Novel Physics of Nitride Devices

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Tutorial

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Flagstaff, Arizona, USA
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
Device Universe Is Both Infinite and Expanding

New Nitride Galactic

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

Number of Publications

Year


0 100 200 300 400 500 600 700 800 900 1000 1100 1200

GaN

SiGe GaAs

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

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

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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

Vasili Kandinsky

Lembach Villa, Munich
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
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
- **Phototherapy 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

<table>
<thead>
<tr>
<th>Crystal system</th>
<th>Crystal class (Schönflies)</th>
<th>Crystal class (Hermann-Mauguin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triclinic</td>
<td>C₁</td>
<td>1</td>
</tr>
<tr>
<td>Monoclinic</td>
<td>Cₘ</td>
<td>m</td>
</tr>
<tr>
<td></td>
<td>C₂</td>
<td>2</td>
</tr>
<tr>
<td>Orthorhombic</td>
<td>C₂ᵥ</td>
<td>2mm</td>
</tr>
<tr>
<td>Tetragonal</td>
<td>C₄</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>C₄ᵥ</td>
<td>4mm</td>
</tr>
<tr>
<td>Rhombohedral</td>
<td>C₃</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>C₃ᵥ</td>
<td>3m</td>
</tr>
<tr>
<td><strong>Hexagonal</strong></td>
<td><strong>C₆</strong></td>
<td><strong>6</strong></td>
</tr>
<tr>
<td><strong>HEXAGONAL</strong></td>
<td><strong>C₆ᵥ</strong></td>
<td><strong>6mm</strong></td>
</tr>
</tbody>
</table>
Wide Gap Semiconductors
Enabling Technology for Piezoelectronics and Pyroelectronics

- Zinc blende structure
- No PE or SP effect in $<100>$ direction
- PE coefficient $<111>$ \(~0.15 \text{ C/m}^2\)
- No PE/SP ‘doping’ reported

- Wurtzite structure
- c-axis growth direction
- PE coefficient in c-direction \(~1 \text{ C/m}^2\)
- PE/SP ‘doping’ demonstrated
Nitride Heterostructures: Polarization Induced Electron and Hole 2D Gases

AlGaN on GaN

$C_{6v}^4 \quad P6_3 mc$


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

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### Spontaneous polarization

<table>
<thead>
<tr>
<th>Material</th>
<th>AlN</th>
<th>GaN</th>
<th>InN</th>
<th>ZnO</th>
<th>BeO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spontaneous polarization (C/m²) (cm⁻²)</td>
<td>-0.081 6.24 10¹⁴</td>
<td>-0.029 2.23 10¹⁴</td>
<td>-0.032 2.46 10¹⁴</td>
<td>-0.057 4.39 10¹⁴</td>
<td>-0.045 3.47 10¹⁴</td>
</tr>
</tbody>
</table>

For comparison, in BaTiO₃, $P_s = 0.25 \text{ C/m}^2 (1.93 \times 10^{15}\text{cm}^{-²})$
Pyroelectric effect

(a) Temperature change over time.
(b) Voltage output over time.
(c) Temperature of sample and bath over time.

Pyroelectric material


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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 300º C (High Temperature Operation!)


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Strain from the lattice mismatch

\[ u_{xx} = \left( a_{\text{GaN}} - a_{\text{AlGaN}} \right) / a_{\text{GaN}} \]

\[ P_{pe} = 2 \ u_{xx} \ (e_{31} - e_{33} \ C_{13}/C_{33}) \]

How Piezoelectric constants are determined?

- Electromechanical coefficients (difficult)
- Optical experiments (indirect)
- Estimate from transport measurements (very indirect)
Effect of Strain on Dislocation-Free Growth

- Critical thickness as a function of Al mole fraction in $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$: 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

![Graph showing the effect of critical thickness on electron mobility at 77K and 300K.](image-url)
SIS sensor

- Piezoelectric sensors
- Pyroelectric sensors


Twice as large as in SiC

Short range superlattice is four times larger than in SiC

Resistance, $\Omega$

Strain (compression), $10^{-4}$
Polarization domain structure

Superlattice Band Diagram and resistance change in SRSL


Relative change in resistance under applied strain. (o) - correspond to [(AlN)$_6$-(GaN)$_3$]$^{150}$ SRSL; ( ) - [(AlN)$_3$-(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.


High Temperature p-GaN Pressure Sensor

Static Gauge factors (GF)
(measured under longitudinal mechanical deformation)

<table>
<thead>
<tr>
<th>Material</th>
<th>GF</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaN</td>
<td>10</td>
</tr>
<tr>
<td>GaN/AlN/GaN Sapphire</td>
<td>50</td>
</tr>
<tr>
<td>AlGaN/GaN Heterostructures</td>
<td>10-15</td>
</tr>
<tr>
<td>AlN/GaN Short Range Superlattices</td>
<td>30-80</td>
</tr>
</tbody>
</table>

Polarization effects in undoped and doped channel GaN/AlGaN HFETs

Piezoelectric and Pyroelectric Doping in AlGaN/GaN

State-of-the-art
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


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New Screening Mechanism in Multilayer Pyroelectrics

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

\[ E_c = \frac{eN}{\varepsilon R^2} = \frac{4\pi en_d R}{3\varepsilon} \]  

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

\[ W = \frac{Q Ea^2}{R} + \frac{Q^2}{\varepsilon a} \]  

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

\[ P_0 \gg en_d R \rightarrow E \gg E_c \]  

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

\[ a \sim \left( \frac{QR}{E} \right)^{1/3} \sim \left( \frac{en_d R}{P_0} \right)^{1/3} R \]  

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 $P_0$.

Oscillation frequency

$$w_0 = \sqrt{\frac{4\rho eP_0}{(e+2)\varepsilon} mR}$$

**MOVABLE QUANTUM DOTS (MQD)**

Oscillation frequency is of the order of a terahertz

$$w_0 p/2 \sim 1 \text{ THZ} \text{ to } 30 \text{ THZ}$$

**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
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]

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

Active region

Passive region

Temperature dependencies

Weaker contribution of impurity scattering for GaN because of heavier mass

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


Effect of Substrates: Bulk GaN on GaN

(A) Hall mobility $\mu_H$ (cm$^2$/V·s)

(B) Carrier density $n_e \times 10^{12}$ (cm$^{-2}$)

Temperature (K)


Shubnikov de Hass (SdHO) and magnetoresistance results

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

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

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

Extracted Deformation potential $a_c = 8.1 \pm 0.2$ eV

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
High field transport in Nitrides

Drift Velocity at Room and Elevated Temperatures

Intervalley Transition

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


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Velocity-Field Curves for Nitride Family

InN is the fastest nitride material

Ballistic and Overshoot Effects in GaN

Velocity ($10^5$ m/s)

More on the overshoot

InN - higher overshoot at smaller fields

High Field Breakdown.

Breakdown field measurement

Higher Breakdown Field in Heterostructures?

Breakdown field might be determined by cladding layers

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

- $E_{C2} < E_{C3}$
- $V_{C2} < V_{C3}$
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
Experimental data

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

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


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Trapping in Nitrides:
Reverse Gate Leakage Modeling

Direct tunneling and trap-assisted tunneling

Comparison with Experiment


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MOSHFET Gate Leakage

Traps and leakage: Complexities of highly non-ideal systems


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GaN 1/f Noise surprises

Device noise is smaller than materials noise!!!
Data from

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

Dependence of noise on the Fermi level position in bulk semiconductor

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

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

No leakage in MOSHFETs
Gate leakage in HFETs

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.

Where the traps are (from GR noise)

\begin{center}
\begin{tikzpicture}
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    axis y line*=left,
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    ytick={-3.5,-3.0,-2.5,-2.0,-1.5,-1.0,-0.5,0.0,1.0,1.6,1.8,2.0},
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\addplot[mark=none,draw=black,thick,mark size=2pt] coordinates {
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};
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};
\end{axis}
\end{tikzpicture}
\end{center}

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™
• Insulated gate designs
• Gate edge engineering

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


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Resolving the issues: AlGaInN, gate dielectrics, InGaN channel

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

Reducing current collapse, Improving carrier confinement

Combining the advantages

AlGaN/InGaN GaN DHFET

MISHFET Si₃N₄

MISDHFET

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Unified charge control model (UCCM)

MOSFETs and HFETs

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

![Graph showing Gate Capacitance and Gate Voltage](image)

Real space transfer

![Graph showing Drain Current vs. Gate Voltage](image)

**V_{DS} = 0.5 V**

www.aimspice.com
Gate Lag and Current collapse in AlGaN/GaN HFETs: Pulsed measurements of "return current"


Nearly Identical Gate Lag Current Collapse was observed in:

- I-SiC/Sapphire
- Pd/Ag/Au
- GaN
- AlN
- AlGaN

- n-GaN
- S G D

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 $V_D = 10\text{ V} \ldots 30\text{ V}$

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

Regular HFET

InGaN channel DHFET

Two Dimensional Simulation (ISE)


ISE 2D GaN device simulator

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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
Electron temperature contour map

$V_D = 10V$ and $V_S = V_G = 0V$

Importance of gate edge engineering confirmed


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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
- **SOLVE THE CURRENT COLLAPSE ISSUE BY CHANNEL AND GATE EDGE ENGINEERING**
RF Power of collapse free DHFET and MISHFET RF Power stability

![Graph showing RF power stability comparison between MISHFET and HFET. The graph includes Pout, W/mm vs Time, min., and Pout, dBm vs Pin, dBm with different voltage conditions.](image-url)
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


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Plasma Wave Electronics

600 GHz radiation response of GaN HEMT at 8 K

8 GHz cutoff

Radiation intensity from 1.5 micron GaN HFET at 8 K.

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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