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Role of defects in limiting the optical efficiency of InGaN/GaN quantum wells

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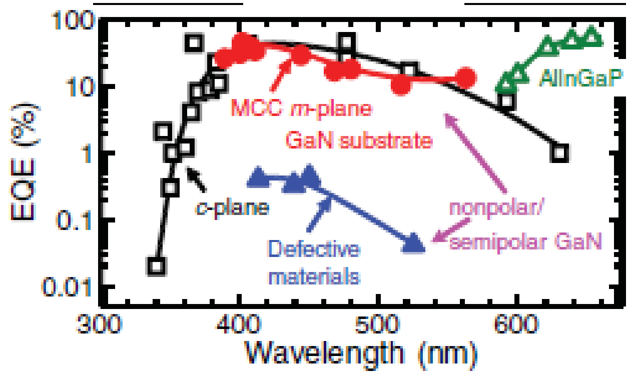
Potential impact of defects in InGaN luminescence

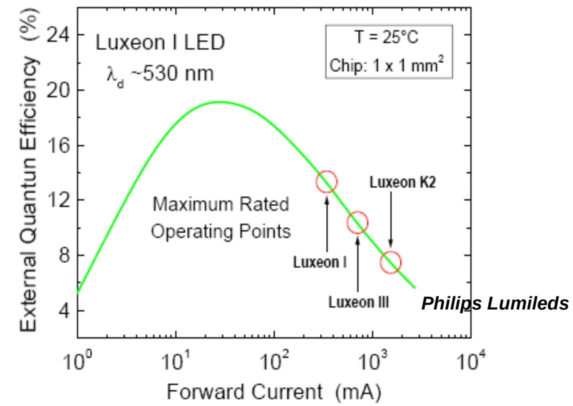
How do InGaN defects impact the “green gap” and “efficiency droop” problems?

EQE vs. λ

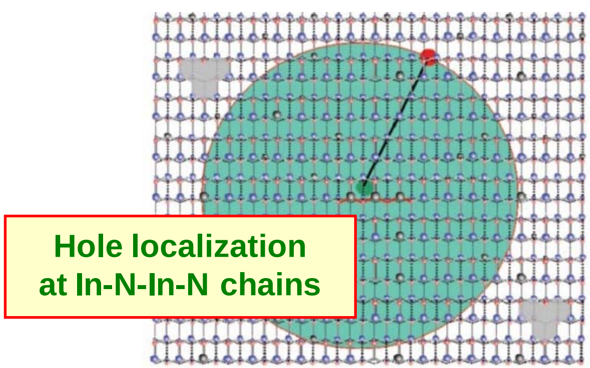


Speck *et al.* MRS Bullet. 34, 304 (2009)

“Efficiency Droop” of InGaN LEDs

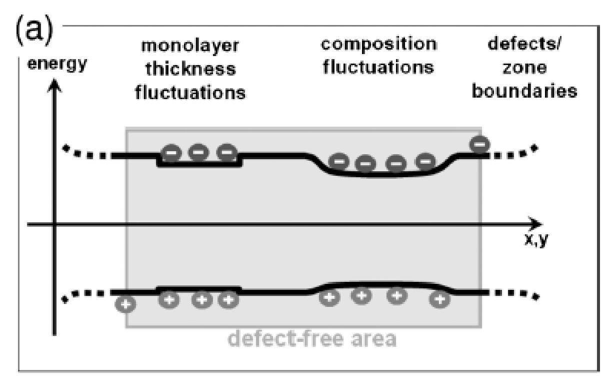


Defects and localization



Chichibu *et al.* Philos. Mag. 87 2019 (2007)

Defects and localization

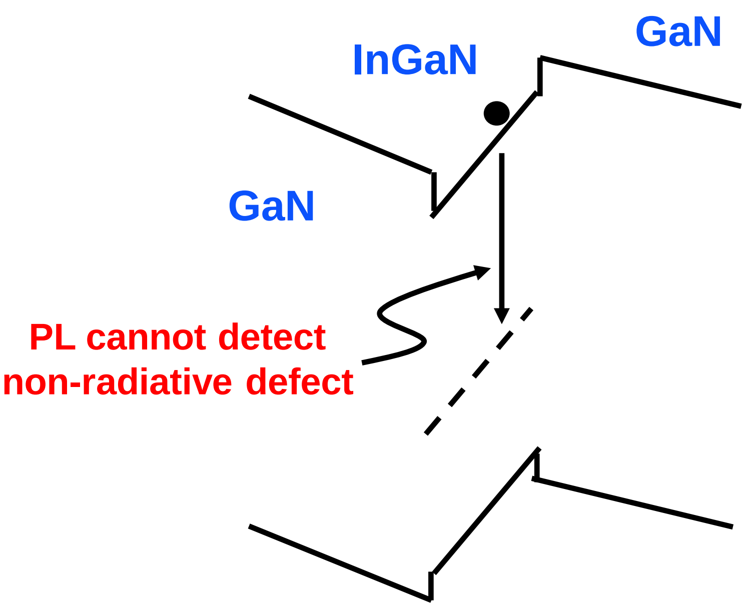


Hader et al. APL 96 221106 (2010)

➢ **Connect InGaN QW growth conditions, defects and IQE**

Defect Study of InGaN QW structures

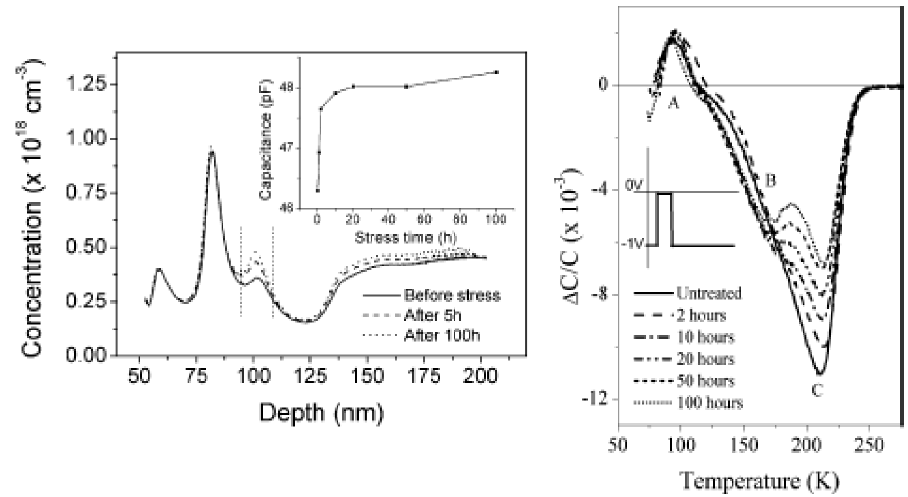
Resonant Photoluminescence



Drawbacks:

1. Non-radiative centers?
2. Quantify deep level energy, concentration?

DLTS of InGaN LEDs



1. F. Rossi *et al.* JAP 99, 053104 (2006).

Drawbacks:

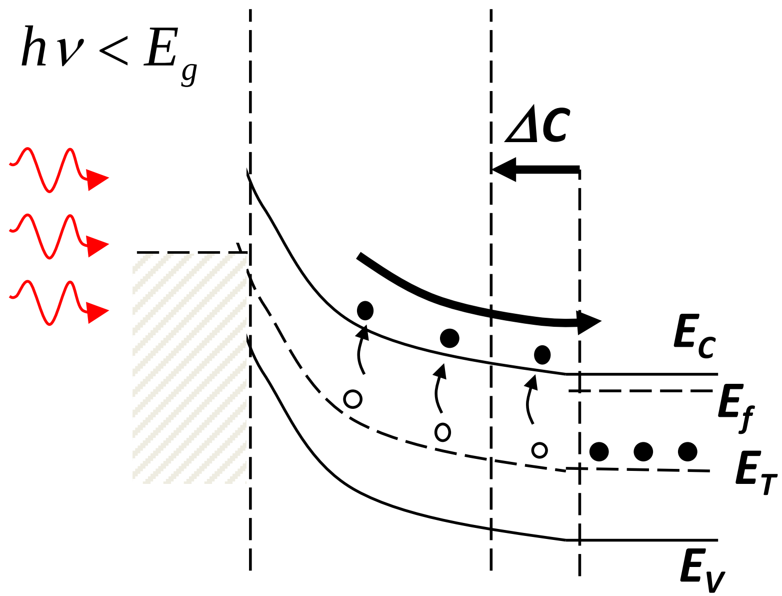
1. DLTS cannot probe mid-gap states
2. Cannot determine defect density
3. No InGaN-related traps were found[1,2]

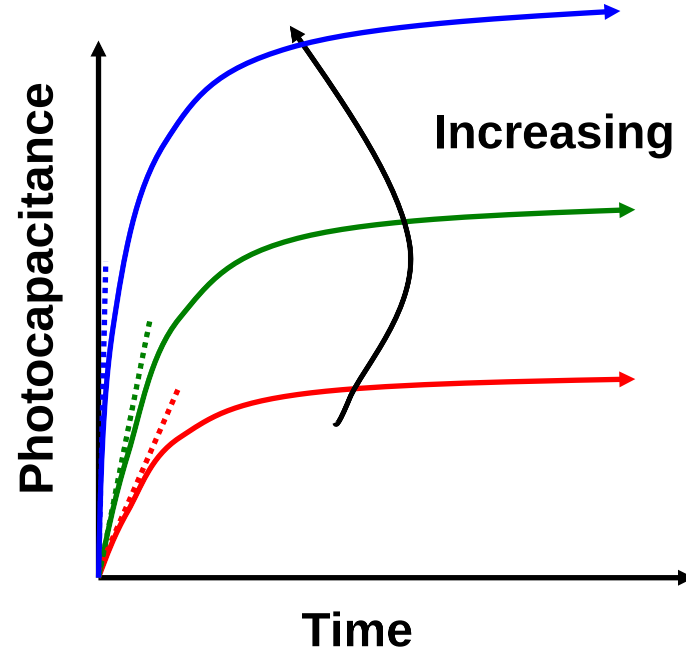
QW-based techniques not quantitative or have insufficient depth resolution

2. L. Rigutti *et al.* PRB 77, 045312 (2008).

Deep Level Optical Spectroscopy

Deep Level Optical Spectroscopy (DLOS)[1]
- **Photocapacitance technique**
  - ➢ ***Sub-band gap optical stimulation*** **to photoionize defect levels (reverse of PL)**
  - ➢ ***Quantify non-radiative*** **defect level energy and density (difficult for PL)**





- **DLOS only sensitive to depleted regions**
- **Enables nano-scale depth resolution**

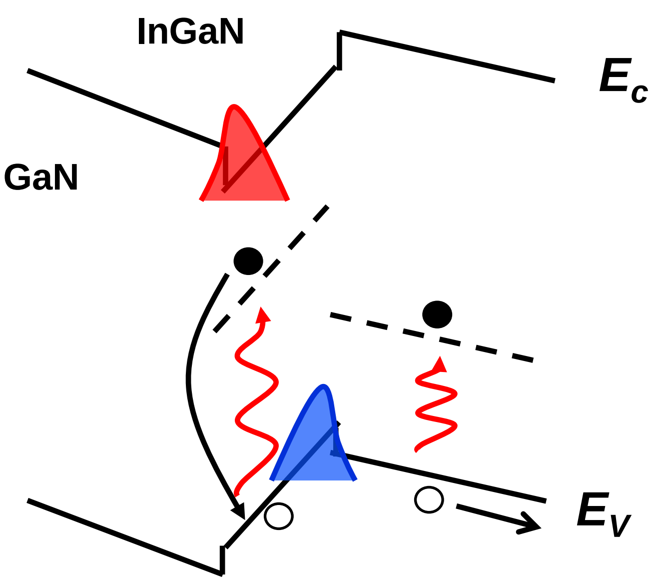
- **Optical cross-section $\sigma^o = e^o/\Phi(h\nu)$**
  - **$dC(t)/dt|_{t=0} \propto \sigma^o(h\nu)$**
- **Optical ionization energy E^O**
- **Defect density D_t from lighted C-V**

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

Defect Study of InGaN QWs

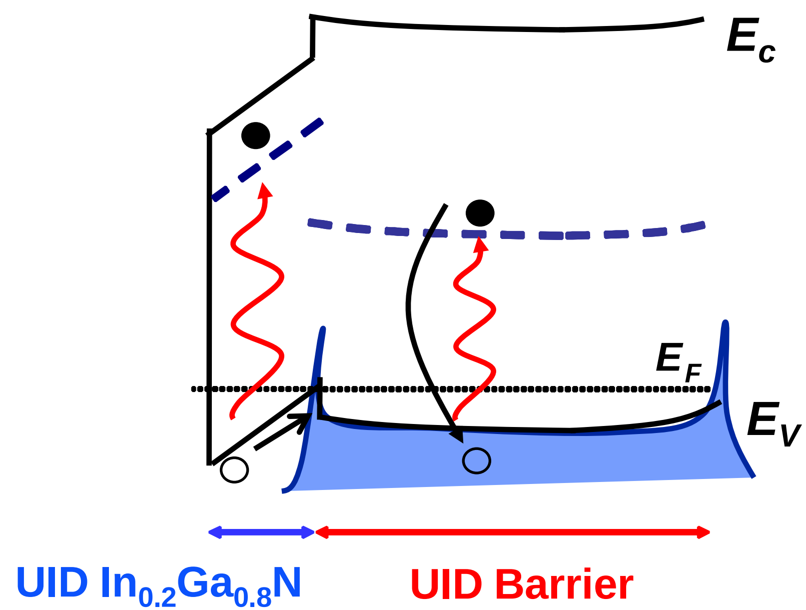
Designed InGaN/GaN heterostructure for depth-resolved DLOS

InGaN/GaN QW



Not sensitive to $In_{0.2}Ga_{0.8}N$ well defects

InGaN/GaN "half QW"



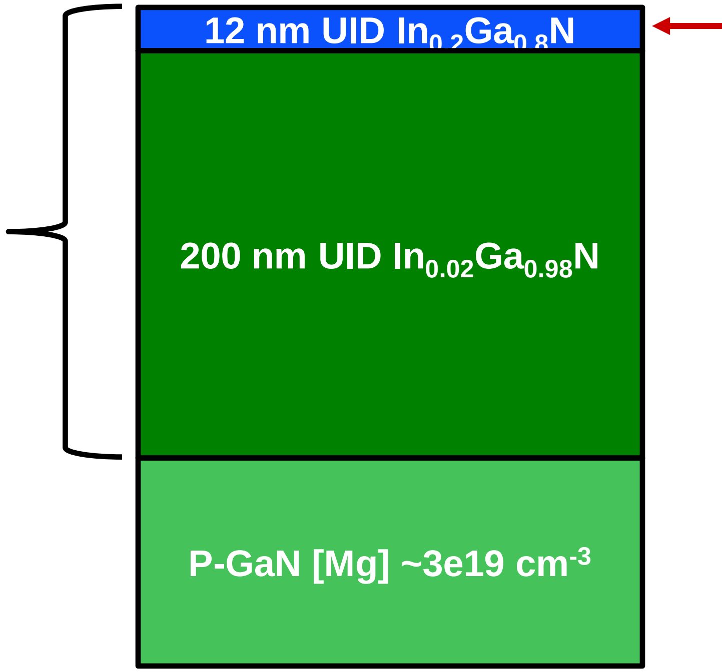
Mainly sensitive to $In_{0.2}Ga_{0.8}N$ cap defects

Same $In_{0.2}Ga_{0.8}N$ growth conditions for both structures

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

Depth-resolved DLOS of InGaN

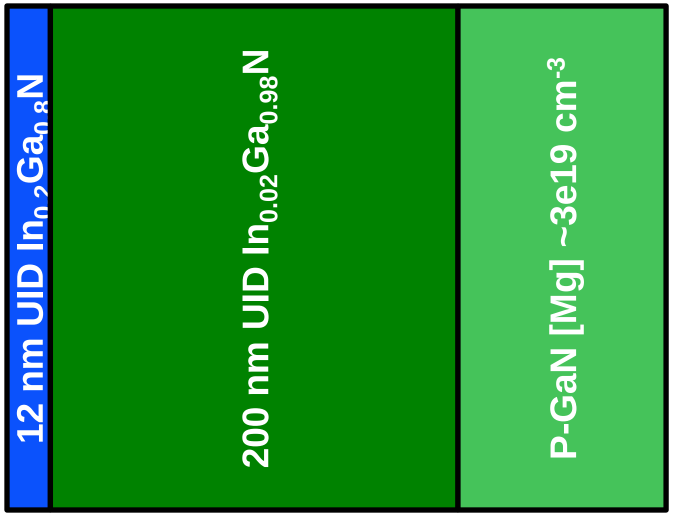
UID regrowth on p-GaN template



- **QW growth conditions**
- **Coherently-strained**

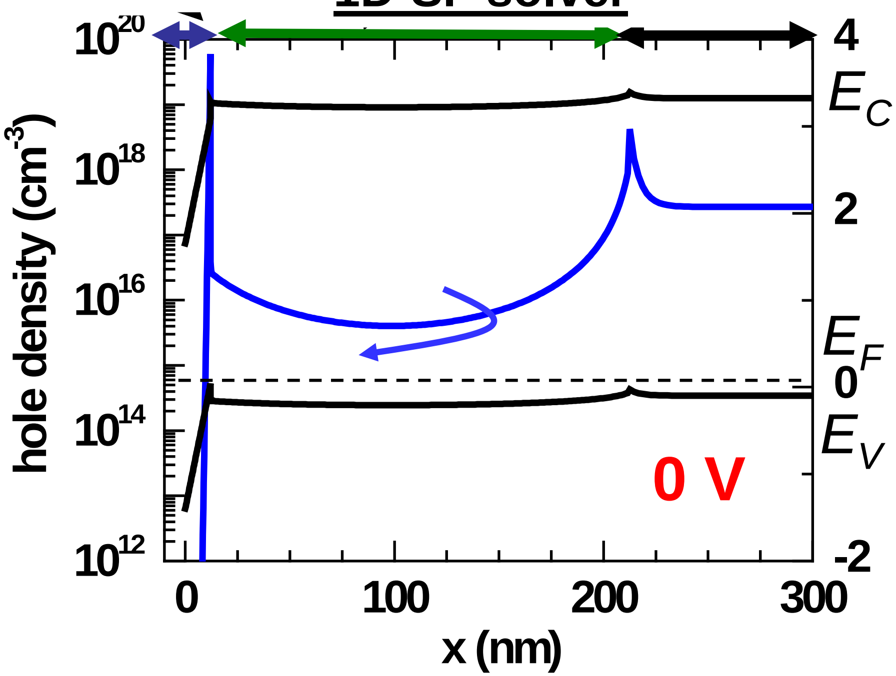
- Grown by MOCVD in a D125 short-jar Veeco reactor
- 300 torr, 15 SLM NH_3, 10 SLM N_2, no H_2
- In content controlled through growth temperature
- $In_{0.02}Ga_{0.83}N$: 24.3 μmoles/min Ga, 72.8 μmoles/min In
- $In_{0.17}Ga_{0.83}N$: 10.4 μmoles/min Ga, 55.8 μmoles/min In

Depth-resolved DLOS of InGaN

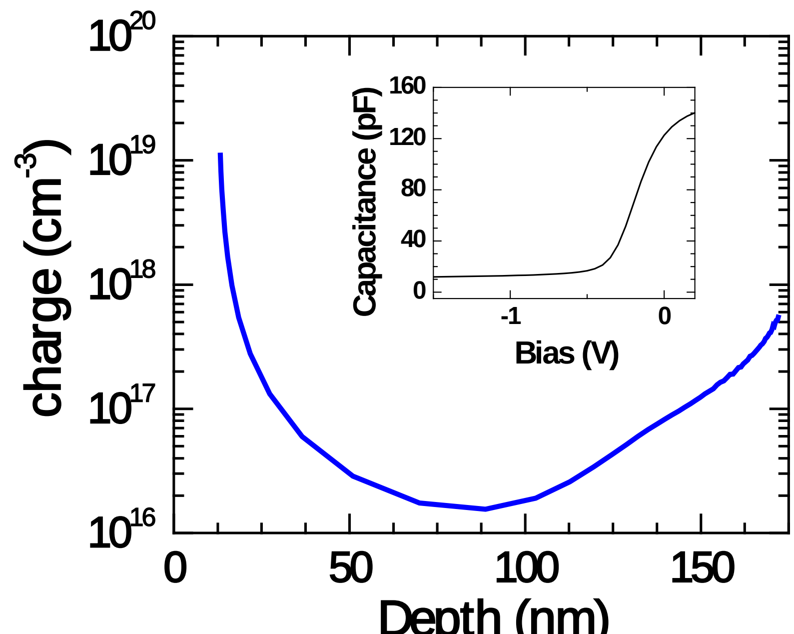


➢ Sensitivity to $In_{0.2}Ga_{0.8}N$ defects

1D-SP solver



Diode C-V and carrier density



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Influence of T_g and Indium alloying

- ***Quantitatively*** **study defects and IQE as function of** ***same InGaN growth conditions***

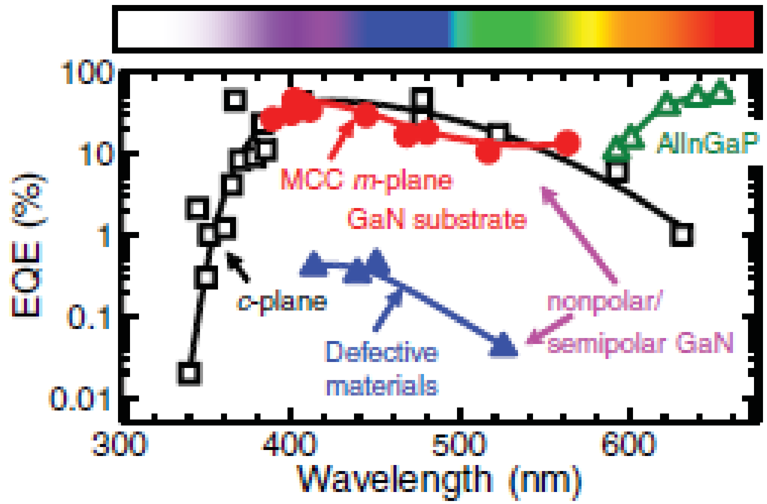
Decreasing T_g
(Impurities, native point defects)

750 ºC
17%
Indium

730 ºC
21%
Indium

Increasing Indium
(Strain, QCSE)

EQE vs. wavelength



Speck *et al.* MRS Bullet. 34, 304 (2009)

- **Decrease in EQE/IQE with increasing λ**
- **Partly QCSE, well width,** ***and defects….?***

- **Decouple T_g vs. indium alloying**

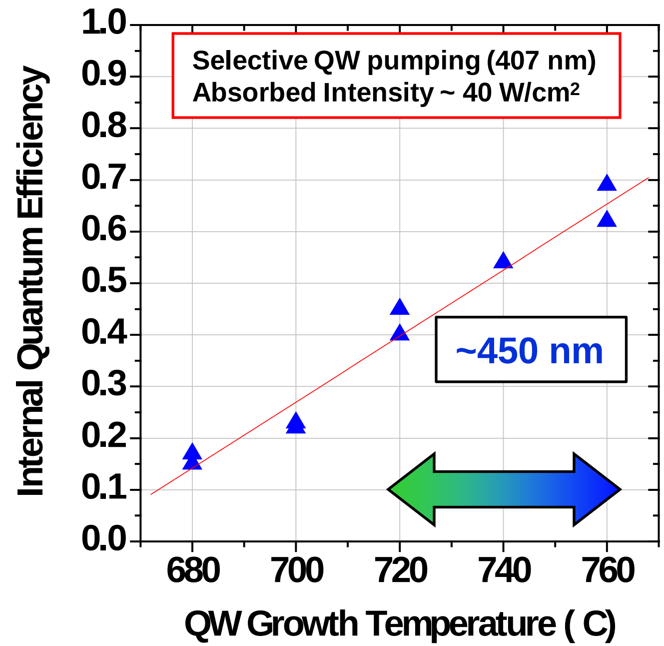
Effect of T_g on MQW IQE

Decreasing T_g
(Impurities, native point defects)

750 ºC 17% Indium		690 ºC 17% Indium

Reduced T_{QW} at fixed Indium

Estimated IQE from Temp. Dep. PL

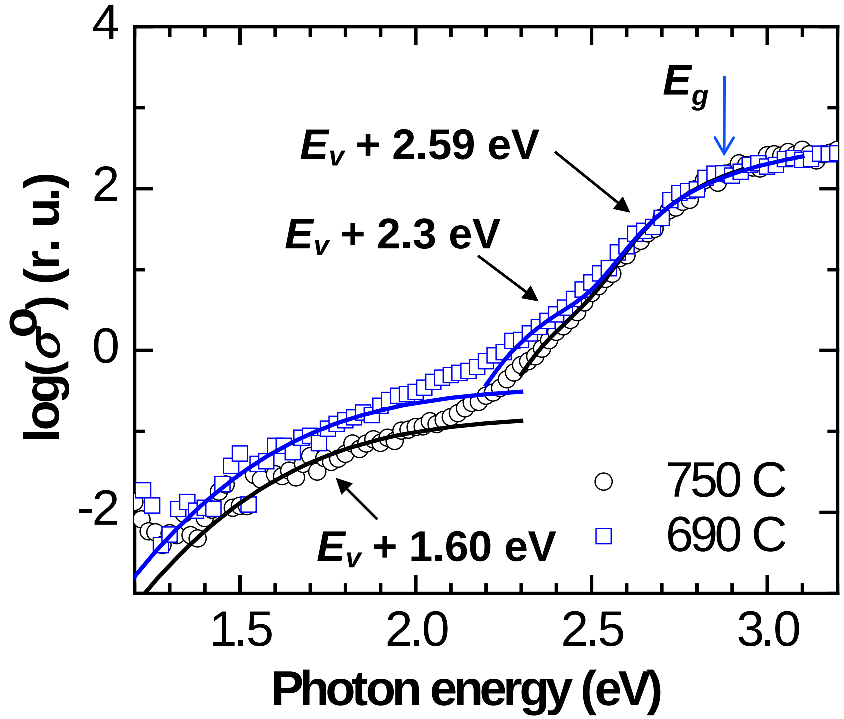


- Isolate impact of ***lower T_g***
  - Vary ***TMIn flow only*** for similar Indium composition at various T_g
- Fixed MQW structure, strain, QCSE
- Fixed [V-defect], TDD

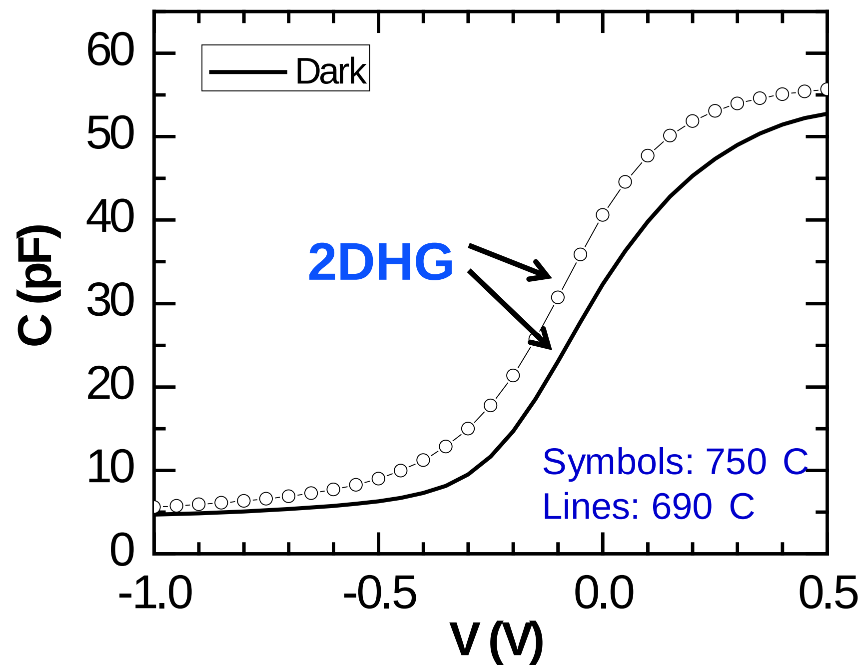
- ➢ Decreasing IQE with decreasing T_{QW}
- ➢ ***Point defects are suspected cause***

Influence of T_g on defect incorporation

DLOS of $In_{0.17}Ga_{0.83}N$



Lighted C-V



- **Similar In $_{0.17}$Ga $_{0.83}$N defect levels**

→ 60 C reduction in T_g does not introduce new deep levels

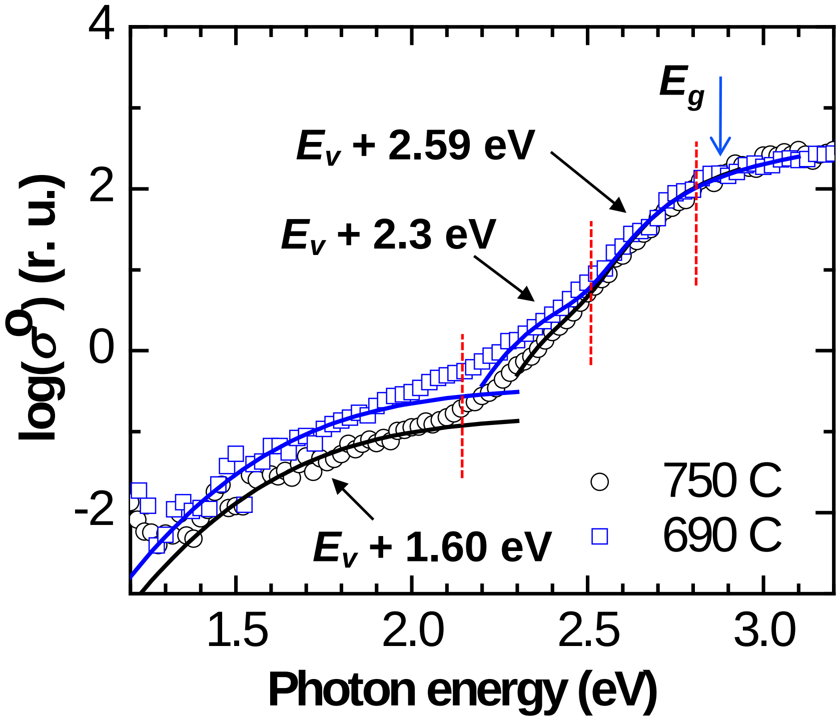
- **Larger dark "threshold voltage" at 750C**

➢ 60 C reduction in T_g introduces excess deep levels

Model used to fit DLOS data:
Paessler JAP 96, 715 (2004)

Influence of T_g on defect incorporation

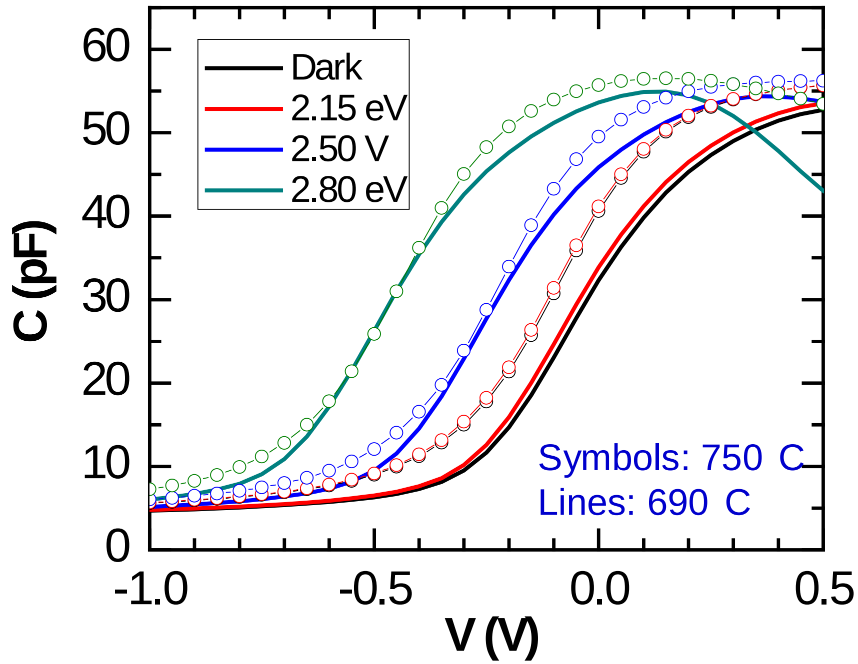
DLOS of $In_{0.17}Ga_{0.83}N$



- Similar In $_{0.17}$Ga $_{0.83}$N defect levels
  → 60 C reduction in T_g does not introduce new deep levels

Model used to fit DLOS data:
Paessler JAP 96, 715 (2004)

Lighted C-V



- Larger dark "threshold voltage" at 750C
  ➢ 60 C reduction in T_g introduces excess deep levels
- Individual areal deep level densities (D_t) using selective photon excitation energy

Influence of T_g on defect incorporation

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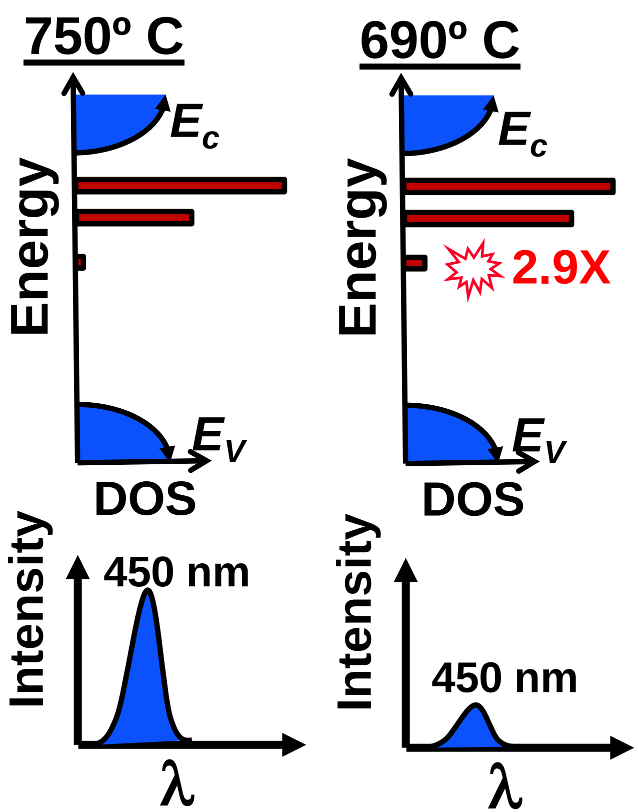
Areal Densities of Deep Levels

	690 C	750 C	Change
E_v + 1.60 eV	$2.0\ \ 10^{11}$	$0.70\ \ 10^{11}$	2.9X
E_v + 2.3 eV	$1.6\ \ 10^{12}$	$1.1\ \ 10^{12}$	1.4X
E_v + 2.59 eV	$2.0\ \ 10^{12}$	$2.0\ \ 10^{12}$	--



- [E_v + 2.59 eV] largest but no change for ↓ T_g
- [E_v + 1.60 eV] greatest increase for ↓ T_g

➢ ***Quantified*** ↑ D_t, ↓ IQE for ↓ T_g

Possible Deep Level Candidates:

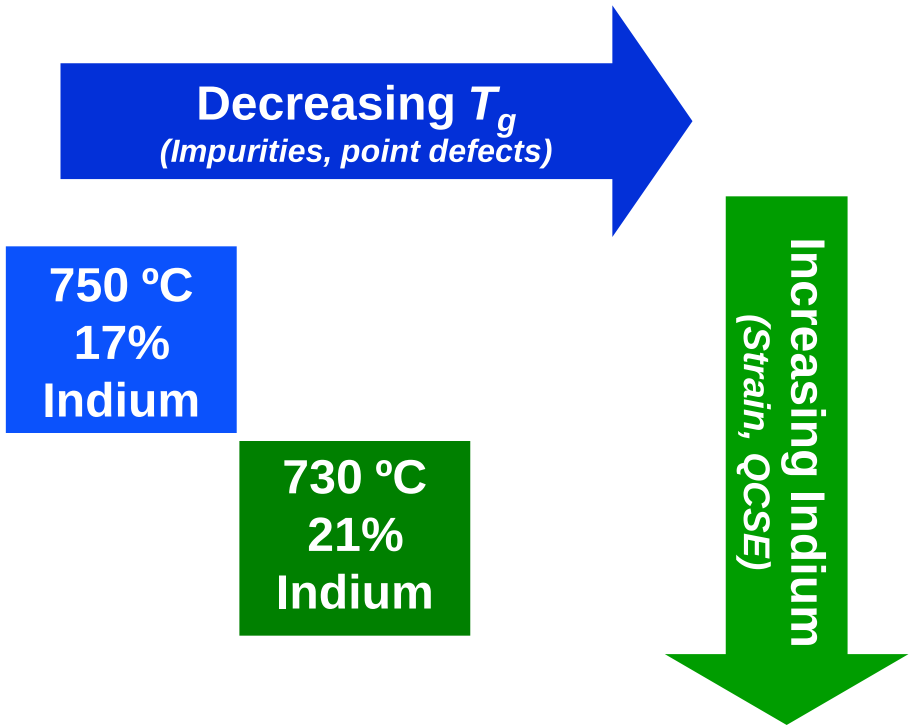
1. ***Carbon related*** (↑with lower T_g[1], nonradiative[2])
2. ***V_{III} and Oxygen related*** (↑ with lower T_g, low formation energy of V_{III}-O complexes[3]

[1] D. D. Koleske, et al., JCG 242, 55 (2002)

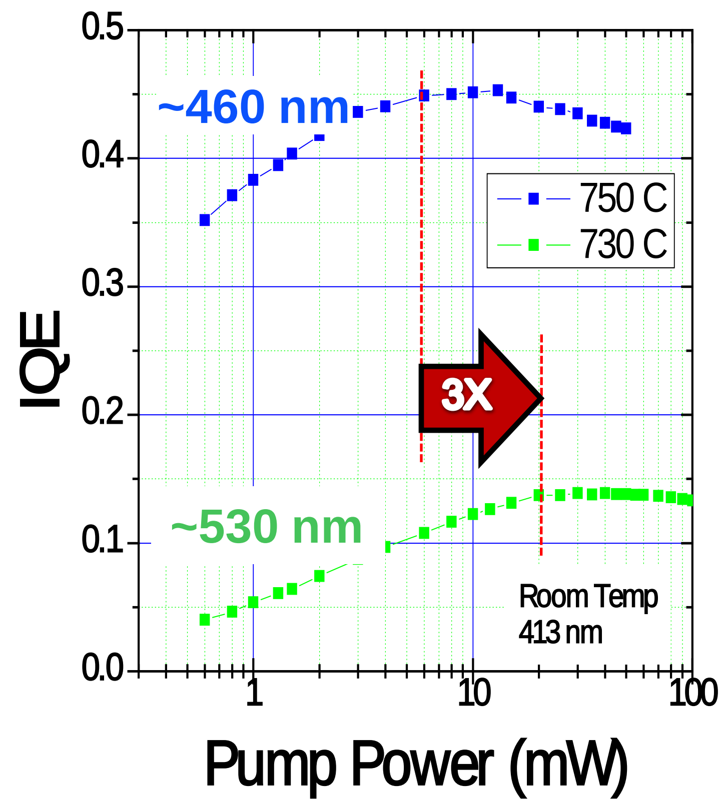
[2] C. H. Seager et al., JAP 92, 6553 (2002)

[3] J. Neugebauer and C. G. Van de Walle, APL 69, 503 (1996)

Influence of T_g and indium alloying



IQE from Power Dep. PL

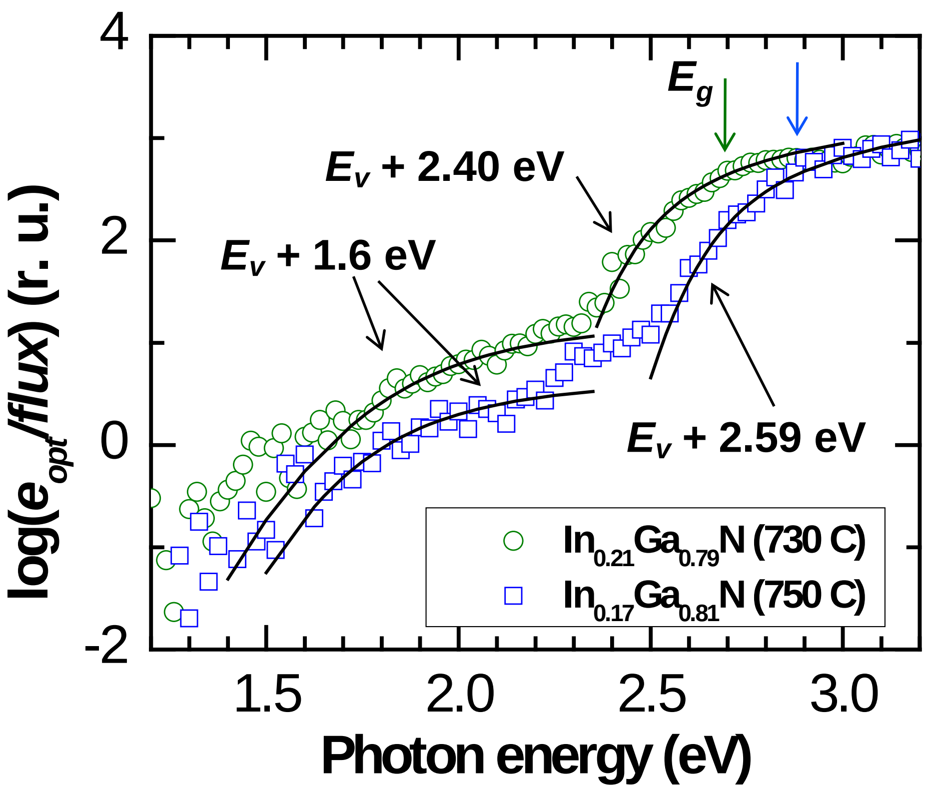


- **Strongly reduced IQE**
- ***3X saturation power suggests more defect recombination for green MQW***

Are the E_v + 1.60 eV, E_v + 2.3 eV levels relevant for green MQWs?

Influence of T_g and indium alloying

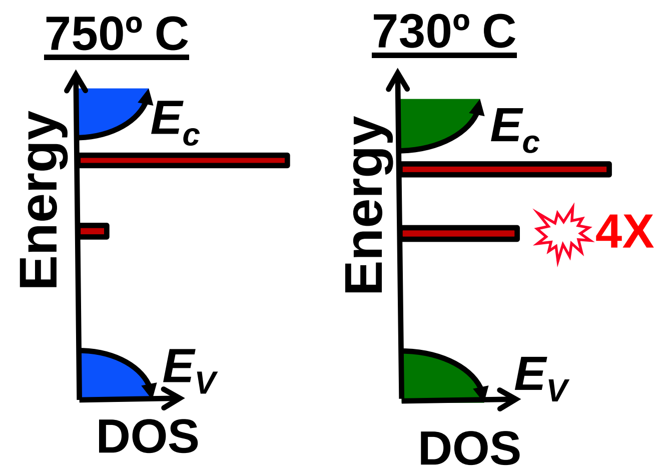
$In_{0.17}Ga_{0.83}N$ vs. $In_{0.21}Ga_{0.79}N$



- Near-E_c level shifts with E_g
- Similar E_v + 1.6 eV deep level
- 2.3 eV level missing

Densities of Deep Levels

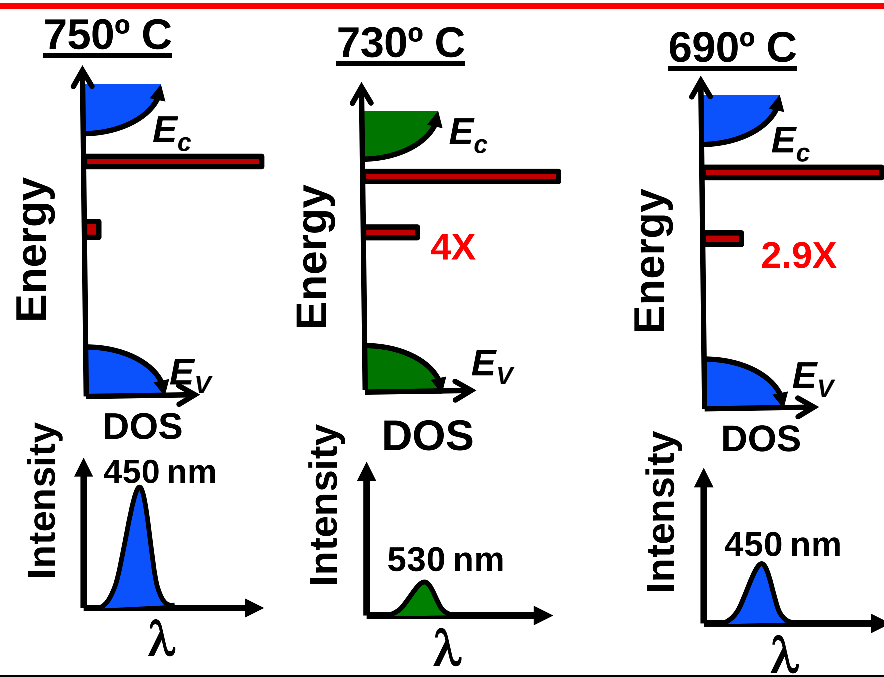
	$In_{0.17}Ga_{0.83}N$	$In_{0.21}Ga_{0.79}N$
E_v + 1.6 eV	**7e10 cm^{-2}**	**28e10 cm^{-2}**
E_v + 2.40 eV	5e11 cm^{-2}	--
E_v + 2.59 eV	--	5e11 cm^{-2}



→ ***Accelerated*** **IQE drop and greater [E_v + 1.6 eV] with ↓T_g and ↑indium**

Conclusions and summary

Used DLOS, Lighted C-V and PL to *quantitatively* study how QW growth conditions and alloying influence defect incorporation and IQE



Reduced T_g at fixed indium (blue MQWs):

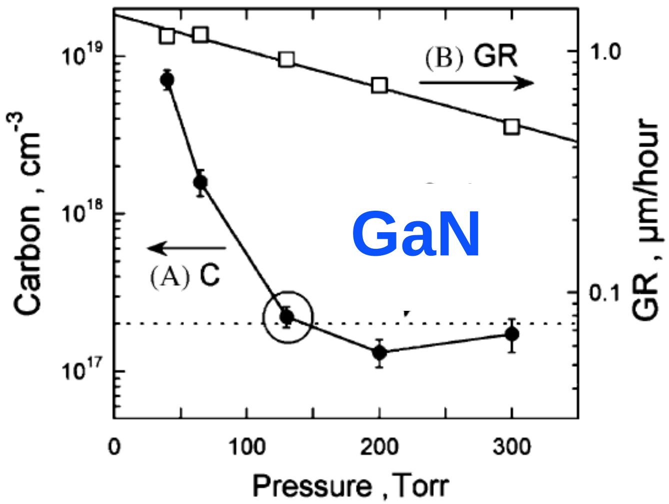
- Does not incorporate new deep levels
- Enhanced [E_v + 1.6 eV] correlates with strongly reduced IQE

Reduced T_g to increase indium (green MQWs):

- IQE degradation and [E_v + 1.6 eV] further enhanced
- **Identify E_v + 1.6 eV deep level as an effective NRC contributing to efficiency roll-off with increasing wavelength**

Future work

Impurity incorporation and growth pressure



Koleske *et al.*, JCG 242 55 (2002)

- **MQW growth optimization**
  - **Expect that $In_{0.2}Ga_{0.8}N$ *growth pressure* is important**
  - **Examine influence of precursor point and defect incorporation**
- **Study $In_{0.2}Ga_{0.8}N$ thermal decomposition**
  - **Design “half-QWs” with high temp. GaN caps**
  - **In-situ thermal cycling to mimic LED growths**

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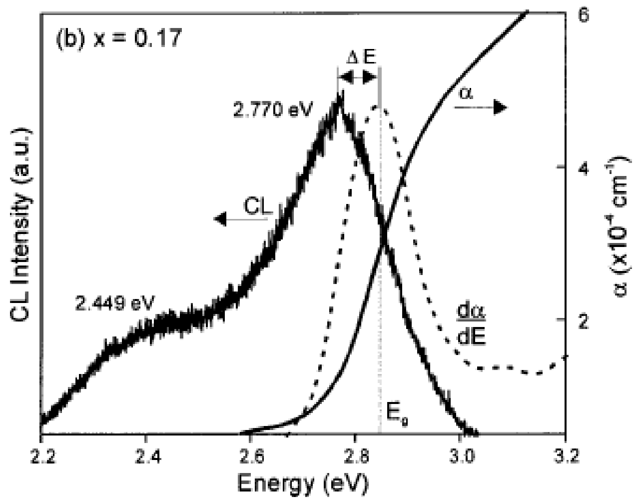
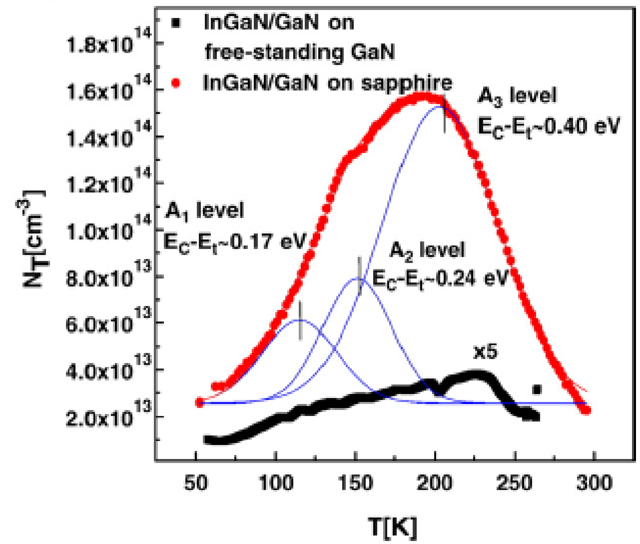
Defect Study of "bulk" InGaN films

Cathodoluminescence of *__100 nm__* thick $In_{0.17}Ga_{0.83}N$



1. S. Srinivasan *et al.* APL 80, 550 (2002).

DLTS of *__200 nm__* thick $In_{0.14}Ga_{0.86}N$



2. C. Soh *et al.* Thin Solid Films 515, 4509 (2007).

- $In_xGa_{1-x}N$ film quality degrades for thick layers (x > 0.15)
  - Strain relaxation and surface roughening
  - V-defect expansion
  - Indium segregation

Unclear that "bulk" $In_xGa_{1-x}N$ reflects optical quality InGaN wells

Potential impact of defects for InGaN LEDs

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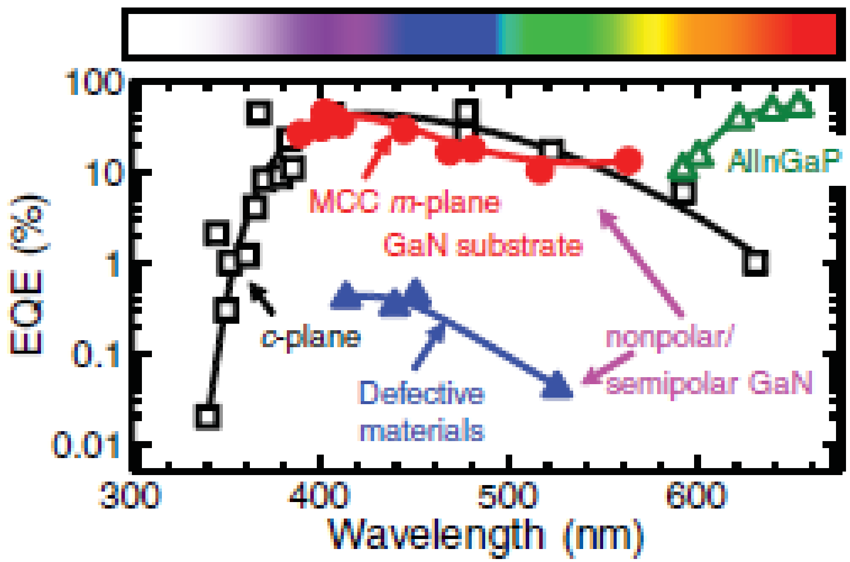
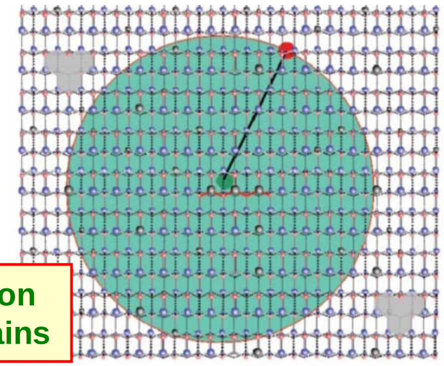
InGaN EQE vs. wavelength



Speck *et al.* MRS Bullet. 34, 304 (2009)

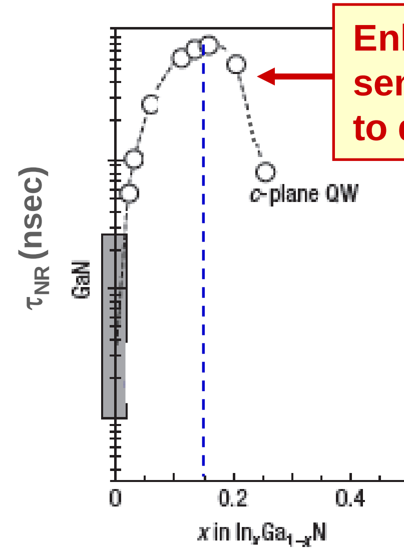
Efficiency roll-off not just QCSE

InGaN defects and efficiency



Hole localization at In-N-In-N chains

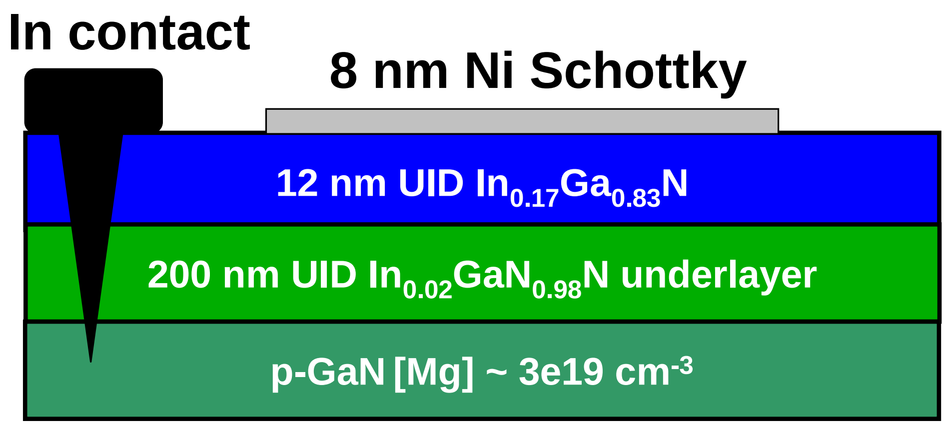
Chichibu *et al.* Philos. Mag. 87 2019 (2007)



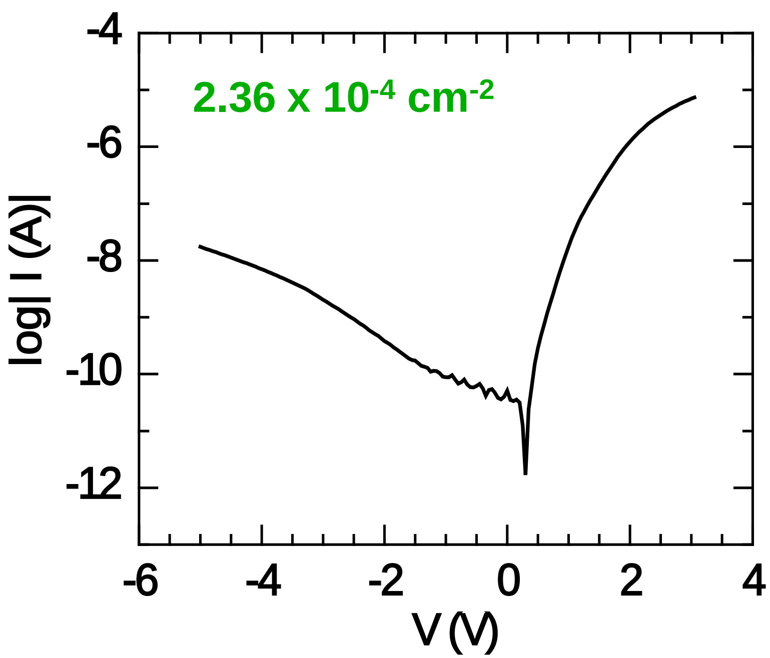
Enhanced sensitivity to defects?

- **Connect InGaN QW growth conditions, defects and IQE**
- **Deep Level Optical Spectroscopy (DLOS) for InGaN epilayers**

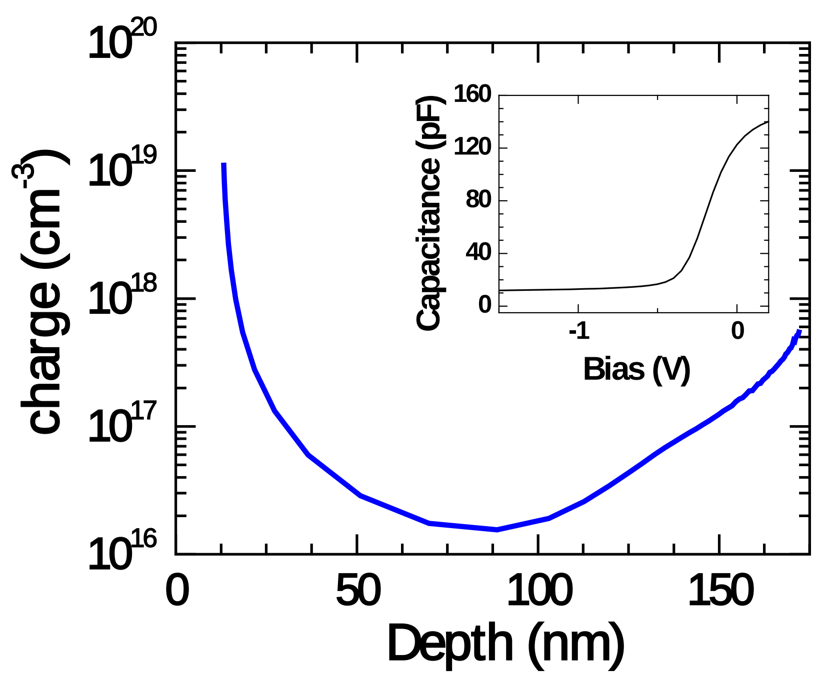
Diode structure



I-V



C-V and carrier density



Growth of InGaN/GaN DLOS structure

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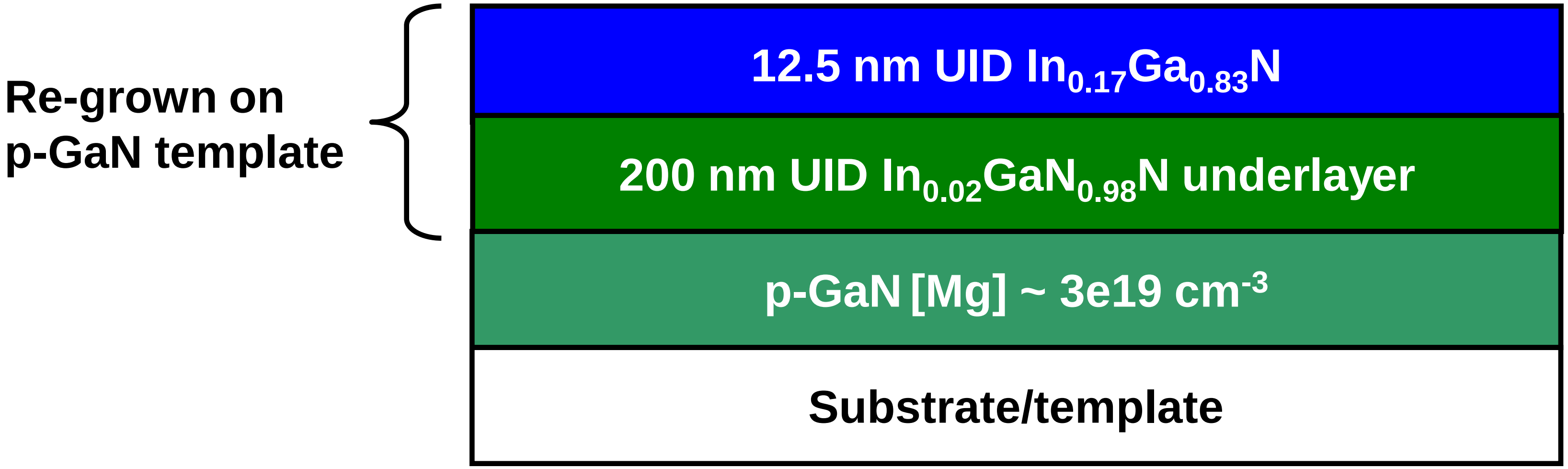
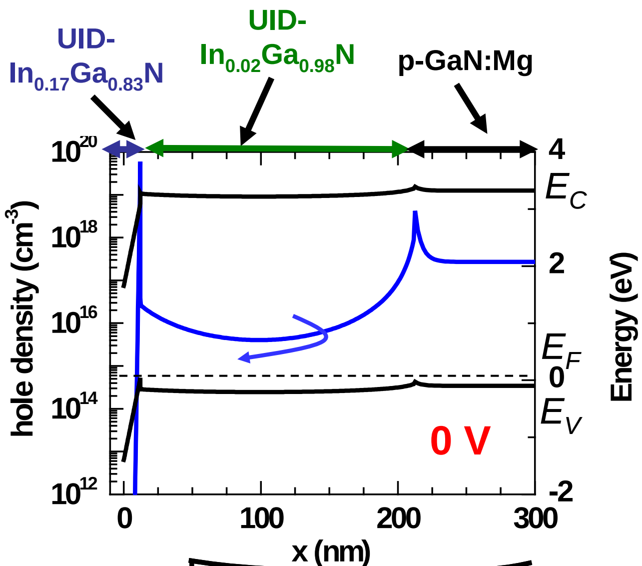
$In_xGa_{1-x}N$ layers grown under nominal QW conditions

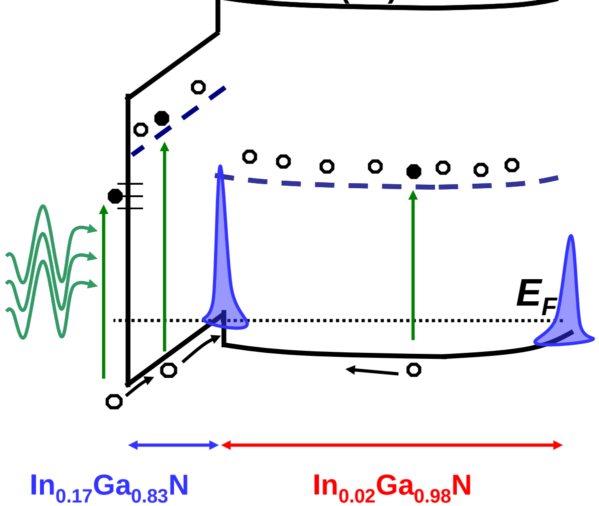


- MOCVD UID-InGaN re-grown on MOCVD p-GaN:Mg template
- $In_{0.02}Ga_{0.83}N$ underlayer (UL) grown at 880 C for 60 min.
- $In_{0.17}Ga_{0.83}N$ "well" grown at 760 C for 7 min.

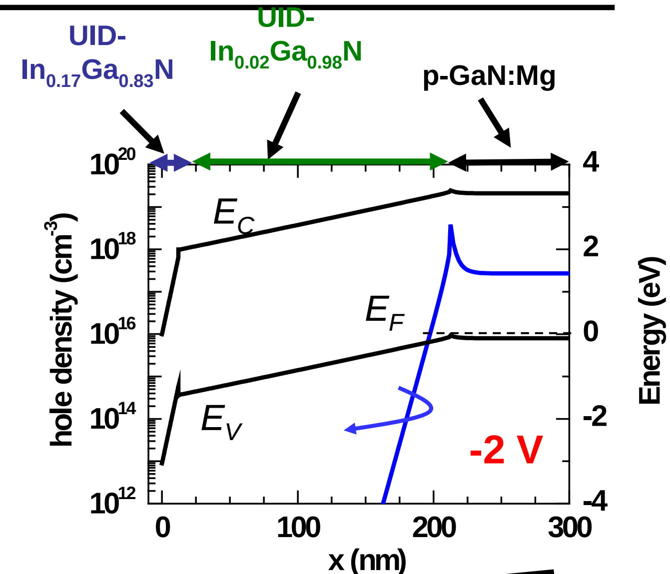
- Grown by MOCVD in a D125 short-jar Veeco reactor
- 300 torr, 15 SLM NH_3, 10 SLM N_2, no H_2
- In content controlled through growth temperature
- $In_{0.02}Ga_{0.83}N$: 24.3 μmoles/min Ga, 72.8 μmoles/min In
- $In_{0.17}Ga_{0.83}N$: 10.4 μmoles/min Ga, 55.8 μmoles/min In

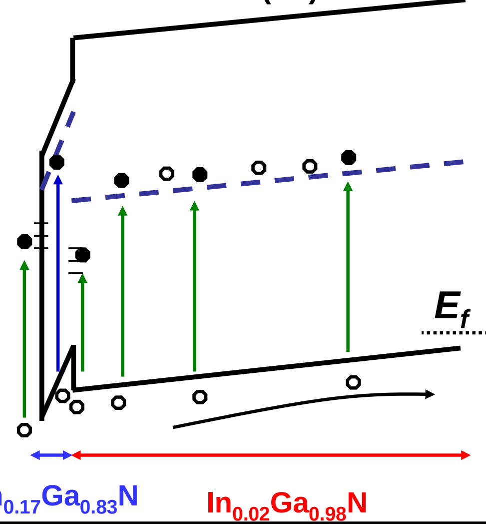
Simulate Depth-resolved DLOS





p-GaN never depleted





<u>Accumulation</u>:
- **"well" and portion of UL depleted**
- **$In_{0.17}Ga_{0.83}N$ defects dominate DLOS**
- ***Defects near 2DHG remain filled***

<u>Depletion</u>:
- **"well", interface, and UL depleted**
- **UL defects dominate DLOS**
- **Contribution from all InGaN regions**

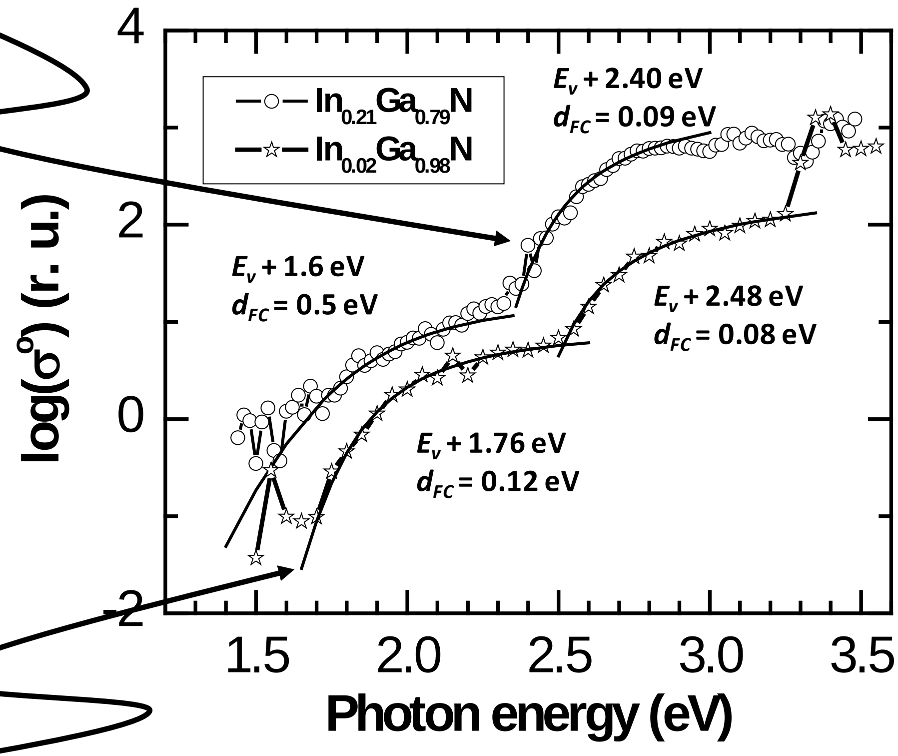
Confirmed DLOS depth-resoltuion

~12 nm UID $In_{0.21}Ga_{0.79}N$

200 nm UID $In_{0.02}GaN_{0.98}N$ underlayer

p-GaN [Mg] ~ 3e19 cm^{-3}

Substrate/template



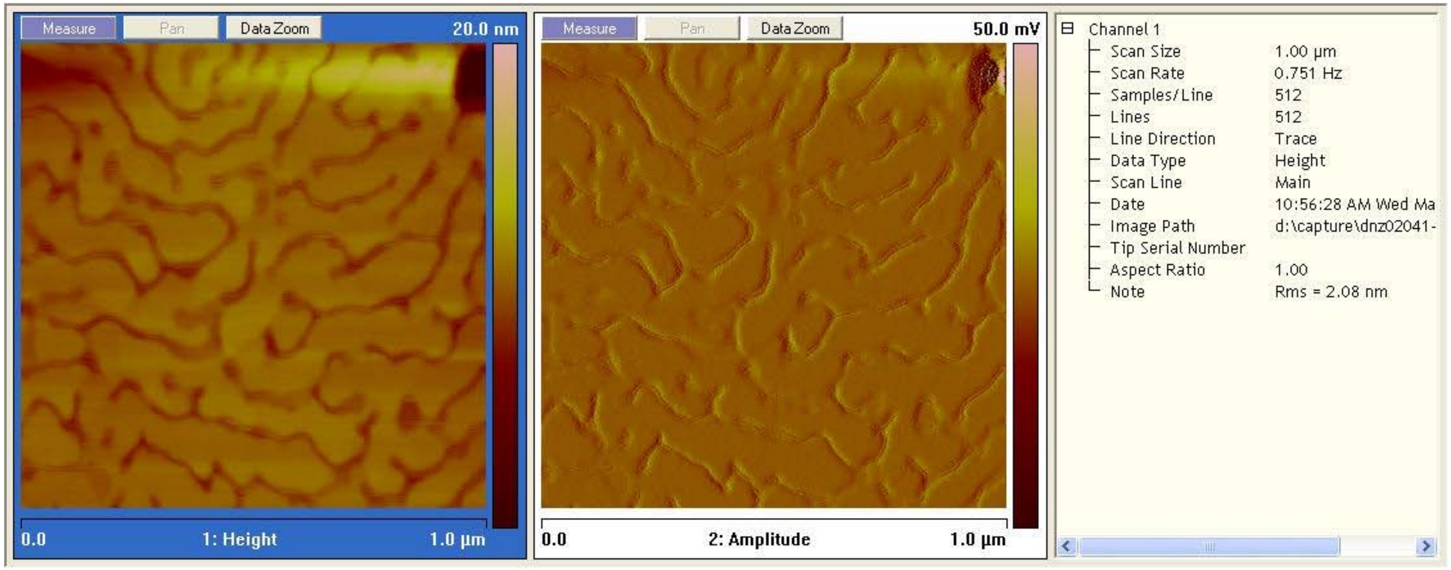
~4 nm UID $In_{0.21}Ga_{0.79}N$

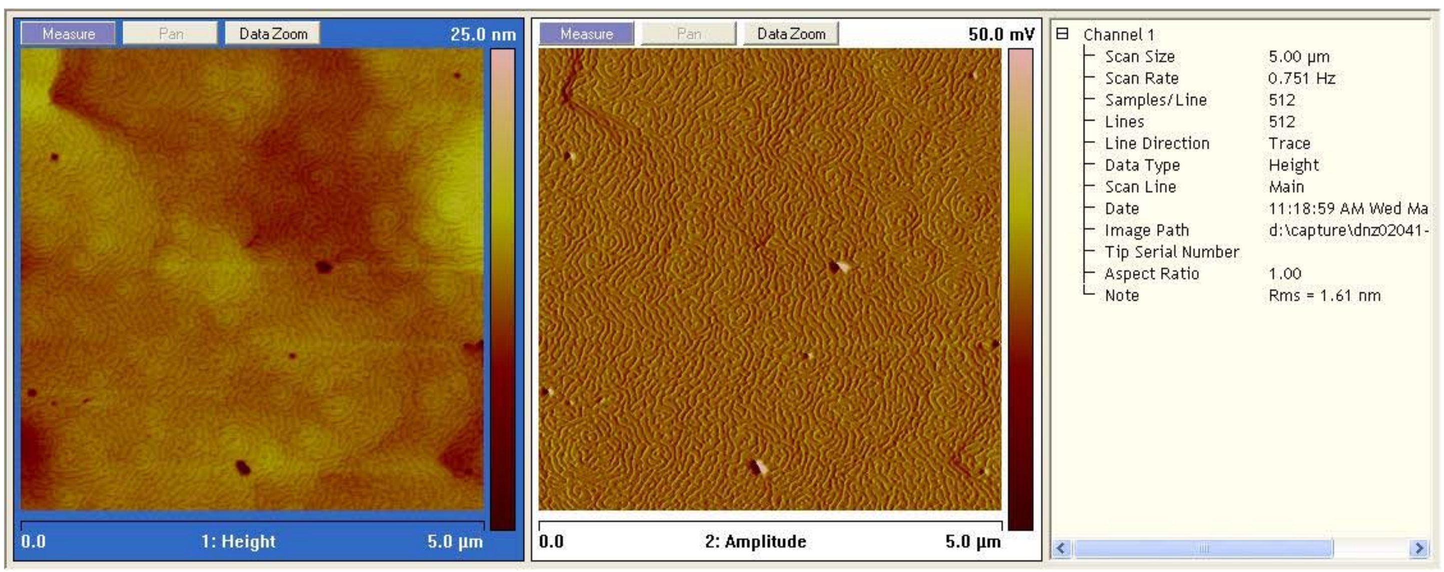
200 nm UID $In_{0.02}GaN_{0.98}N$ underlayer

p-GaN [Mg] ~ 3e19 cm^{-3}

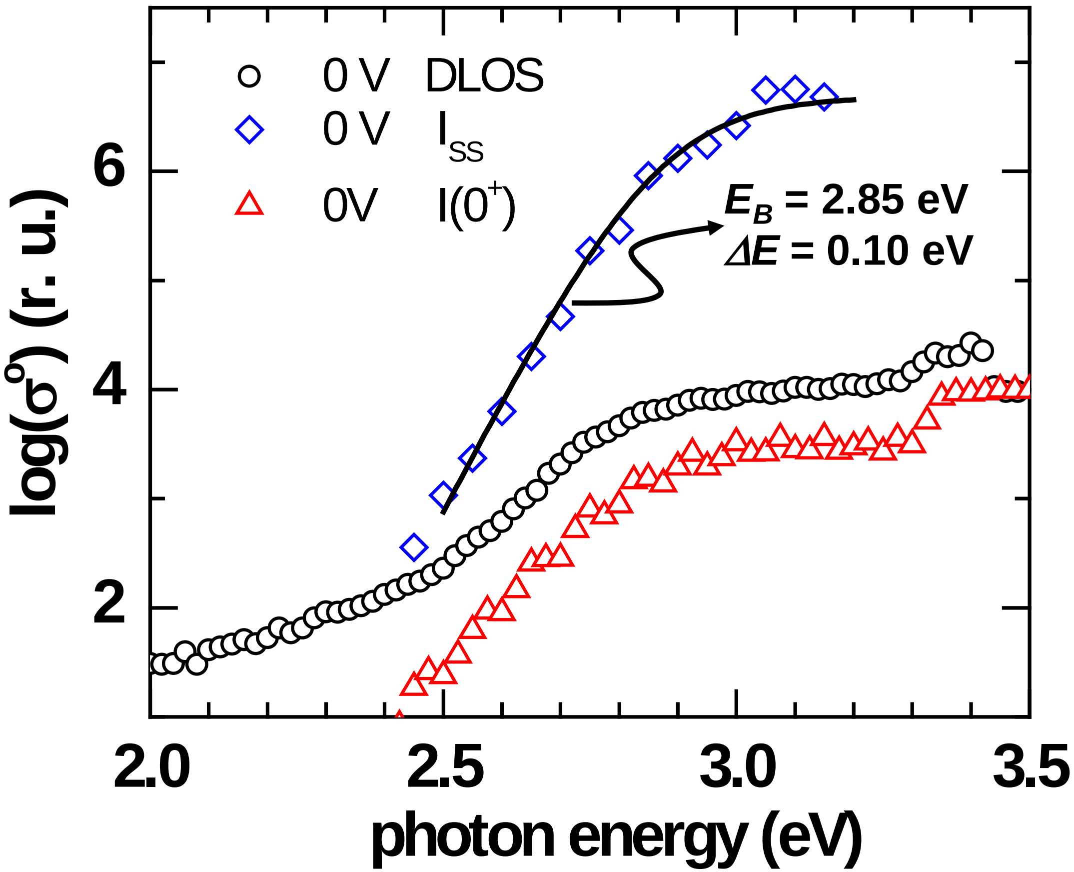
Substrate/template

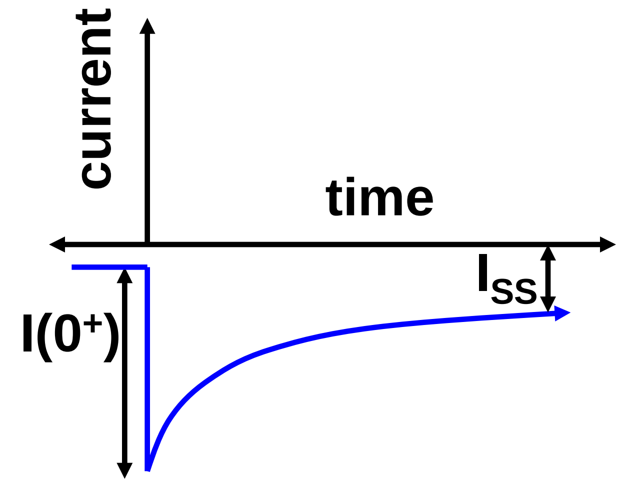
AFM of $In_{0.17}Ga_{0.83}N$ surface





Photocurrent





$$I(0^+) \propto e^o$$

1. C. T. Sah *et al*. SSE 13, 759 (1970).

$$I_{SS} = \frac{A}{1 + \exp\left(\frac{E_B - h\nu}{\Delta E}\right)}$$

2. R. W. Martin *et al*. APL 74, 263 (1999).

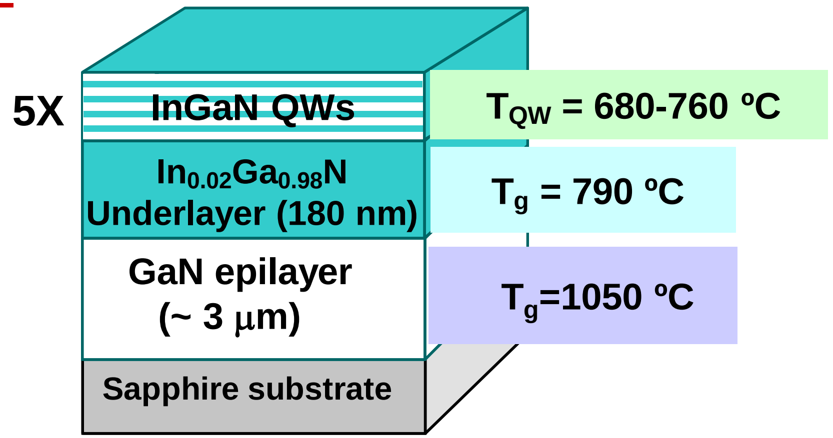
- **Steady-state photocurrent suggests band tailing**
- **Photocurrent deep level spectrum agrees with DLOS**

T_{QW} Study: Sample Designs and Structural Data

Goal: produce identical InGaN MQWs over a wide range of growth temperatures:

- Green QWs (In ≥ 0.20); limited range of T_{QW} for sufficient indium incorporation
- Work with lower In comps (~17 %, blue emission wavelengths)
- Vary ***TMIn flow only*** to maintain similar QW In composition at various T_{QW}

MOCVD-grown InGaN QW Samples



Typical QW Tg for LEDs:
Blue ~750-780 C
Green ~700-740 C

- GaN barrier Tg = 850 C
- Threading dislocation densities ~1e9 cm^{-2} (XRD)

Structural Parameters from XRD and Modeling

T_{QW} (C)	QW Indium Composition	QW Thickness (nm)	GaN Barrier Thickness (nm)
680	0.161	2.56	10.3
700	0.172	2.20	10.0
720	0.166	2.20	10.1
740	0.177	1.89	8.4
760	0.167	2.31	9.4

QW In comp: 16.9 +/- 0

QW Width: 2.2 +/- 0.3