SAND2016-11003PE

Ultra-Wide Bandgap AlGaN Materials for Electronics and Opto-electronics

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Outline

- **Ultra-wide band gap (UWBG) AlGaN: Needs and opportunities**
- Wide band gap GaN has achieved its fundamental material limit
- Mechanism for conductivity collapse in UWBG AlGaN
- Electrically functionalizing UWBG AlGaN
- UV-C opto-electronics of UWBGs

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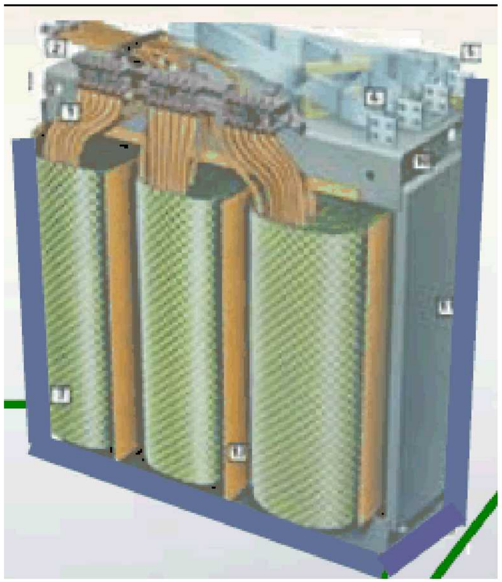
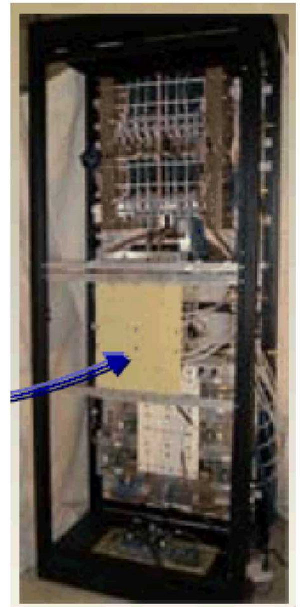
Why UWBG semiconductors for Power Electronics?

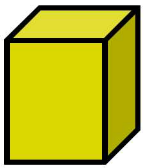
Si



SiC



UWBG



- 2.7 MVA
- 6 tons
- 10 m^3

- 2.7 MVA
- 2 tons
- 6.5 m^3

- 2.7 MVA
- <1 ton
- <1 m^3

- ➢ DoD-wide electrification of propulsion, sensors, weapons and armor
- ➢ Electrified systems demand > 100 kV, > 1000 kA, and > 100 MW
- ➢ Requires higher voltage, power density, and thermal margin than SiC or GaN provides

III-Nitride Semiconductors Are Ideal WBG and UWBG Materials

Band gap energy (E_g) is the fundamental material property driving SWaP-C at the device-, circuit-, and system-level

Fundamental Materials Capabilities

	Conventional		WBG		UWBG
Property	**Si**	**GaAs**	**4H-SiC**	**GaN**	**AlN**
Bandgap (eV)	1.1	1.4	3.3	3.4	6.2
Critical Electric Field (MV/cm)	0.3	0.4	2	3.3	15.9
Saturated electron velocity (10^7 cm/s)	1	1	2	2.5	2
Thermal conductivity (W/cm·K)	1.5	0.5	4.5	4	3.4
Ionization energy (eV/e-h pair)	3.6	4.8	8.7	10.3	18

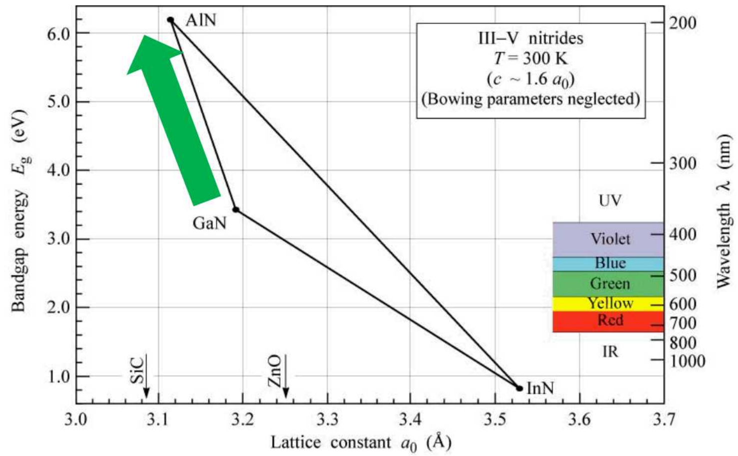


Fig. 12.12. Bandgap energy versus lattice constant of III–V nitride semiconductors at room temperature.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

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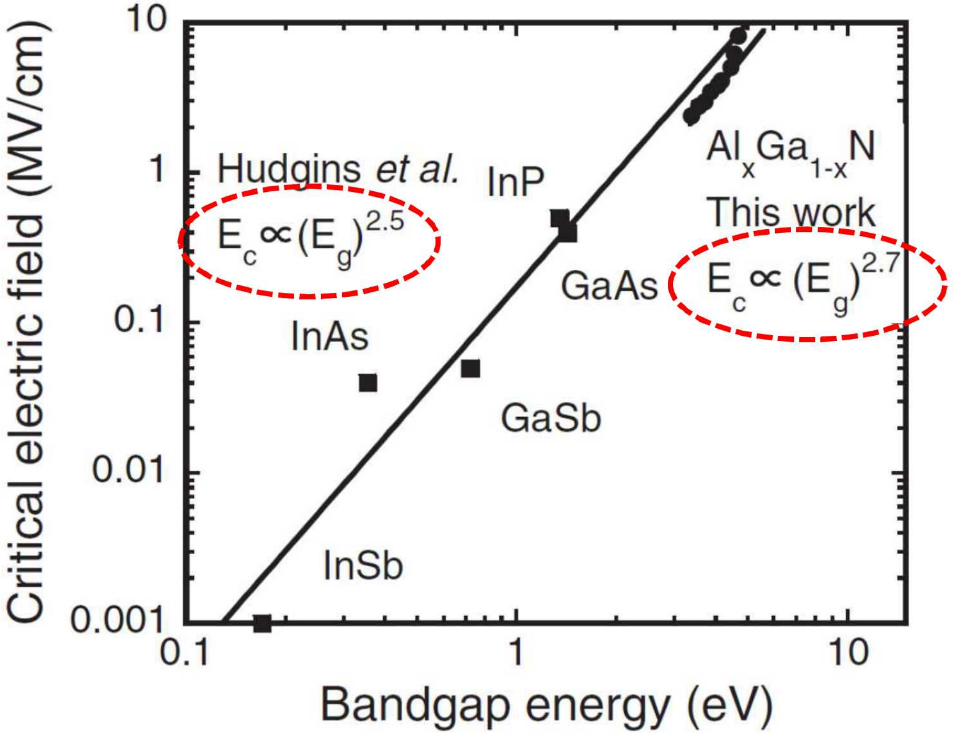
Electrical power density scales *dramatically* with band gap

$$R_{on,sp} = \frac{4V_{br}^2}{\epsilon\mu E_{crit}^3}$$

$$\textbf{Power density} \sim 1/R_{on,sp} \sim \epsilon\mu E_g^8$$

$$V_{br} \sim E_g^{5.5}$$



Nishikawa, *et al.*, JJAP 46, 2316 (2007).

Electrical power density of AlN > 30x GaN and > 60,000x Si

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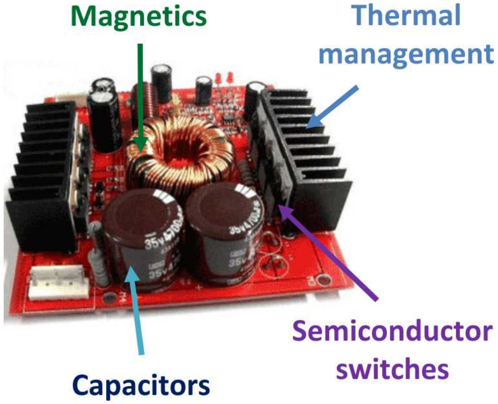
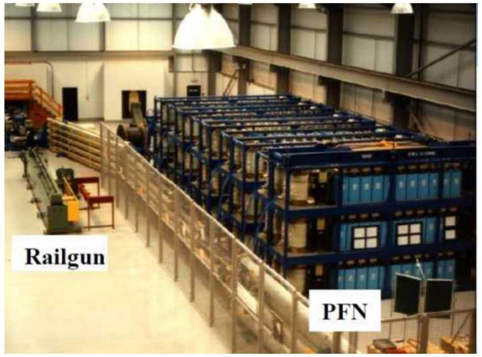
Why UWBG semiconductors for Power Electronics?

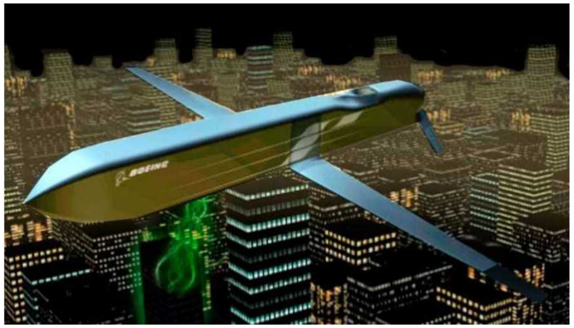
UWBGs for continuous power: Size and Weight

Functionality	4H-SiC	GaN	UWBGs
> 10 kV device	YES	NO	YES
> 1 MHz switching	NO	YES	YES
100% I_{ds} @ 250 °C	NO	NO	YES



UWBGs for pulsed-power: Size, Weight, and Rep-rate





Rep-rate ~ $1/R_{on}$ ~ E_g^{8} ~ 30x improvement over WBG

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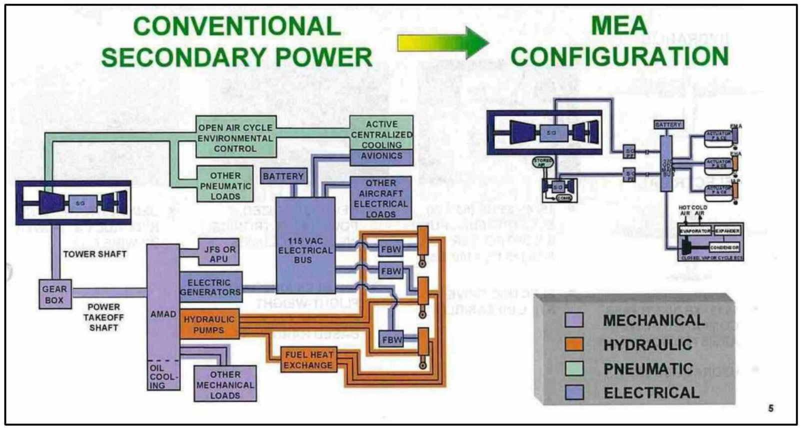
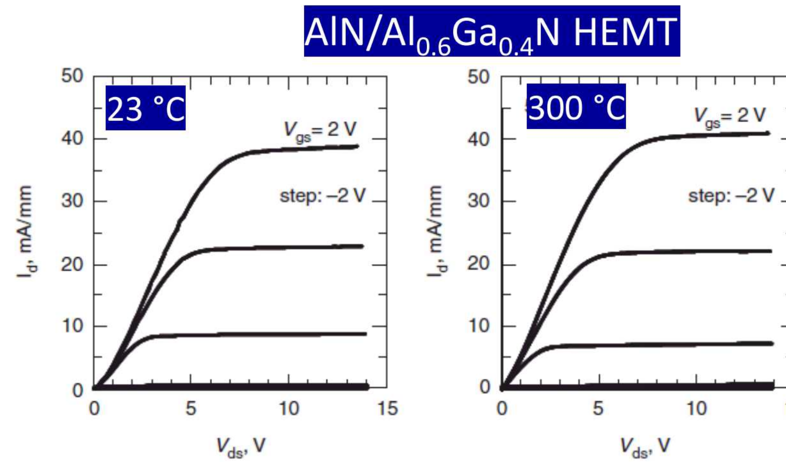
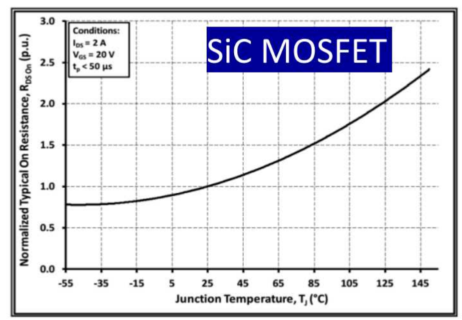
Need for post-GaN, post-SiC power electronics: USAF

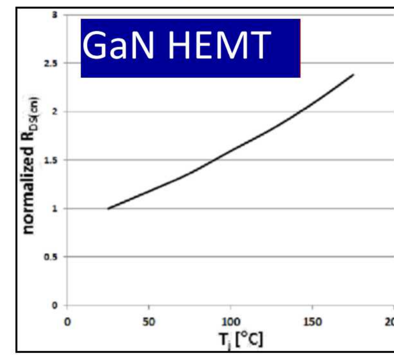
Thermal margin: Eliminate liquid PE cooling in MEA and HALE



Brett A. Jordan, Wide Temperature Power Electronics for the More Electric Aircraft, Air Force Research Laboratory, 13 February 2005







➢ UWBG PE could run at > 250 °C to maximize weight savings in MEA

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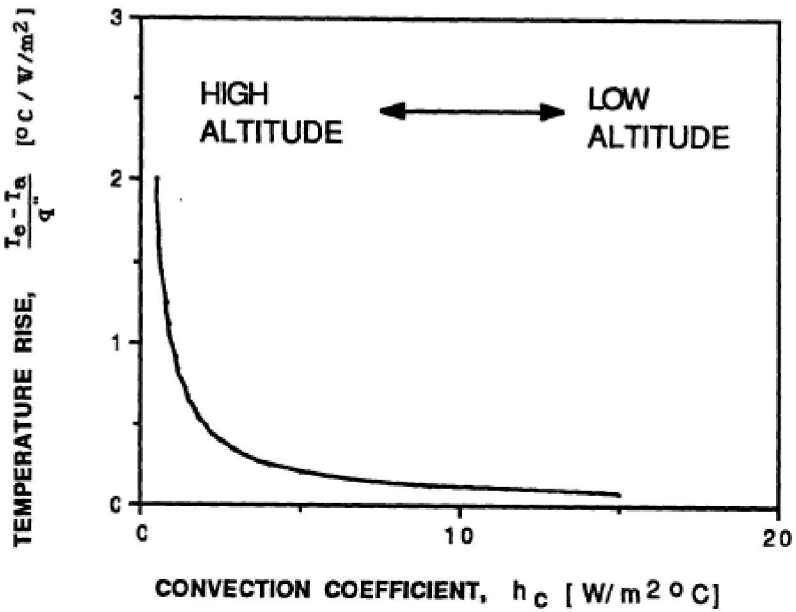
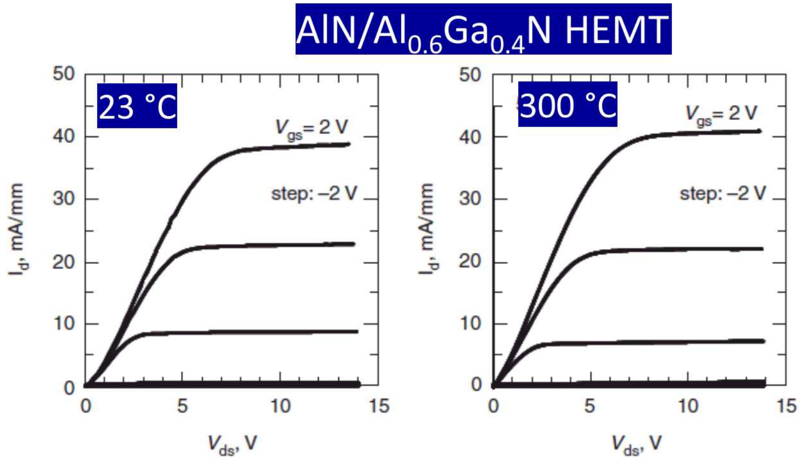
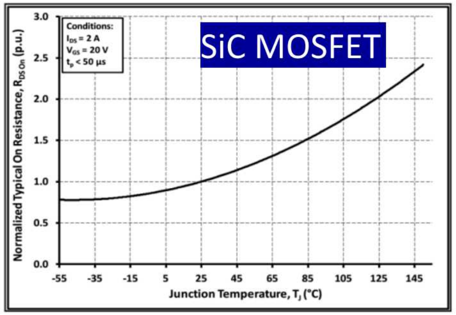
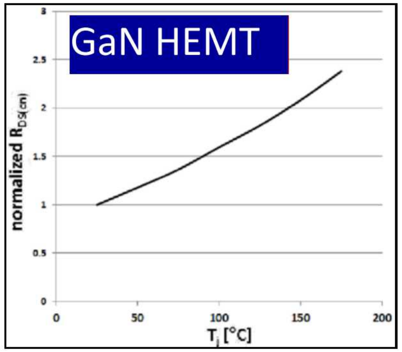


D. Bar-Shalom MS Thesis MIT 1989







- ➢ UWBG PE could run at > 250 °C to maximize weight savings in MEA
- ➢ High altitude: UWBG avionics operating in absence of convective cooling
- ➢ High altitude: rad-hard UWBG avionics

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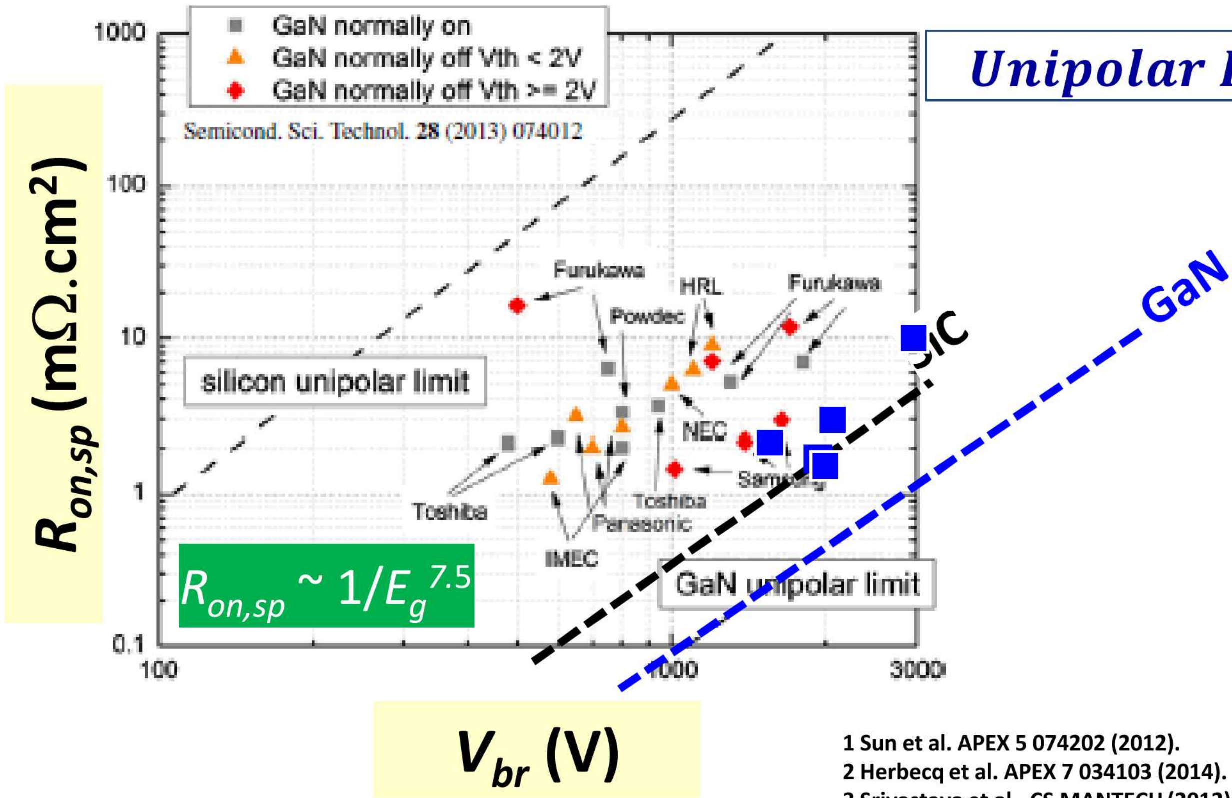
GaN power HEMT SOA plateauing



$$Unipolar\ FOM = \varepsilon\mu E_{crit}^{3}$$

1 Sun et al. APEX 5 074202 (2012).
2 Herbecq et al. APEX 7 034103 (2014).
3 Srivastava et al., CS MANTECH (2012).
4 Seok et al., Electron. Lett. 49 425 (2013).
5 Herbecq et al., Electron. Lett. 51 1532 (2015).

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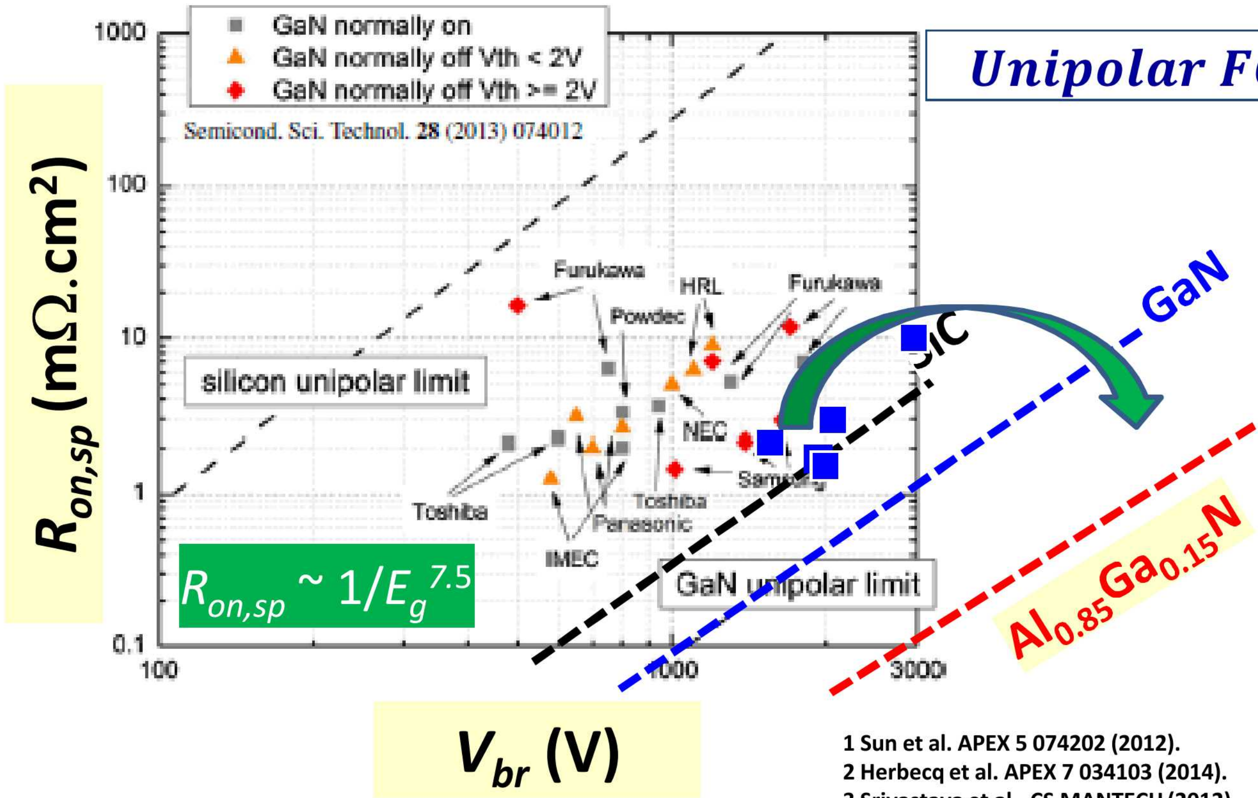
Solution: UWBG Power electronics



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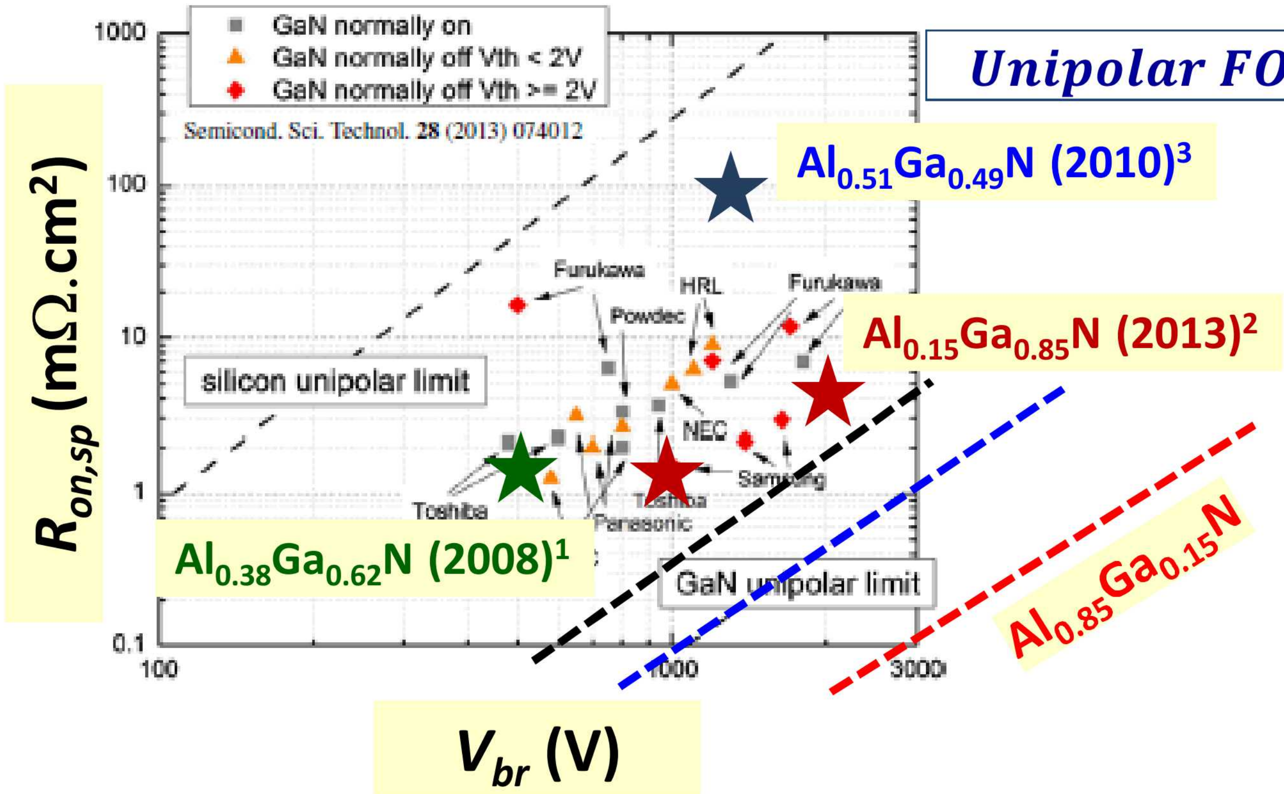
AlGaN HEMT development



$$Unipolar\ FOM = \varepsilon\mu E_{crit}^3$$

1. Nanjo et al. Appl. Phys. Lett. 92 263502 (2008).
2. Nanjo et al. IEEE Trans. Electron Dev. 60 1046 (2013).
3. Tokuda et al. APEX 3 121003 (2010).

- Emerging AlGaN channel HEMTs moving into GaN locus
- Proves that AlGaN devices can realize material advantages of AlGaN

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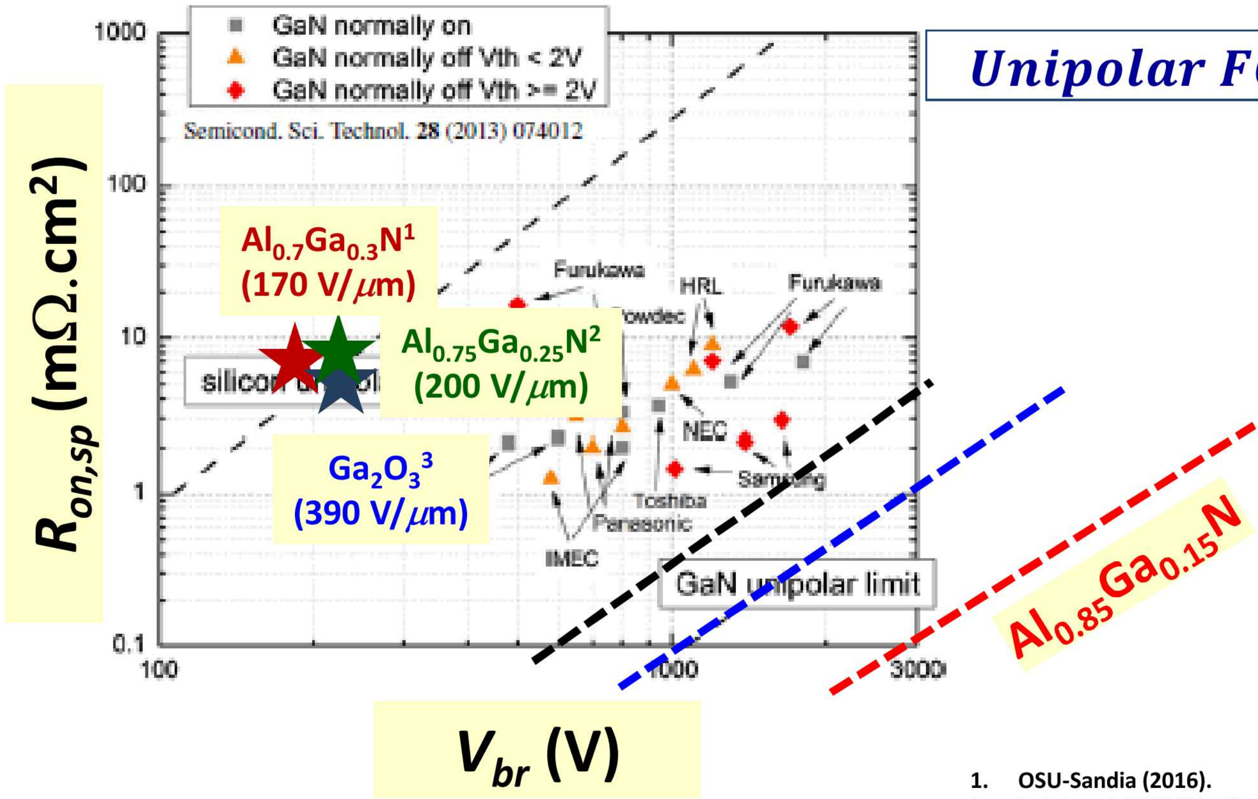

$$Unipolar\ FOM = \varepsilon\mu E_{crit}^3$$

1. OSU-Sandia (2016).
2. Bajaj et al. IWN (2016).
3. Green et al. IEEE EDL 37 902 (2016).

- UWBG transistors have proven viability
- Experimental E_{crit} exceed that of GaN HEMTs

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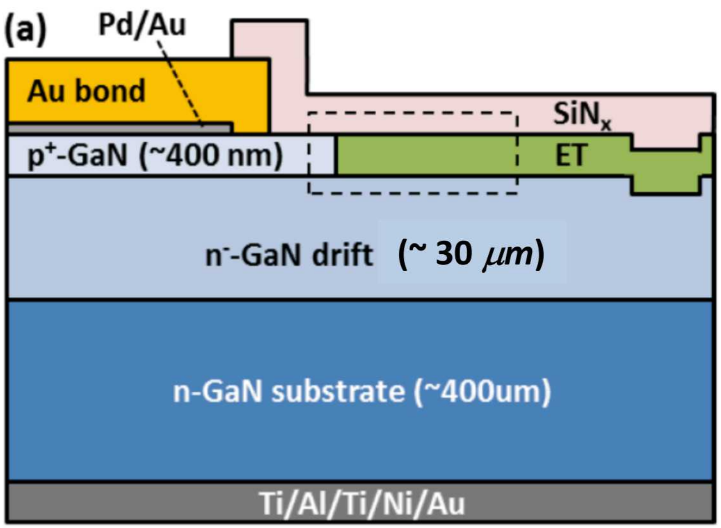
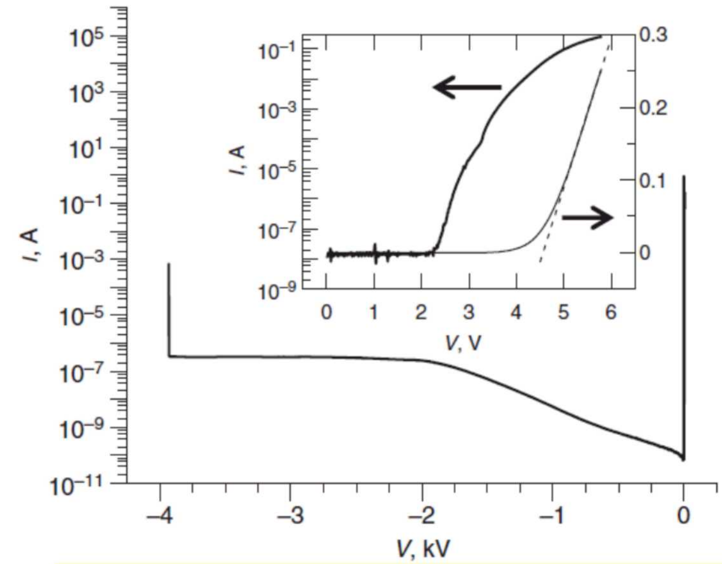
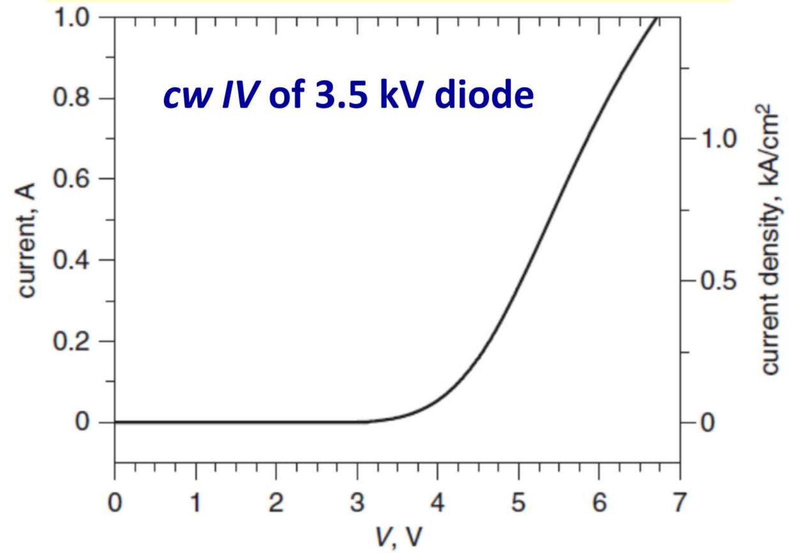
GaN *p-i-n* diode foundation



- MOVPE-grown GaN on Ammono substrate
- ~ 3 × 10^{15} cm^{-3} net doping in drift layer
- Ion-implanted junction termination extension



A.M. Armstrong, et al., Electronics Letters 52, 1170 (2016).



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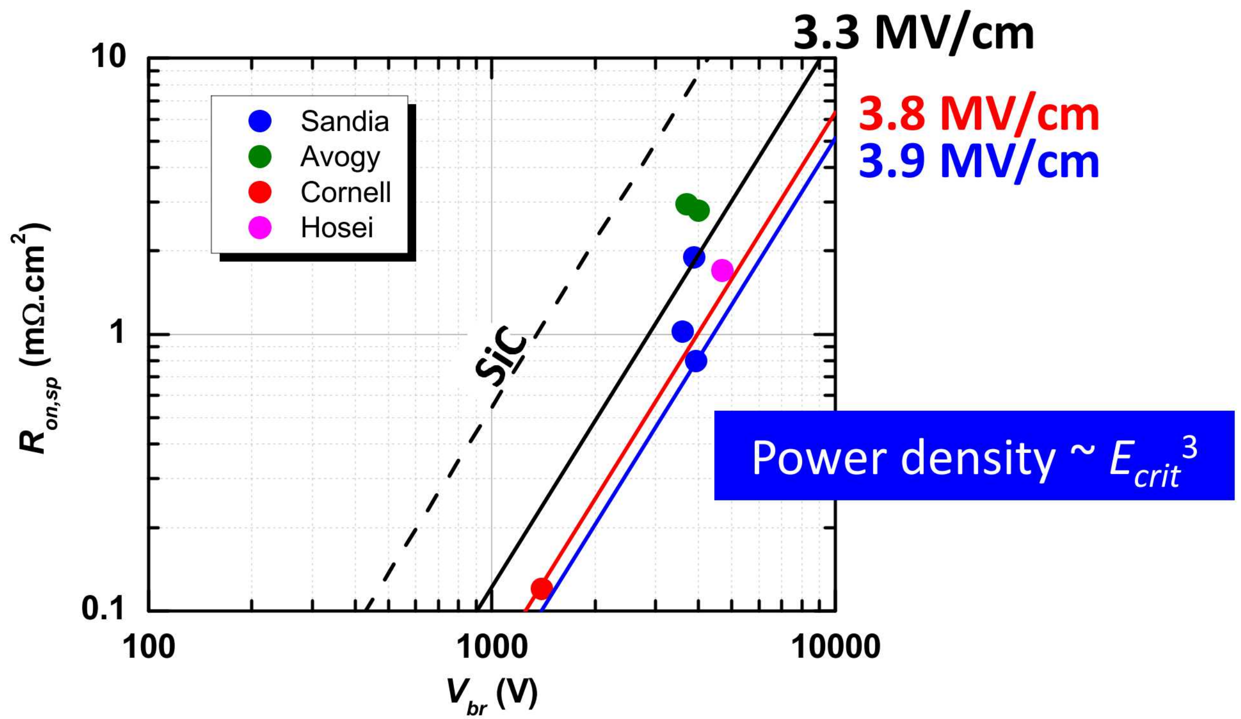
Record UFOM for high voltage GaN diode



A.M. Armstrong, et al., Electronics Letters 52, 1170 (2016).

- Demonstrated E_{crit} for GaN 33% higher than previously thought
- Fundamental power density of GaN >2x larger than previously thought
- Achieved fundamental limit for GaN (probably)

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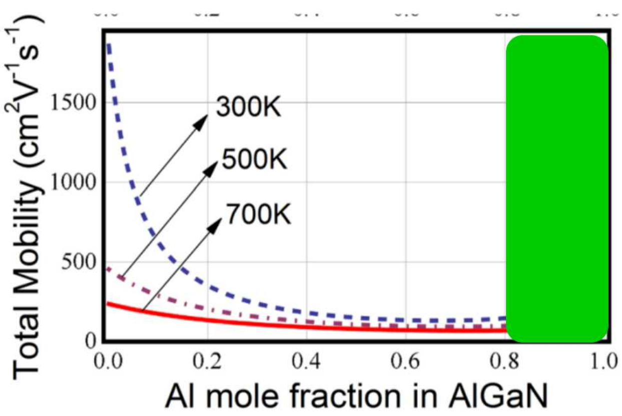
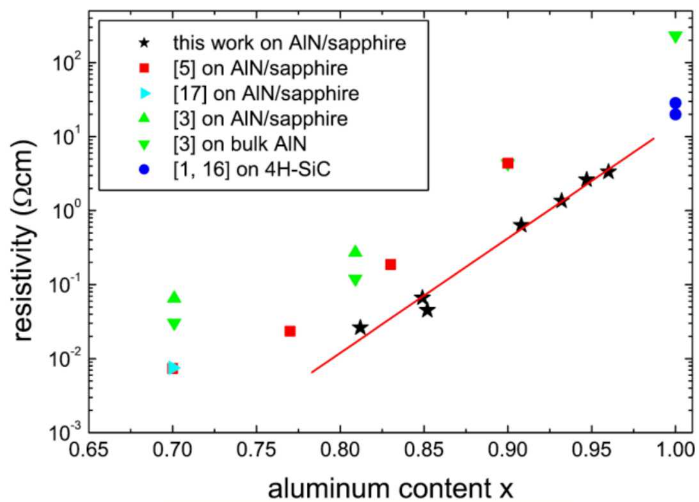
How to electronically functionalize UWBG AlGaN?

AlGaN electron mobility



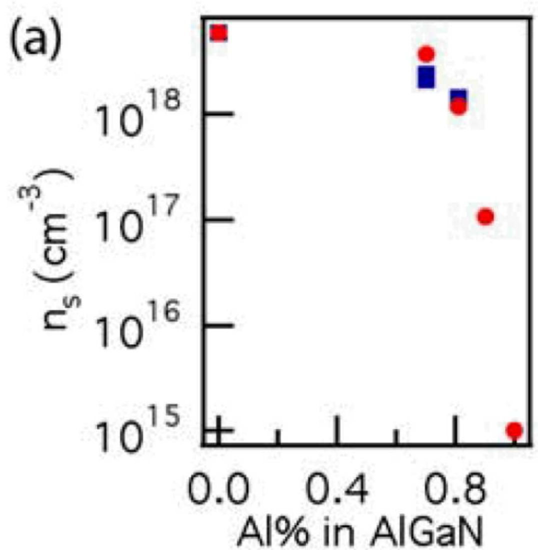
Bajaj *et al*. APL 105 263503 (2014)

AlGaN resistivity



Mehnke *et al*. APL 103 212109 (2013)

AlGaN electron concentration



Collazo *et al*. pss(c) 8 2031 (2011)

- AlGaN suffers conductivity collapse for Al > 80%
- Understand mechanism: defect compensation or deep dopants?

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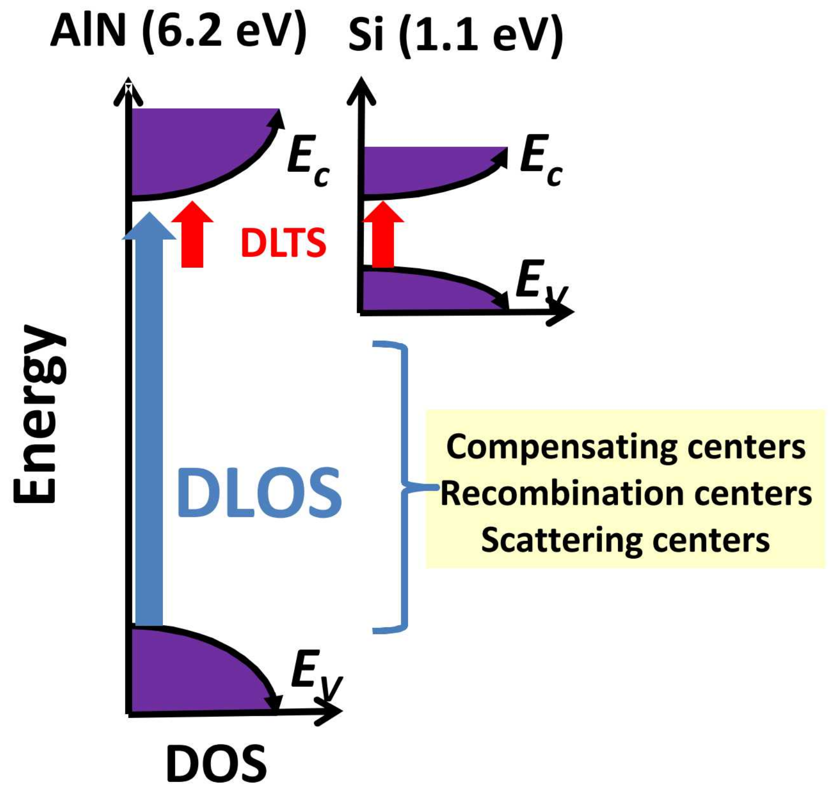
Challenges to studying defects in III-Nitrides

Quantitative defect spectroscopy is difficult for ultra-wide bandgap semiconductors

- Thermal emission techniques limited to ~ 1 eV of band edge
- Luminescence insensitive to non-radiative centers and not usually quantitative



Solution: Deep Level Optical Spectroscopy (DLOS)

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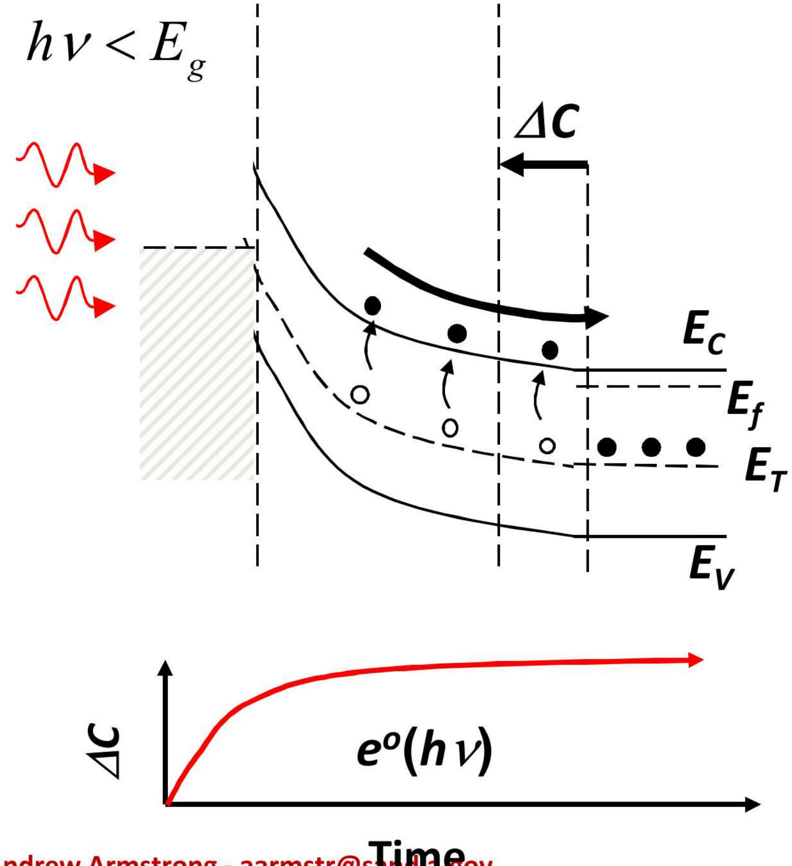
Deep Level Optical Spectroscopy

Deep Level Optical Spectroscopy (DLOS)[1]

- Photocapacitance technique
- *Electrical measurement* of *optical absorption* by deep level defects
- Sub-band gap optical stimulation to photoionize defect levels



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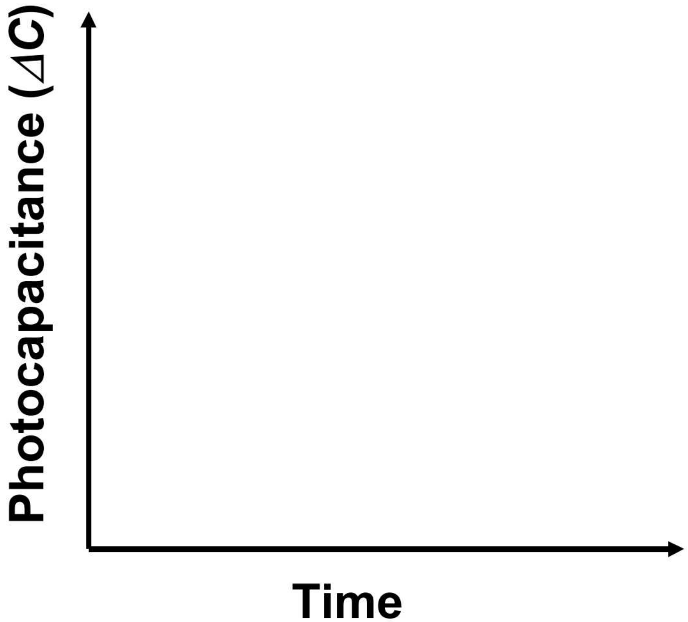
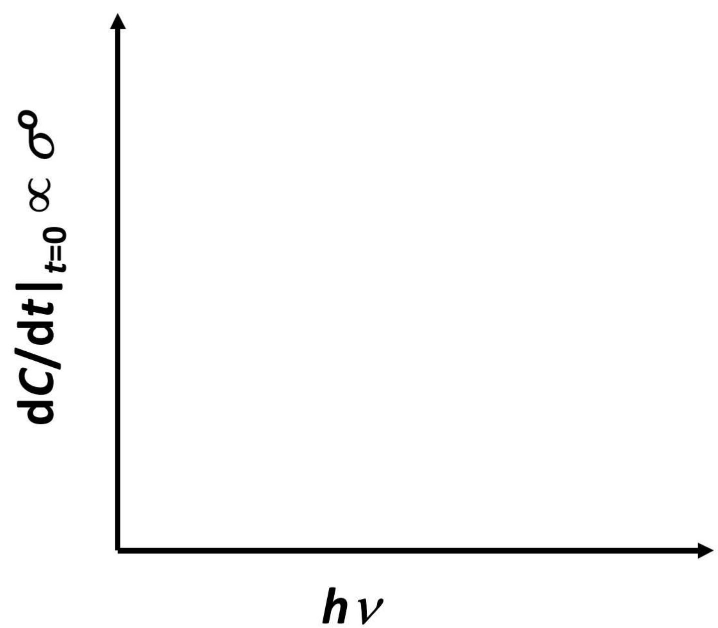
1. Chantre *et al.* PRB 23, 5335 (1981).

Deep Level Optical Spectroscopy

Deep Level Optical Spectroscopy (DLOS)[1]

- Deep level defect optical cross-section: $\sigma^o = e^o/\phi = \alpha/N_t$
- $\sigma^o(h\nu) \propto dC(t)/dt|_{t=0}$





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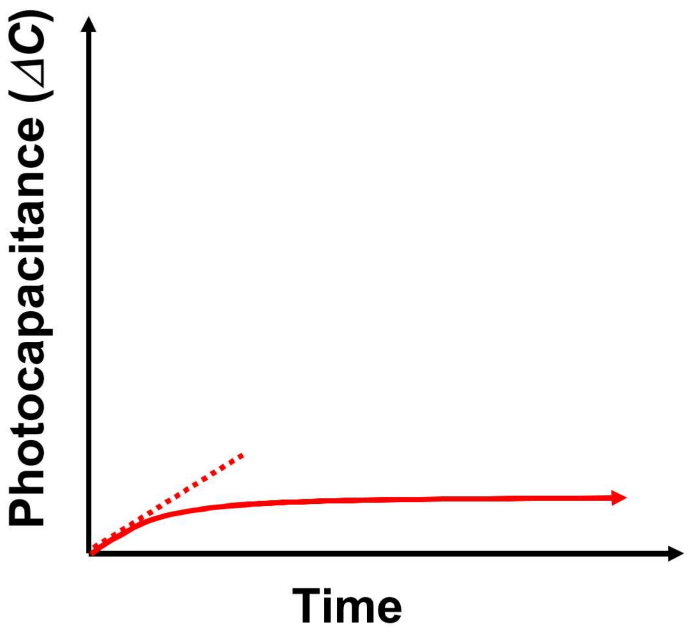

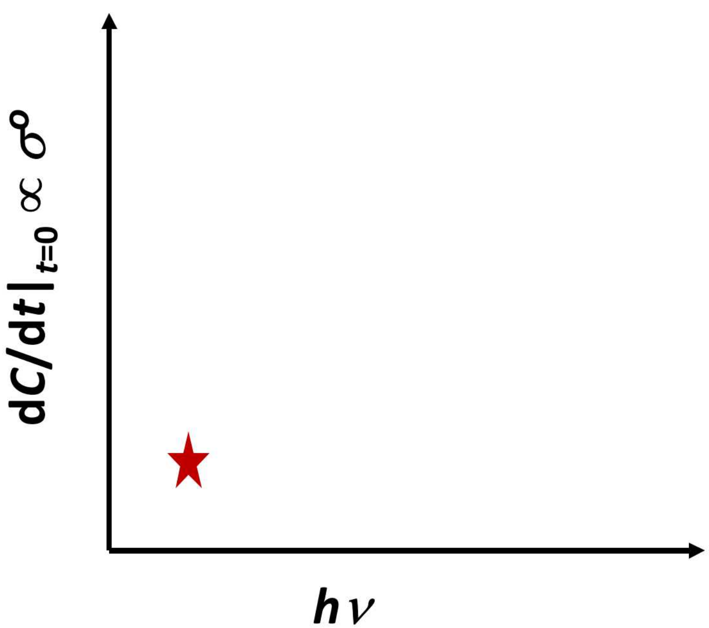

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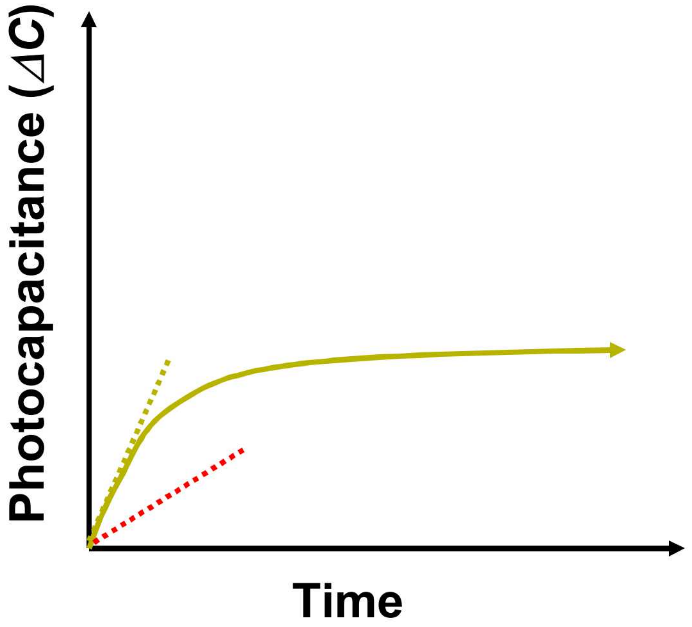

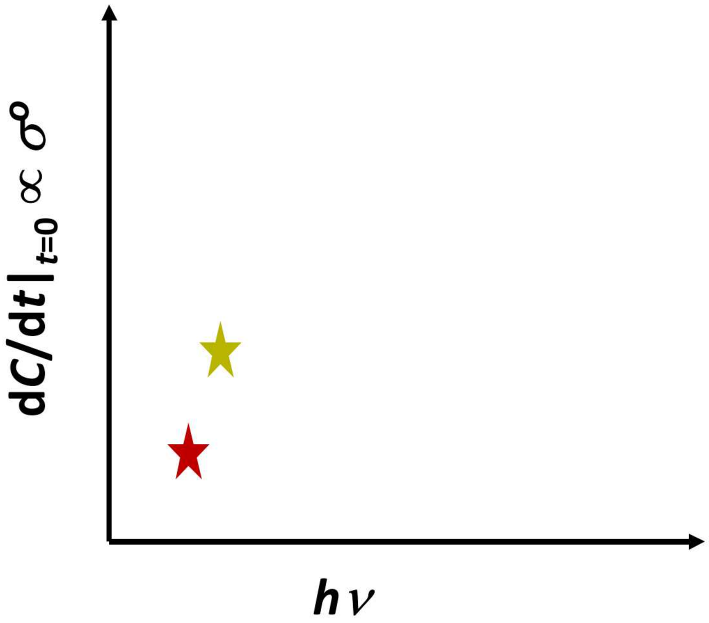

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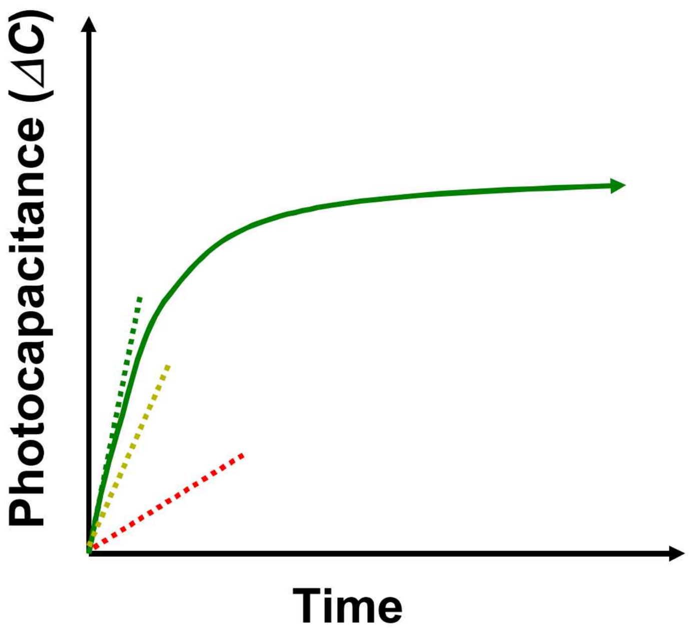

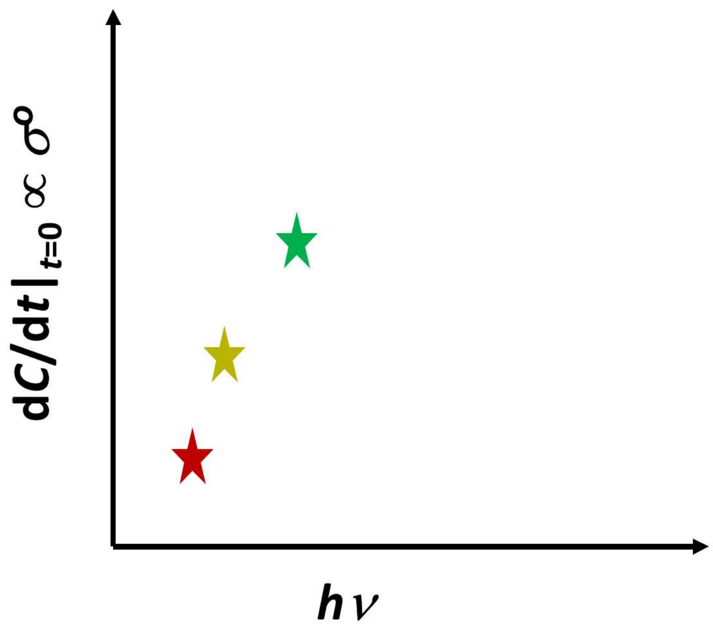

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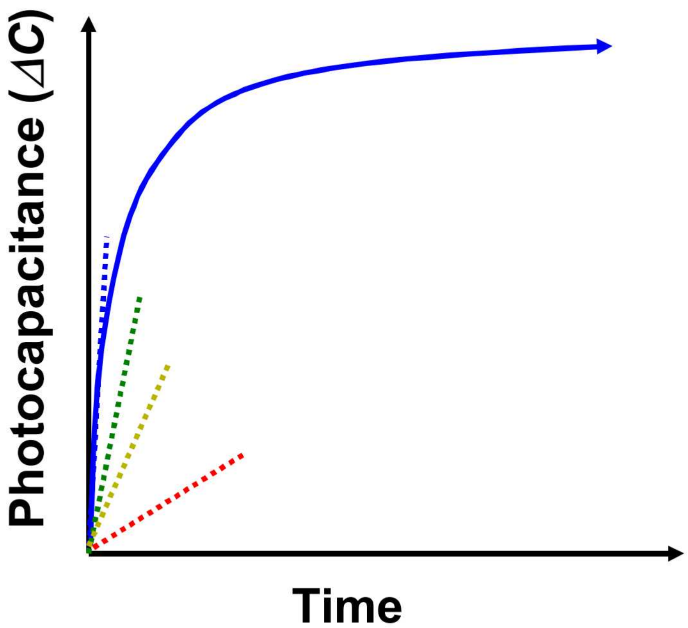

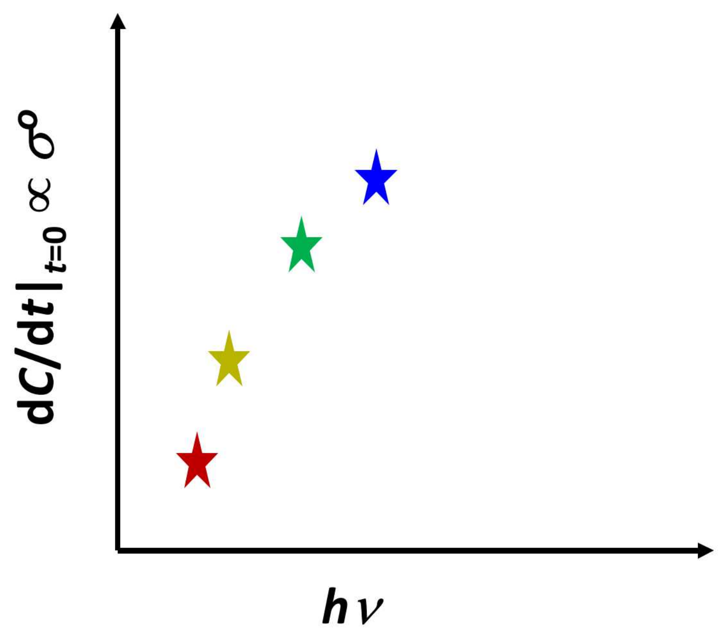

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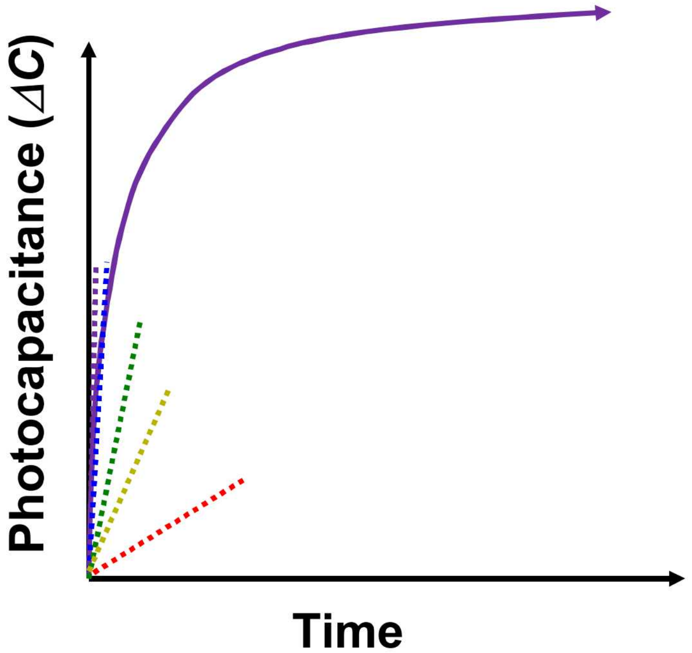

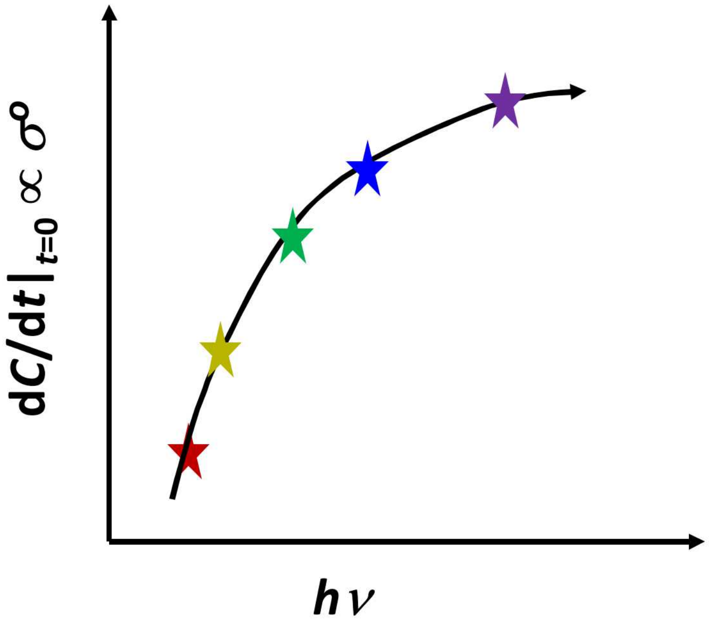

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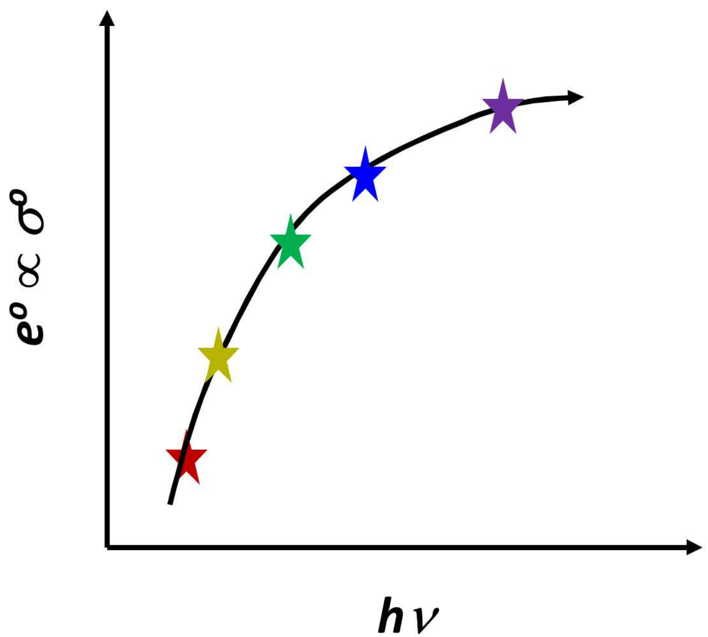
Optical analog of Arrhenius plot



$$\sigma^o(h\nu) \propto \frac{1}{E_0}\left\{\left(\frac{E_0}{h\nu}\right)\cdot\left(1-\frac{E_0}{h\nu}\right)\right\}^{3/2}$$

$$\sigma^o(h\nu,T) \propto \frac{E_o^2}{h\nu\sqrt{4k_B T\pi d_{FC}}}\int_1^\infty dx\sqrt{\frac{x-1}{E_o}}\frac{1}{[(x-1)/E_o+m]^2} \times\exp\left[-\frac{E_o^2(h\nu/E_o-x)^2}{4k_B T d_{FC}}\right], \quad (4)$$

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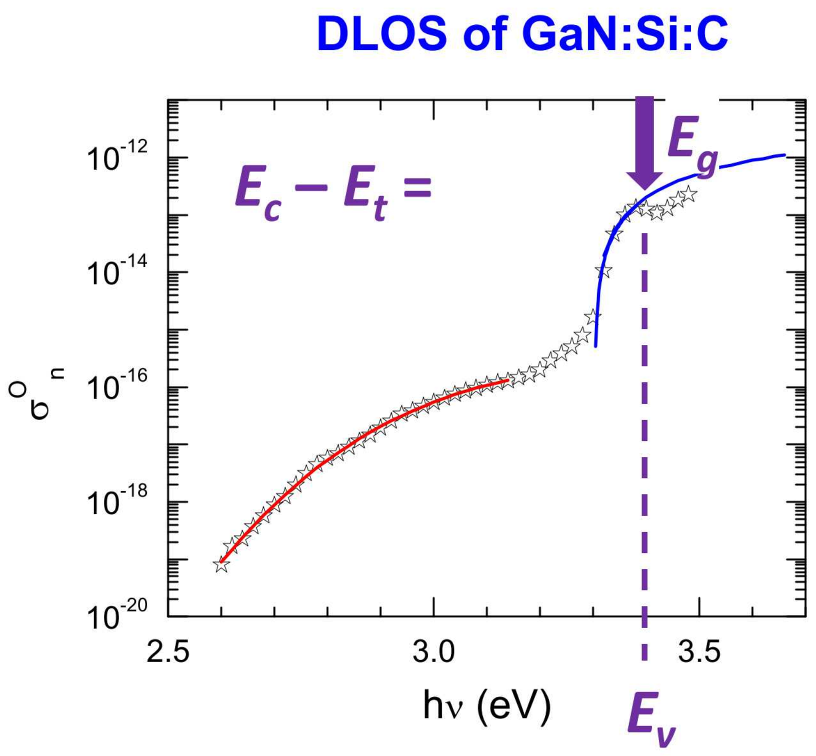
1. Chantre *et al.* PRB 23, 5335 (1981).

Interpretation of DLOS spectra



Armstrong et al, APL 84, 374 (2004)

Andr

Chantre, et al., PR B 23, 5335 (1981)

Lucovsky, Solid State Commun. 3, 299 (1965)

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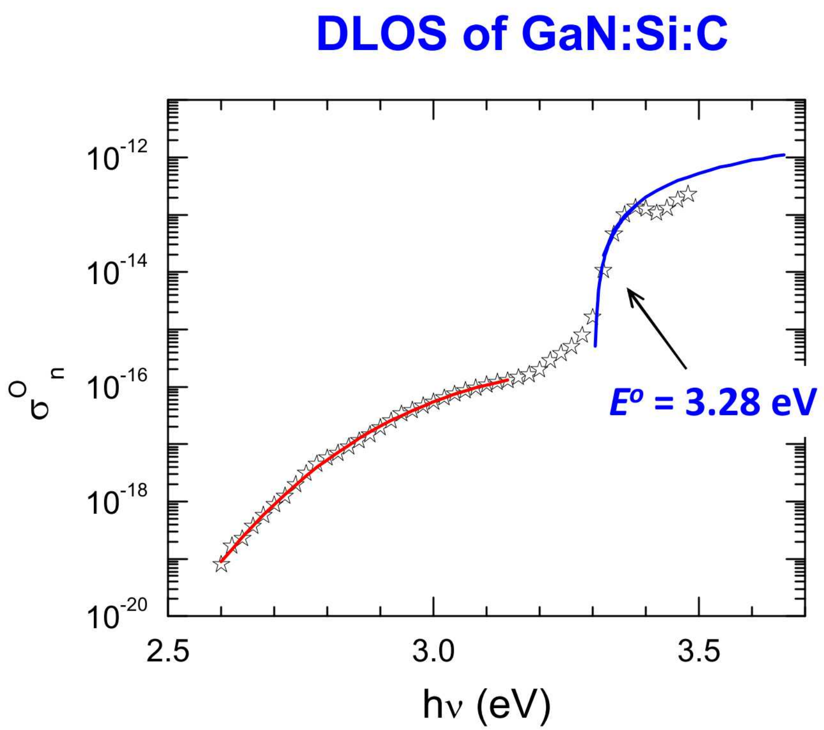

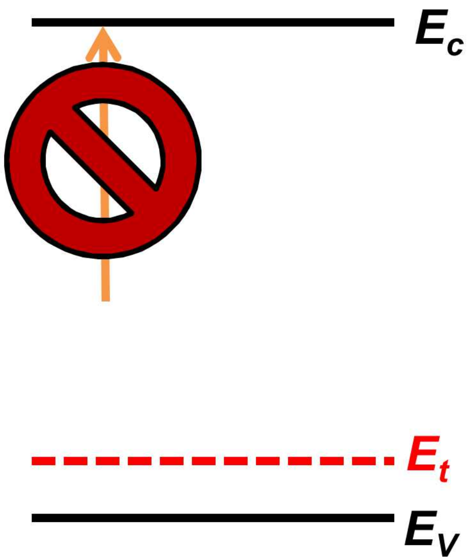

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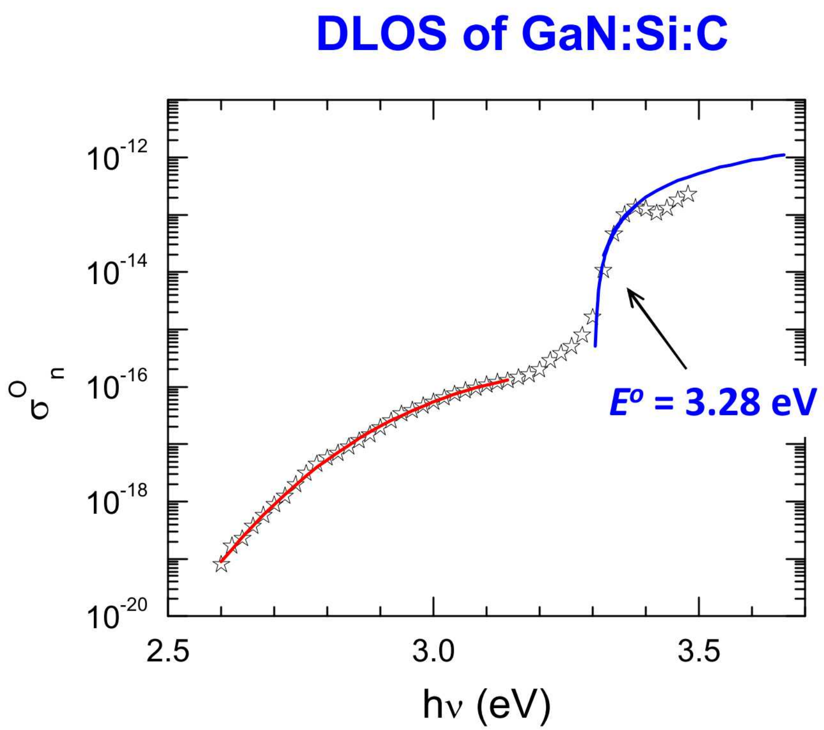
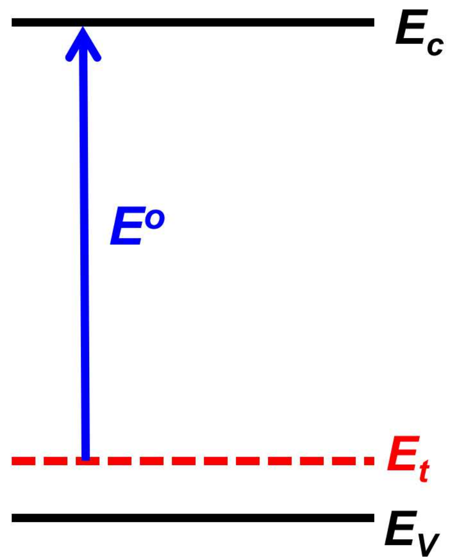
Lucovsky, Solid State Commun. 3, 299 (1965)

Interpretation of DLOS spectra





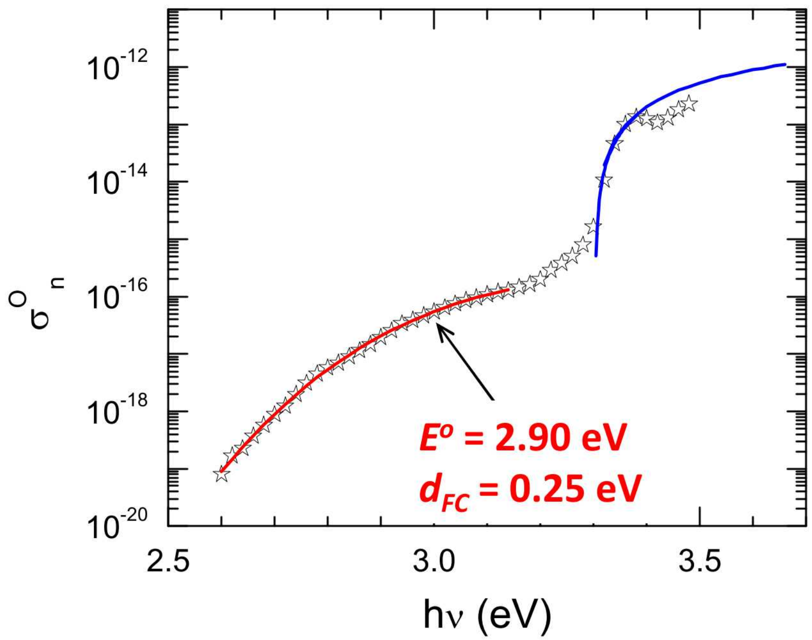
Armstrong et al, APL 84, 374 (2004)

Chantre, et al., PRB 23, 5335 (1981)

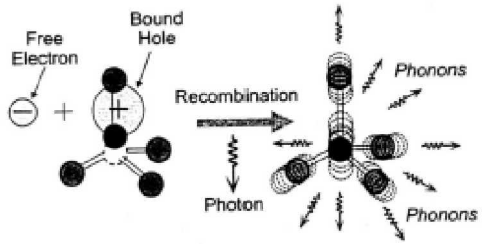
Lucovsky, Solid State Commun. 3, 299 (1965)

Interpretation of DLOS spectra

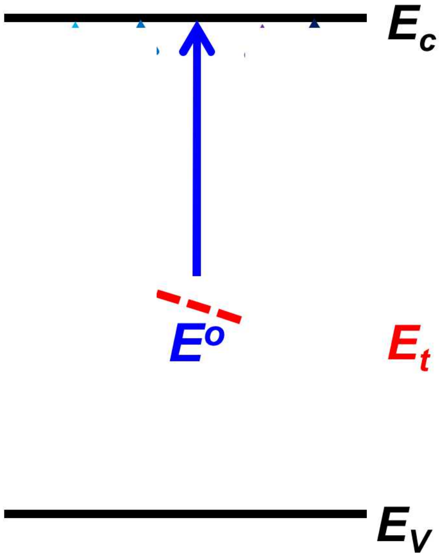
DLOS of GaN:Si:C



Armstrong et al, APL 84, 374 (2004)



M. A. Reshchikov JAP 97 061301 2005

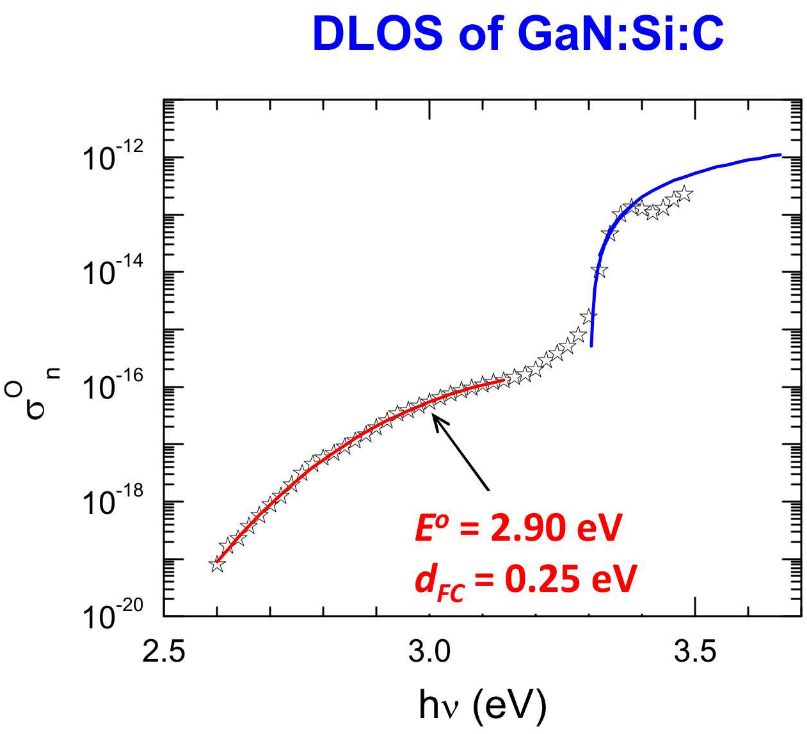


Andr

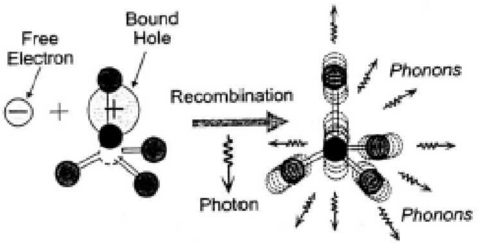
Chantre, et al., PRB 23, 5335 (1981)

Lucovsky, Solid State Commun. 3, 299 (1965)

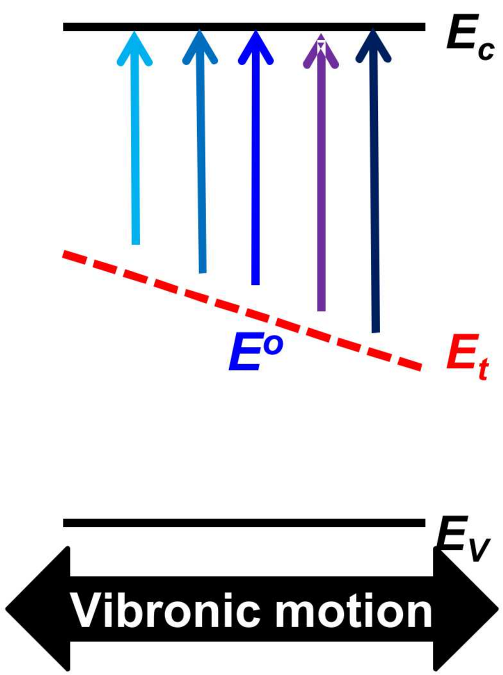
Interpretation of DLOS spectra



Armstrong et al, APL 84, 374 (2004)



M. A. Reshchikov JAP 97 061301 2005



Quantify E^o for sharp and broad defect absorption spectra

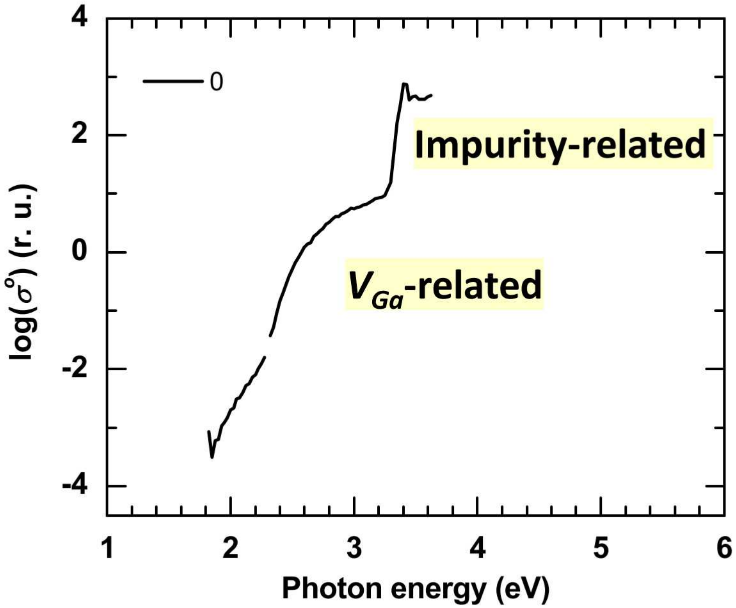
Andr

Chantre, et al., PRB 23, 5335 (1981)

Lucovsky, Solid State Commun. 3, 299 (1965)

Understand role of deep level defects

DLOS spectra vs. Al mole fraction



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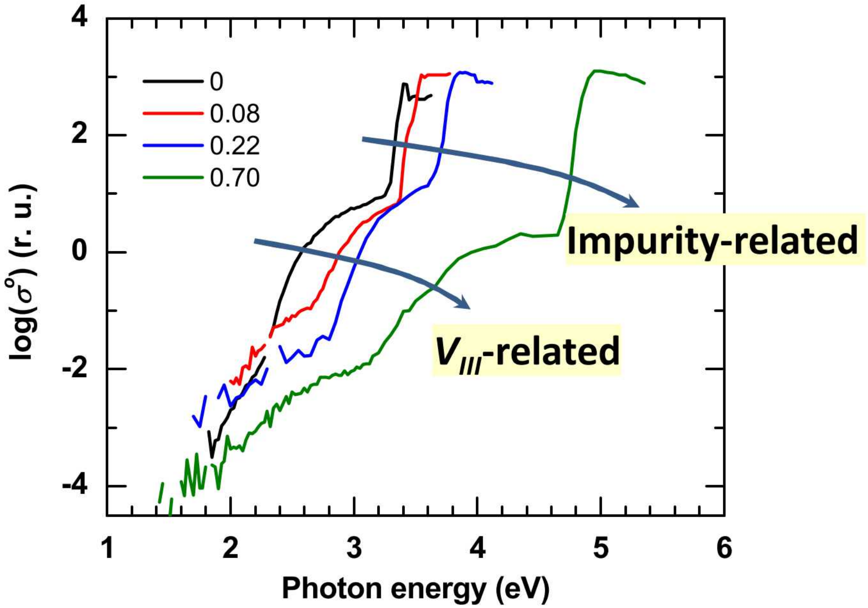
Understand role of deep level defects

DLOS spectra vs. Al mole fraction



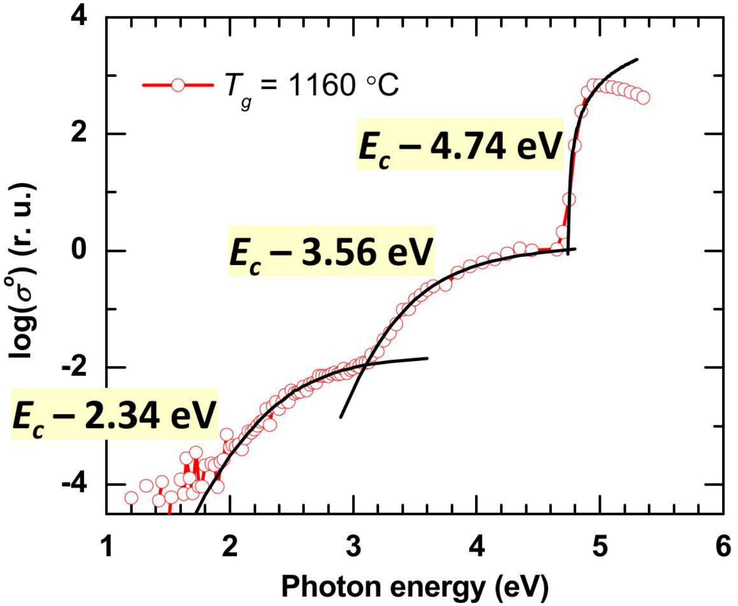
- V_{III}-related and near-E_v impurity states dominate
- Quantify defect density to assess impact on doping efficacy

Andrew Armstrong - aarmstr@sandia.gov

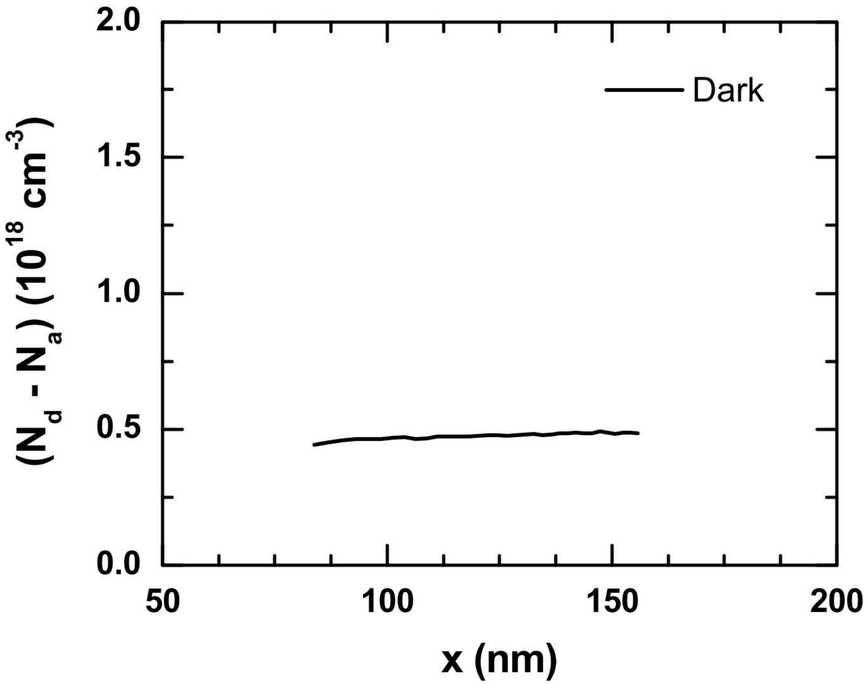
T. A. Henry, A. Armstrong,[a] A. A. Allerman, and M. H. Crawford
APPLIED PHYSICS LETTERS 100, 043509 (2012)

Lighted Capacitance-Voltage identifies compensators

DLOS of n-$Al_{0.7}Ga_{0.3}N$ for T_g = 1160 °C



LCV of n-$Al_{0.7}Ga_{0.3}N$ for T_g = 1160 °C

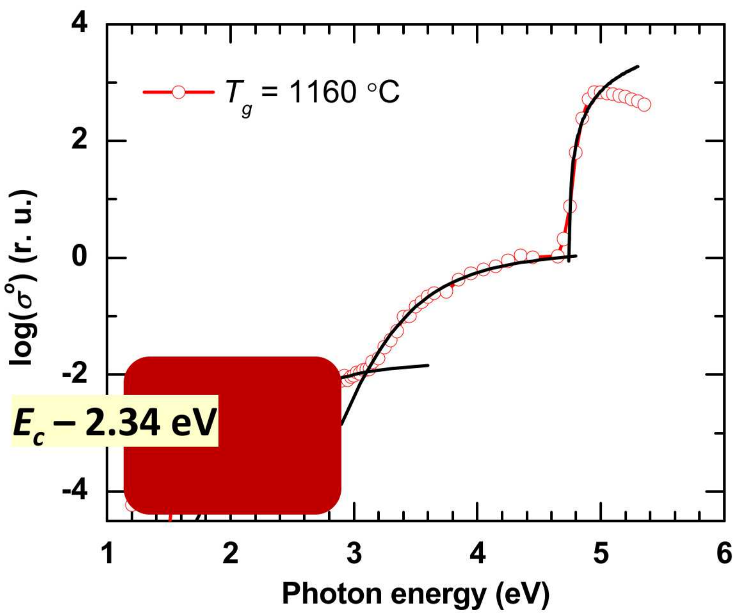


- Deep level defect too large to measure in usual manner (*a la* DLTS)
- Lighted Capacitance-Voltage (LCV) measures defect density (N_t)
- $N_t = \Delta(N_d - N_a)$ measured by CV under sub-gap, monochromatic illumination

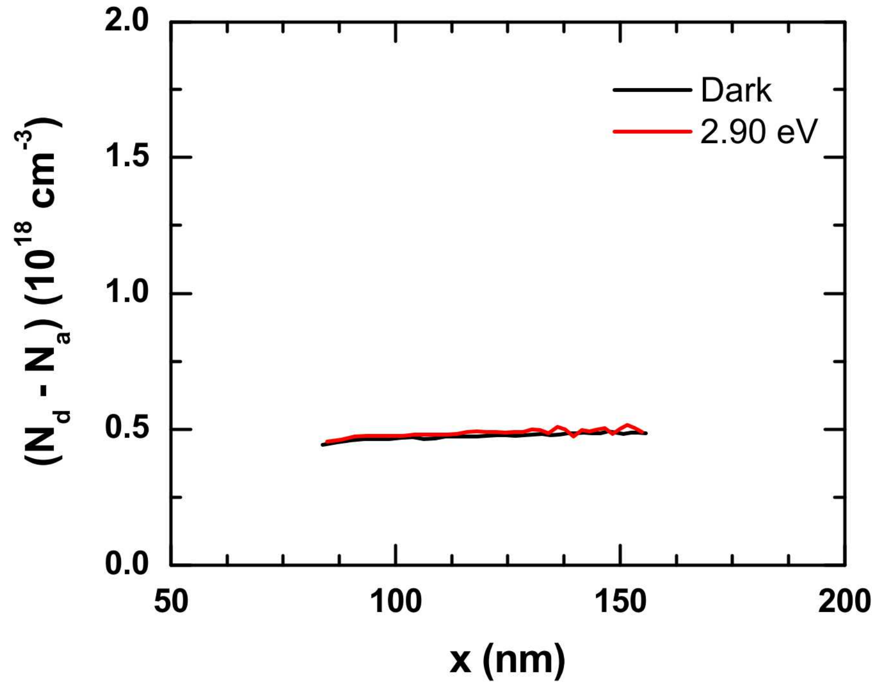
Andrew Armstrong - aarmstr@sandia.gov

Lighted Capacitance-Voltage identifies compensators

DLOS of n-$Al_{0.7}Ga_{0.3}N$ for T_g = 1160 °C



LCV of n-$Al_{0.7}Ga_{0.3}N$ for T_g = 1160 °C



- E_c – 2.34 eV level is not a strong compensation center

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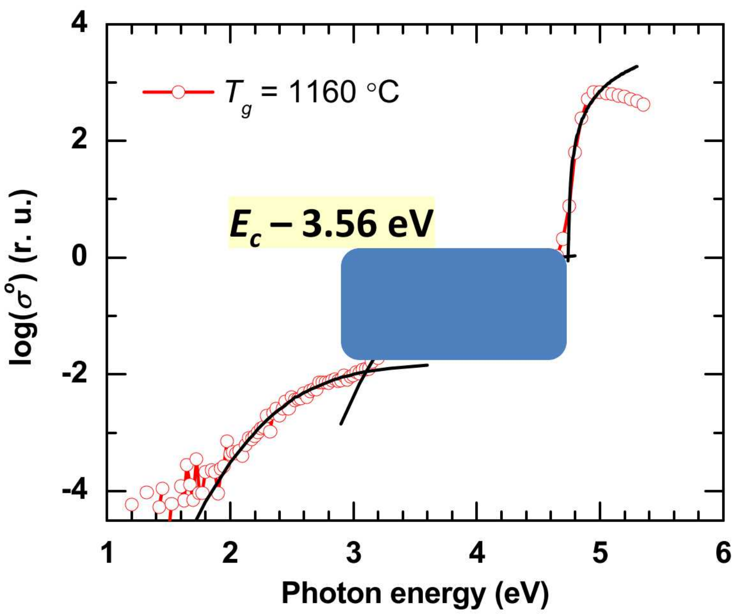
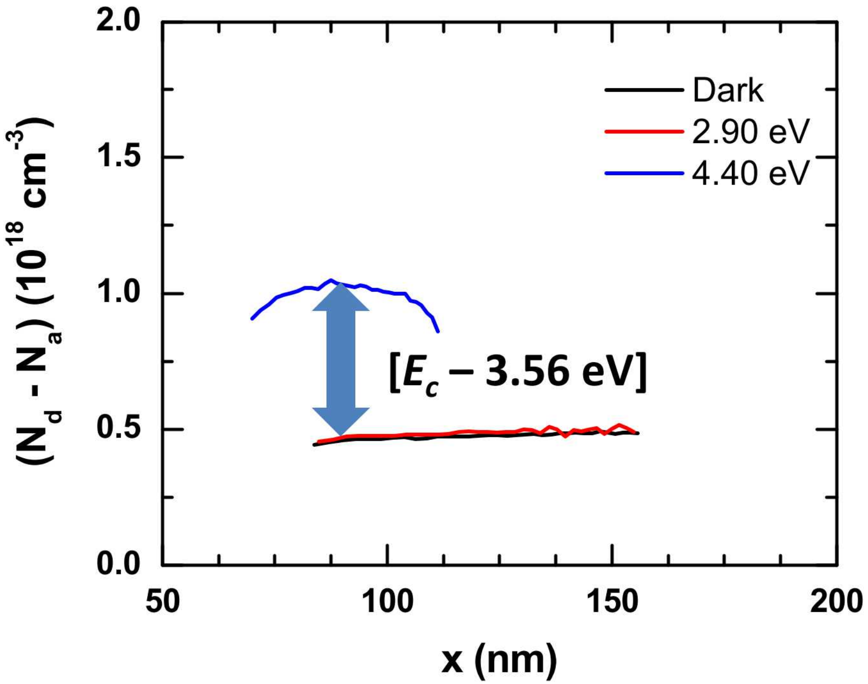
Lighted Capacitance-Voltage identifies compensators

DLOS of n-$Al_{0.7}Ga_{0.3}N$ for T_g = 1160 °C



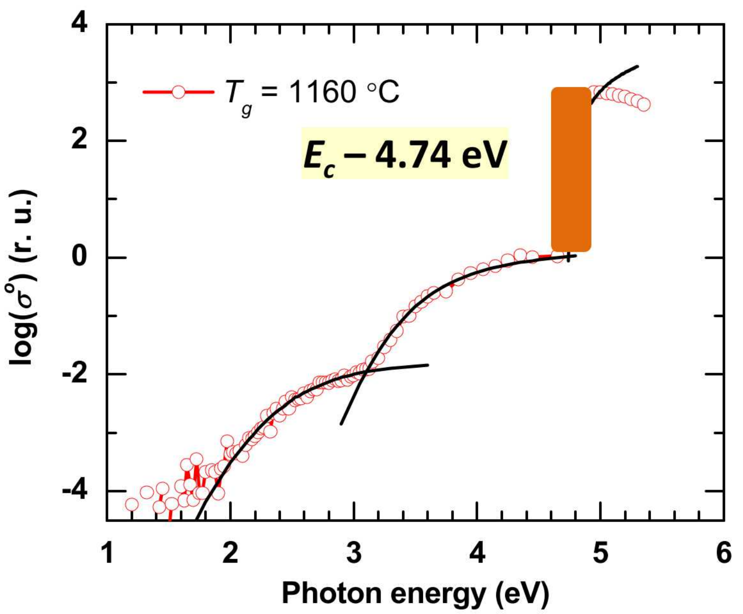
LCV of n-$Al_{0.7}Ga_{0.3}N$ for T_g = 1160 °C



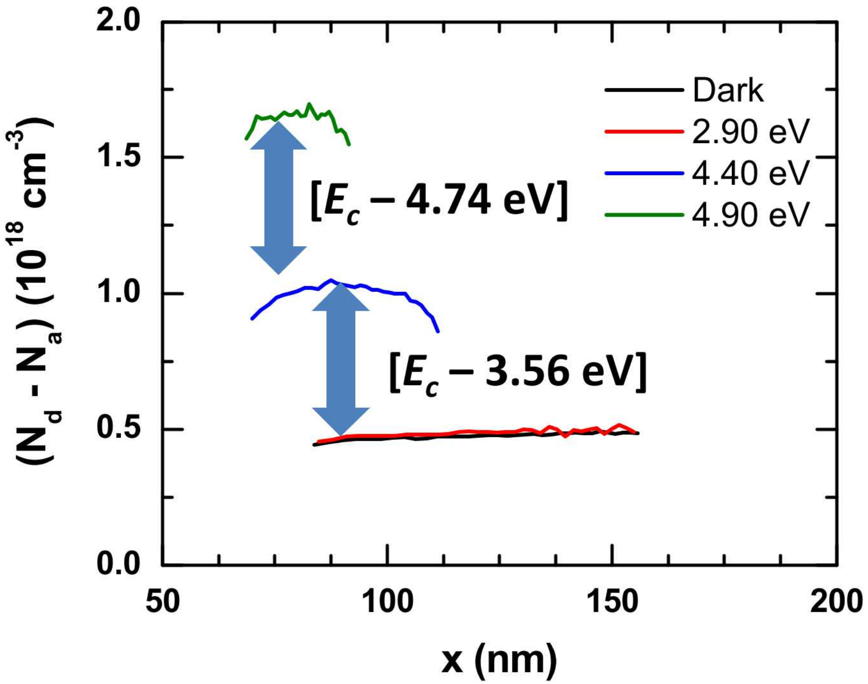
Andrew Armstrong - aarmstr@sandia.gov

Lighted Capacitance-Voltage identifies compensators

DLOS of n-$Al_{0.7}Ga_{0.3}N$ for T_g = 1160 °C



LCV of n-$Al_{0.7}Ga_{0.3}N$ for T_g = 1160 °C



- E_c – 3.56 eV and E_c – 4.74 eV defects are dominant compensating centers

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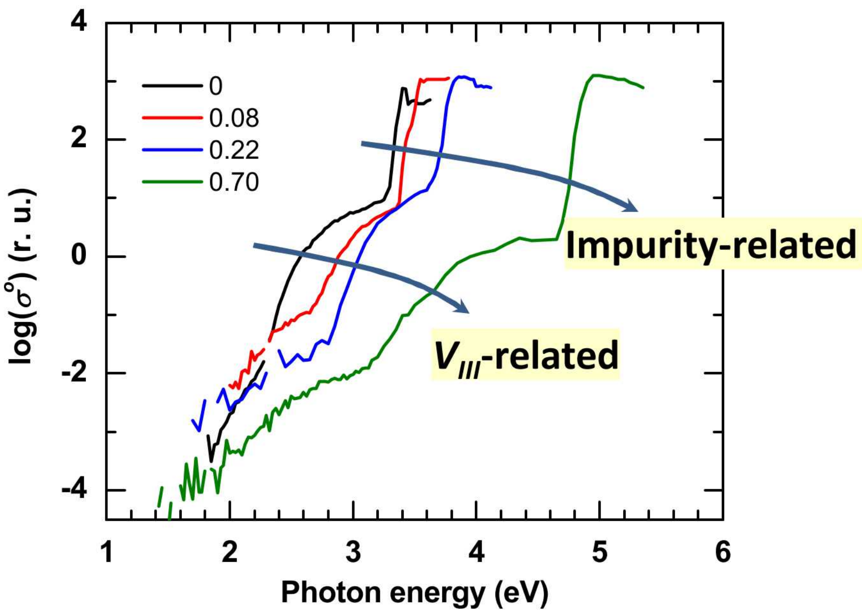
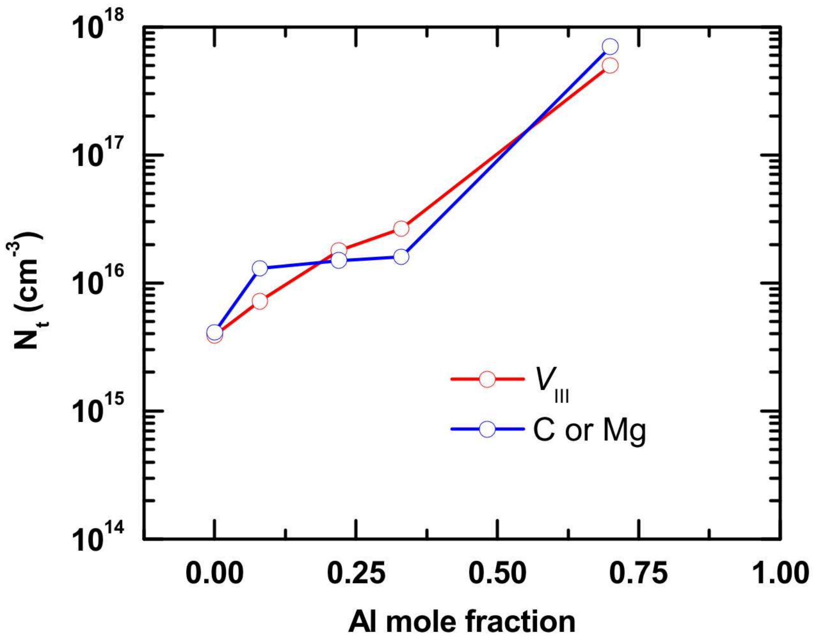
Understand role of deep level defects

DLOS spectra vs. Al mole fraction



AlGaN deep level defect density vs. *x*



- V_{III}-related and near-E_v impurity states dominate
- General trend of increasing deep level defect density with increasing Al
- 75% compensation of Si doping level (2×10^{18} cm^{-3})

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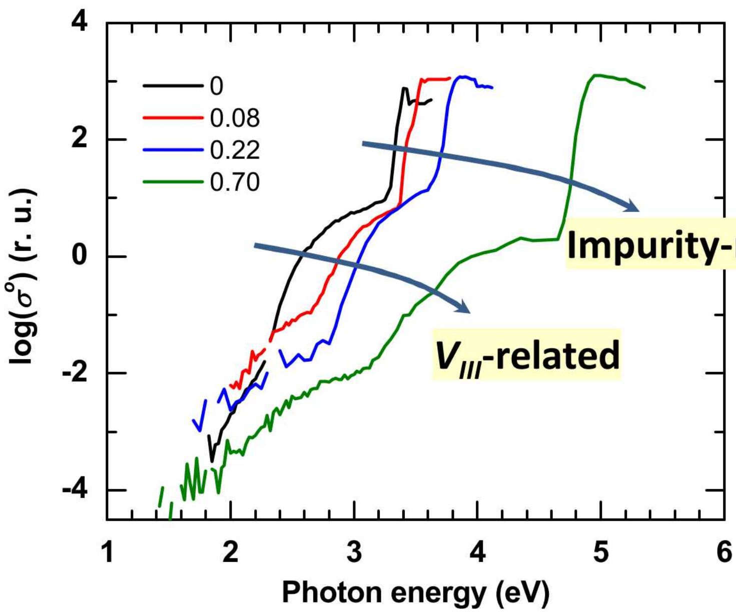
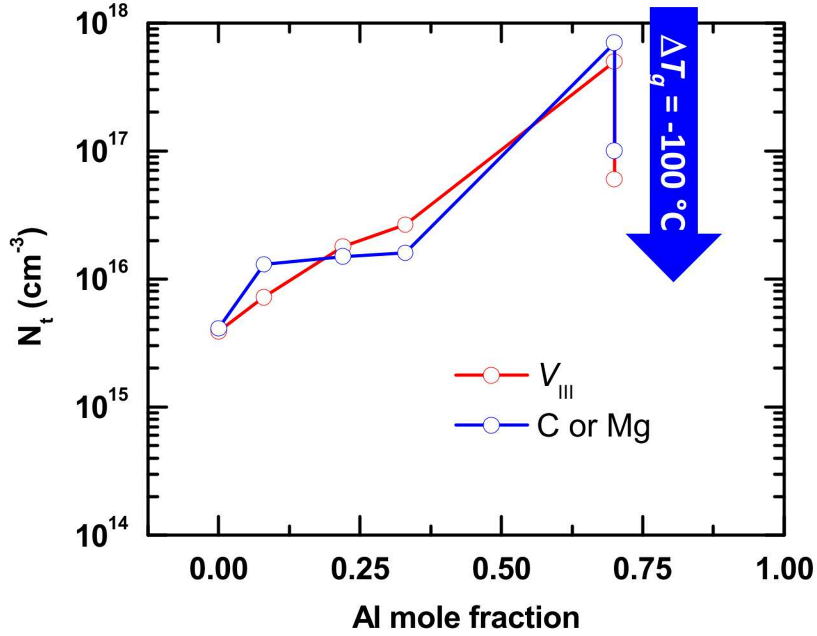
T. A. Henry, A. Armstrong,[a] A. A. Allerman, and M. H. Crawford
APPLIED PHYSICS LETTERS 100, 043509 (2012)

Understand role of deep level defects

DLOS spectra vs. Al mole fraction



AlGaN deep level defect density vs. *x*



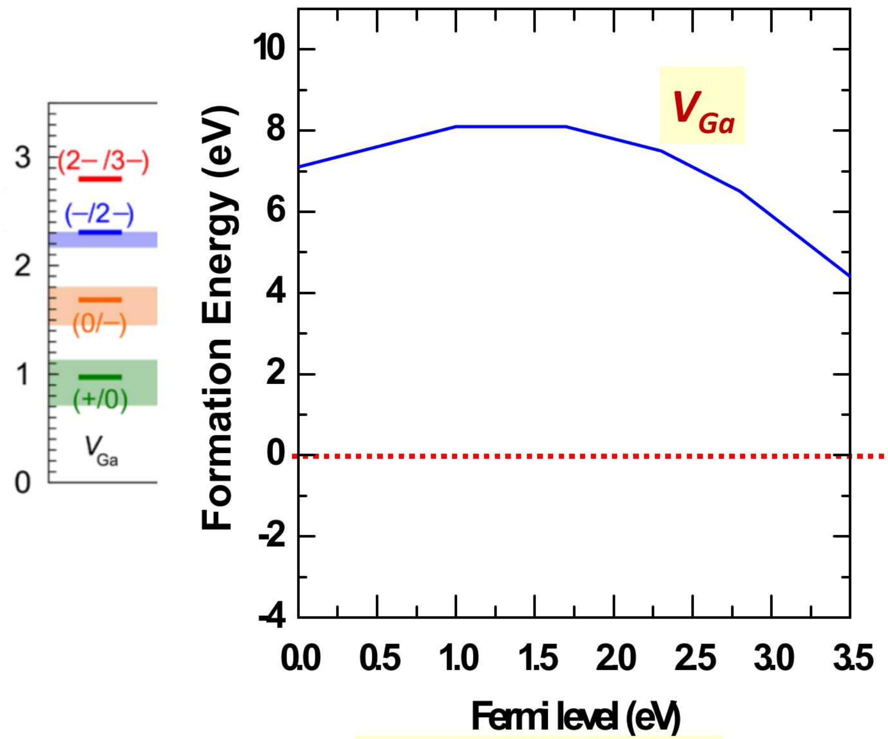
➢ Large reduction in T_g improves doping efficacy through defect reduction

Andrew Armstrong - aarmstr@sandia.gov

T. A. Henry, A. Armstrong,[a] A. A. Allerman, and M. H. Crawford
APPLIED PHYSICS LETTERS 100, 043509 (2012)

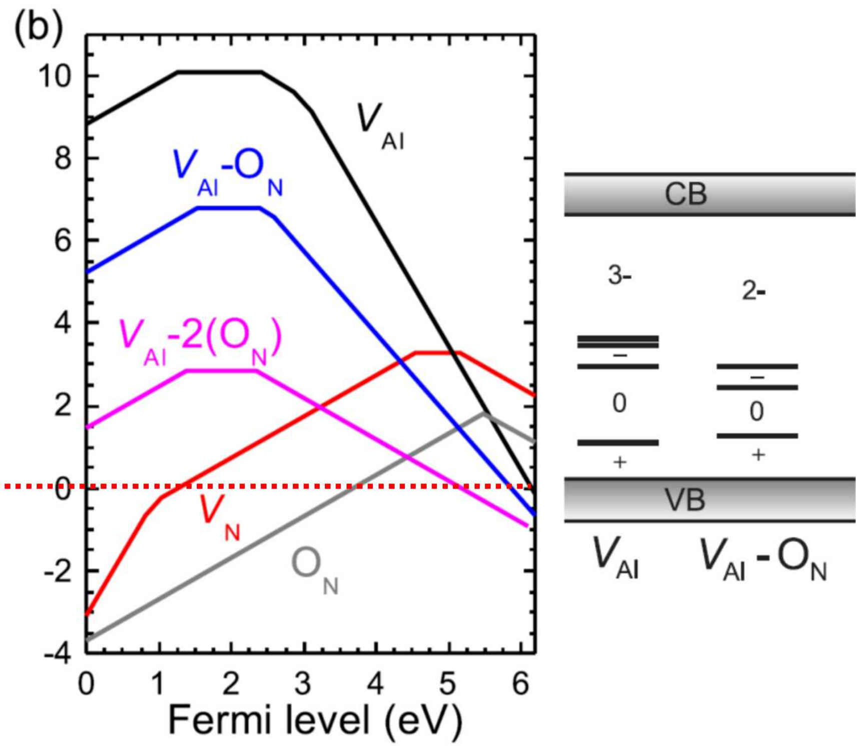
UWBGs self-compensate by native defect formation

V_{Ga} defect formation in GaN



Lyons *et al*. PSS B 252 900 (2015)

V_{Al} defect formation in AlN



Yan *et al*. APL 105 111104 (2014)

- Compensating defect formation energy reduced by ~ E_g
- Defect formation pins E_F and completely compensates dopants

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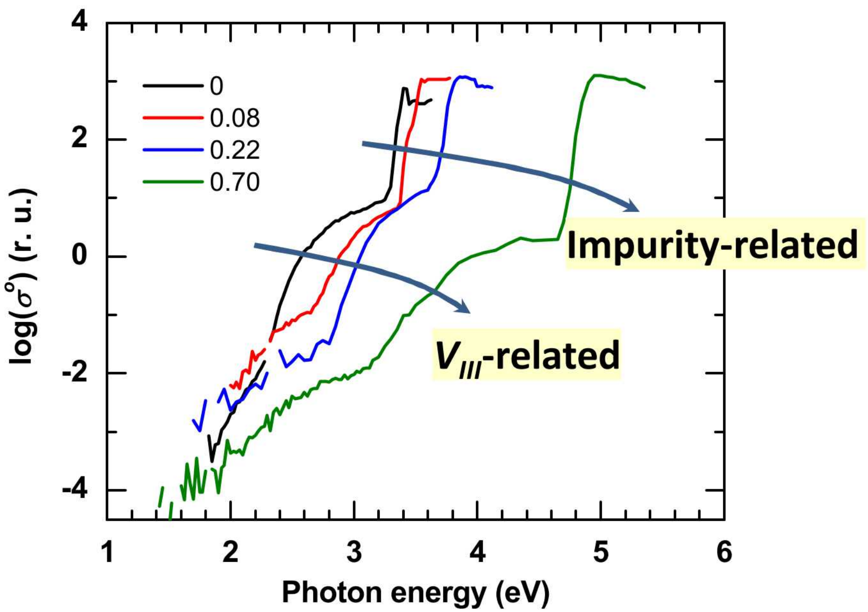
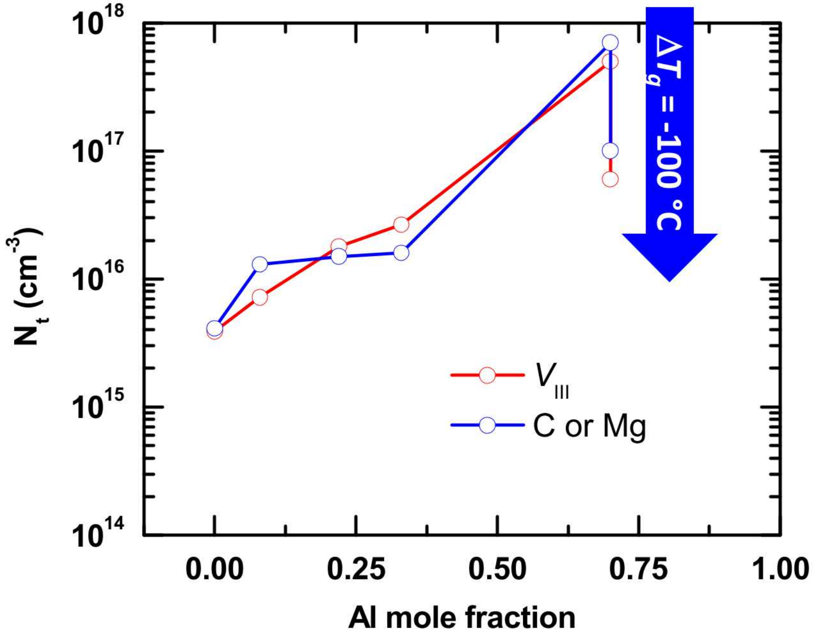
Understand role of deep level defects

DLOS spectra vs. Al mole fraction



AlGaN deep level defect density vs. Al



- Large reduction in T_g improves doping efficacy through defect reduction
- Deep level defects are managed for Al < 0.8 by optimized growth conditions
- What about Al > 0.8?

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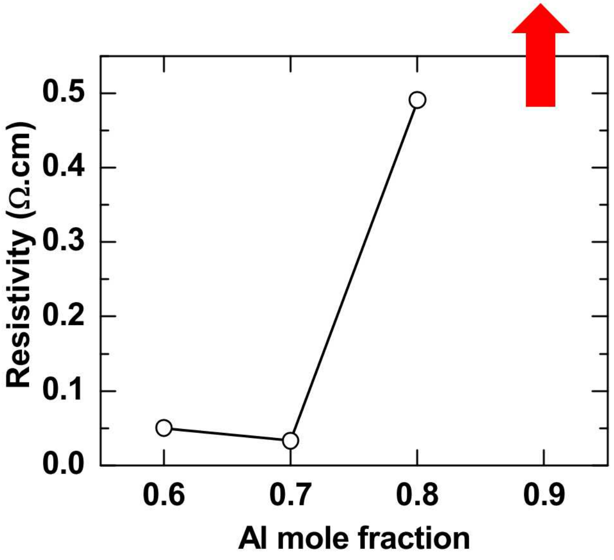
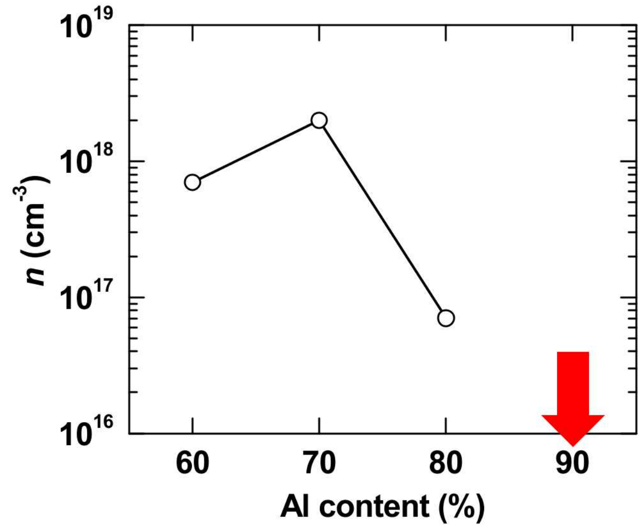
T. A. Henry, A. Armstrong,[a] A. A. Allerman, and M. H. Crawford
APPLIED PHYSICS LETTERS 100, 043509 (2012)

Understand role of deep level defects

SNL AlGaN resistivity vs. Al



SNL AlGaN *n* vs. Al



- Studied AlGaN:Si Al composition series from 60 – 90%
- Conductivity collapse due to decrease in free electrons
- Shallow-to-deep dopant transition or increasing compensation by defects?

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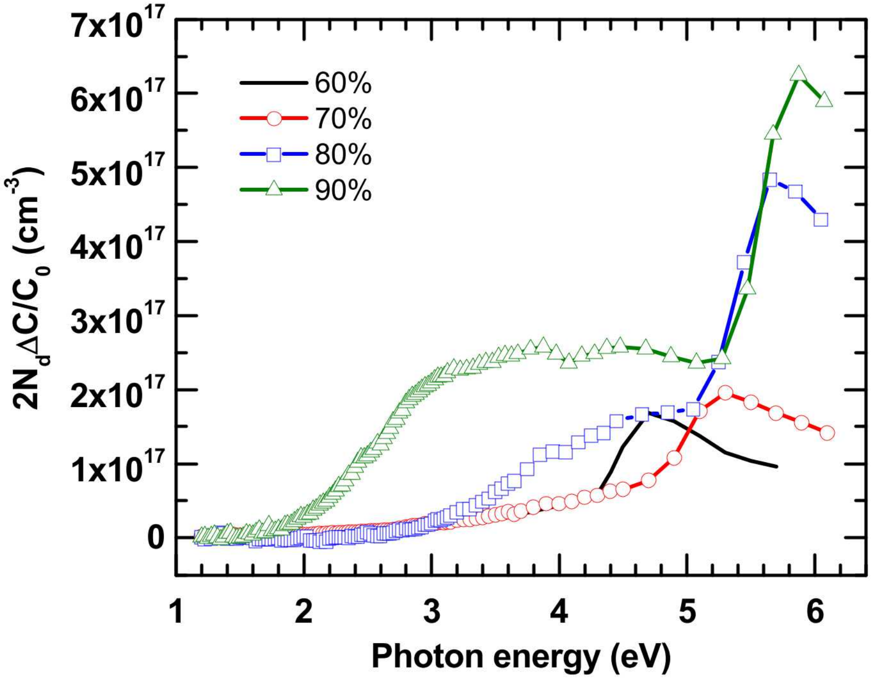
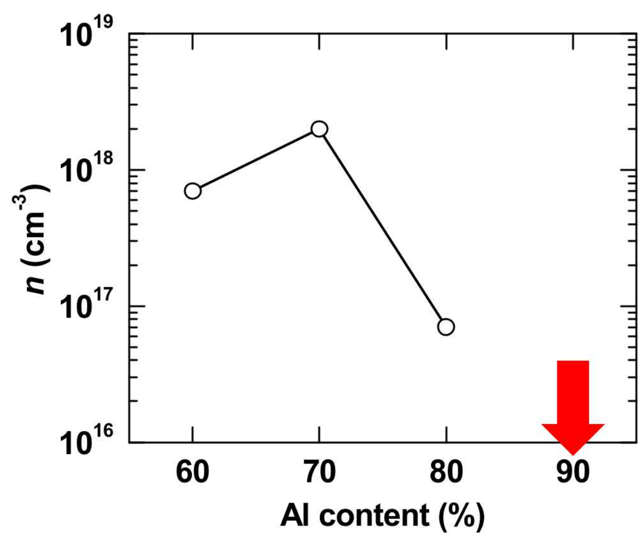
Understand role of deep level defects

AlGaN deep level defects vs. Al



SNL AlGaN *n* vs. Al



- Deep level defect density increases strongly with increasing Al
- Not sufficient to account for > 2×10^{18} cm-3 reduction in *n*
- Conductivity collapse due to Si *DX* transition to a deep dopant

Andrew Armstrong - aarmstr@sandia.gov

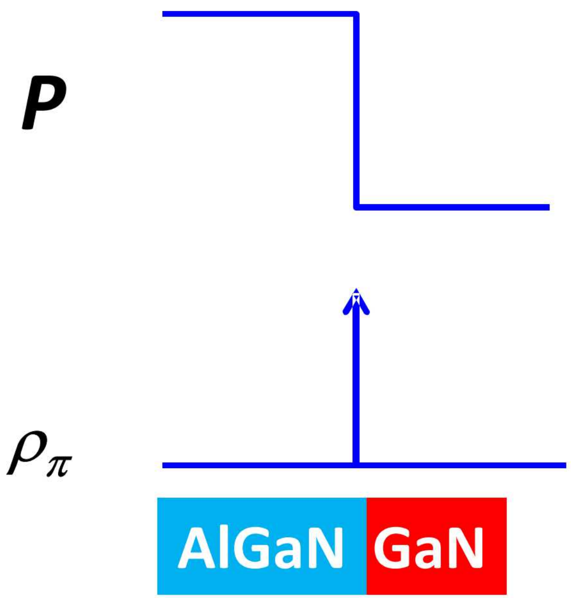
Outline

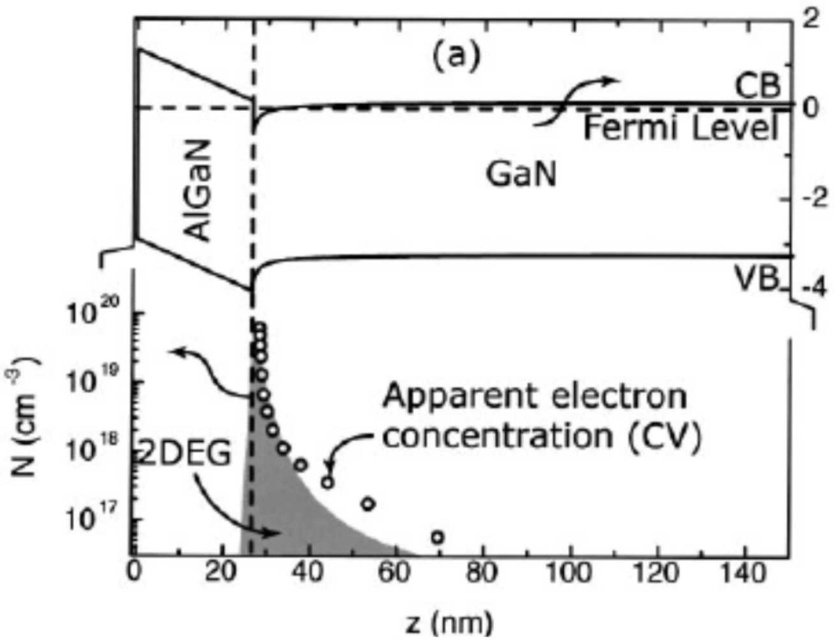
- Ultra-wide band gap (UWBG) AlGaN: Needs and opportunities
- Wide band gap GaN has achieved its fundamental material limit
- Mechanism for conductivity collapse in UWBG AlGaN
- **Electrically functionalizing UWBG AlGaN**
- UV-C opto-electronics of UWBGs

Andrew Armstrong - aarmstr@sandia.gov

How to overcome UWBG AlGaN deep dopant problem?

$$\rho_\pi = \nabla \cdot \boldsymbol{P}$$





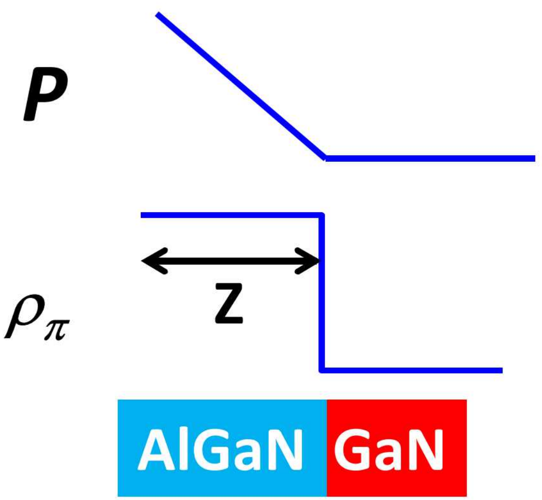
Jena et al APL 81 4395 2002

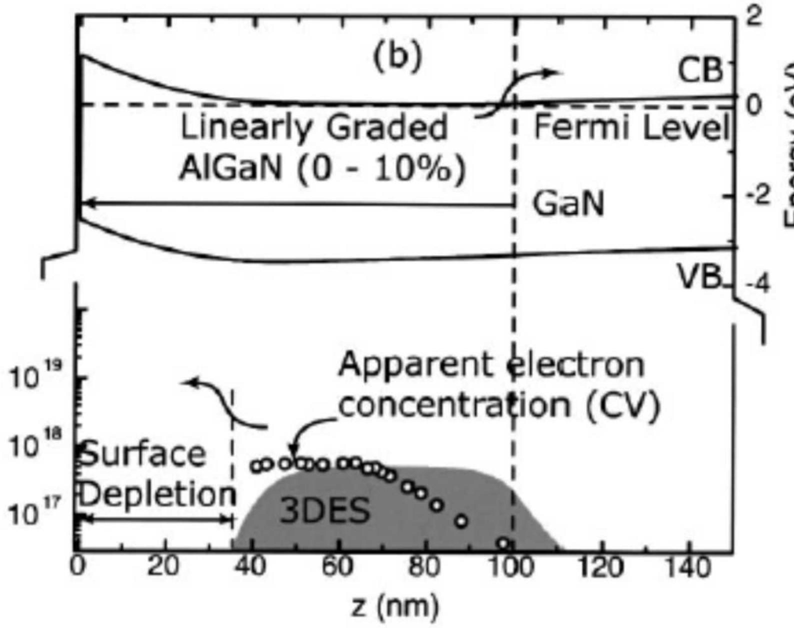
- Strong AlGaN piezoelectricity due to ionicity and non-centro-symmetric lattice
- Abrupt heterostructures induce dopant-free 2DEG

Andrew Armstrong - aarmstr@sandia.gov

AlGaN/GaN system operative without impurity dopants

$$\rho_\pi = \Delta P / z$$





Jena et al APL 81 4395 2002

- Generalize concept to form a three-dimensional electron gas (3DES)
  - Linear grade in Al composition spreads 2DEG evenly over a volume
- Acts like uniform impurity doping with zero thermal ionization energy

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Investigate polarization-doping in graded UWBG AlGaN

Graded 80 – 90% AlGaN

200 nm UID-graded AlGaN
$Al_{0.8}Ga_{0.2}N \rightarrow Al_{0.9}Ga_{0.1}N$

0.5 μm UID-$Al_{0.8}Ga_{0.2}N$

AlN on sapphire

R_{sh} = 20,000 $\Omega/\square$

Graded 80 – 100% AlGaN

200 nm UID-graded AlGaN
$Al_{0.8}Ga_{0.2}N \rightarrow AlN$

0.5 μm UID-$Al_{0.8}Ga_{0.2}N$

AlN on sapphire

R_{sh} = 2500 $\Omega/\square$

$Al_{0.86}Ga_{0.14}N$

700 nm UID-$Al_{0.86}Ga_{0.14}N$

AlN on sapphire

R_{sh} > 100,000 $\Omega/\square$

- Sheet resistance of graded AlGaN indicates strong electrical conductivity
- Sheet resistance decreases with more abrupt grade, as expected
- UID-$Al_{0.86}Ga_{0.14}N$ control sample showed no electrical conductivity

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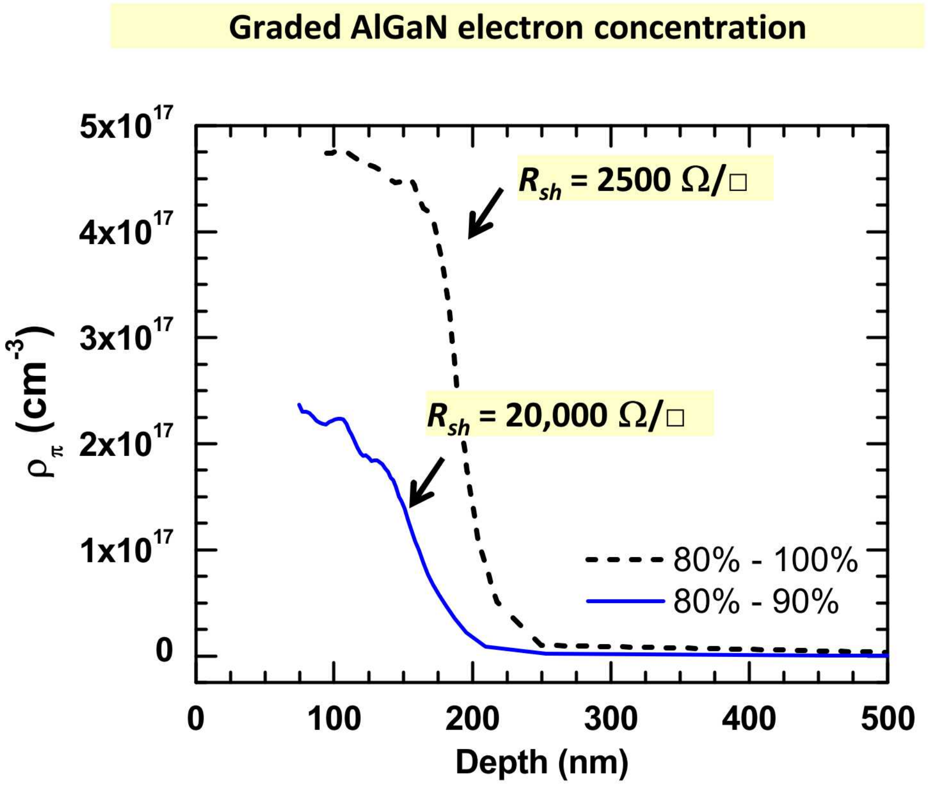
Highly conductive UID graded UWBG AlGaN behaves as expected

Graded AlGaN electron concentration



- Uniform polarization-doping scales with Al grade
- Confirm expected 200 nm range of polarization-induced doping
- Comparison of ρ_π and R_{sh} indicates μ is a strong function of Al composition

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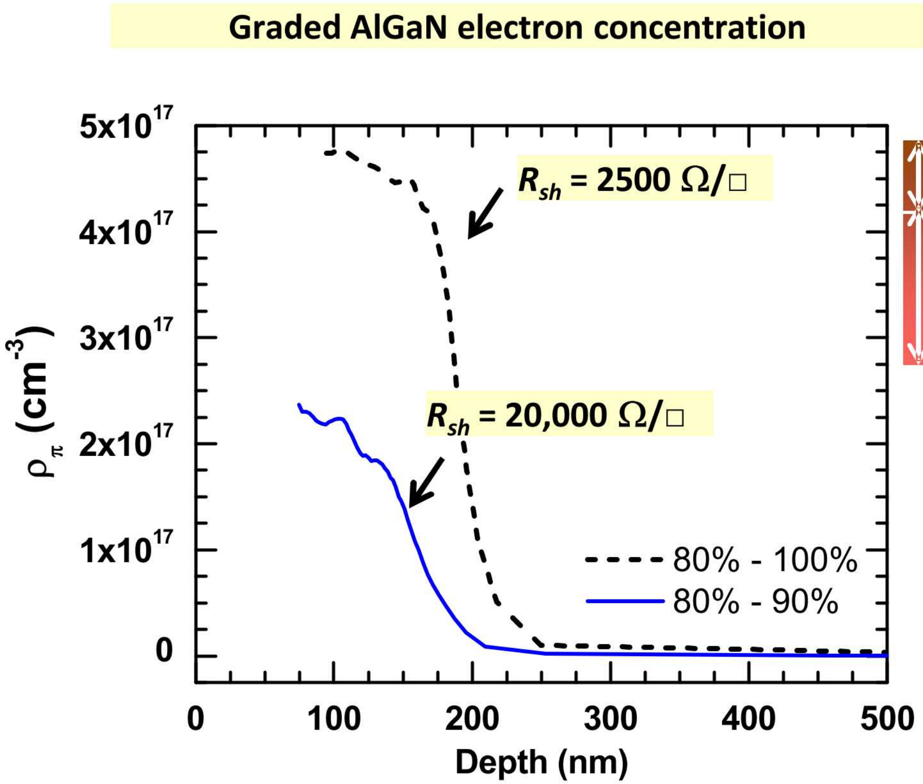
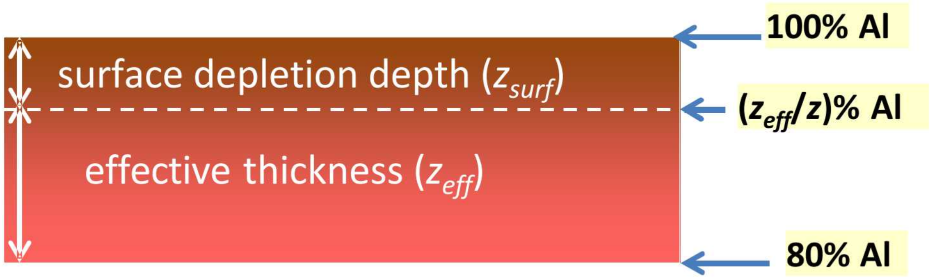
Calculate electron mobility vs. Al composition

Graded AlGaN electron concentration





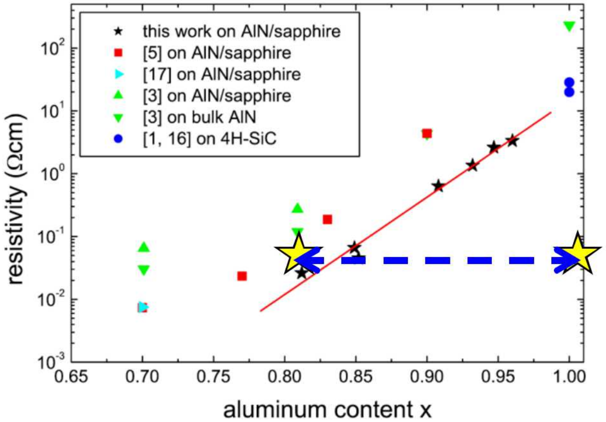
$$\bar{\mu} = \frac{1}{qR_{sh}z_{eff}n}$$

- Account for surface depletion assuming 1 eV surface potential
- $\bar{\mu}_{80\%\text{-}96\%}$ = 331 $cm^{-2}V^{-1}s^{-1}$ and $\bar{\mu}_{80\%\text{-}87\%}$ = 105 $cm^{-2}V^{-1}s^{-1}$
- Weighted average of mobility ranges gives $\bar{\mu}_{88\%\text{-}96\%}$ = 509 $cm^{-2}V^{-1}s^{-1}$

Andrew Armstrong - aarmstr@sandia.gov

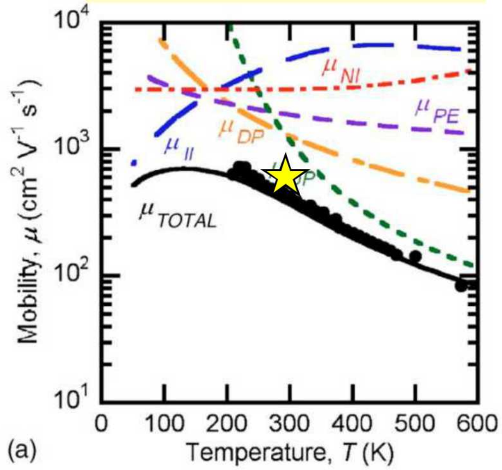
UWBG graded AlGaN electronic properties exceed homoepitaxial AlN

AlGaN resistivity



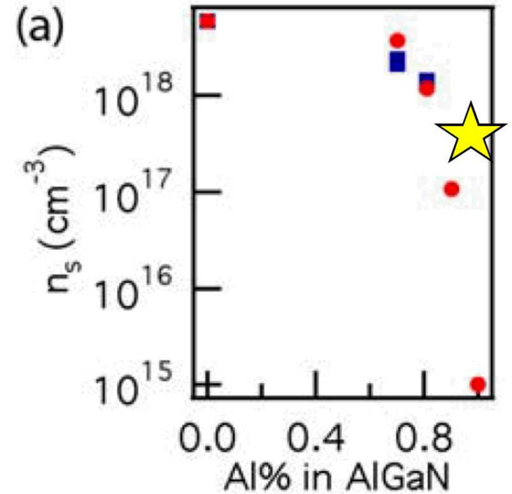
Mehnke *et al*. APL 103 212109 (2013)

homoepitaxial AlN mobility



Taniyasu *et al*. APL 89 182112 (2006)

homoepitaxial AlN electron concentration



Collazo *et al*. pss(c) 8 2031 (2011)

- Resistivity, *n*, and $\overline{\mu}$ values are highest reported for $Al_xGa_{1-x}N$ for *x* > 0.85 at 300K
- Graded UID-AlGaN electronic properties exceed those of homoepitaxial AlN:Si

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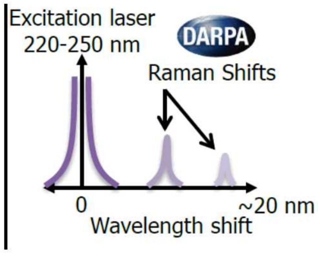
Outline

- Ultra-wide band gap (UWBG) AlGaN: Needs and opportunities
- Wide band gap GaN has achieved its fundamental material limit
- Mechanism for conductivity collapse in UWBG AlGaN
- Electrically functionalizing UWBG AlGaN
- **UV-C opto-electronics of UWBGs**

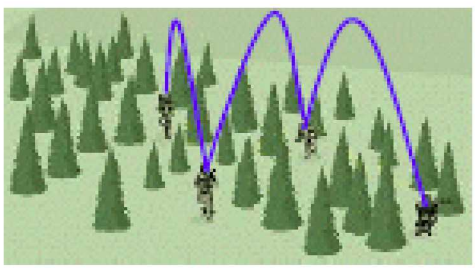
Andrew Armstrong - aarmstr@sandia.gov

UWBG solutions to UV-C technology gaps

Raman Spectroscopy
(biological agents)

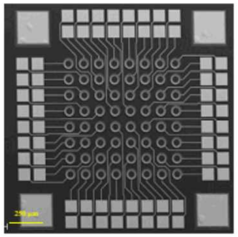


Non-line of sight communication
(covert radio)



Solar-blind detection
(missile launch, sniper fire)

Benchtop → **Man-portable** → **Microelectronic**



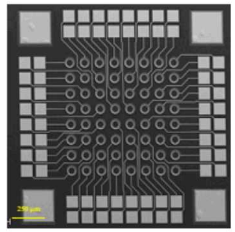
- ➢ Miniaturization and efficiency are key technology drivers
- ➢ UWBGs can provide both

Andrew Armstrong - aarmstr@sandia.gov

UWBGs for single photon solar-blind detectors

Technology and Systems Goals

Portable to wearable NLOS

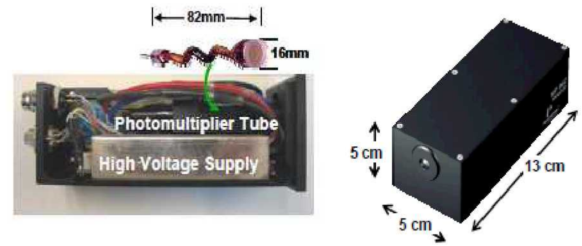


μ-UAS bio-chem locators

Technology and Systems Challenges

Photomultiplier Tubes (PMTs)

High Voltage = Large



Si Avalanche Photodiodes (APDs)

Parameter	Hamamatsu S10362-11 Series Device Suffix			
	-025C	-050C	-100C	
Physical area	1x1	1x1	1x1	mm
Number pixels	40x40	20x20	10x10	
Pixel size	25	50	100	µm
Fill factor	30.8	61.5	78.5	%
SPDE at 400nm	25	50	65	%
SPDE at 270nm	8	12	20	%

Cryogenic

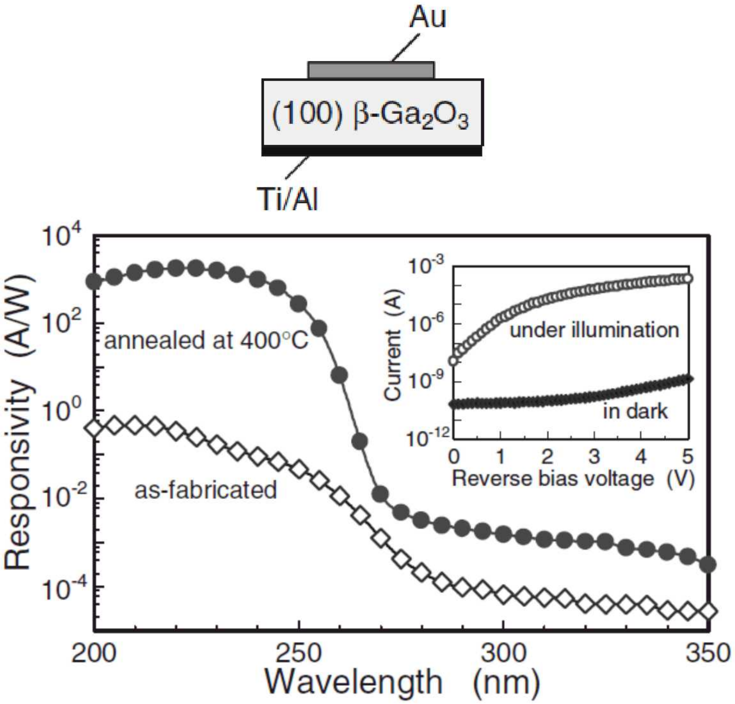
Expensive (~$20K) optical filters

Proc SPIE 7320 1 2009

Andrew Armstrong - aarmstr@sandia.gov

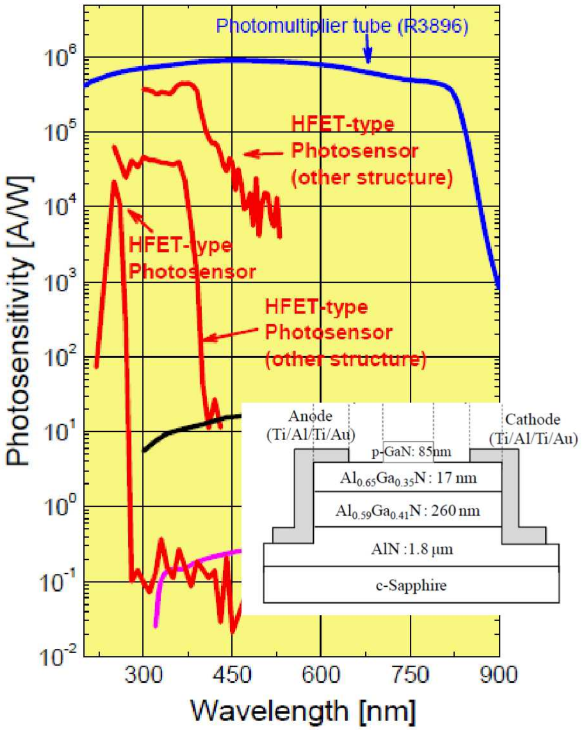
New UWBG solar-blind photodetector capabilities

β-Ga_2O_3 Schottky diode



Suzuki et al. APL 94, 222102 (2009).

UWBG AlGaN HEMT



Iwaya MetaNano14

- UWBG solar-blind detectors can be low voltage (small), non-avalanche (low dark count), filter-free (inexpensive), non-cryogenic (robust)
- Pathway toward ubiquitous, unobtrusive/clandestine, multi-vector threat detection

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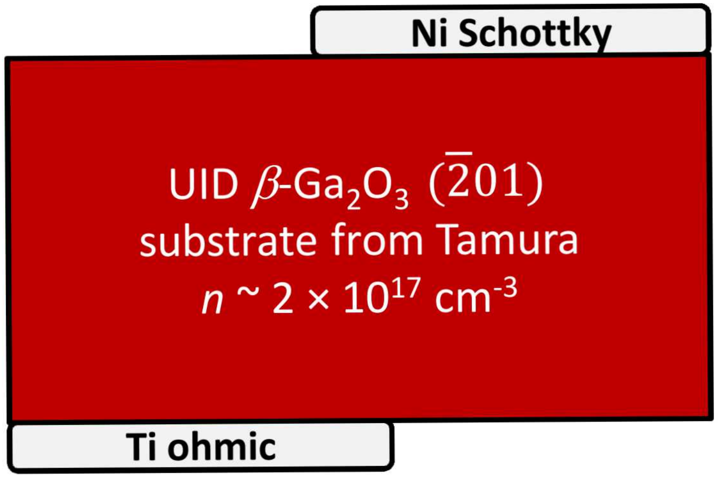
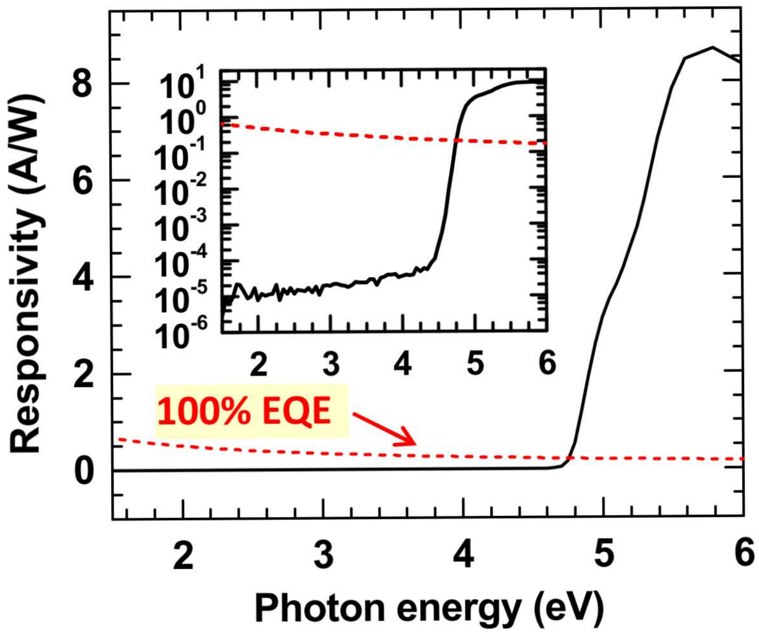
Strong β-Ga_2O_3 Schottky diode photoconductive gain



Spectral Photoresponse



- Solar rejection-ratio > 10^5
- Peak optical gain > 50x
- Strong optical gain not expected for Schottky diodes
  - Attributed to Schottky metal-induced gap states*

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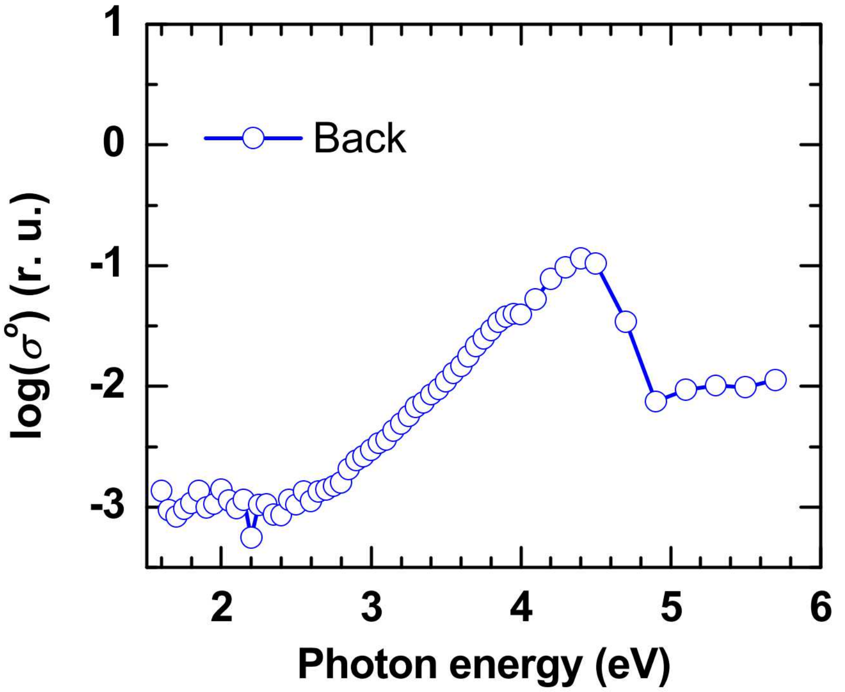
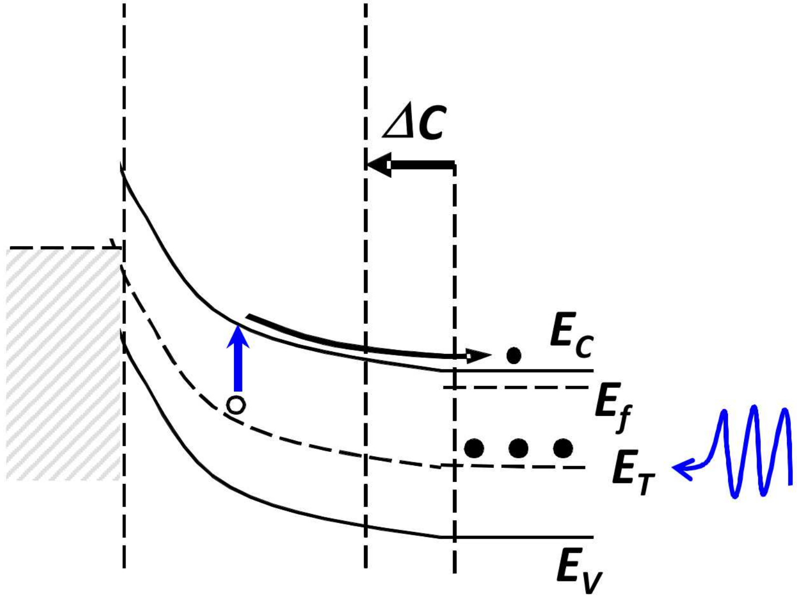
*R. Suzuki et al., APL 94 222102 (2009).

Defects and hole localization

Deep Level Optical Spectroscopy





➢ Backside: DLOS only senses deep level defects

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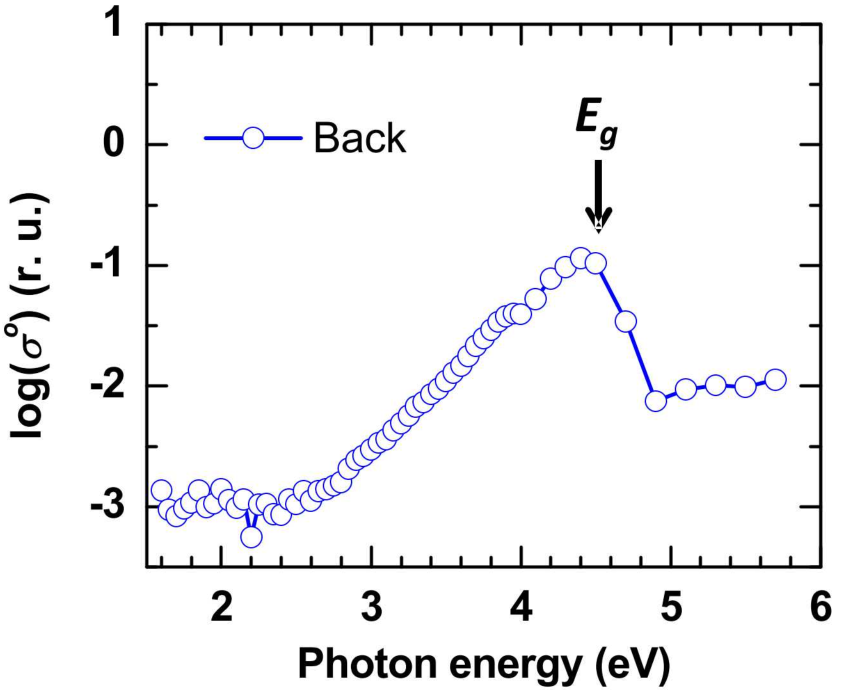
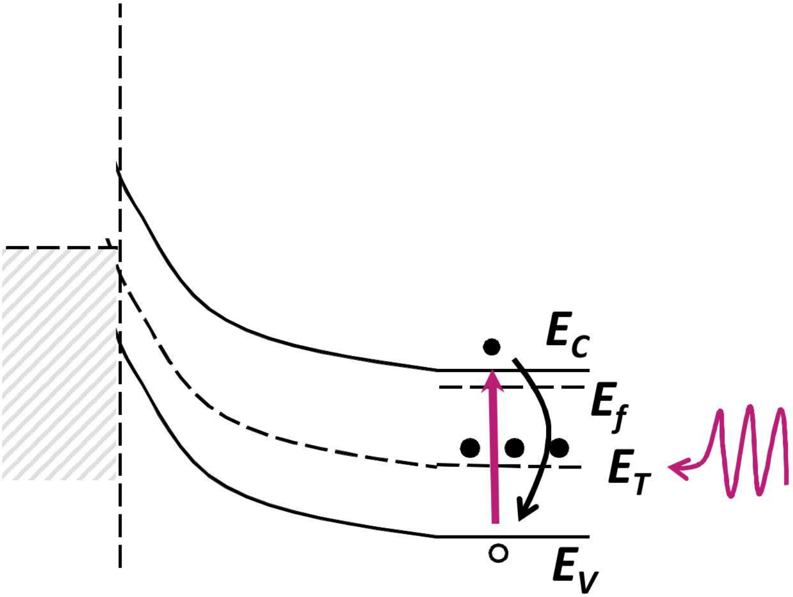
Defects and hole localization

Deep Level Optical Spectroscopy





➢ Backside: DLOS only senses deep level defects

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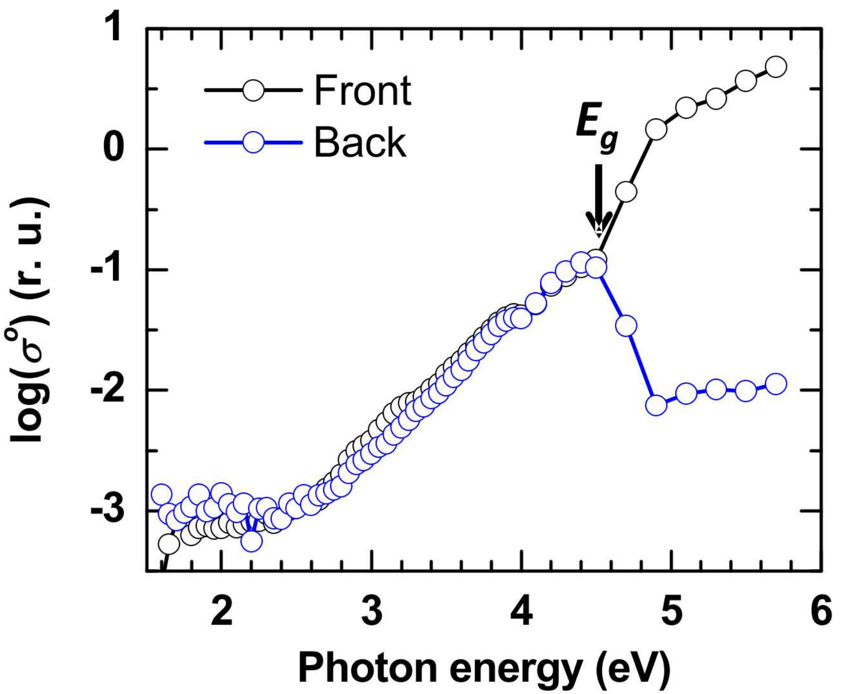
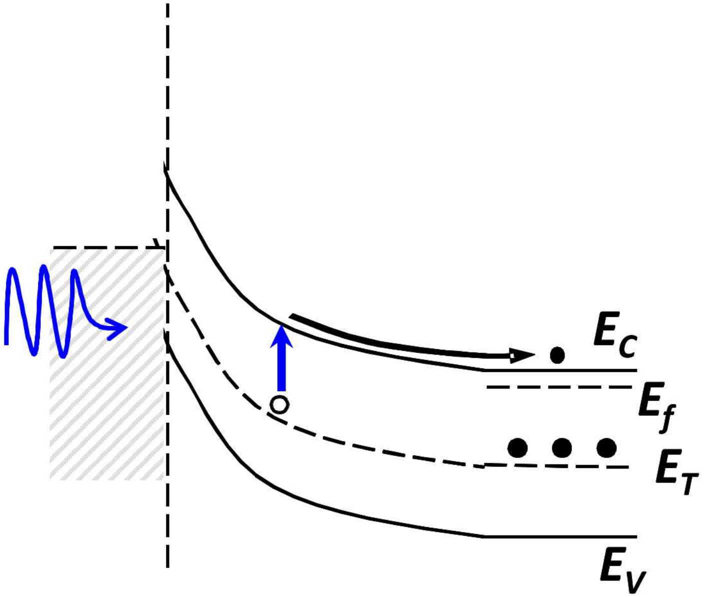
Defects and hole localization

Deep Level Optical Spectroscopy





- Backside: DLOS only senses deep level defects
- Frontside: DLOS shows hole localization for above-gap illumination

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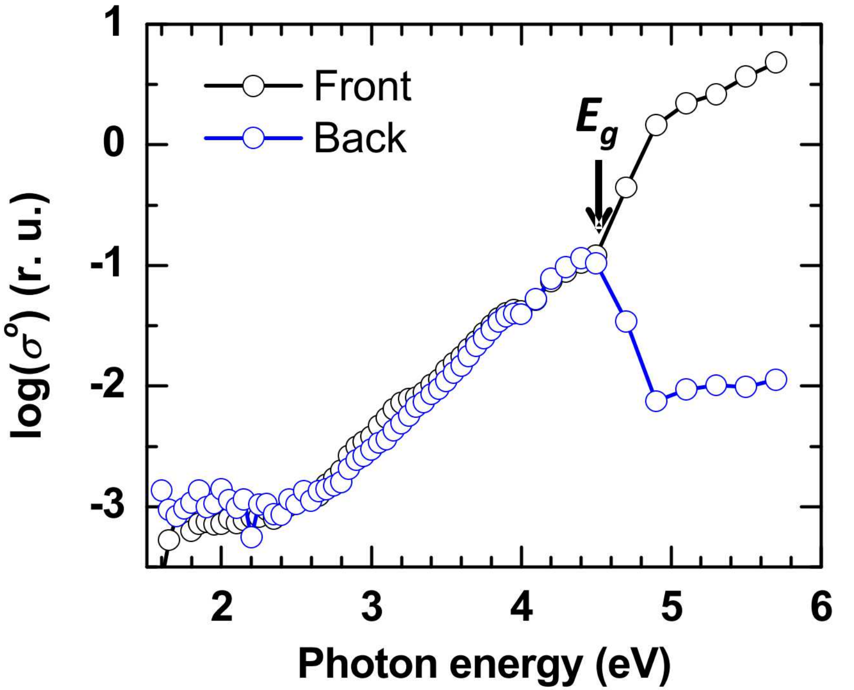
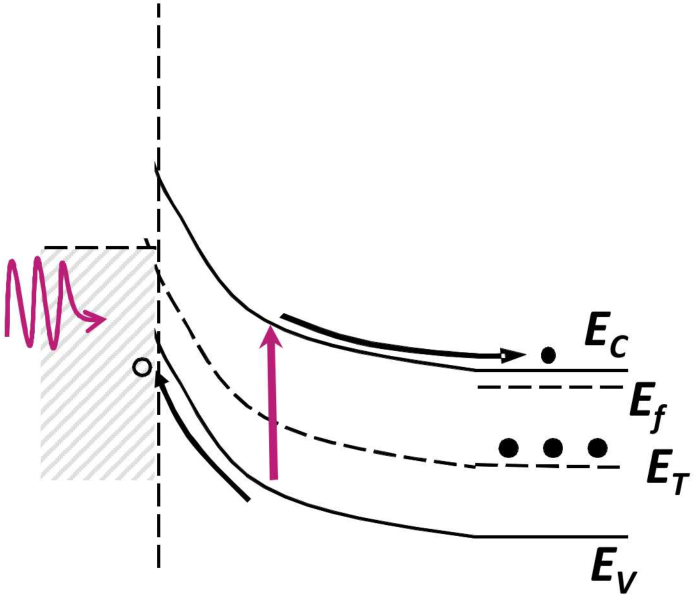
Defects and hole localization

Deep Level Optical Spectroscopy





- Backside: DLOS only senses deep level defects
- Frontside: DLOS shows hole localization for above-gap illumination

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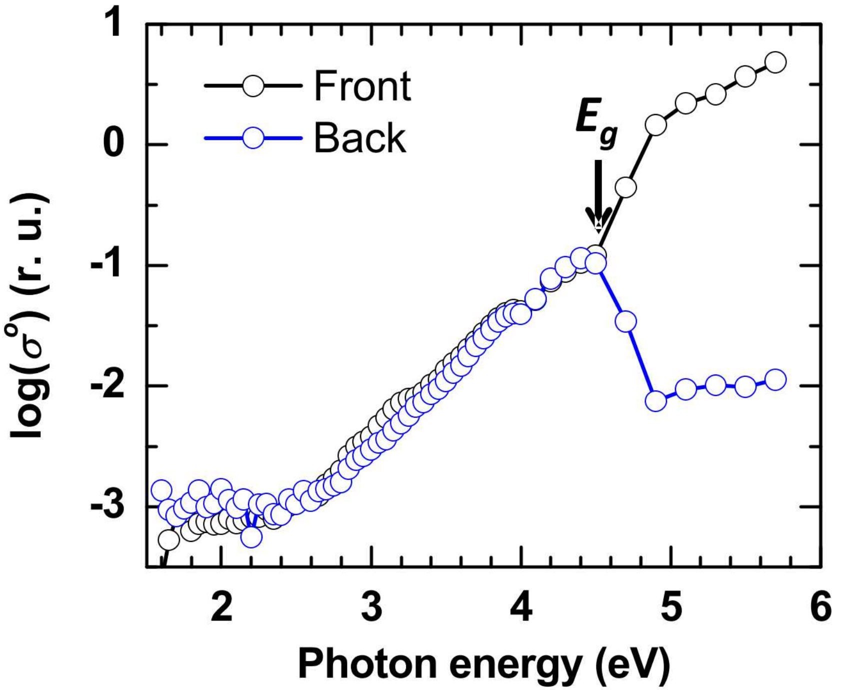
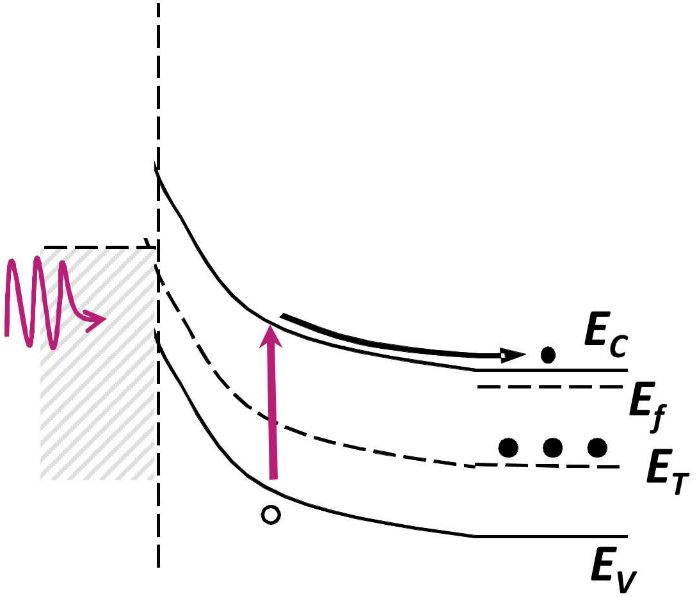
Defects and hole localization

Deep Level Optical Spectroscopy





- ➢ Backside: DLOS only senses deep level defects
- ➢ Frontside: DLOS shows hole localization for above-gap illumination
- ➢ *Hole localization unrelated to deep level defects*

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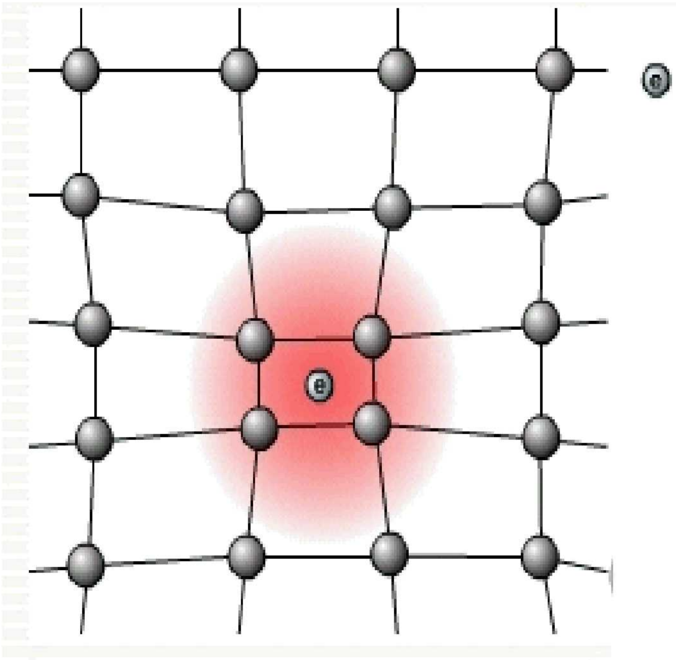
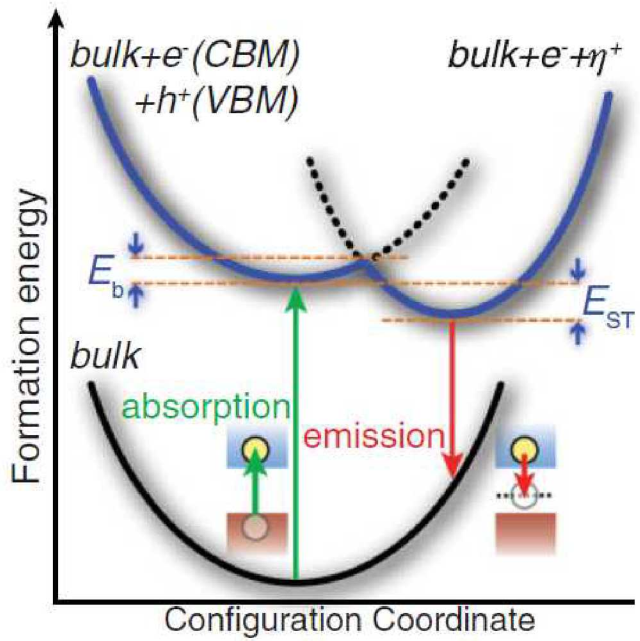
Self-trapped holes predicted to form in β-Ga_2O_3



STH configuration-coordinate



*Varley, *et al.*, PRB 85 081109(R) (2012).

- Self-trapped holes (STH) or small polarons are localized in the valence band
- Self-trapped holes behave similarly to an *AX* center*

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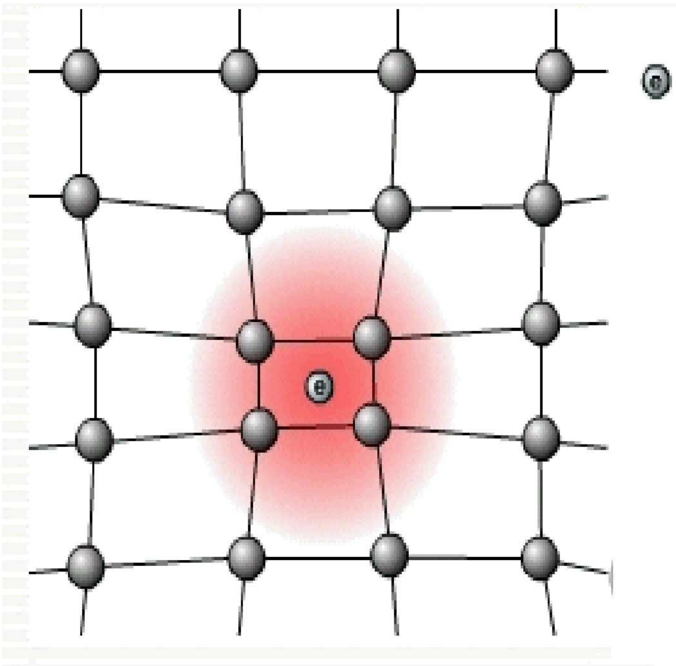
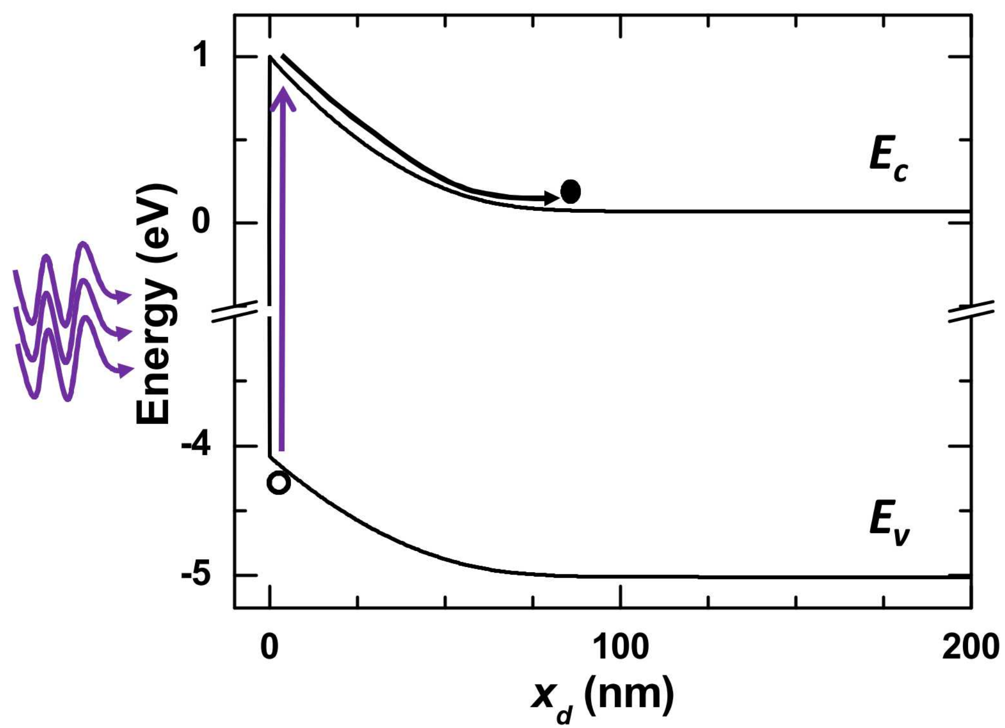
#Wei et al., J. Semicond. 33 07003 (2012).

Photo-gain from self-trapped holes





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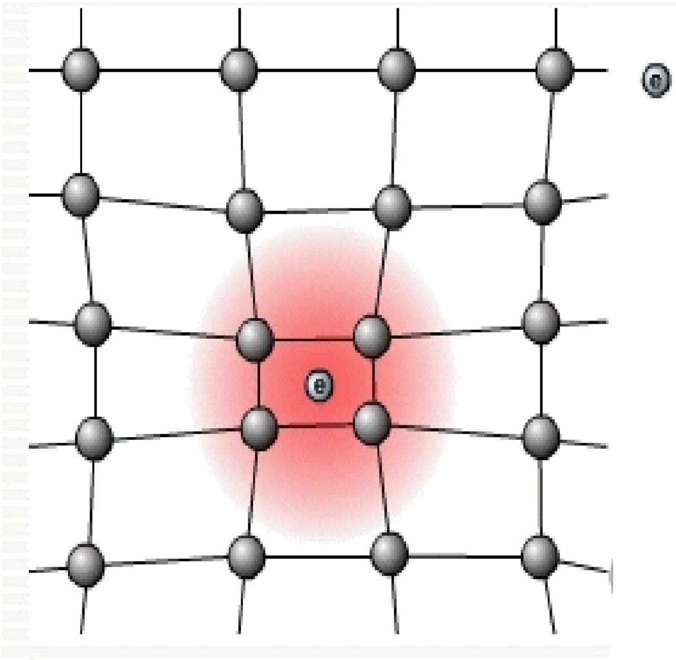
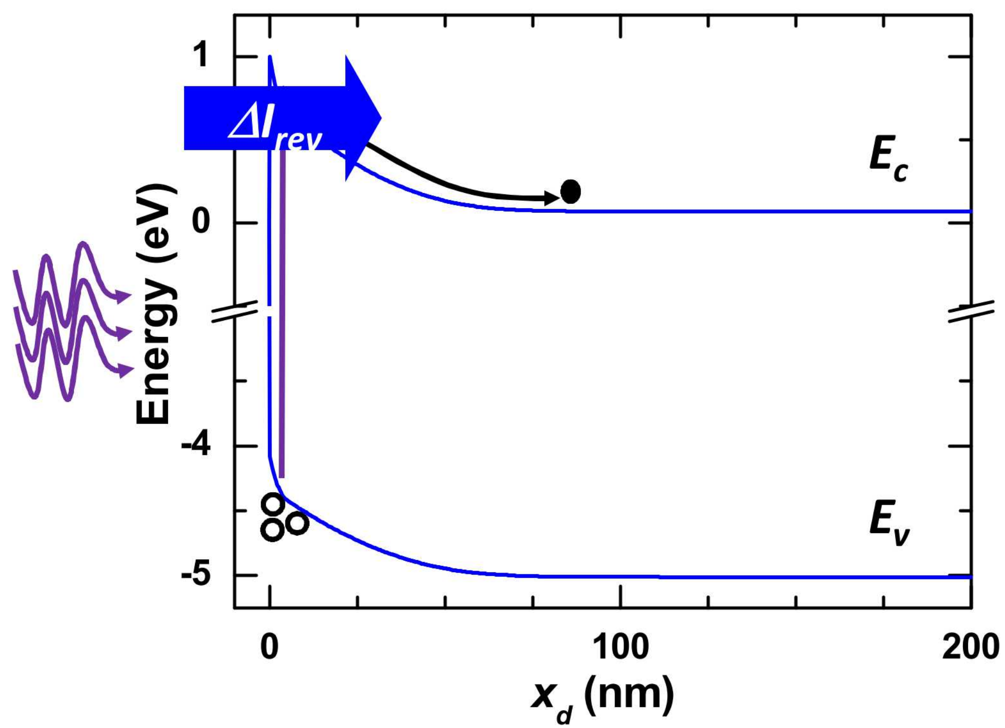
#Wei et al., J. Semicond. 33 07003 (2012).

Photo-gain from self-trapped holes





- Intrinsic mechanism for long-lived, near-surface holes in β-Ga_2O_3
  - $\alpha > 10^7$ cm$^{-1\#}$
- STHs lower ϕ_b by 300 meV and increase reverse current as $\exp(\Delta\phi_b/kT) \sim 10^5$

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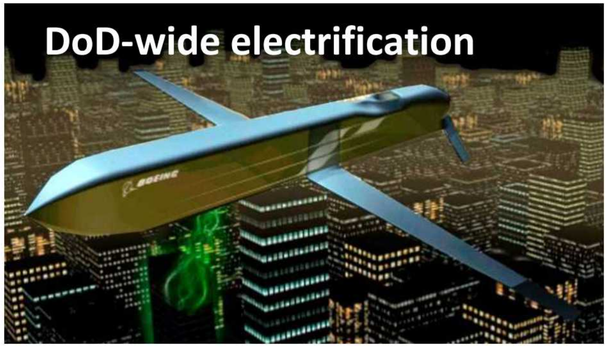
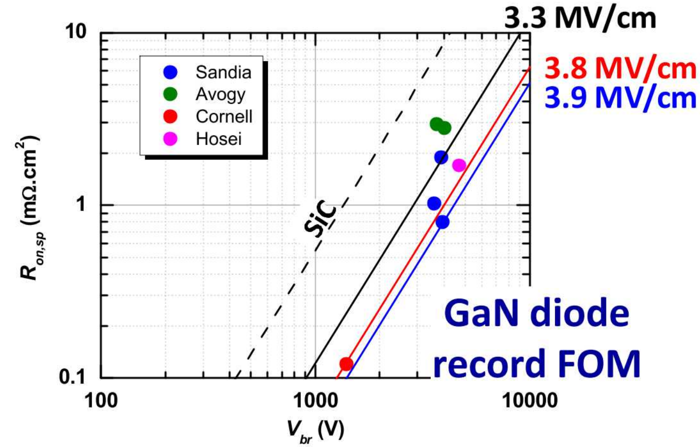
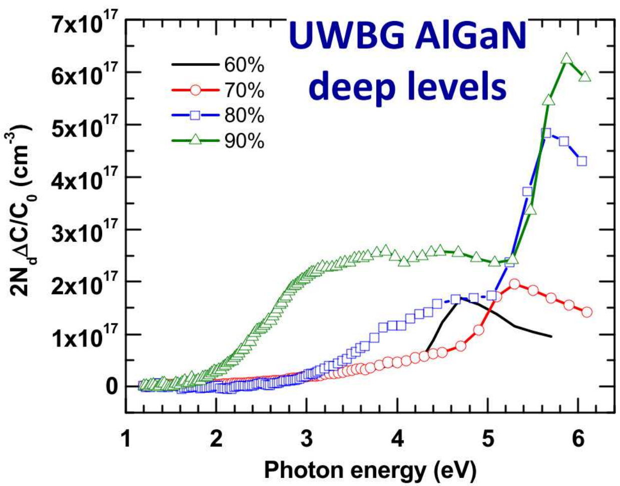
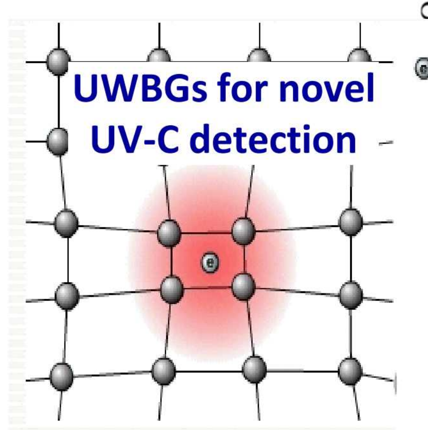
#Takaura et al., Physica B 404 4854 (2009).

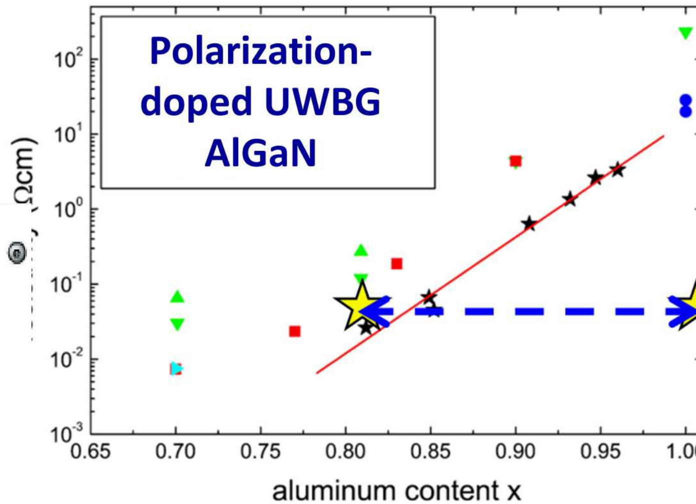
Summary











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