTs capabilities: proven!

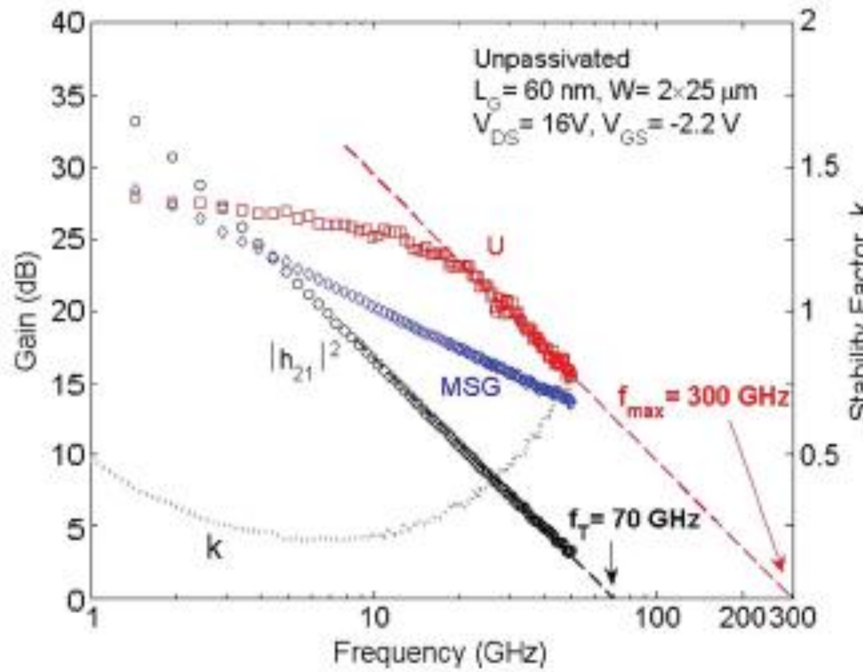
IEEE ELECTRON DEVICE LETTERS, VOL. 31, NO. 3, MARCH 2010 195

AlGaN/GaN HEMT With 300-GHz f_{max}

Jinwook W. Chung, William E. Hoke, Eduardo M. Chumbes, *Member, IEEE*, and Tomás Palacios, *Member, IEEE*







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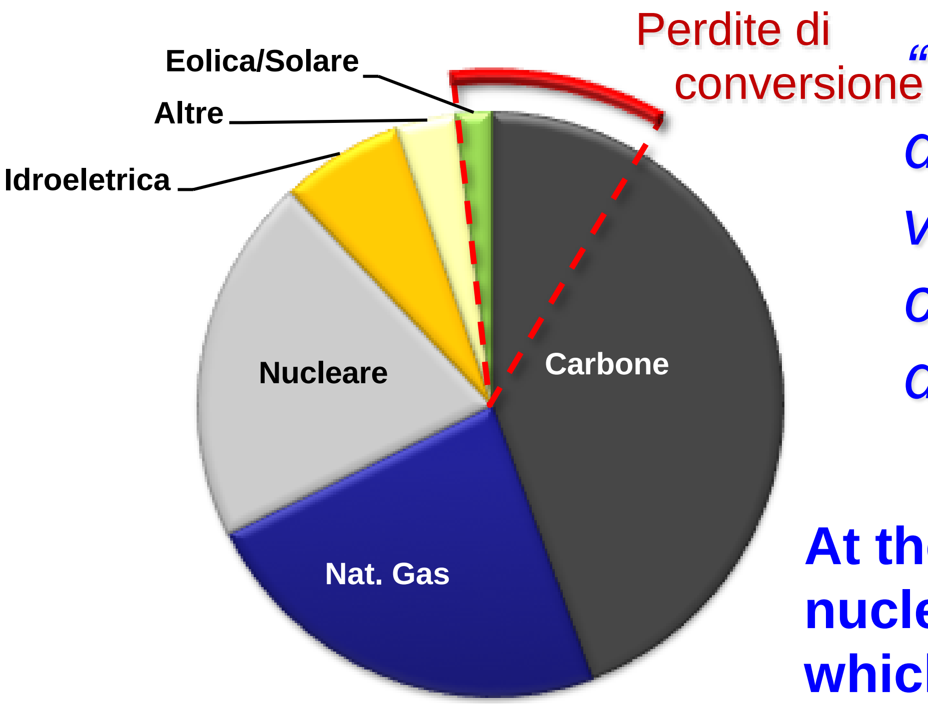
Efficienza Energetica



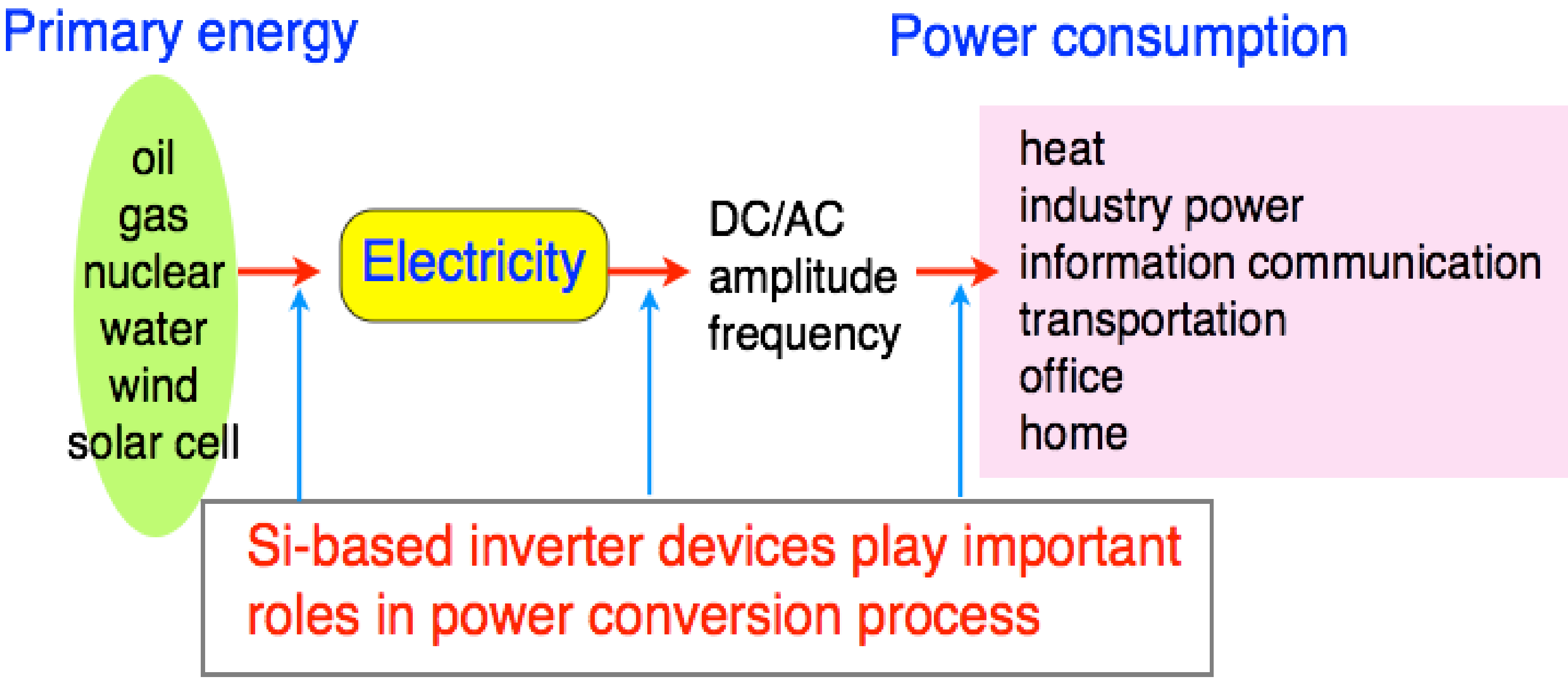
"Oggigiorno, oltre il 10% dell'energia elettrica globale viene completamente persa a causa dell'inefficienza dei sistemi di conversione."

Chart: EIA U.S. Electric Power Generation

At the moment there are more than 400 nuclear power plants all over the world, which produce about 17% of the world's electricity. **http://www.icjt.org/an/tech/jesvet/jesvet.htm**

Perdere il 10 % di energia elettrica e' equivalente a sperperare l'energia prodotta da più di 200 centrali nucleari.

POWER APPLICATIONS



Efficiency of present inverter : 80~ 90%

10~20% loss still remains !!

mainly due to the limitation of material properties of Si

Ultra-low loss inverter is a key device for next-generation energy saving society

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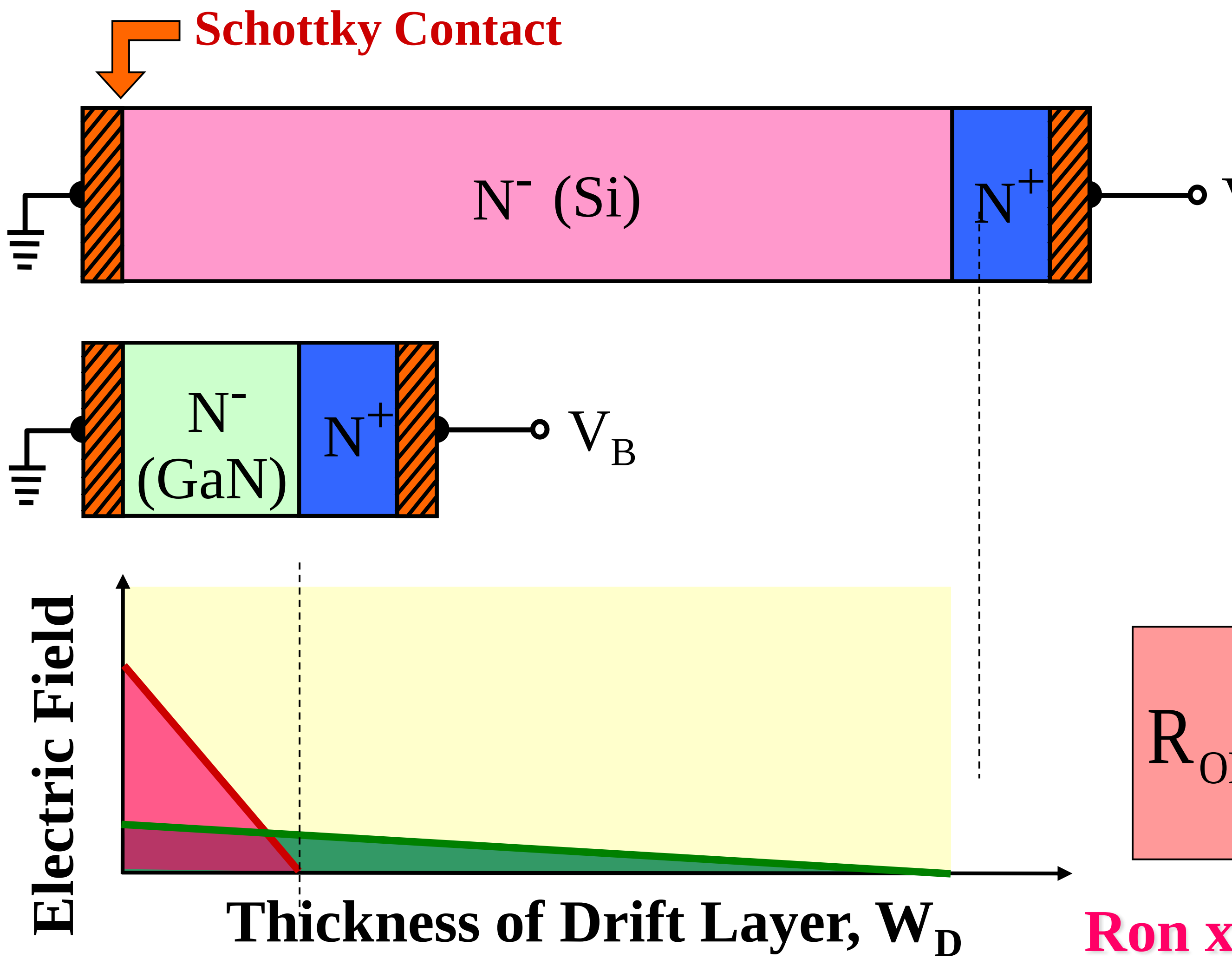
Breakdown Voltage vs On-Resistance



Why nitride?

$$V_B = E_C \times W_D$$

$$R_{ON} = W_D / q \mu_n N_D$$

$$E_{max} = \left(q \times N_D \times W_D\right) / \varepsilon_{Si}$$

$$R_{ON} = \frac{V_B^{\,2}}{\varepsilon_{Si} \mu_n E_C^{\,3}}$$

Ron x10^3 lower for GaN

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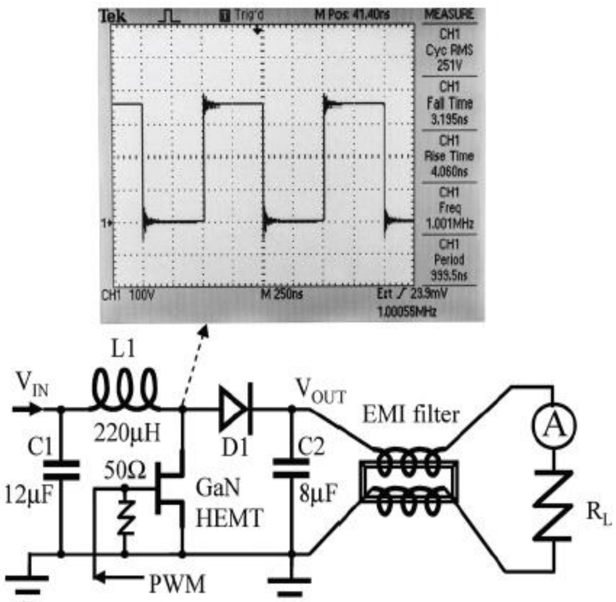
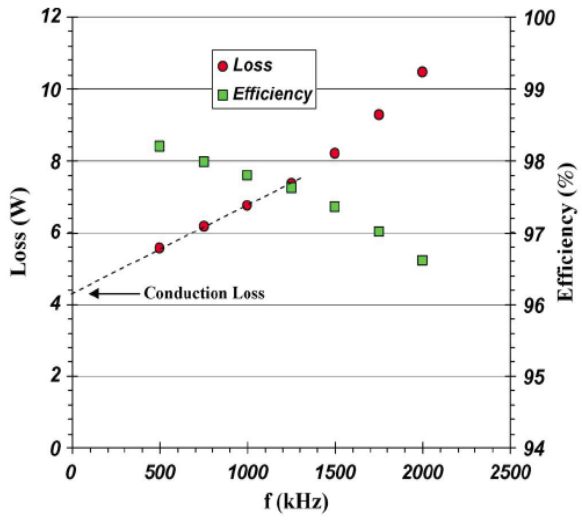
IEEE ELECTRON DEVICE LETTERS, VOL. 29, NO. 8, AUGUST 2008

A 97.8% Efficient GaN HEMT Boost Converter With 300-W Output Power at 1 MHz

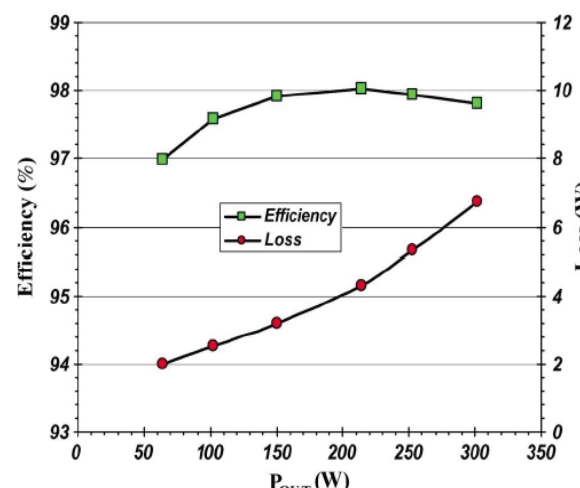
Yifeng Wu, Matt Jacob-Mitos, Marcia L. Moore, and Sten Heikman



@ 300-W output power

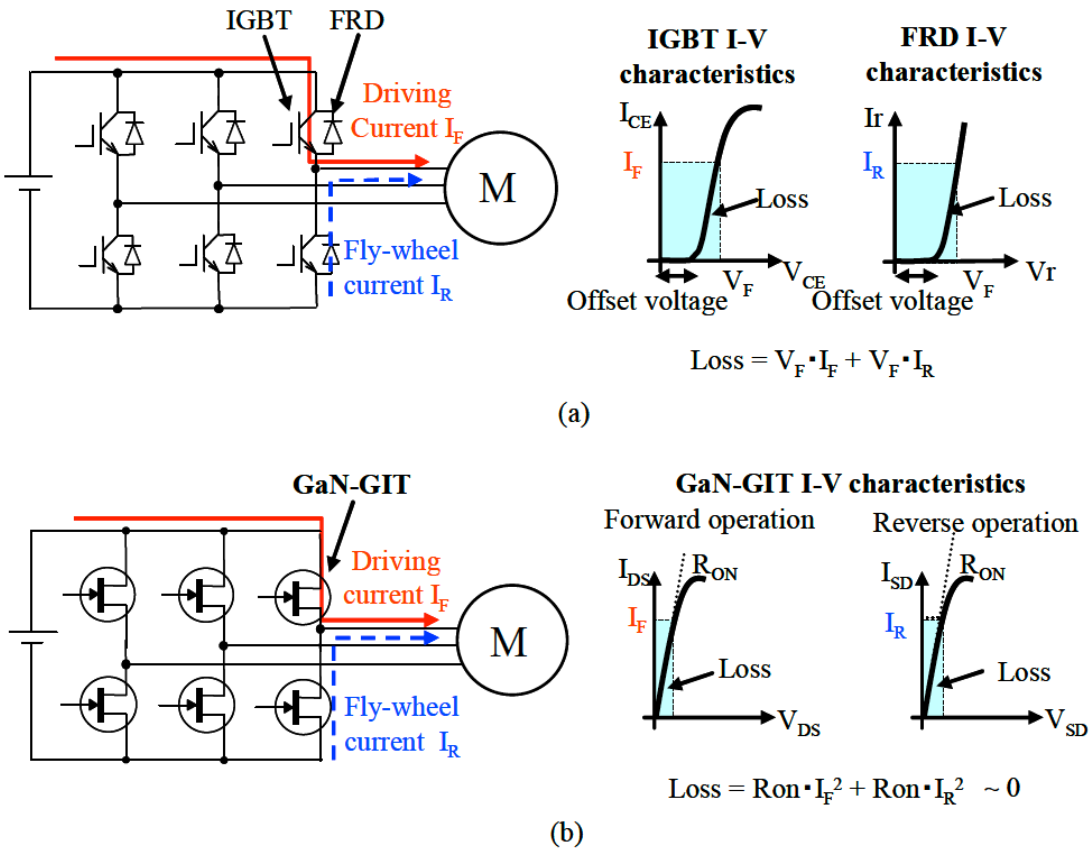


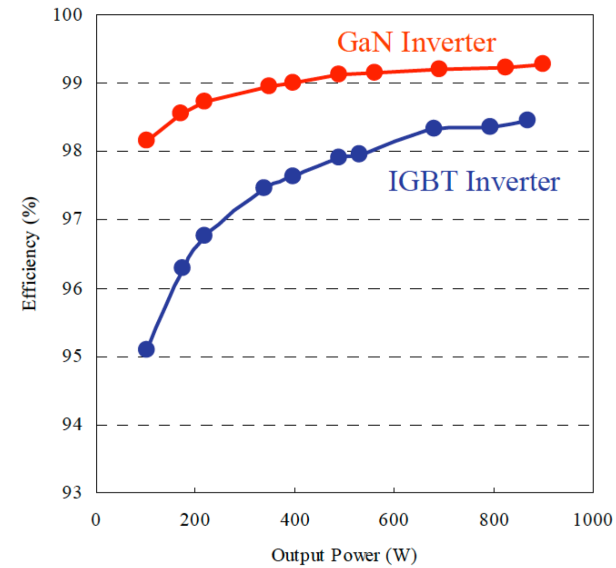
@ 1 MHz



“The peak efficiency of 98% at 214 W is the highest for a hard-switched converter at 1 MHz to date”

99.3% Efficiency of three-phase inverter for motor drive using GaN-based Gate Injection

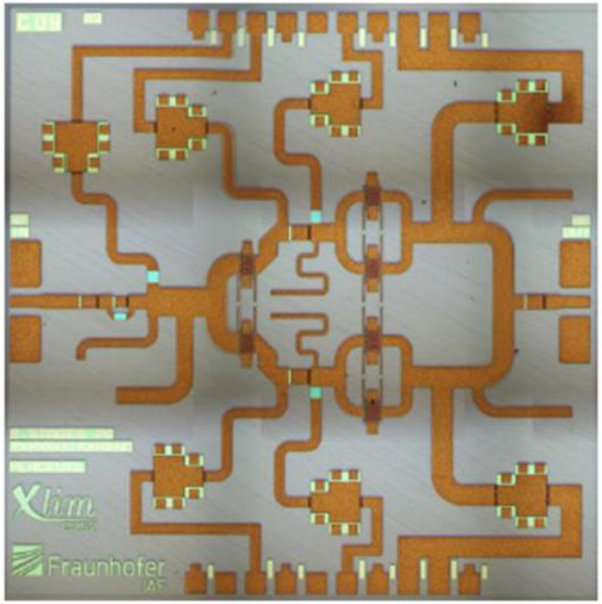




Panasonic ideas for life

Morita, T.; Tamura, S.; Anda, Y.; Ishida, M.; Uemoto, Y.; Ueda, T.; Tanaka, T.; Ueda, D.
99.3% Efficiency of three-phase inverter for motor drive using GaN-based Gate Injection
TransistorsApplied Power Electronics Conference and Exposition (APEC),
2011 Twenty-Sixth Annual IEEE 2011 , Page(s): 481 – 484

Status of the GaN MMIC Technology in Europe



GaN 50 (0,5 µm) 0.5..6 GHz

- Products at UMS: hybrid process

GaN 25 (lg= 0,25 µm) to 20 GHz

- Products and further development

GaN 10 (lg=0,10 µm) 20 GHz-94 GHz

- Development at IAF

- Power electronics at various players

Fraunhofer
IAF

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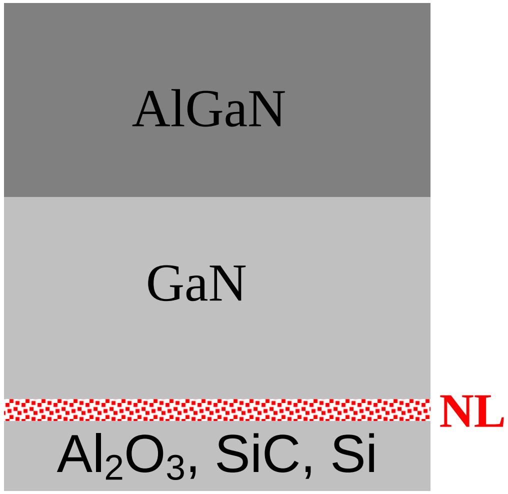
No GaN substrates available!!

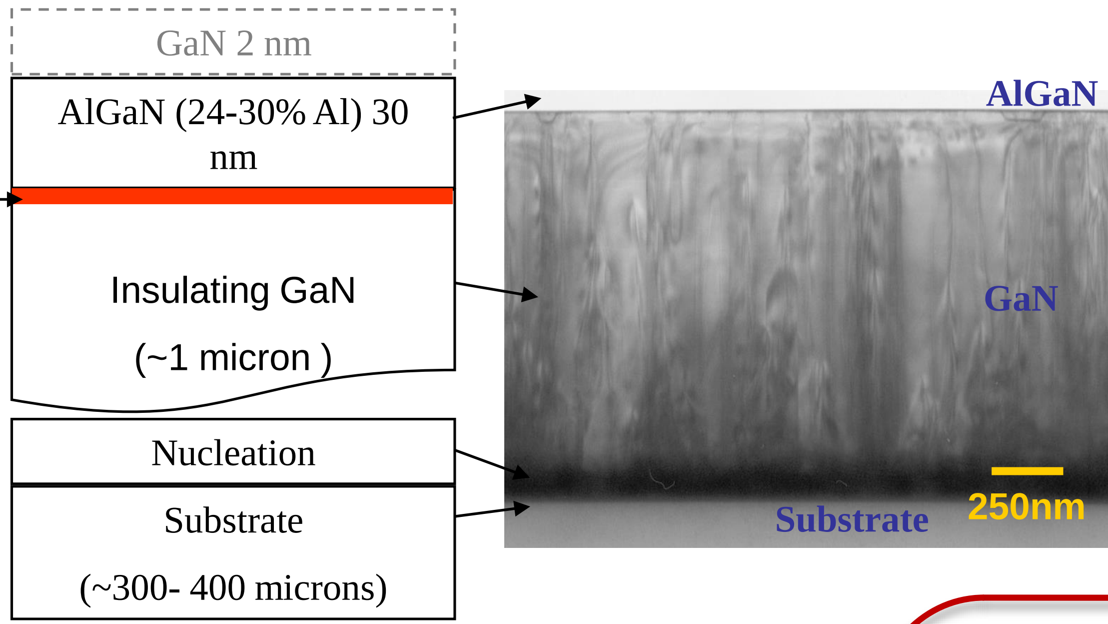


- no native substrate of reasonable size
- heteroepitaxy of (0001) GaN typically on sapphire, silicon carbide or silicon

Channel

C Conc. $1 \times 10^{13}\ cm^{-2}$

Resistivity 400-700 ohms / sq



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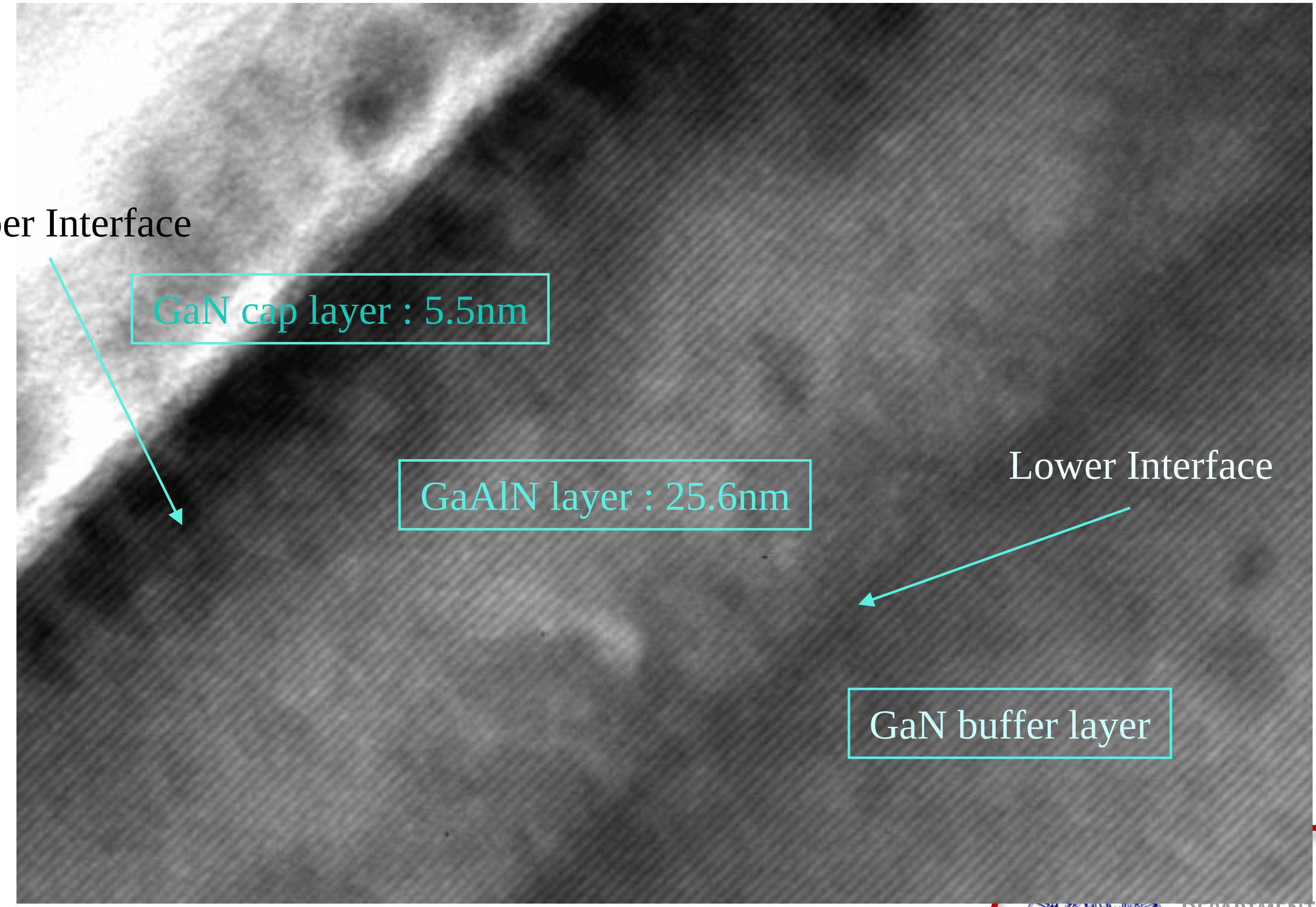
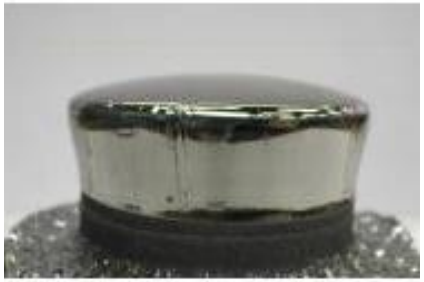
GaN/AlGaN Epitaxy good but not enough!

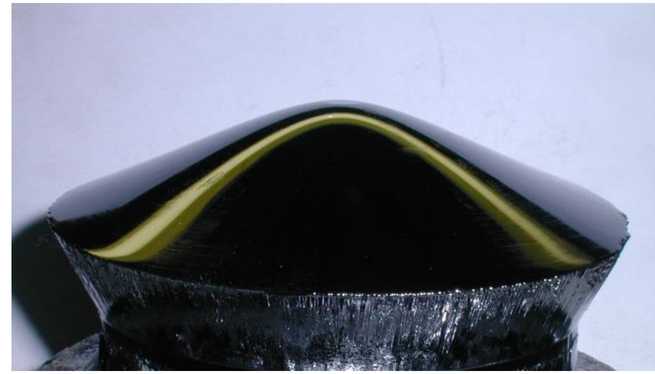
Good structural quality heterostructure confirmed at the atomic scale

Sharp and perfectly delineated heterointerfaces



SiC Substrates (2”-4”)





- Very expensive (2-5-kE – 4”, 6”)
- Good thermal conductivity
- Good mismatch

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Sapphire Substrates (2”-6”)

- Cheap (0,5kE – 2” 4”)
- poor thermal conductivity
- Good/poor mismatch

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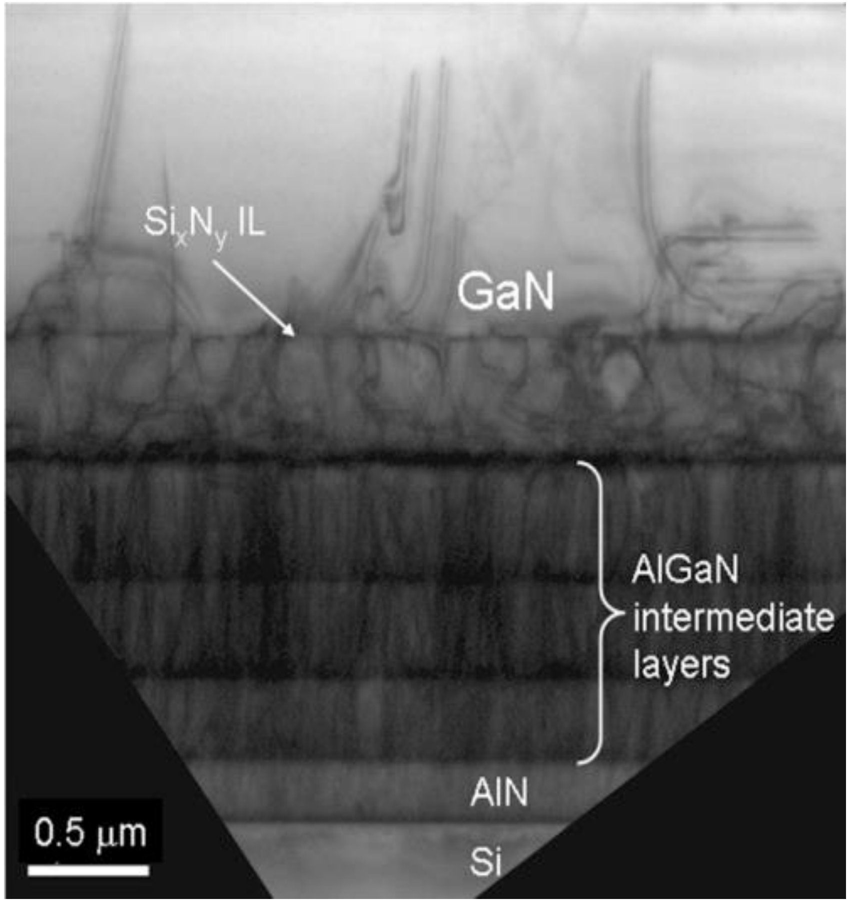
GaN on Si (6" - 8")



The use of Si_xN_y interlayers in GaN grown on sapphire substrates is very successful and a dislocation density reduction by two or three orders of magnitude has been reported. However, it is not straightforward to implement Si_xN_y interlayers in GaN grown on Si due to the large thermal mismatch between GaN and Si.

-Cheap and large diameter
- good/poor thermal conductivity
- bad mismatch

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GaN growth …. always a difficult task!

◆Substrates for GaN Epitaxy

	GaN / Sapphire	GaN / n SiC	GaN / S.I. SiC	GaN / Bulk-GaN	GaN / Silicon	GaN / 3C SiC / Silicon	GaN / Glass
Epiwafer providers	TDI Hitachi Cable NTT Kyma OptoGaN AZZURRO	CREE TDI Hitachi Cable NTT	CREE Hitachi Cable NTT Toyoda Gosei AZZURRO IQE,Kopin Picogiga	Sumitomo SEI Kyma LumiLOG Samsung-corning Hitachi Cable AZZURRO	Nitronex AZZURRO Picogiga IMEC IQE NTT DOWA	Toshiba Ceramic (TOCERA)	BlueGlass
Device maker	Lumileds Osram Nichia Toyoda Gosei Velox	CREE Osram	CREE Fujistu RFMD NXP Freescale NEC, TriQuint	Sony Nichia NEC Toyota	**Nitronex** **OKI** **TriQUINT** **MicroGaN, ST,** **IR, Sanken,Fuji** **GaN system**	R&D	R&D
Application	Blue/white LED, **power devices**	Blue/white LED	RF devices	Blue/violet laser diode, **power devices**	**Power devices** ,RF,LED	RF devices **Power devices**	Blue/white LED

Ref.:Website of Yole

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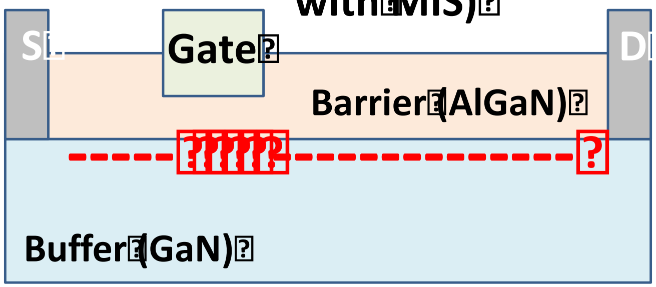
Normally OFF

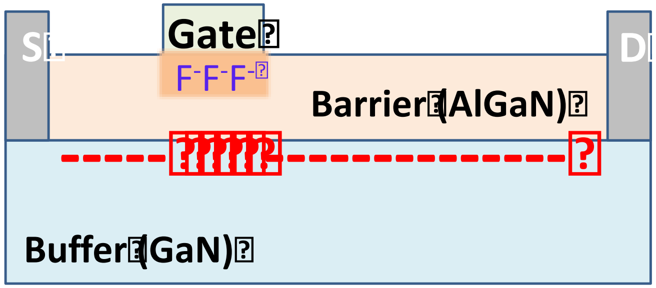
Recess on the Schottky Gate (also with MIS)



- Leakage, trapping, ...

Oka et al., IEEE EDL 29, 668 (2008)

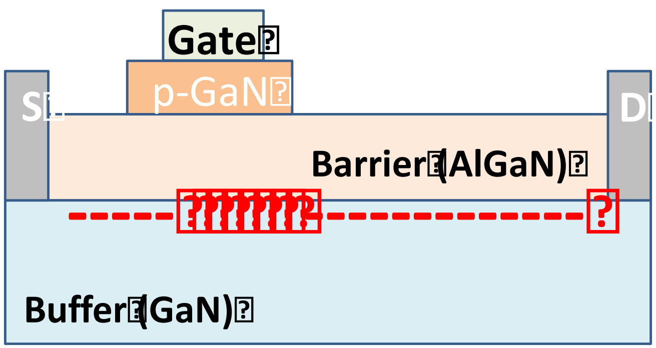
Fluorine implantation



- Vth instabilities, leakage, ...

Feng et al., IEEE EDL 31, 2386 (2010)

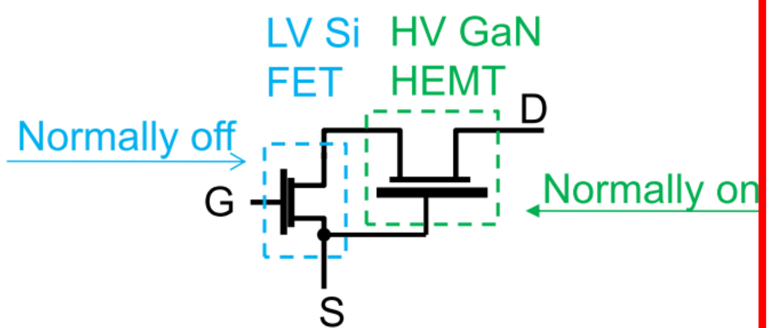
p-type Gate



- Need for p-type, Vth~1.5 V, ...

Uemoto et al., IEEE TED 54, 3393 (2007)

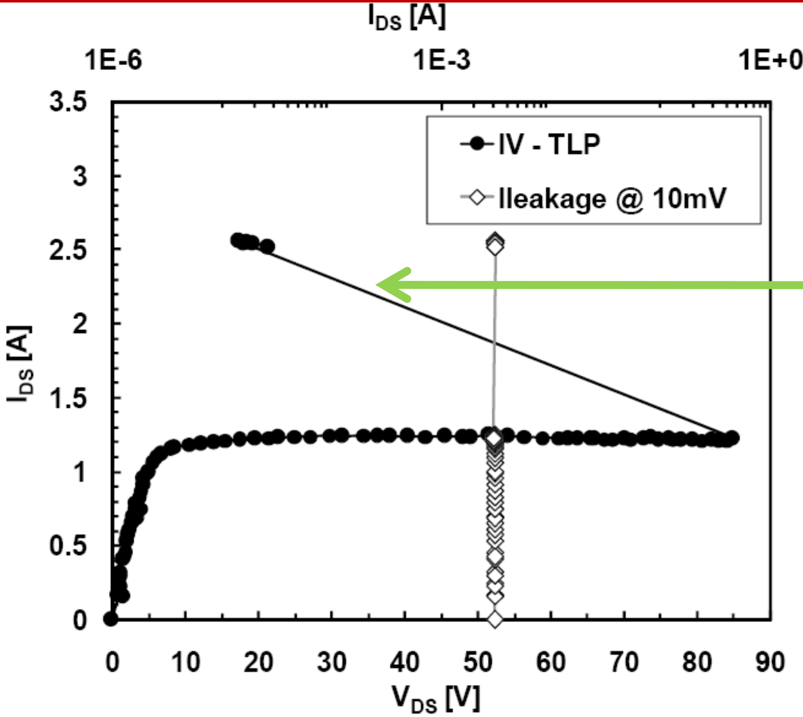
Cascode config ration



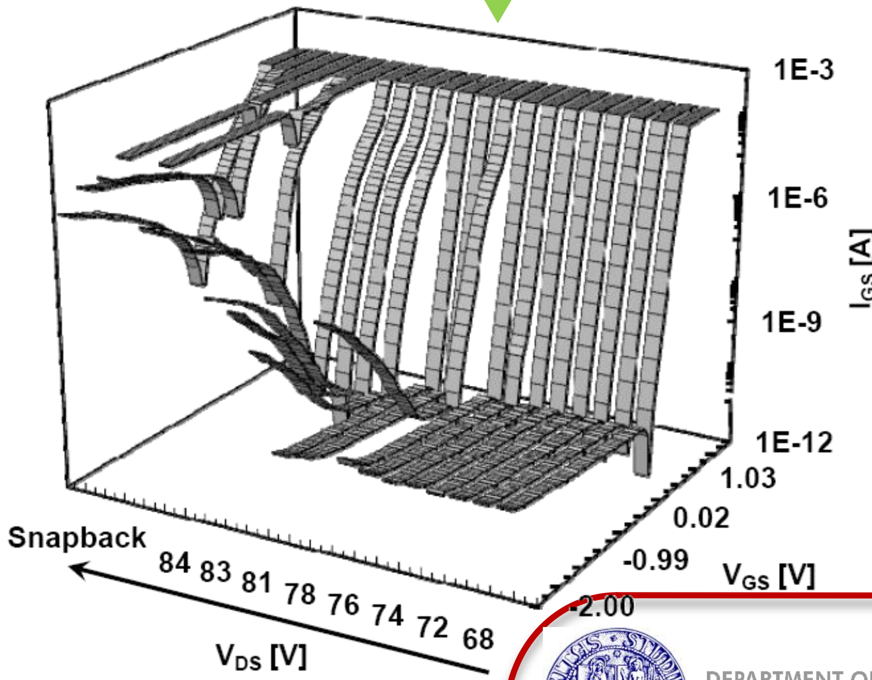
- Combined Si/GaN, MIS gate, ...

Eg. Transphorm, ...

Breakdown measurements



- The breakdown voltage of AlGaN/GaN HEMTs can be evaluated by pulsed ID-VD measurements
- When BDV is reached → Snapback, due to degradation, hot spots
- The junction can degrade even before BDV



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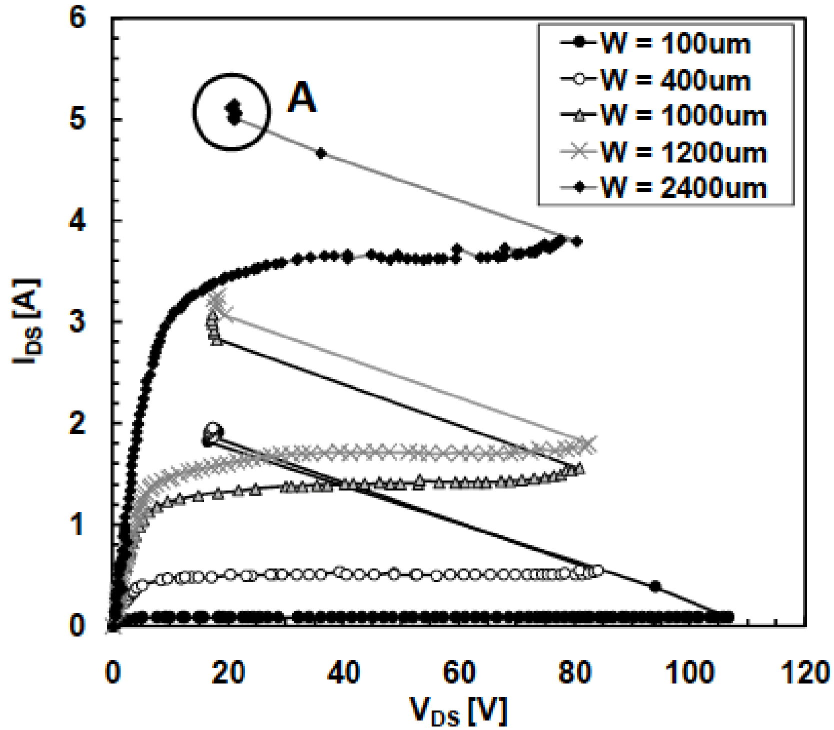
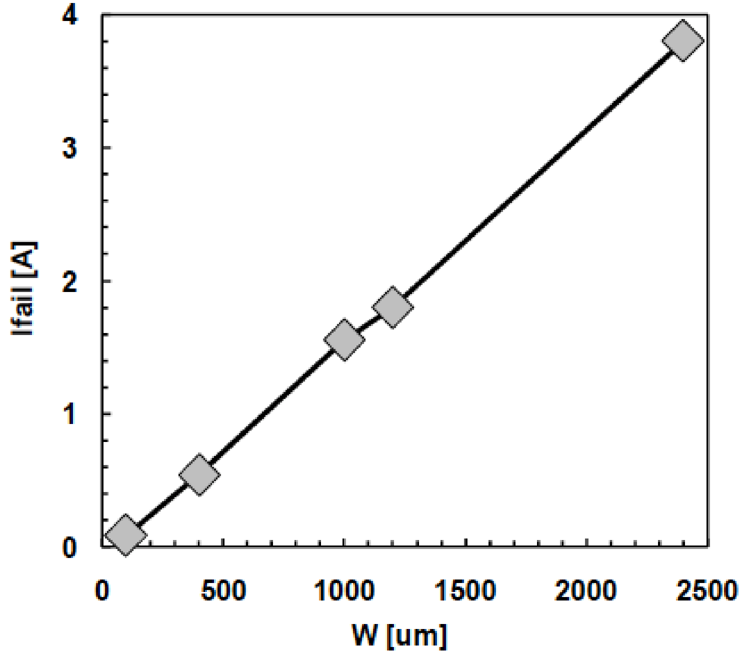
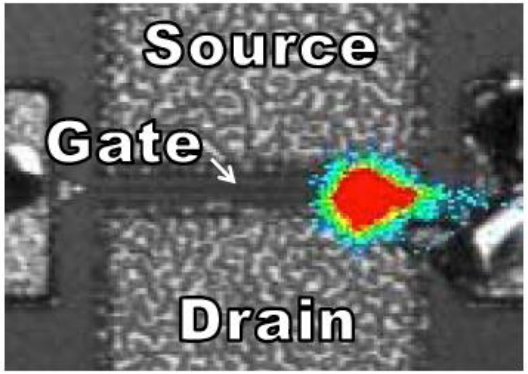
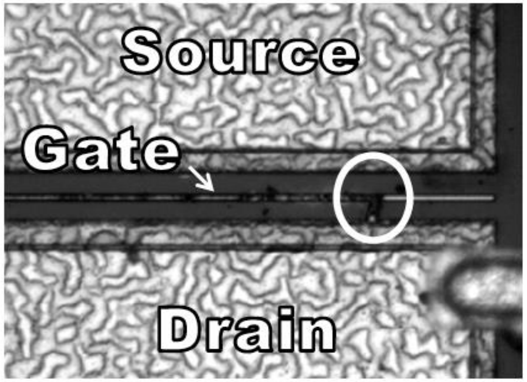
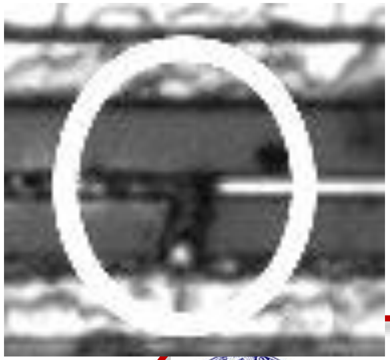
Pulsed ID-VD breakdown measurements











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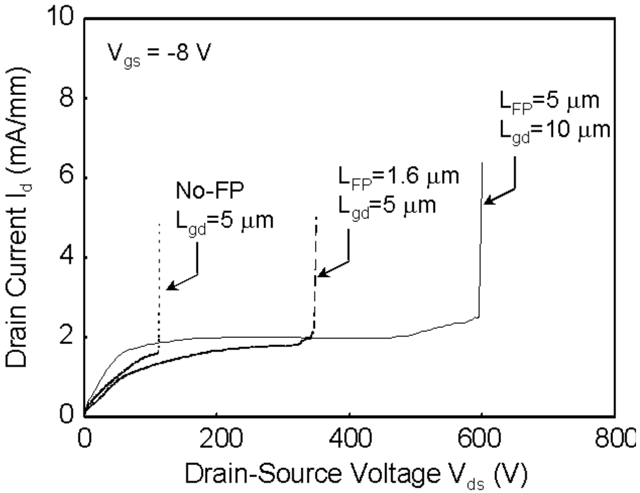
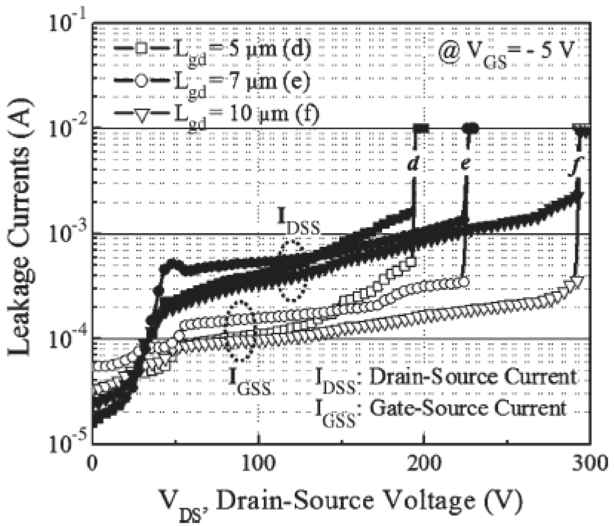
Typical Breakdown in GaN HEMTs

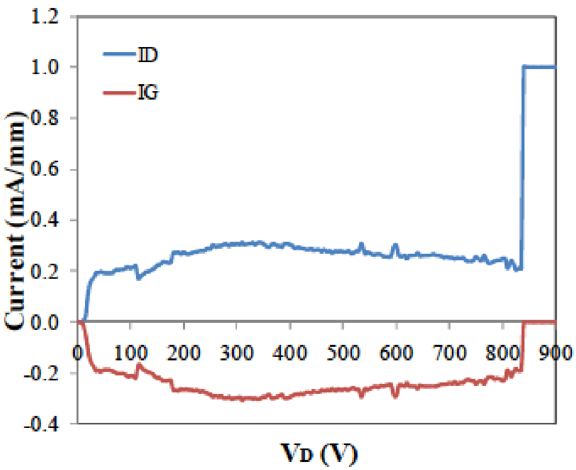
Breakdown measured in voltage controlled mode is very abrupt. (no sustainable breakdown present in GaN HEMTs)



S. Wataru et al. IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 50, NO. 12, DECEMBER 2003



Choi et al. IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 53, NO. 12, DECEMBER 2006



Hwang, ISPSD 2012 3-7 June 2012 - Bruges, Belgium

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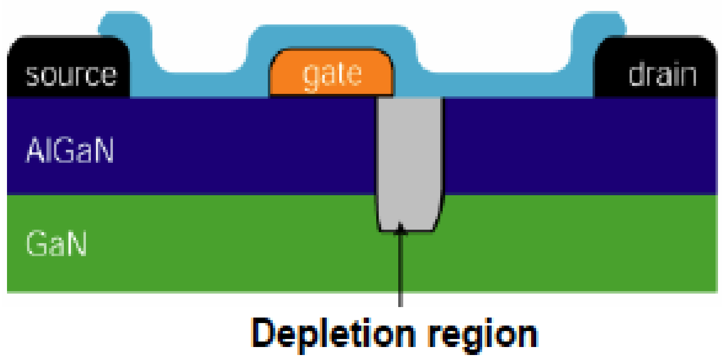
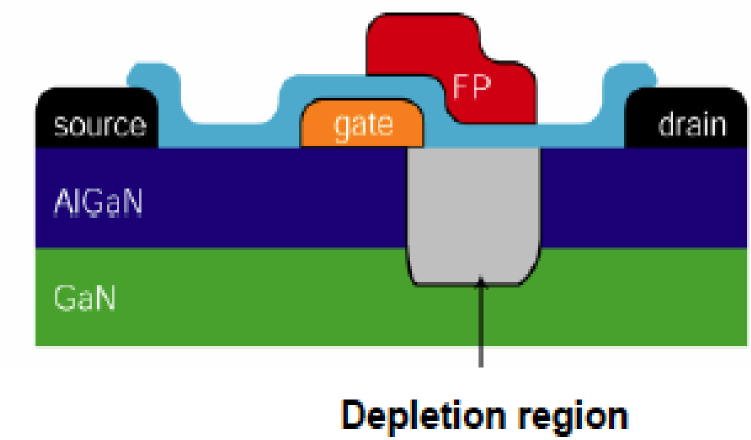
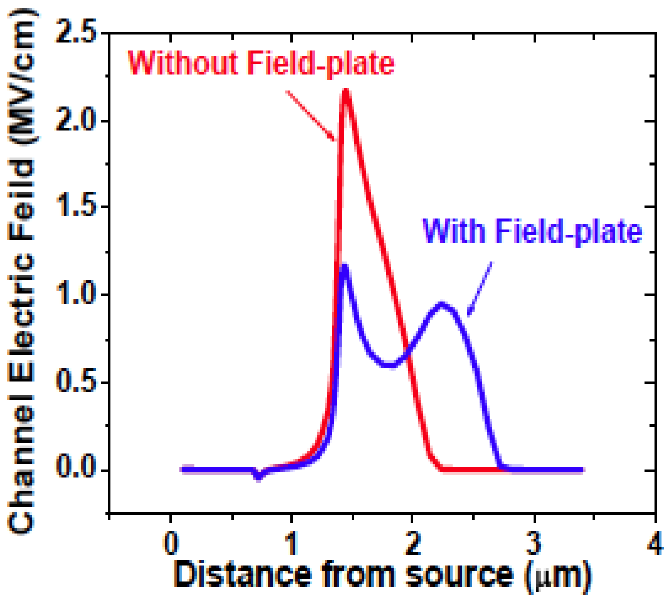
Field-plate Optimization







Field-plate reduces electric field

- Increase breakdown voltage
- lower electron injection into traps ➡ less dispersion

courtesy: Umesh Mishra, UCSB

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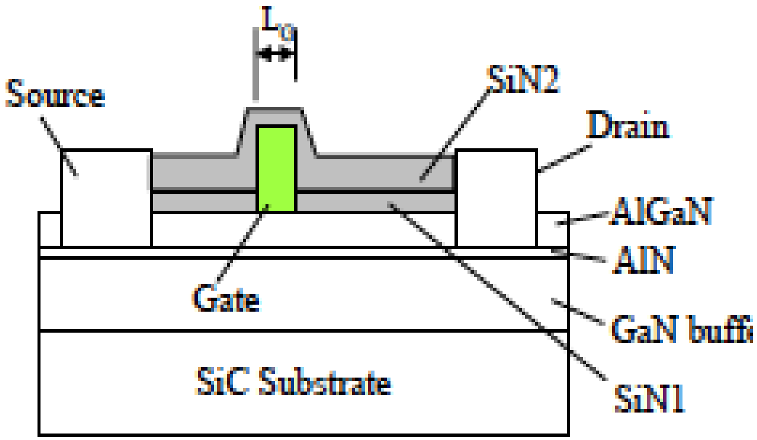
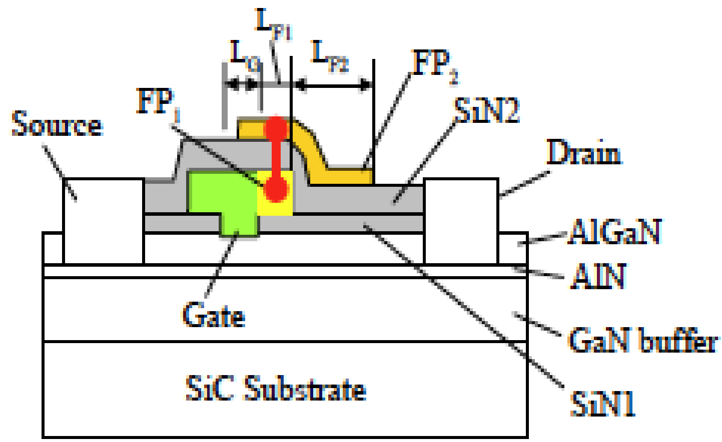
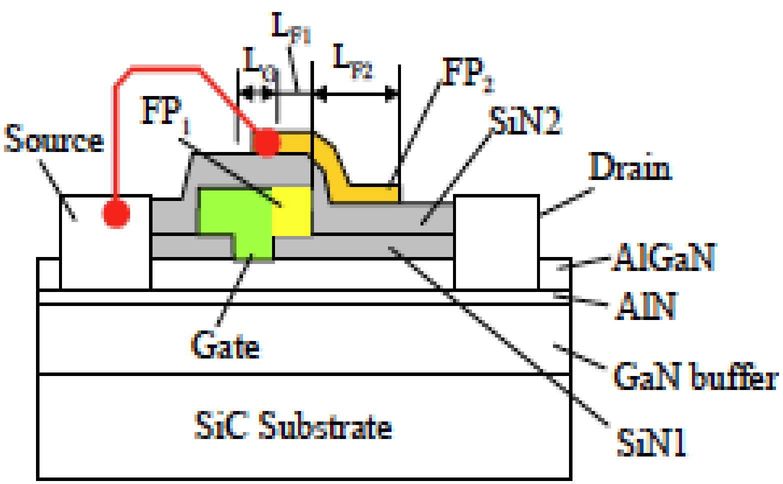
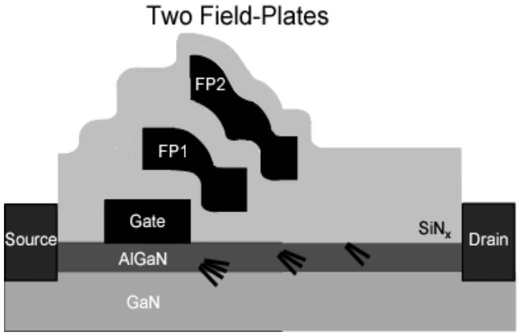
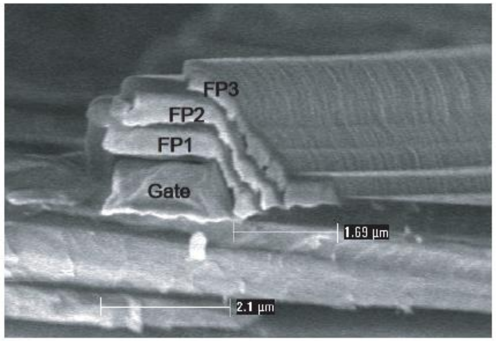
Schematics of GaN HEMTs with Various FP Configurations











Very high blocking voltage with compact size

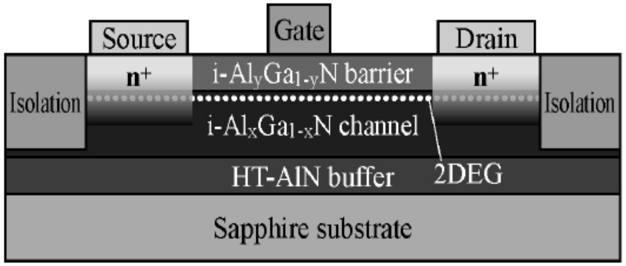
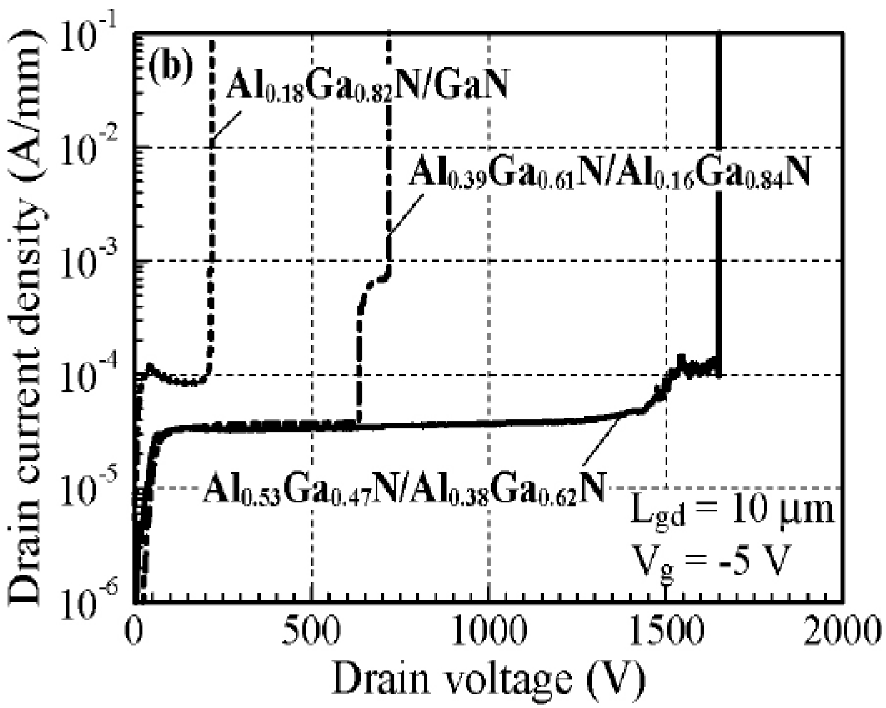
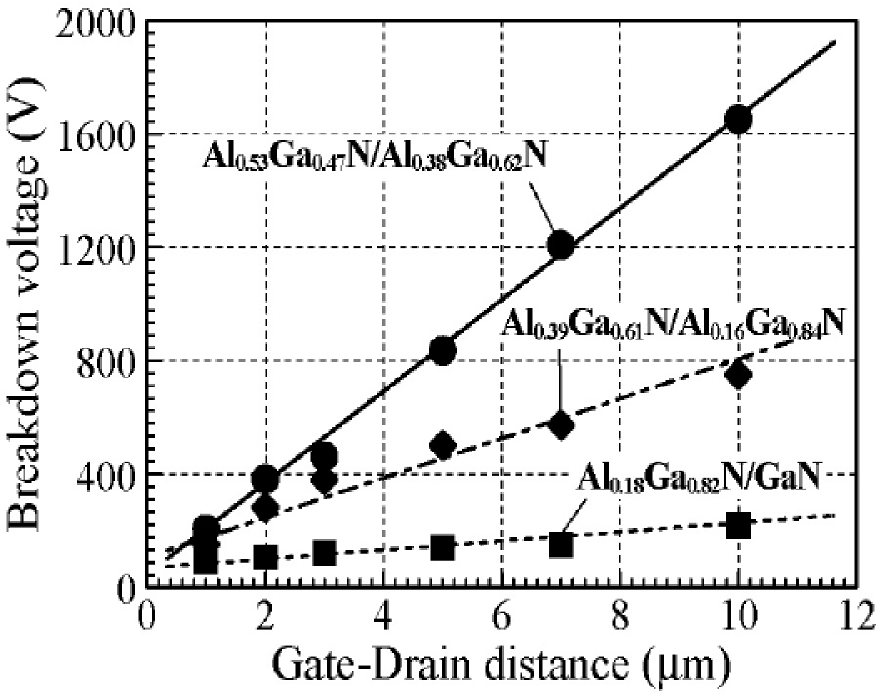


Fig.1 Schematic structure of HEMTs with the hetero-structure consisted of the $Al_xGa_{1-x}N$ channel layer and the $Al_yGa_{1-y}N$ barrier layer ($Al_yGa_{1-y}N/Al_xGa_{1-x}N$, y > x).

Takuma Nanjo et al, "Remarkable Breakdown Voltage Enhancement in AlGaN Channel HEMTs", **IEDM 2007**





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IOP Publishing — Semiconductor Science and Technology
Semicond. Sci. Technol. **28** (2013) 074014 (8pp) doi:10.1088/0268-1242/28/7/074014

Vertical vs Lateral GaN HEMT

INVITED REVIEW

Current status and scope of gallium nitride-based vertical transistors for high-power electronics application*

Srabanti Chowdhury[1], Brian L Swenson[2], Man Hoi Wong[3] and Umesh K Mishra[4]

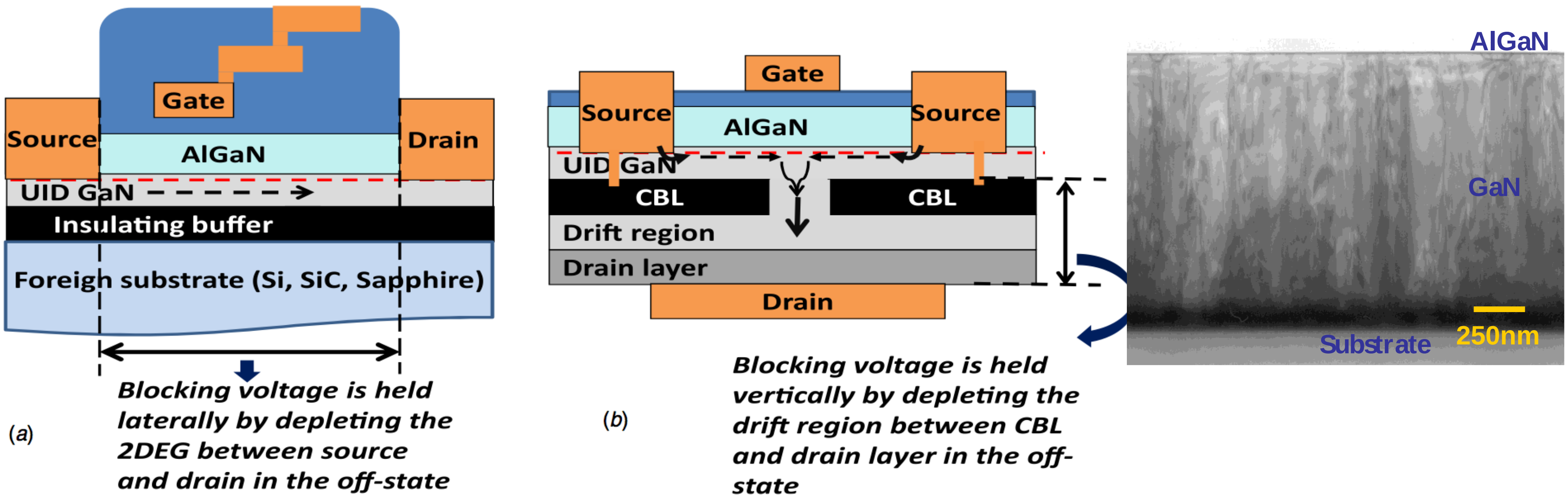

Figure 4. (*a*) A lateral AlGaN/GaN power HEMT (*b*) A vertical transistor using AlGaN/GaN layer structure on bulk GaN drift layer and substrate.

Department of Information Engineering
University of Padova

Outline

- Introduction & GaN properties
- Applications opportunities
- Open issues
  - Materials
  - Technology (E-Mode, Breakdown, Vertical vs lateral)
  - Parassitic & Reliability
- GaN Activities within IU.NET
- Conclusions

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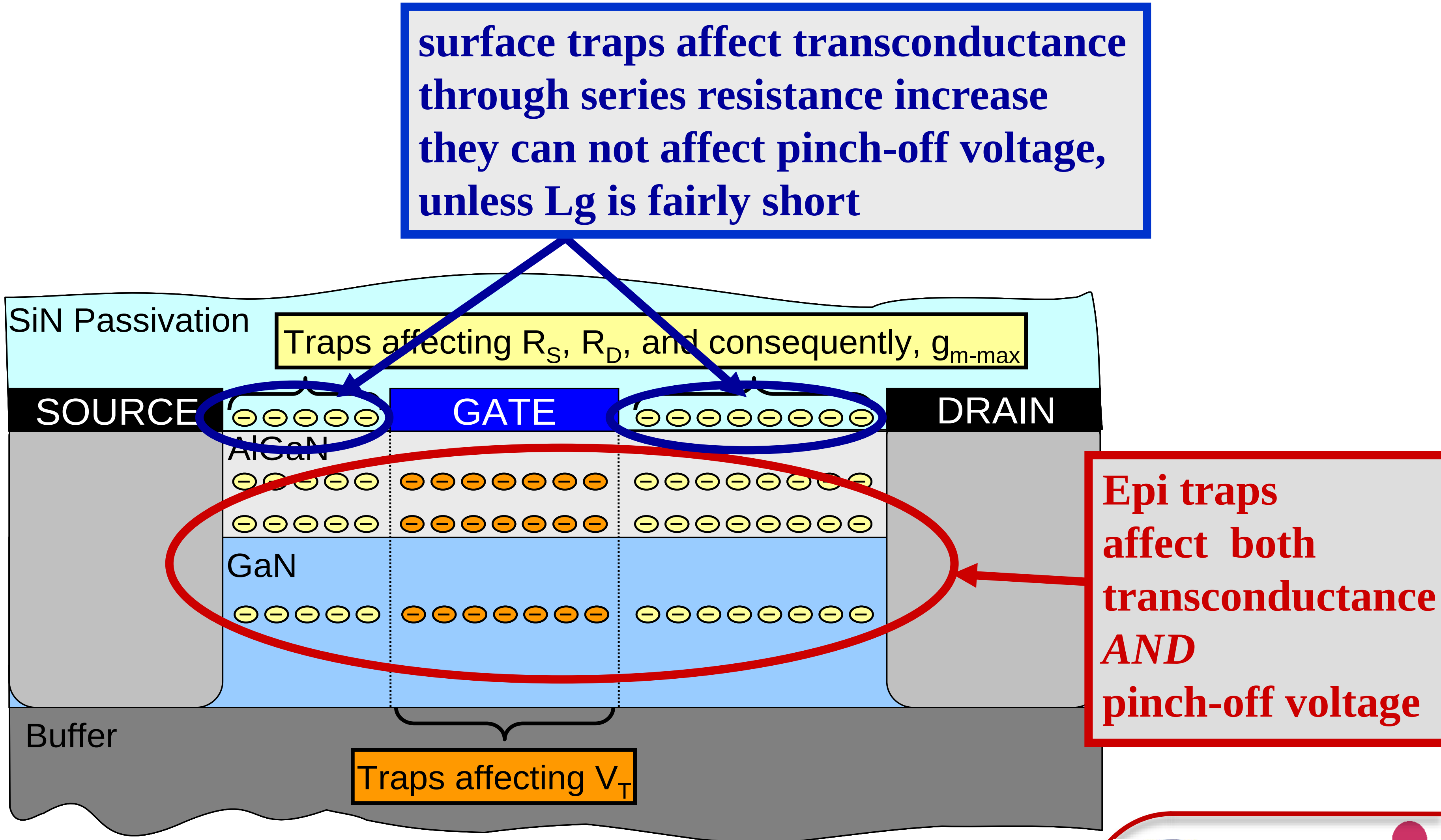
Parasitic and Reliability (UniPD)



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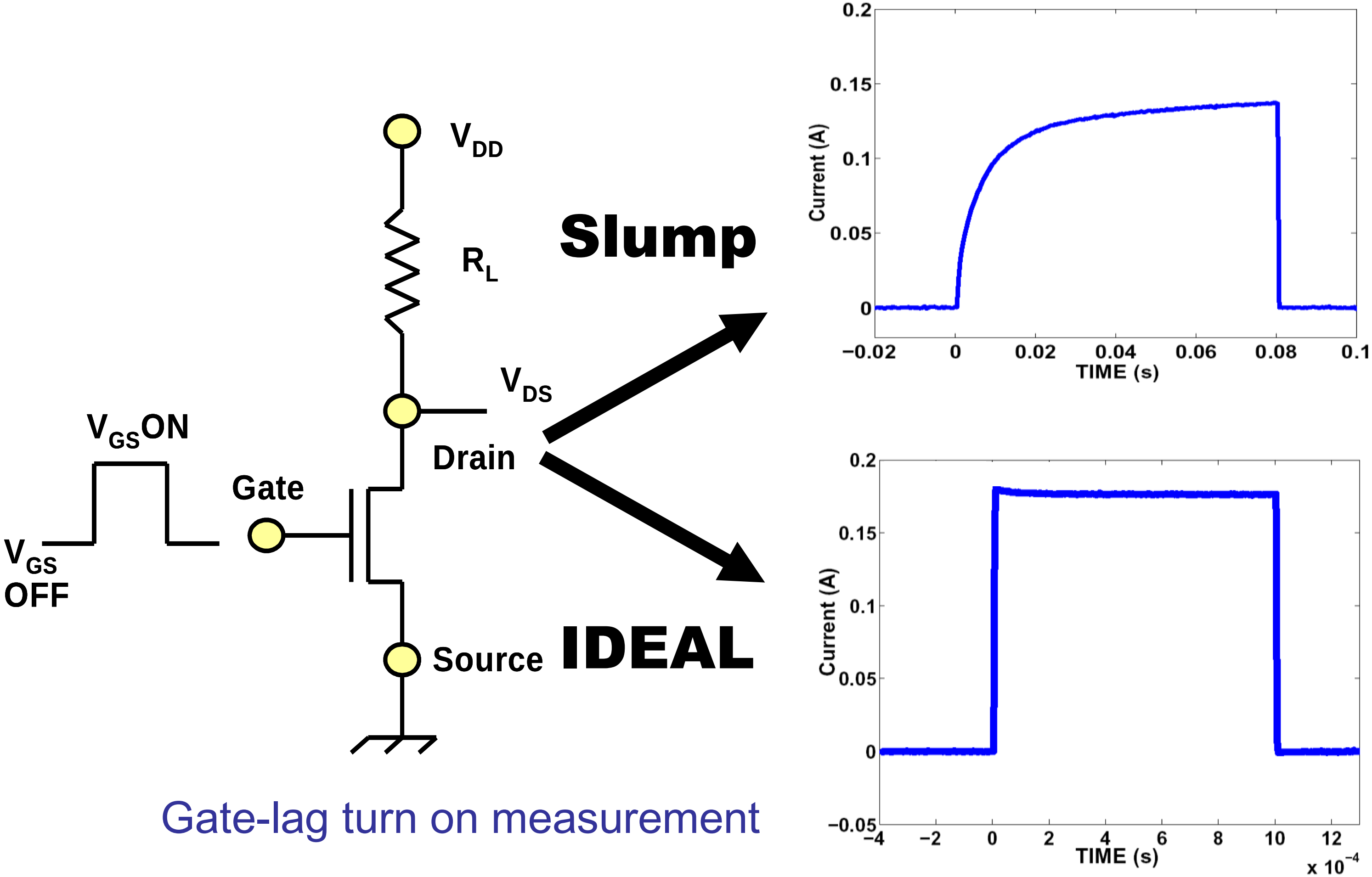
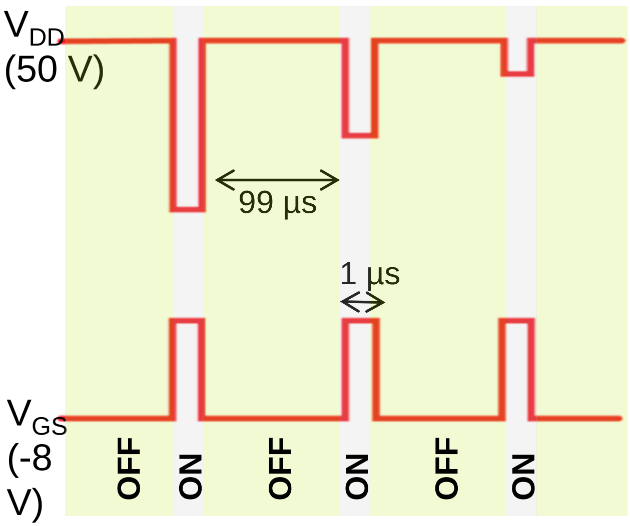
Parassitic and Reliability (UniPD)

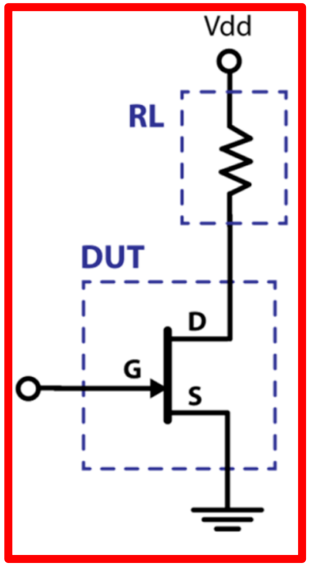


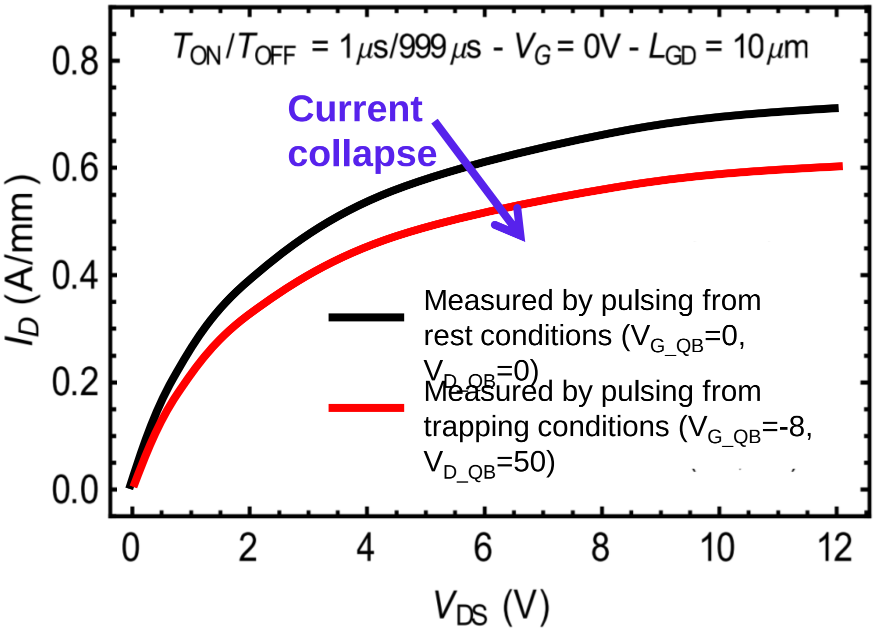
Gate-lag turn on measurement

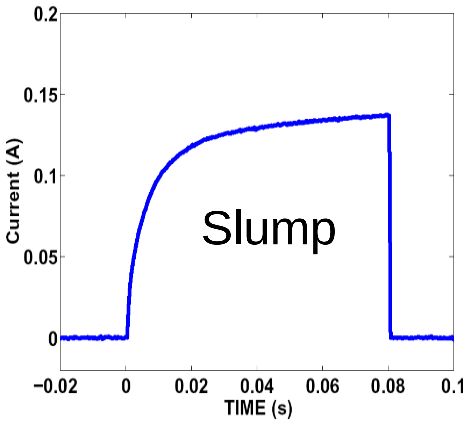
[7] STEVEN C. BINARI, et al., "Trapping Effects in GaN and SiC Microwave FETs", PROCEEDINGS OF THE IEEE, VOL. 90, NO. 6, . 1048- 1058, JUNE 2002

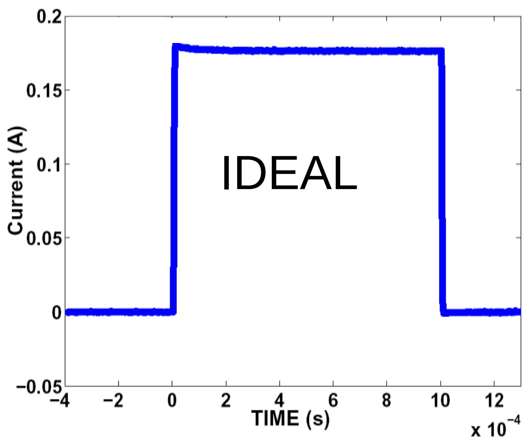
Parassitic and Reliability (UniPD)









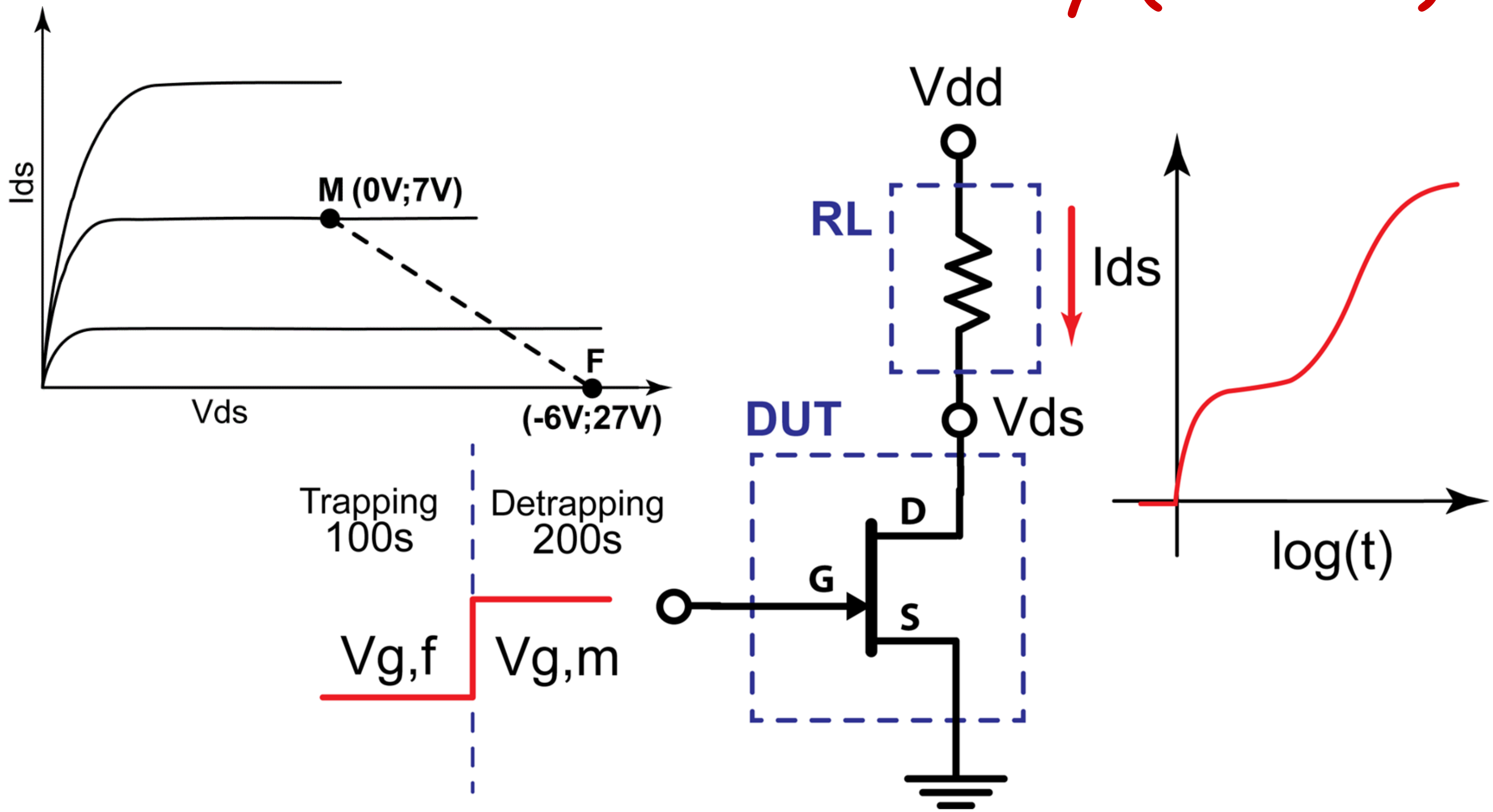


Current collapse → recoverable decrease in drain current induced by trapping

When a HEMT is switched on after a trapping phase → current shows an exponential transient before reaching steady-state value (de-trapping transient)

The same happens if ID-VD curves are measured from several QBPs

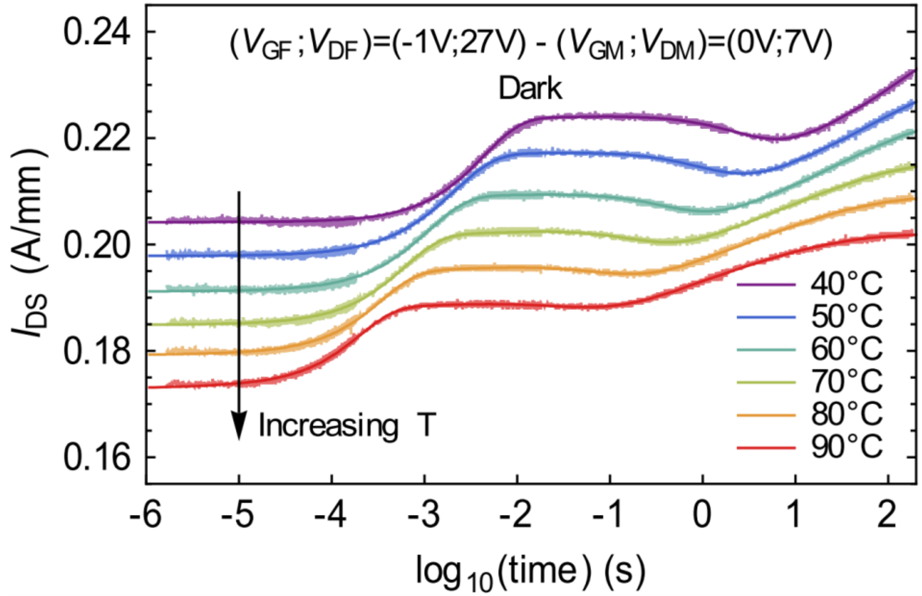
Parasitic and Reliability (UniPD)

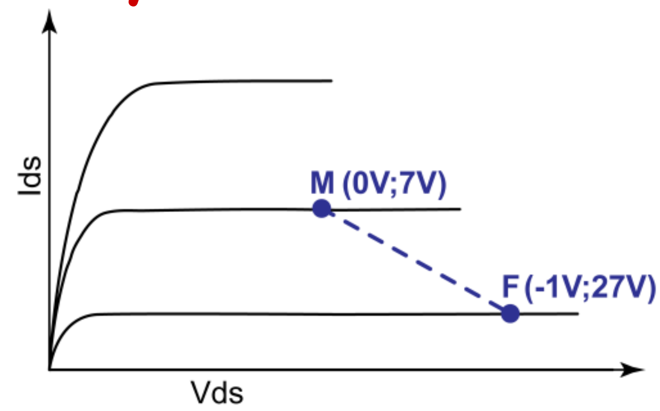


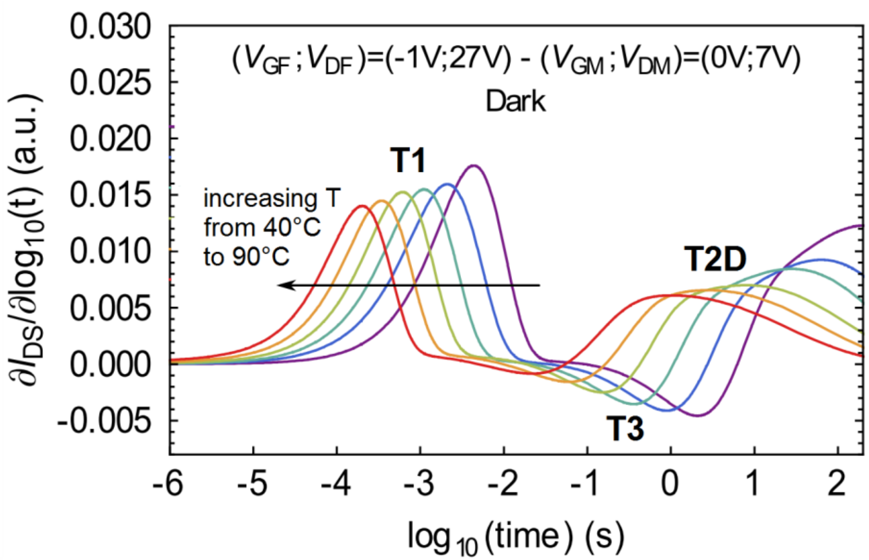
The Drain Current Transient analysis comprehensively investigate the **time evolution of carrier (de)trapping processes**. The **deep-levels** signatures – **activation energies** and **capture cross-sections** – and **their localization** can be achieved by performing the measurements under different bias conditions and different base-plate temperatures.

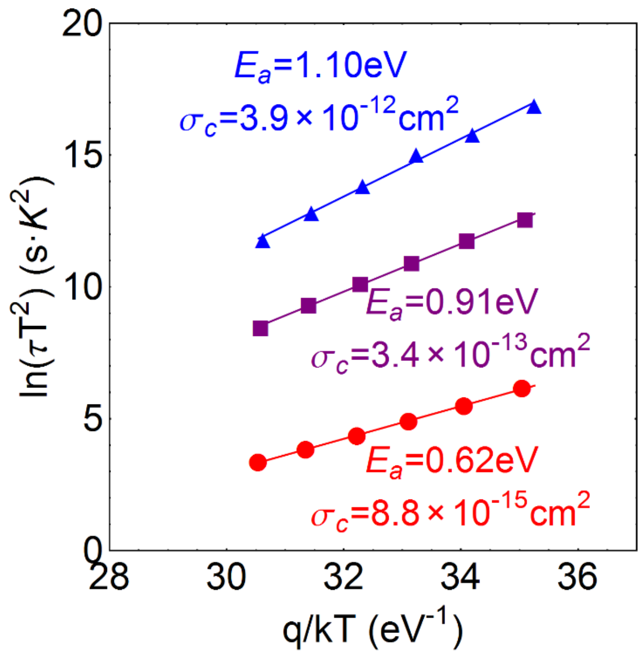
45

Parasitic and Reliability (UniPD)



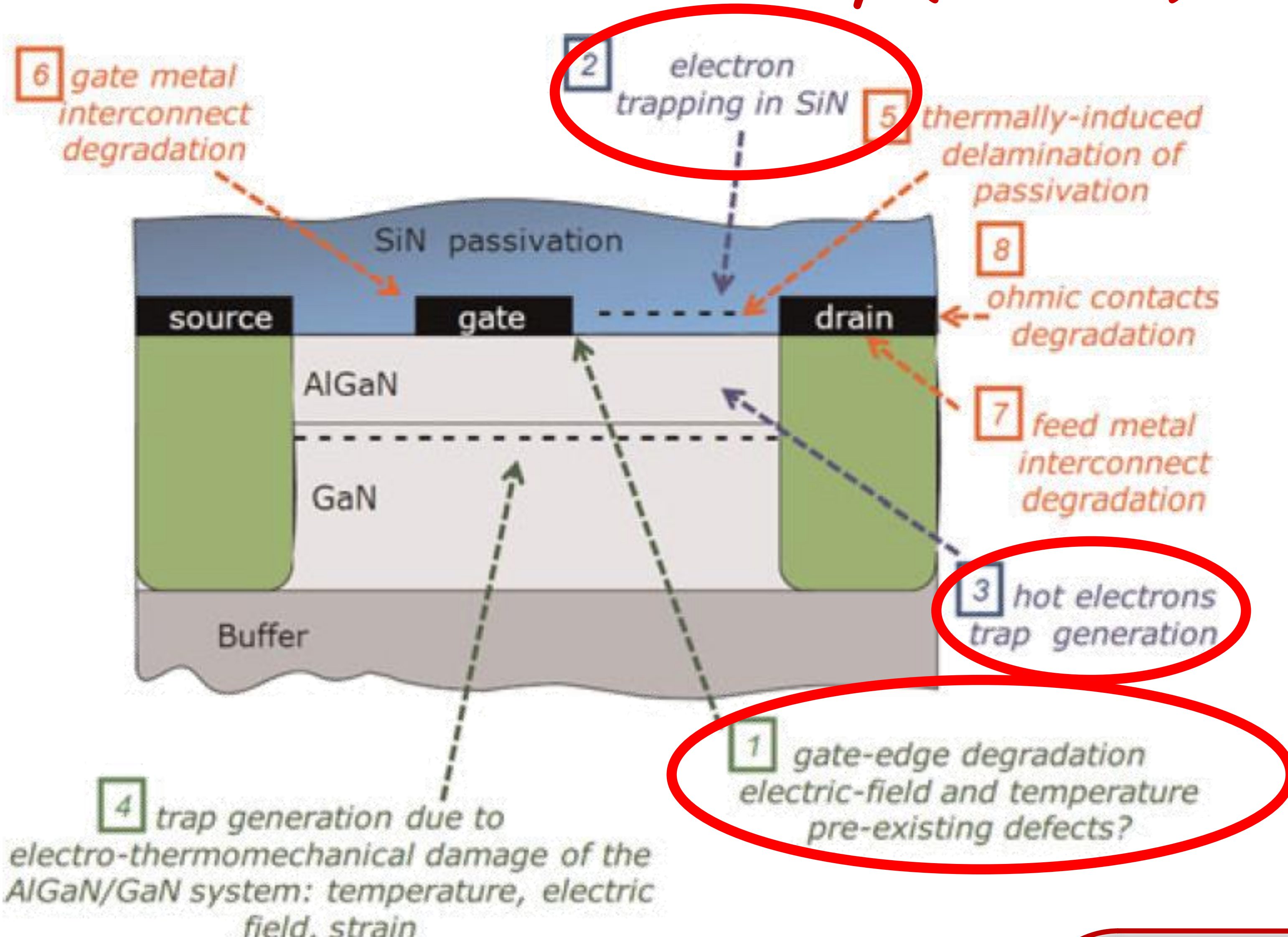






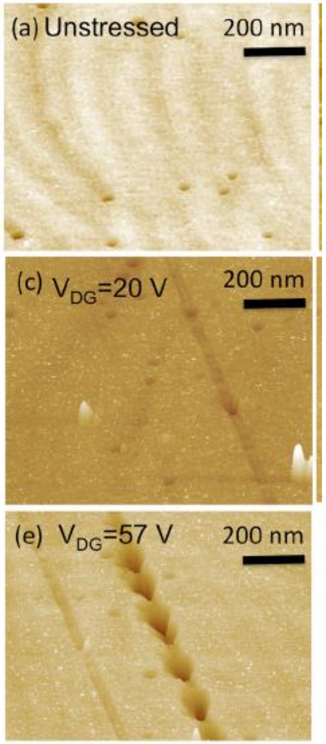
D. Bisi *et al.*, "Deep-Level Characterization in GaN HEMTs-Part I: Advantages and Limitations of Drain Current Transient Measurements," *IEEE Trans. Electr. Dev.*60, 3166, 2013.

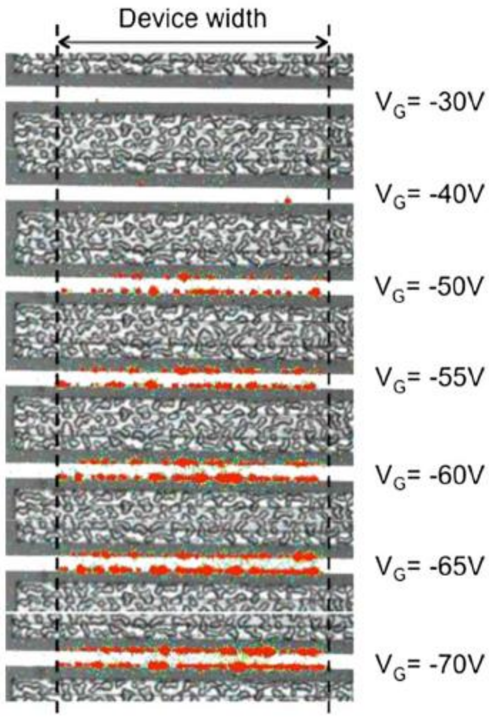
Parasitic and Reliability (UniPD)

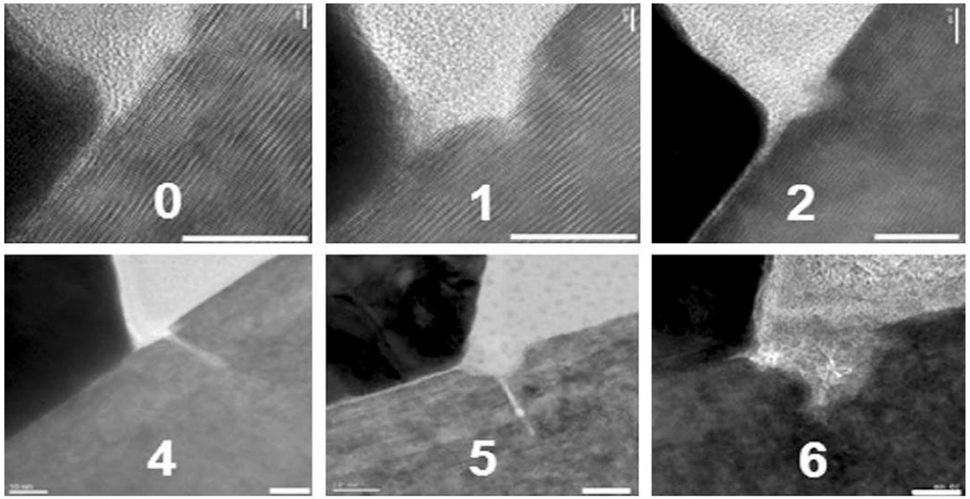


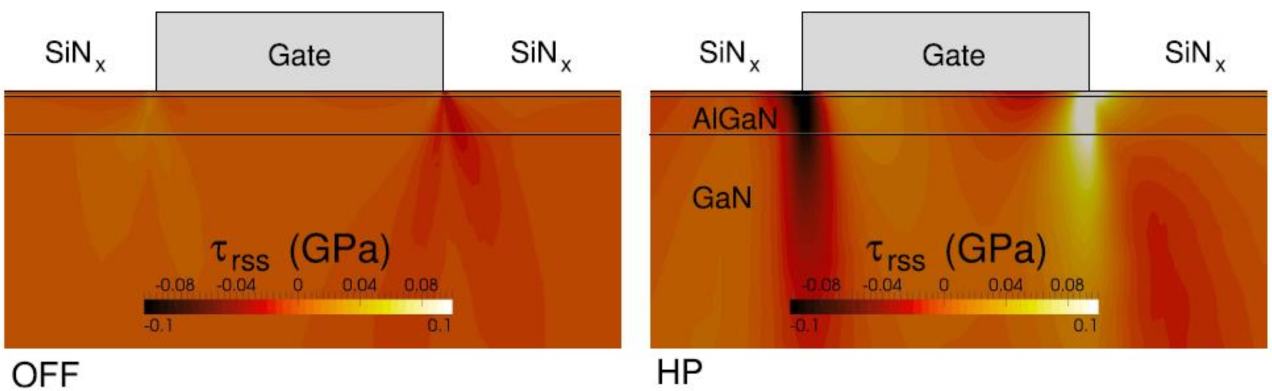
Meneghesso et al., Int. Jour. of Microwave and Wireless Technologies, 2010, 2(1), 39–50

Parasitic and Reliability (UniPD)









Gate edge degradation due to the high filed. Structural degradation has been identify (Traps, percolation path, increase on resistance)

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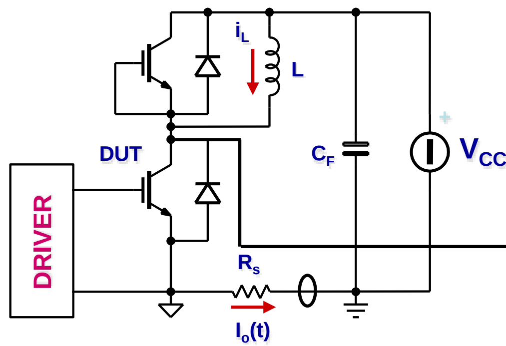
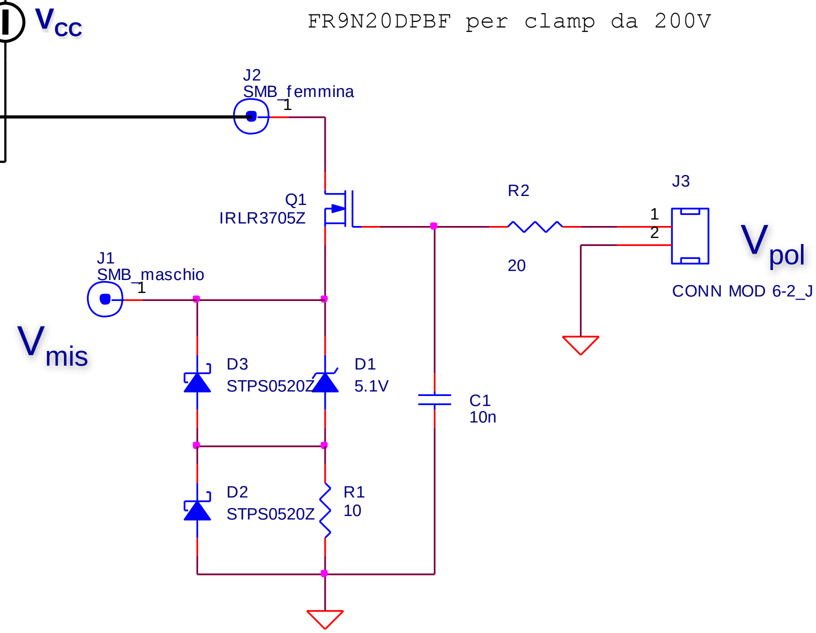
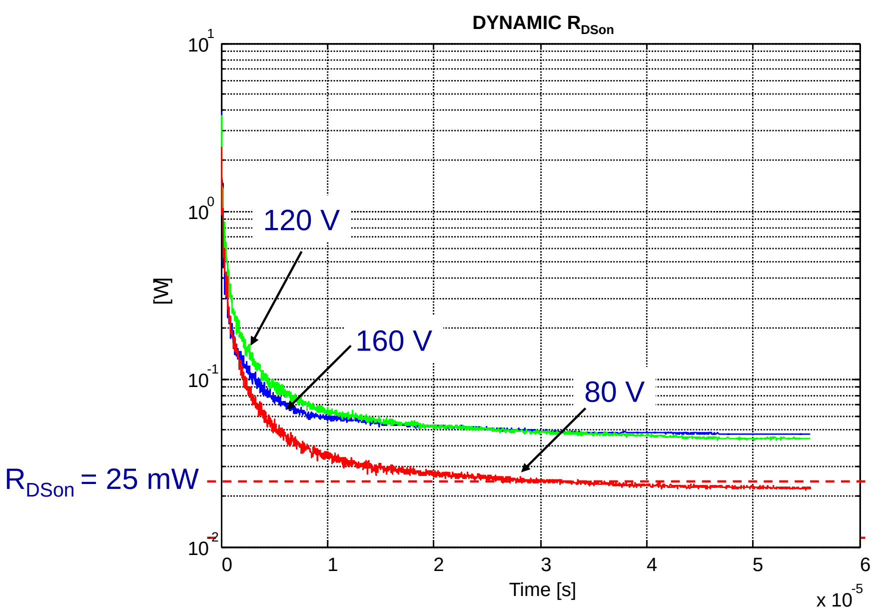
Activity at Power Electronic (PEL) Group - UniPD

P. Tenti,
L. Rossetto,
G. Spiazzi,
S. Buso,
P. Mattavelli
L. Corradini







- **Characterization of commercial GaN MOSFET power devices**
- **Design and implementation of optimized switching cells for device parameter in-circuit characterization**
- **Realization of a Pont of Load (PoL) converters using GaN devices**

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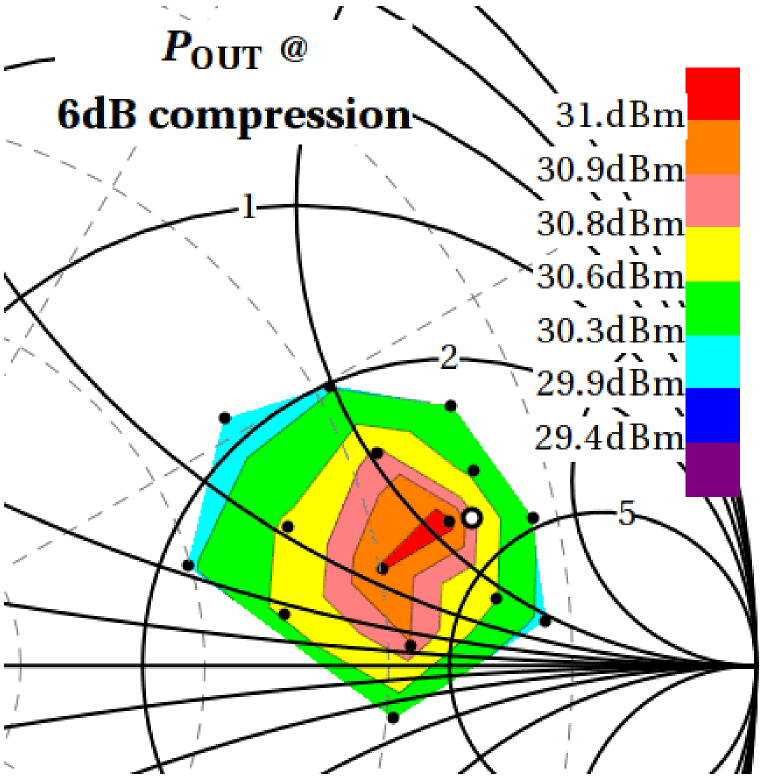
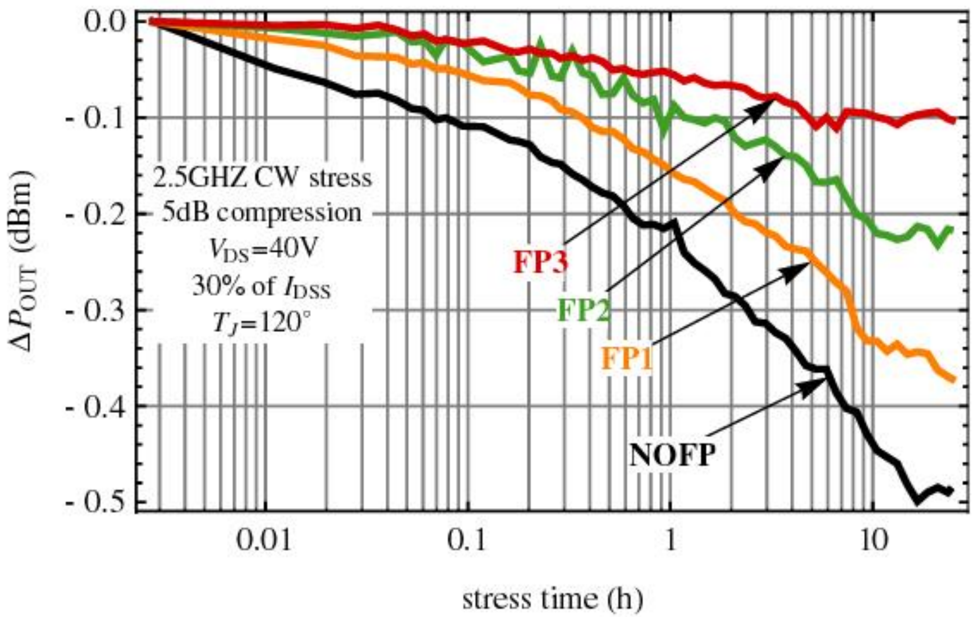
GaN HEMTs RF Characterization and Stress Tests

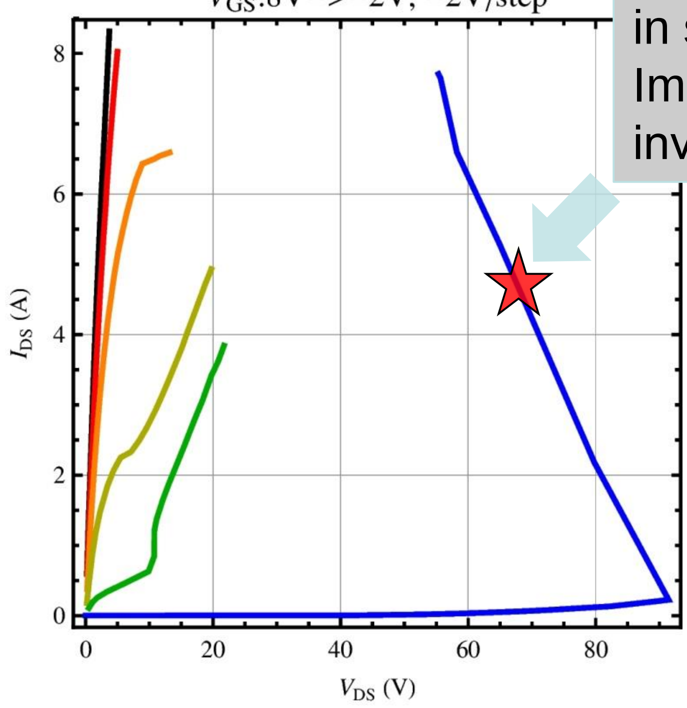


Both large-signal and small-signal RF characterization is carried out in order to evaluate device performance. RF stress are also carried out for reliability investigation

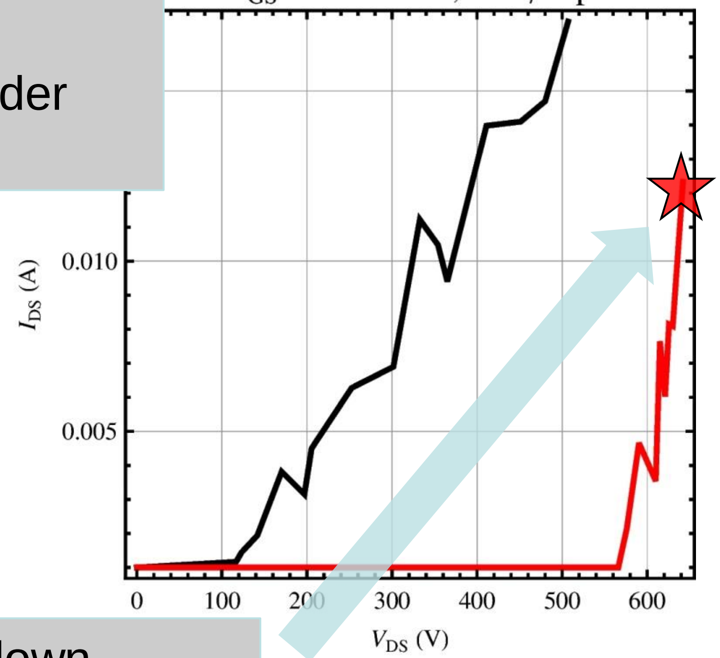


Breakdown Phenomena Investigation

Preliminary results on non-optimized large-periphery devices tested by applying short (1us) voltage pulses at the drain terminal.



Snap-back feature observed in semi-off conditions Impact Ionization?? Under investigation…



Destructive breakdown occuring at 650V

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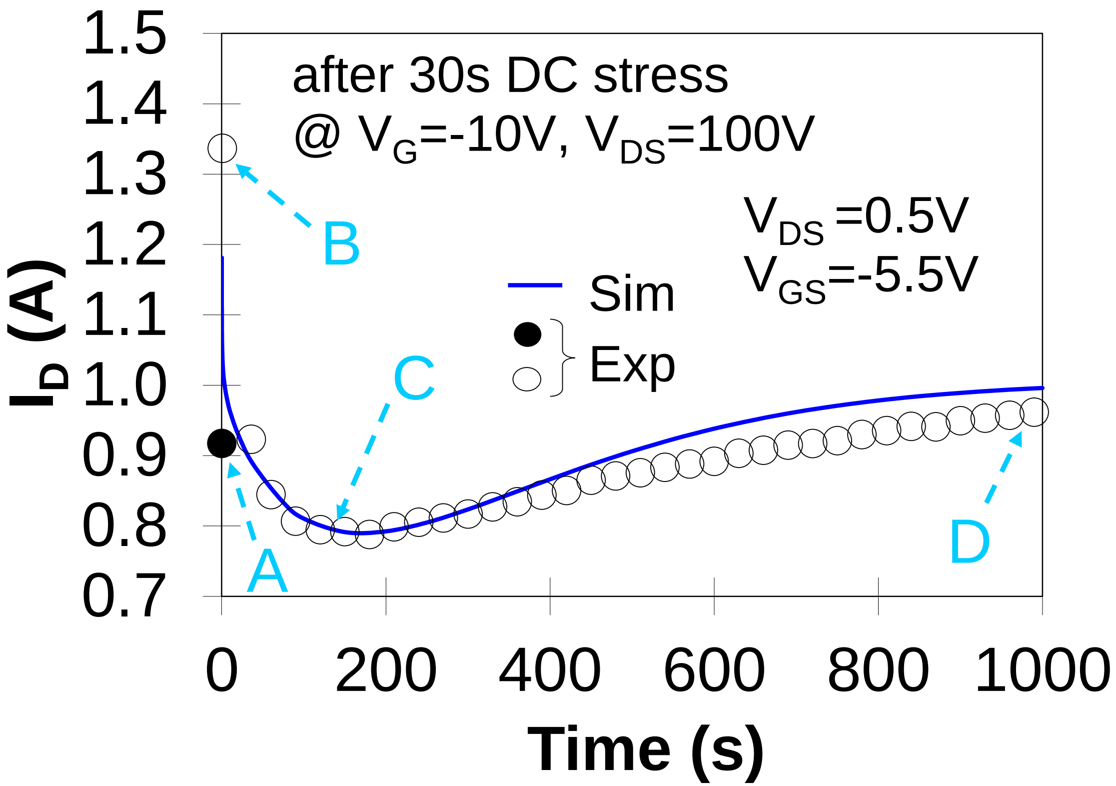
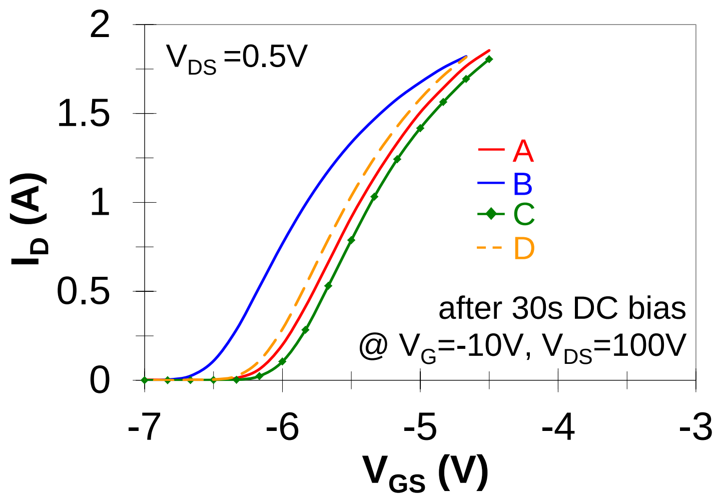
A: pre-stress

B: neutral GaN:UID traps (no e^-) & neg. GaN:C traps (no h^+)





B to C: e^- capture into GaN:UID traps

C: neg. GaN:UID traps & neg. GaN:C traps

C to D: h^+ capture into GaN:C traps

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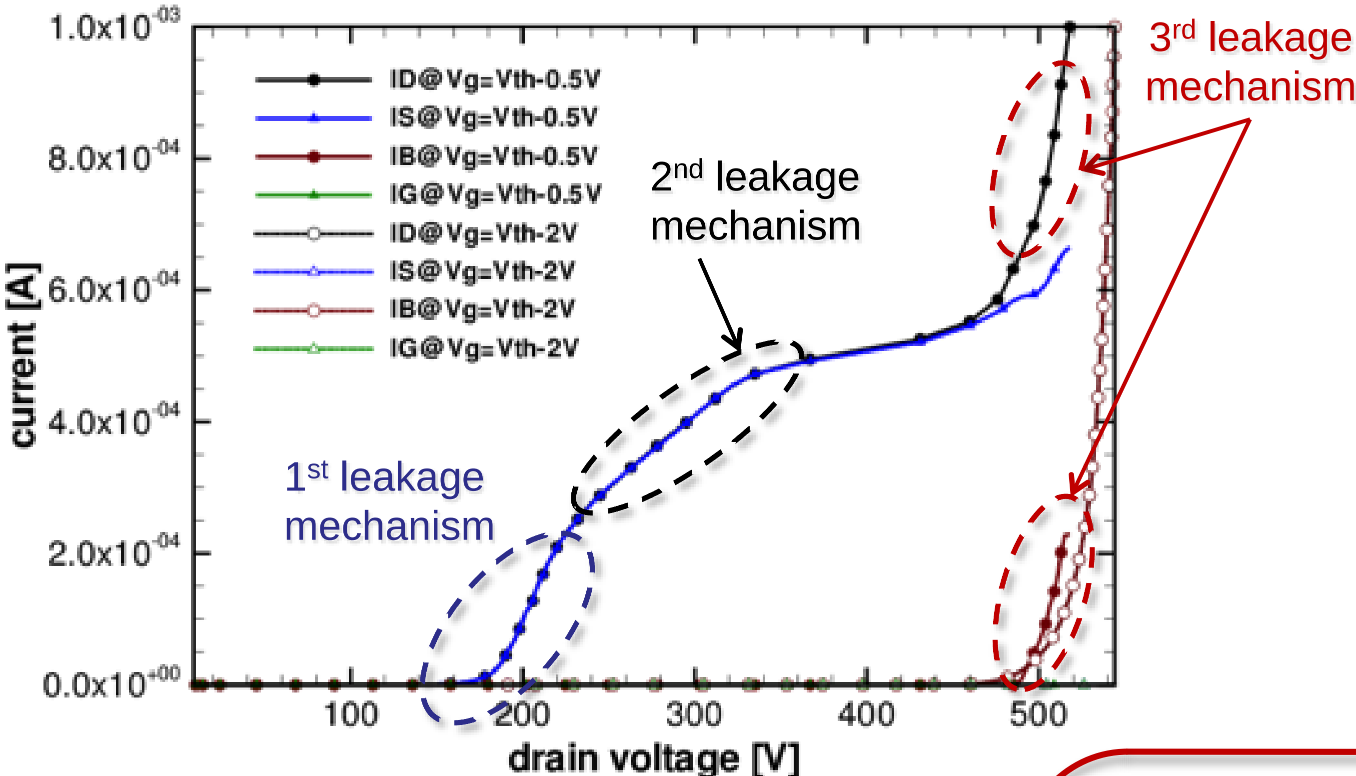
Breakdown (UniMO + UniPD)

For Vg=-6.5V, at least three different breakdown/leakage mechanisms take place:

1)1st BK: BTB, Impact Ionization, Poole-Frenkel related or something else?
2)2nd BK: Back-barrier electron transfer
3)3rd BK: BTB tunneling between drain & substrate

Whereas, for Vg=-8V only the BTB phenomena between drain & substrate can be identified.



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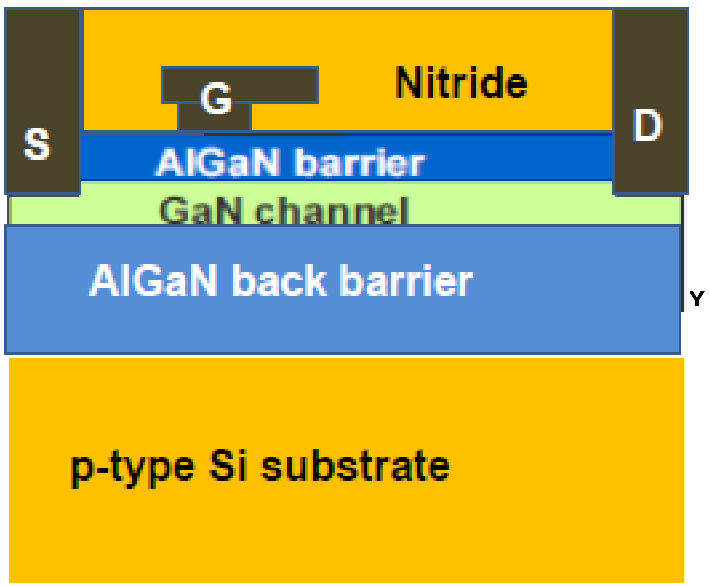
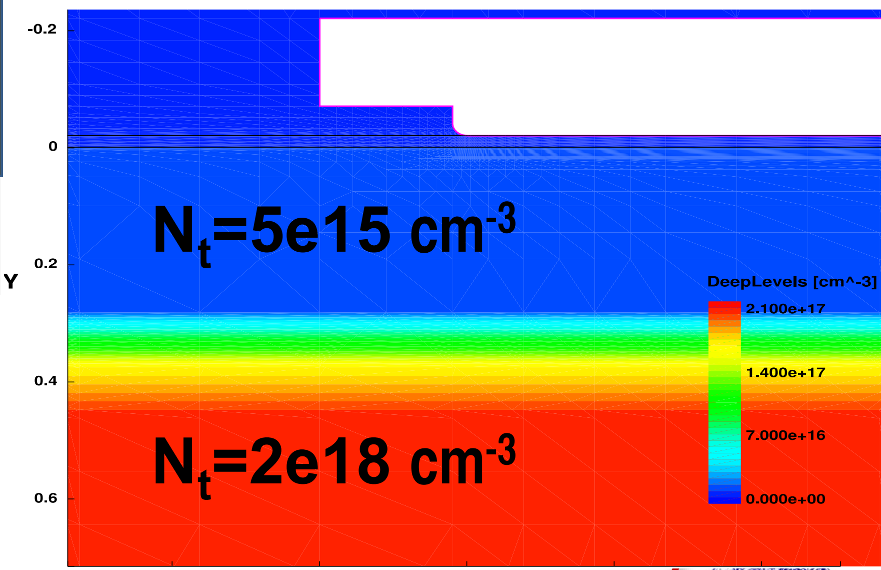
GaN-HEMTs - UniBO

Simulation of a GaN-on-Si power HEMT in off-state up to breakdown – Comparison against literature data

F. Monti, D. Cornigli, S. Reggiani, E. Gnani, A. Gnudi, G. Baccarani

- Simulations with both electron and hole impact-ionization contributions
- Deep acceptor levels in the GaN buffer (0.4 eV above midgap) with a step-like distribution at 0.4um from the surface





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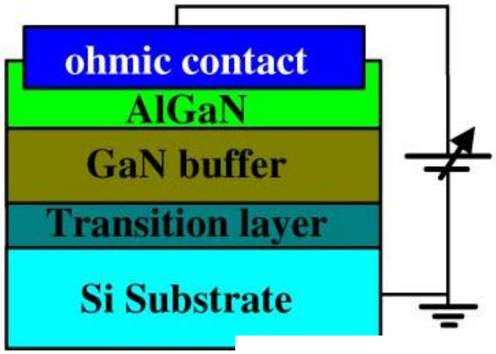
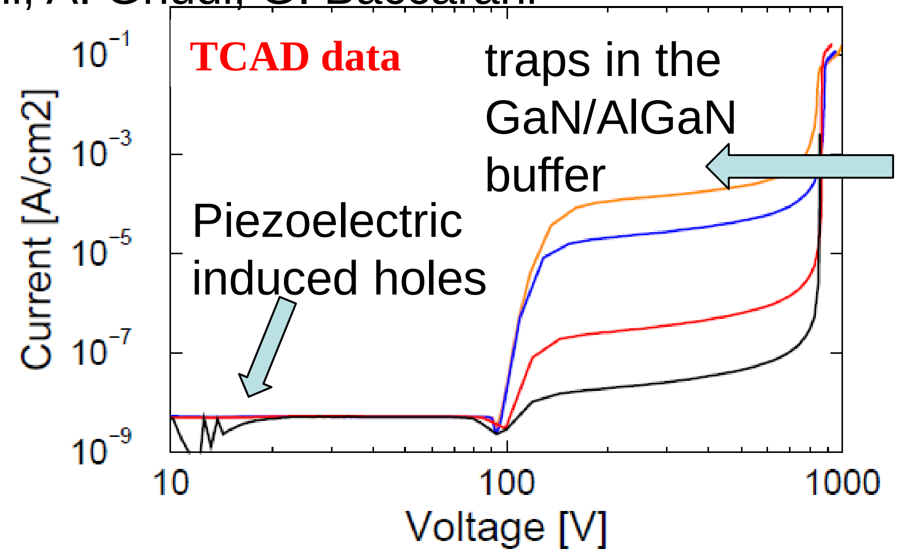
GaN-HEMTs - UniBO

Simulation of vertical leakage/breakdown in GaN-on-Si buffers up to 150°C – Comparison against literature data

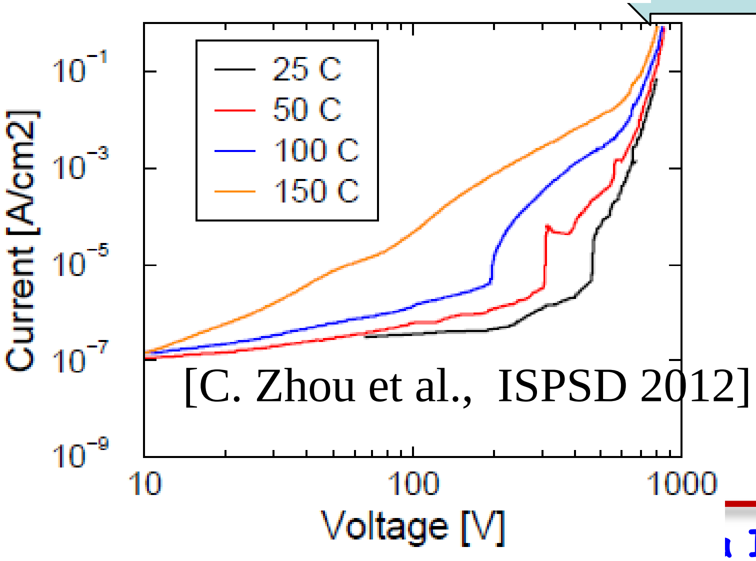
F. Monti, D. Cornigli, S. Reggiani, E. Gnani, A. Gnudi, G. Baccarani

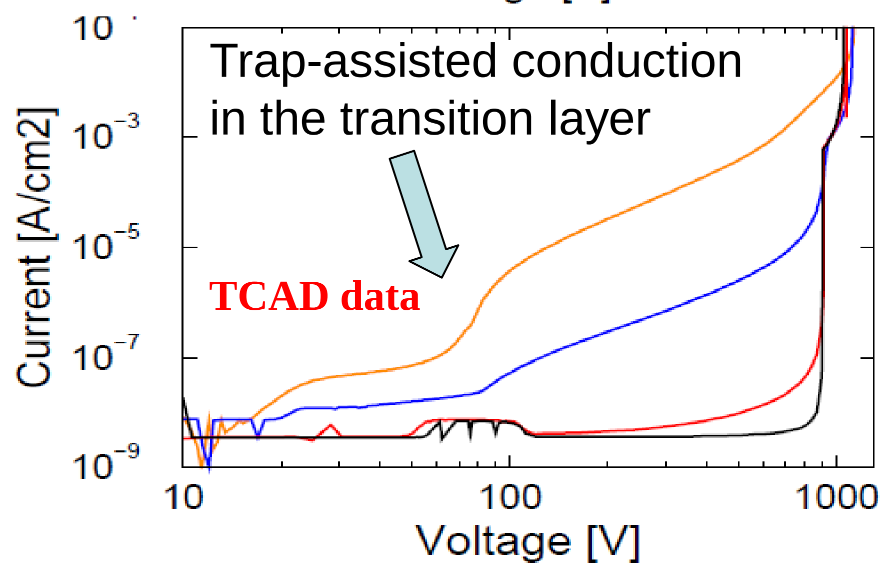


Vertical buffer in forward bias



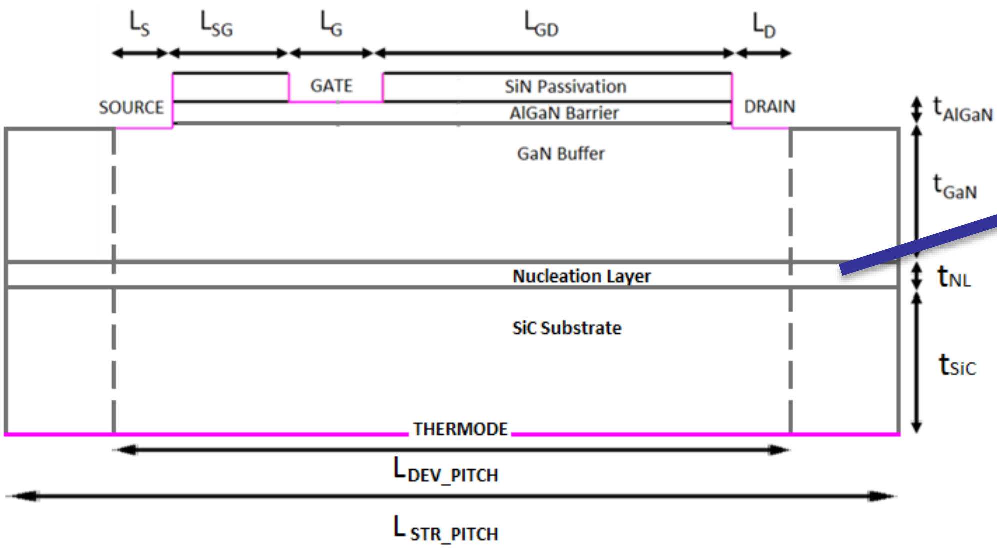
Experiments

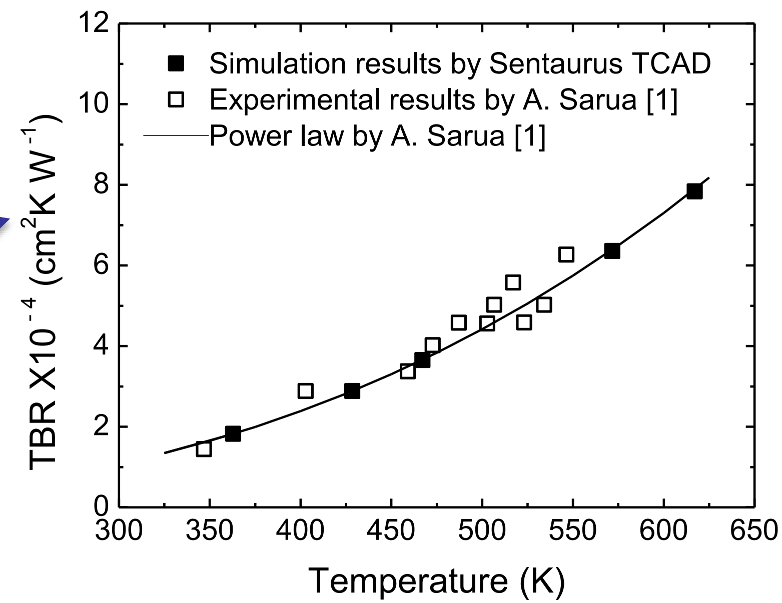




Modeling Self-Heating Effects in AlGaN/GaN HEMT

A. N. Tallarico, P. Magnone, E. Sangiorgi, C. Fiegna





- The TBR (thermal boundary resistance), between GaN layer and SiC substrate is modeled according to [1].
- PMI (physical model interface) implemented in Sentaurus TCAD [2].

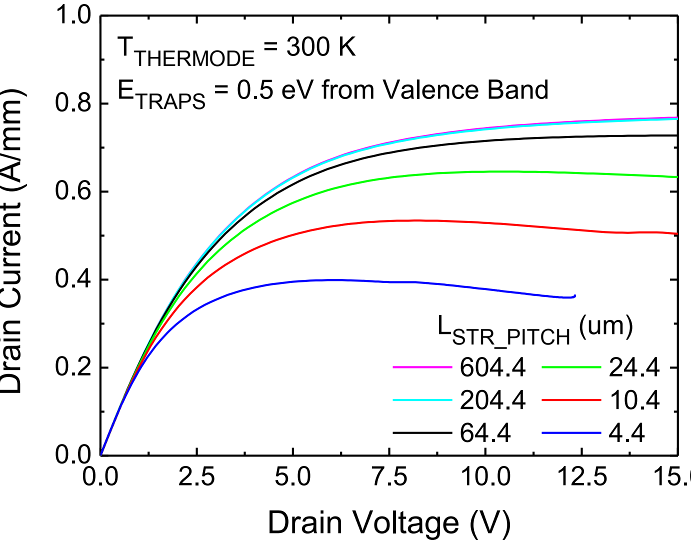
[1] A. Sarua et al., *IEEE Trans. Electron Devices*, 2007

[2] A. N. Tallarico, SISPAD, 2014

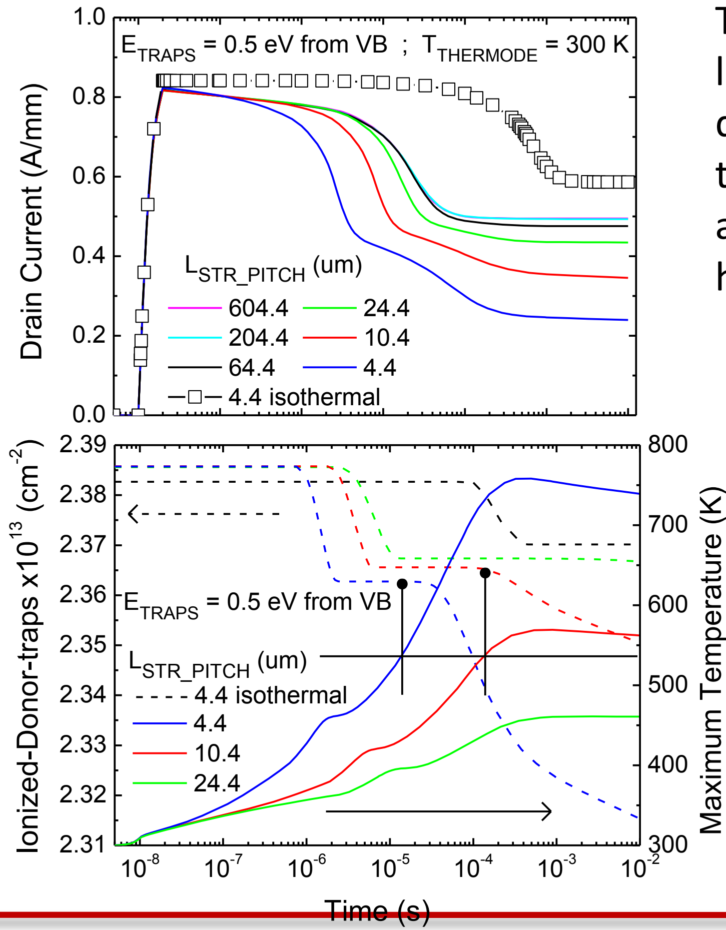
GaN-HEMTs - UniBO

Modeling Self-Heating Effects in AlGaN/GaN HEMT

Drain-lag simulations accounting for both self-heating and traps at AlGaN/Nitride interface



By reducing the pitch (distance between adjacent devices) because of the temperature increase a strong reduction of current is observed.



The current overshot is linked to the transient of donor traps which is time-reduced and amplitude-increased for higher temperatures.

Two different transients:
- the first is intrinsic to the donor-traps,
- the second transient is a temperature-driven effect (activated at T ≈ 540 K).

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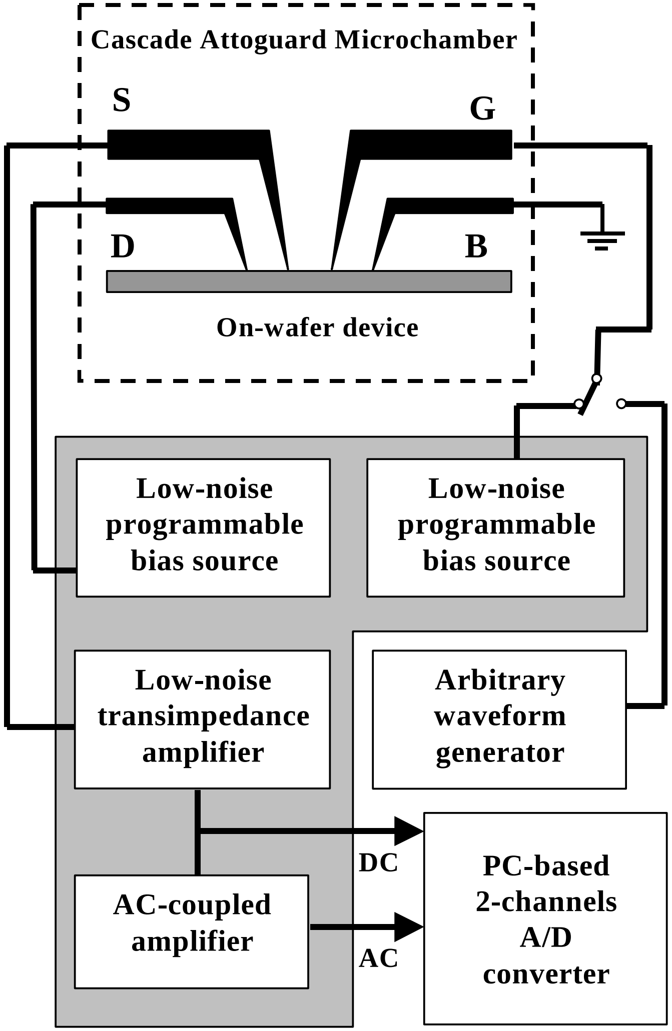
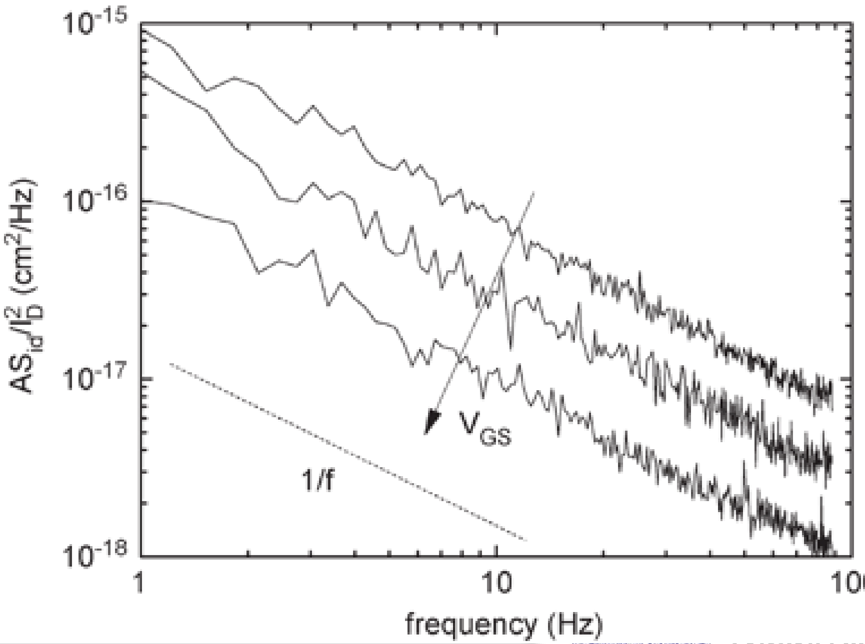
E2COGaN - Unical Contribution



1/f noise measurements on GaN devices

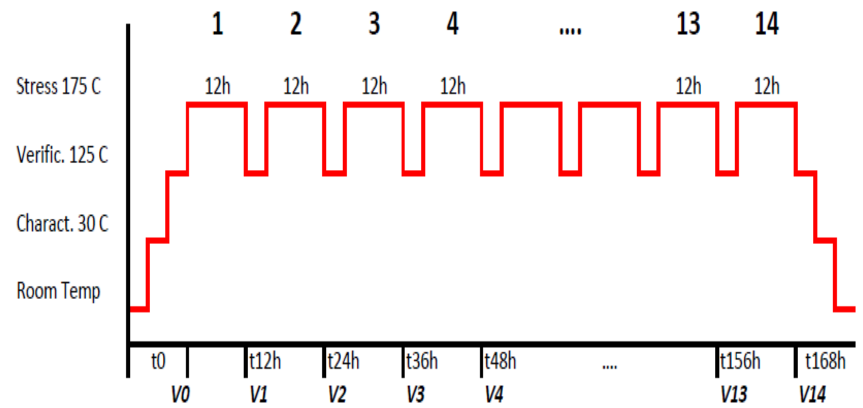
- Design and prototyping of instrumentation for low-frequency noise characterization
- Measurements of 1/f noise of gate and drain currents
- Evaluating trap density from 1/f noise in fresh and stressed devices

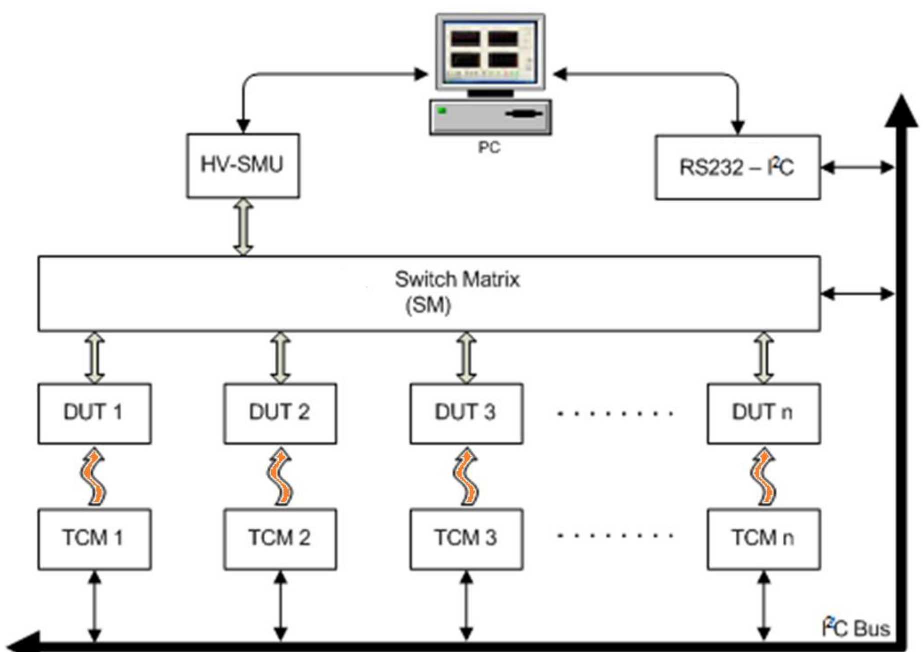


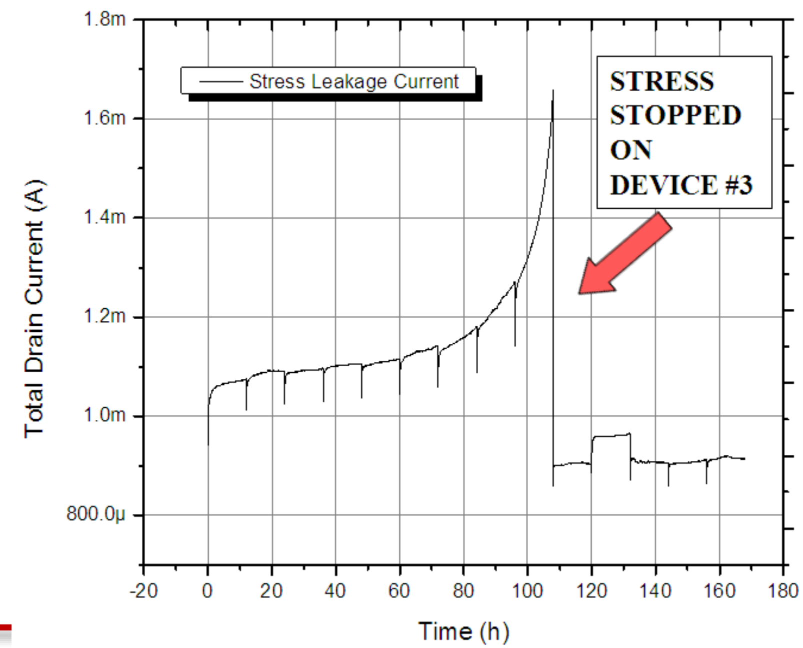
E2COGaN - Unical Contribution

Advanced HTRB characterization

- Individual device mini-heater for HTRB test with true constant T_C
- Individual stress-sense procedure up to a preset degradation threshold
- Large number of devices tested in parallel for statistical evaluation







Progetti Europei – Contratti – Collaborazioni

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