High-voltage GaN-HEMT devices, simulation and modelling

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Outline

- GaN and related materials
- The AlGaN/GaN heterostructure
- GaN wafers
- GaN devices
- Issues facing high-voltage GaN-HEMT development
- High-voltage breakdown
- GaN-HEMT device simulation
- Compact modelling of GaN HEMTs
- Summary and conclusion

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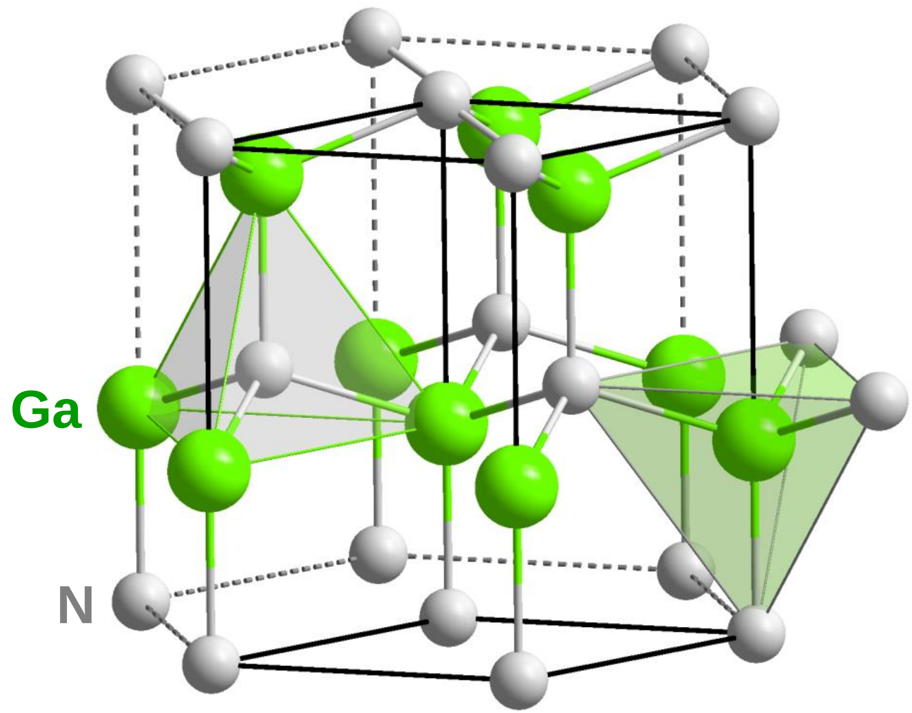
Gallium nitride

- Gallium nitride (GaN) is a binary III-V compound material, with:
  - Wurtzite (hexagonal) crystal structure
  - Wide band gap of 3.4 eV (direct)
  - High thermal conductivity

12	13	14	15	16	17	18
	III	IV	**V**			2 He
	5 B	6 C	7 N	8 O	9 F	10 Ne
	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo



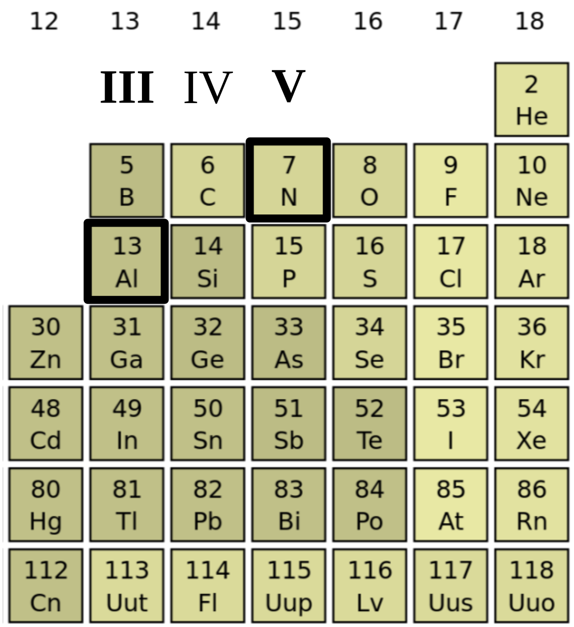
Properties of GaN

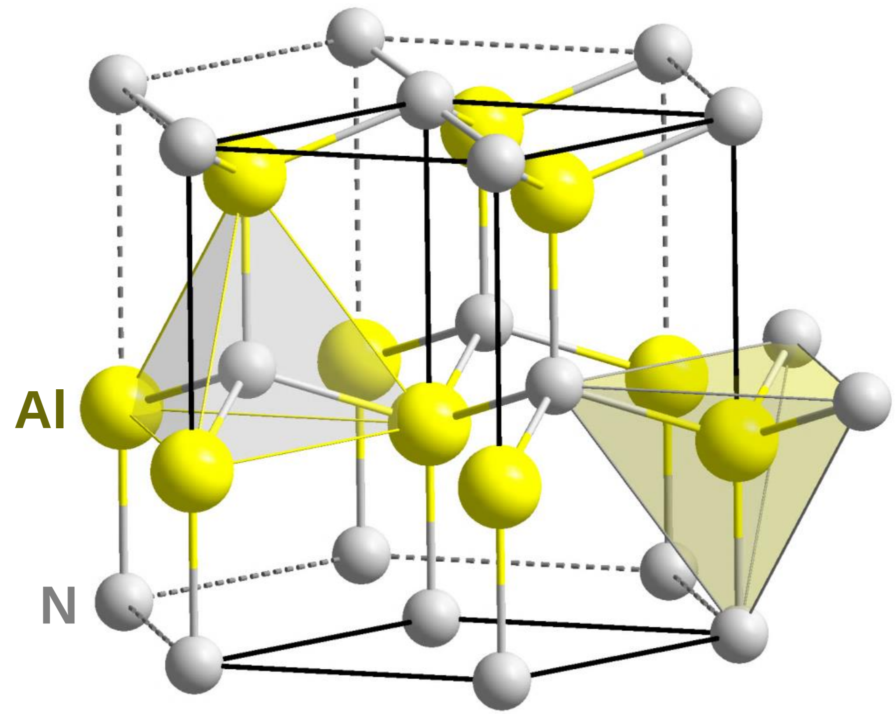
- Selected properties at 300 K:

Property	Si	4H-SiC	Diamond	GaAs	GaN
Band gap (eV)	1.1	3.2	5.5	1.4	**3.4**
Relative permittivity	11.9	10	5.5	12.5	**9–10**
Breakdown field (MV/cm)	0.3	3	5	0.4	**3**
Thermal conductivity (W/K/cm)	1.48	3.30	20.00+	0.54	**1.30**

Aluminium nitride

- Aluminium nitride (AlN) is a binary III-V compound material, with:
  - Wurtzite (hexagonal) crystal structure
  - Wide band gap of 6.2 eV (direct)
  - High thermal conductivity





AlGaN

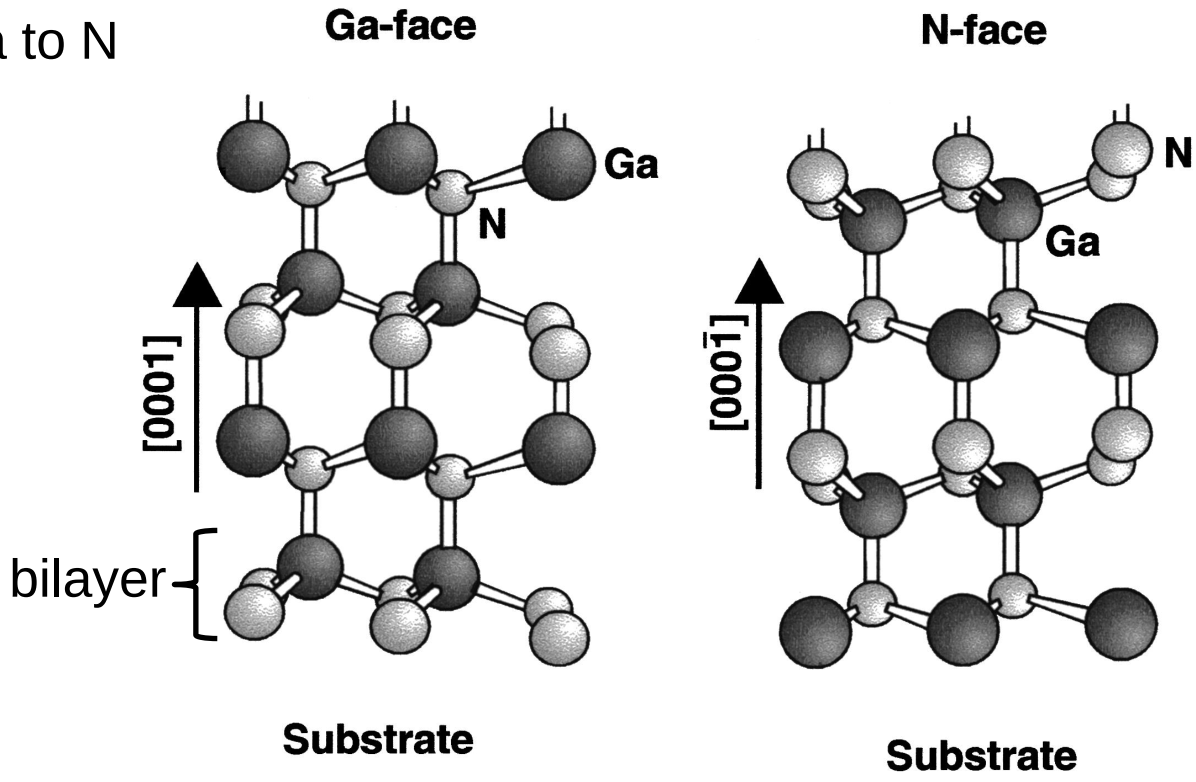
- Take GaN and replace a fraction *x* (the *mole fraction*) of the Ga atoms with Al atoms ⇒ $\mathbf{Al_{x}Ga_{1-x}N}$
- Most material properties are then intermediate between those of GaN and AlN

Quantity	GaN	$Al_{0.2}Ga_{0.8}N$	AlN	Units	Interpolation
Band gap	3.43	3.77	6.20	eV	Bowed, factor −1.33
Breakdown field	3.3	4.32	8.4	MV/cm	Linear (?)
Relative permittivity	9.5	9.3	8.5		Linear

[R. Quay, *Gallium Nitride Electronics*, ISBN 978-3-540-71890-1]

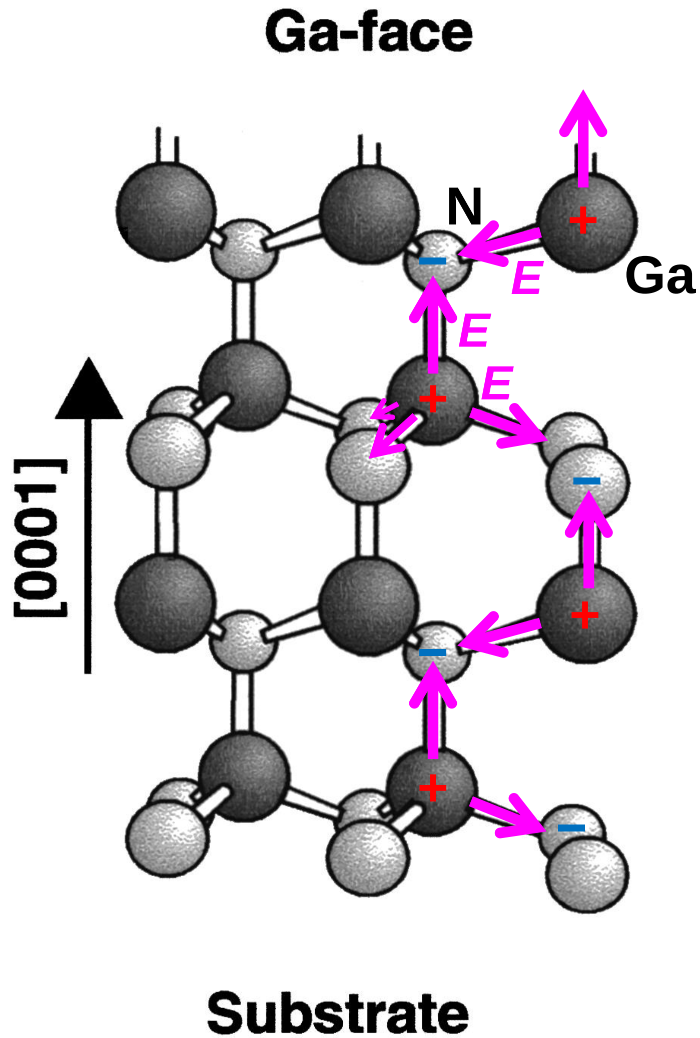
GaN crystal growth

- Convention: [0001] direction is along *c* axis from Ga to N
- A-face: atom of type A is on top of bilayer
- Single-bond (low energy) surface



[O. Ambacher *et al.*, J. Appl. Phys. **85 (6)**, 3222 (1999)]

Polarisation



- Ga–N bonds are *polar*
- The Wurtzite crystal structure is *non-centrosymmetric* (*i.e.*, it lacks inversion symmetry)
- Result: **spontaneous polarisation** of the material

Note: P_{SP} of AlN is stronger than that of GaN

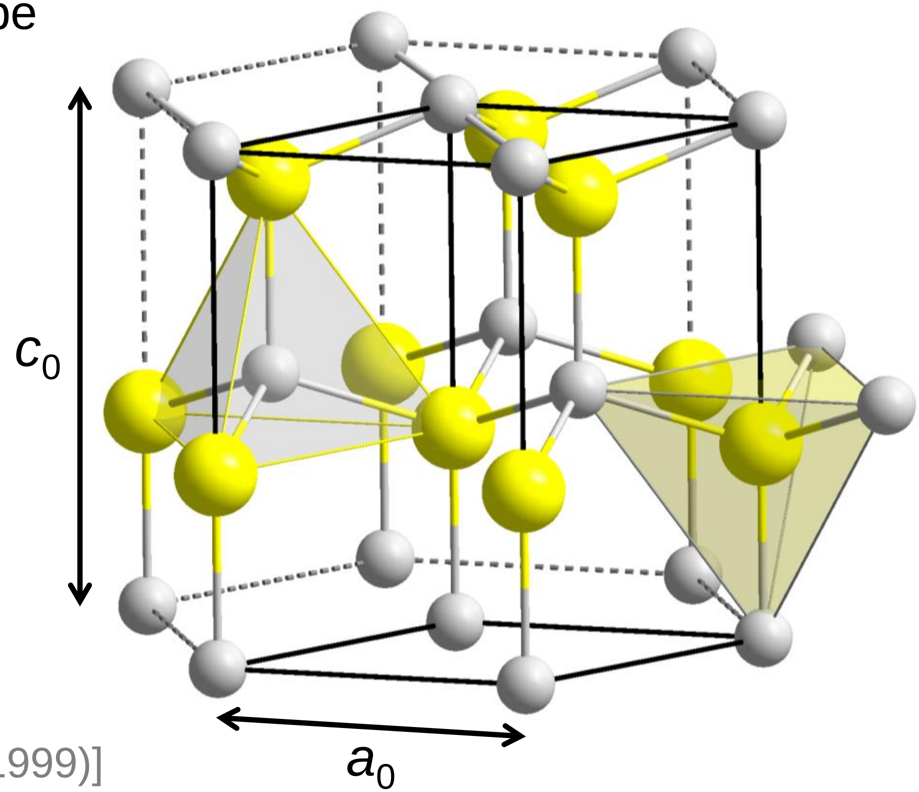
[O. Ambacher *et al.*, J. Appl. Phys. **85 (6)**, 3222 (1999)]

[E. T. Yu *et al.*, J. Vac. Sci. Technol. B **17 (4)**, 1742 (1999)]

Piezoelectric effect

- Applying stress to the material distorts the crystal structure, causing further polarisation: **piezoelectric polarisation** P_{PE}
  - If the horizontal lattice parameter a is varied from its natural value a_0 there will be non-zero piezoelectric polarisation along the vertical (c) axis:

$$P_{\mathrm{PE}} = 2\frac{a - a_0}{a_0}\underbrace{\left(e_{31} - e_{33}\frac{C_{13}}{C_{33}}\right)}_{\text{Constant for a given } x \text{ (Al fraction)}}$$



[O. Ambacher *et al.*, J. Appl. Phys. **85 (6)**, 3222 (1999)]

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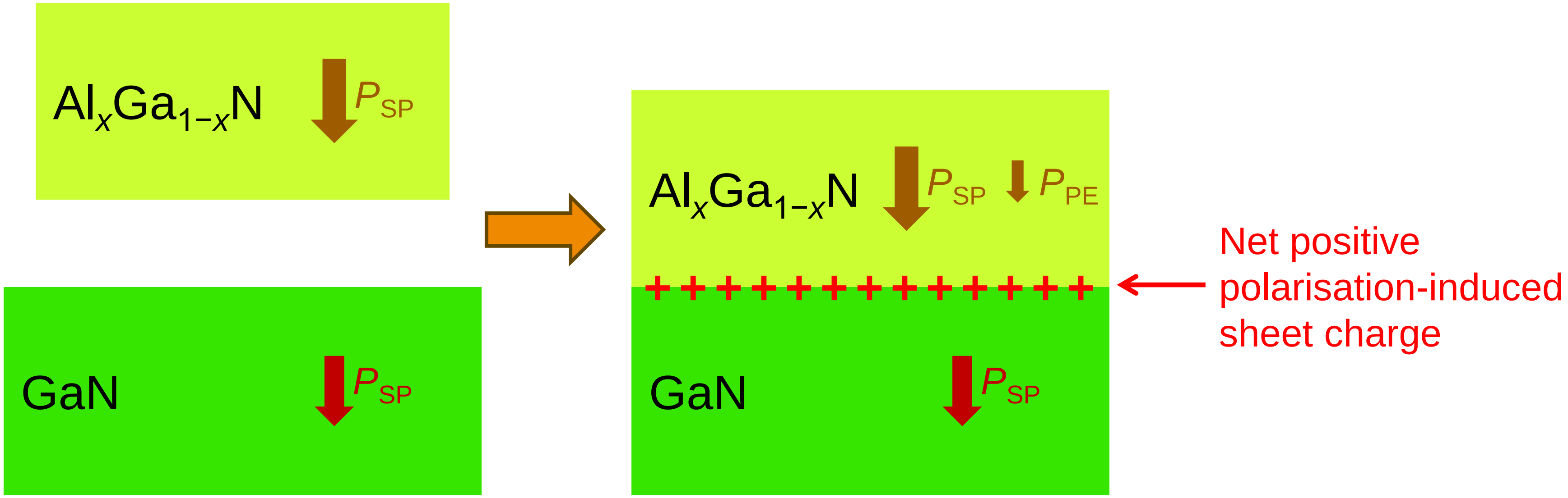
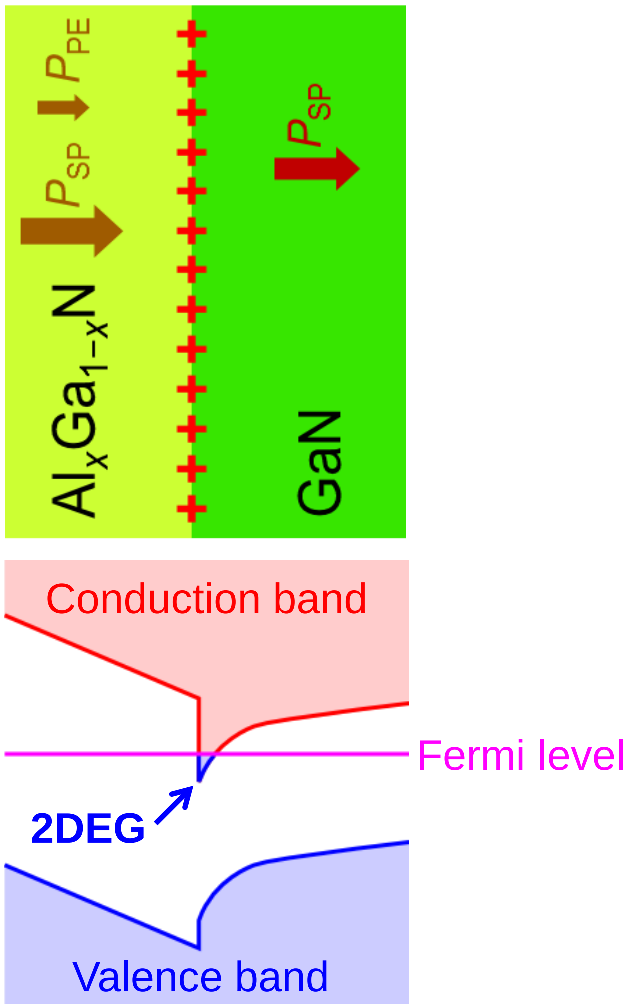
The AlGaN/GaN heterostructure

- AlN has a smaller lattice constant a_0 than GaN
- …and more spontaneous polarisation P_{SP}
- Grow $Al_xGa_{1-x}N$ on top of (relaxed) GaN:



The AlGaN/GaN heterostructure

- Electronic band gap of AlN is larger than that of GaN
  - The band gap of $Al_xGa_{1-x}N$ is somewhere in-between
- Electrons confined to a thin region near the $Al_xGa_{1-x}N$/GaN interface
- This is the **two-dimensional electron gas** (2DEG)
  - Areal density ~10^{13} electrons/cm^{-2}
- No doping ⇒ no impurity scattering ⇒ **very high mobility**

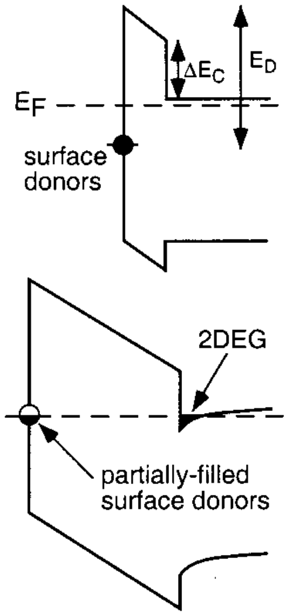


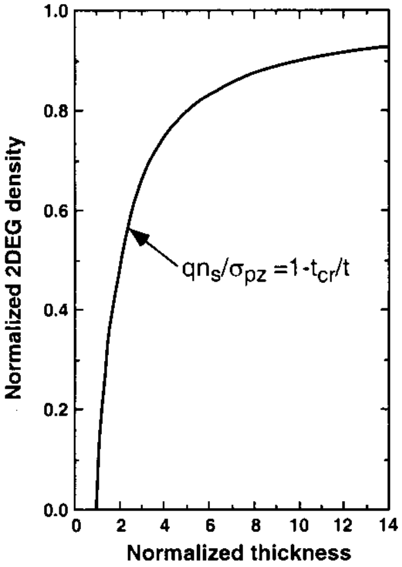
Formation of the 2DEG

- Where do the electrons for the 2DEG "come from"?
- Model: donor-like surface states "provide" electrons

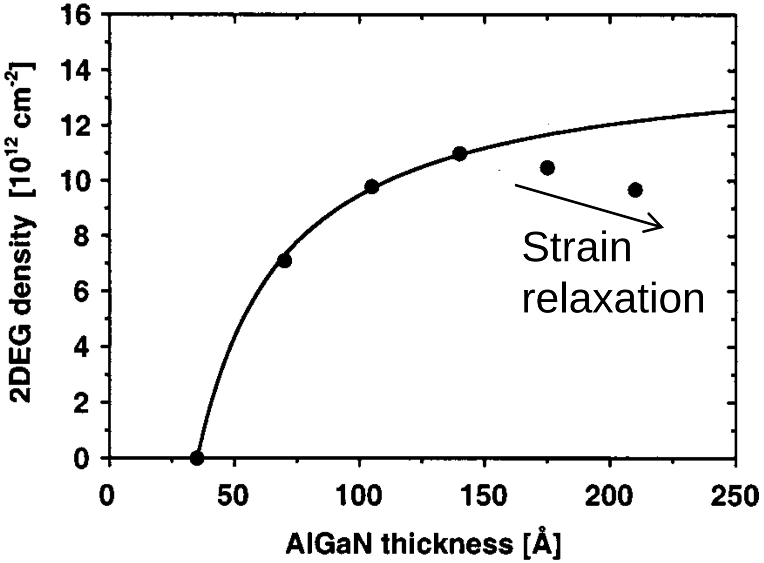
Electrons can come from Ohmic contacts. Surface donors play a role in the electrostatics.

Theory





Measurements



[J. P. Ibbetson *et al.*, Appl. Phys. Lett. **77 (2)**, 250 (2000)]

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GaN wafers

- Choice of substrate is very important

- **Sapphire** (Al_2O_3)
  - ☺ Semi-insulating, can withstand high growth temperatures, relatively cheap
  - ☹ Very low thermal conductivity, large lattice mismatch, large CTE mismatch

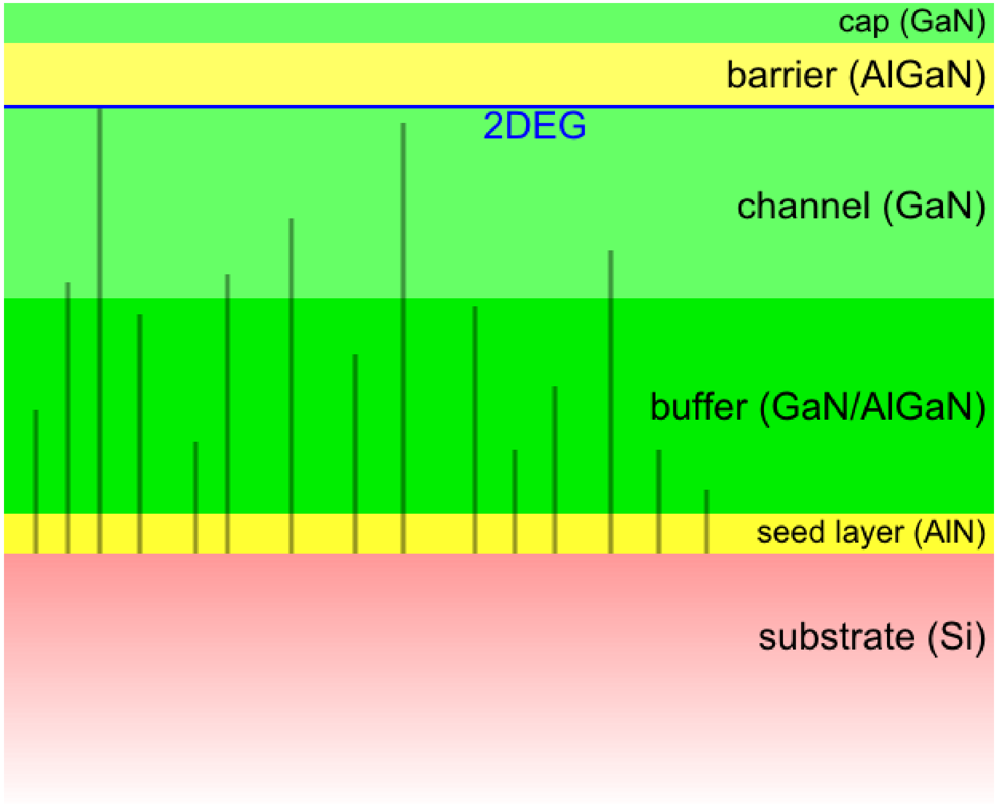
Coefficient of thermal expansion

- **Silicon carbide** (SiC)
  - ☺ High thermal conductivity, low lattice mismatch, relatively low CTE mismatch
  - ☹ High cost, crystallographic defects

- **Silicon** (Si)
  - ☺ Low cost, excellent availability of large diameters, acceptable thermal conductivity, processing in standard silicon fabs (high productivity)
  - ☹ Large lattice mismatch, very large CTE mismatch

GaN-on-Si wafers

- Base: silicon substrate with (111) face
- Example recipe:
  1. Thin seed layer of AlN
  2. Thick buffer layer: superlattice of alternating GaN and AlGaN layers
  3. High-quality GaN layer
  4. AlGaN barrier
  5. GaN cap layer



- Reduce dislocation density
- Stress control / wafer bow

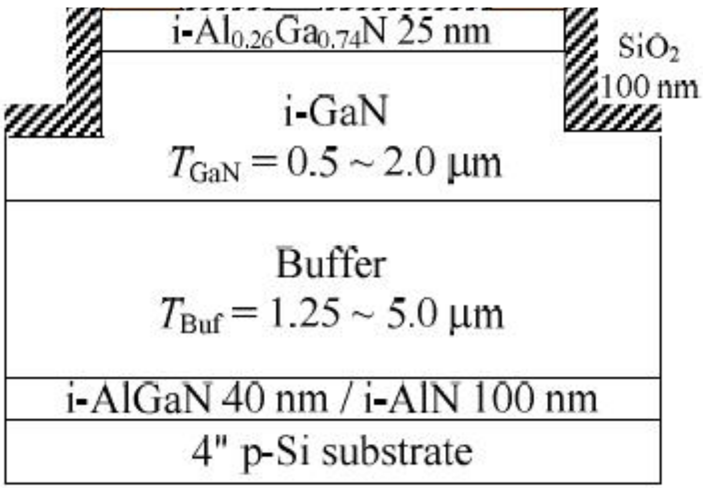
[H. F. Liu *et al.*, J. Appl. Phys. **113**, 023510 (2013)]

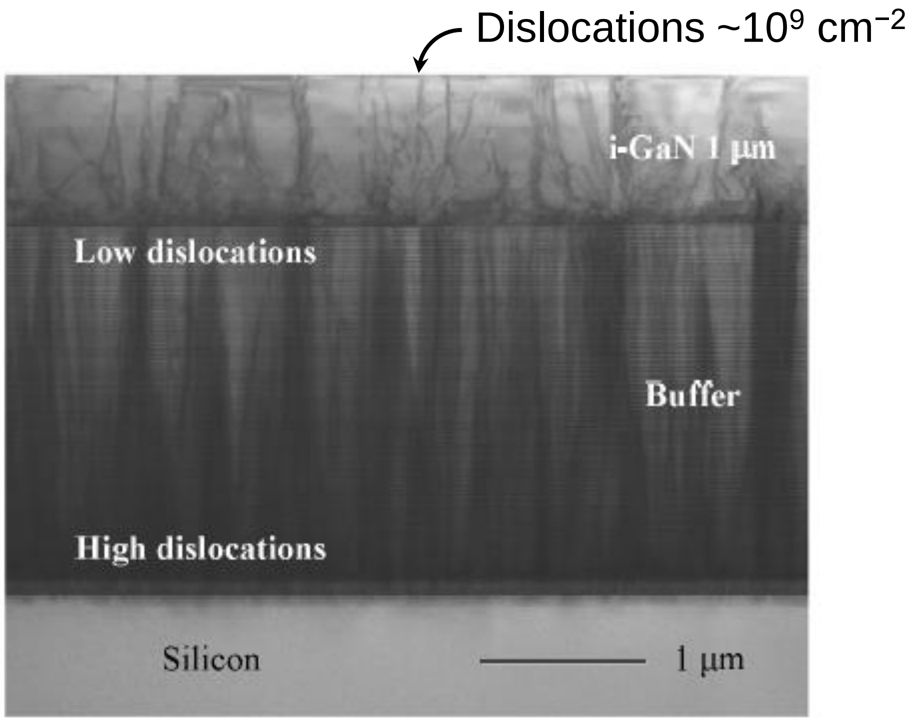
[S. Lenci *et al.*, Elec. Dev. Lett. **34 (8)**, 1035 (2013)]

[D. Marcon *et al.*, Trans. Semi. Manu. **26 (3)**, 361 (2013)]

Dislocations

- High initial dislocation density reduced towards surface (2DEG) by optimisation of buffer design





[S. L. Selvaraj *et al.*, Proc. DRC 2012, 53 (2012)]

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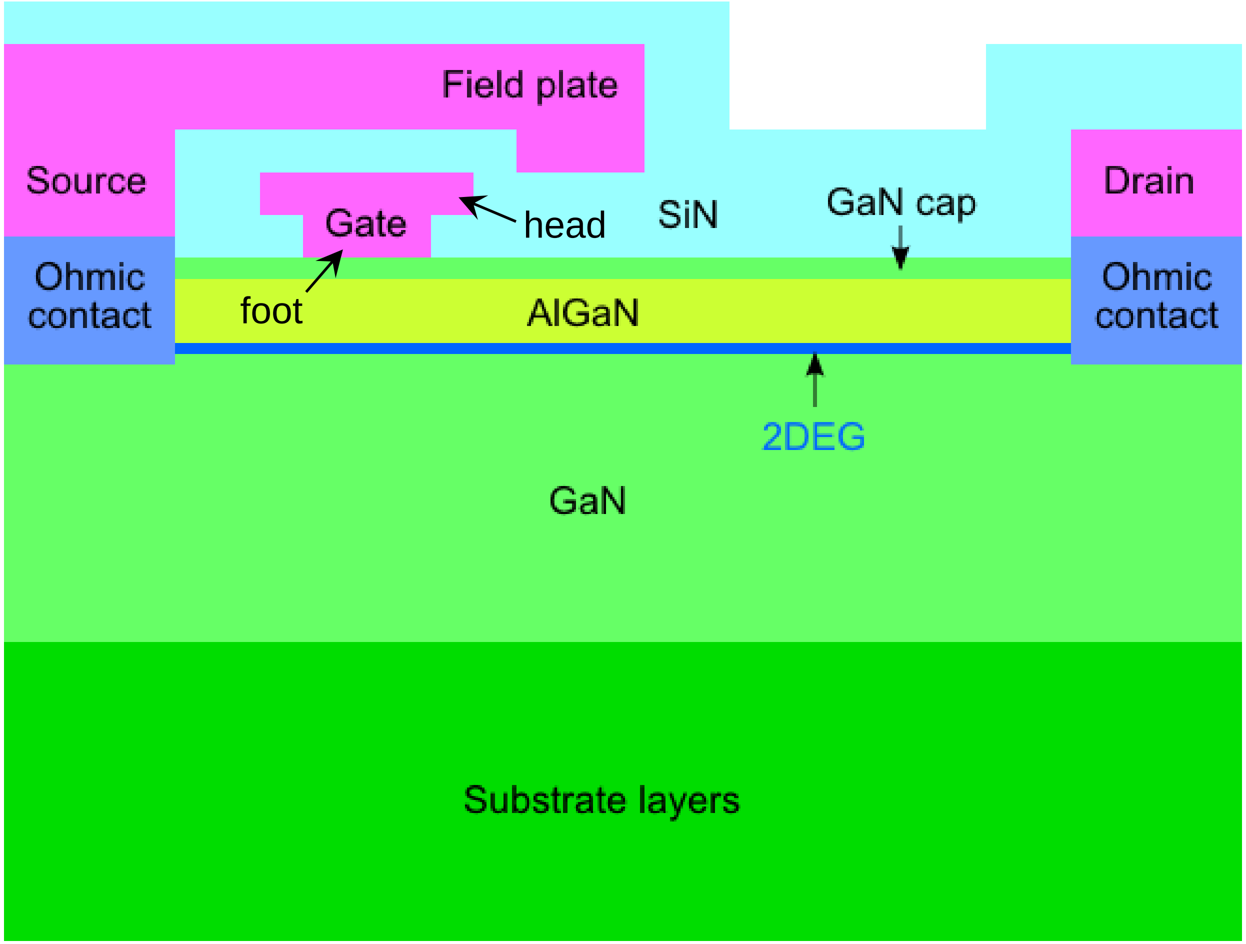
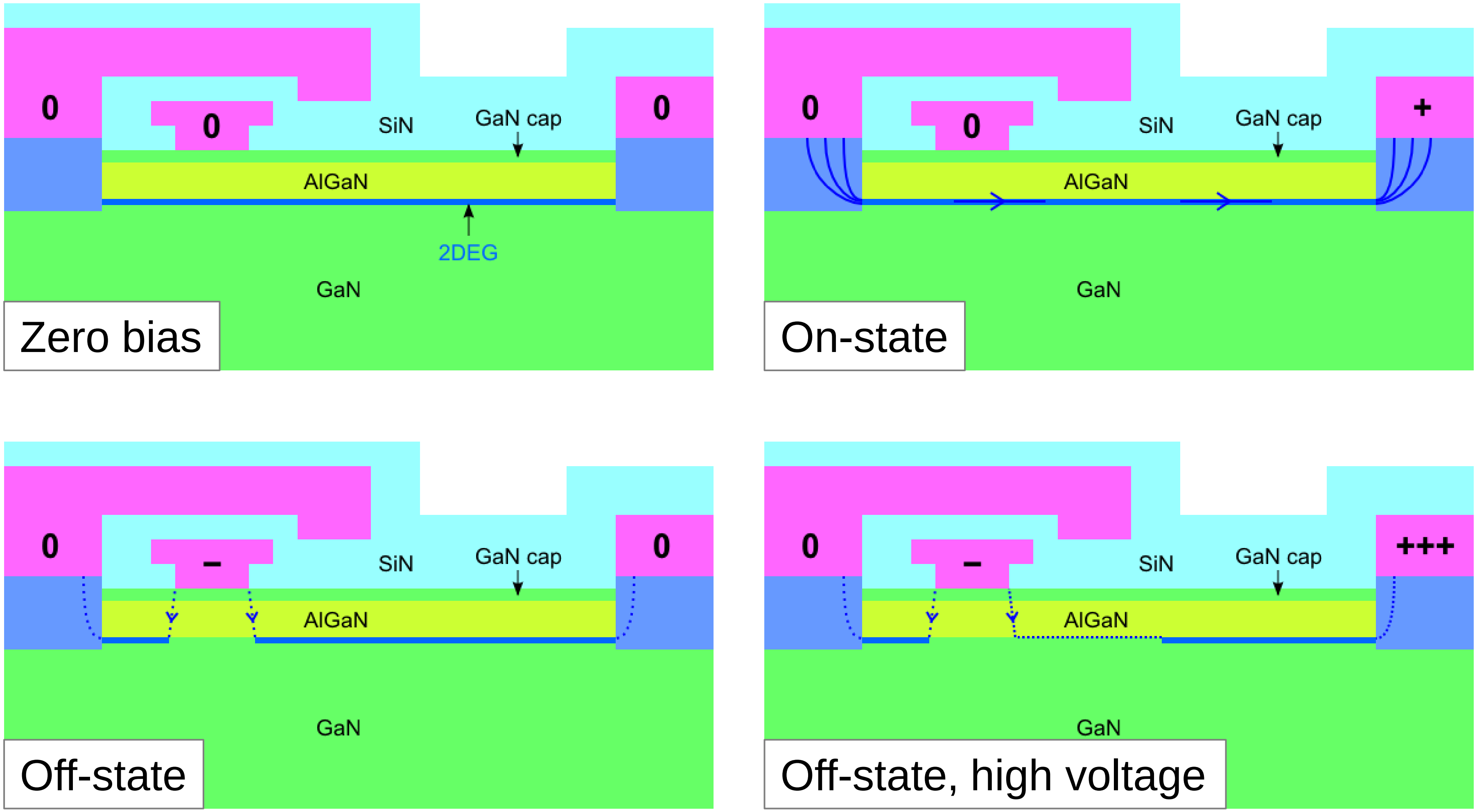
GaN devices
High–electron-mobility transistor (HEMT)

- Ohmic contacts to 2DEG (Ti/Al)
- Source and drain metallisation (Al)
- Gate metal (Ni) on top of GaN cap
  - Schottky contact
- SiN passivation
- Metal field plate(s)



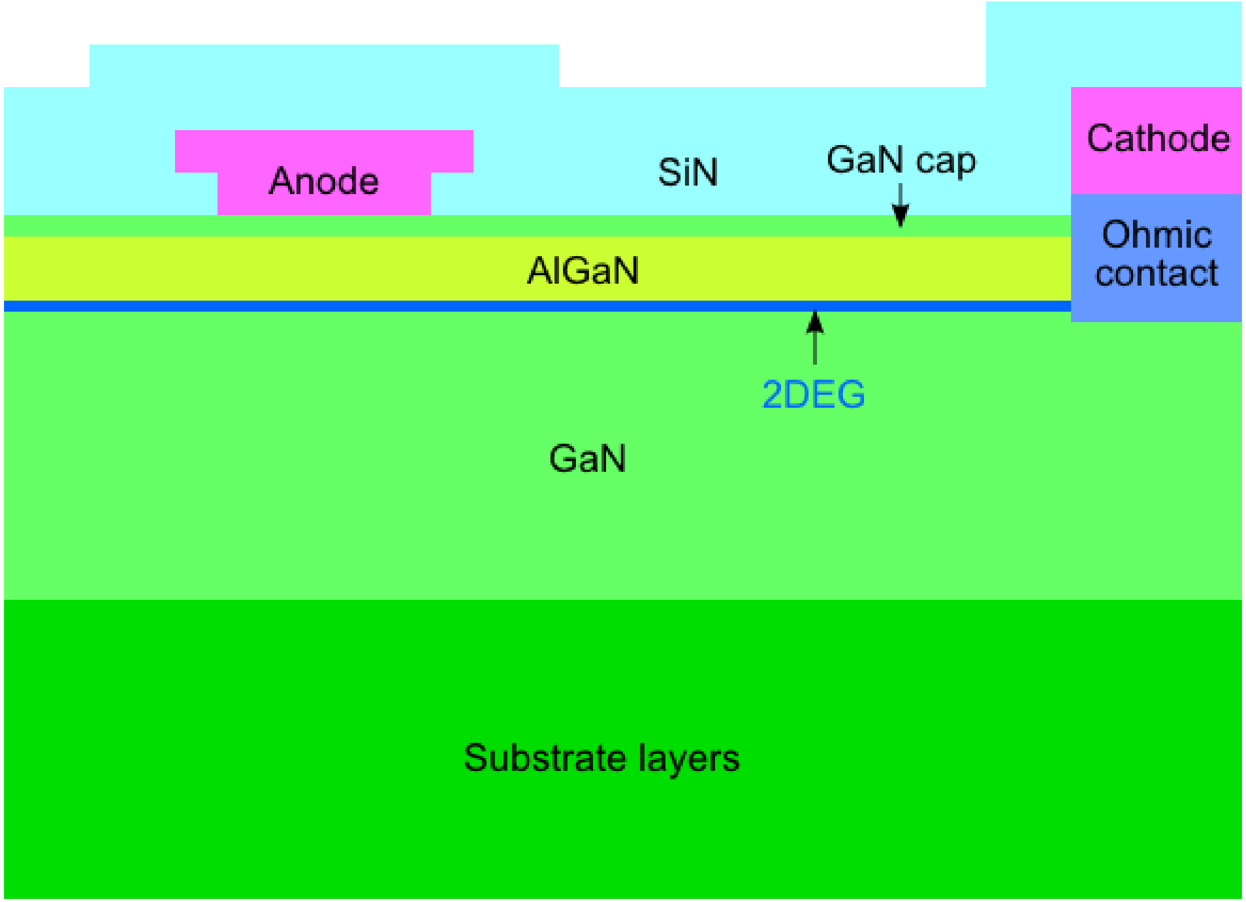
NXP process: [J. J. T. M. Donkers *et al.*, CS-MANTECH 2013, 259]

GaN devices – HEMT operation

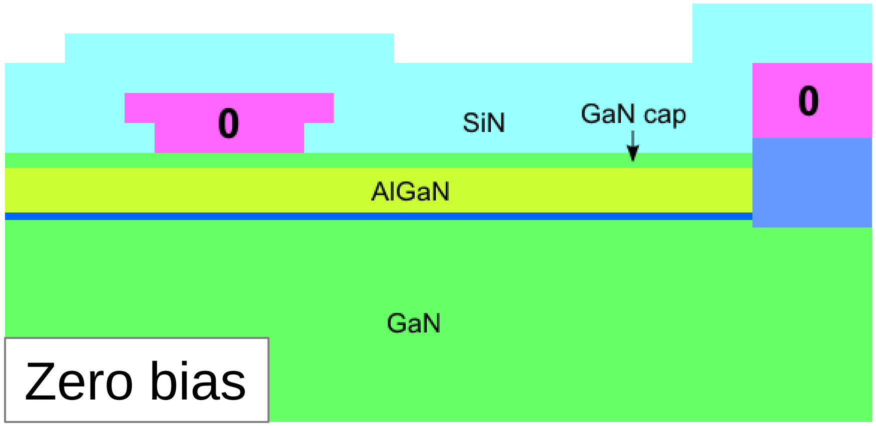


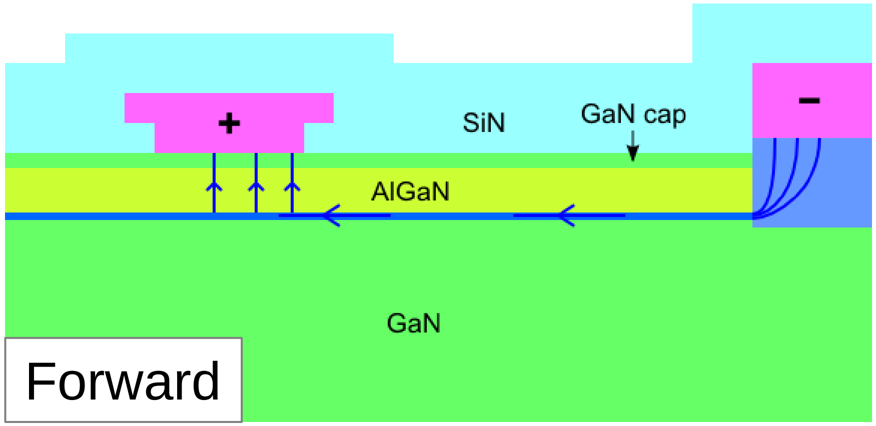
GaN devices
Schottky barrier diode (SBD)

- “HEMT without a source”
- “Gate” → **anode**
  - Longer to handle high current
- “Drain” → **cathode**

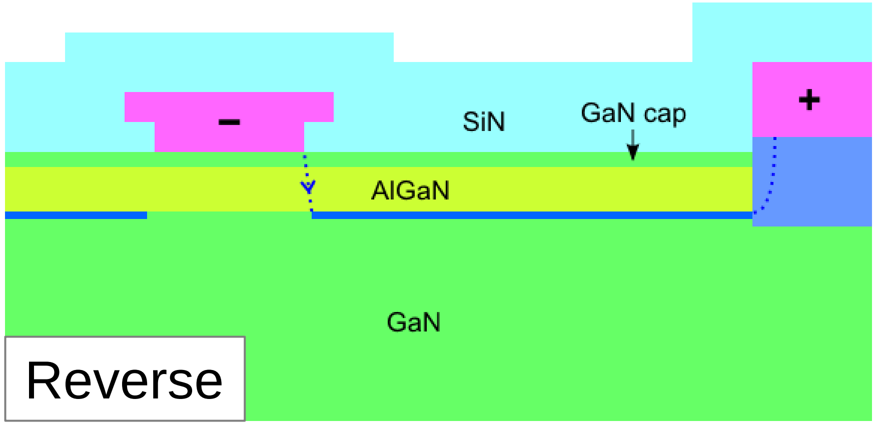


GaN devices – diode operation



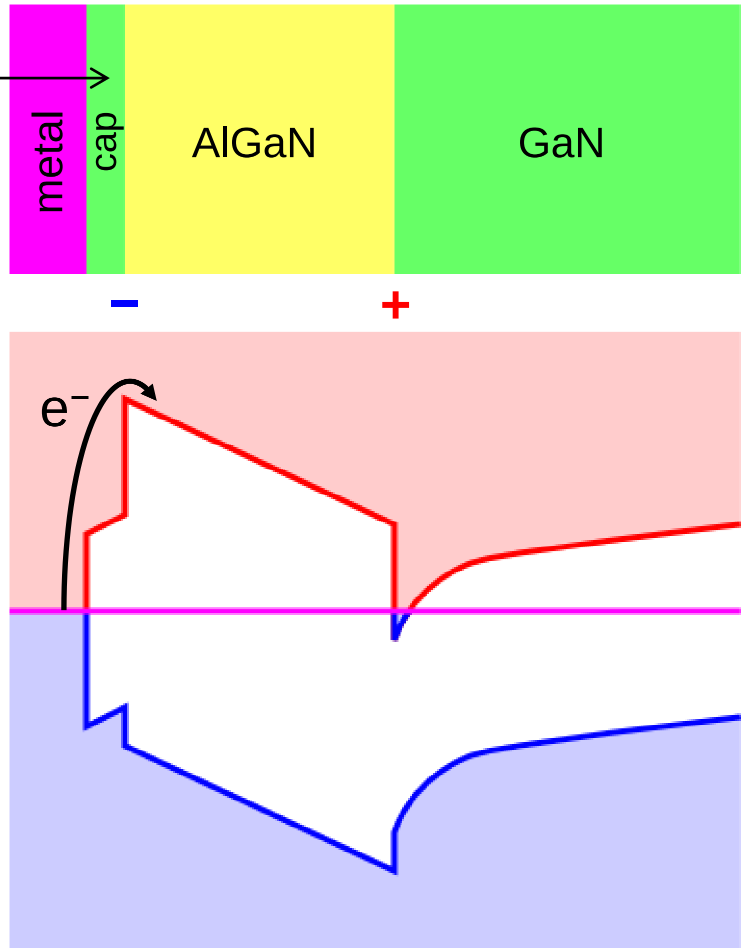


- Forward operation (anode+, cathode−)
  - Electrons flow from 2DEG across AlGaN into anode
- Reverse operation
  - Electron leakage from anode edges



GaN devices – cap layer

- A few extra nanometres of GaN grown on top of AlGaN
- Possible advantages:
  - Decreased reverse leakage through Schottky contact
  - Reduced peak electric field
  - AlGaN protected against processing
  - Nitrogen degassing prevented
  - Increased device gain
  - Increased power added efficiency
  - Improved DC reliability



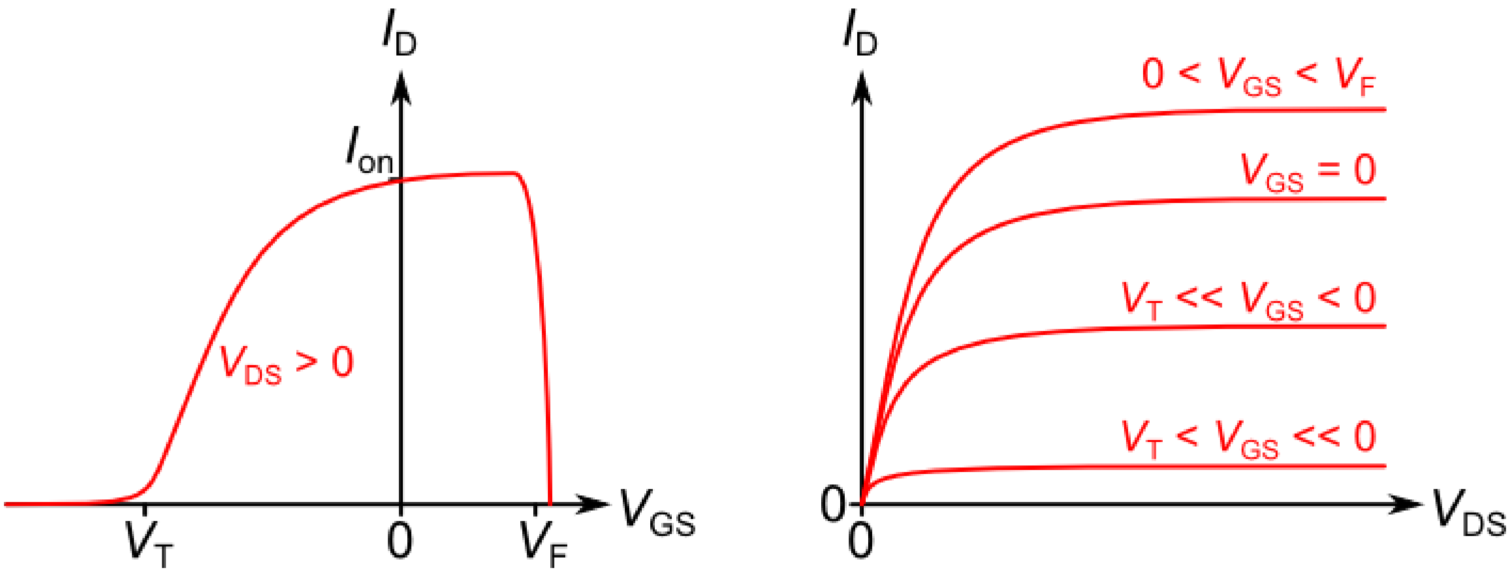
[P. Waltereit *et al.*, J. Appl. Phys. **106**, 023535 (2009)]

[E. T. Yu *et al.*, Appl. Phys. Lett. **73 (13)**, 1880 (1998)]

[S. Arulkumaran *et al.*, Jpn. J. Appl. Phys. **44**, 2953 (2005)]

GaN devices – HEMT characteristics

- V_T: threshold voltage, typically −2 to −4 V
- V_F: diode forward turn-on voltage, typically +1 to +2 V



- I_{on}: on-current, typically taken at V_{GS} = 0 V for V_{DS} = 0.1 V
- ⇒ On-resistance $R_{on} = V_{DS} / I_{on}$

GaN devices – performance

- Wide band gap ⇒ high critical field ⇒ **high voltage**
- High carrier concentration and velocity ⇒ **high current**

High power (high voltage + high current)

High frequency (carrier concentration and velocity)

	Si	GaAs	4H-SiC	GaN	Diamond
E_g (eV)	1.1	1.42	3.26	3.39	5.45
n_i (cm^{-3})	1.5×10^{10}	1.5×10^{6}	8.2×10^{-9}	1.9×10^{-10}	1.6×10^{-27}
ε_r	11.8	13.1	10	9.0	5.5
μ_n (cm^2/V s)	1350	8500	700	1200(Bulk) 2000(2DEG)	1900
v_{sat} (10^7cm/s)	1.0	1.0	2.0	2.5	2.7
E_{br} (MV/cm)	0.3	0.4	3.0	3.3	5.6
Θ (W/cm K)	1.5	0.43	3.3-4.5	1.3	20
$JM = \frac{E_{br}v_{sat}}{2\pi}$	1	2.7	20	27.5	50

[U. K. Mishra *et al.*, Proc. IEEE **96 (2)**, 287 (2008)]

Johnson's figure of merit (rel. to Si) → Suitability for high-frequency power applications

[A. Johnson, RCA Review **26**, 163 (1965)]

GaN devices – performance

$$\text{BFOM} = \varepsilon_r \, \mu \, E_c^3$$

Relative permittivity (ε_r); Carrier mobility (μ); Critical electric field (E_c)

- **Baliga figure of merit**
  - Based on minimising the conduction losses in power FETs
  - Assumes power losses are solely due to the on-state power dissipation
  - Applies to lower frequencies where conduction losses dominate

[B. J. Baliga, Elec. Dev. Lett. **10 (10)**, 455 (1989)]

Material	E_g (eV)	ε_s	μ_n (cm^2/Vs)	E_c (MV/cm)	v_{sat} (10^7 cm/s)	n_i (cm^{-3})	BFOM*
Si	1.12	11.8	1350	0.3	1.0	1.5×10^{10}	1
GaAs	1.42	13.1	8500	0.4	2.0	1.8×10^{6}	17
4H-SiC	3.26	10	720	2.0	2.0	8.2×10^{-9}	134
6H-SiC	2.86	9.7	370	2.4	2.0	2.4×10^{-5}	115
2H-GaN	3.44	9.5	900	3.0	2.5	1.0×10^{-10}	537

E_g, bandgap; ε_s, dielectric constant; μ_n, electron mobility; E_c, critical electric field; v_{sat}, saturation velocity; n_i, intrinsic carrier density.

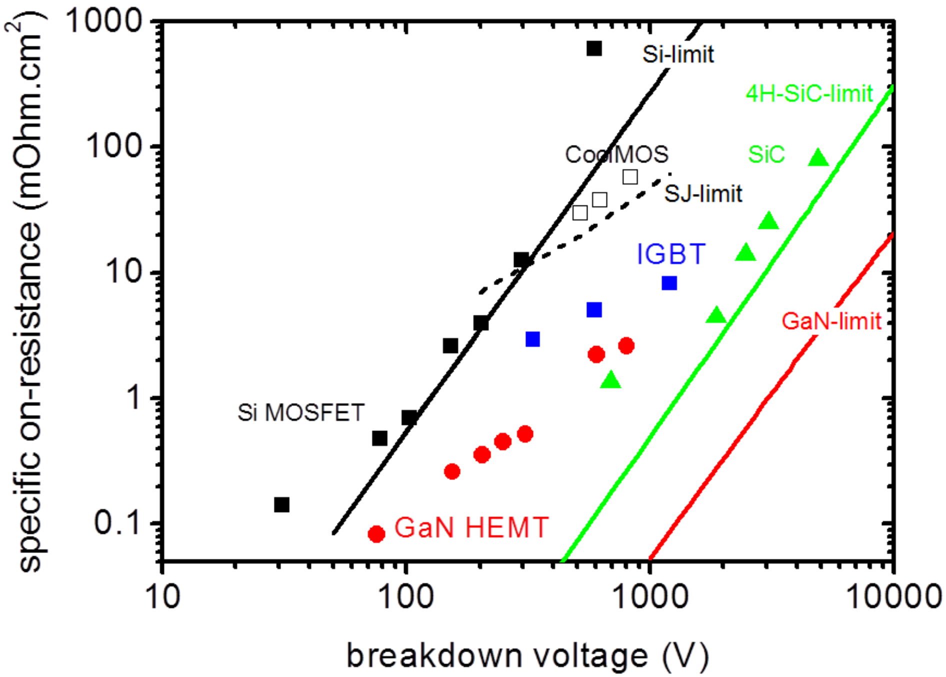
*BM=$\varepsilon\mu E_c^3$, BFOM was normalized by the BM of Si.

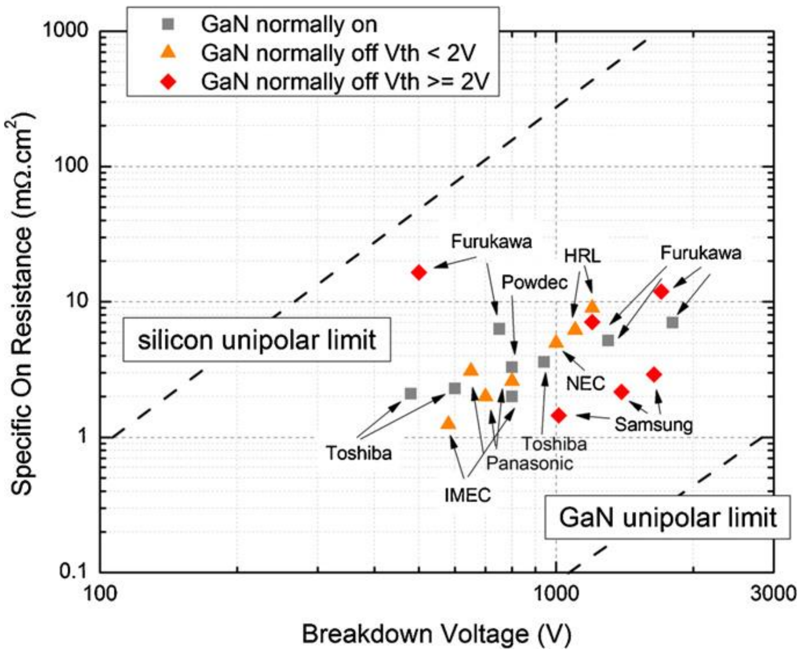
Sometimes E_g is used!

[N. Ikeda *et al.*, Proc. IEEE **98 (7)**, 1151 (2010)]

GaN devices – benchmarking

- Minimise **specific on-resistance** ($R_{on} \times A$)
- Maximise **breakdown voltage**

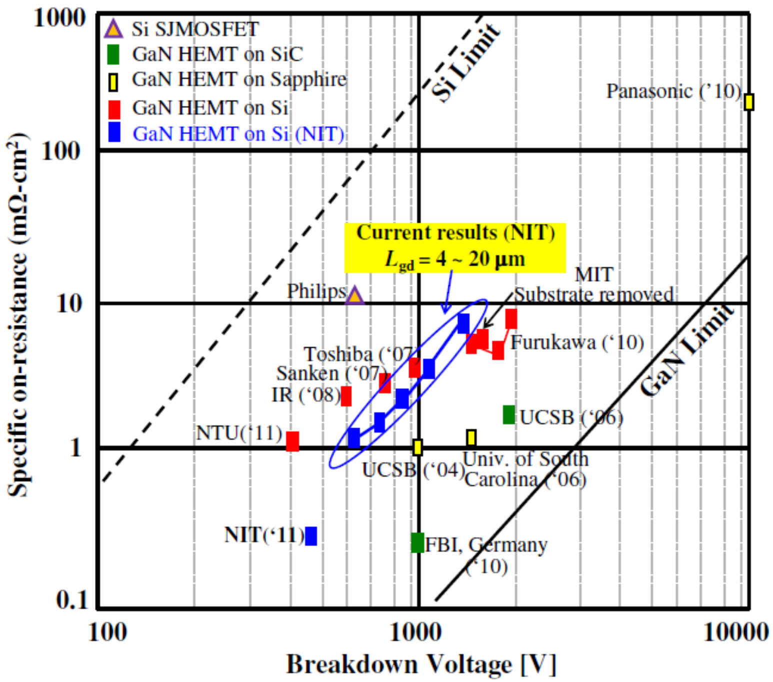




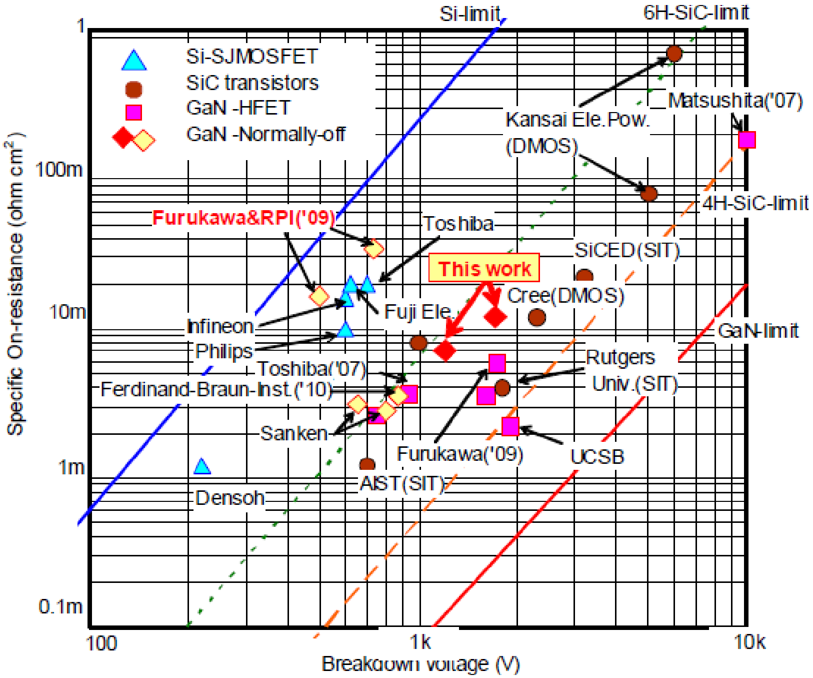
[M. Su *et al.*, Semicond. Sci. Technol. **28**, 074012 (2013)]

GaN devices – benchmarking

- Some more **specific–on-resistance *vs.* breakdown-voltage** plots



[S. L. Selvaraj *et al.*, Proc. DRC 2012, 53]



[N. Ikeda *et al.*, Proc. ISPSD 2011, 284]

See also [Q. Jiang *et al.*, EDL **34 (3)**, 357 (2013)] and
[Z. Tang *et al.*, EDL **34 (3)**, 366 (2013)]

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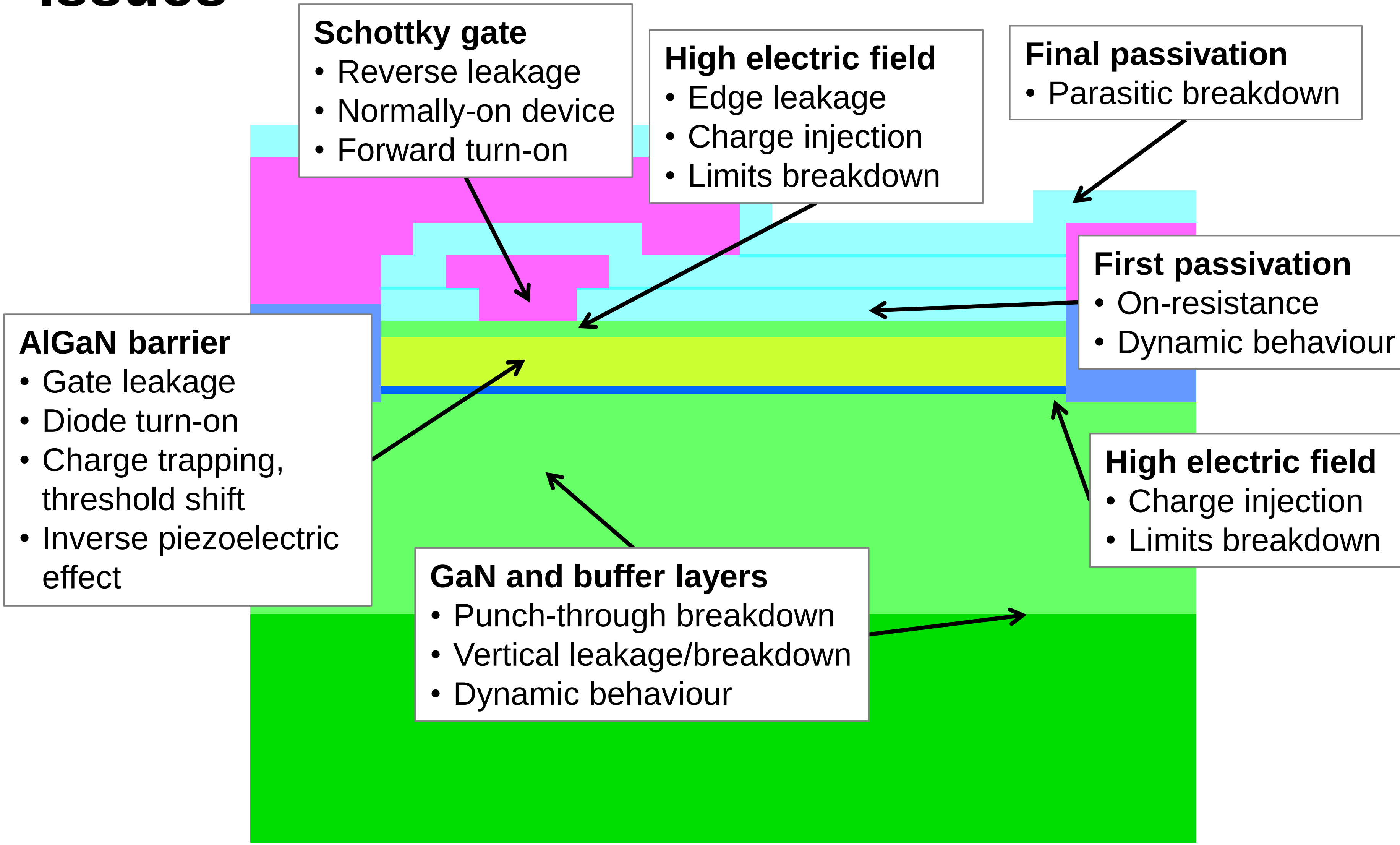
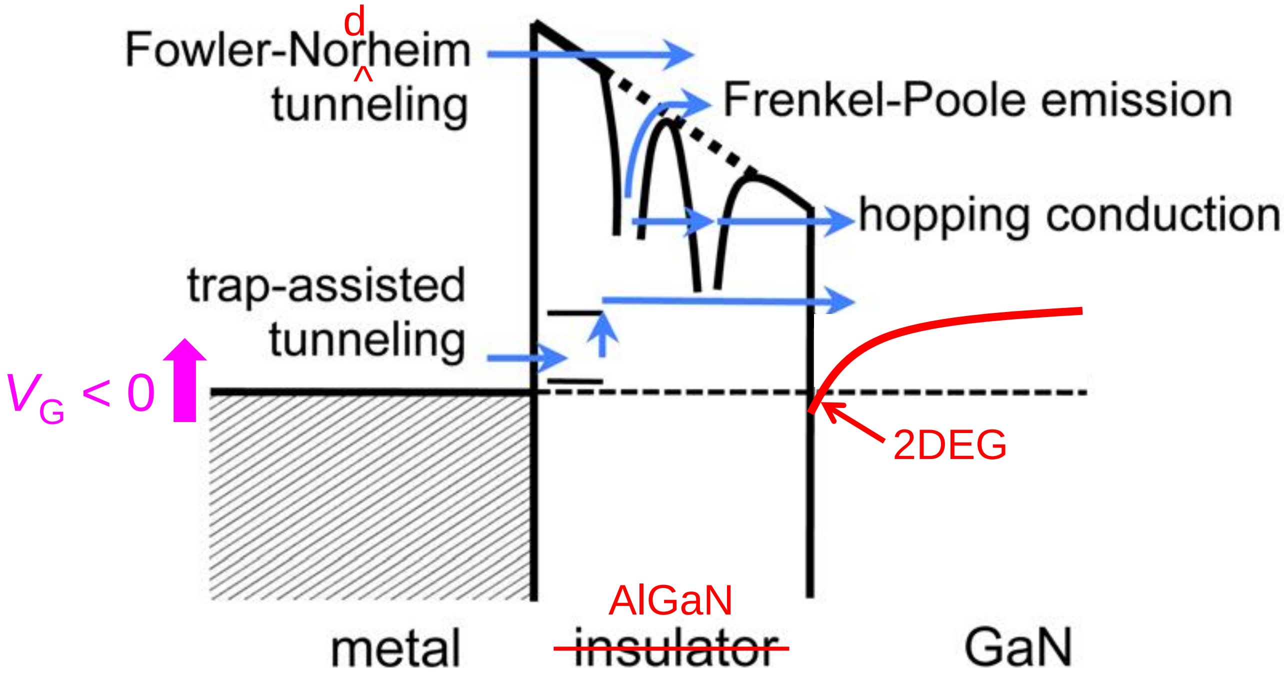
Issues



Schottky gate
• Reverse leakage
• Normally-on device
• Forward turn-on
High electric field
• Edge leakage
• Charge injection
• Limits breakdown
Final passivation
• Parasitic breakdown
First passivation
• On-resistance
• Dynamic behaviour
AlGaN barrier
• Gate leakage
• Diode turn-on
• Charge trapping, threshold shift
• Inverse piezoelectric effect
High electric field
• Charge injection
• Limits breakdown
GaN and buffer layers
• Punch-through breakdown
• Vertical leakage/breakdown
• Dynamic behaviour

Issues – gate leakage

- Various mechanisms potentially involved in gate leakage

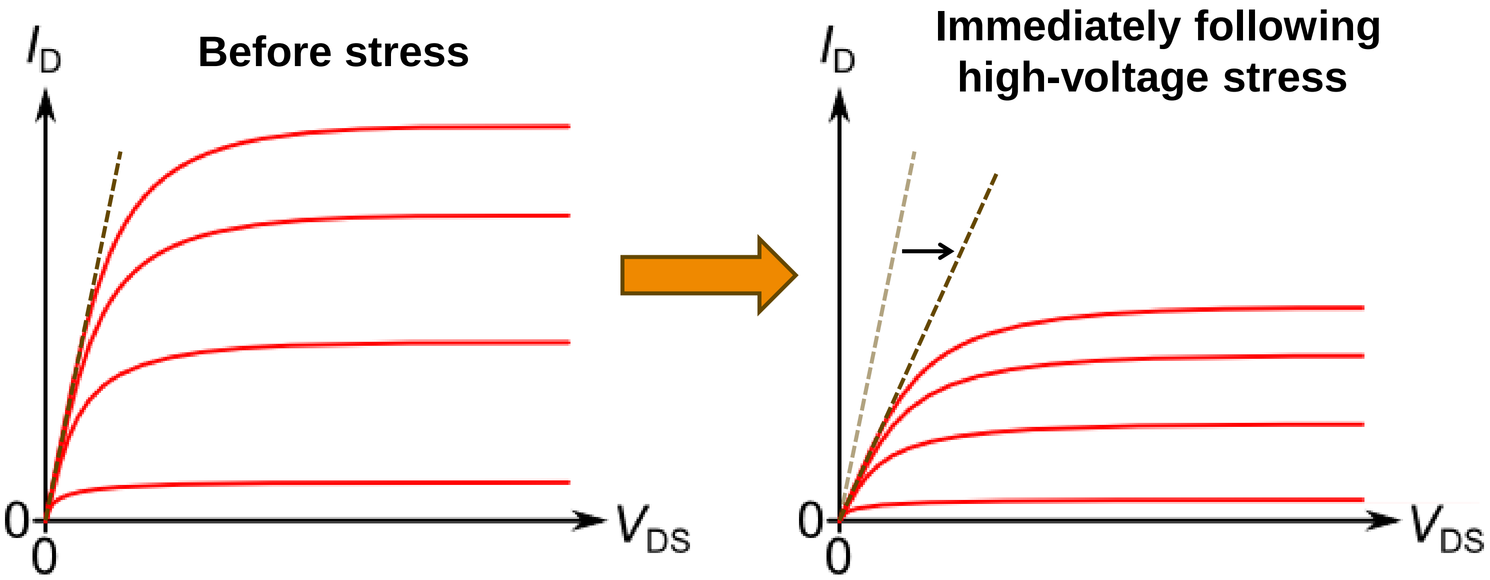


[B. S. Eller *et al.*, J. Vac. Sci. Technol. A **31 (5)**, 050807 (2013)]

See also [L. Xia *et al.*, Appl. Phys. Lett. **102 (11)**, 113510 (2013)]

Issues – current collapse

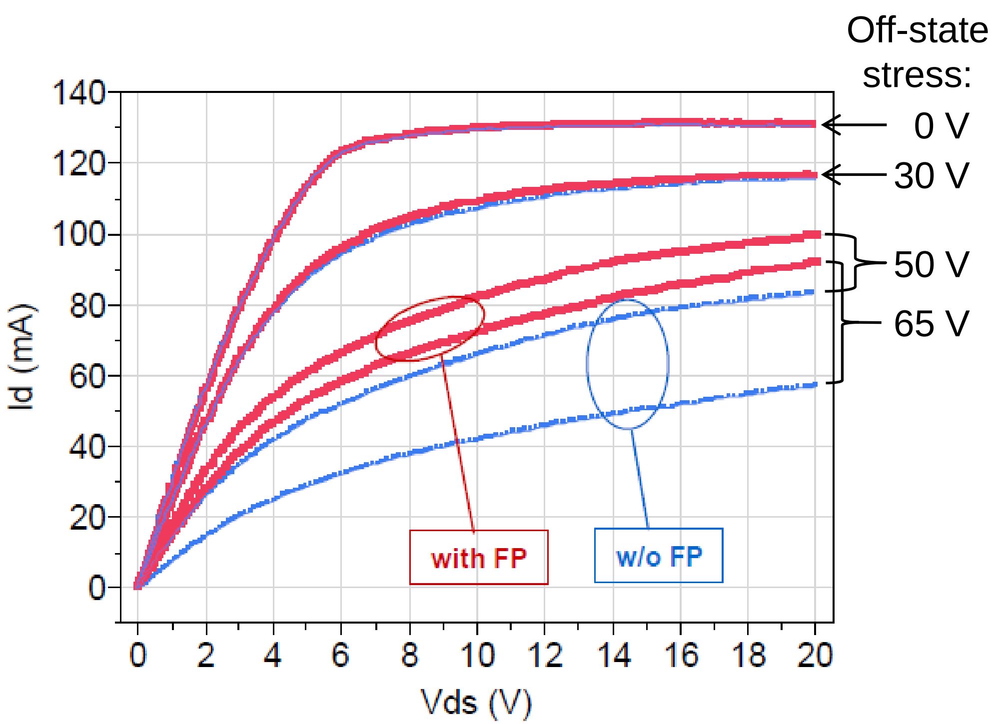
- On-state current temporarily reduced following off-state stress

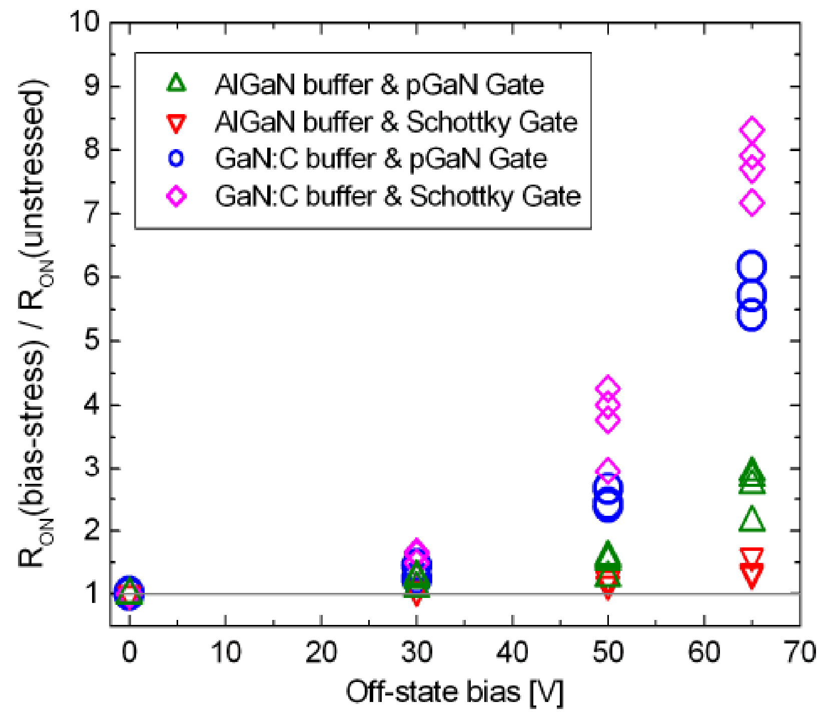


- Also known as **dynamic *R*$_{on}$**
  – On-state resistance depends on recent history of device biasing

Issues – current collapse

- Device design and substrate composition can have a strong influence on the magnitude of current collapse (dynamic-R_{on} increase)



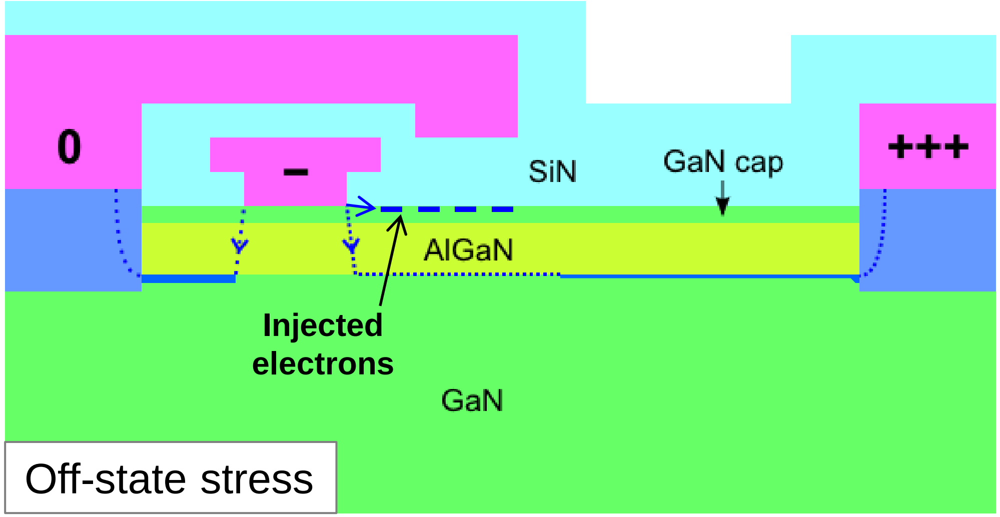


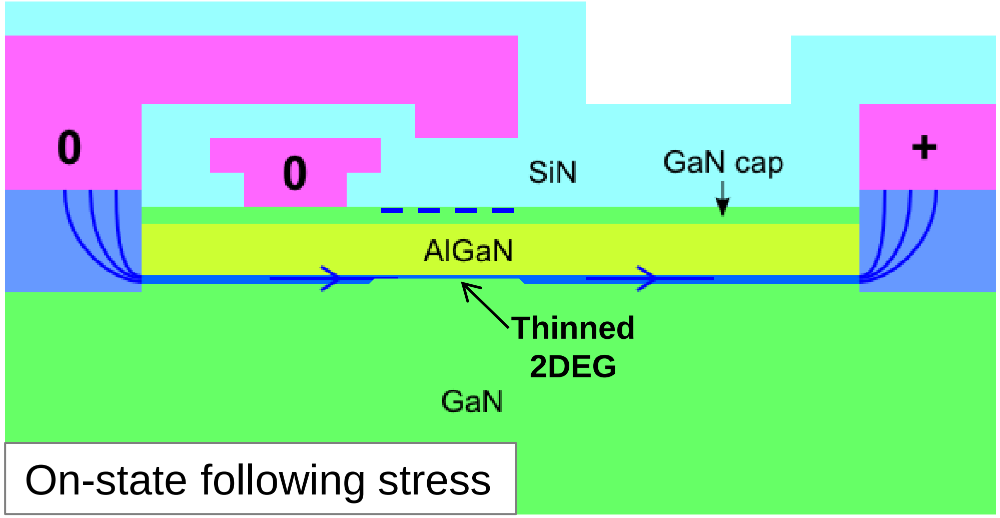
[O. Hilt *et al.*, Proc. ISPSD 2012, 345 (2012)]

Also [S. DasGupta *et al.*, Appl. Phys. Lett. **101 (24)**, 243506 (2012)]

Issues – virtual-gate effect

- **Off-state stress:**
  - Electrons from gate injected into trap states next to gate
- **On-state after stress:**
  - Trapped electrons act like a negatively biased gate
  - 2DEG partially depleted underneath ⇒ increased R_{on}
- **Later (~seconds):**
  - Electrons de-trap, 2DEG current restored



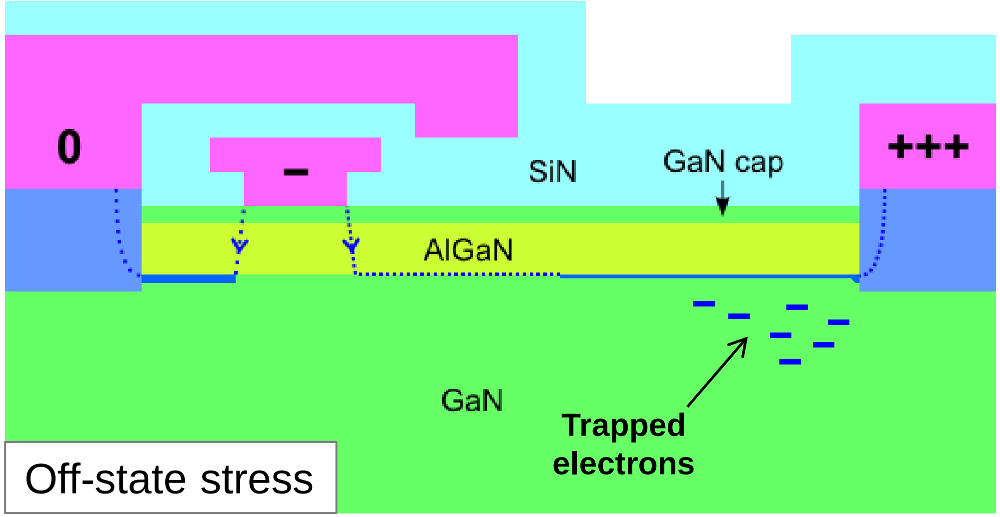


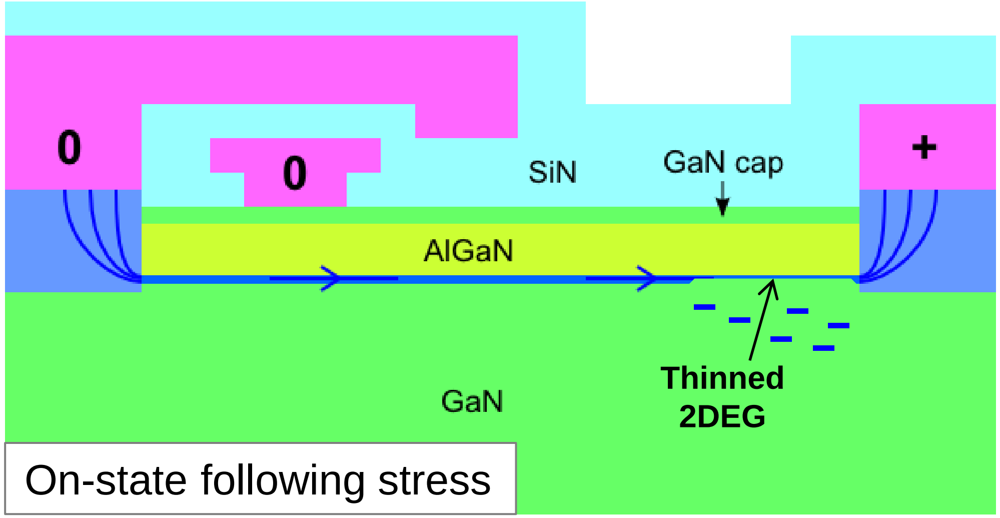
[R. Vetury *et al.*, Trans. Elec. Dev. **48 (3)**, 560 (2001)]
[T. Mizutani *et al.*, TED **50**, 2015 (2003)]

Issues – buffer trapping

- **Off-state stress:**
  - Electrons trapped in bulk (deep donors/acceptors?)
- **On-state after stress:**
  - Trapped electrons partially deplete the 2DEG above $\Rightarrow$ increased R_{on}
- **Later (~minutes):**
  - Electrons de-trap, 2DEG current restored

[M. J. Uren *et al.*, Trans. Elec. Dev. **59 (12)**, 3327 (2012)] and refs. therein





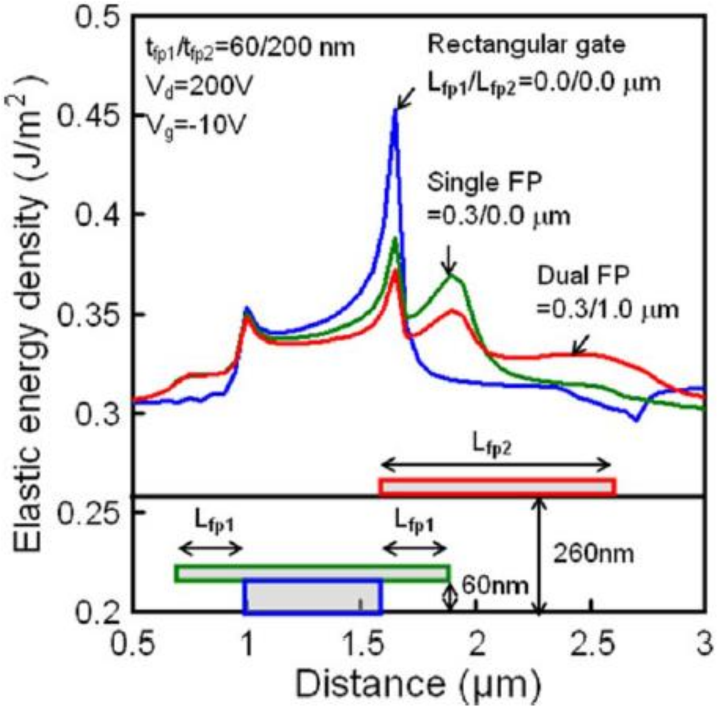
[E. Kohn *et al.*, Trans. Microw. Theory Tech. **51 (2)**, 634 (2003)]

Issues – inverse piezoelectric effect

- **Piezoelectric effect:**
  mechanical stress ⇒ polarisation (*i.e.*, internal electric field)
- **Inverse (or converse) piezoelectric effect:**
  applied voltage ⇒ electric field
  ⇒ mechanical stress

  [J. Joh *et al.*, Microelec. Reliab. **50 (6)**, 767 (2010)]

- High field at drain-side edge of gate
  ⇒ local stress ⇒ defect formation
  ⇒ device degradation (reliability)
  - Mitigate with field-plate design →
  - Not the full story…
    See [Meneghesso / Meneghini / Zanoni]



[Y. Ando *et al.*, TED **59 (12)**, 3350 (2012)]

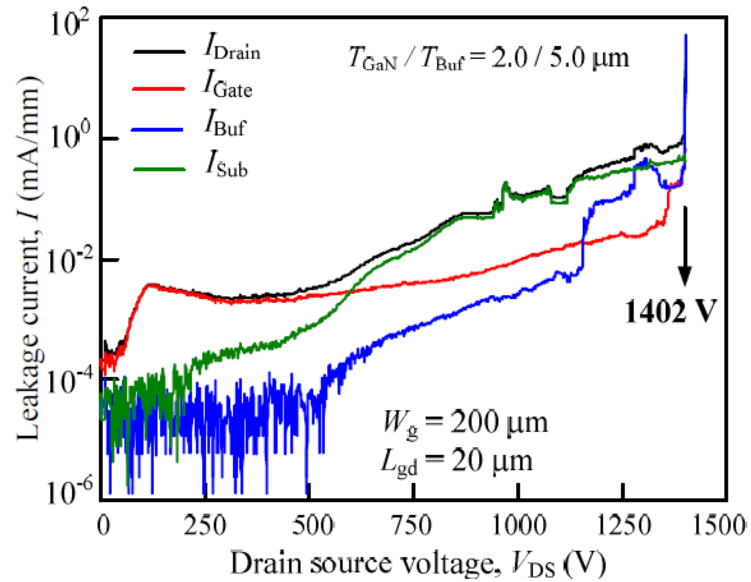
Also [N. A. Mahadik *et al.*, Appl. Phys. Lett. **93 (26)**, 262106 (2008)]

Outline

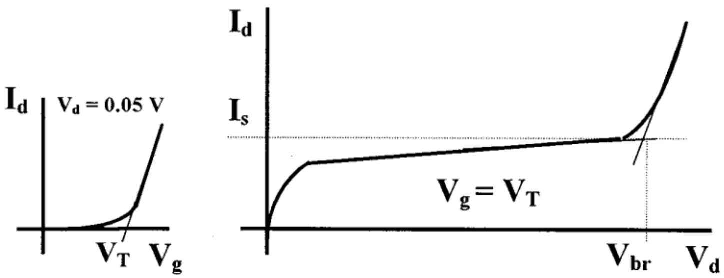
- GaN and related materials
- The AlGaN/GaN heterostructure
- GaN wafers
- GaN devices
- Issues facing high-voltage GaN-HEMT development
- **High-voltage breakdown**
- GaN-HEMT device simulation
- Compact modelling of GaN HEMTs
- Summary and conclusion

Breakdown – measurement

- Typical breakdown measurement:
  - Start with all terminal biases zero
  - Reduce V_G to a few volts below threshold
  - Increase V_D and record terminal currents
- Current criterion often used for defining breakdown voltage V_{br} (*e.g.*, V_{DS} for I_D = 1 mA/mm)
- Other definitions for V_{br} used!



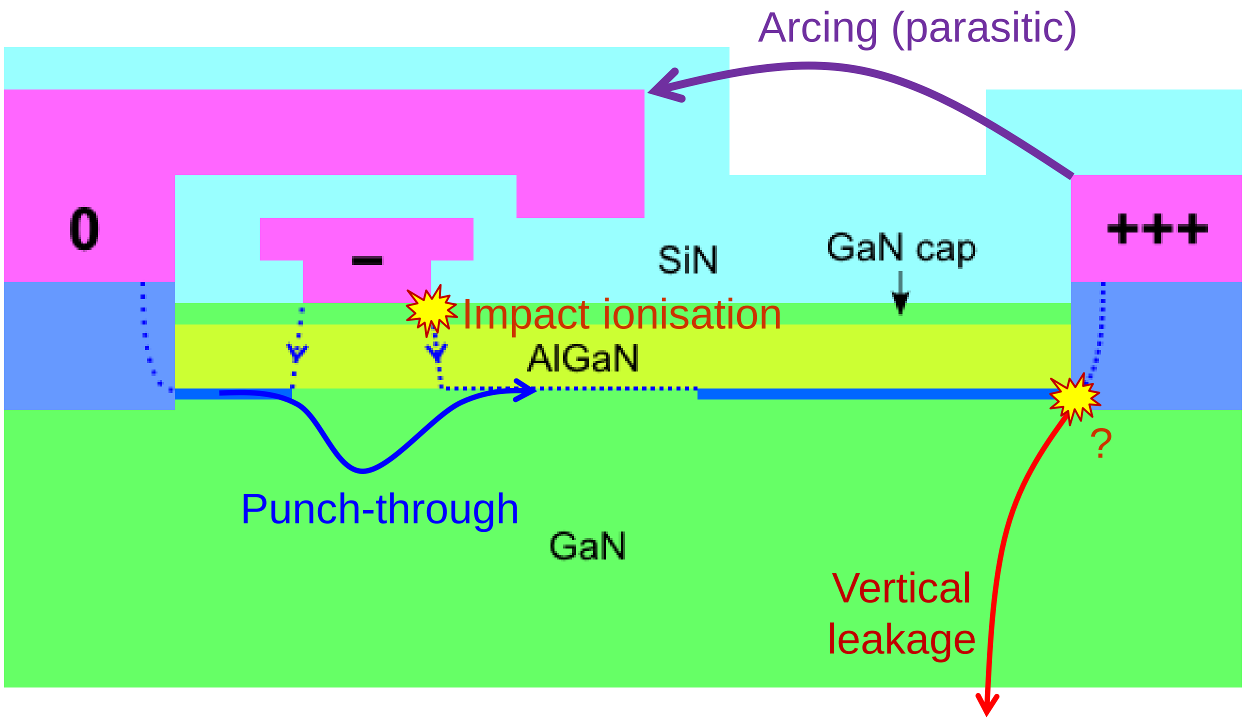
[S. L. Selvaraj *et al.*, Elec. Dev. Lett. **33 (10)**, 1375 (2012)]



[S. Karmalkar and U. K. Mishra, Trans. Elec. Dev. **48 (8)**, 1515 (2001)]

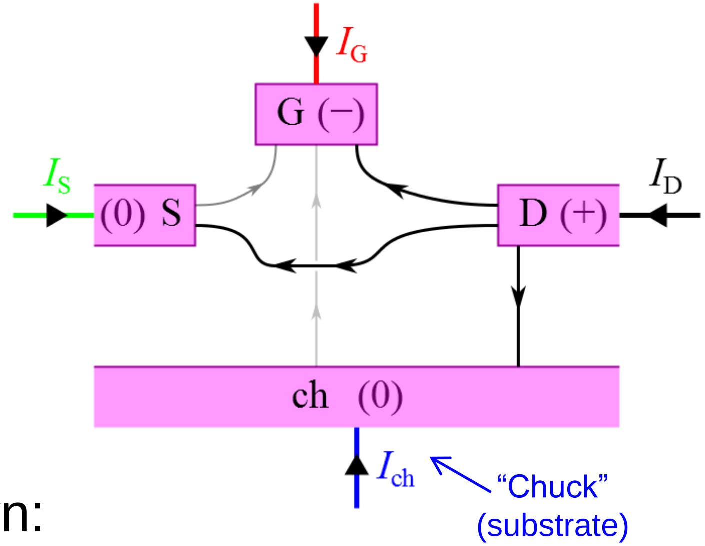
- Drain injection technique: V_S = 0, set I_D, sweep V_{GS} and find max. V_{DS}
  [S. R. Bahl and J. A. del Alamo, Trans. Elec. Dev. **40 (8)**, 1558 (1993)]
  [M. Wang and K. J. Chen, Tran. Elec. Dev. **57 (7)**, 1492 (2010)]

Breakdown – mechanisms

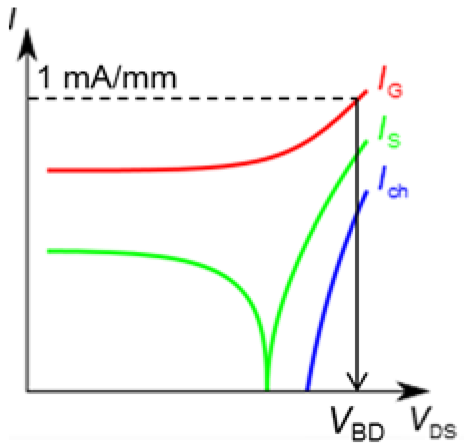


- **Extrinsic:** air arcing, conductive surface layer
- **Intrinsic:** impact ionisation, punch-through, vertical breakdown

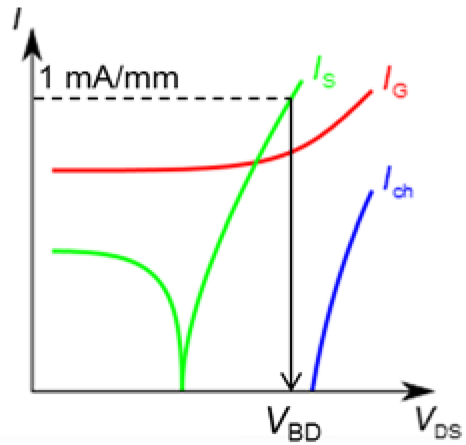
Breakdown – mechanisms



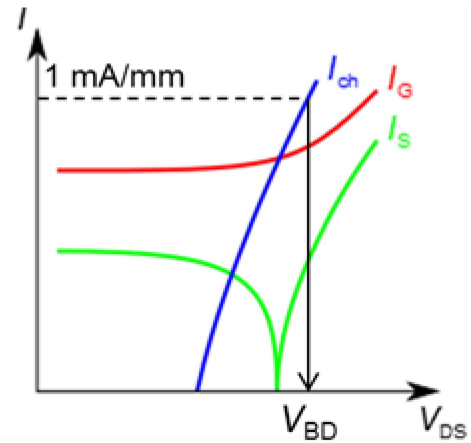
- Compare terminal currents to assess the relative contributions of different physical mechanisms to breakdown
- Example using current criterion for breakdown:



Dominated by gate-leakage impact-ionisation



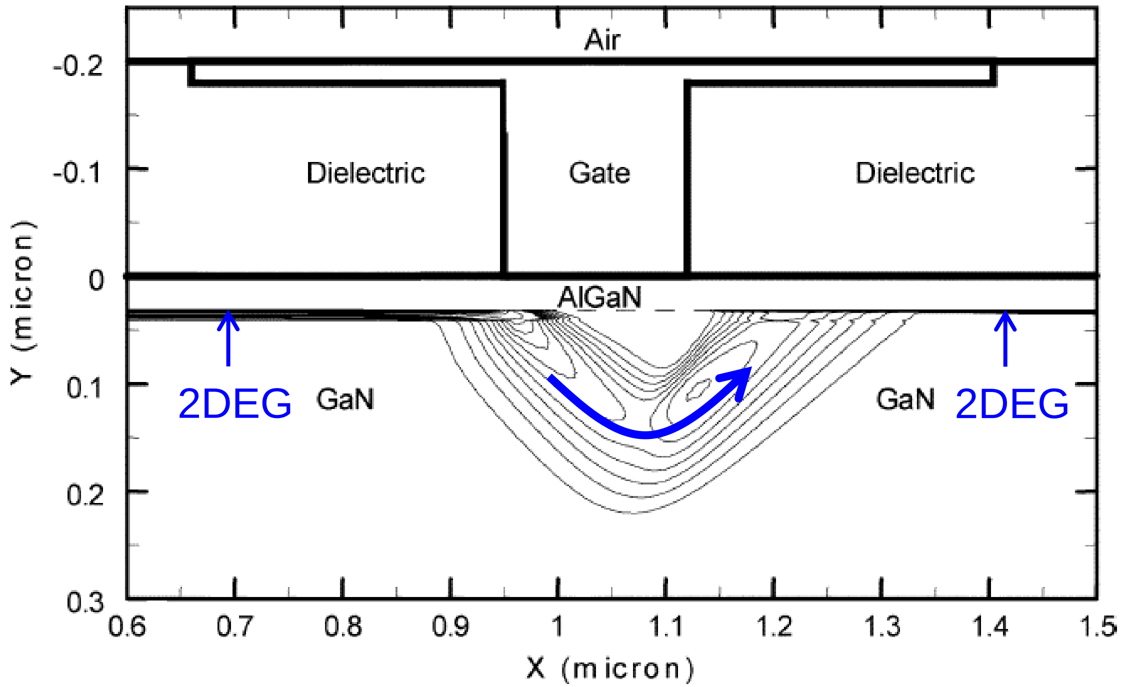
Dominated by drain-to-source punch-through



Dominated by vertical current

Breakdown – punch-through

- At high drain biases in the off-state, electrons can travel through the bulk GaN underneath the (turned-off) gate ⇒ drain-to-source current

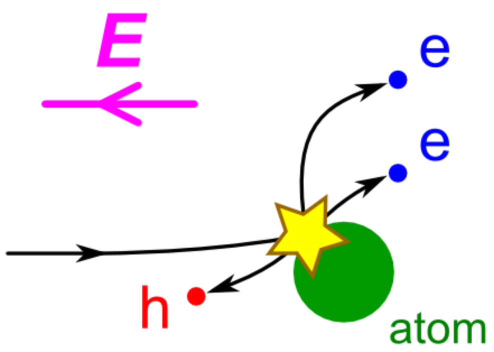


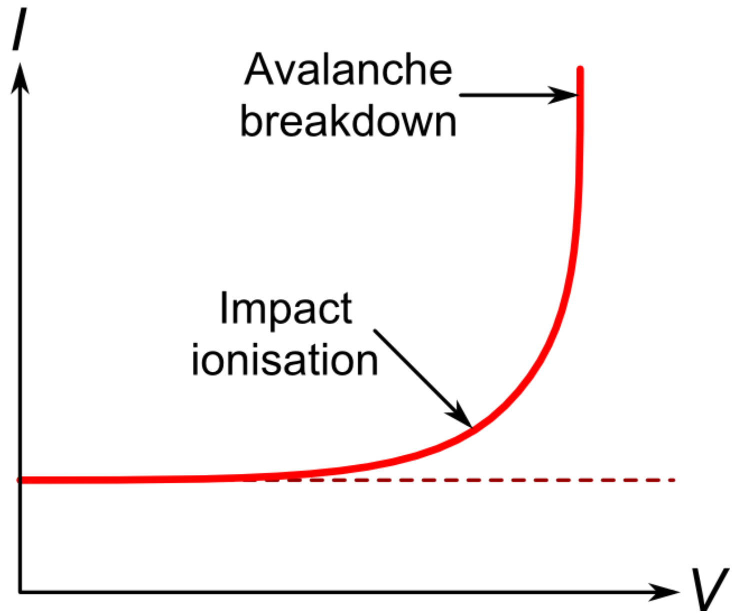
- Prevent using: longer gate, acceptor doping in the bulk, back barrier, …

[M. J. Uren *et al.*, Trans. Elec. Dev. **53 (2)**, 395 (2006)]

Breakdown – impact ionisation

- **Impact ionisation:** high-energy electrons (or holes) can knock other electrons out of valence-band states into conduction-band states, creating electron-hole pairs and hence raising the current





- **Avalanche breakdown:** *every* electron (or hole) creates another electron-hole pair, and the current grows uncontrollably

Breakdown – impact ionisation

- Positive temperature coefficient: V_{br} increases with increasing T
  $\Rightarrow$ suggests impact ionisation (increased phonon scattering)

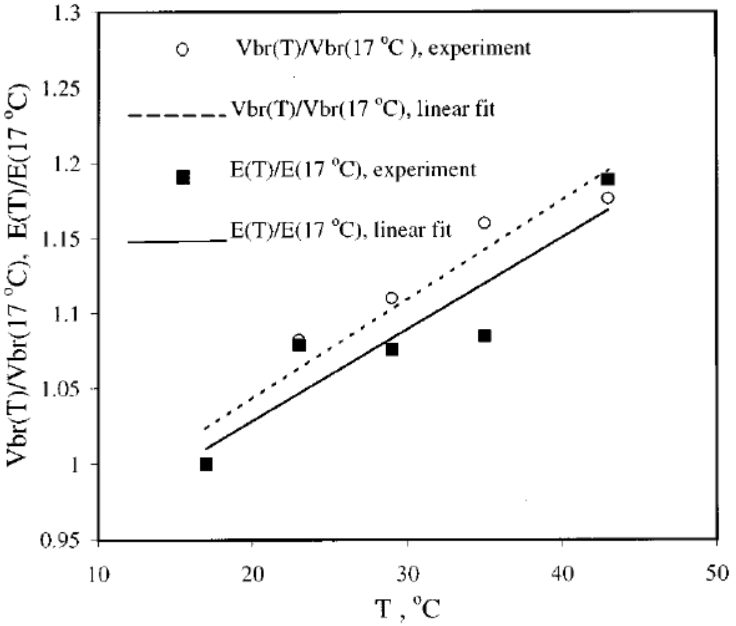
  [N. Dyakonova *et al.*, Electron. Lett. **34 (17)**, 1699 (1998)]
  [T. Nakao *et al.*, Phys. Stat. Sol. (c) **0 (7)**, 2335 (2003)]
  [M. Wang and K. J. Chen, TED **57 (7)**, 1492 (2010)]
  [X. Z. Dang *et al.*, Electron. Lett. **35 (7)**, 602 (1999)]
  [B. Brar *et al.*, Proc. HPD 2002, 487 (2002)]

- Impact-ionisation parameters for GaN have been evaluated theoretically

  [J. Kolník *et al.*, J. Appl. Phys. **81 (2)**, 726 (1997)]
  [F. Bertazzi *et al.*, J. Appl. Phys. **106**, 063718 (2009)]

- …and determined experimentally

  [K. Kunihiro *et al.*, EDL **20 (12)**, 608 (1999)]

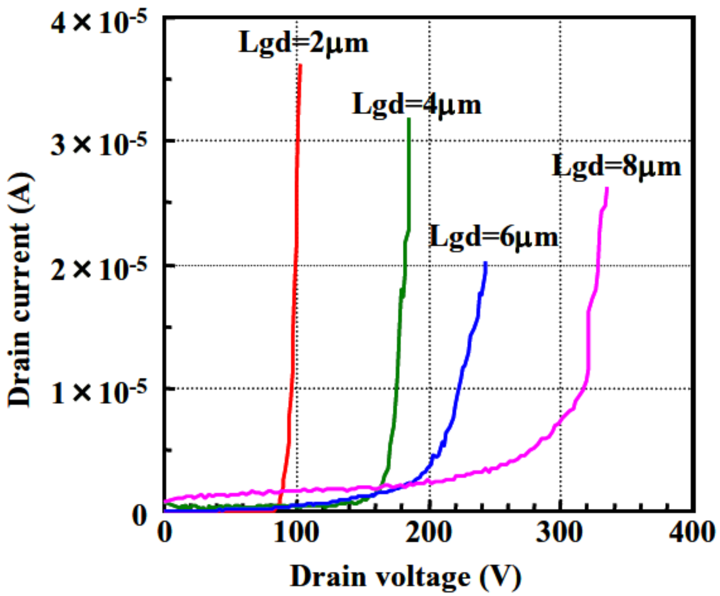


[N. Dyakonova *et al.*, Appl. Phys. Lett. **72 (10)**, 2562 (1998)]

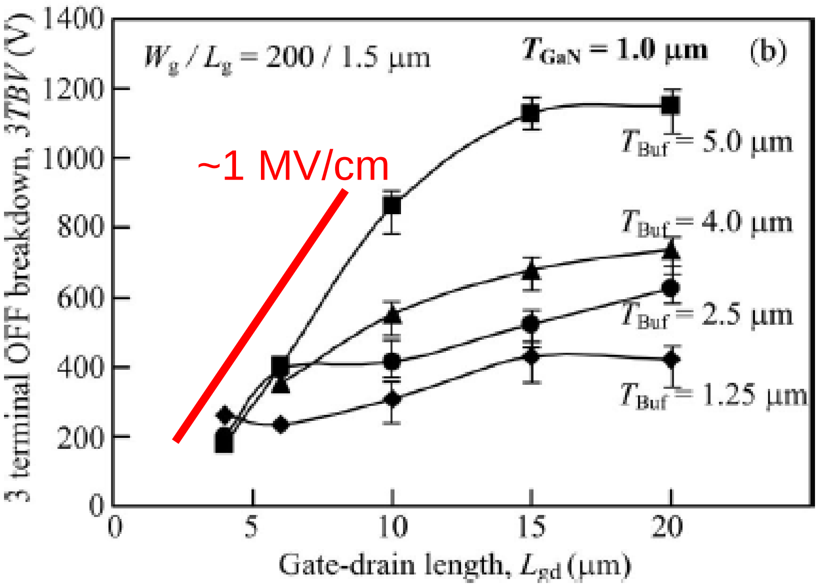
Not the full story? See also [Meneghesso / Meneghini / Zanoni]

Breakdown – gate-to-drain length scaling

- Breakdown voltage V_{br} scales with gate-to-drain length L_{GD} until vertical breakdown becomes dominant



[H. Ueda *et al.*, Proc. ISPSD 2005, 311 (2005)]



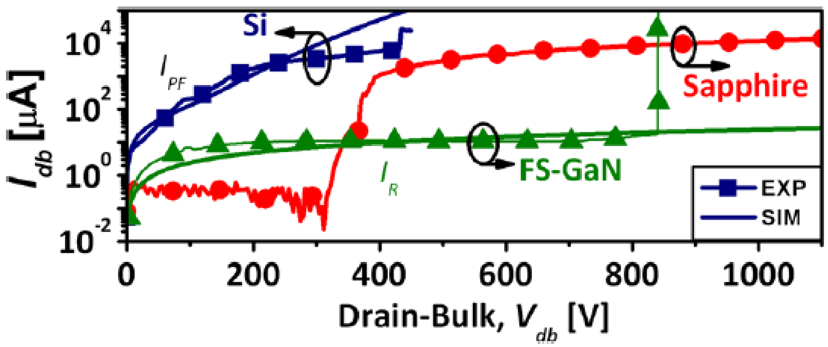
[S. L. Selvaraj *et al.*, EDL **33 (10)**, 1375 (2012)]

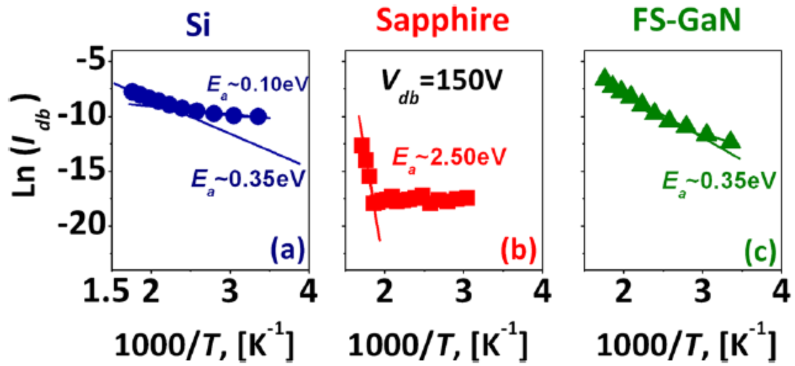
- Why is ΔV_{br} / ΔL_{GD} < 3 MV/cm? – leakage, electric field peaks, *etc.*…

See also [N. Ikeda *et al.*, Proc. IEEE **98 (7)**, 1151 (2010)]

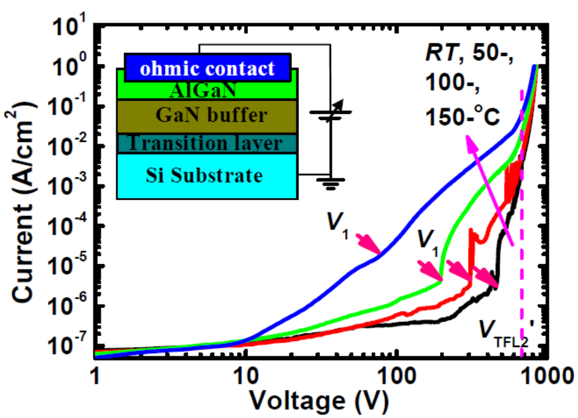
Breakdown – vertical current

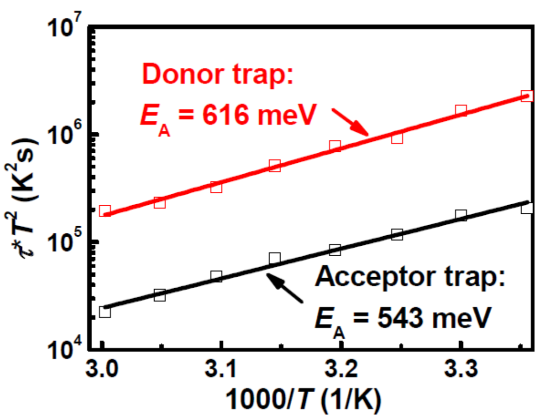
- Vertical leakage mechanisms / activation energies depend on wafer type
  [A. Pérez-Tomás *et al.*, J. Appl. Phys. **113**, 174501 (2013)]

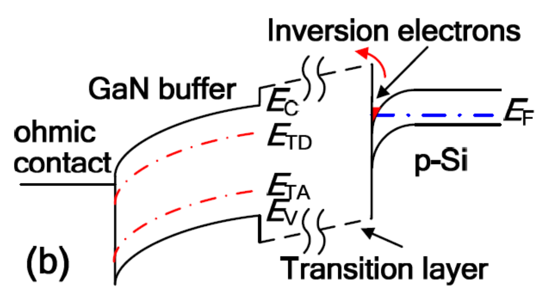




- Traps identified in carbon-doped GaN-on-Si buffer layers



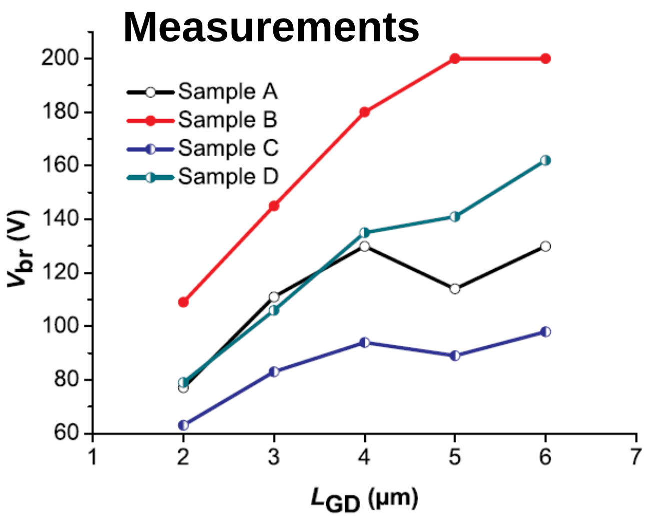


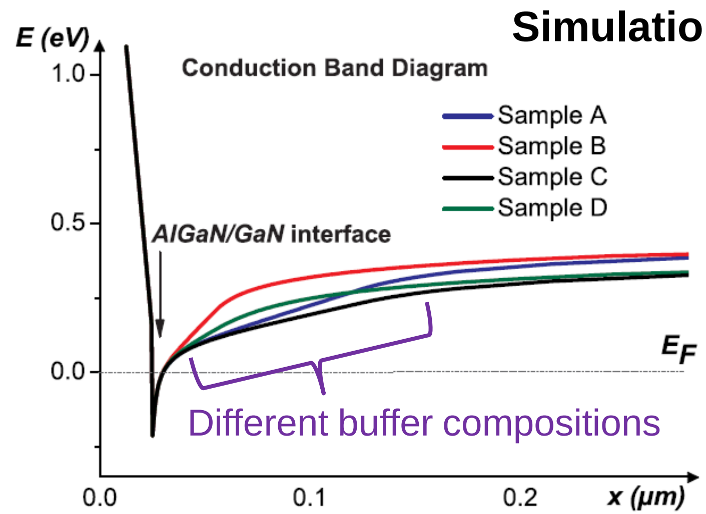


[C. Zhou *et al.*, Proc. ISPSD 2012, 245 (2012)]

Breakdown – buffer optimisation

- Increasing the thickness of the buffer can increase breakdown voltage due to improved material quality and reduced vertical leakage
  [S. L. Selvaraj *et al.*, Elec. Dev. Lett. **33 (10)**, 1375 (2012)] (see earlier slide)
- The inclusion of a carbon-doped “back barrier” can postpone punch-through to higher V_{DS} (at the expense of increased on-resistance)
  [E. Bahat-Treidel *et al.*, Trans. Elec. Dev. **57 (11)**, 3050 (2010)]
  [S. A. Chevtchenko *et al.*, Appl. Phys. Lett. **100**, 223502 (2012)] ↓

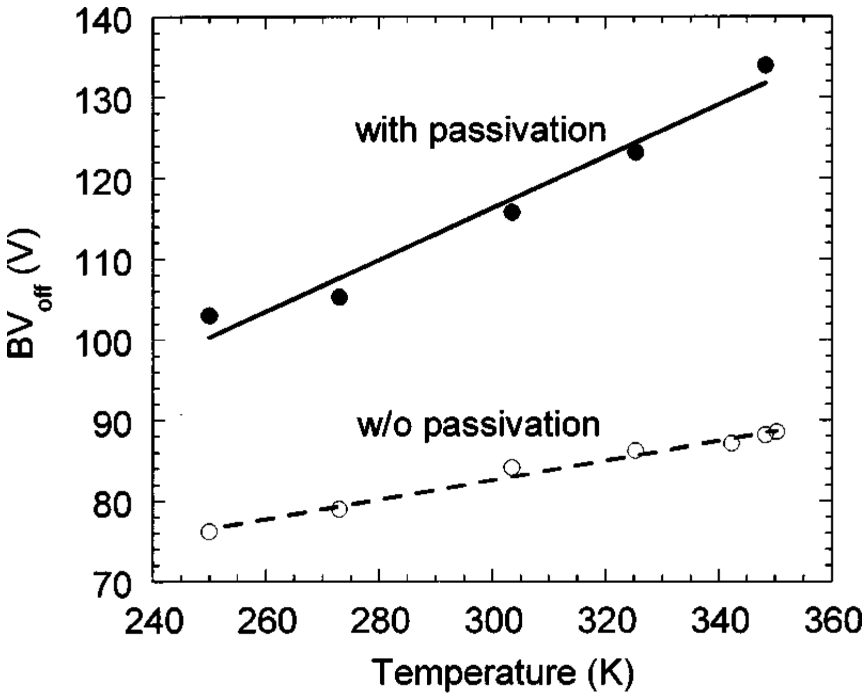




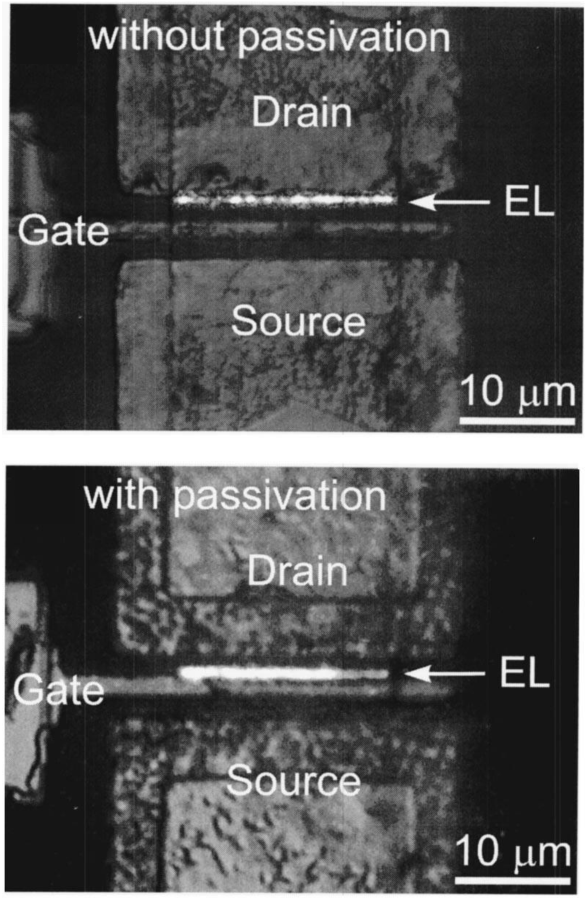
See also [N. Ikeda *et al.*, Proc. IEEE **98 (7)**, 1151 (2010)]

Breakdown – passivation optimisation

- SiN surface passivation can increase the breakdown voltage by modifying the surface charges/traps (and hence the electric field)



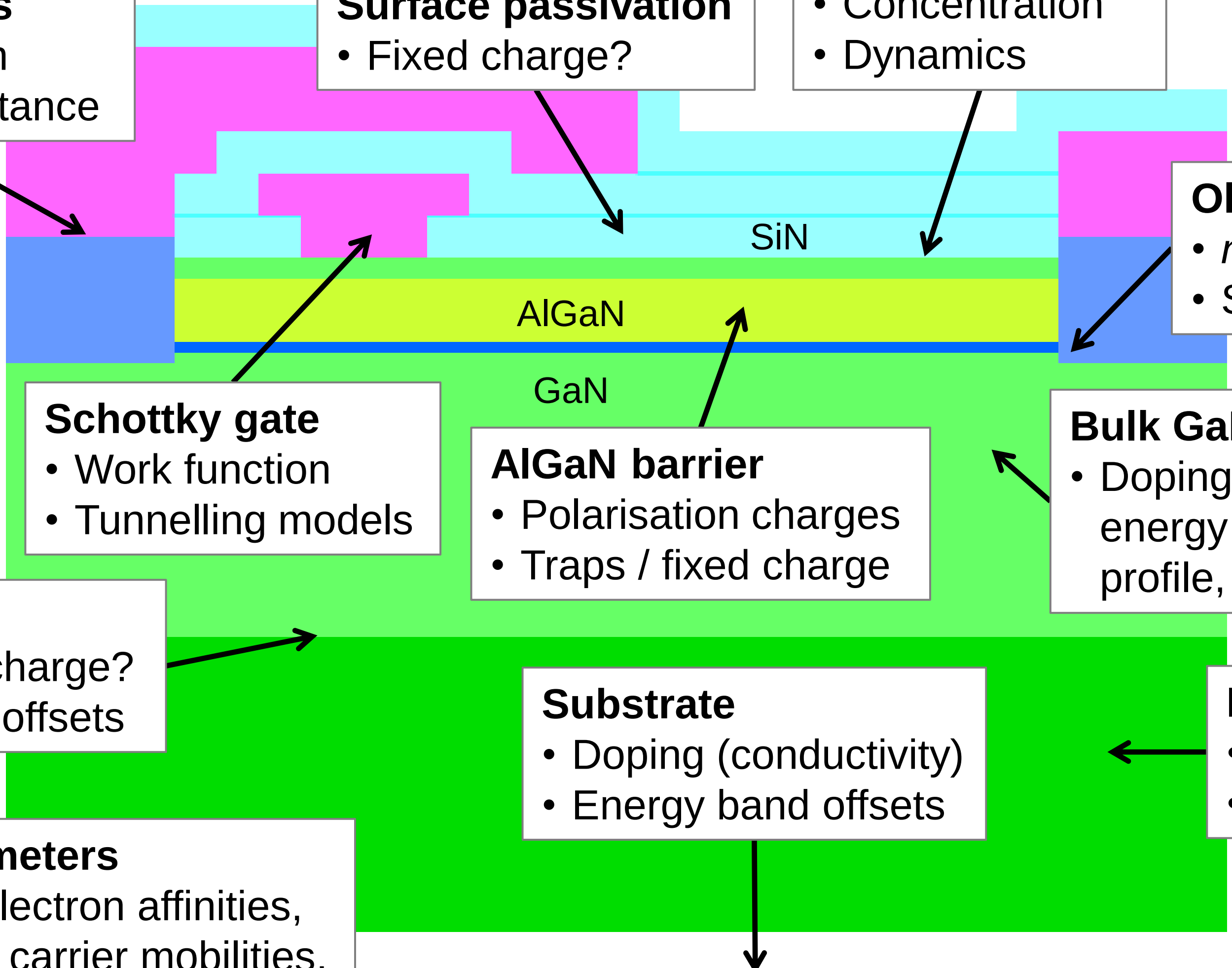
Electroluminescence



[Y. Ohno *et al.*, Appl. Phys. Lett. **84 (12)**, 2184 (2004)]

Outline

Simulation – structure



S/D electrodes
- Work function
- Contact resistance

Surface passivation
- Fixed charge?

Interface donors
- Energy level(s)
- Concentration
- Dynamics

Ohmic contacts
- *n*-type doping
- Shape / profile

Schottky gate
- Work function
- Tunnelling models

AlGaN barrier
- Polarisation charges
- Traps / fixed charge

Bulk GaN
- Doping concentration, energy level, depth profile, and dynamics

Interface(s)
- Polarisation charge?
- Energy band offsets

Substrate
- Doping (conductivity)
- Energy band offsets

Buffer layer(s)
- Superlattice?
- Doping

Material parameters
- Band gaps, electron affinities, permittivities, carrier mobilities, impact-ionisation parameters…

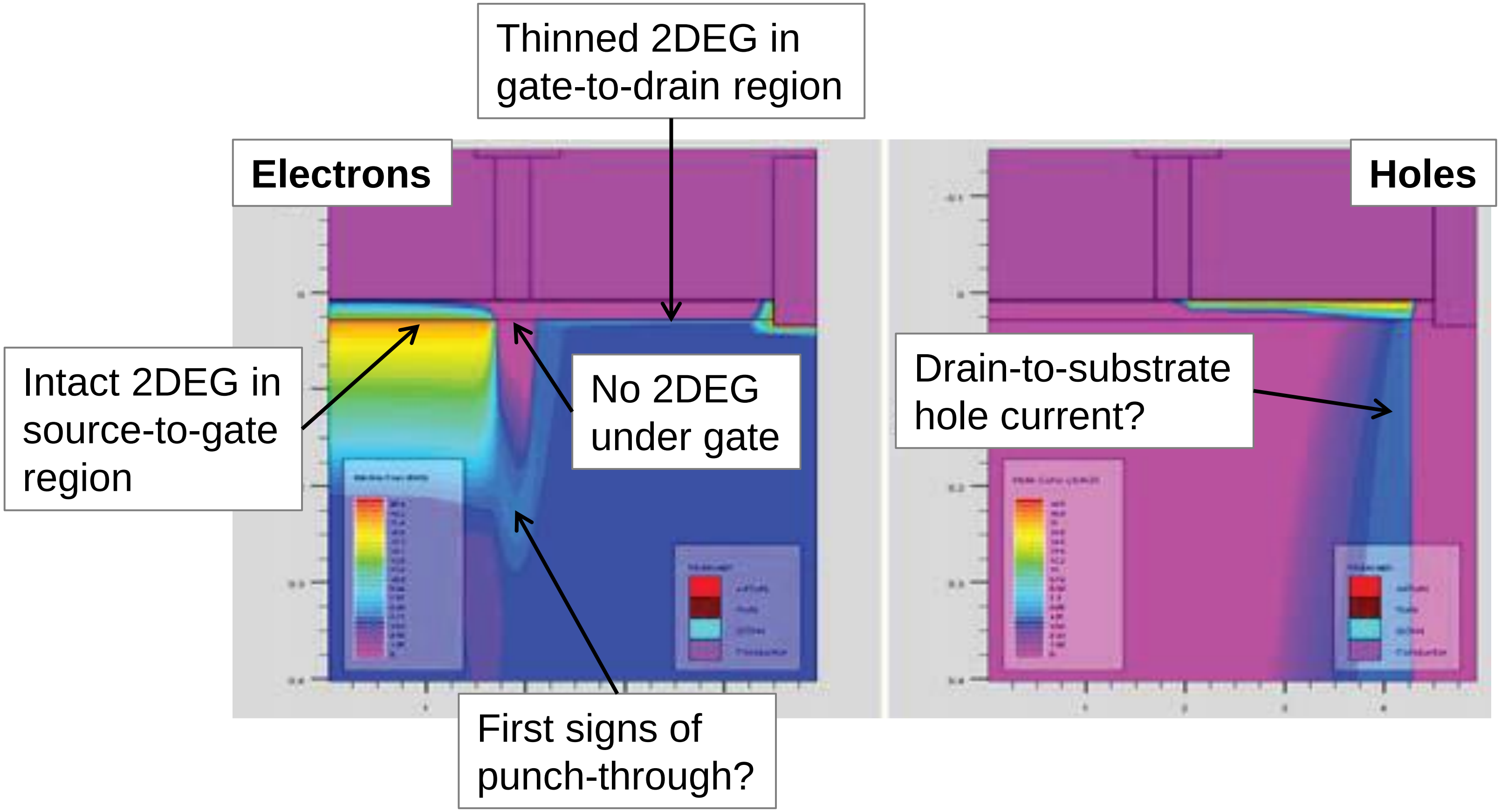
Simulation – set-up

- Density gradient *vs.* classical simulation
- Lattice temperature equation – necessary for high-power simulation
- Drift-diffusion *vs.* hydrodynamic model
- Tunnelling at contacts and interfaces – Schottky gate
- Different levels of polarisation models – fixed charges *vs.* built-in polarisation
- Thermionic heterointerface condition
- Mobility models – doping dependence, saturation, surface (2DEG) *vs.* bulk
- Anisotropy? – mobility / impact ionisation
- Fermi-Dirac *vs.* Boltzmann statistics, incomplete ionisation of impurities
- Generation – band-to band, impact ionisation
- Recombination – direct (band-to-band), Shockley-Read-Hall
- Numerical precision – low carrier concentrations, steep gradients

[Synopsys]

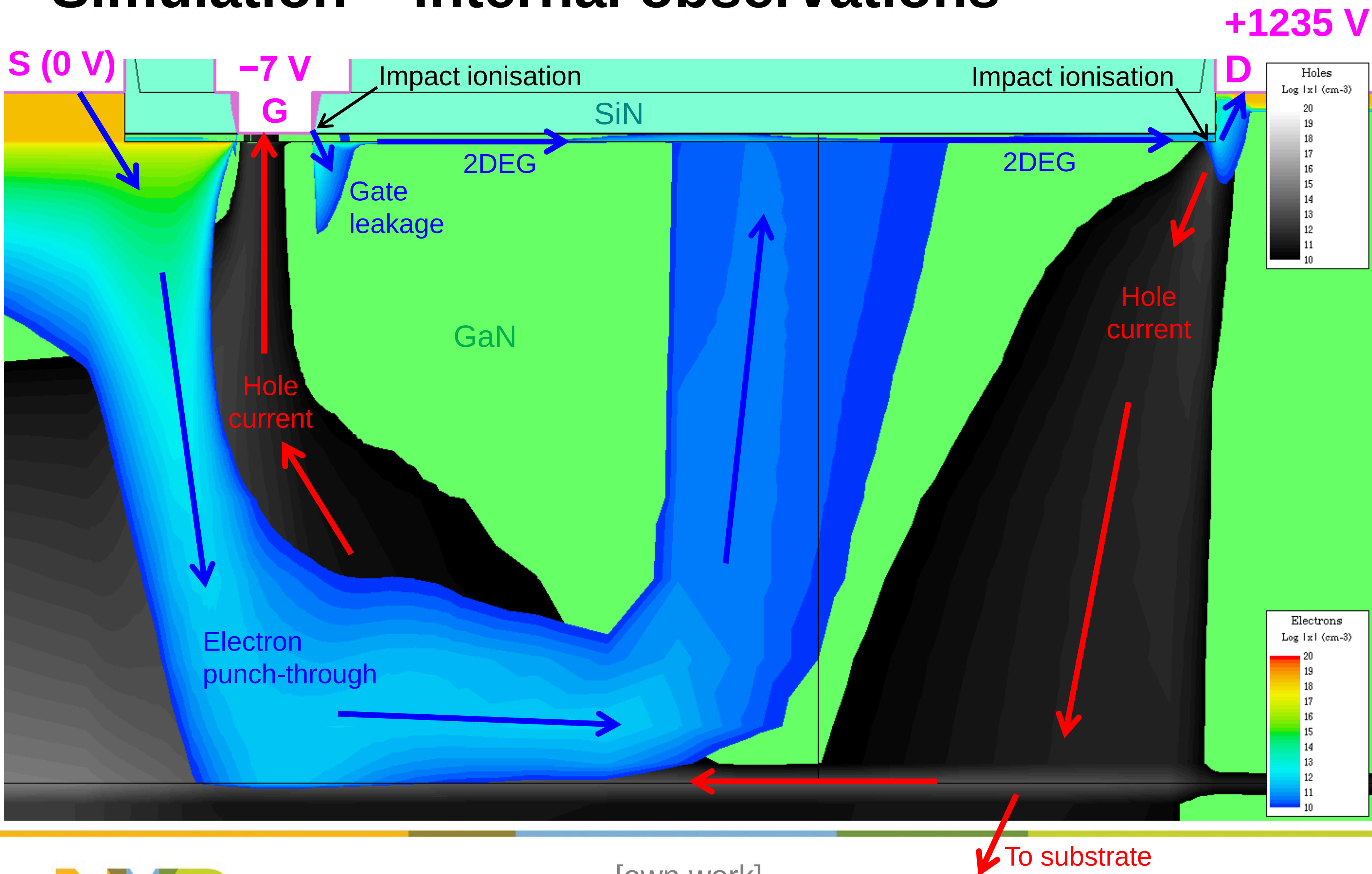
Simulation – internal observations

- Electron and hole distribution in off-state at high drain bias
  – Can be correlated to (for example) electroluminescence measurements



[Y. Kong *et al.*, Proc. ICMMT 2012, 1]

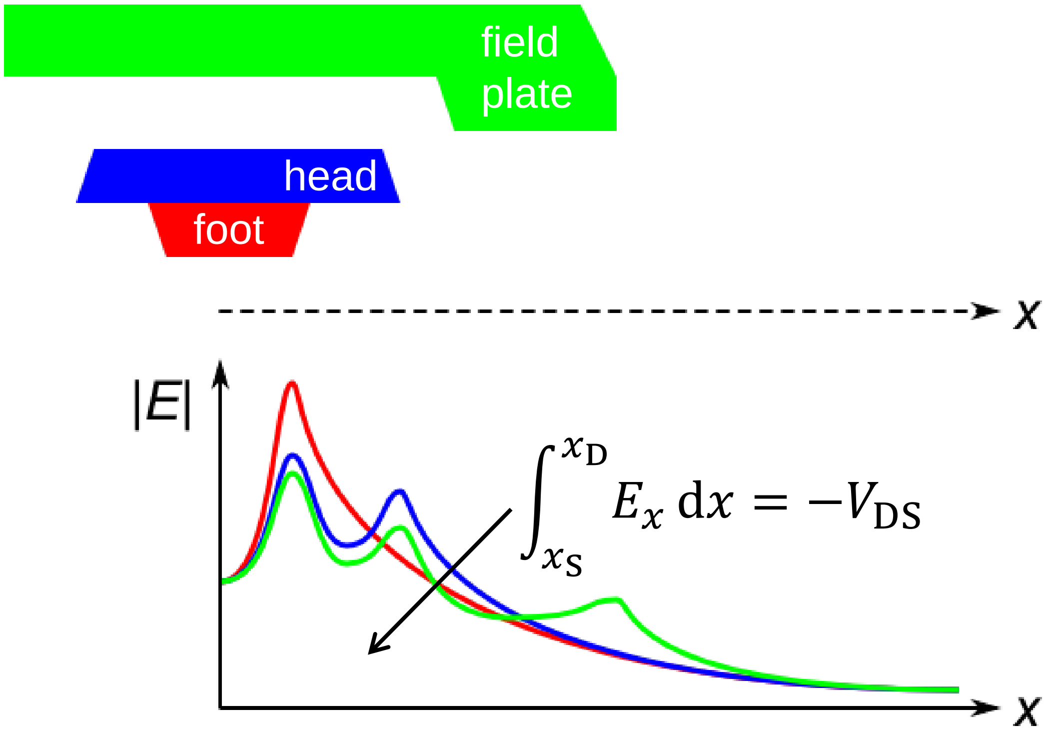
Simulation – internal observations



[own work]

Simulation – field plates

- There is a large **peak in the surface electric field** at the drain side of the **gate** (foot)
- Using a **gate field plate** (head) can reduce this field peak, but adds a new one
- Using **another field plate** can reduce these peaks but adds a third one



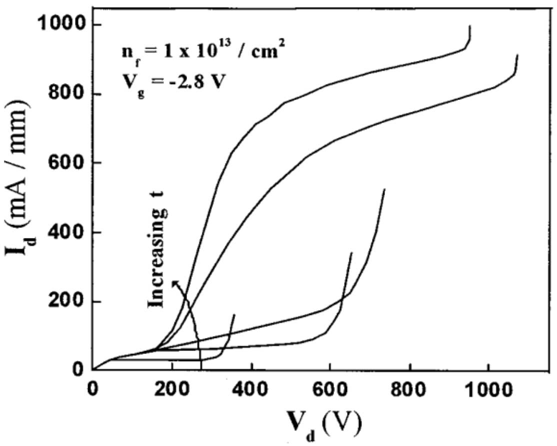
- Field-plate design must be **optimised**
  - Can affect breakdown, capacitances, current collapse, degradation, *etc.*

[N.-Q. Zhang *et al.*, Elec. Dev. Lett. **21 (9)**, 421 (2000)]
[J. Li *et al.*, Elec. Lett. **37 (3)**, 196 (2001)]
[A. Wakejima *et al.*, Appl. Phys. Lett. **90**, 213504 (2007)]
[W. Saito *et al.*, Trans. Elec. Dev. **54 (8)**, 1825 (2007)]
[H. Hanawa *et al.*, IRPS 2013, CD.1.1]

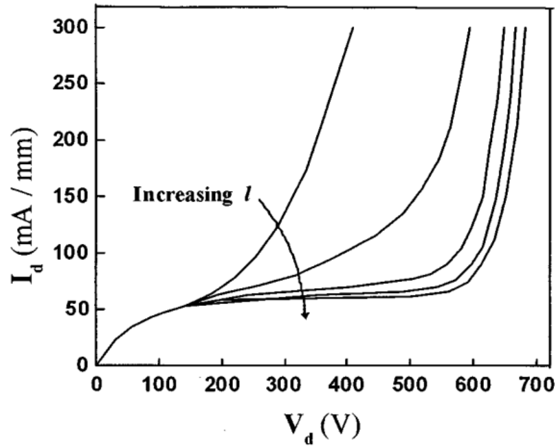
Simulation – field plates

- Simulations can be used to optimise the device geometry to obtain the maximum V_{br} with minimum degradation in frequency response and R_{on}
  [S. Karmalkar and U. K. Mishra, Trans. Elec. Dev. **48 (8)**, 1515 (2001)]

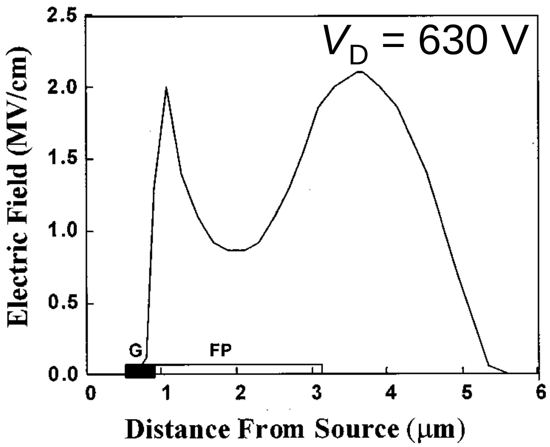
FP height (SiN thickness)



FP length



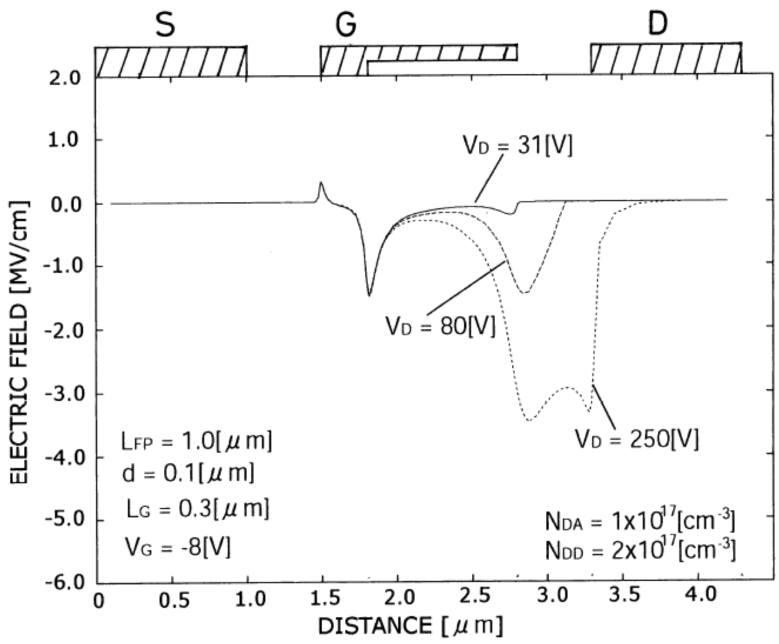
Surface field at V_{br}

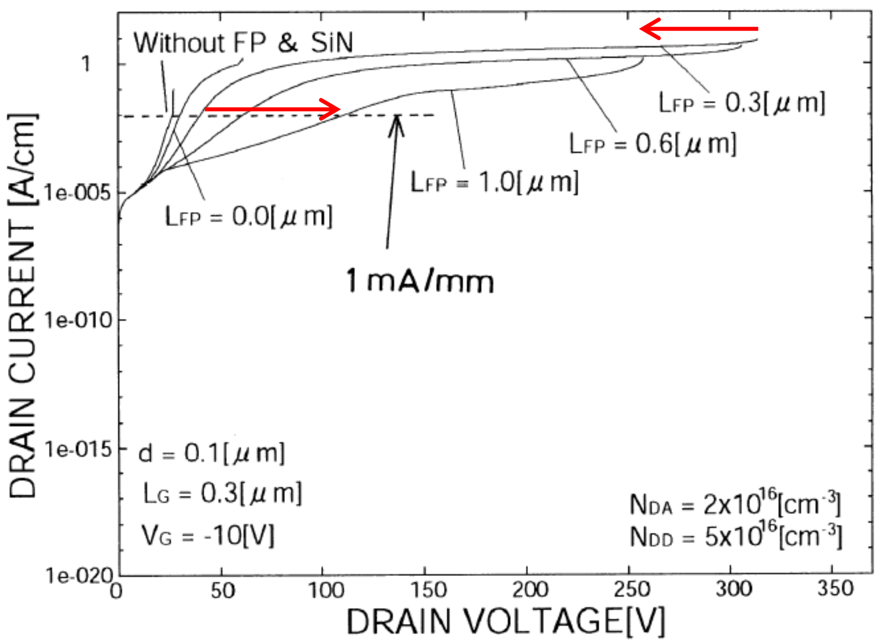


- Unity current gain (cut-off) frequency: $f_T = \dfrac{g_m}{2\pi C_G}$ ⟵ Minimise increase in gate capacitance

Simulation – field plates

- Making the gate-connected field plate too long can reduce V_{br}
  - Depending on definition of V_{br}!





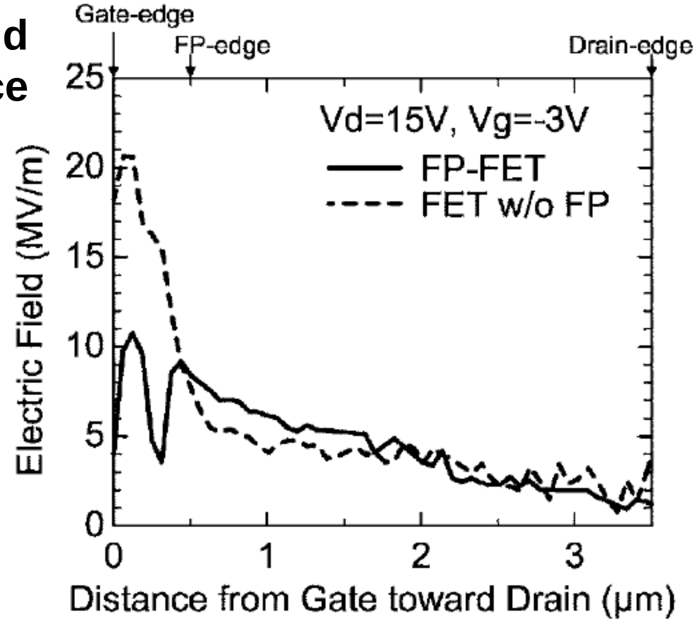
[H. Onodera and K. Horio, Proc. EMICC (EuMIC) 2012, 401]

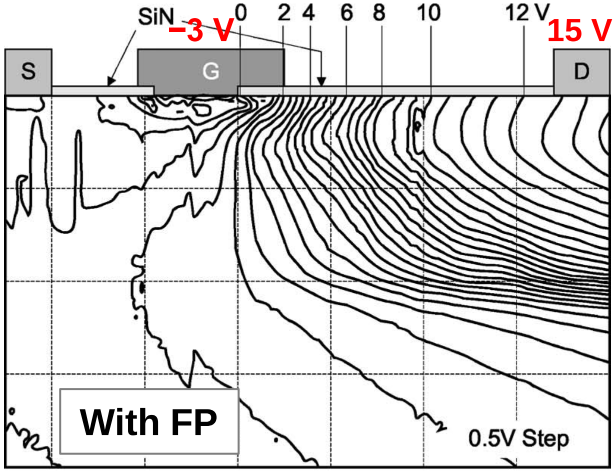
Simulation – comparison to measurements

- Kelvin probe force microscopy used to map internal potential distribution (w/wo FP)

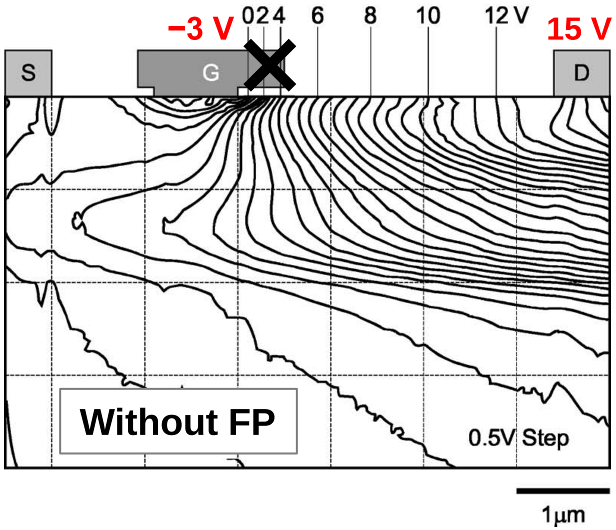
[A. Wakejima *et al.*, Appl. Phys. Lett. **90**, 213504 (2007)]

Electric field along surface





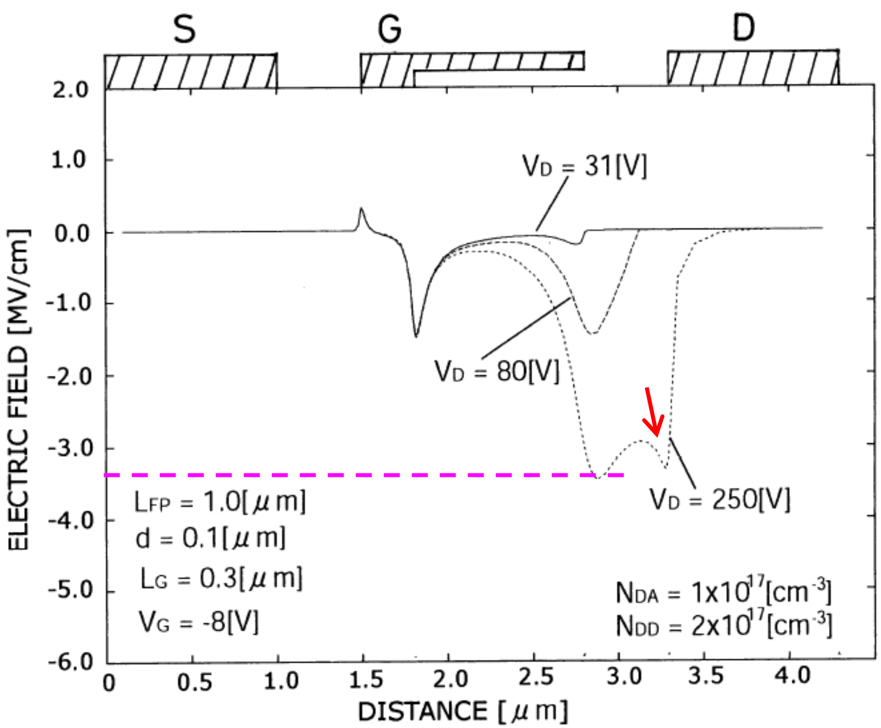
Internal potential distribution



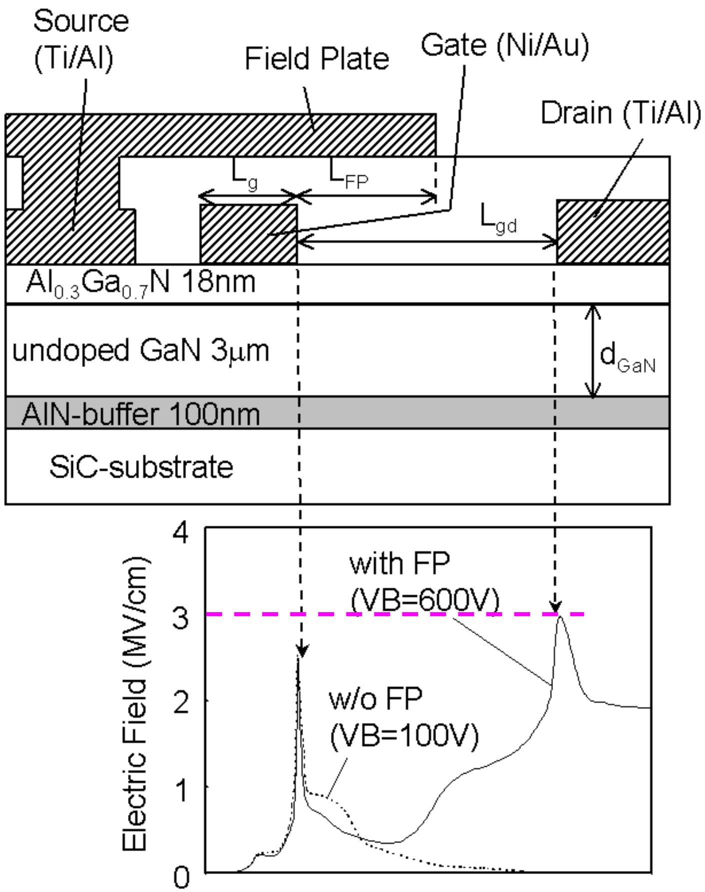
See also [S. Kamiya *et al.*, Appl. Phys. Lett. **90**, 213511 (2007)]

Simulation – drain field peak?

- Electric field peak at drain at very high voltage – enough to cause breakdown?
  - Dependent on specific details of Ohmic-contact implementation?



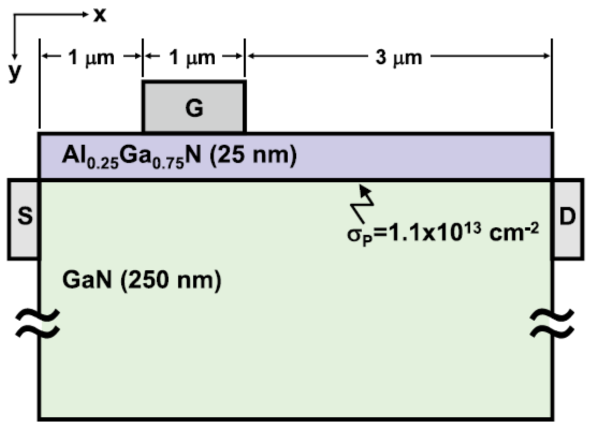
[H. Onodera and K. Horio, Proc. EMICC (EuMIC) 2012, 401]

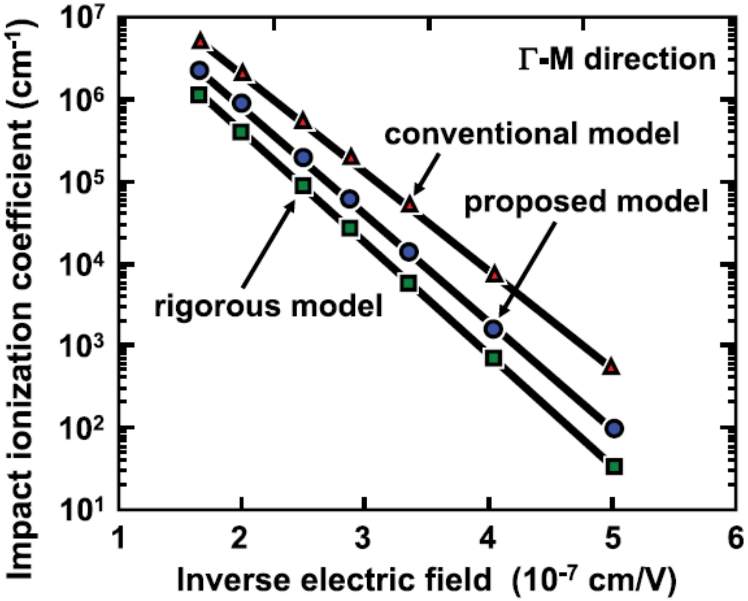


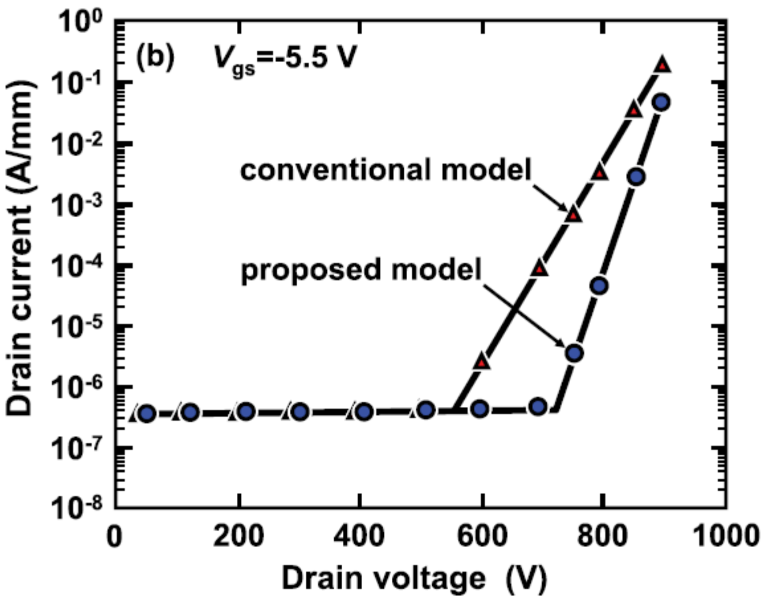
[W. Saito *et al.*, TED **50 (12)**, 2528 (2003)]
also [W. Saito *et al.*, Proc. IEDM 2003, 687]

Simulation – impact ionisation

- Improved modelling of impact ionisation can have a significant effect on simulated breakdown voltages
  - Treat impact-ionisation parameters as tuning parameters





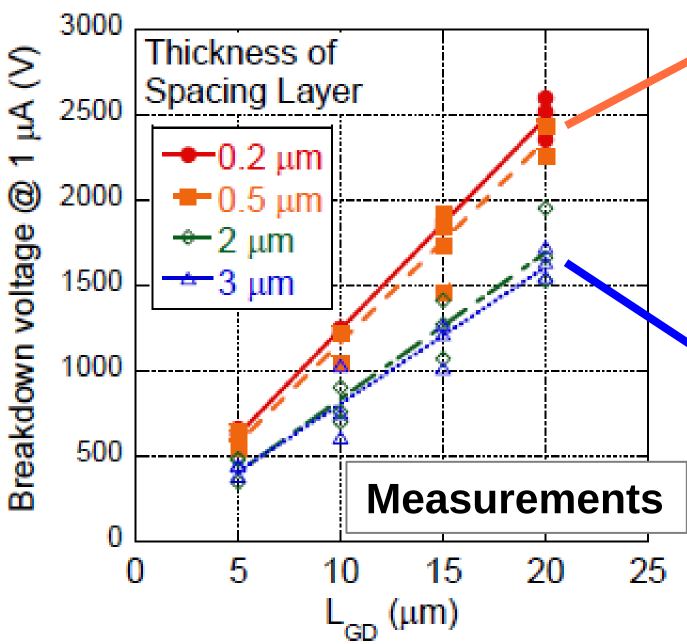


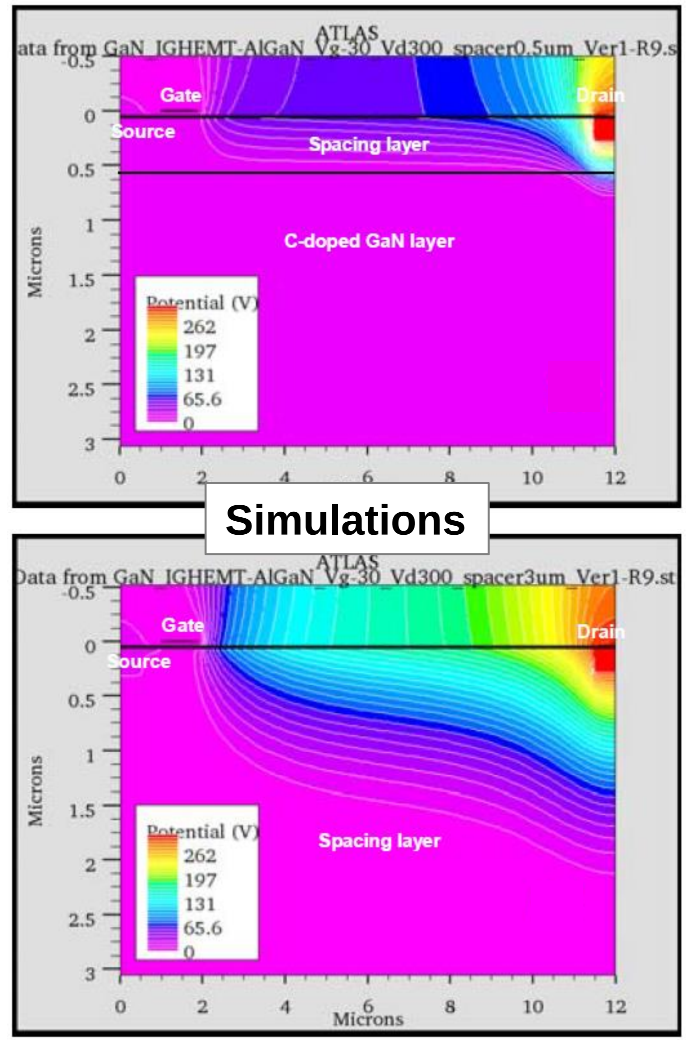
[K. Kodama *et al.*, J. Appl. Phys. **114**, 044509 (2013)]

Simulation – buffer optimisation

- Thinning the lowly doped "spacing layer" between surface and carbon-doped layer can increase breakdown voltage via a decrease in the surface electric field peak

V_D = 300 V

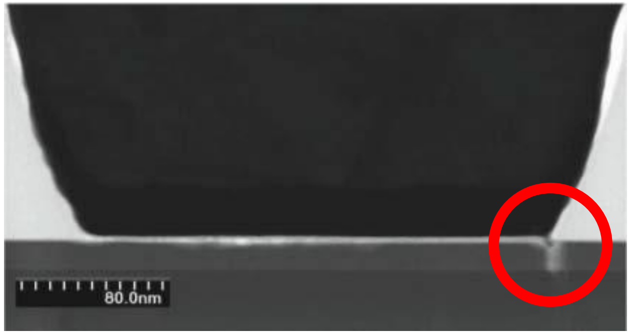




[T. Narita *et al.*, Phys. Stat. Solidi C **9 (3–4)**, 915 (2012)]

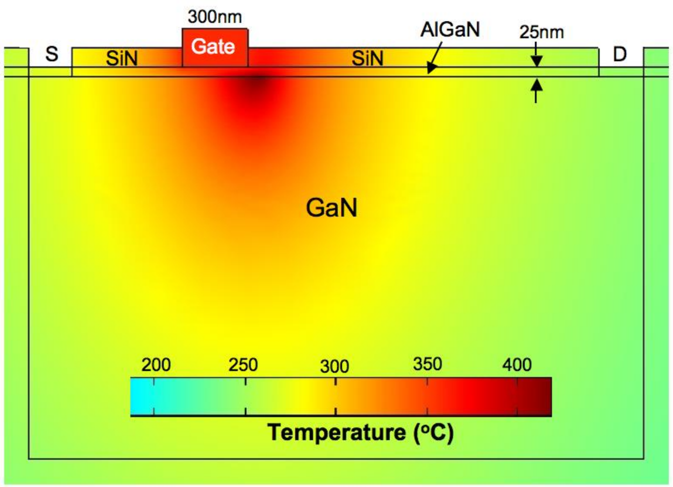
See also [M. J. Uren *et al.*, Trans. Elec. Dev. **59 (12)**, 3327 (2012)]

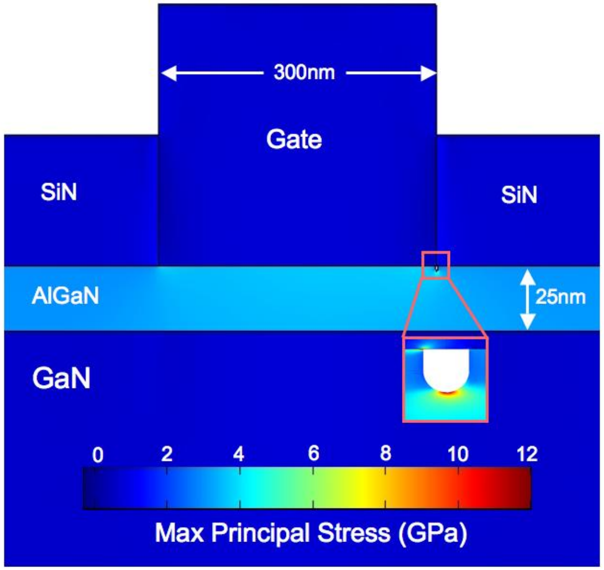
Simulation – multiphysics

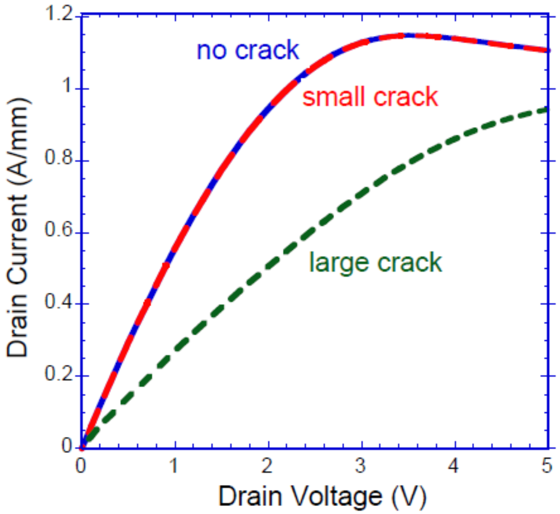


TEM [U. Chowdhury *et al.*, EDL **29 (10)**, 1098 (2008)]

- Thermo-electro-elastic simulations:
  - fully coupled thermal, mechanical, and electrical equations
- Used to investigate (for example):
  - The role of thermal and piezoelectric stresses on defect formation
  - …and the impact on electrical characteristics







[M. G. Ancona *et al.*, J. Appl. Phys. **111**, 074504 (2012)]
[M. G. Ancona, Proc. IEDM 2012, 315]

Outline

- GaN and related materials
- The AlGaN/GaN heterostructure
- GaN wafers
- GaN devices
- Issues facing high-voltage GaN-HEMT development
- High-voltage breakdown
- GaN-HEMT device simulation
- **Compact modelling of GaN HEMTs**
- Summary and conclusion

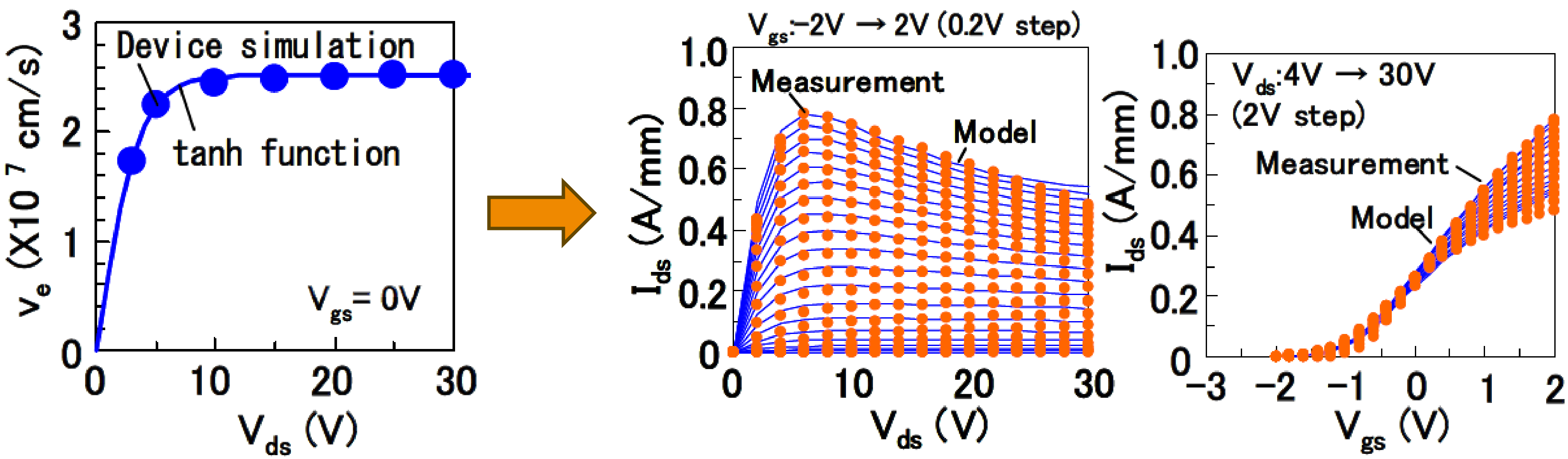
Modelling – compact models

- Models for GaN devices are needed to enable application development via circuit simulation and optimisation
- Different types of compact model:
  - **Table-based:** measured device data stored in large look-up tables
    - Very fast, but extrapolation outside of measured range is treacherous, and accurate scaling to other device dimensions is not possible
  - **Empirical:** uses whichever mathematical functions have the right shape
    - Good fits possible, but parameters are not physically meaningful, scaling is not physical, and extrapolation is still dubious
  - **Physics-based:** equations derived from modelling physical phenomena
    - Parameters physically meaningful, scaling is physical, extrapolation reliable
    - **Threshold-voltage–based:** physical expressions smoothed together
    - **Surface-potential–based:** uses a single expression for all regimes, inherent symmetry, established as the preferred approach in MOS modelling [Gildenblat *et al.*, J. Solid-State Circ. **39 (9)**, 1394 (2004)]

See also [L. Dunleavy *et al.*, Microwave Magazine **11 (6)**, 82 (2010)]

Modelling – empirical model

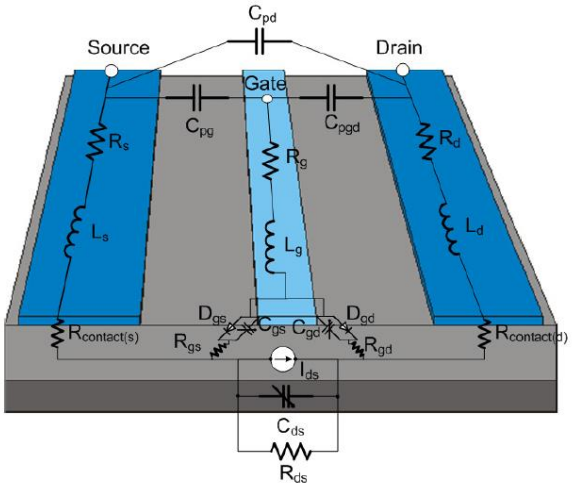
- **Chalmers** (a.k.a. **Angelov**) **model**
  - An empirical model for HEMT and MESFET devices, introduced in 1992
    [I. Angelov *et al.*, Trans. Micro. Theory. Tech. **40 (12)**, 2258 (1992)]
  - Extended in 1996 to include temperature, dispersion, and soft breakdown
    [I. Angelov *et al.*, TMTT **44 (10)**, 1664 (1996)]
  - **Widely used for (RF) GaN-HEMTs**
  - Modified in 2010 to make parameters more physical
    [T. Oishi et al., Proc. INMMIC 2010, 20 (2010)]



[I. Angelov *et al.*, Proc. MTT 2012, 1 (2012)]
[I. Angelov *et al.*, Proc. APMC 2006, 279]

Modelling – empirical model

- Modified form of the Angelov model for GaN-on-Si power switches



$$I_{ds} = I_{pkt}\left[1+\tanh\left(\psi\left(V_{gs}\right)\right)\right]\cdot\tanh(\alpha_T V_{ds} + k_T V_{ds}^3)\,[1+\lambda V_{ds}]$$

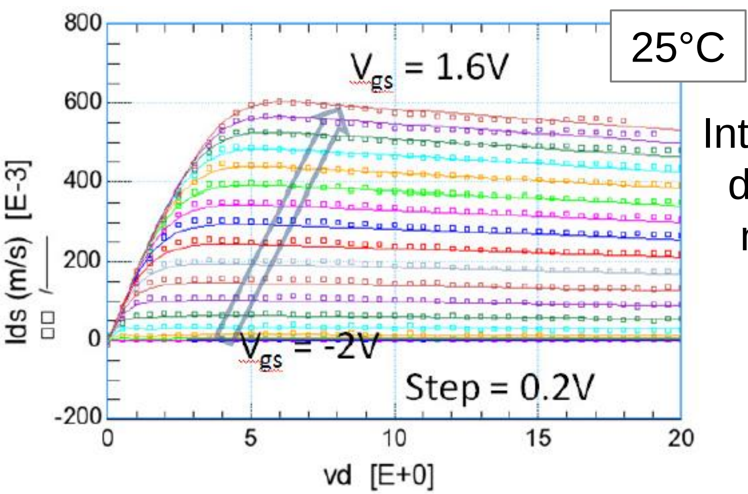
$$\psi = \sinh\left[P_{1t}\left(V_{gs}-V_{pkt}\right) + P_{2t}\left(V_{gs}-V_{pkt}\right)^2 + P_{3t}\left(V_{gs}-V_{pkt}\right)^3\right]$$

$$\alpha_T = \alpha_R + \alpha_S[1+\tanh(\psi)]$$

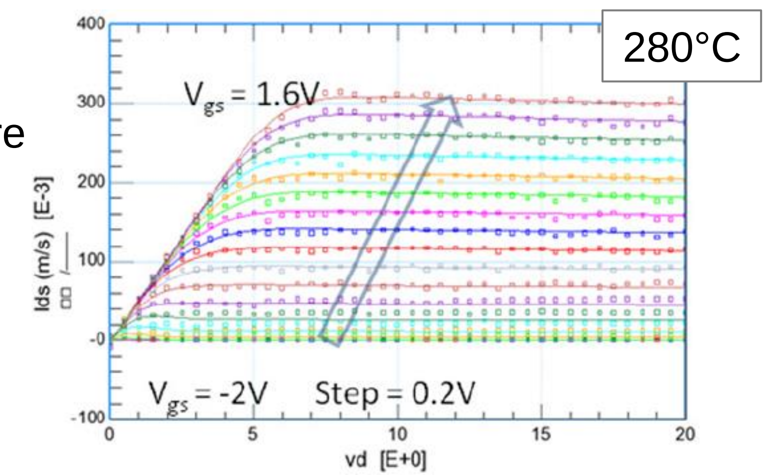
$$I_{pkt} = I_{pk0} + \left(I_{pk} - I_{pk0}\right)\tanh(\alpha_R V_{ds})$$

$$V_{pkt} = V_{pk0} + \left(V_{pk} - V_{pk0}\right)\tanh(\alpha_R V_{ds})$$

$$P_{it} = P_{i0} + (P_i - P_{i0})\tanh(\alpha_R V_{ds})$$



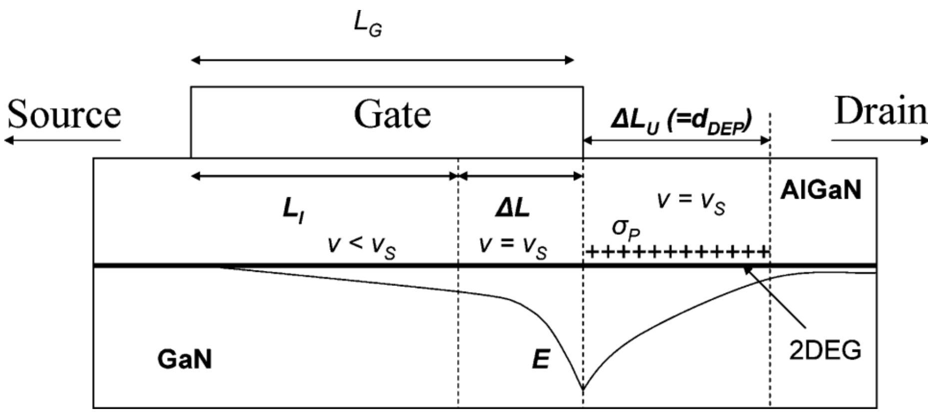
Introduce temperature dependence for the model parameters

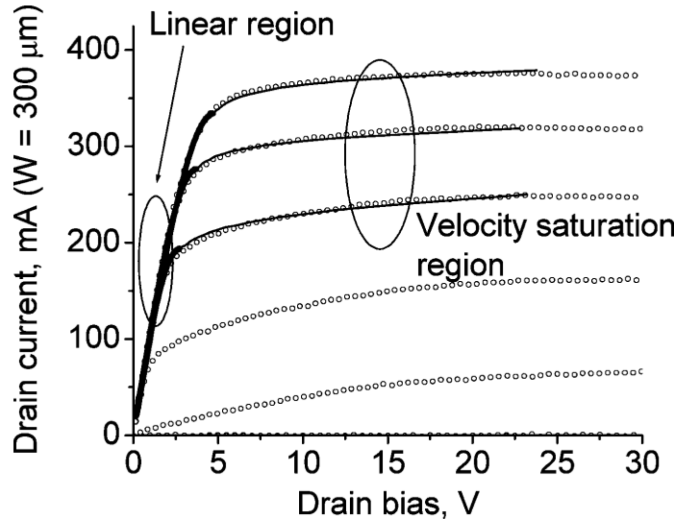


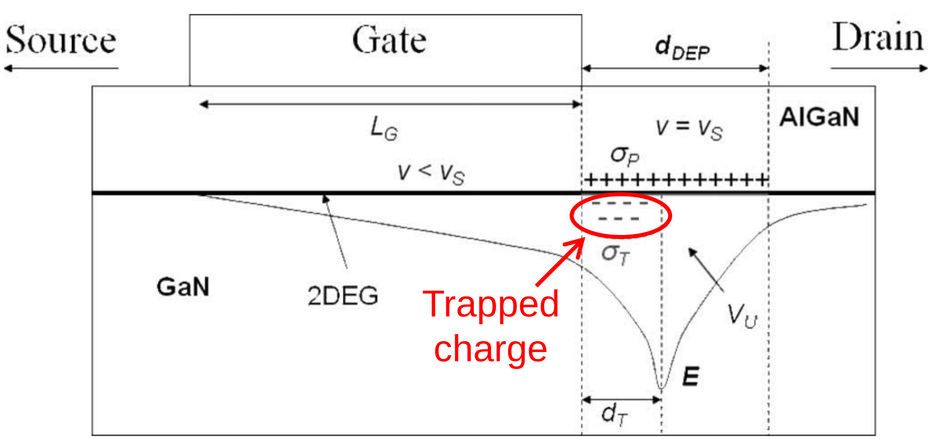
[S. Stoffels *et al.*, Proc. THERMINIC 2011, 1 (2011)]
See also [S. Stoffels THERMINIC 2012]

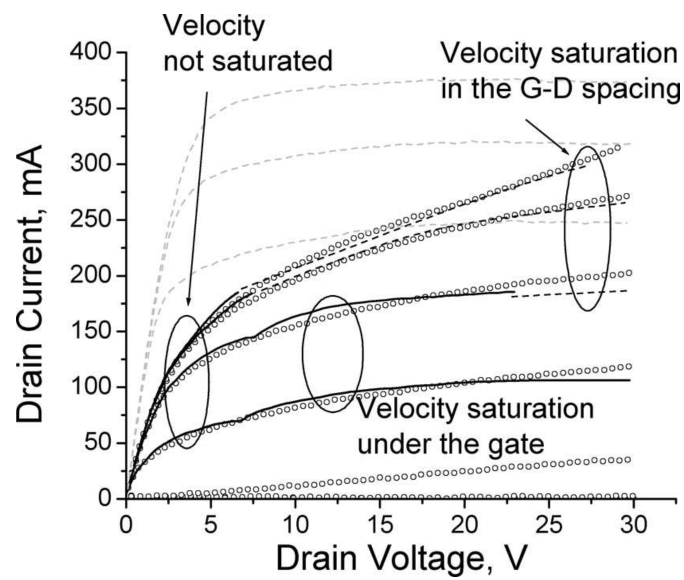
Modelling – empirical model

- Analytical model including **current collapse**









[A. Koudymov *et al.*, Trans. Elec. Dev. **55 (3)**, 712 (2008)]

Modelling – physics-based model

- Model for 2DEG charge density: [S. Khandelwal *et al.*, Trans. Elec. Dev. **58 (10)**, 3622 (2011)]

$$n_s = \frac{C_g V_{go}}{q} \frac{V_{go} + V_{th}\left[1 - \ln(\beta V_{gon})\right] - \frac{\gamma_0}{3}\left(\frac{C_g V_{go}}{q}\right)^{2/3}}{V_{go}\left(1 + \frac{V_{th}}{V_{god}}\right) + \frac{2\gamma_0}{3}\left(\frac{C_g V_{go}}{q}\right)^{2/3}}$$

- Expression extended for validity in sub-threshold regime…

$$n_{s,unified} = \frac{2V_{th}(C_g/q)\ln\{1 + \exp(V_{go}/2V_{th})\}}{1/H(V_{go,p}) + (C_g/qD)\exp(-V_{go}/2V_{th})}$$

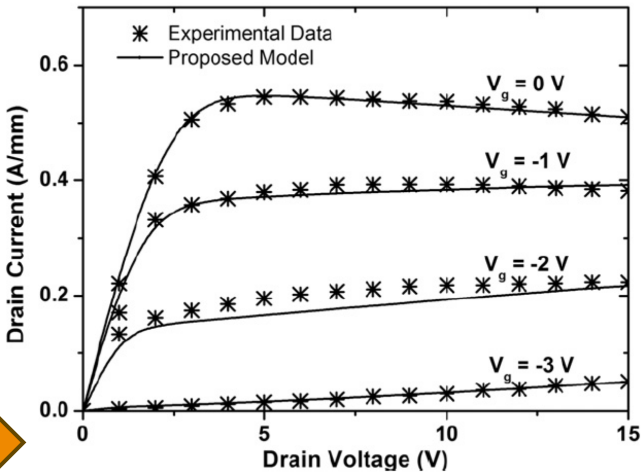
…and used as basis for drain-current model…

Smoothly connected

$$I_{d,above} = \frac{\mu_0 C_g W_g}{L_g G_{mob} G_{field}}\left\{\sum_{i=1}^{6} c_i\{\psi_{gd}^i - \psi_{gs}^i\} + c_0 \ln\left(\frac{\psi_{gd}}{\psi_{gs}}\right)\right\}$$

$$I_{d,sub} = \frac{2\mu_0 W_g q D V_{th}^2}{L_g G_{mob} G_{field}} \exp\left(\frac{V_{go}}{V_{th}}\right)\left(1 - \exp\left(\frac{-V_{ds}}{V_{th}}\right)\right)$$

…to which carrier velocity saturation, channel-length modulation, short-channel effects, and self-heating are added

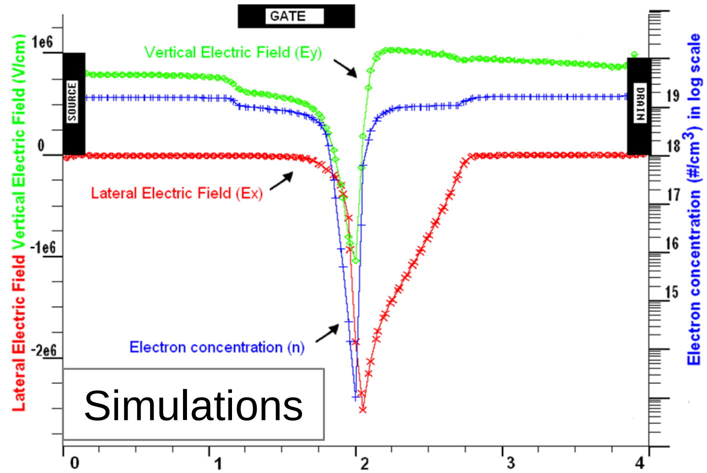


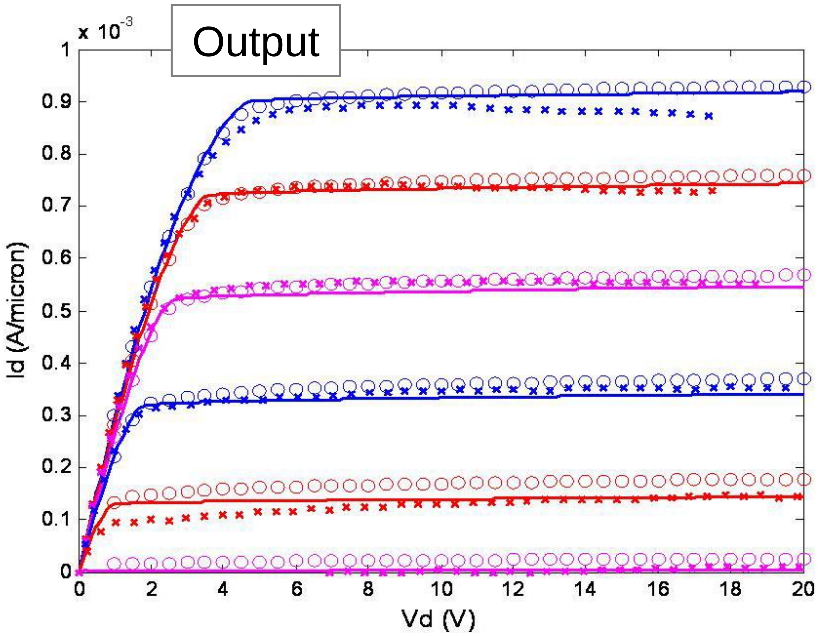
[S. Khandelwal and T. A. Fjeldly, Solid-State Electronics **76**, 60 (2012)]
See also [Yigletu *et al.*, Proc. WiSNet / SiRF / RWS / PAWR 2013]

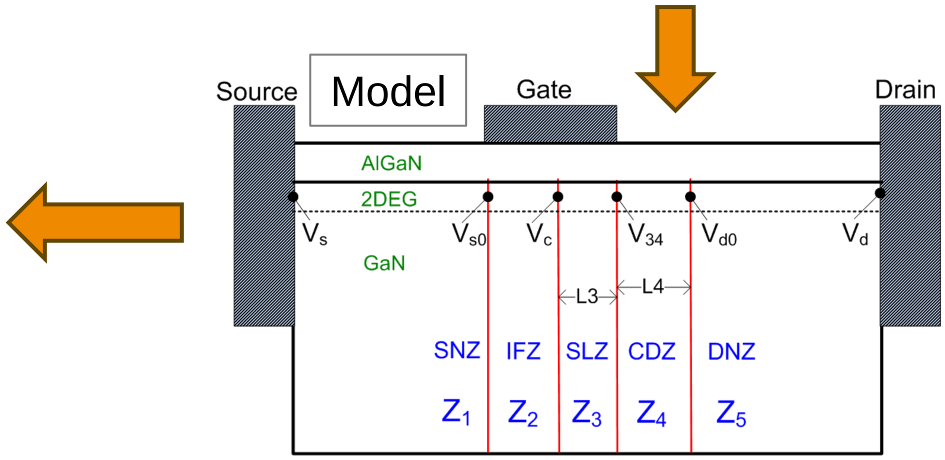
See also [U. Radhakrishna *et al.*, Proc. IEDM 2012, 319/13.6.1 (2012)] and [X. Cheng *et al.*, TED **56**, 2881 (2009)]

Modelling – physics-based model

- "Zone-based" compact model based on observations from device simulations
  - Different equations derived for different regions of the device, then smoothly joined
  - Alternative to equivalent-circuit models





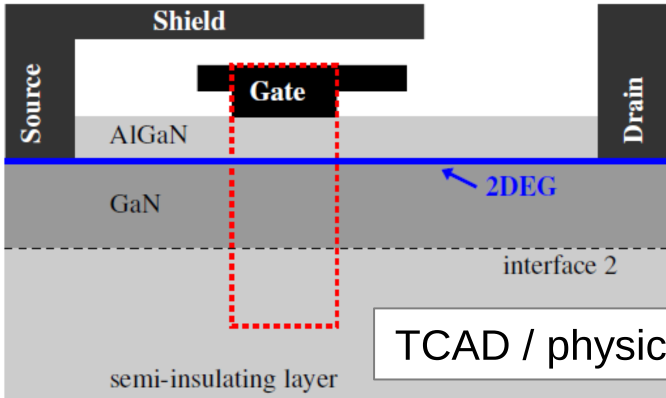


[R. J. Trew, Proc. CSICS 2010, 1 (2010)]
[R. J. Trew *et al.*, Proc. ICWITS 2012, 1 (2012)]

[H. Yin *et al.*, Proc. IMS 2007, 787 and Proc. IMS 2008, 1425]
and [D. Hou *et al.*, TED **60 (2)**, 639 (2013)]

Modelling – surface-potential–based model

- The "first surface-potential–based compact model for RF GaN HEMTs"



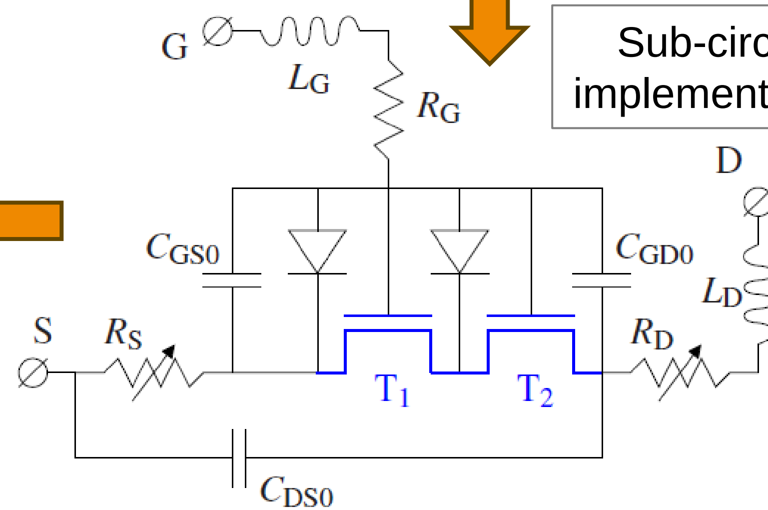
TCAD / physics

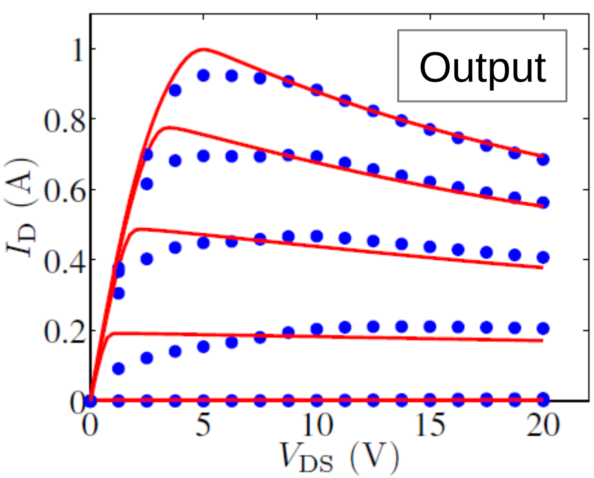
$$(V_{GS}^{*}-\psi_s)^2 = k_0^2\left\{\phi_T\left[\exp\left(\frac{\psi_s - V}{\phi_T}\right)-1\right]-\psi_s+V\right\}$$

$$I_D = \frac{W\mu_0}{G_v L}\left\{qN_D t_{GaN} V_{DS} - \bar{Q}_{tot}\Delta\psi + C_{ins}k_0\phi_T^{\frac{3}{2}}\left[F(\psi_{s_0}) - F(\psi_{s_L} - V_{DS})\right]\right\}$$

Model

Sub-circuit implementation



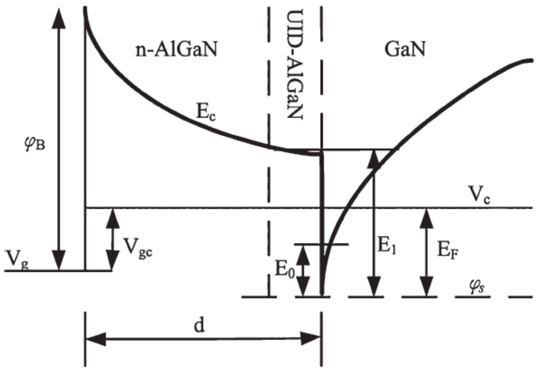


Output

[D. L. John *et al.*, Proc. IEDM 2010, 186/8.3.1 (2010)]

Modelling – surface-potential–based model

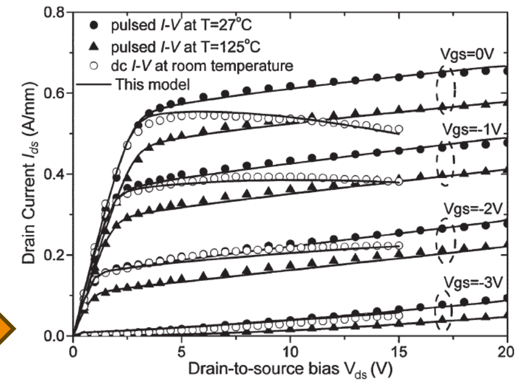
- *A Surface-Potential-Based Compact Model for AlGaN/GaN MODFETs*
  [X. Cheng and Y. Wang, Trans. Elec. Dev. **58 (2)**, 448 (2011)]



$$\varphi_s = E_F + V_c$$

$$n_s = c_{\mathrm{ox}}(V_{\mathrm{go}} - V_{\mathrm{off}} - \varphi_s)$$

$$I_{ds} = \beta\mu_{\mathrm{LF}}\frac{(V_{gs} - V_{\mathrm{off}} + V_q - \varphi_{\mathrm{sm}})\varphi}{r_L + \delta_0\varphi\mu_a/V_{\mathrm{CL}}}$$

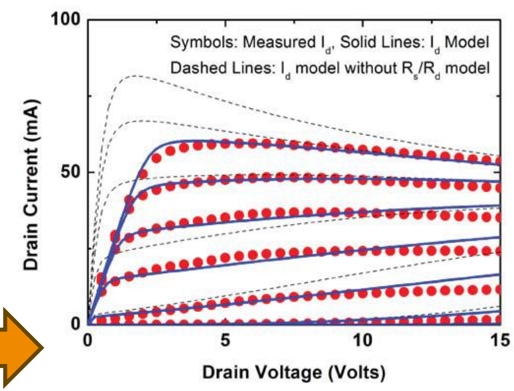


- *Analytical Modeling of Surface-Potential and Intrinsic Charges in AlGaN/GaN HEMT Devices*
  [S. Khandelwal *et al.*, Trans. Elec. Dev. **59 (10)**, 2856 (2012)] and unpub. Trans. Elec. Dev.

$$n_s = DV_{\mathrm{th}}\left[\ln\left(1 + e^{\frac{E_f - E_0}{V_{\mathrm{th}}}}\right) + \ln\left(1 + e^{\frac{E_f - E_1}{V_{\mathrm{th}}}}\right)\right]$$

$$E_{0,1} = \gamma_{0,1} n_s^{2/3} \qquad n_s = \frac{\epsilon}{qd}(V_{\mathrm{go}} - E_f - V_x)$$

$$I_{\mathrm{ds}} = \frac{\mu_{\mathrm{eff}} C_g}{\sqrt{1 + \theta_{\mathrm{sat}}^2 \psi_{\mathrm{ds}}^2}} \frac{W}{L}\left(V_{\mathrm{go}} - \psi_m + V_{\mathrm{th}}\right)(\psi_{\mathrm{ds}})(1 + \lambda V_{\mathrm{ds}})$$



See also [R. Jana and D. Jena, Proc. DRC 2012, 147 (2012)] and [Martin / Hahe / Lucci (2012–2013)]

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- GaN and related materials
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Summary and conclusion

- The **material properties** of GaN and AlGaN, together with the remarkable properties of the AlGaN/GaN **heterostructure**, enable the creation of **high-power**, **high-frequency** devices

- **Issues** affecting AlGaN/GaN-based device development include: leakage currents, current collapse (dynamic behaviour), reliability, and sub-optimal breakdown

- **Device simulation** can be used to explore and address these issues, for example through buffer-composition and field-plate optimisation

- **Compact models** for GaN HEMTs are maturing into surface-potential– (physics-) based models with high accuracy, efficiency, and scalability (the Compact Model Council is currently choosing a standard GaN-HEMT compact model)

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NXP Semiconductors: Dick Büthker, Jeroen Croon, Romain Delhougne, Johan Donkers, Valerie Girault, Dirk Gravesteijn, Stephan Heil, Fred Hurkx, Ponky Ivo, Dick Klaassen, Robert Lander, Twan van Lippen, Ralf van Otten, Saurabh Pandey, Matthias Rose, Jan Šonský, Poh Cheng Tan, and Marnix Willemsen

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