Novel Physics of Nitride Devices

M. S. Shur
CIE and ECSE Department, RPI, Troy, 12180, US

Tutorial

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Flagstaff, Arizona, USA

shurm@rpi.edu

Outline

- Potential applications
- Polarization effects
  - Piezo –Pyro -Movable Quantum Dots and THz
- Electron transport
  - Low field - High field
  - Ballistic and overshoot transport
- Trapping
- Noise
- New FET physics – MOSHFET and Current Collapse
- Plasma wave electronics
- Conclusions

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Device Universe Is Both Infinite and Expanding

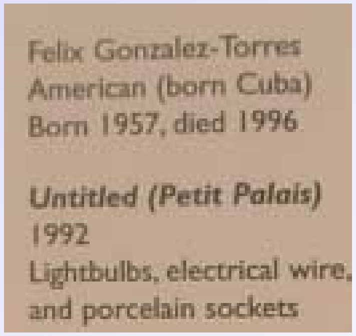
HgTe

SiC

Si

SiGe

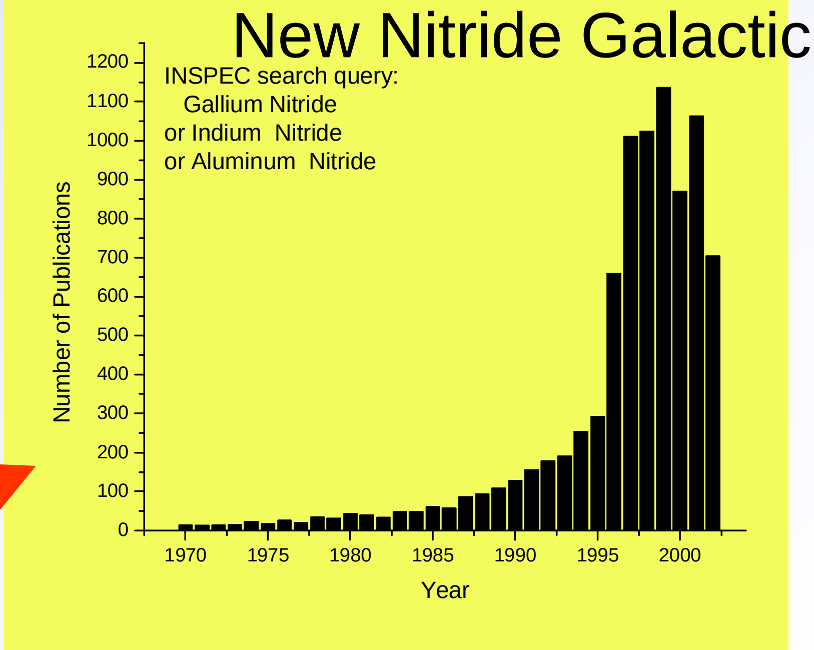
GaAs



Felix Gonzalez-Torres
American (born Cuba)
Born 1957, died 1996

Untitled (Petit Palais)
1992
Lightbulbs, electrical wire,
and porcelain sockets

GaN



New Nitride Galactic

INSPEC search query:
Gallium Nitride
or Indium Nitride
or Aluminum Nitride

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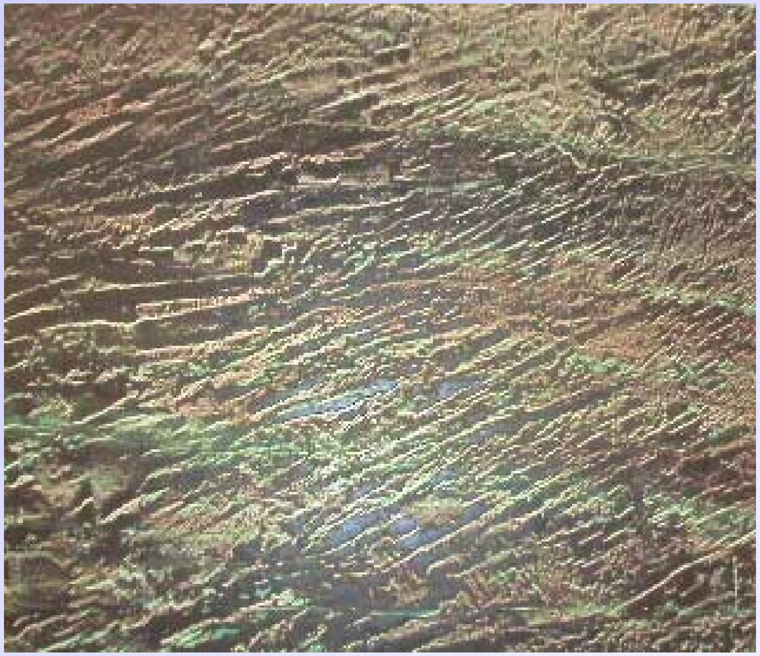
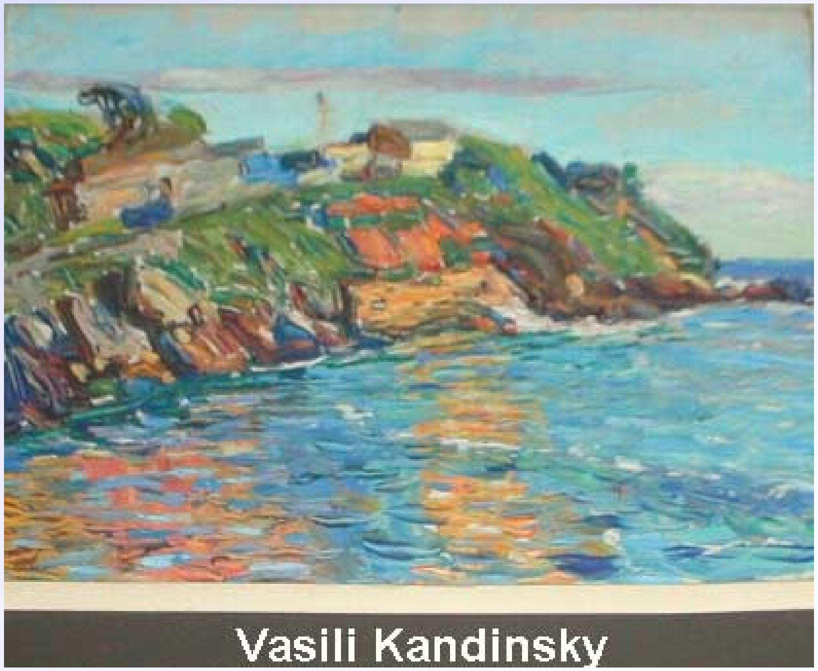
"The Universe is full of magical things patiently waiting for our wits to grow sharper"

Eden Phillpott



Isa Genzken (born 1948)
Basic research



Lembach Villa, Munich

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Potential and Existing Applications of Nitride Devices

- Blue, green, white light, and UV emitters
  - Traffic lights
  - Displays
  - Water, food, air sterilization and detection of biological agents
  - Solid state lighting
- Visible-blind and solar-blind photodetectors
- High power microwave sources
- High power and microwave switches
- Wireless communications
- High temperature electronics
- SAW and acousto-optoelectronics
- Pyroelectric sensors
- Terahertz electronics
- Non volatile memories

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White and UV applications (for 250 nm – 340 nm). Sensing and beyond

- Environmental protection
- Homeland security
- Plant growth
- Surgery lighting
- Visual stimuli
- Capillaroscopy
- Monitoring of arterial oxygen
- Phototherapyherapy of Seasonal Affective Disorder
- Water and air purification
- Solid-state white lighting
- Dense data storage
- Ballistic missile defense
- Photopolymerization of Dental Composites
- Photobioreactors

UV-LED Based Fluorimeter with Integrated Lock-in Amplifier (after Prof. Zukauskas, U of V.)

Applications of U of V/RPI/SET quadrichromatic Versatile Solid-State Lamp: Phototherapy of seasonal affective disorder at Psychiatric Clinic of Vilnius University

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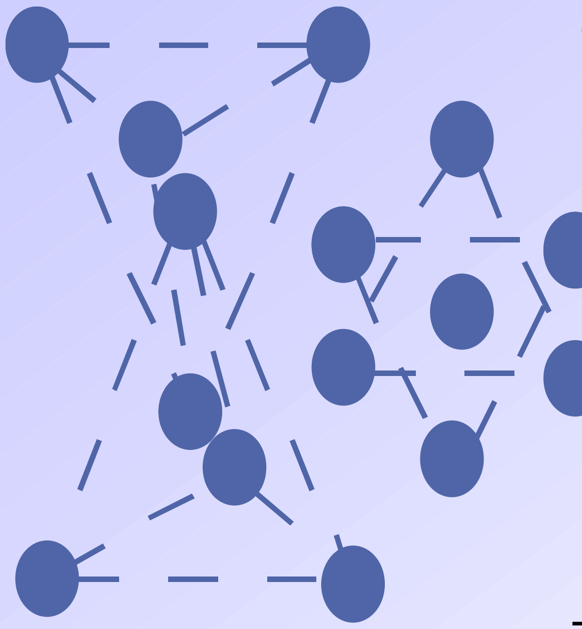
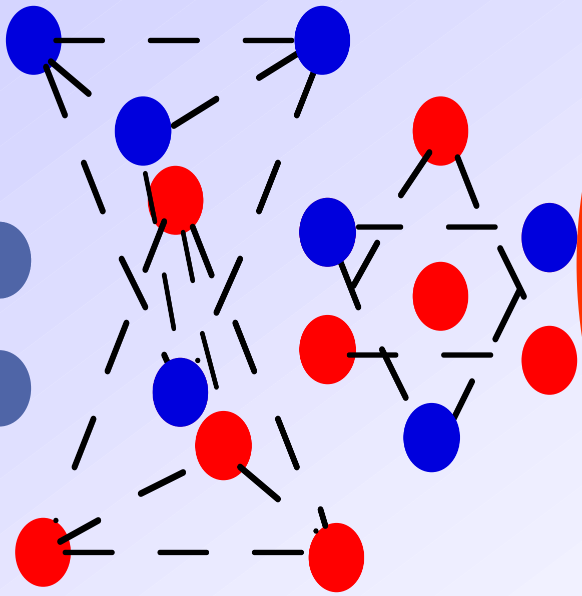
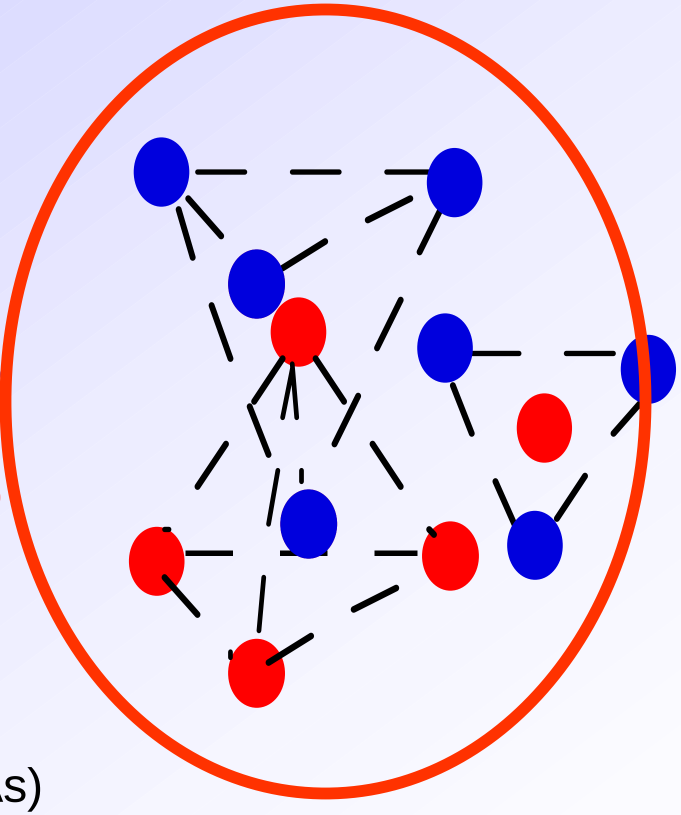
Nitrides: New Symmetry, New Physics



Diamond Structure (Si, Ge)



Zinc Blende Structure (GaAs)



Wurtzite Structure (SiC, GaN)

Si boule

GaAs boule

AlN boule (Courtesy Crystal IS

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Crystal symmetry of pyroelectric crystals

Crystal system	Crystal class (Schönflies)	Crystal class (Hermann-Mauguin)
Triclinic	C_1	1
Monoclinic	C_s C_2	m 2
Orthorhombic	C_{2v}	2mm
Tetragonal	C_4 C_{4v}	4 4mm
Rhombohedral	C_3 C_{3v}	3 3m
Hexagonal HEXAGONAL	C_6 C_6 C_{6v} C_{6V}	6 6 6mm 6mm

?

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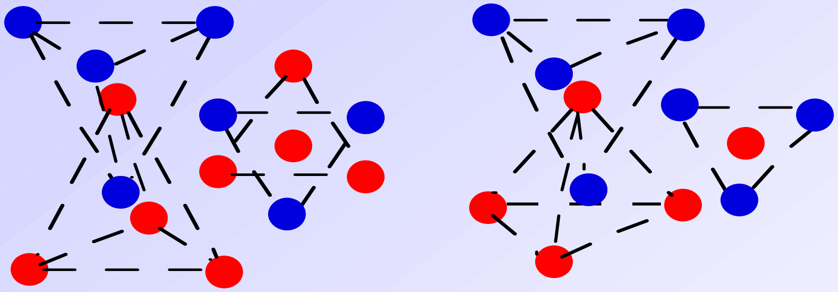
Wide Gap Semiconductors Enabling Technology for Piezoelectronics and Pyroelectronics

GaAs



GaN/AlN

- **Zinc blende structure**
- **No PE or SP effect in <100> direction**
- **PE coefficient <111> ~0.15 C/m^2**
- **No PE/SP 'doping' reported**

- **Wurtzite structure**
- **c-axis growth direction**
- **PE coeficient in c-direction ~1 C/m^2**
- **PE/SP 'doping' demonstrated**

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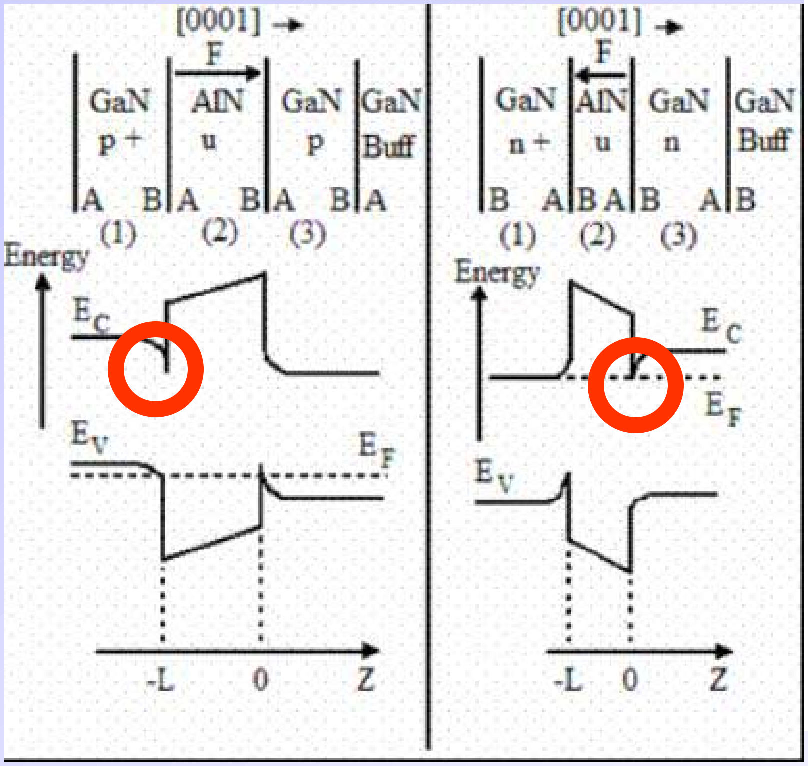
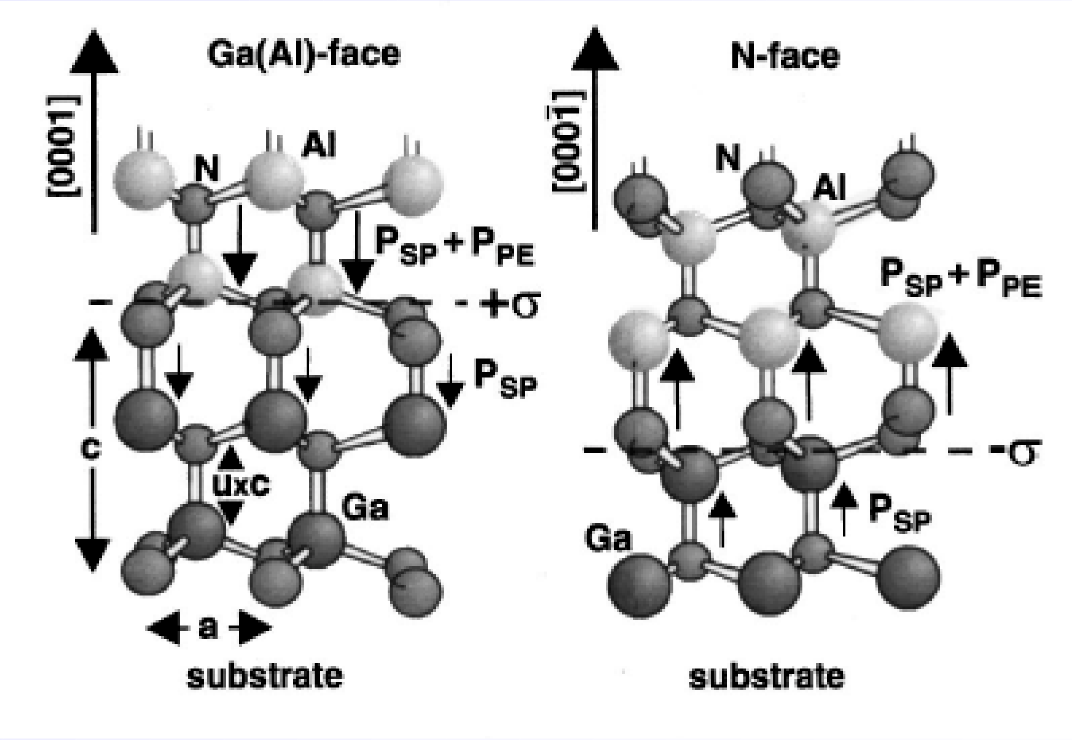
Nitride Heterostructures:
Polarization Induced Electron and Hole 2D Gases

AlGaN on GaN

C_{6v}^{4} $P6_3mc$

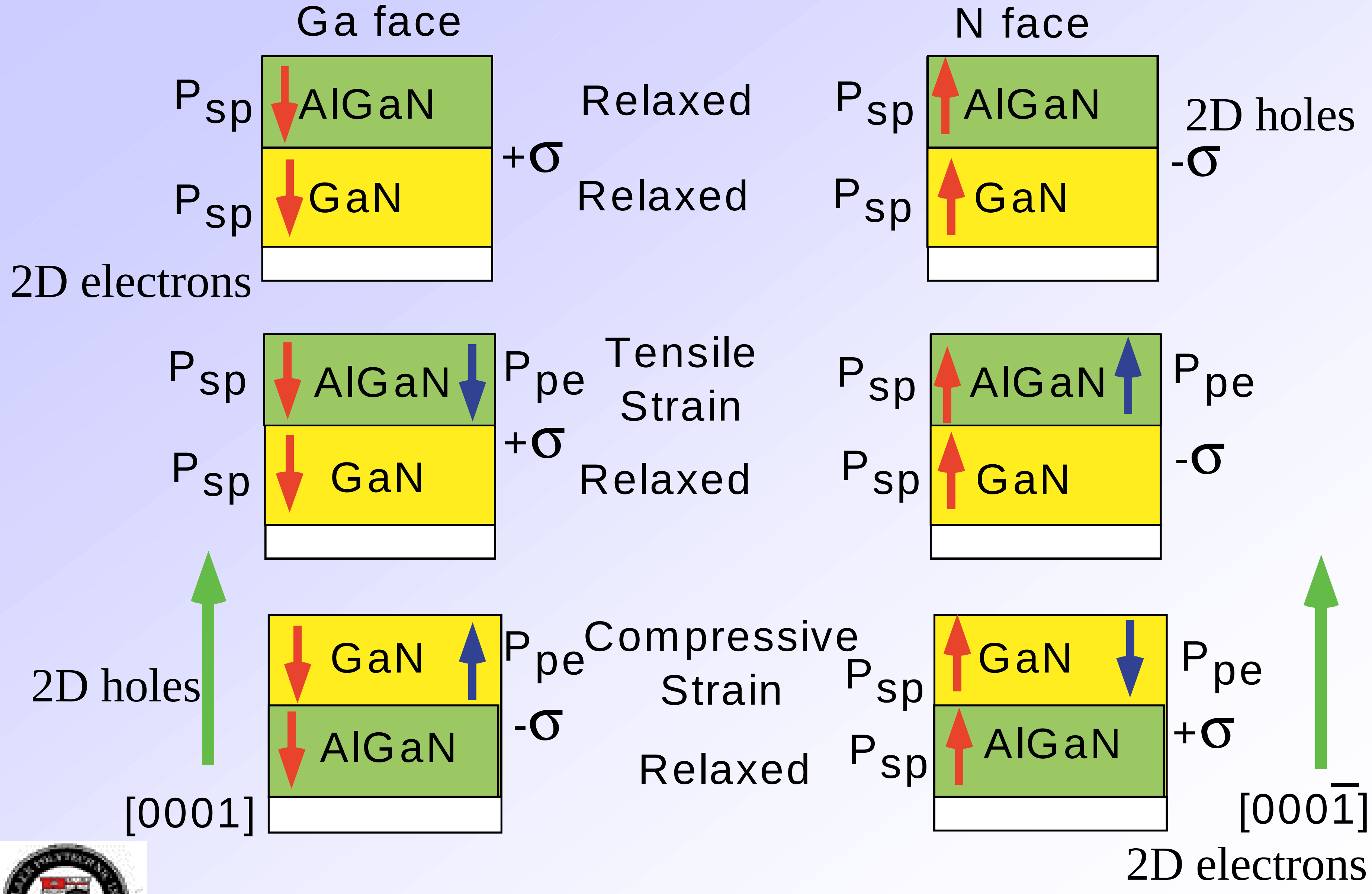




From A. Bykhovski, B. Gelmont, and M. S. Shur, J. Appl. Phys.74, p. 6734-6739 (1993)

From O. Ambacher et al JAP 87, 334 (2000)

Polarization signs



Ga face

P_{sp} AlGaN

P_{sp} GaN

$+\sigma$

Relaxed

Relaxed

2D electrons

N face

P_{sp} AlGaN

P_{sp} GaN

$-\sigma$

2D holes

P_{sp} AlGaN P_{pe}

P_{sp} GaN

$+\sigma$

Tensile Strain

Relaxed

P_{sp} AlGaN P_{pe}

P_{sp} GaN

$-\sigma$

2D holes

GaN P_{pe}

AlGaN

$-\sigma$

[0001]

Compressive Strain

Relaxed

P_{sp} GaN P_{pe}

P_{sp} AlGaN

$+\sigma$

$[000\bar{1}]$

2D electrons

After O. Ambacher et al. J.Appl. Phys. 85, 3222 (1999)

Spontaneous polarization

After F. Bernardini et al. Phys Rev. 56, 10024(1997)	AlN	GaN	InN	ZnO	BeO
Spontaneous polarization (C/m^2) (cm^{-2})	-0.081 $6.24\ 10^{14}$	-0.029 $2.23\ 10^{14}$	-0.032 $2.46\ 10^{14}$	-0.057 $4.39\ 10^{14}$	-0.045 $3.47\ 10^{14}$

For comparison, in $BaTiO_3$, $P_s = 0.25\ C/m^2\ (1.93\times10^{15} cm^{-2})$

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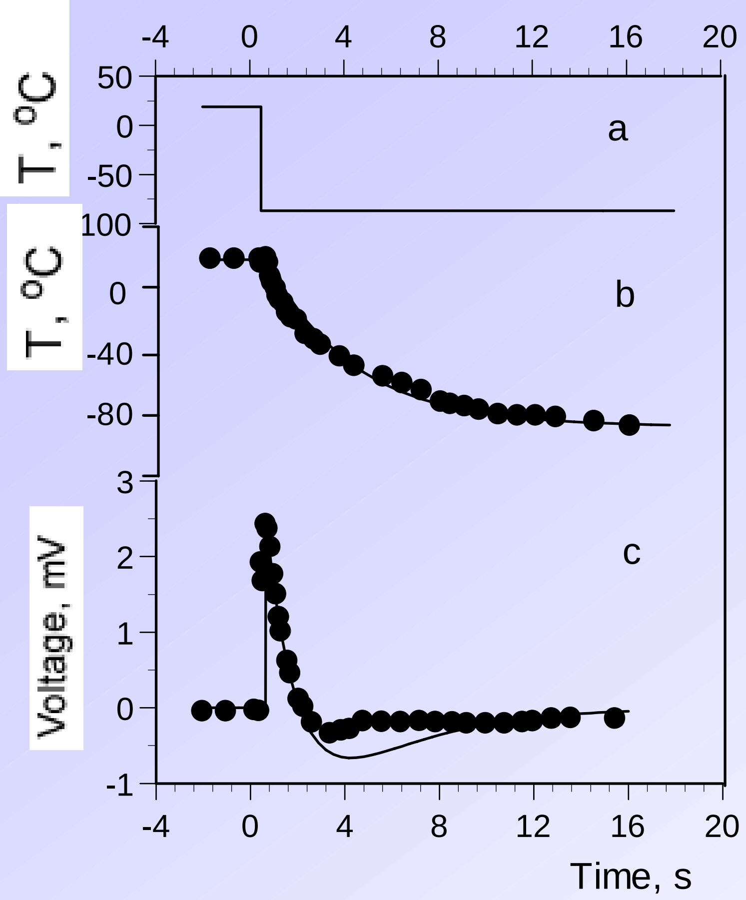
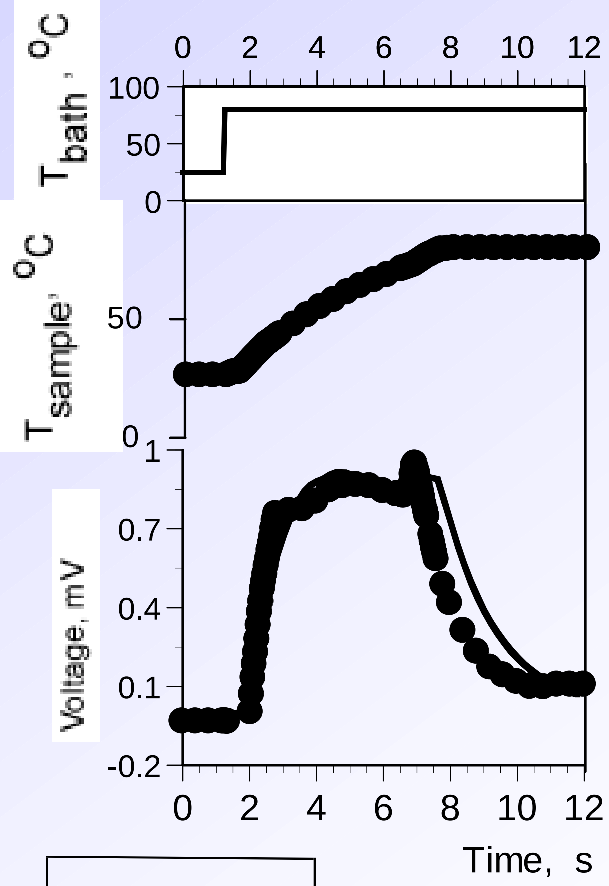
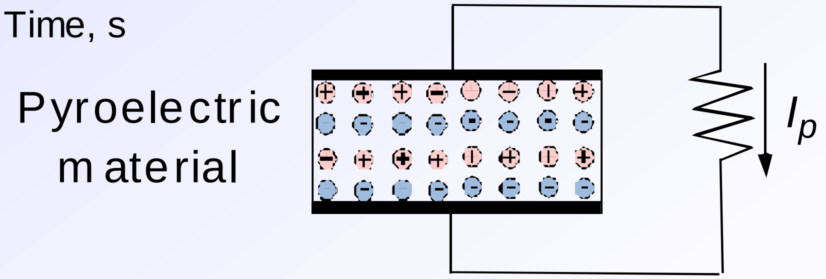
Pyroelectric effect







(after A. D. Bykhovski, V. V. Kaminski, M. S. Shur, Q. C. Chen, and M. A. Khan "Pyroelectricity in gallium nitride thin films", Appl. Phys. Lett., 69, 3254 (1996)).

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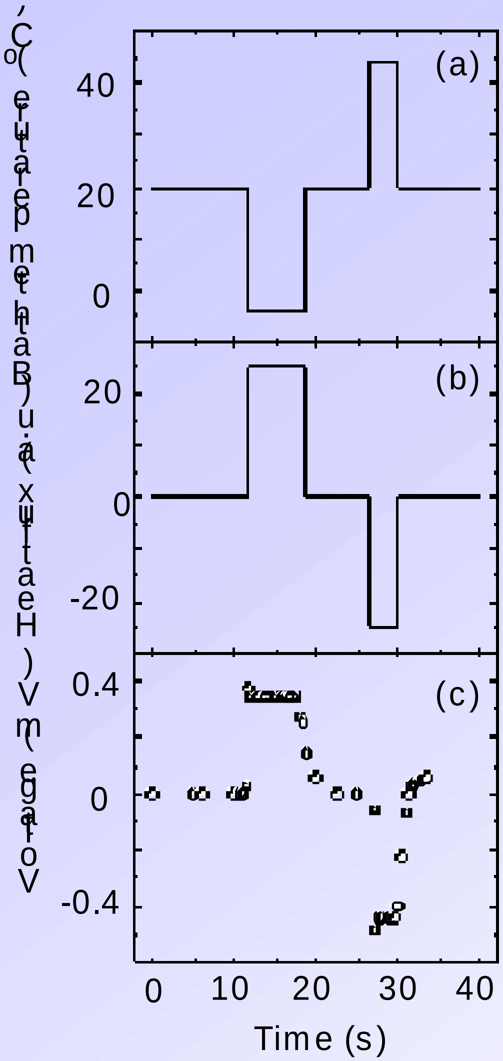
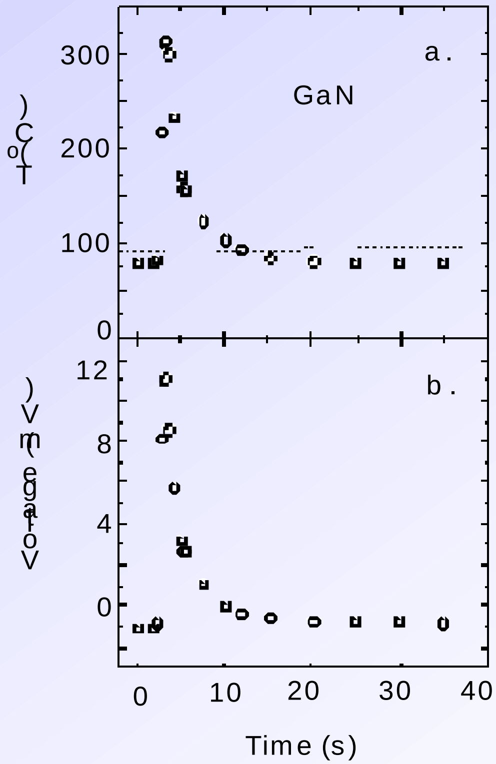
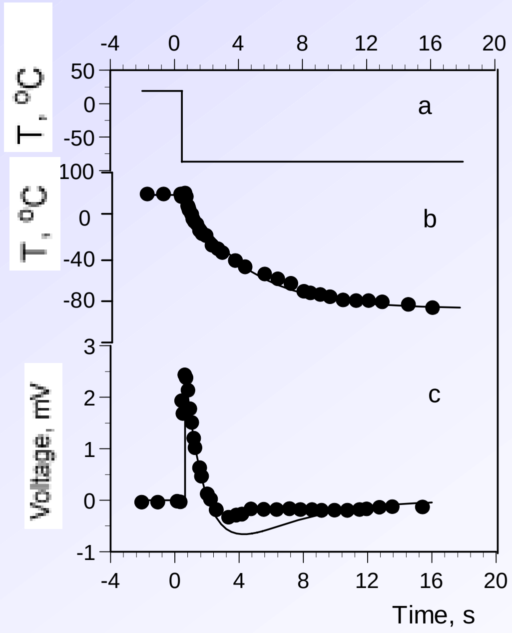
Pyroelectric voltage for primary pyroelectric effect (changing flux magnitude and direction)



Two time constants:
Sample cooling and
Charge relaxation





Primary pyroelectric effect at 300^o C (High Temperature Operation!)

(after A. D. Bykhovski, V. V. Kaminski, M. S. Shur, Q. C. Chen, and M. A. Khan "Pyroelectricity in gallium nitride thin films", Appl. Phys. Lett., 69, 3254 (1996)).

Strain from the lattice mismatch

- $u_{xx} = (a_{GaN} - a_{AlGaN})/a_{GaN}$
- $P_{pe} = 2\ u_{xx}\ (e_{31} - e_{33}\ C_{13}/C_{33})$

How Piezoelectric constants are determined?

- Electromechanical coefficients (difficult)
- Optical experiments (indirect)
- Estimate from transport measurements (very indirect)

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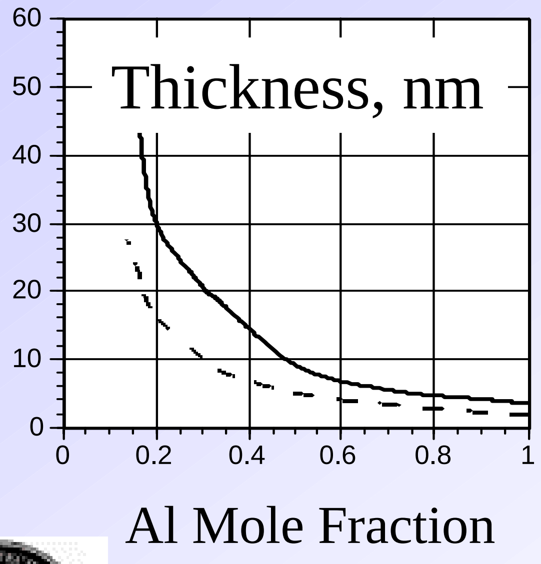
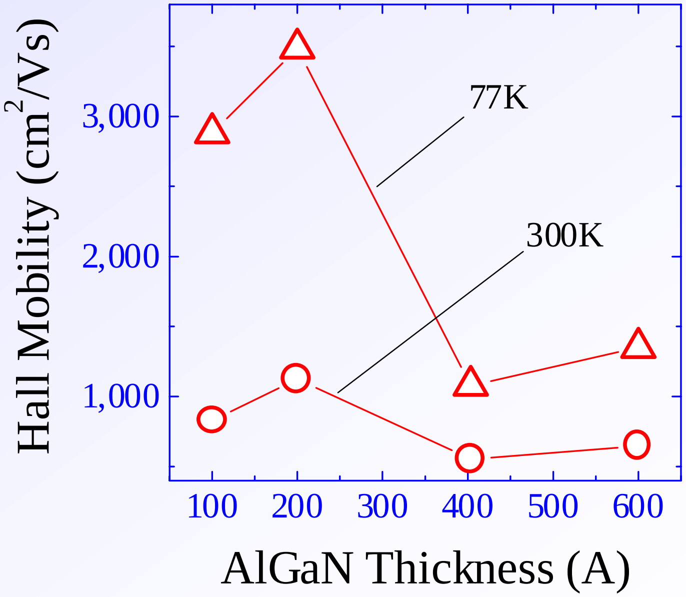
Effect of Strain on Dislocation-Free Growth

- Critical thickness as a function of Al mole fraction in $Al_xGa_{1-x}N/GaN$: superlattice (solid line), SIS structure (dashed line).

From A. D. Bykhovski, B. L. Gelmont, and M. S. Shur, J. Appl. Phys. 81 (9), 6332-6338 (1997)



Effect of Critical Thickness on Electron Mobility



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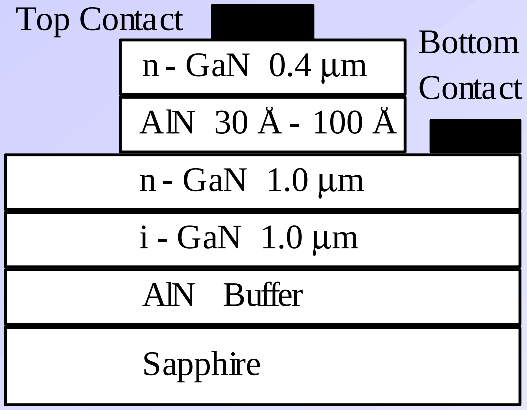
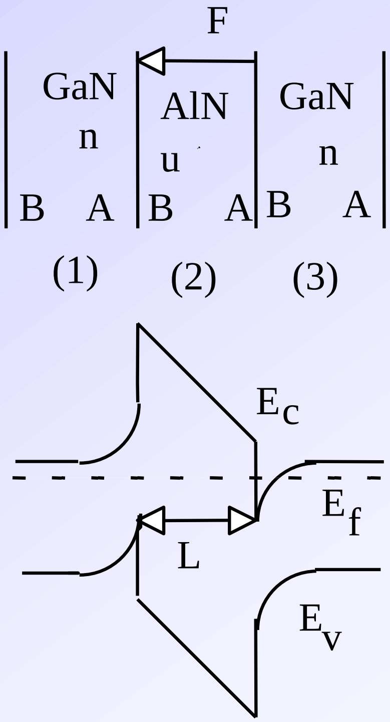
SIS sensor

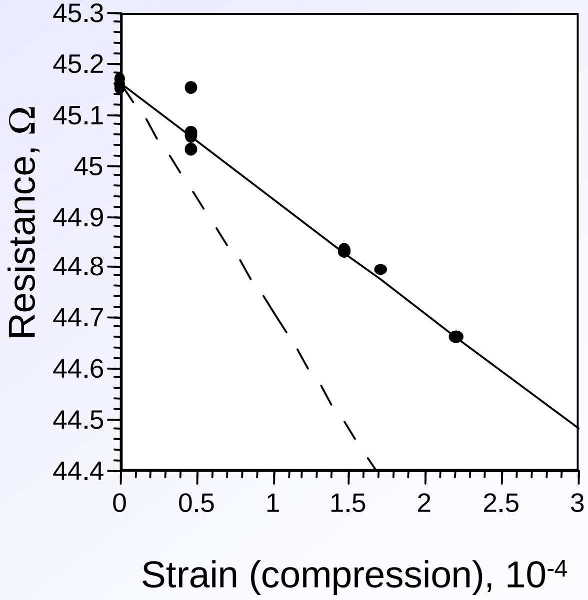
- Piezoelectric sensors
- Pyroelectric sensors





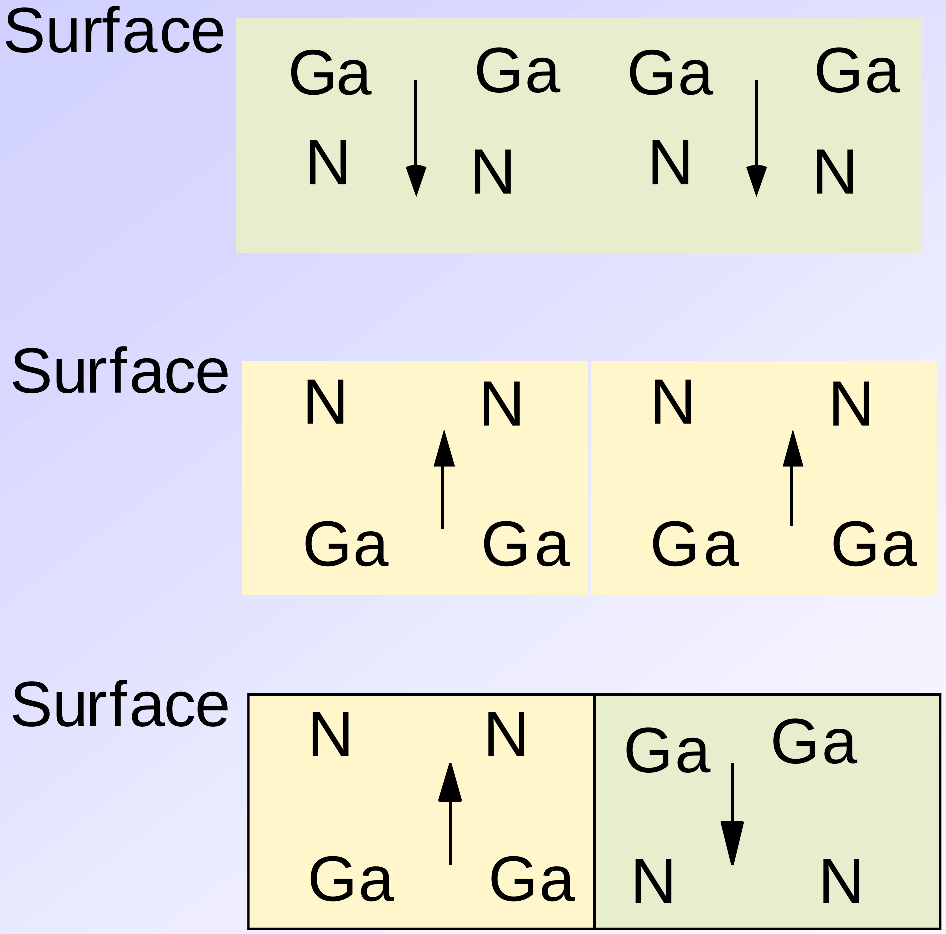
Twice as large as in SiC

Short range superlattice is four times larger than in SiC



After R. Gaska, J. Yang, A. D. Bykhovski, M. S. Shur, V. V. Kaminski, S. M. Soloviev, Appl. Phys. Lett. 71(26), 3817 (1997)

Polarization domain structure



After A. D. Bykhovski, V. V. Kaminskii, M. S. Shur, Q. C. Chen, and M. Asif Khan, Piezoresistive Effect in Wurtzite *n*-type GaN, Appl. Phys. Lett., 68 (6), pp. 818-819 (1996)

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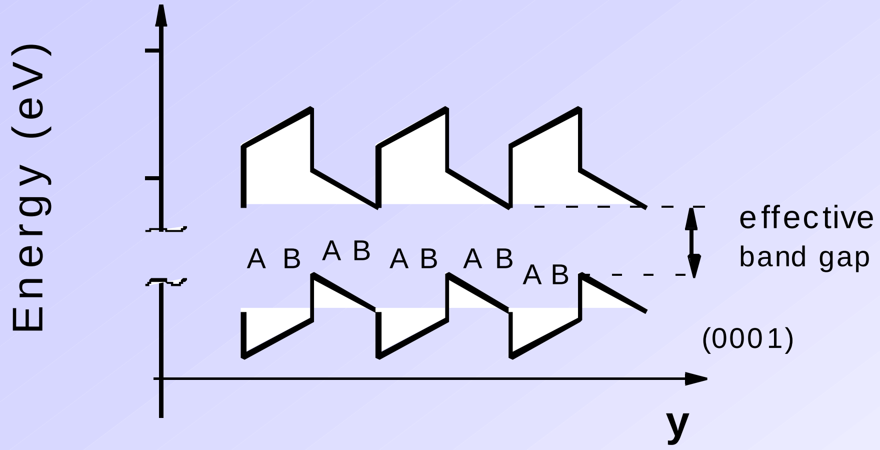
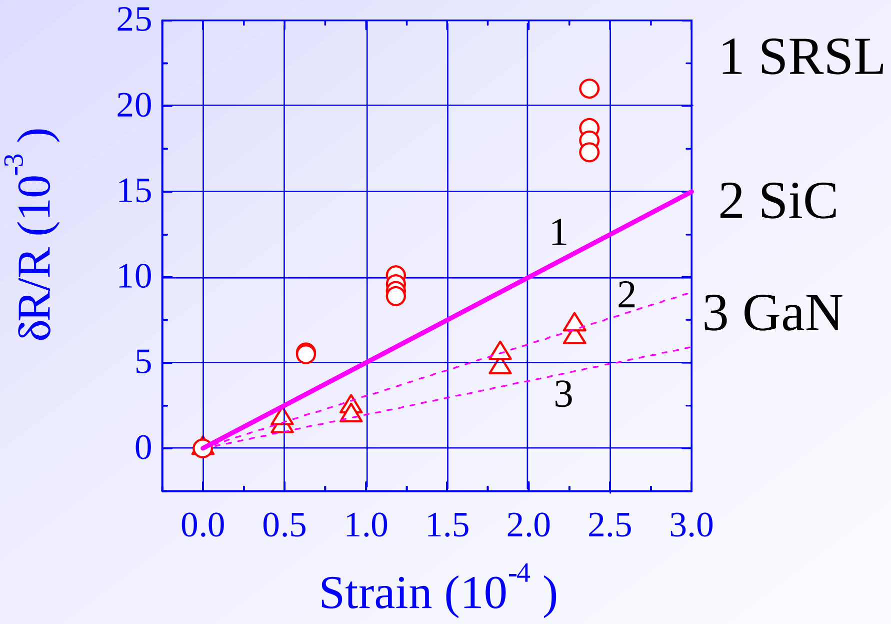
Superlattice Band Diagram and resistance change in SRSL





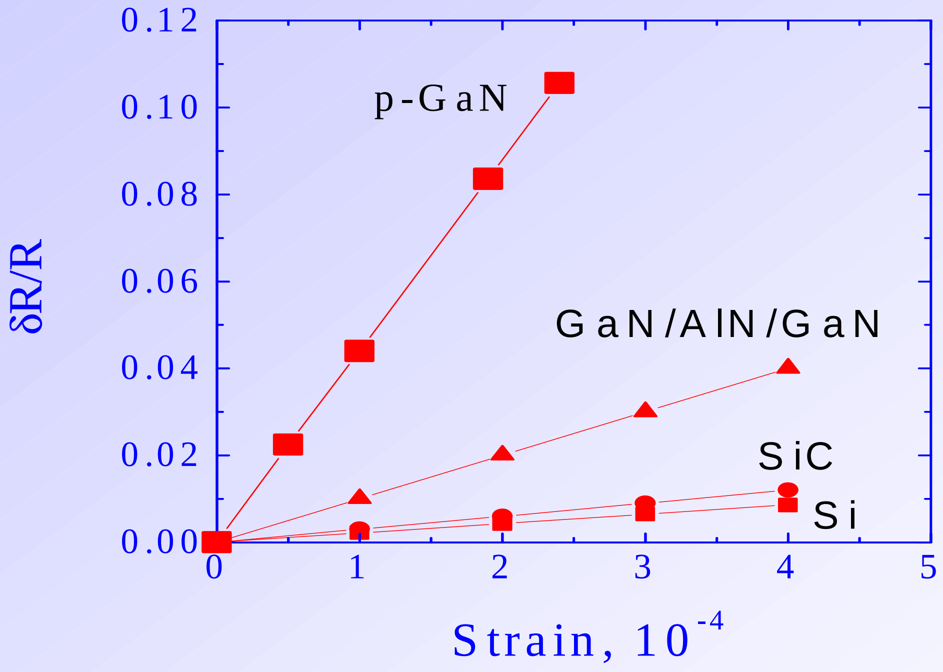
After A. D. Bykhovski, B. L. Gelmont, and M. S. Shur, Elastic Strain Relaxation in GaN-AlN, GaN-AlGaN, and GaN-InGaN Superlattices, J. Appl. Phys. Vol. 81, No. 9, pp. 6332, May (1997)

Relative change in resistance under applied strain. (o) - correspond to $[(AlN)_6\text{-}(GaN)_3]_{150}$ SRSL ; ( ) - $[(AlN)_3\text{-}(GaN)_8]_{150}$ SRSL; solid line 1 shows dependence measured for GaN-AlN-GaN SIS [1]; dashed line 2 - SiC *p-n* junction [1] ; 3 - GaAs [2]. The GF for the measured samples was in the 30 to 90 range. The larger GF (higher sensitivity to strain) was measured in SRSLs with higher Al content.

[1] J. S. Shor, L. Bemis, and A. D. Kurtz, IEEE Trans. Electron Dev. , 41 (5), 661 (1994).

[2] A. Sagar, Phys. Rev., 112, 1533 (1958); 117, 101 (1960).

High Temperature p-GaN Pressure Sensor



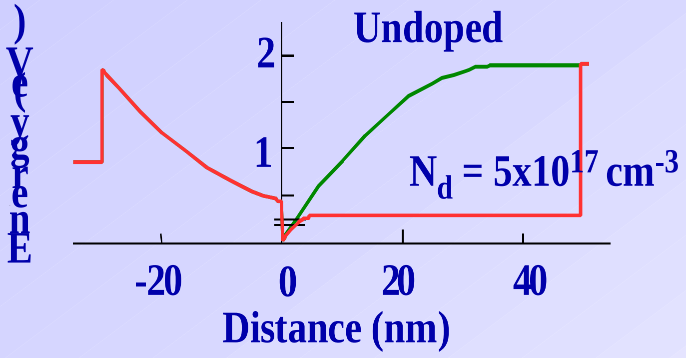
From R. Gaska, M. S. Shur, A. D. Bykhovski, J. W. Yang, M. A. Khan, V. V. Kaminski and S. M. Soloviov, Piezoresistive Effect in Metal-Semiconductor-Metal Structures on *p*-type GaN, Appl. Phys. Lett., vol. 76, No. 26, pp. 3956-3958, June 26 (2000)

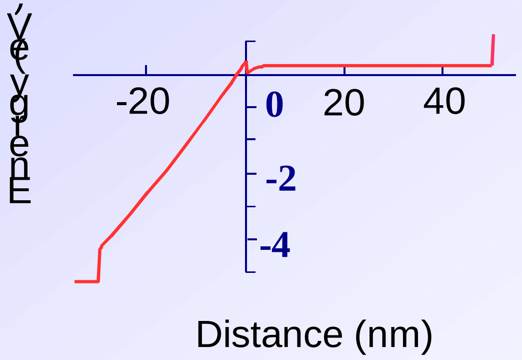
Static Gauge factors (GF)

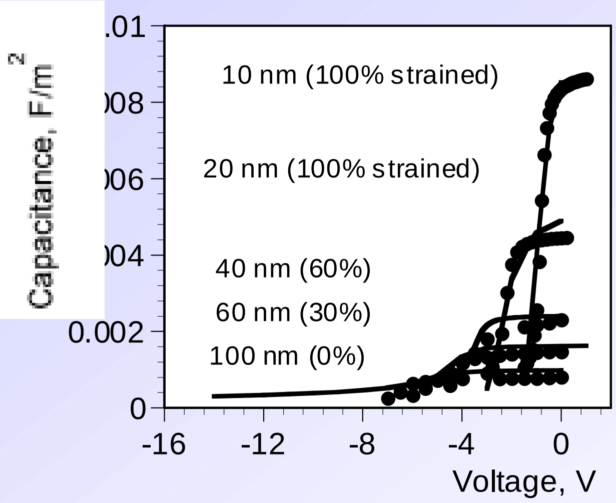
(measured under longitudinal mechanical deformation)

GaN	GaN/AlN/GaN Sapphire	AlGaN/GaN Heterostructures	AlN/GaN Short Range Superlattices
n-type GF=10 p-type GF > 200	GF = 50	GF = 10-15	GF = 30-80

Polarization effects in undoped and doped channel GaN/AlGaN HFETs



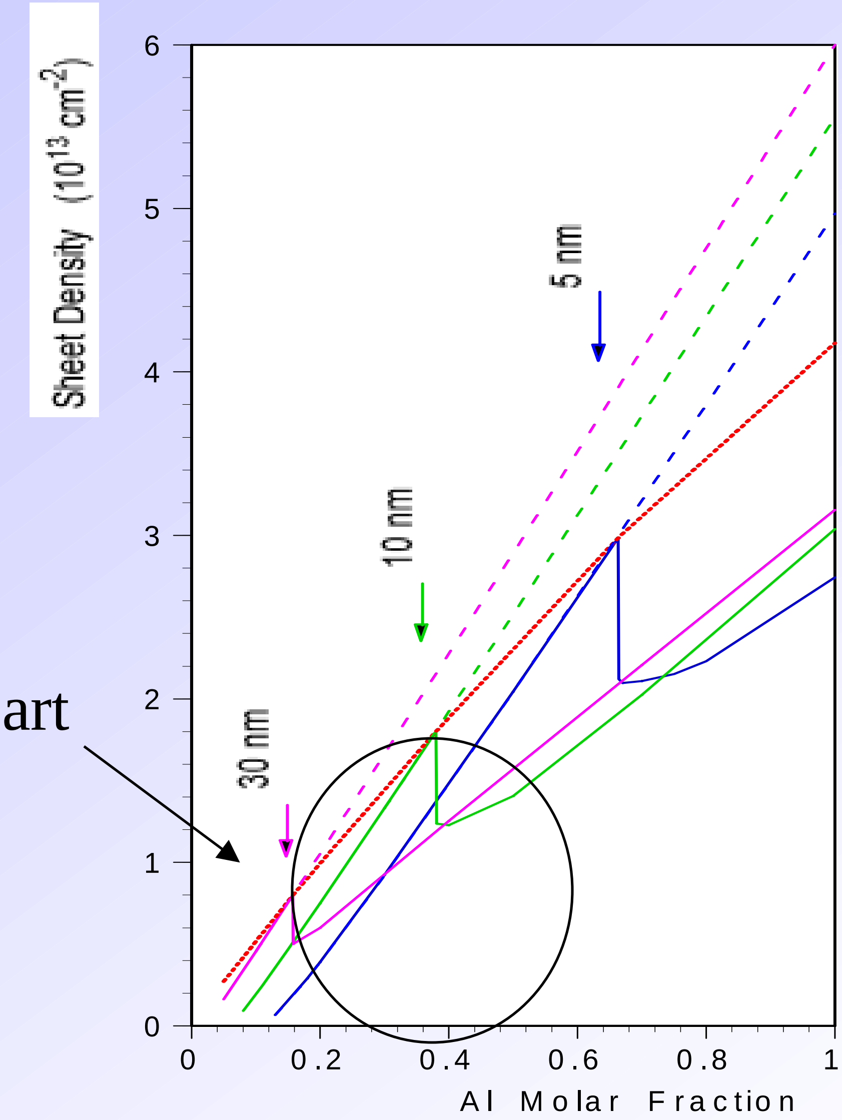


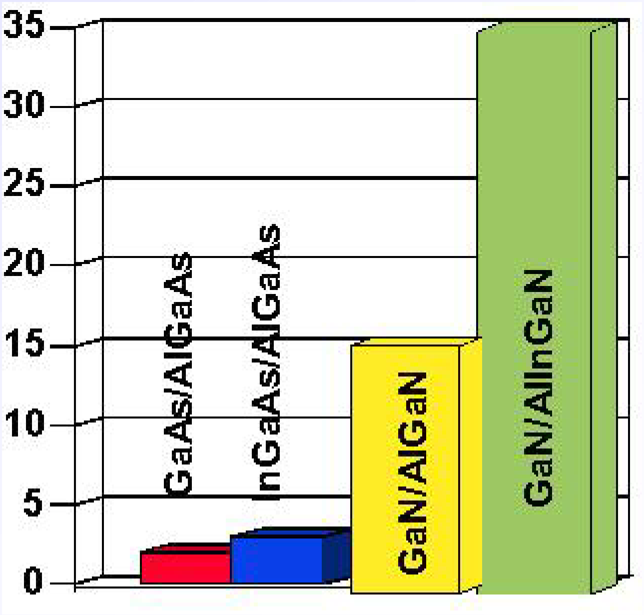


After M. S. Shur, GaN and related materials for high power applications, Mat. Res. Soc. Proc. Vol. 483, pp. 15-26 (1998) and From A. D. Bykhovski, R. Gaska, and M. S. Shur, Appl. Phys. Lett. 73 (24) (1998).

Piezoelectric and Pyroelectric Doping in AlGaN/GaN

State-of-the-art





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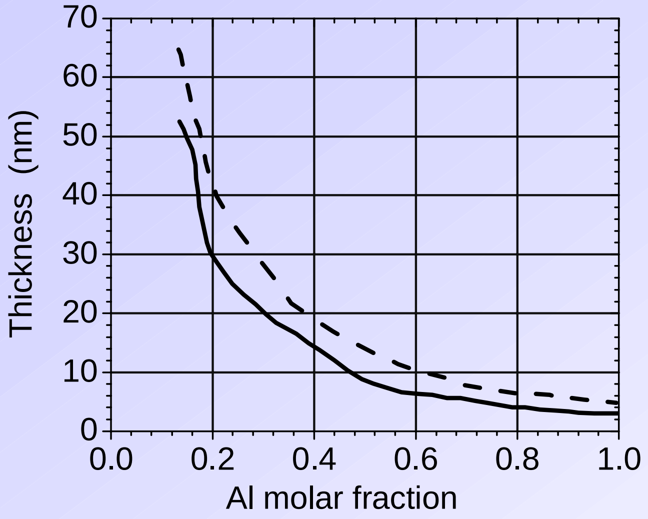
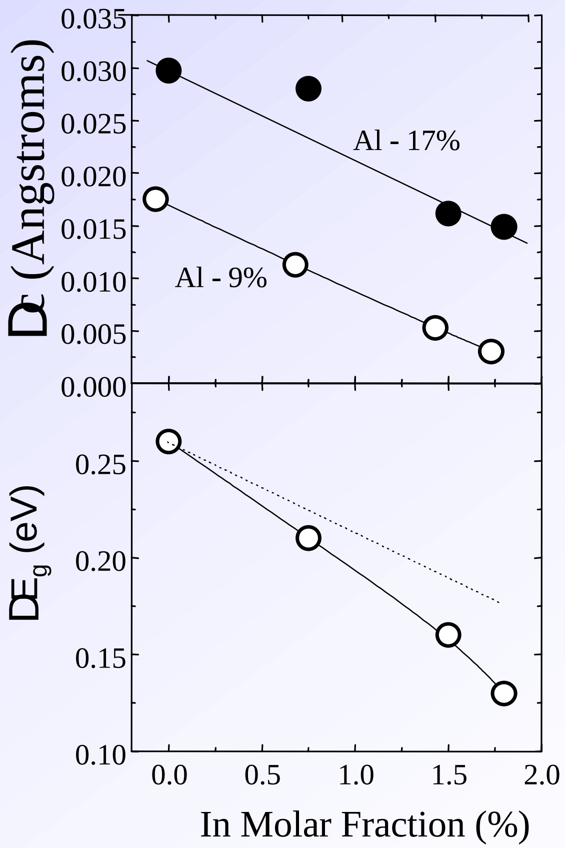
Strain and Energy Band Engineering

- Graded composition profile and quaternary AlGaInN
- Superlattice buffers for strain relief
- PALE and MEMOCVD epitaxial growth
- Homoepitaxial substrates
- Non-polar substrates

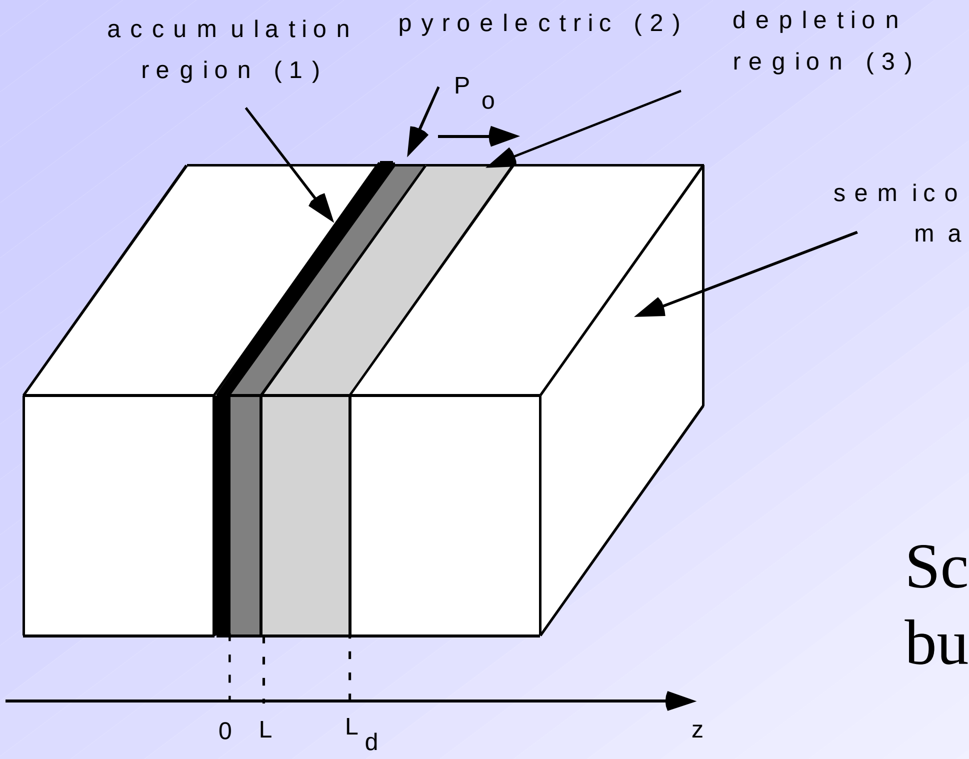


A. D. Bykhovski, B. L. Gelmont, and M. S. Shur, *Elastic Strain Relaxation in GaN-AlN Superlattices*, Proceedings of International Semiconductor Device Research Symposium, Vol. II, pp. 541-544, Charlottesville, VA, ISBN 1-880920-04-4, Dec. 1995



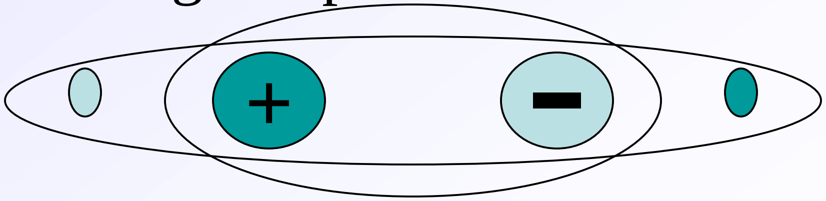
M. Asif Khan, J. W. Yang, G. Simin, R. Gaska, M. S. Shur, Hans-Conrad zur Loye, G. Tamulaitis, A. Zukauskas, David J. Smith, D. Chandrasekhar, and R. Bicknell-Tassius, *Lattice and Energy Band Engineering in AlInGaN/GaN Heterostructures,* Appl. Phys. Lett 76 (9) pp. 1161-1163 (2000)

New Screening Mechanism in Multilayer Pyroelectrics



Screening the polarization induced dipole involves smaller charges than the charges in polarization dipole

Screening dipole – smaller changes but at larger separation

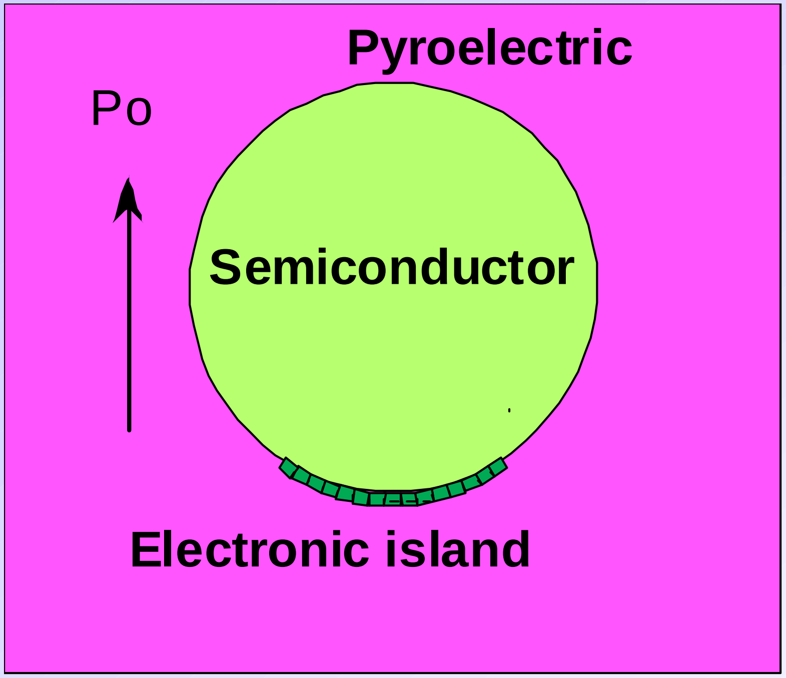


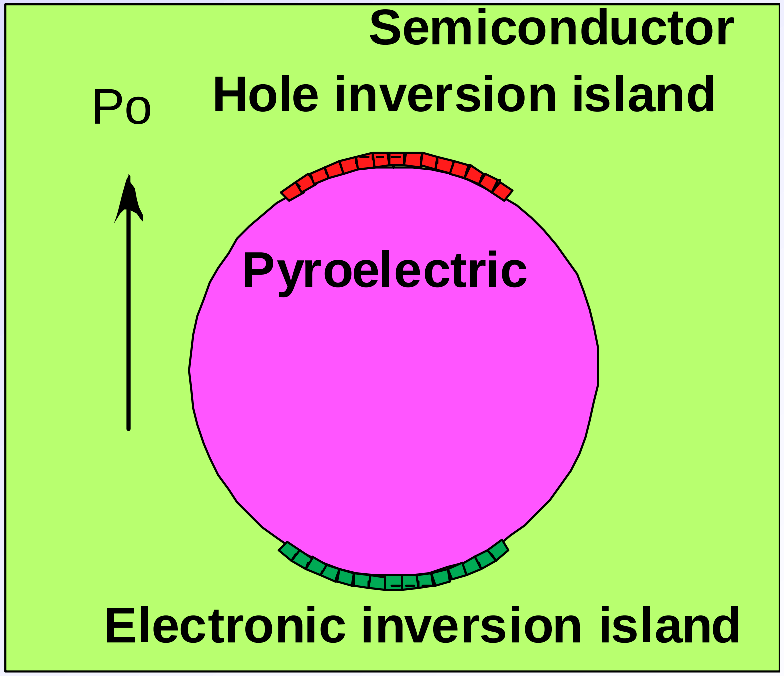
Polarization dipole

New screening length (larger than Debye but smaller than depletion)

Electronic island at the surface of semiconductor grain in pyroelectric matrix (MQDs -Moveable Quantum Dots)

Inversion electron and hole islands at the surface of pyroelectric grain in semiconductor matrix





Control by external field – Zero dimensional Field Effect (ZFE)

V. Kachorovskiy and M. S. Shur, APL, March 29 (2004)

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Basic Equations

$$E = \frac{4\pi P_0}{\varepsilon + 2\varepsilon_p}$$

polarization induced electric field

$$E_c = \frac{eN}{\varepsilon R^2} = \frac{4\pi e n_d R}{3\varepsilon}$$

screening field

$$N = \frac{4\pi}{3} n_d R^3$$

total number of electrons in the grain

n_d donor concentration

The size of the island should be determined by the minimum of the total energy

$$P_0 >> e n_d R \longrightarrow E >> E_c$$

Electrons cannot screen polarization induced field. Strong field push electrons into small 2D island

$$W = \frac{QEa^2}{R} + \frac{Q^2}{\varepsilon a}$$

Potential energy in the field *E*

Coulomb repulsion energy

W should be minimal provided that the total charge of the island, Q=eN , is constant

$$\Longrightarrow$$

$$a \sim \left(\frac{QR}{E}\right)^{1/3} \sim \left(\frac{e n_d R}{P_0}\right)^{1/3} R$$

For typical values of polarization the size of electron island is small compared to *R*

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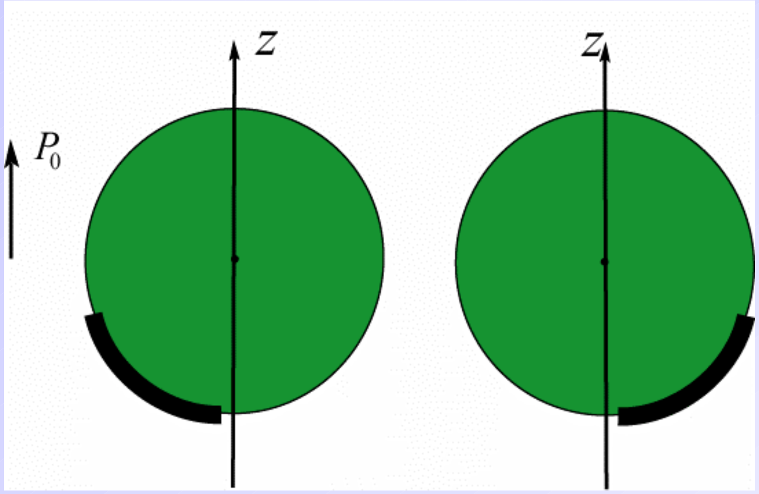
Terahertz oscillations

2D island might oscillate as a whole over grain surface. The oscillations can be exited by *ac* field perpendicular to $\boldsymbol{P_0}$



Oscillation frequency

$$\omega_0 = \sqrt{\frac{4\pi e P_0}{(\varepsilon + 2\varepsilon_p)\, mR}}$$

MOVABLE QUANTUM DOTS (MQD)

Oscillation frequency is of the order of a terahertz

$$\omega_0\pi/2 \sim 1\ THz \text{ to } 30\ THz$$

SWITCH OR SHIFT FREQUENCY BY EXTERNAL FIELD OR BY LIGHT

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New Physics of Movable Quantum Dots

- Self-assembled quantum dot arrays
- Coulomb blockade
- Light concentration in quantum dots
- Left handed materials

New Potential Applications

- Terahertz detectors
- Terahertz emitters
- Terahertz mixers
- Photonic terahertz devices
- Photonic crystals
- Plasmonic crystals
- Solar cells and thermo voltaic cells

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New features of electron transport in nitrides

- Large polar optical phonon energy leads to **two step scattering optical photon absorption and re-emission** resulting in an elastic scattering process [1]

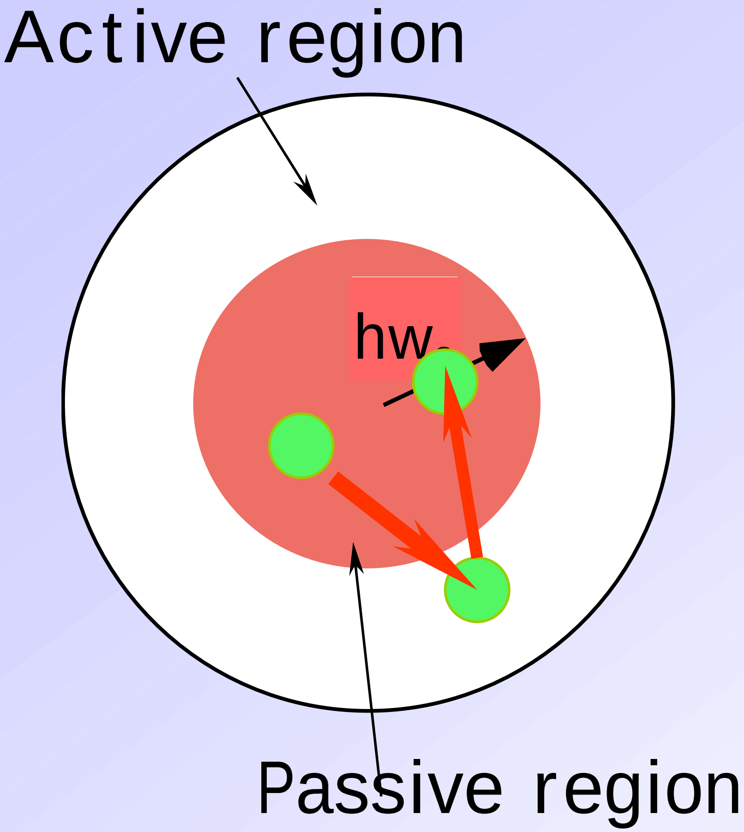
- In high electric fields, an **electron runaway** plays a key role [2]. The runaway effects are **enhanced in 2D electron gas** [3]

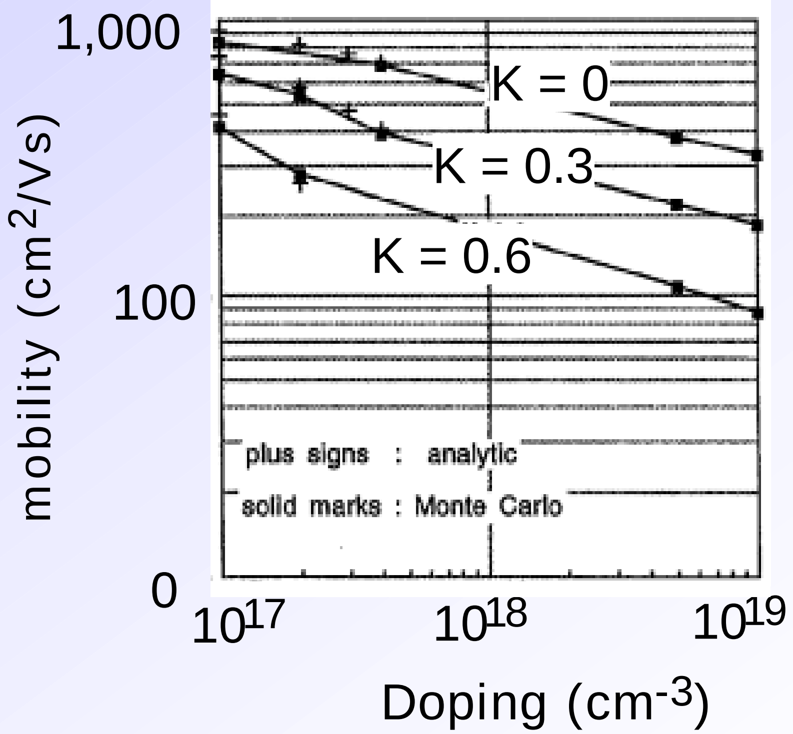
- In very **short GaN-based structures, ballistic and overshoot effects are very pronounced** [4]

1. B. Gelmont, K. S. Kim, and M. S. Shur, *J. Appl. Phys.* **74**, 1818 (1993)
2. B. E. Foutz, S. K. O'Leary, M. S. Shur, and L. F. Eastman, *Solid State Communications*. **118**, 79(2001)
3. A. Dmitriev, V. Kachorovskii, M. S. Shur, and M. Stroscio, *International Journal of High Speed Electronics and Systems*, **10**, 103 (2000)
4. B. E. Foutz, S. K. O'Leary, M. S. Shur, and L. F. Eastman, *J. Appl. Phys.* **85**, 7727 (1999)

shurm@rpi.edu

Consequence of high polar optical energy: two step optical polar scattering process

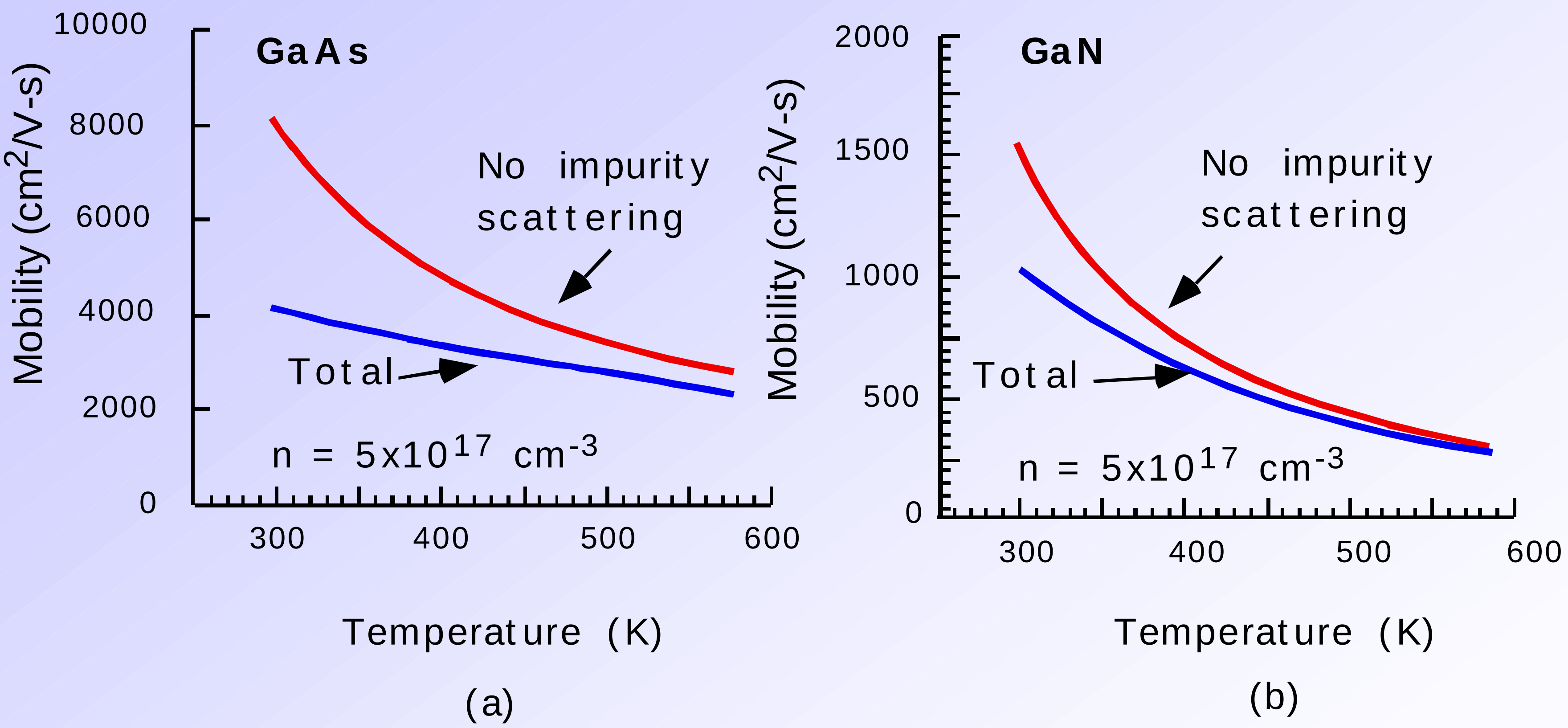




From B. Gelmont, K. S. Kim, and M. S. Shur, *J. Appl. Phys.* **74**, 1818 (1993)

shurm@rpi.edu

Temperature dependencies



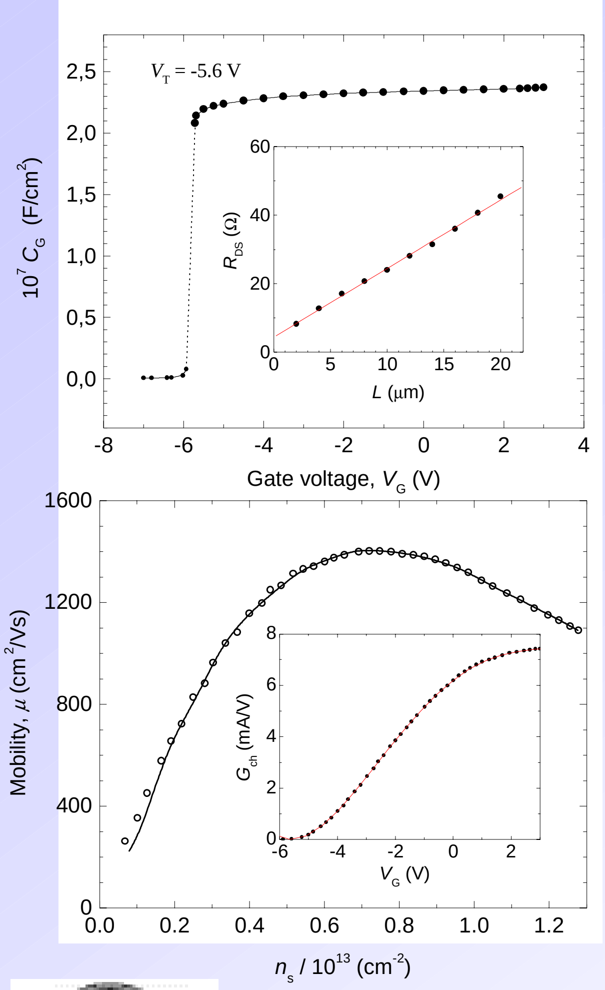
(a) (b)

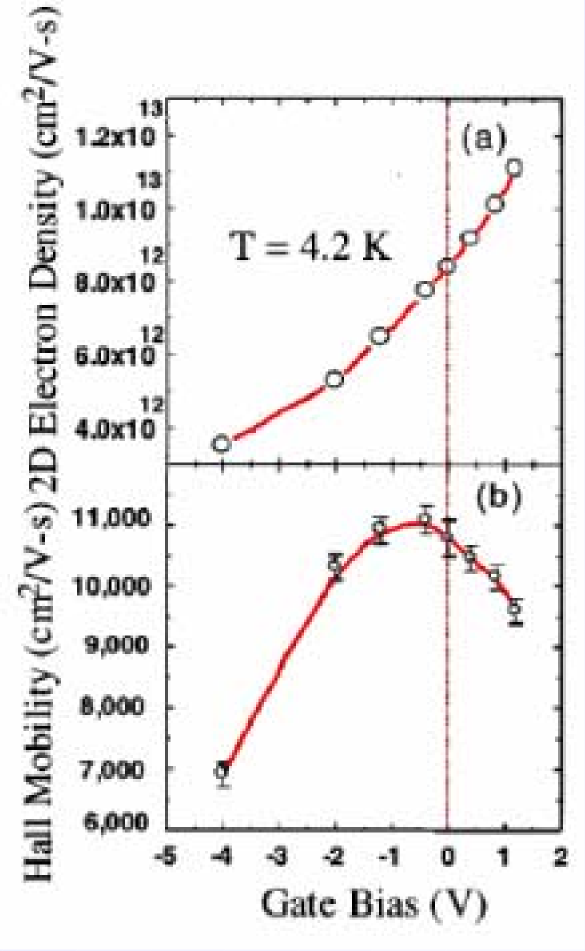
Weaker contribution of impurity scattering for GaN because of heavier mass

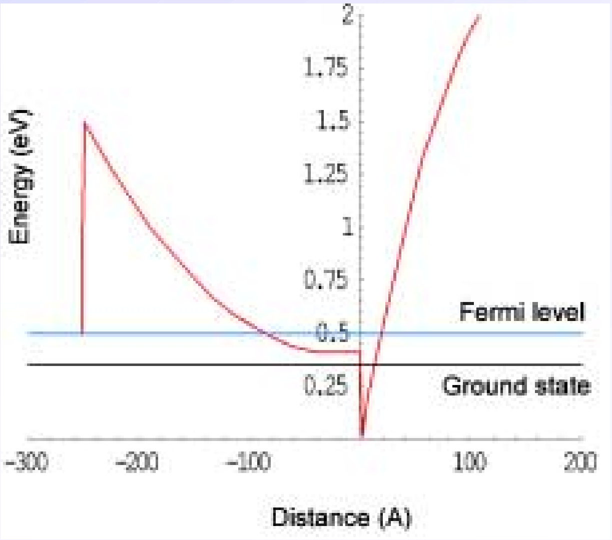
After M. S. Shur, *Solid State Electronics*, **42**, 2131 (1998)

shurm@rpi.edu

Evidence of penetration into AlGaN or 2D-3D transition



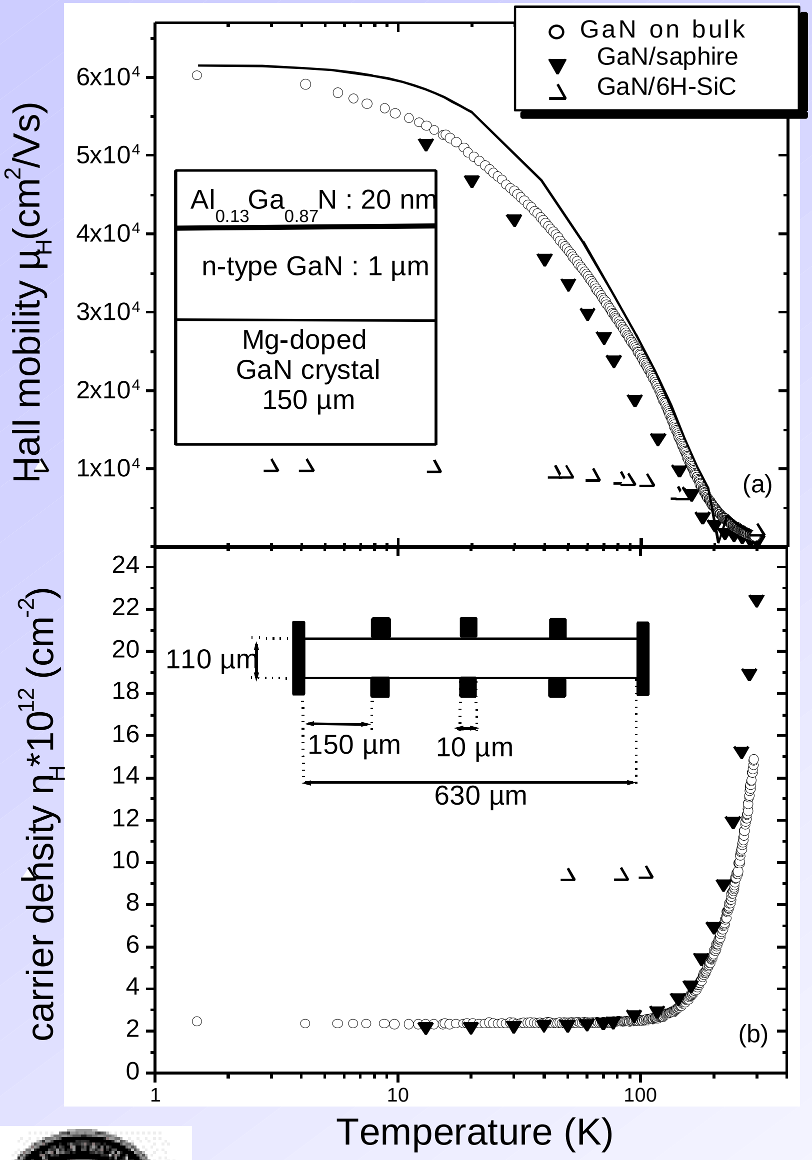


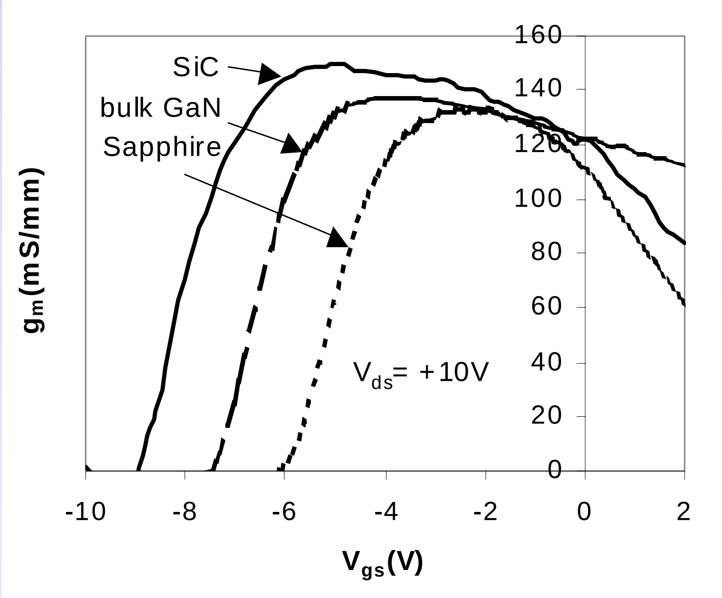


X. Hu, J. Deng, N. Pala, R. Gaska, M. S. Shur, C. Q. Chen, J. Yang, S. Simin, and A. Khan, C. Rojo, L. Schowalter, AlGaN/GaN Heterostructure Field Effect Transistor on Single Crystal Bulk AlN, Appl. Phys. Lett, 82, No 8, pp. 1299-1302, 24 Feb (2003)

From R. Gaska, M. S. Shur, A. D. Bykhovski, A. O. Orlov, and G. L. Snider, *Appl. Phys. Lett.* **74**, 287 (1999)

Effect of Substrates: Bulk GaN on GaN





After M. Asif Khan and J. W. Yang, W. Knap, E. Frayssinet, X. Hu and G. Simin, P. Prystawko, M. Leszczynski, Grzegory, S. Porowski, R. Gaska, M. S. Shur, B. Beaumont, M. Teisseire, and G. Neu, GaN-AlGaN Heterostructure Field Effect Transistors Over Bulk GaN Substrates, Appl. Phys. Lett. 76, No. 25, pp. 3807-3809, 19 June (2000)

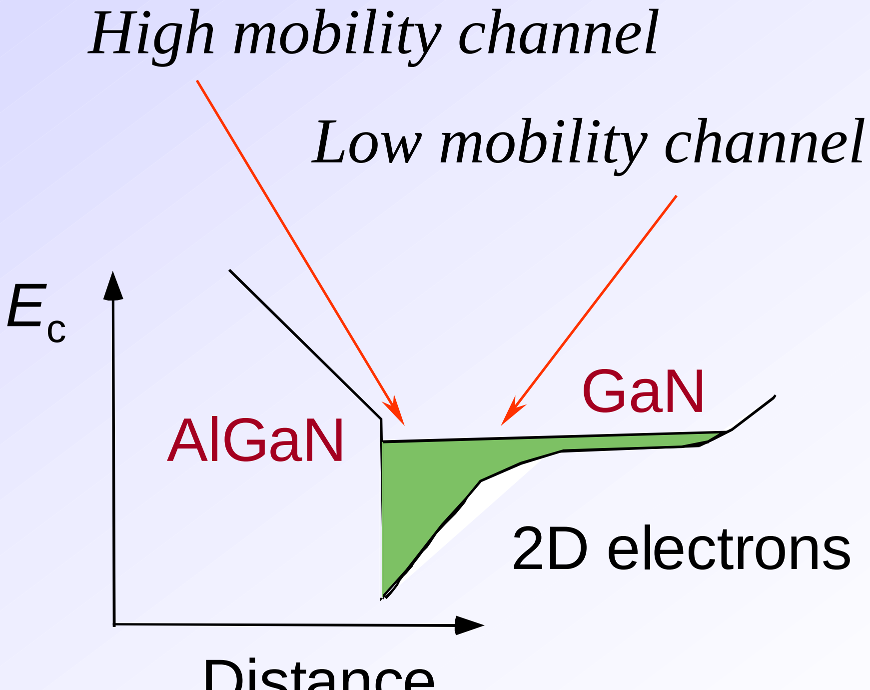
From E. Frayssinet, W. Knap, P. Lorenzini,
N. Grandjean and J. Massies,
C. Skierbiszewski, T. Suski, I. Grzegory,
S. Porowski, G. Simin, X. Hu, M. Asif Khan,
M. Shur, R. Gaska, and D. Maude,
Applied Physics Letters, **77**, 2551 (2000)

shurm@rpi.edu

Shubnikov de Hass (SdHO) and magnetoresistance results

- Parallel conduction model yields the room-temperature 2D carrier mobility exceeded 2,650 cm^2/Vs

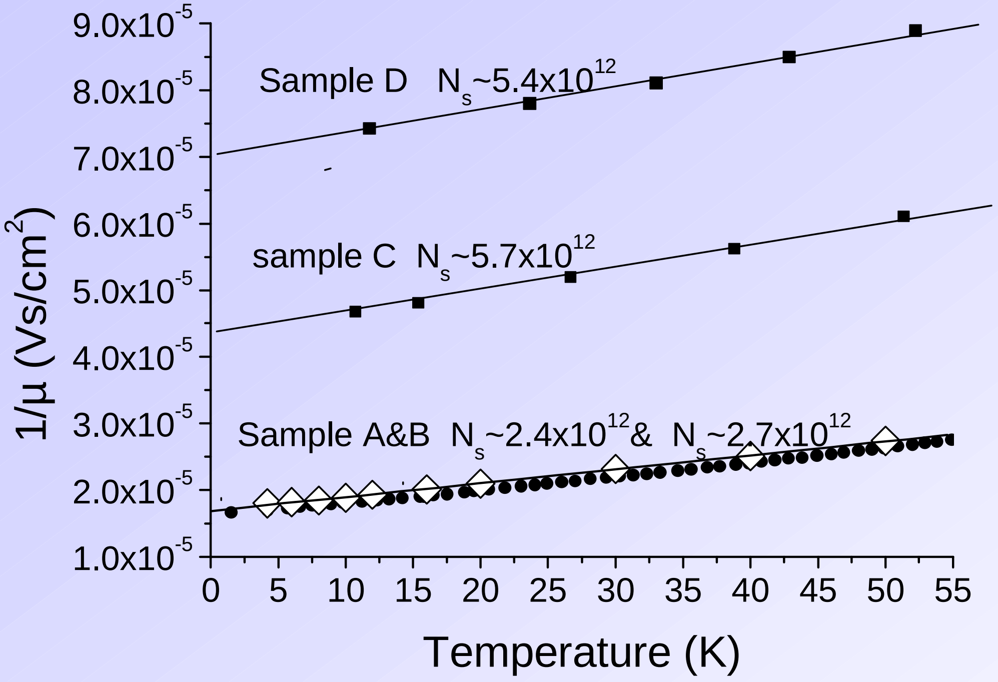
After E. Frayssinet, W. Knap, P. Lorenzini, N. Grandjean and J. Massies, C. Skierbiszewski, T. Suski, I. Grzegory, S. Porowski, G. Simin, X. Hu, M. Asif Khan, M. Shur, R. Gaska, and D. Maude, *Applied Physics Letters*, **77**, 2551 (2000)



2D-3D transition

shurm@rpi.edu

Cryogenic low field transport:
Acoustic Scattering
Inverse Linear Dependence at Low Temperatures



Extracted

Deformation potential

a_c=8.1 0.2 eV

$$\frac{1}{\mu} = \alpha T + \frac{1}{\mu_0}$$

From W. Knap, E. Borovitskaya, M. S. Shur, L. Hsu, W. Walukiewicz, E. Frayssinet, P. Lorenzini, N. Grandjean, C. Skierbiszewski, P. Prystawko, M. Leszczynski, I. Grzegory, *Appl. Phys. Lett.*, **80**, 1228 (2002)

shurm@rpi.edu

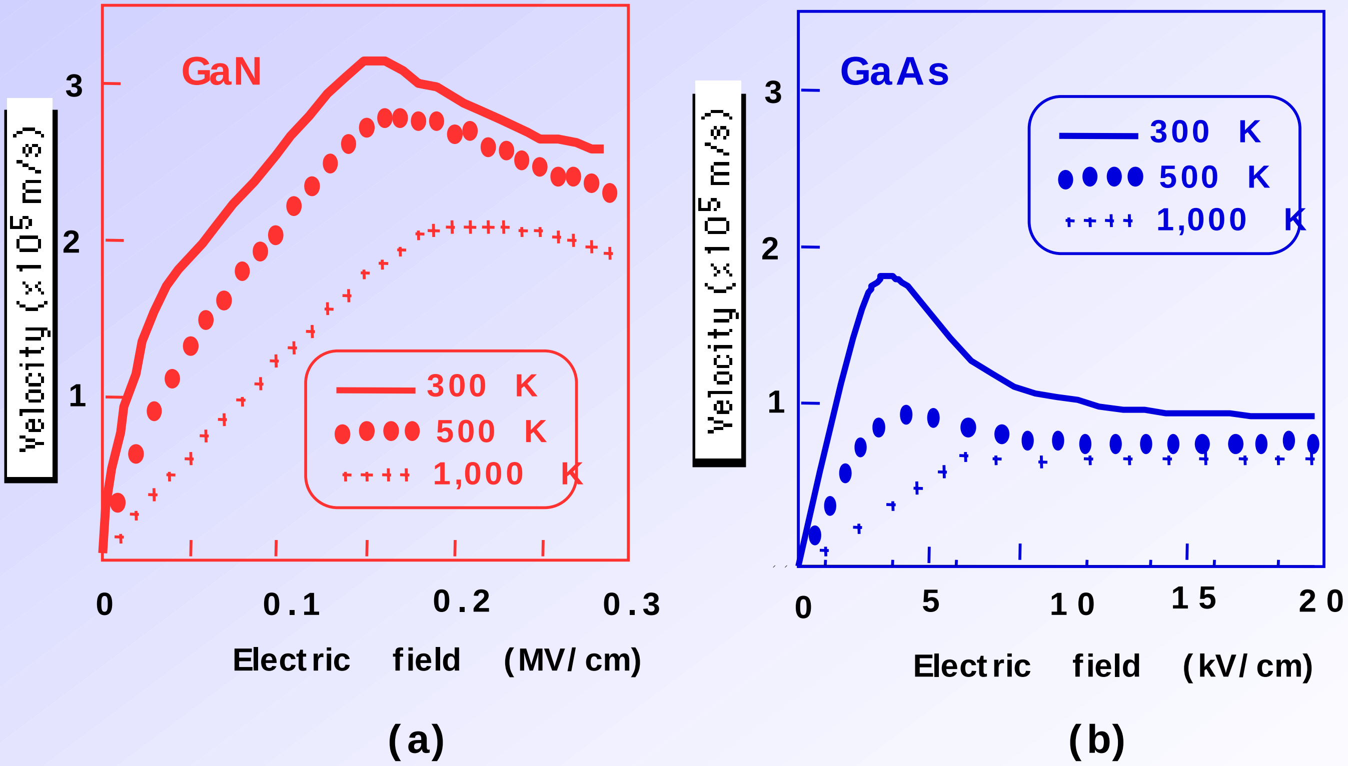
New Features of Low Field Transport

- "Quasi-elastic" optical polar scattering
- 2D electron wave function penetration into AlGaN in undoped GaN channels
- 2D-3D electron transition in doped GaN channels
- Limiting role of acoustic scattering at cryogenic temperatures

shurm@rpi.edu

High field transport in Nitrides

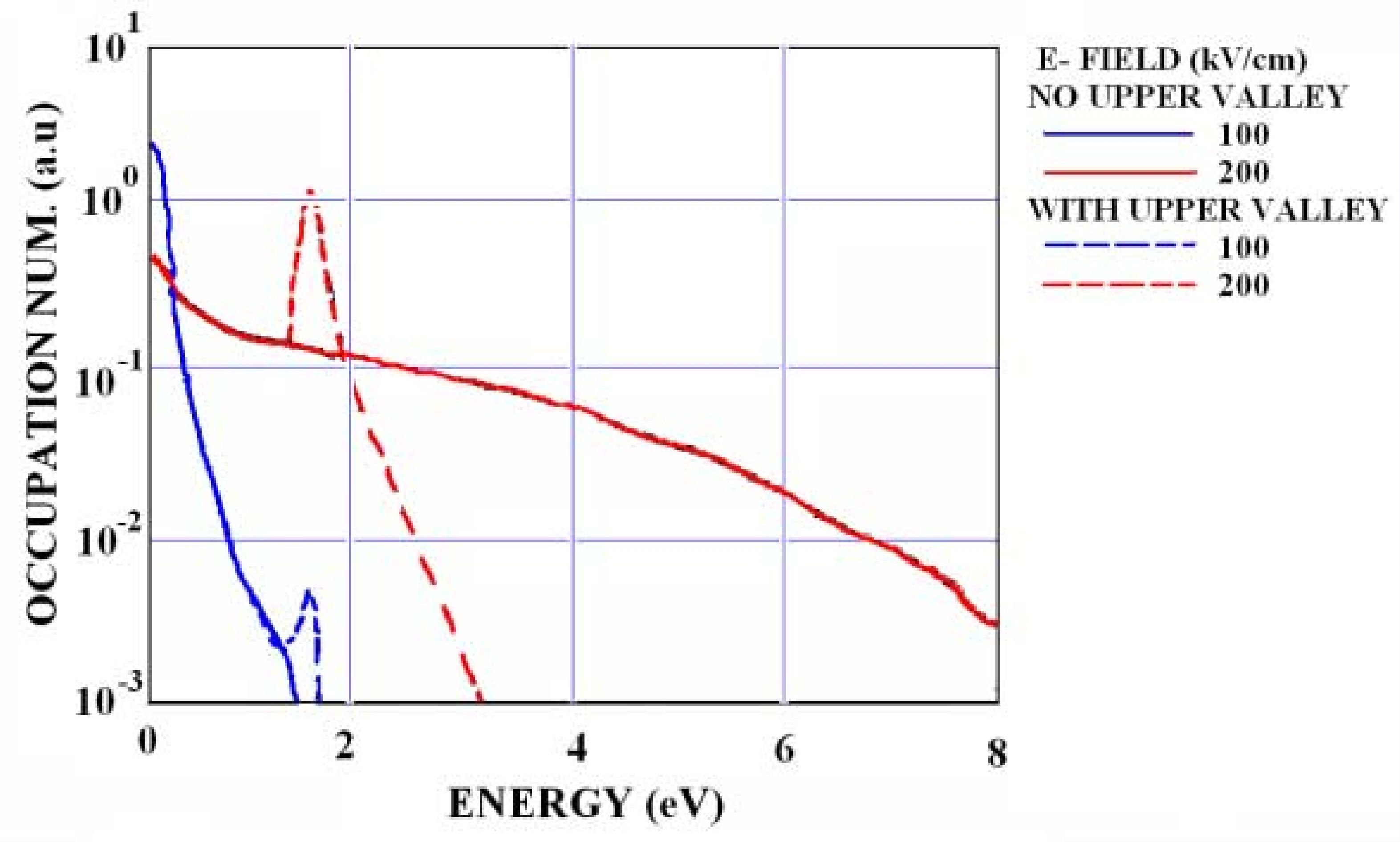
Drift Velocity at Room and Elevated Temperatures



From: M. S. Shur, GaN and related materials for high power applications, Mat. Res. Soc. Symp. Proc., vol. 483, pp. 15-26 (1998)

shurm@rpi.edu

Intervalley Transition



From B. Gelmont, K. S. Kim, and M. S. Shur, *J. Appl. Phys.* **74**, 1818 (1993)

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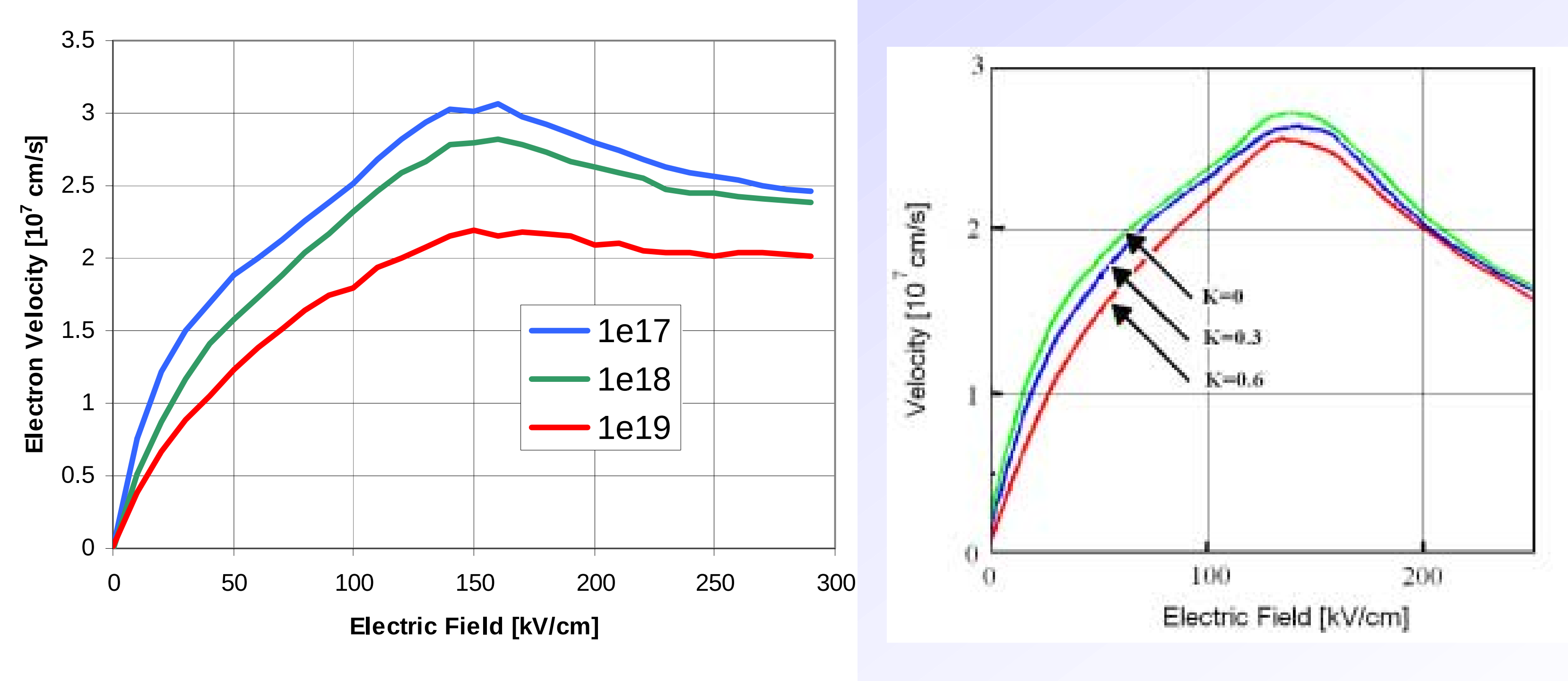
Velocity-field characteristics of GaN: effect of doping and compensation



After B. E. Foutz, L. F. Eastman, U. V. Bhapkar, M. S. Shur, Appl. Phys. Lett., 70, No 21, pp. 2849-2851 (1997)

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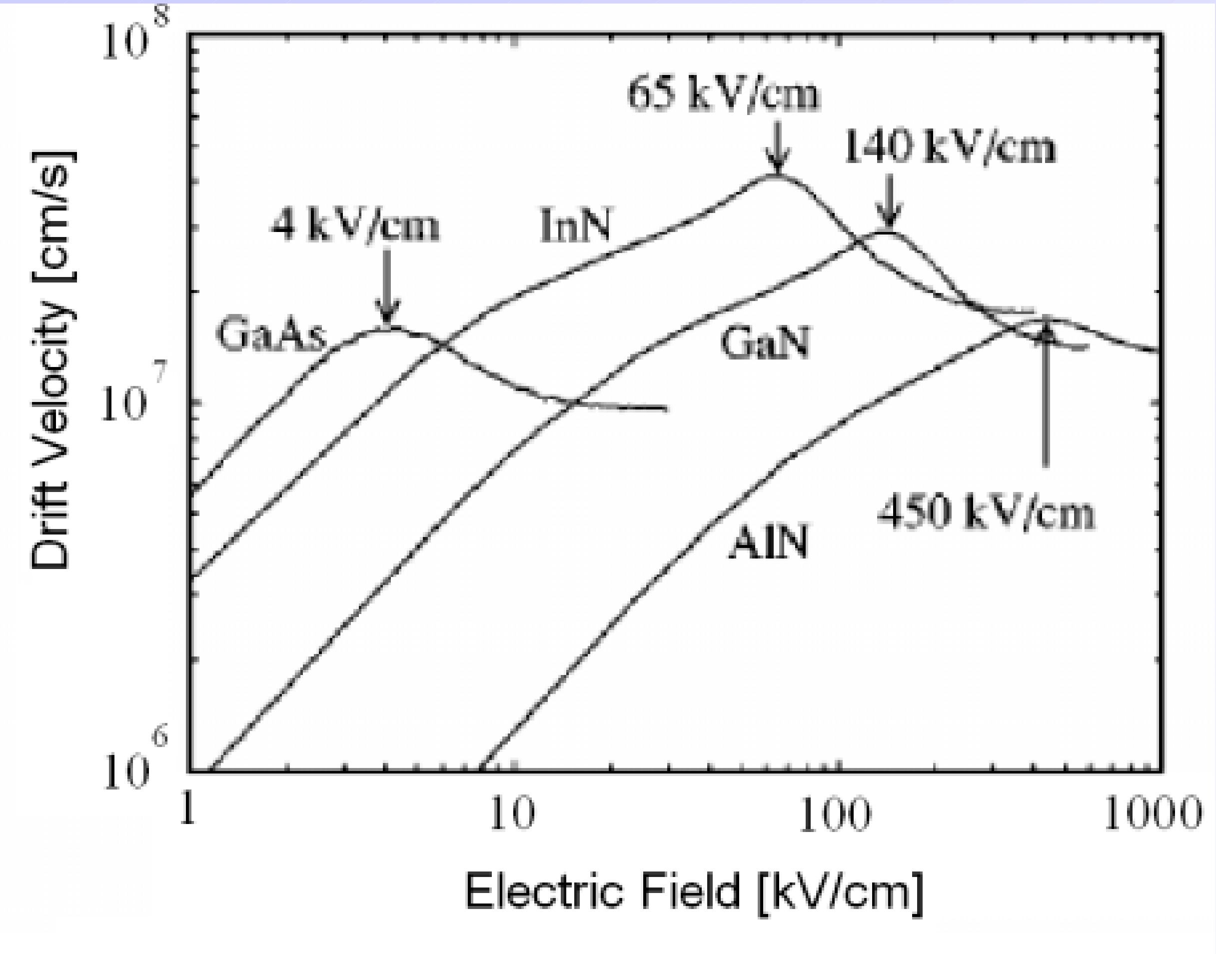
Velocity-Field Curves for Nitride Family

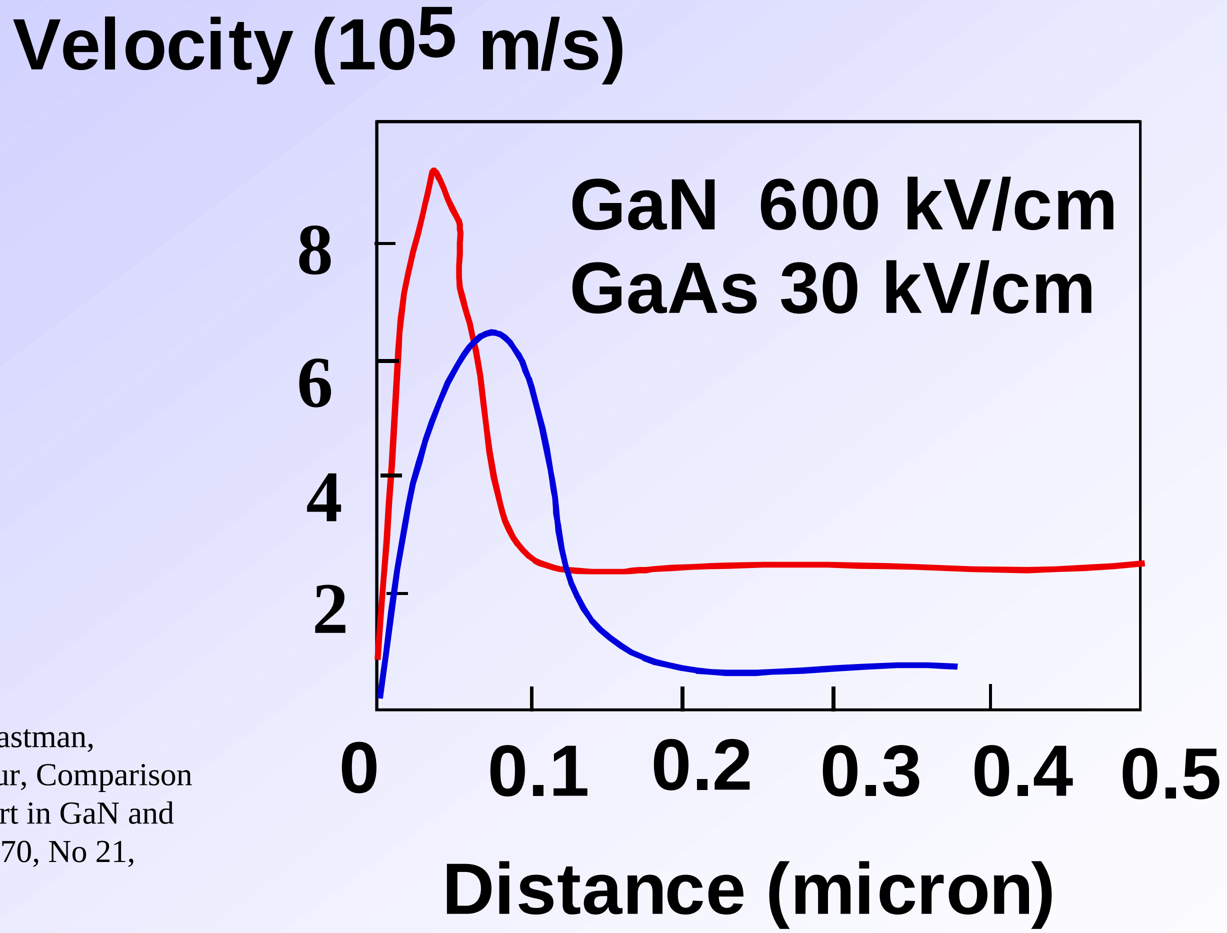


InN is the fastest nitride material

From B. E. Foutz, S. K. O'Leary, M. S. Shur, and L. F. Eastman, *J. Appl. Phys.* **85**, 7727 (1999)

shurm@rpi.edu

Ballistic and Overshoot Effects in GaN



After B. E. Foutz, L. F. Eastman,
U. V. Bhapkar, M. S. Shur, Comparison
of High Electron Transport in GaN and
GaAs, Appl. Phys. Lett., 70, No 21,
pp. 2849-2851, 1997

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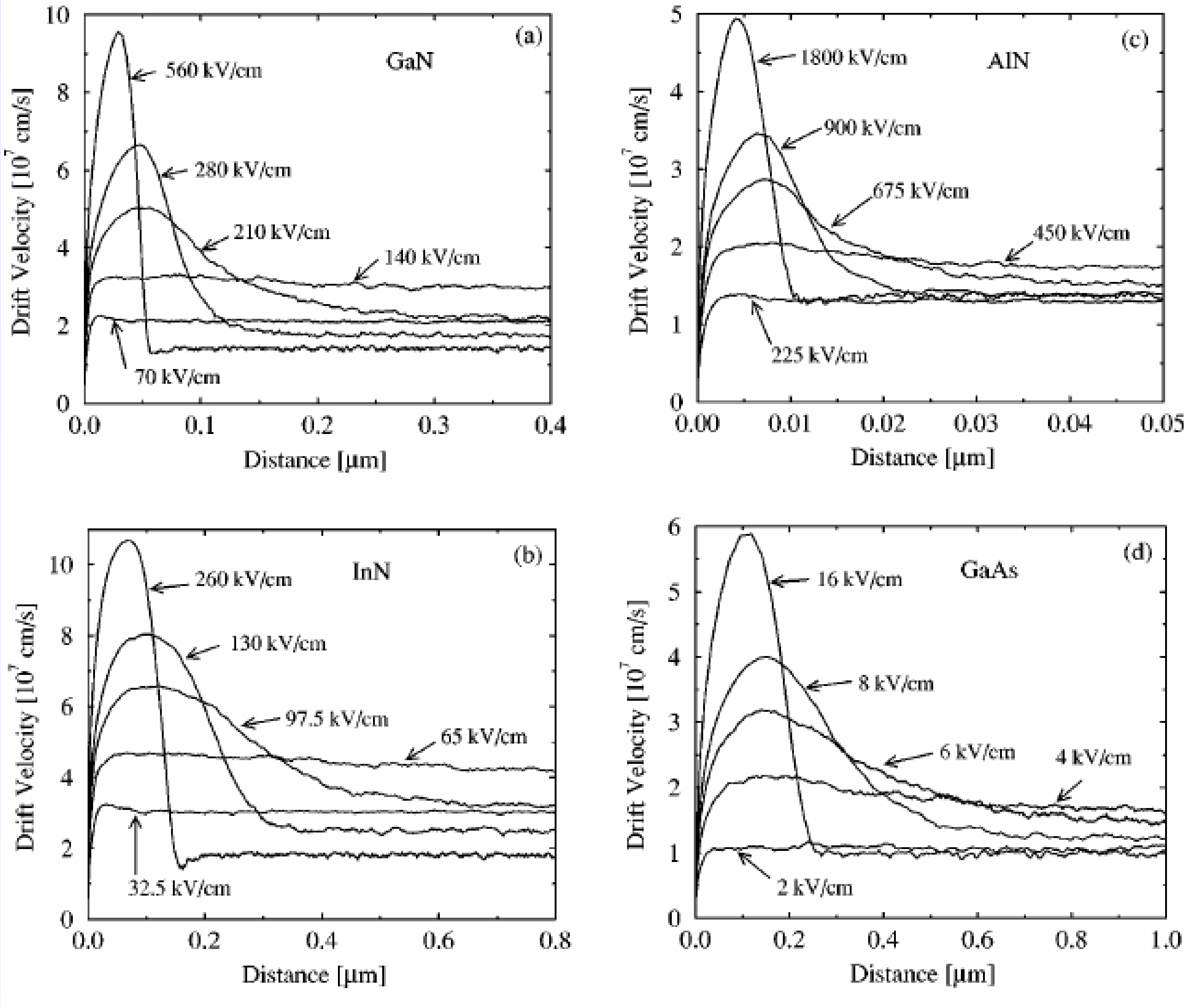
More on the overshoot

InN – higher overshoot at smaller fields



From B. E. Foutz, S. K. O'Leary, M. S. Shur, and L. F. Eastman,
J. Appl. Phys. **85**, 7727 (1999)

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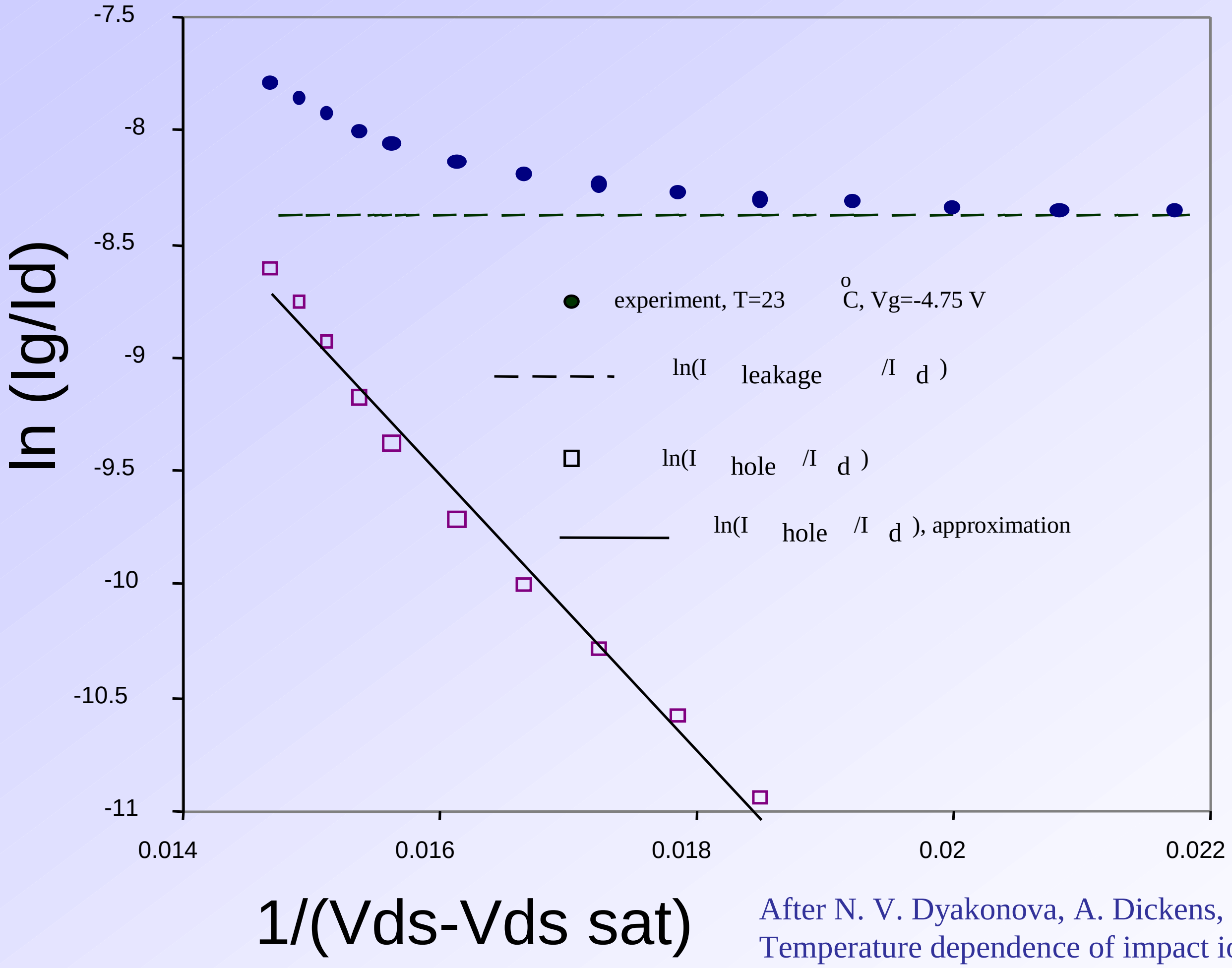
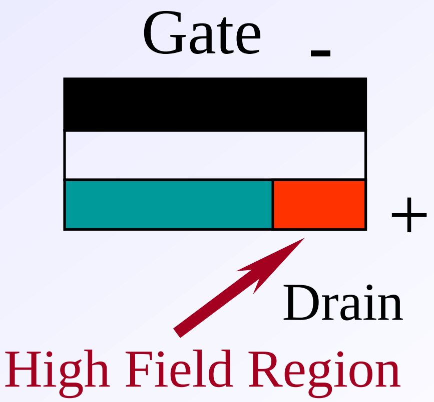
High Field Breakdown.

Breakdown field measurement





After N. V. Dyakonova, A. Dickens, M. S. Shur, R. Gaska, J. W. Yang, Temperature dependence of impact ionization in AlGaN-GaN Heterostructure Field Effect Transistors, Applied Physics Letters, 72 (20), pp. 2562-2564, May 18 (1998)

Higher Breakdown Field in Heterostructures?

Breakdown field might be determined by cladding layers

(see M. Dyakonov and M. S. Shur, Consequences of Space Dependence of Effective Mass in Heterostructures,
J. Appl. Phys. Vol. 84, No. 7, pp. 3726-3730, October 1 (1998))

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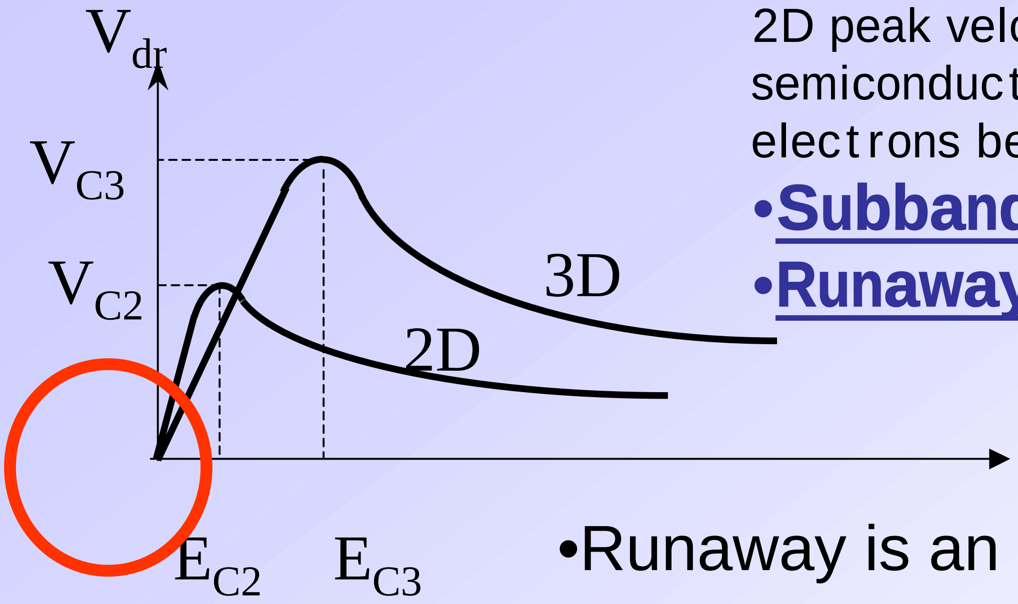
3D and 2D Velocity-Field Characteristics



2D peak velocity and peak field in compound semiconductors are smaller than for 3D electrons because of

- **Subband shift**
- **Runaway effect**

- Runaway is an unstable situation when
- the electron energy loss as a result of the
- collision is smaller then the average
- energy gain in the electric field during
- the free light time

Both E_C and V_C are smaller for 2D case than for 3D case: !

$$E_{C2} < E_{C3}$$
$$V_{C2} < V_{C3}$$

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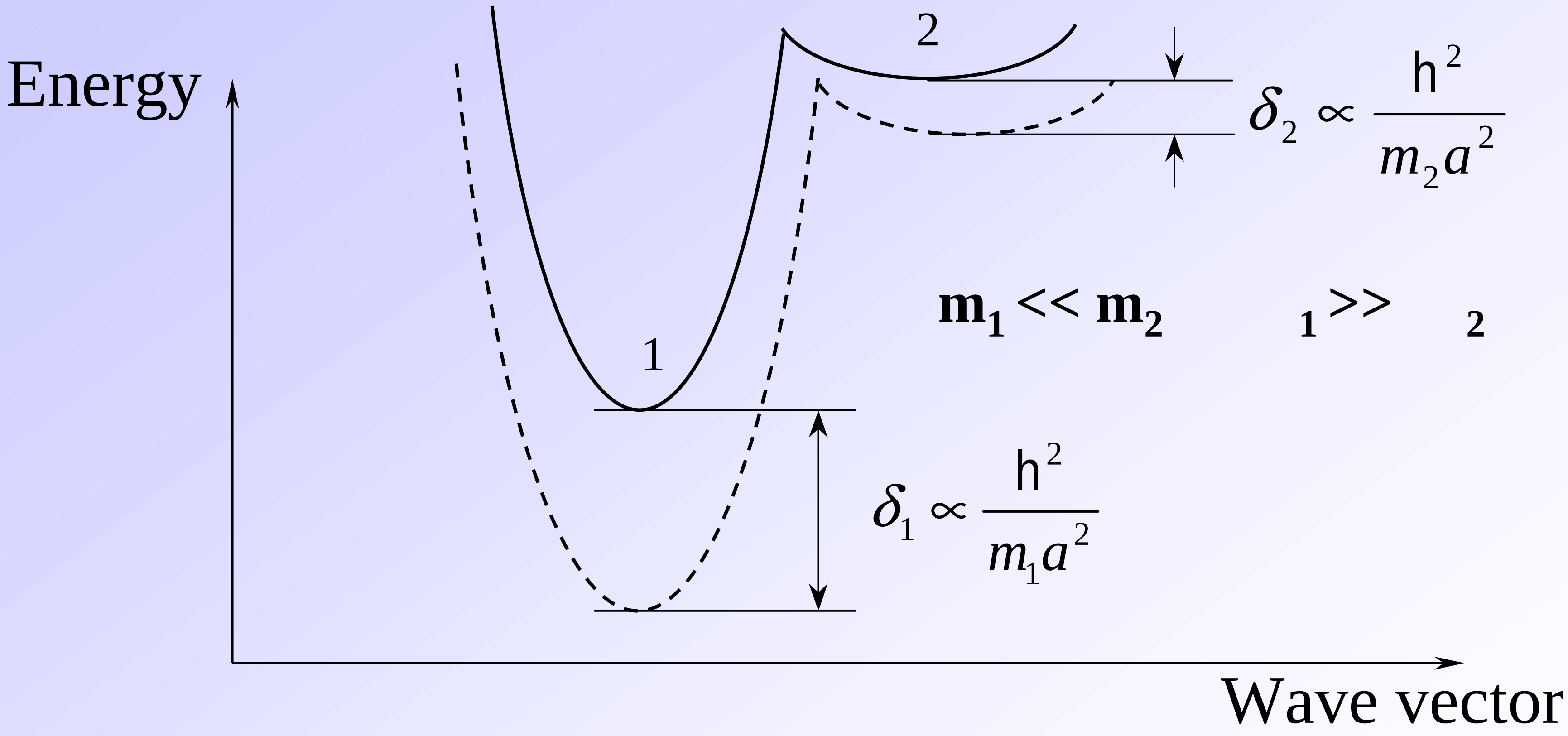
Shift of Valley Bottoms in 2D Case



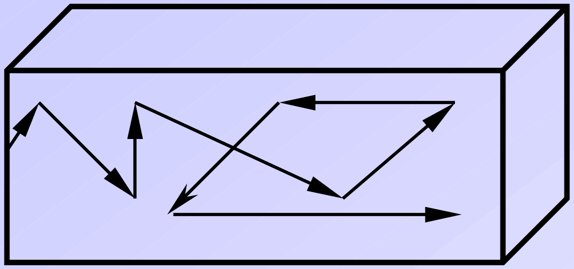
$$\delta_2 \propto \frac{h^2}{m_2 a^2}$$

$$\delta_1 \propto \frac{h^2}{m_1 a^2}$$

$\mathbf{m_1 << m_2}$ $\quad {}_{\mathbf{1}} >> {}_{\mathbf{2}}$

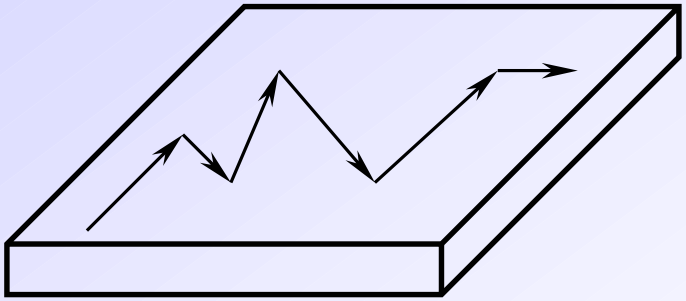
The bottom of the upper valley (2) with heavy mass rises less than the bottom of the central valley (1) with light mass.

Comparison of Runaway in 2D and 3D Systems



3D Case

- Deformation scattering on acoustic and optical phonons does not lead to runaway
- Polar optical scattering (forward!) leads to runaway



2D Case

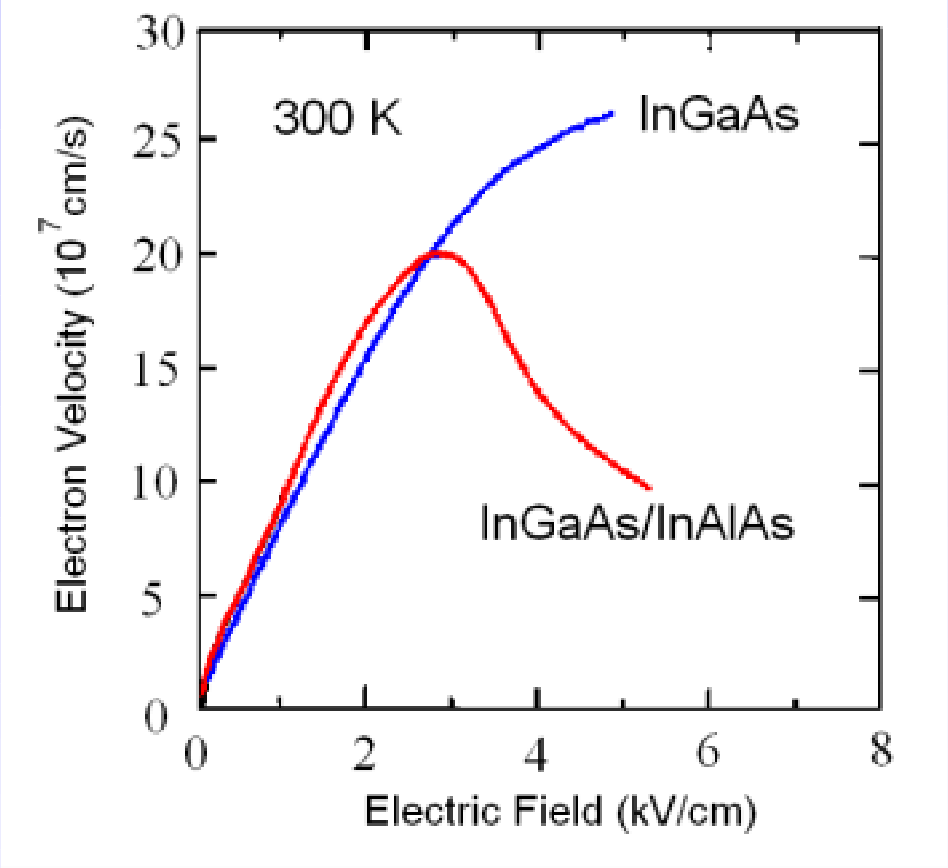
- Even deformation scattering leads to runaway

!

shurm@rpi.edu

Experimental data

After V.T. Masselink, Applied Physics Letters, vol. 67(6), 801-805, 1995



Comparison of electron velocity in lightly doped $In_{0.53}Ga_{0.47}As$ with that in a InGaAs/InAlAs modulation-doped heterostructure

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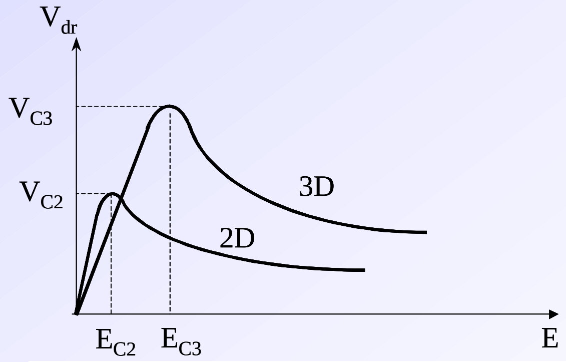
New physics of 2D transport

- High field velocity is smaller than in bulk (because of runaway)
- Impact ionization in quantum well is determined by cladding layers



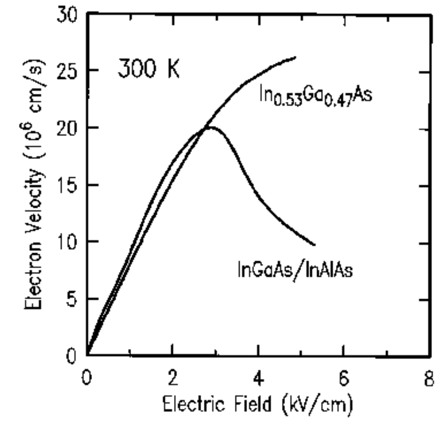
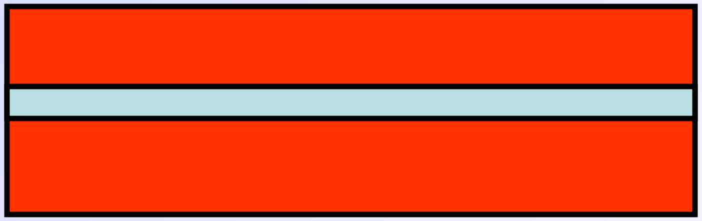


FIG. 2. Comparison of electron velocity in lightly doped $In_{0.53}Ga_{0.47}As$ with that in a InGaAs/InAlAs modulation-doped heterostructure.



Experimental date after V.T. Masselink, Applied Physics Letters, vol. 67(6), 801-805, 1995

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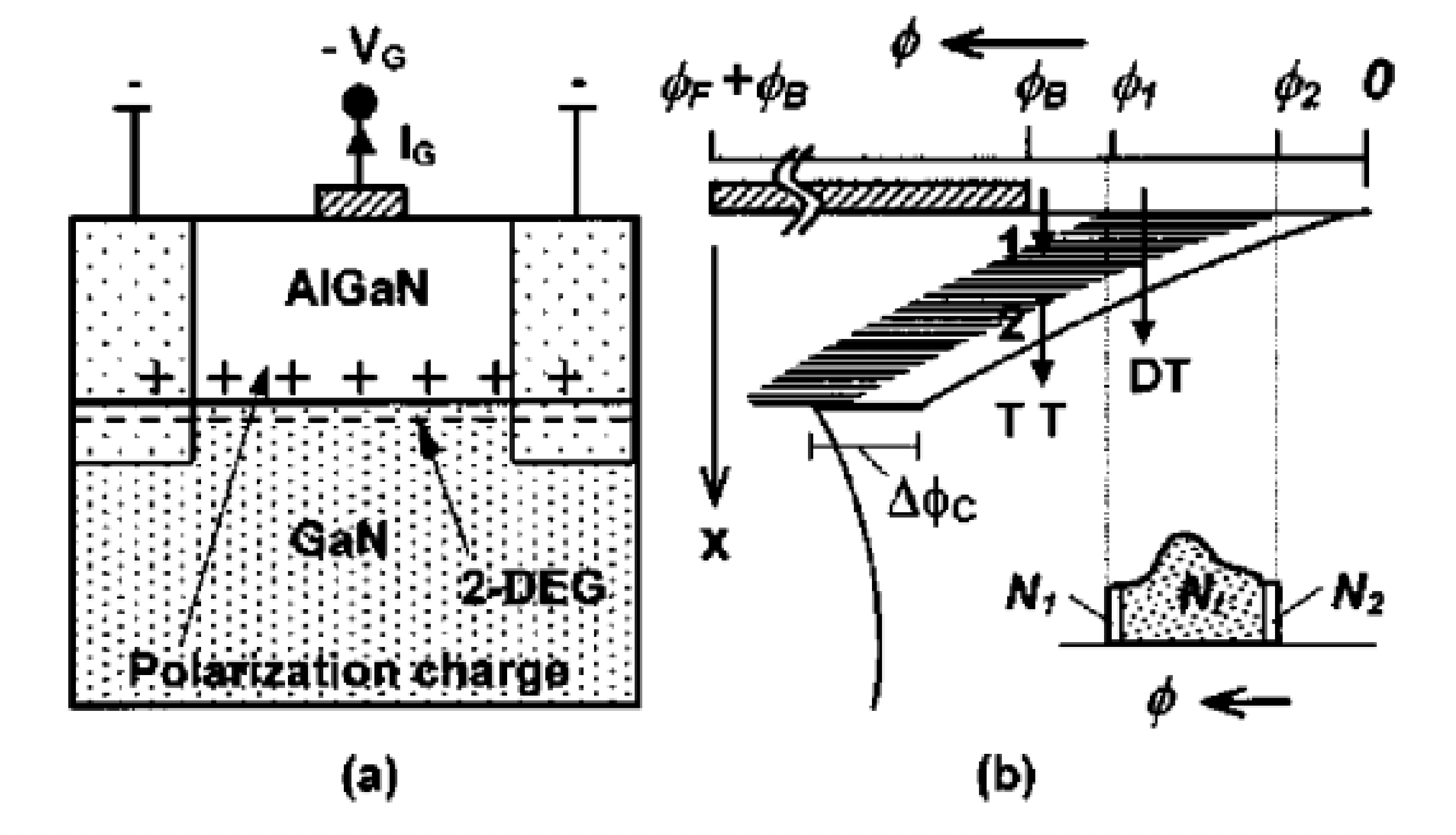
Trapping in Nitrides: Reverse Gate Leakage Modeling

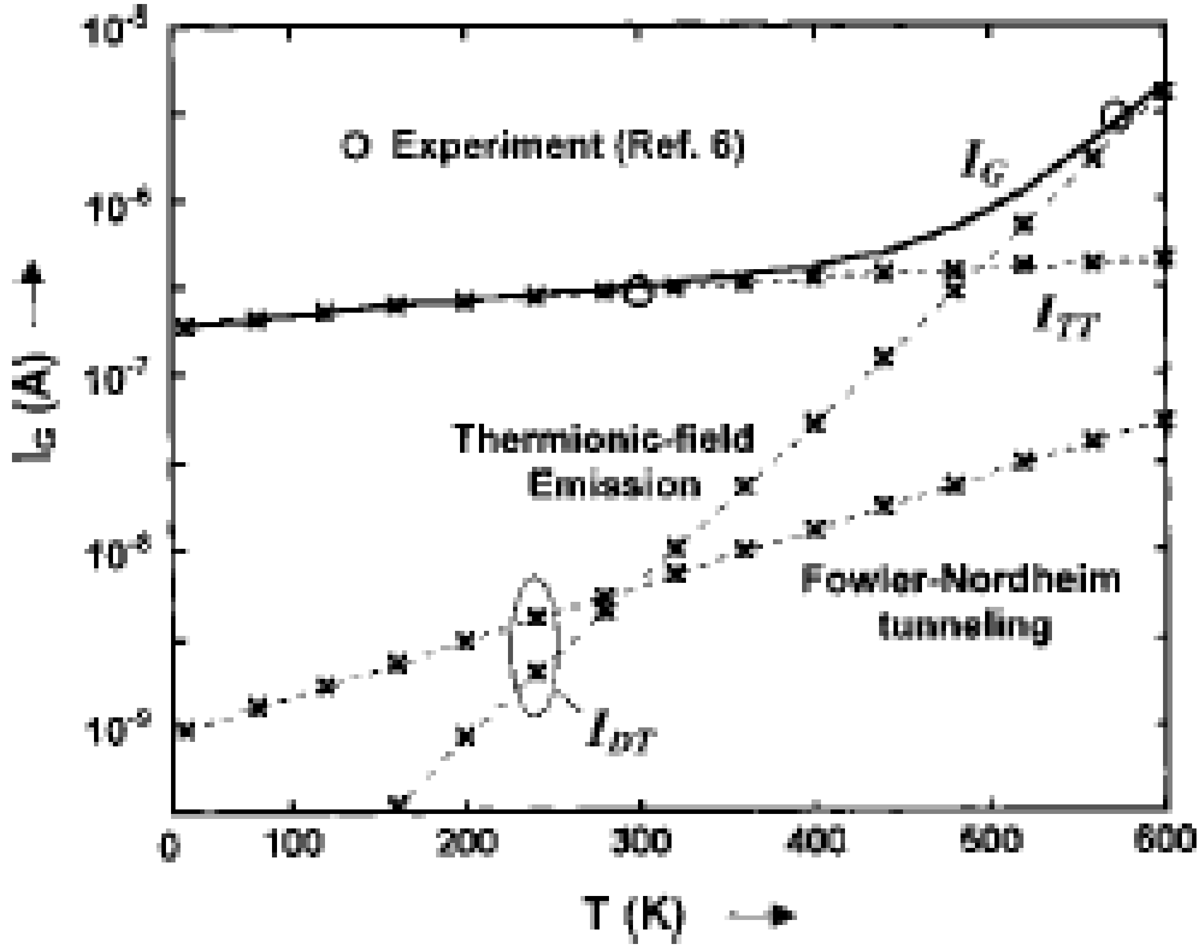


Direct tunneling and trap-assisted tunneling

From S. Karmalkar, D. Mahaveer Sathaiya, M. S. Shur, Mechanism of the Reverse Gate Leakage in AlGaN / GaN HEMTs, Appl. Phys. Lett. **82**, 3976-3978 (2003)

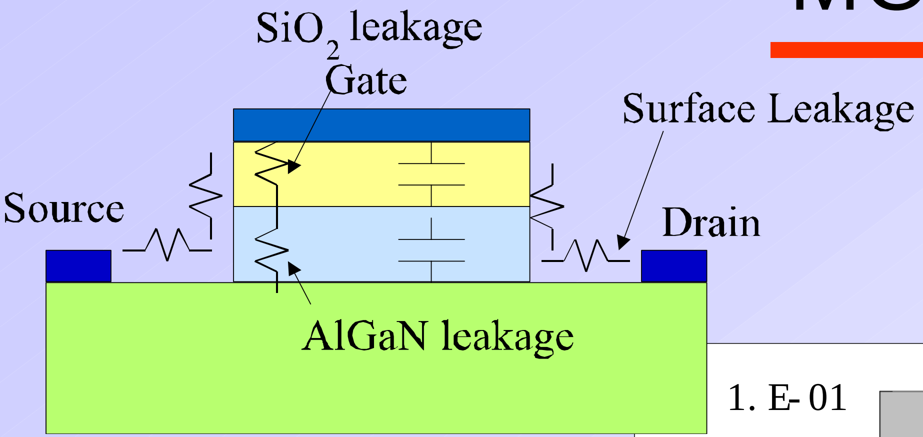
shurm@rpi.edu

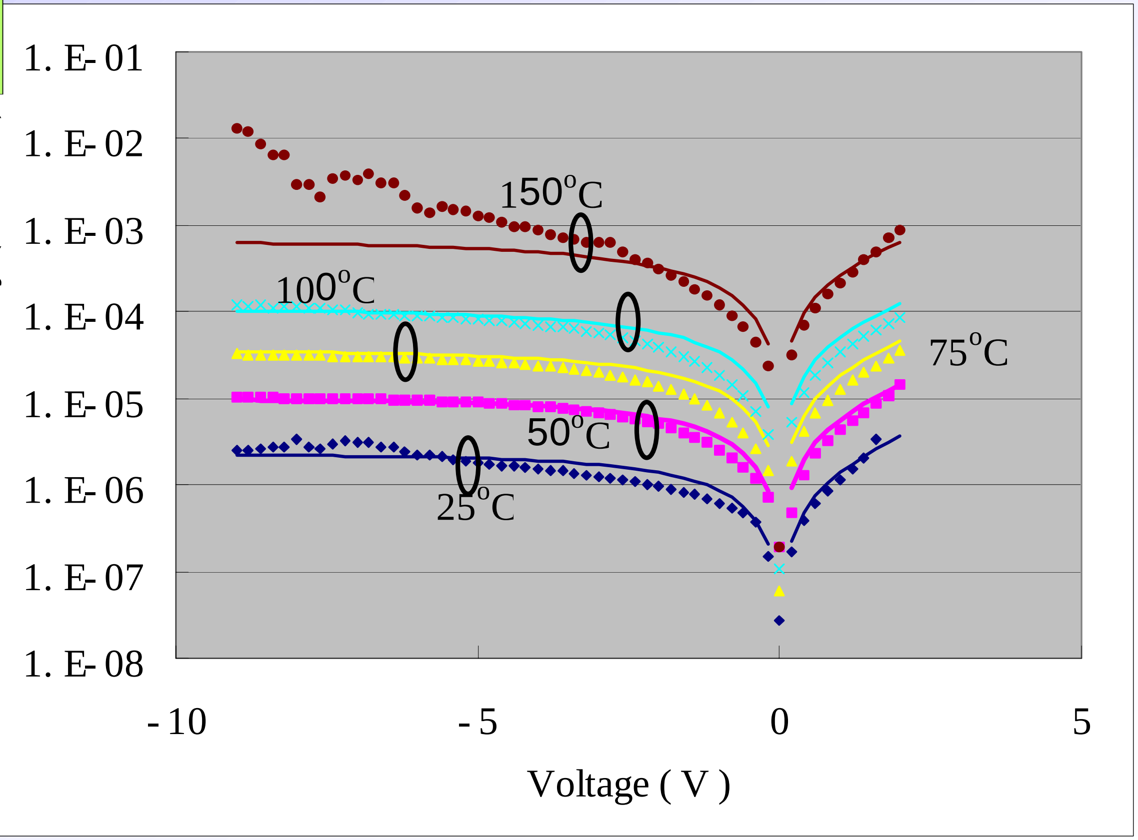
Comparison with Experiment



From S. Karmalkar, D. Mahaveer Sathaiya, M. S. Shur, Mechanism of the Reverse Gate Leakage in AlGaN / GaN HEMTs, Appl. Phys. Lett. **82**, 3976-3978 (2003)

MOSHFET Gate Leakage



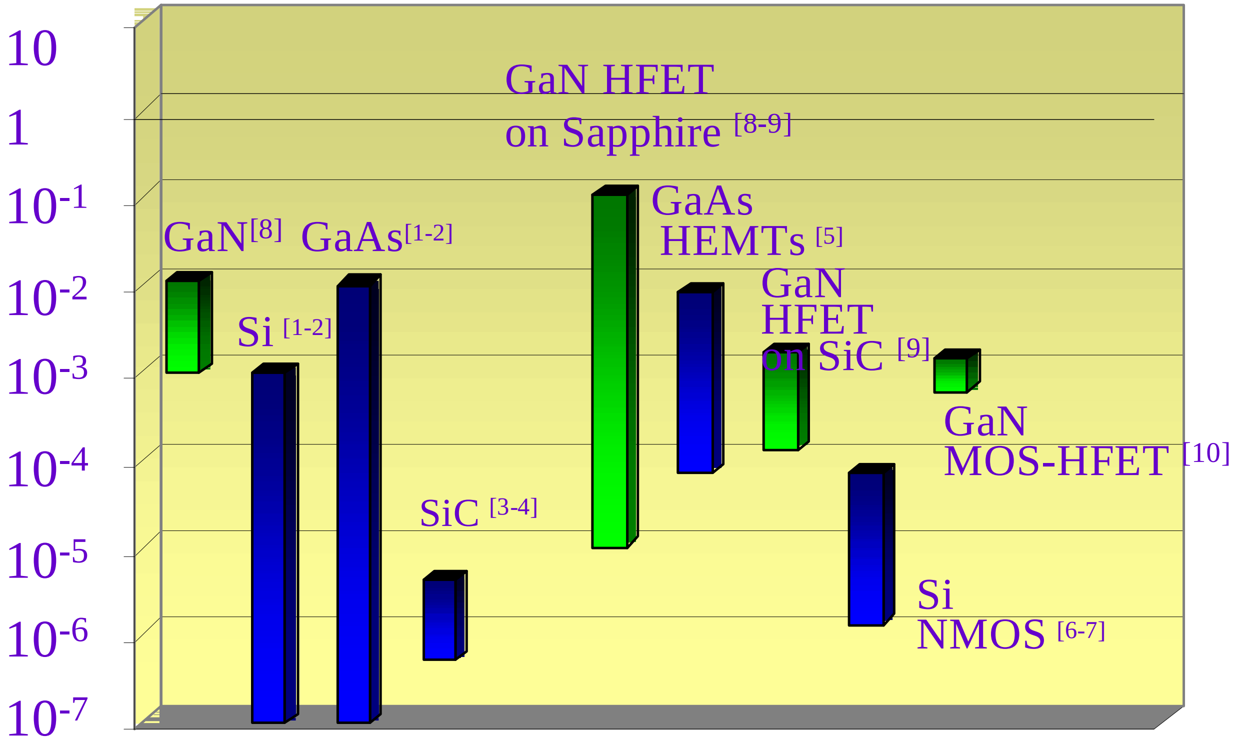


Traps and leakage: Complexities of highly non-ideal systems

From F. W. Clarke, Fat Duen Ho, M. A. Khan, G. Simin, J. Yang, R. Gaska, M. S. Shur, J. Deng, S. Karmalkar, Gate Current Modeling for Insulating Gate III-N Heterostructure Field-Effect Transistors, Mat. Res. Symp. Proc. Vol. 743, L 9.10 (2003)

shurm@rpi.edu

GaN 1/f Noise surprises



Device noise is smaller than materials noise!!!

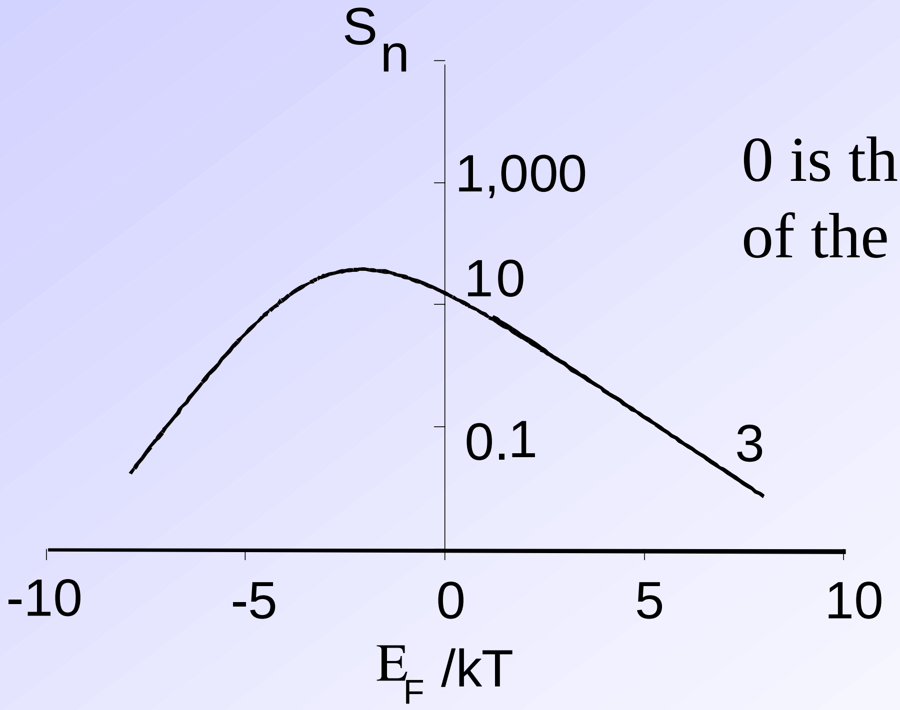
shurm@rpi.edu

Data from

- [1] R.H. Clevers, Volume and temperature dependence of the 1/f noise parameter alpha in Si, Physica B Vol.154, pp. 214-224, (1989)
- [2] F.N. Hooge, M. Tacano, Experimental studies of 1/f noise in n-GaAs Physica B Vol.190, pp. 145-149, (1993)
- [3] M. Levinshtein, S. Rumyantsev, J. Palmour, and D. Slater, Low frequency noise in 4H Silicon Carbide, Journ. Appl. Phys. Vol. 81, No.4, 1758-1762, (1997))
- [4] M. Tacano and Y. Sugiyama, Comparison of 1/f noise of AlGaAs/GaAs HEMTs and GaAs MESFETs, Solid State Elect. Vol.34. No 10, pp. 1049-53,(1991).
- [5] D. Fleetwood, T.L. Meisenheimer, J. Scofield, 1/f noise and radiation effects in MOS devices IEEE Trans. Electron Dev. Vol. 41, No 11, pp. 1953-1964 (1994)
- [6] L.K. J Vandamme, X. Li, D. Rigaud, 1/f noise in MOS devices, mobility or number fluctuations? IEEE Trans. Electron Dev. Vol. 41, No:11, pp. 1936-1945 (1994)
- [7] A. Balandin, S. Morozov, G. Wijeratne, C. Cai, L. Wang, C. Viswanathan, Effect of channel doping on the low-frequency noise in GaN/AlGaN heterostructure field-effect transistors, Appl. Phys. Lett. V. 75, No 14 pp. 2064-2066 (1999)
- [8] S. Rumyantsev, M.E. Levinshtein, R. Gaska, M. S. Shur, J. W. Yang, and M. A. Khan, Low-frequency noise in AlGaN/GaN heterojunction field effect transistors on SiC and sapphire substrates" Journal of Applied Physics, Vol. 87, No4, pp. 1849-1854 (2000)
- [9] N. Pala, R. Gaska, S. Rumyantsev, M. S. Shur M. Asif Khan, X. Hu, G. Simin, and J. Yang, Low frequency noise in AlGaN/GaN MOS-HFETs, Electronics Lett. Vol.36,No.3, pp. 268-270, (2000)

shurm@rpi.edu

A relatively low level of noise in GaN-based HFETs is related to a very high density of channel carriers



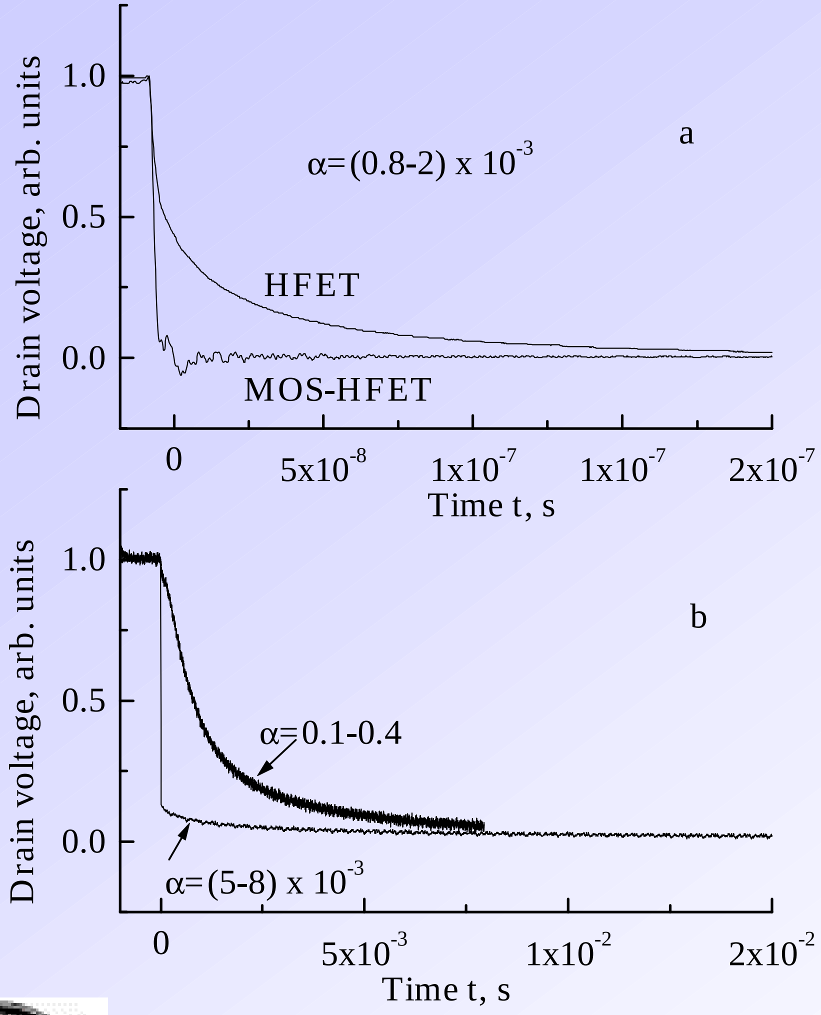
0 is the bottom
of the conduction band

Dependence of noise on the Fermi level position in bulk semiconductor

from E. Borovitskaya, M. Shur, On theory of 1/f nose in semiconductors Solid-State Electronics Vol. 45, No. 7, 1067 (2001)

shurm@rpi.edu

Correlation between current slump and 1/f noise in GaN transistors

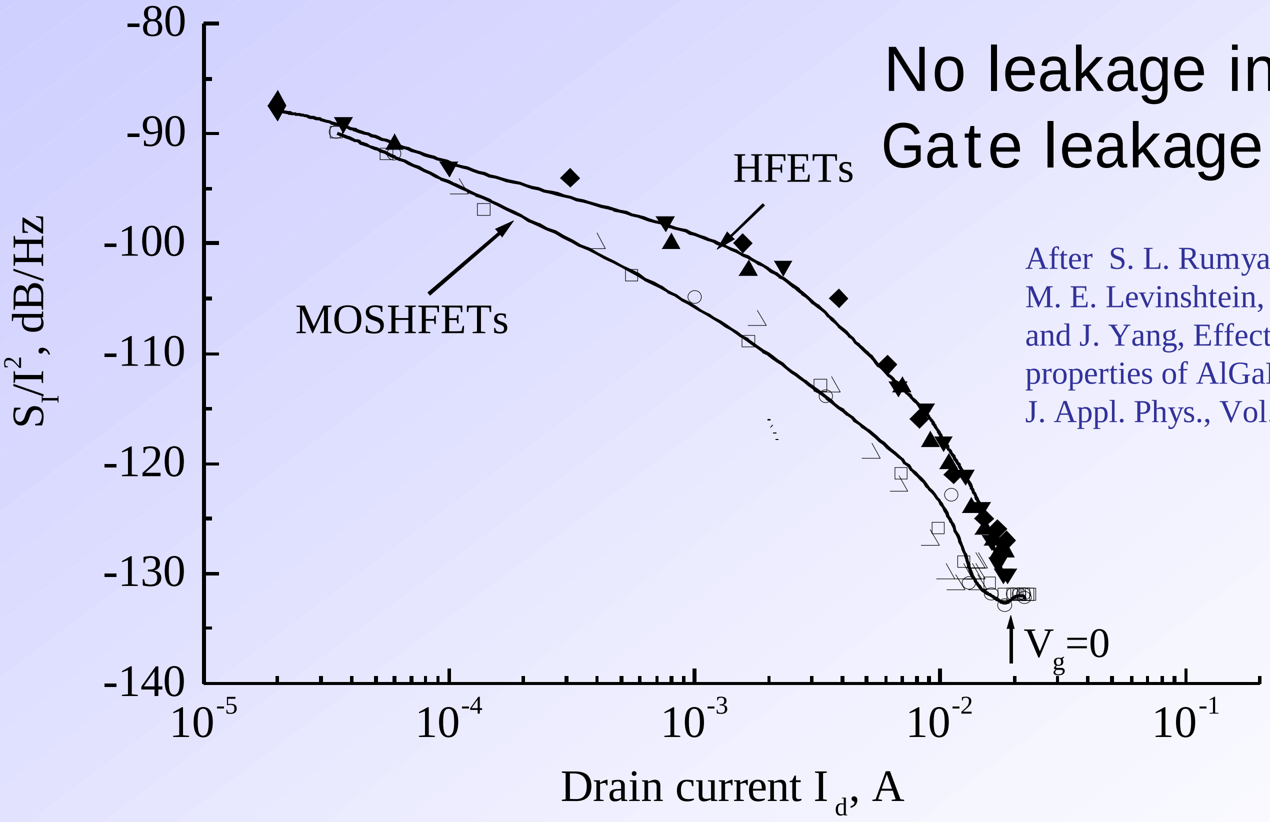


Longer transient – higher Hooge constant

From S. L. Rumyantsev, M. S. Shur, R. Gaska, M. Asif Khan, G. Simin, J. Yang, N. Zhang, S. DenBaars, and U. Mishra, Transient Processes in AlGaN/GaN Heterostructure Field Effect Transistors, Electronics Letters, vol. 36, No.8, p. 757-759 (2000)

shurm@rpi.edu

In devices with relatively high noise no correlation between 1/f noise and gate leakage

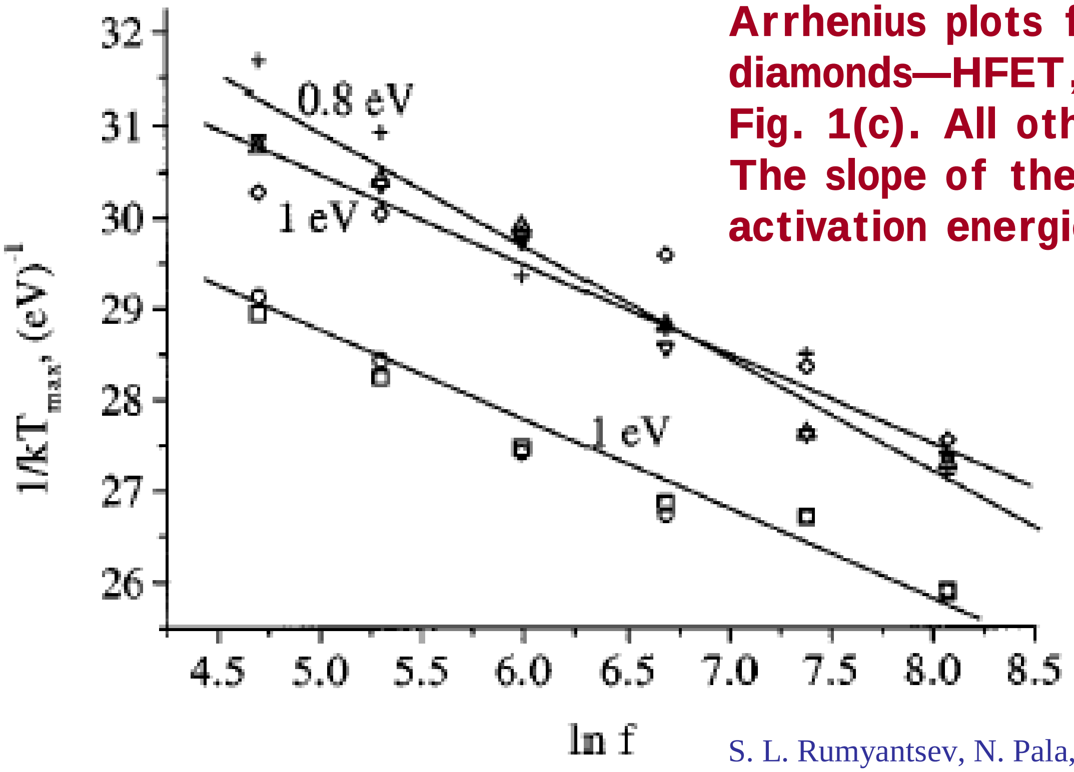


No leakage in MOSHFETs
Gate leakage in HFETs

After S. L. Rumyantsev, N. Pala, M. S. Shur, R. Gaska, M. E. Levinshtein, M. Asif Khan, G. Simin, X. Hu, and J. Yang, Effect of gate leakage current on noise properties of AlGaN/GaN field effect transistors", J. Appl. Phys., Vol. 88, No. 11, pp. 6726-6730, (2000)

shurm@rpi.edu

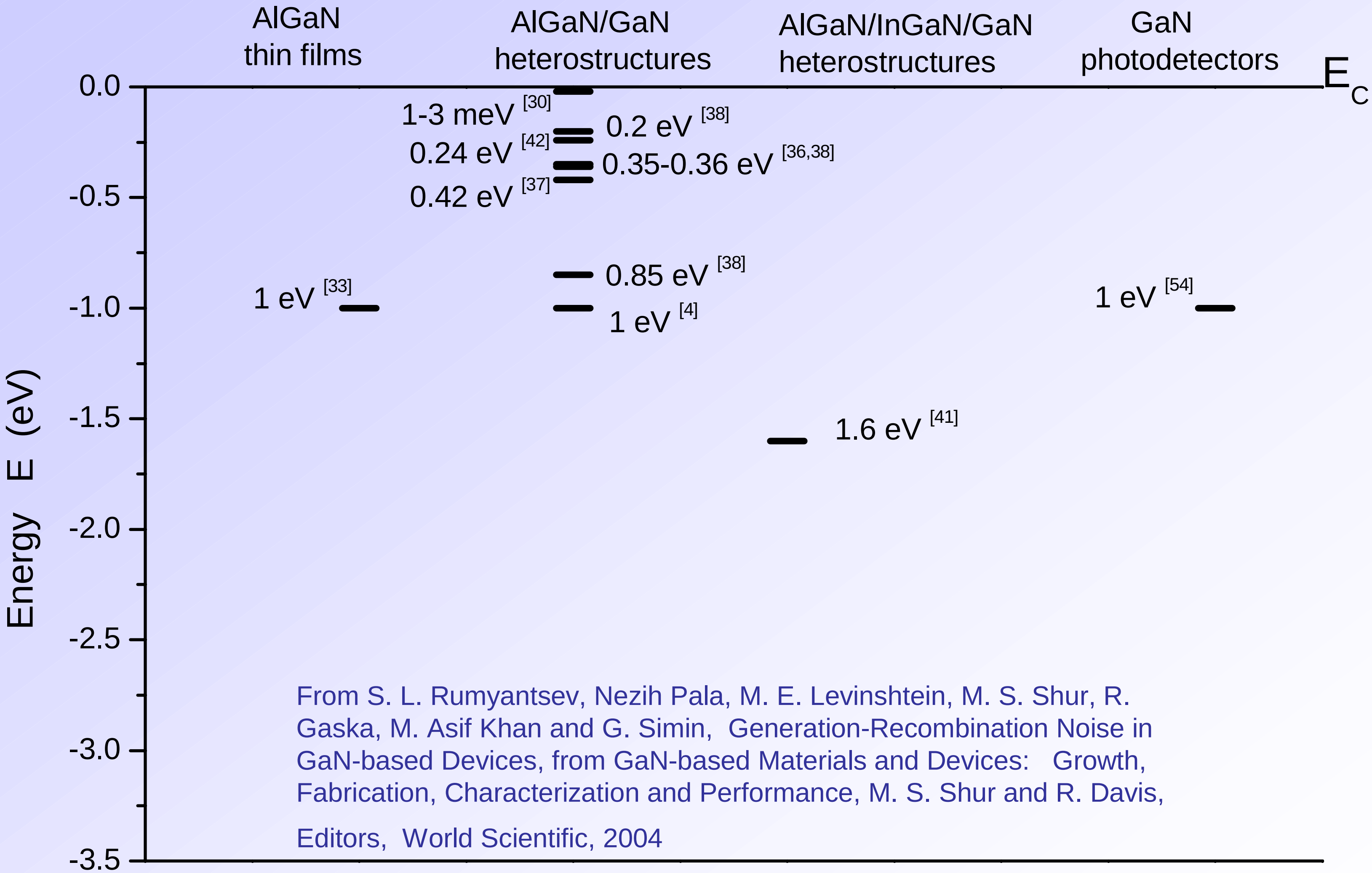
AlGaN barrier layer is main source of generation-recombination noise



Arrhenius plots for several samples. diamonds—HFET, Fig. 1(b); crosses—MOS-HFET, Fig. 1(c). All other symbols represent HFETs. The slope of the lines determines activation energies of local level E 0:8–1.0 eV.

S. L. Rumyantsev, N. Pala, M. S. Shur, E. Borovitskaya, A. P. Dmitriev, M. E. Levinshtein, R. Gaska, M. A. Khan, J. Yang, X. Hu, and G. Simin, Generation-Recombination Noise in GaN/ GaAlN Heterostructure Field Effect Transistors, IEEE Trans. Electron Dev. Vol. 48, No 3, pp. 530-533 (2001)

Where the traps are (from GR noise)



From S. L. Rumyantsev, Nezih Pala, M. E. Levinshtein, M. S. Shur, R. Gaska, M. Asif Khan and G. Simin, Generation-Recombination Noise in GaN-based Devices, from GaN-based Materials and Devices: Growth, Fabrication, Characterization and Performance, M. S. Shur and R. Davis, Editors, World Scientific, 2004

Nitride-based FETs – promises and problems

Promises

- 30 W/mm at 10 GHz versus 1.5 W/mm
- > 150 W per chip

Problems

- Gate leakage
- Gate lag and current collapse →
- Reliability
- Yield

Solutions

- Strain energy band engineering
- MEMOCVD^{tm}
- Insulated gate designs
- Gate edge engineering

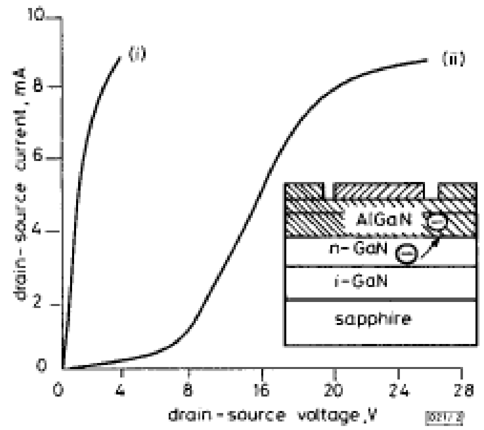


Fig. 2 *Current/voltage characteristic collapse*

(i) on-state (before application of a high drain basis)
(ii) off-state (after application of a high drain bias)
Inset: suggested collapse mechanism which is electron trapping in barrier layer at drain side of gate

M. A. Khan, M. S. Shur, Q. C. Chen, and J. N. Kuznia, Current-Voltage Characteristic Collapse in AlGaN/GaN Heterostructure Insulated Gate Field Effect Transistors at High Drain Bias, Electronics Letters, Vol. 30, No. 25, p. 2175-2176, Dec. 8, 1994

shurm@rpi.edu

High Electron Sheet Density Allows for a New Approach: AlGaN/GaN MISFET

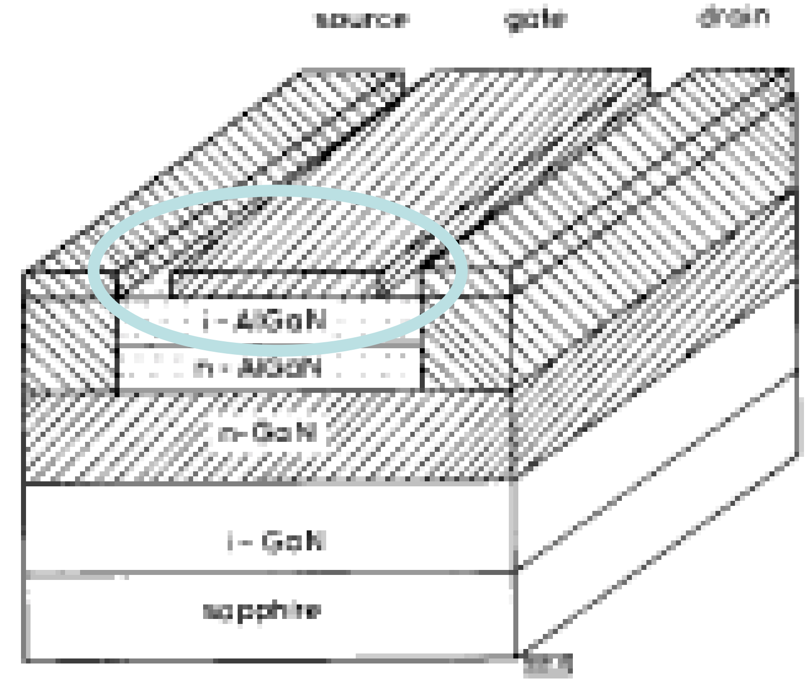


Fig. 1 Schematic diagram of AlGaN/GaN HIGFET

M. A. Khan, M. S. Shur, Q. C. Chen, and J. N. Kuznia, Current-Voltage Characteristic Collapse in AlGaN/GaN Heterostructure Insulated Gate Field Effect Transistors at High Drain Bias, Electronics Letters, Vol. 30, No. 25, p. 2175-2176, Dec. 8, 1994

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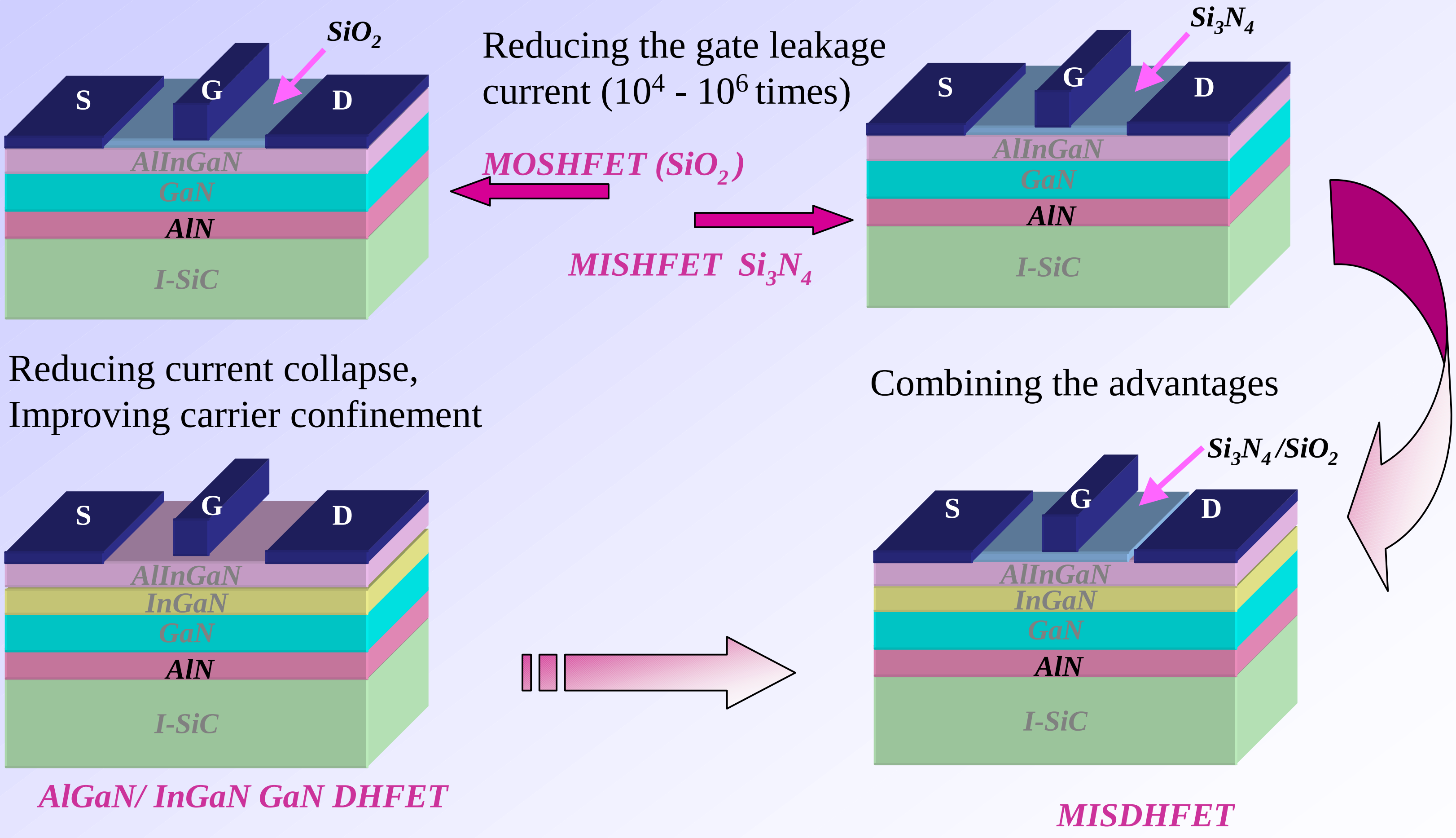
Resolving the issues: AlGaInN, gate dielectrics, InGaN channel



Reducing the gate leakage current (10^4 - 10^6 times)

MOSHFET (SiO_2)

MISHFET Si_3N_4

Reducing current collapse, Improving carrier confinement

Combining the advantages

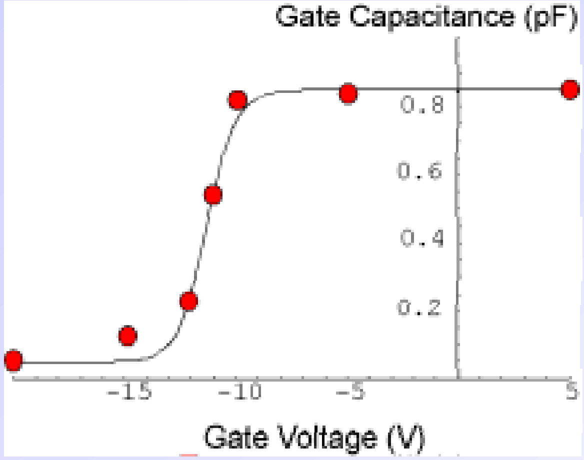
AlGaN/ InGaN GaN DHFET

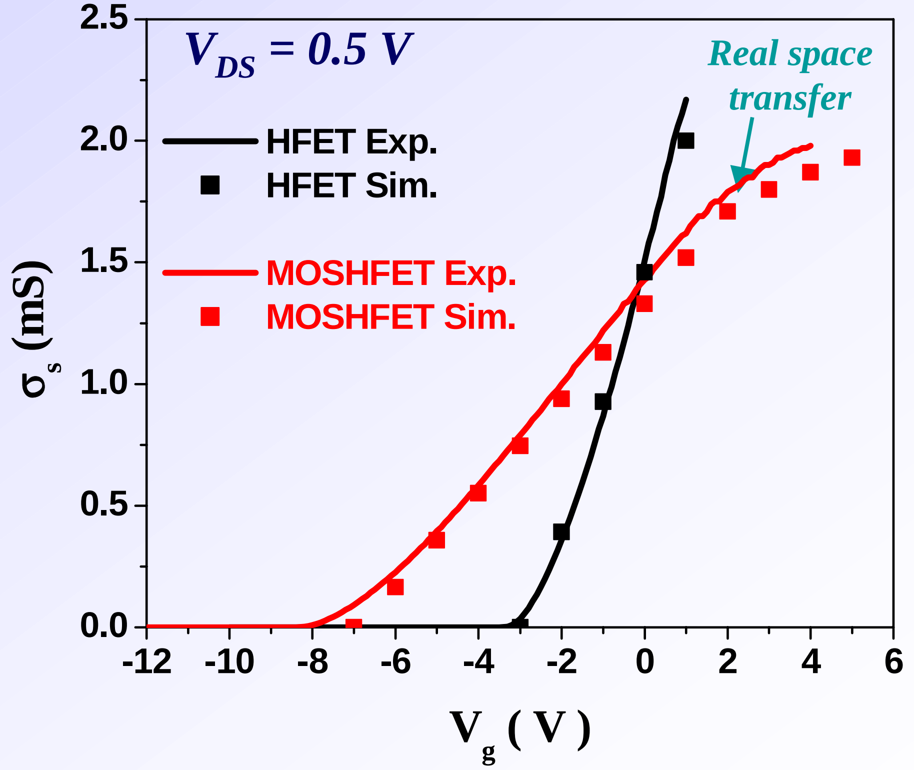
MISDHFET

Unified charge control model (UCCM)

MOSFETs and HFETs

$$V_{GT} - \alpha V_F = a(n_s - n_0) + \eta V_{th} \ln\left(\frac{n_s}{n_0}\right)$$





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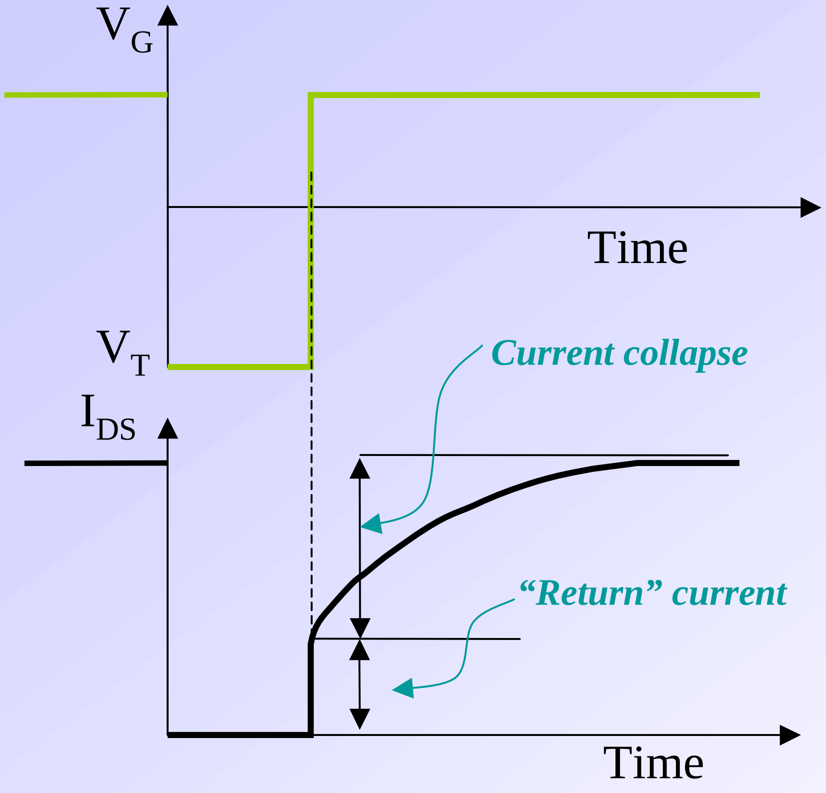
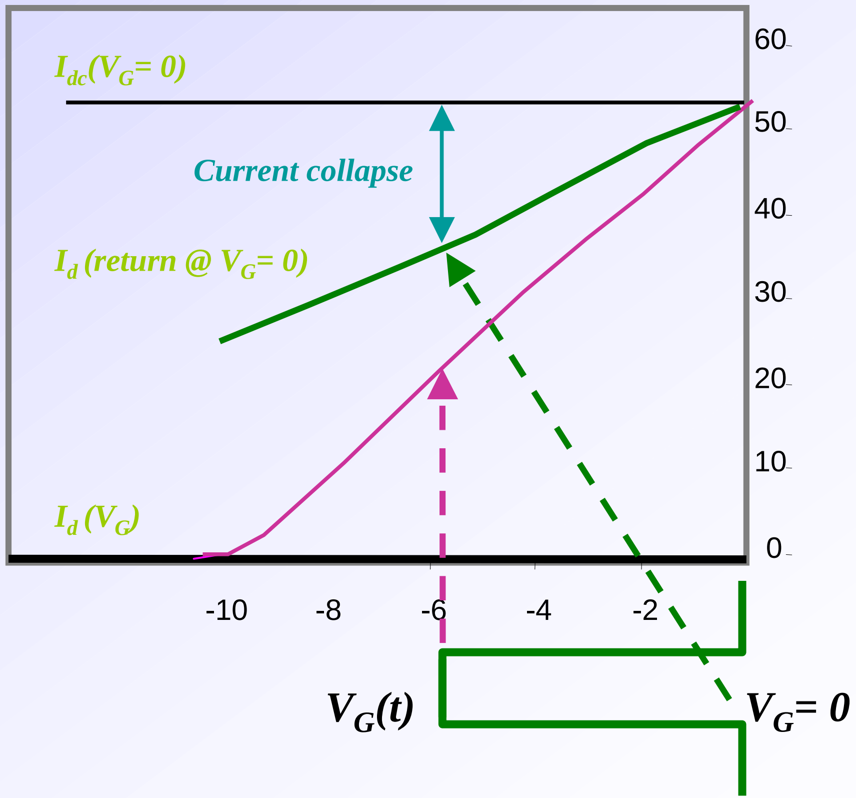
Gate Lag and Current collapse in AlGaN/GaN HFETs: Pulsed measurements of **“return current”**

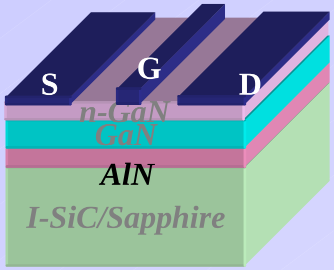




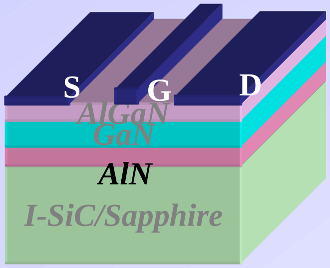
Tarakji, G. Simin, N. Ilinskaya, X. Hu, A. Kumar, A. Koudymov, J. Zhang, and M. Asif Khan, M.S. Shur and R. Gaska, Appl. Phys. Lett., 78, N 15, pp. 2169-2171 (2001)

G. Simin, A. Koudymov, A. Tarakji , X. Hu, J. Yang and M. Asif Khan, M. S. Shur and R. Gaska APL October 15 2001

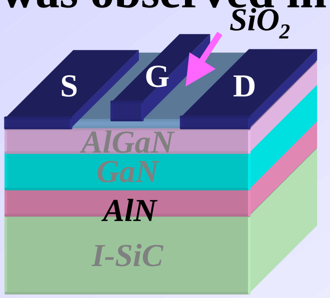
Nearly Identical Gate Lag Current Collapse was observed in:



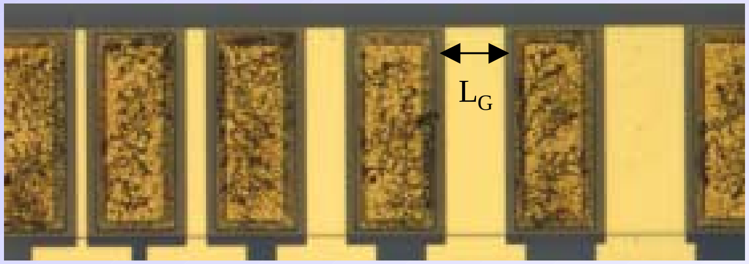
GaN MESFET



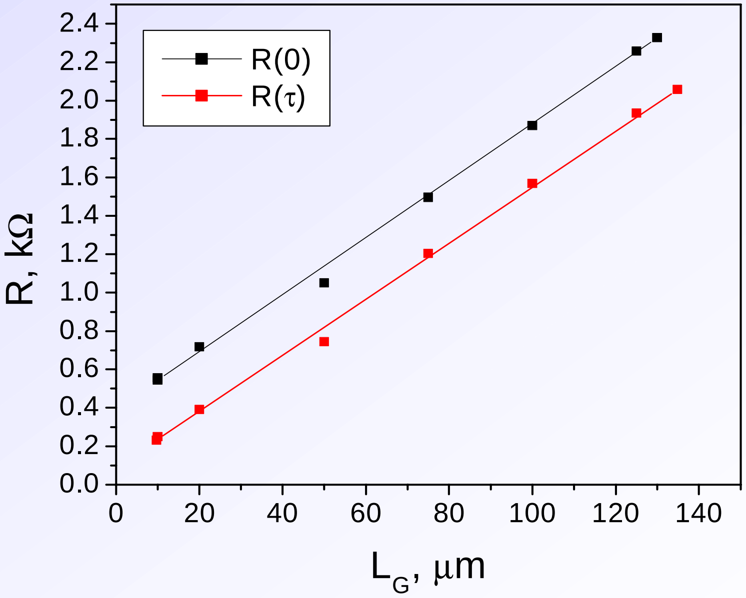
AlGaN/GaN HFET



AlGaN/GaN MOSHFET



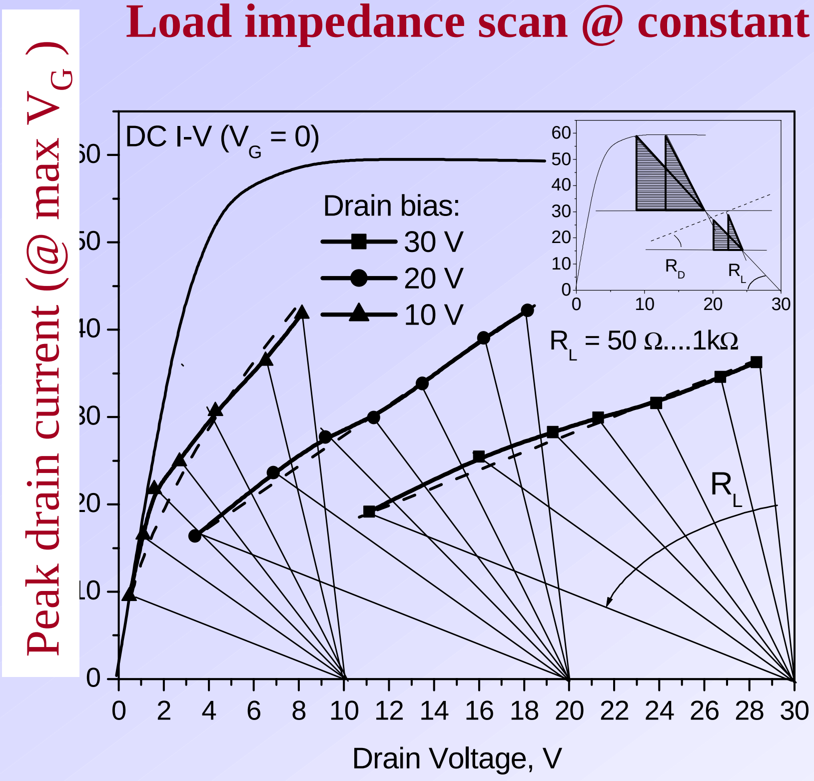
GTLM pattern
(L_G variable, $L_{GS}= L_{GD}$ =const)

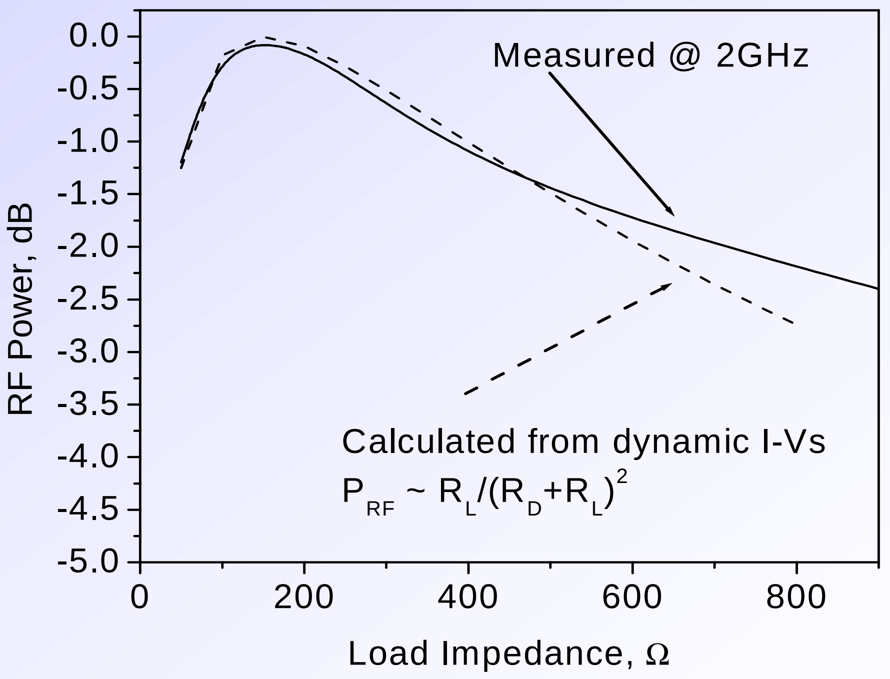


- ***AlGaN cap layer is not primarily responsible for CC***
- ***Only the gate edge regions contribute to the CC***

Dynamic I-V characteristics of AlGaN-GaN HFETs

Load impedance scan @ constant V_D = 10 V… 30 V



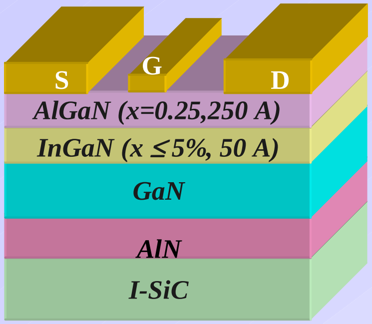


A. Koudymov, G. Simin and M. Asif Khan, A. Tarakji, M. S. Shur, and R. Gaska, Dynamic *I-V* Characteristics of III-N Heterostructure Field Effect transistors, IEEE EDL, Vol. 24, No. 11, pp. 680-682, November (2003)

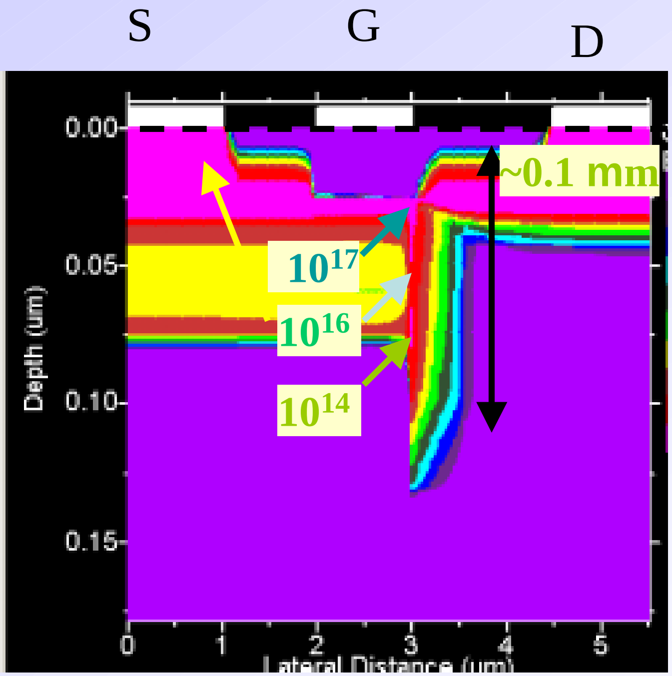
InGaN channel DHFET Design – 2D simulations

G-Pisces (VG= -1; VD = 20 V)

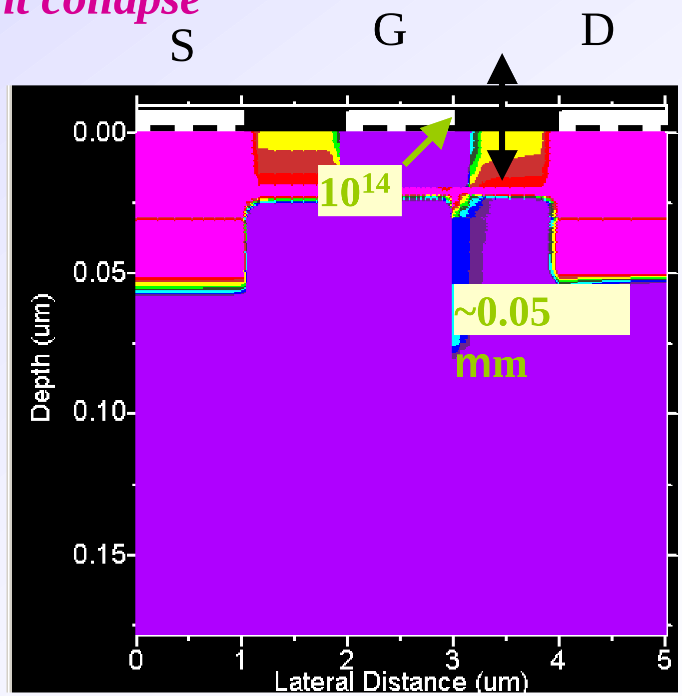
- *Better 2DEG confinement and Partial strain compensation*
- *Significantly reduced carrier spillover*
- *No current collapse*



Electron conc
🟪 < 1.0(+14)
🟪 > 1.0(+14)
🟦 > 3.2(+14)
🟦 > 1.0(+15)
🟩 > 3.2(+15)
🟩 > 1.0(+16)
🟨 > 3.2(+16)
🟥 > 1.0(+17)
🟥 > 3.2(+17)
🟪 > 1.0(+18)



Regular HFET

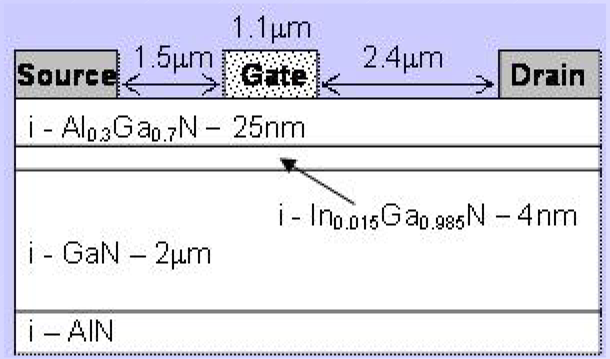


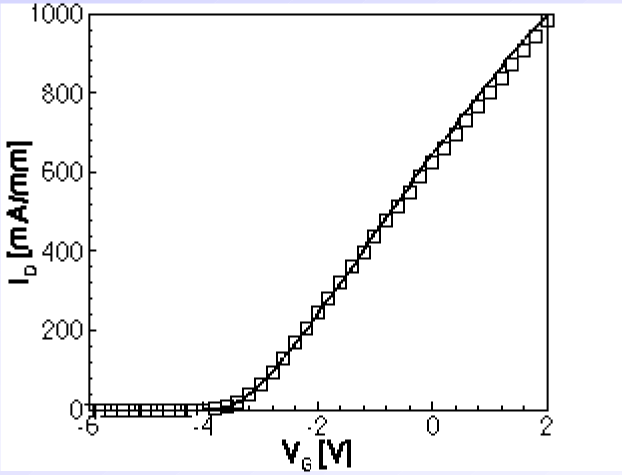
InGaN channel DHFET

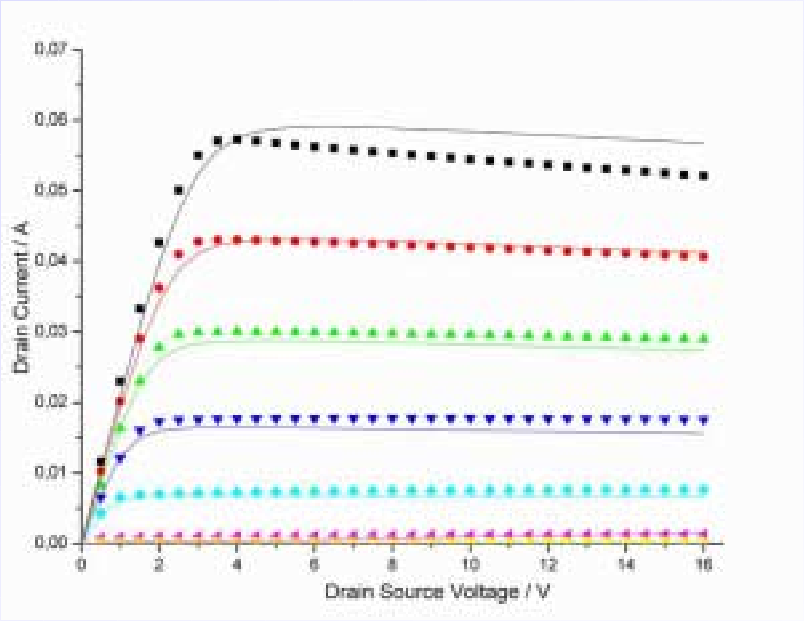
G. Simin et.al. Jpn. J. Appl. Phys.
Vol.40 No.11A pp.L1142 - L1144 (2001)

shurm@rpi.edu

Two Dimensional Simulation (ISE)



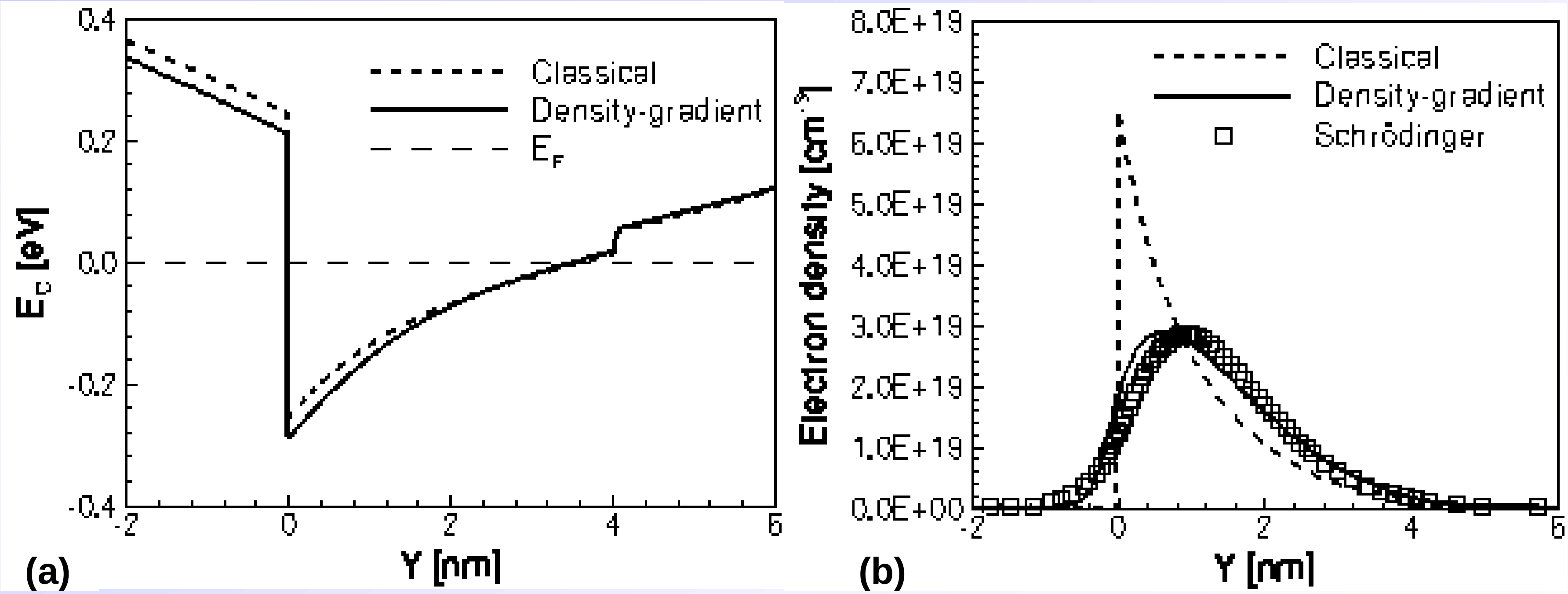




ISE 2D GaN device simulator

From N. Braga, R. Gaska, R. Mickevicius, M. S. Shur, M. Asif Khan, G. Simin, Simulation of Hot Electron and Quantum Effects in AlGaN/GaN HFET, submitted to JAP

Band Diagrams



From N. Braga, R. Gaska, R. Mickevicius, M. S. Shur, M. Asif Khan, G. Simin, Simulation of Hot Electron and Quantum Effects in AlGaN/GaN HFET, accepted in JAP

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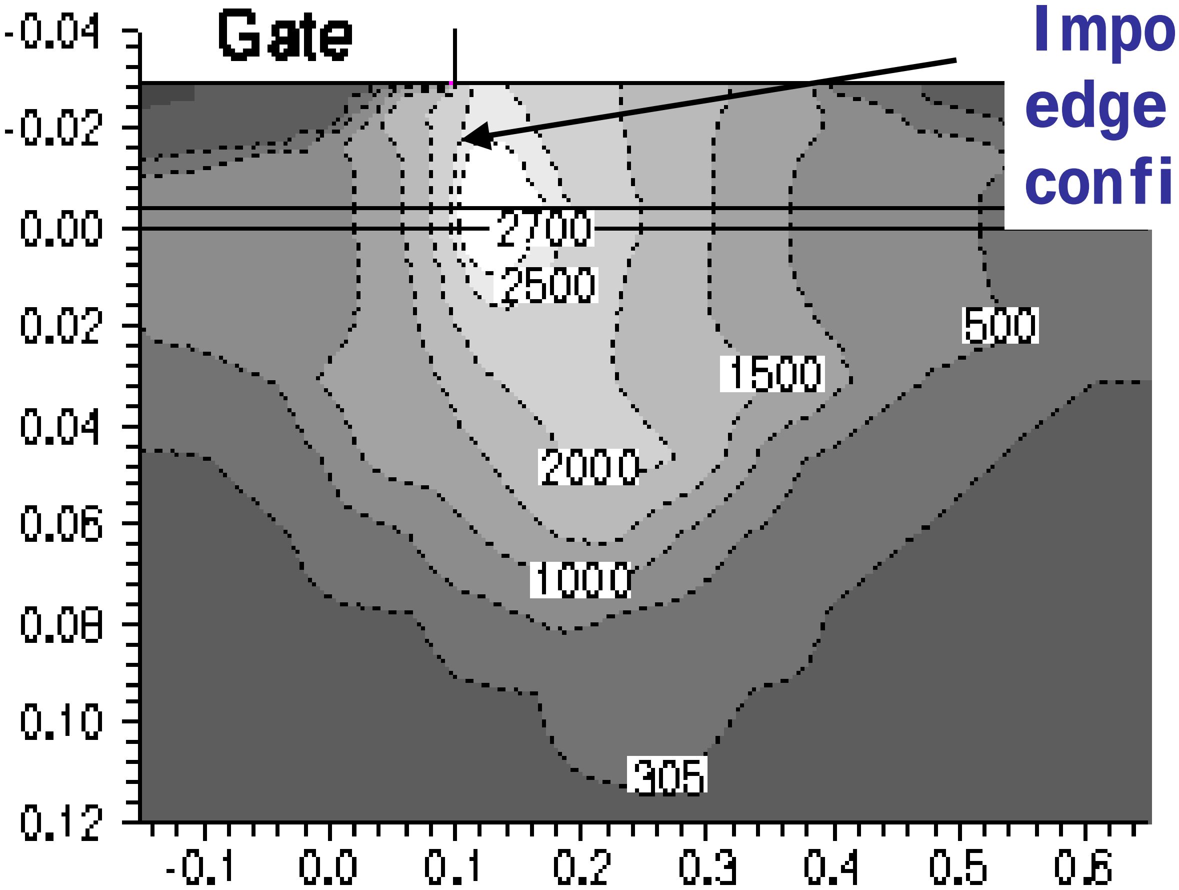
Electron temperature contour map

VD = 10V and VS = VG = 0V



Importance of gate edge engineering confirmed

From N. Braga, R. Gaska, R. Mickevicius, M. S. Shur, M. Asif Khan, G. Simin, Simulation of Hot Electron and Quantum Effects in AlGaN/GaN HFET, submitted to JAP

shurm@rpi.edu

Mechanism of current collapse in GaN FETs

- Current collapse is not related to AlGaN layer alone
- Current collapse is caused by trapping at gate edges
- Current collapse can be eliminated by using DHFET structures
- Current collapse time delay correlates with 1/f noise spectrum
- **<u>SOLVE THE CURRENT COLLAPSE ISSUE BY CHANNEL AND GATE EDGE ENGINEERING</u>**

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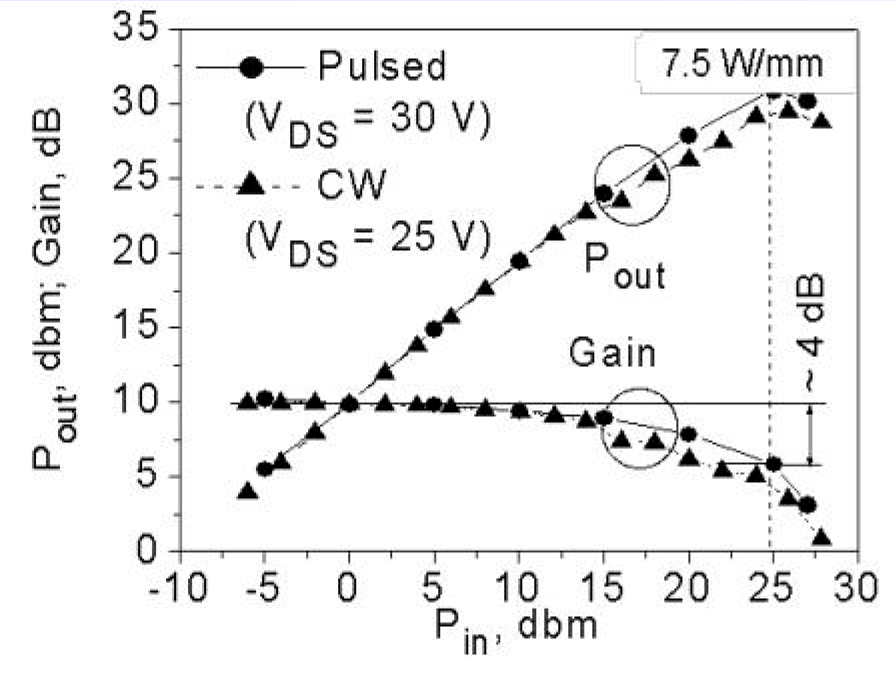
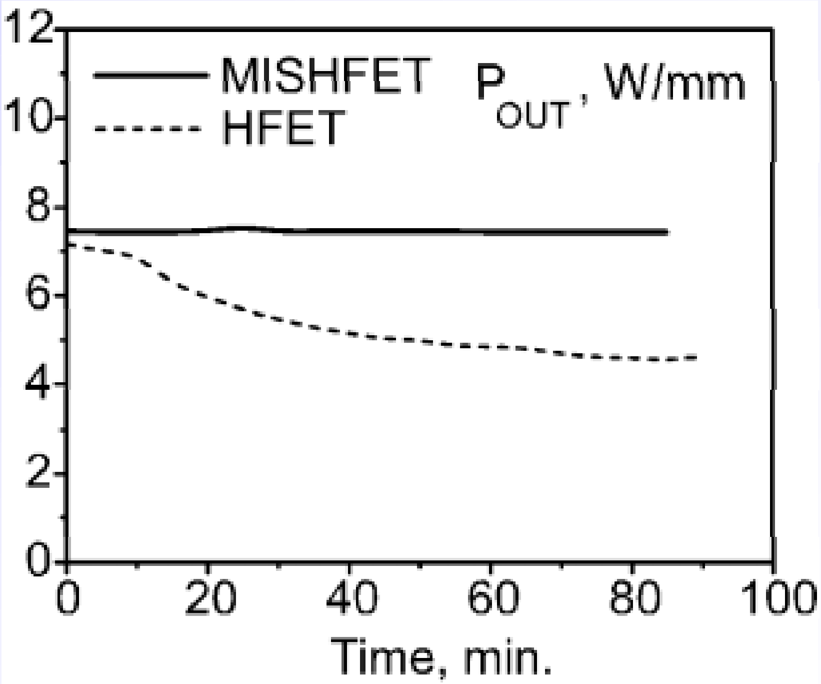
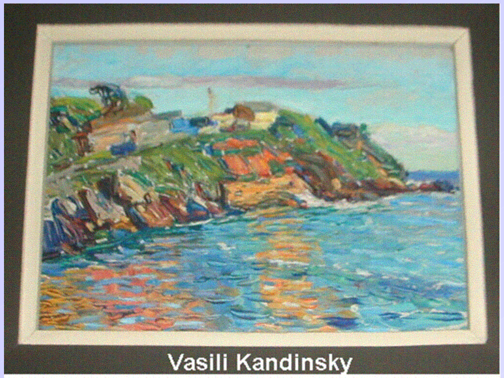
RF Power of collapse free DHFET and MISHFET RF Power stability

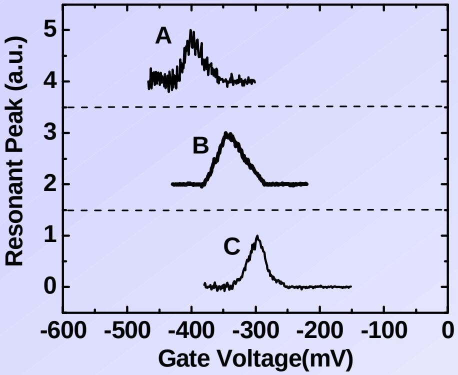


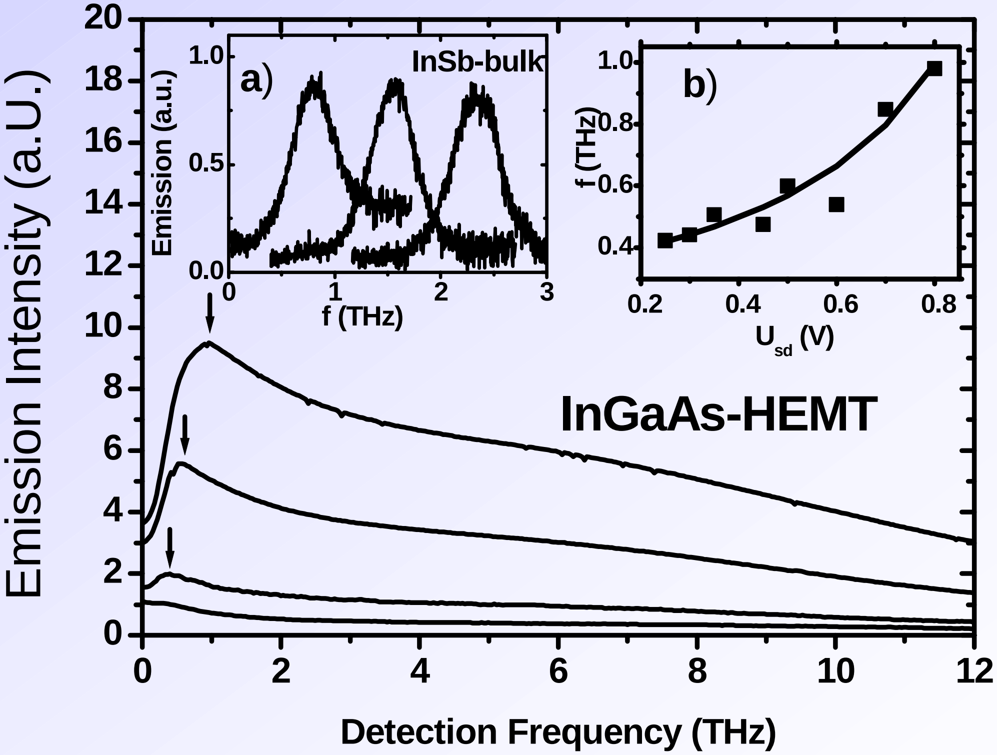


Plasma Wave THz Devices

Deep submicron FETs can operate in a new **PLASMA** regime at frequencies up to 20 times higher than for conventional transit mode of operation







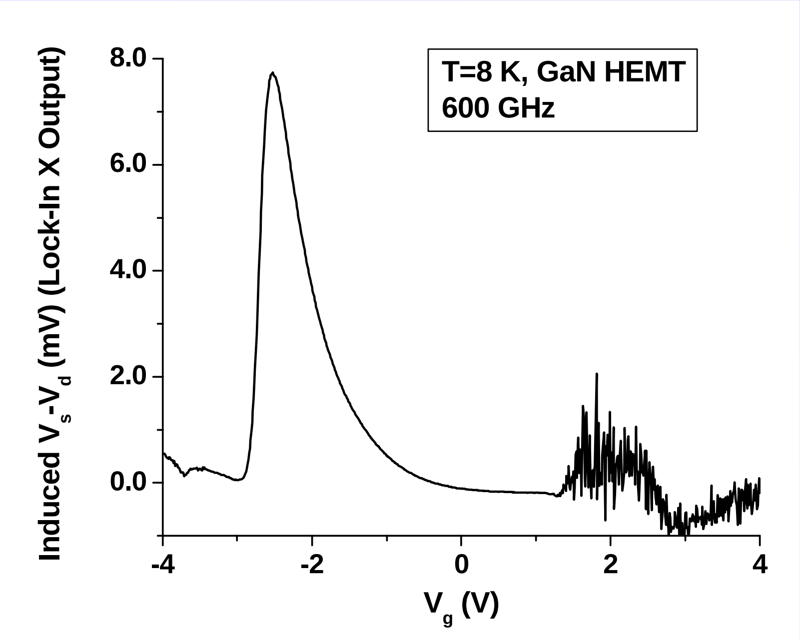
Resonant detection Of sub-THz and THz

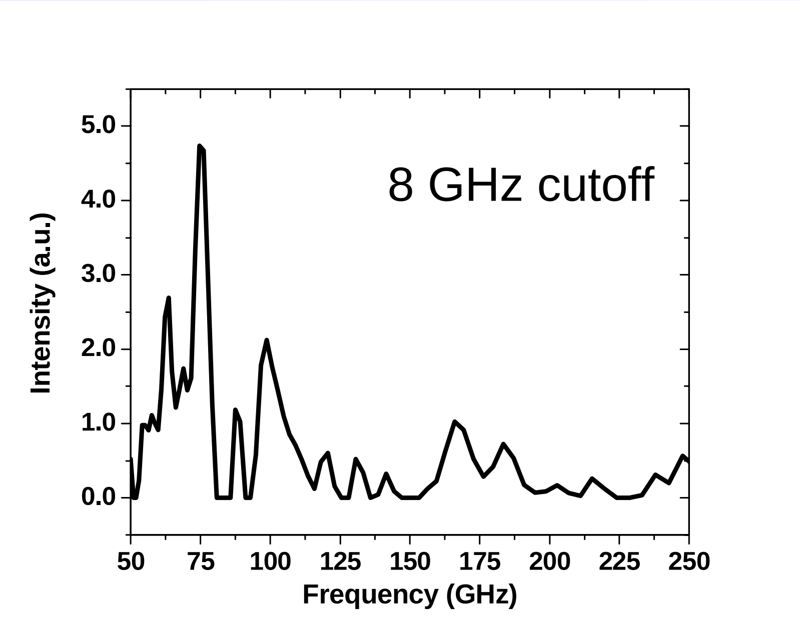
THz emission from 60 nm InGaAs HEMT

From W. Knap, J. Lusakowski, T. Parenty, S. Bollaert, A. Cappy, V. Popov, and M. S. Shur, Emission of terahertz radiation by plasma waves in sub-0.1 micron AlInAs/InGaAs high electron mobility transistors, Appl. Phys. Lett. , March 29 (2004)

shurm@rpi.edu

Plasma Wave Electronics





600 GHz radiation response of GaN HEMT at 8 K

Radiation intensity from 1.5 micron GaN HFET at 8 K.

shurm@rpi.edu

Conclusions

- New device physics of nitride based materials requires new designs and new modeling approaches

  - Polarization devices
    - Pyroelectric sensors
    - Piezoelectric sensors
  - Electron runaway and overshoot effects determine high field transport
  - Traps can be easier filled because of high electron densities
  - Noise determined by tunneling into traps
  - Strain control: Strain Energy Band Engineering
  - FETs – MOSHFET, DHFET, MOSDHFET
  - Terahertz applications – plasma wave devices

shurm@rpi.edu