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Assessment of factors controlling conversion efficiency of single-junction III-nitride solar cells

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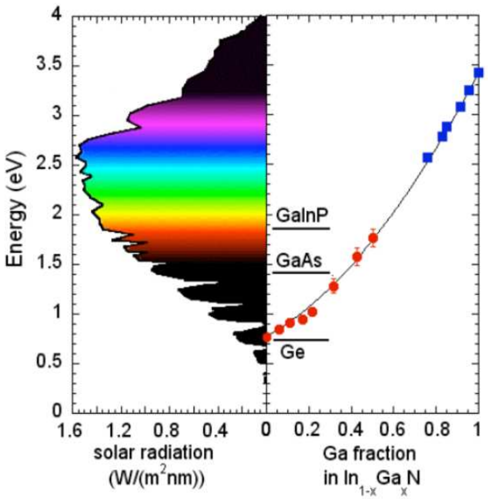
Focus of the reported study



J. W. Ager III et al., Proc. SPIE 5530 (2004) 308

challenges for III-nitride tandem SC fabrication

for tandem structure

- lack of suitable tunnel junctions
  - high acceptor activation energy does not allow getting degenerate p-type bulk materials
- current matching

for every cascade

- hetero-structure design
- defects in InGaN
  - strain relaxation
  - phase separation

→ shunting of the SC p-n junction

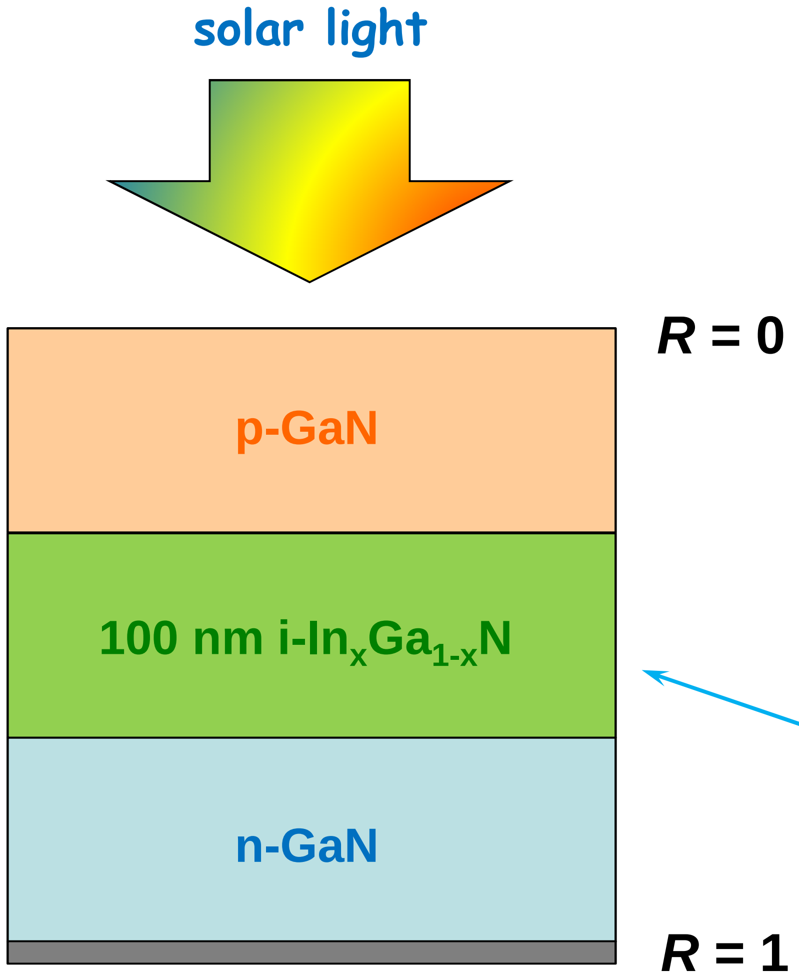
→ shortening of carrier life times & enhancing parasitic recombination

M. Mori et al., APEX 5 (2012) 082301

the effect is closely related to the V-pit formation in InGaN forming conductive channels shunting the SC p-n junction and lowering the open-circuit voltage

Single-junction solar cell structure

PVcell simulator: http://www.str-soft.com/products/solar/



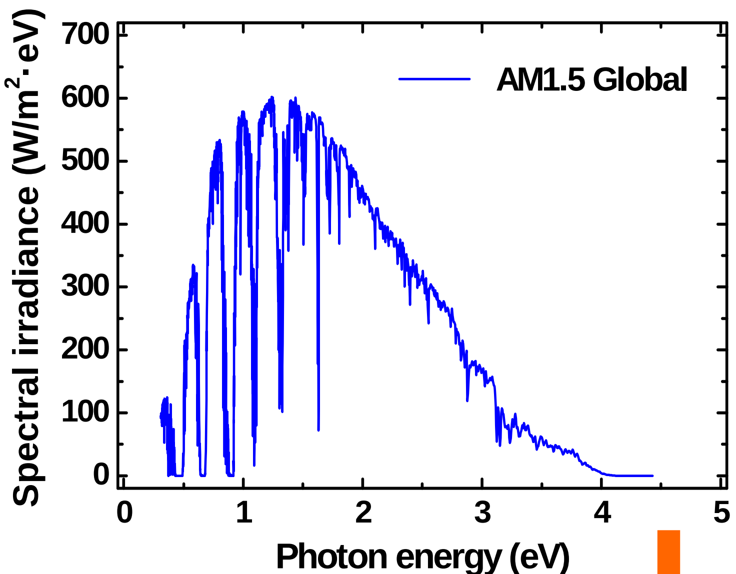
- Poisson equation with account of spontaneous and piezoelectric polarization
- Drift-diffusion model of carrier transport enhanced with the quantum-potential approach for MQWs and superlattices
- Strain effect on the band structure of III-nitride materials, including complex structure of the valence band

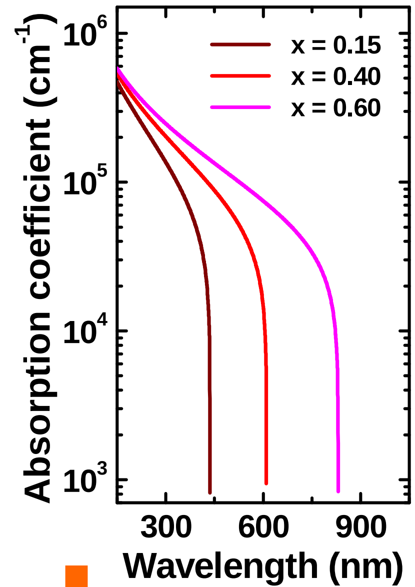
the same electron and hole non-radiative carrier life time τ in the InGaN active layer was chosen for the seek of simplicity

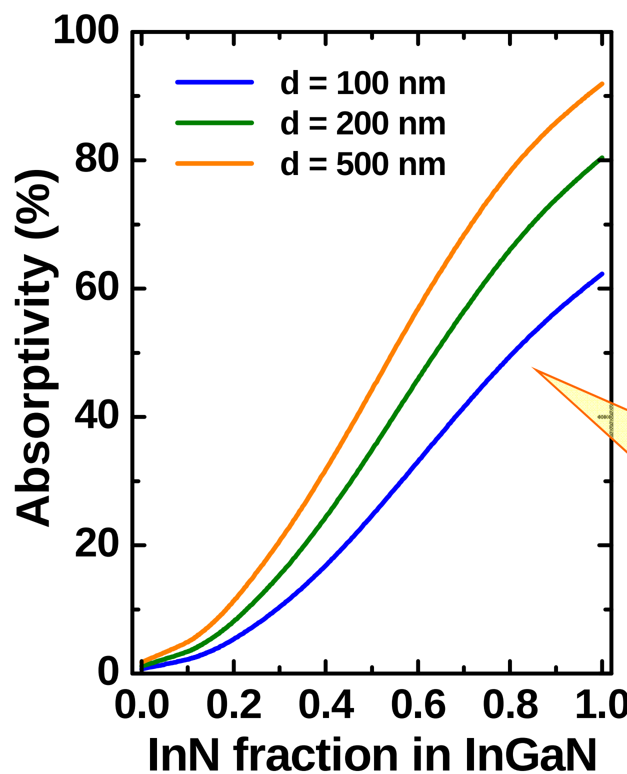
Solar light absorptivity of InGaN layers

$$\alpha(E) = \alpha_0 \sqrt{a(E - E_g) + b(E - E_g)^2}$$

G. F. Brown et al., Solar Energy Mat. & Solar Cells, 94, 478 (2010)





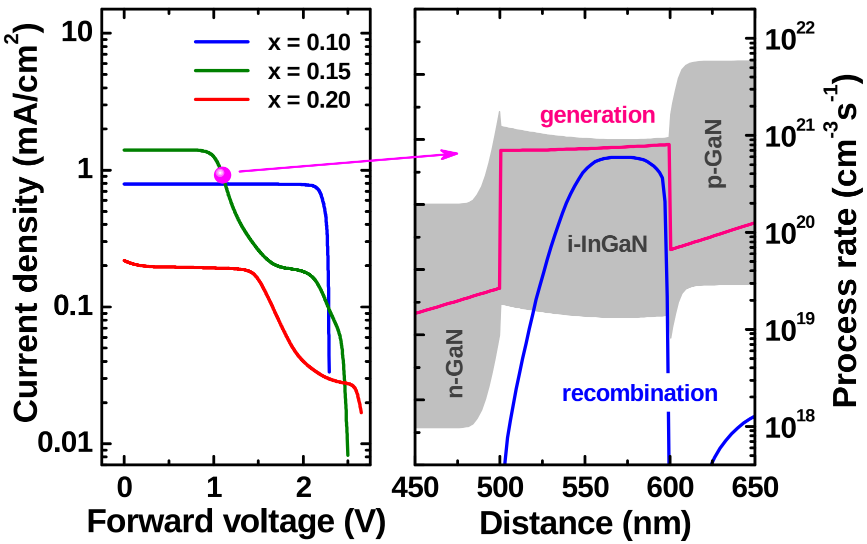


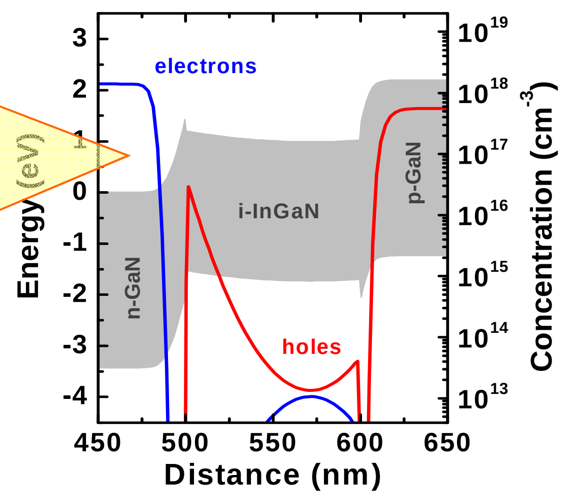
strong dependence on the InGaN alloy composition

even in the layers as thick, as 500 nm, the absorptivity is still incomplete, eventually limiting the solar light conversion efficiency

Polarity effect on operation of strained solar cell structures

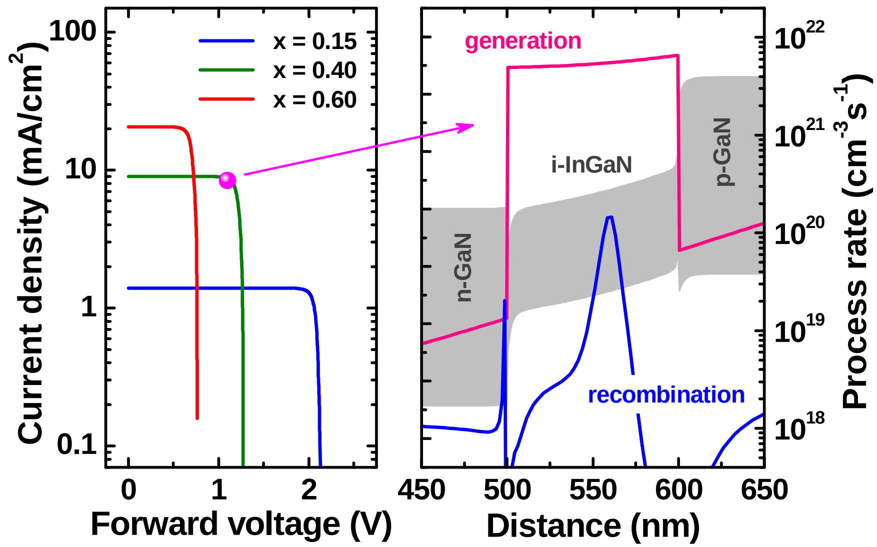
III-polar structure

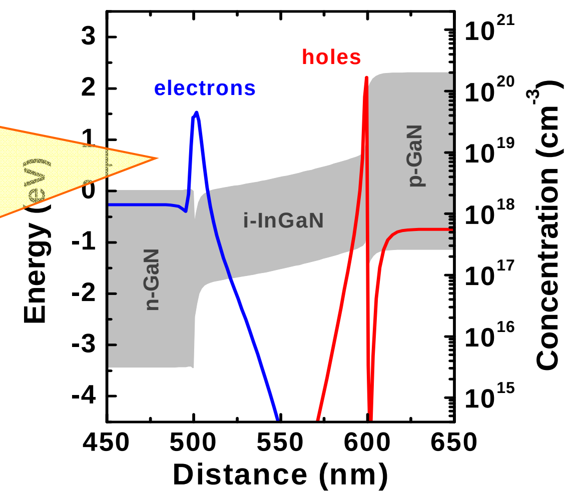




electric field in InGaN hinders separation of electrons and holes, making the structure inoperable at X > 0.20

N-polar structure

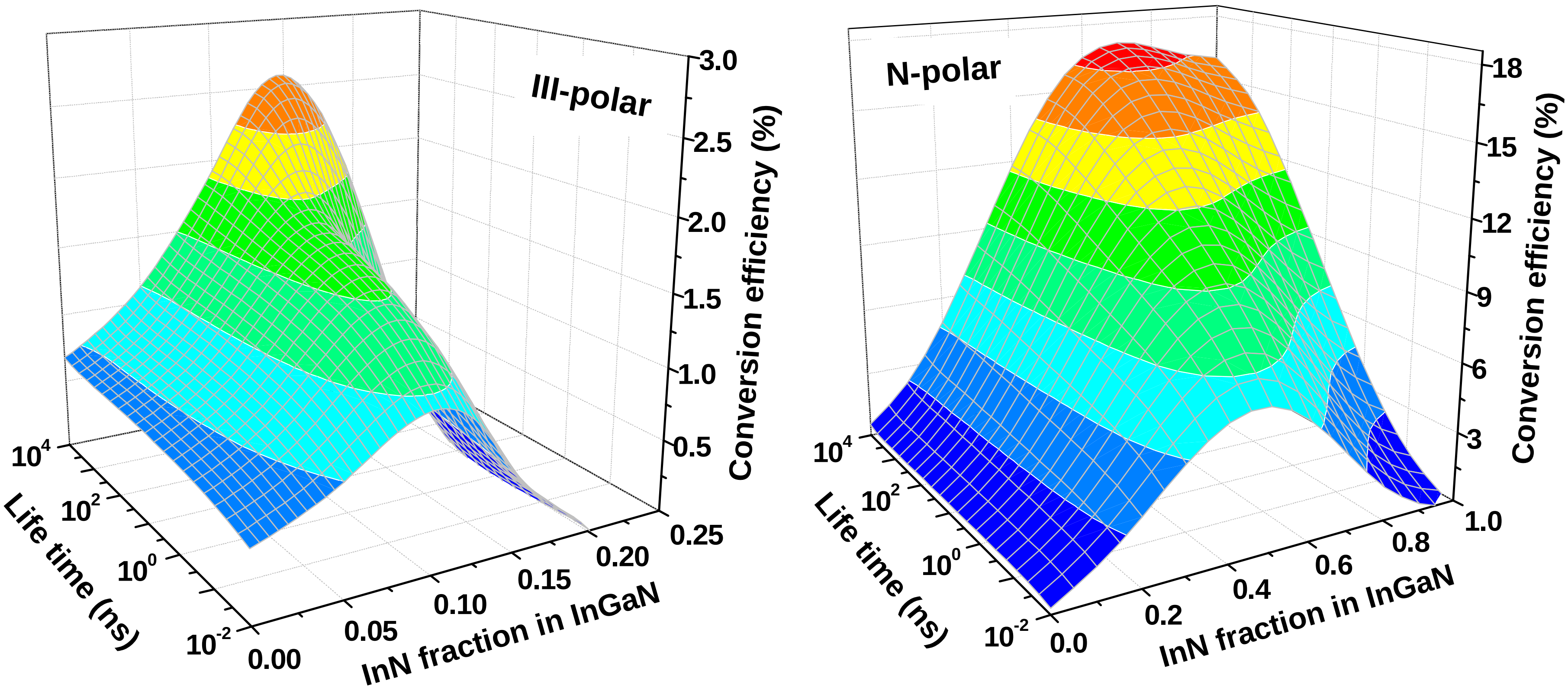




electric field in InGaN favors separation of electrons and holes at any alloy composition

Conversion efficiency of strained solar cell structures

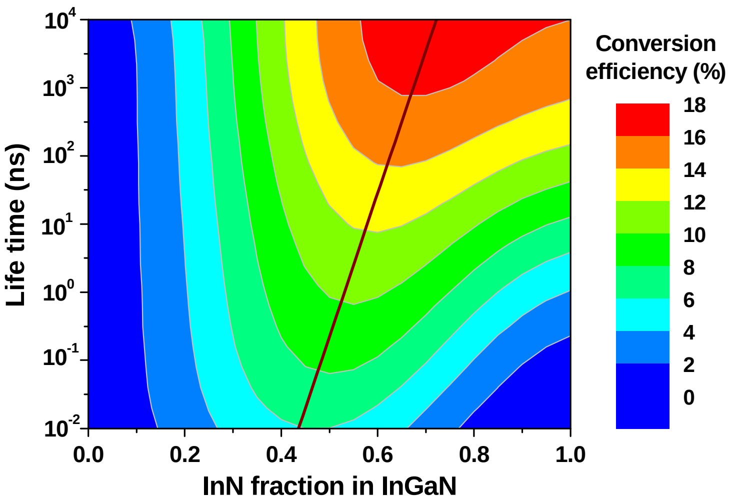
conversion efficiency at 1 sun (AM1.5 Global spectrum)

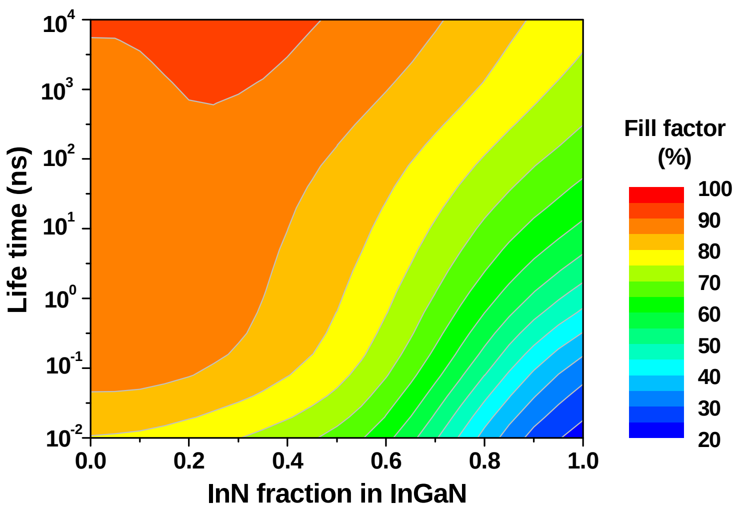


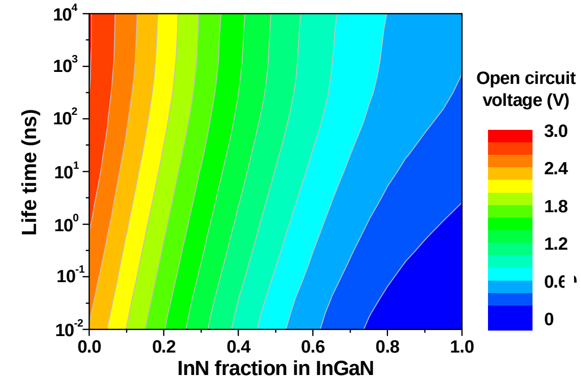
at every polarity, the conversion efficiency is limited by the absorptivity of the InGaN active layer corresponding to the optimal alloy composition; the optimal composition does not exceed ~0.2 in the case of III-polar structure

Characteristics of the strained N-polar structure

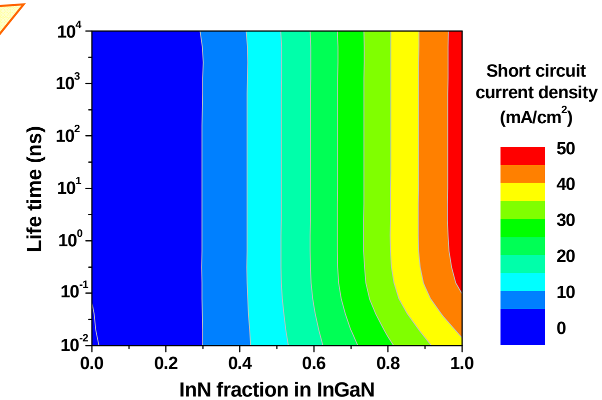
$$X_{opt} = 0.436 + \frac{2 + \log_{10}\tau}{21}$$







open-circuit voltage & short-circuit current do not practically depend on the carrier life time

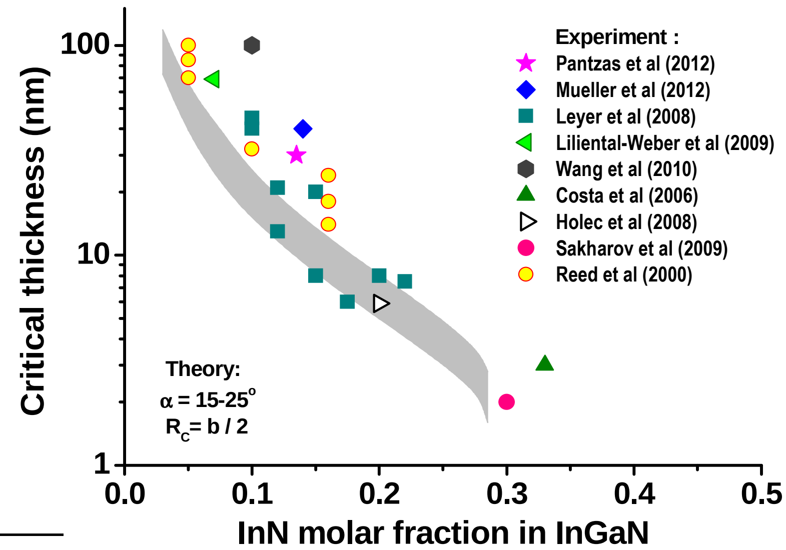


weak dependence of the conversion efficiency on the carrier life time τ : variation of the time by 6 orders of magnitude produces ~2.5-fold change of the conversion efficiency !

Effect of strain relaxation on the solar cell conversion efficiency

full strain relaxation results in inversion of the polarization charges at the InGaN/GaN interfaces, making the structure polarity a factor of secondary importance !

at the same τ , conversion efficiency of the relaxed structures are comparable with that of the strained N-polar structure



A. V. Lobanova et al., ICNS-10, AP1.27

Structure	III-polar strained	III-polar relaxed	N-polar strained	N-polar relaxed
η_{max} @ 10 μs	2.6%	14.2%	17.2%	13.8%
x_{max} @ 10 μs	0.15	0.58	0.70	0.55
η_{max} @ 10 ps	1.0%	5.3%	6.1%	5.4%
x_{max} @ 10 ps	0.10	0.44	0.48	0.45
x_{crit}	0.25	0.80	none	0.70
absorptivity*	3-5%	28-44%	34-57%	29-40%

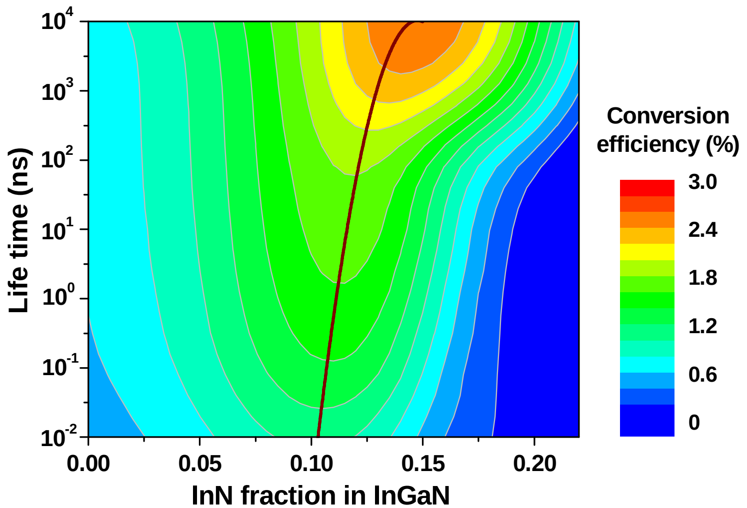
* The ranges of the absorptivity values given in the table correspond to the variation of x_{max} with the carrier life time.

how the defect density produced by strain relaxation affects the SC conversion efficiency ?

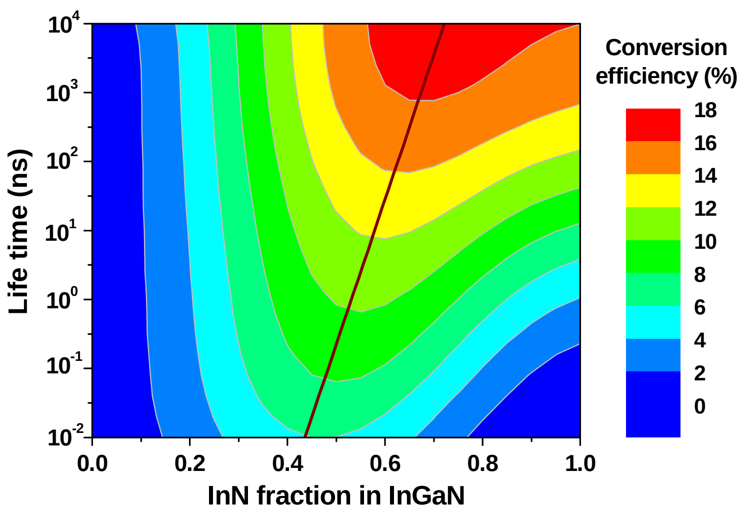
Weak dependence of the conversion efficiency on the carrier life time

variation of τ by 6 orders of magnitude produces ~2.5-fold change of the conversion efficiency !

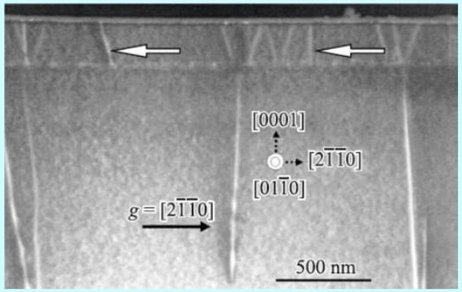
III-polar structure



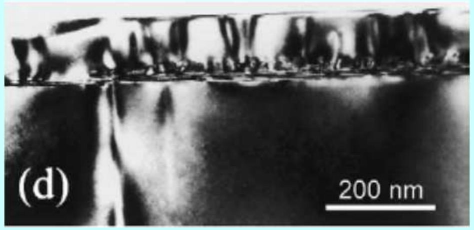
N-polar structure



TEM images of InGaN/GaN structures



A. V. Sakharov et al., Semiconductors 43 (2009) 812



H. K. Cho et al., Appl. Surf. Sci. 221 (2004) 288

experimentally TDD produced in InGaN by strain relaxation may exceed that in underlying GaN by 2-3 orders of magnitude, shortening the life time by a similar factor [S. Karpov & Yu. Makarov, Appl.Phys.Lett. 81 (2002) 4721]; this reduces the SC conversion efficiency by less than ~20%

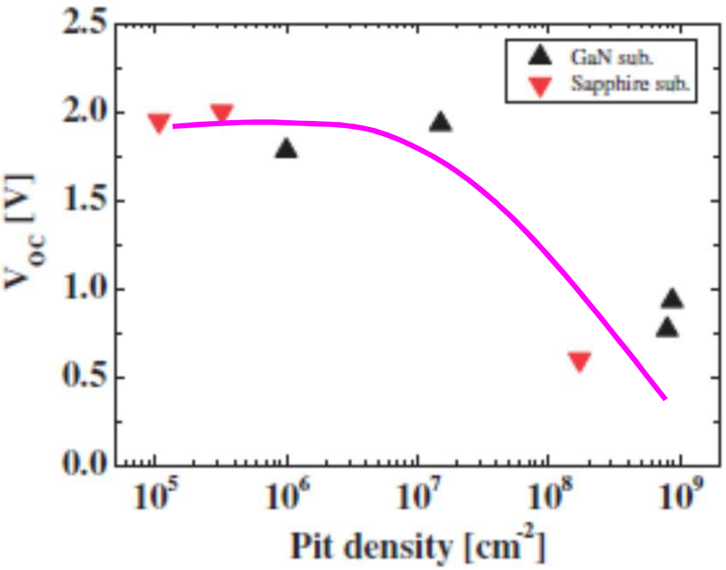
Beyond the scope of theoretical model

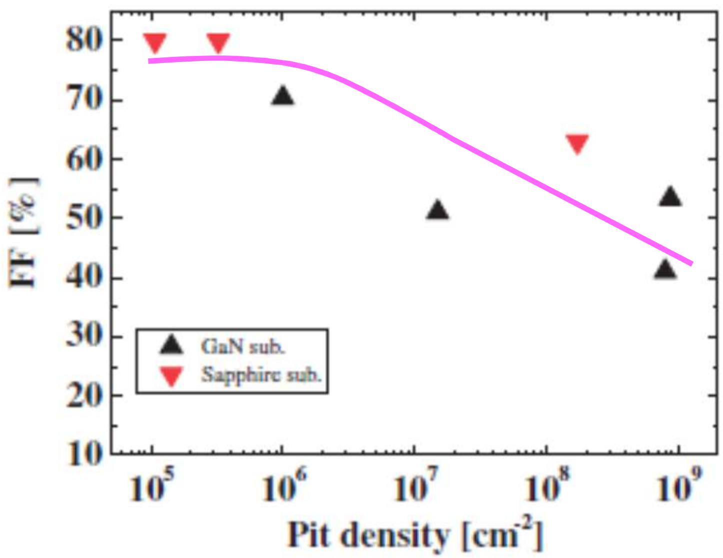
M. Mori et al., APEX 5 (2012) 08230

experiments have revealed a strong correlation between the V-pit density in the grown p-i-n and MQW SC structures and open-circuit voltage and fill-factor, suggesting shunting of the SC p-n junction by conductive channels formed in the V-pits

the V-pit formation largely depends not only on the InGaN composition but also on the growth conditions; therefore their impact on the SC performance cannot be accounted for within our theoretical model

the observed 3-4-fold reduction of the open-circuit voltage caused by the V-pit formation may affect considerably the SC conversion efficiency





Conclusions

- a proper SC structure design should account for the built-in polarization fields affected by both InGaN composition and strain state of the whole heterostructure; a strained N-polar n-GaN/InGaN/p-GaN seems to be most advantageous for achieving high efficiency
- conversion efficiency of a properly designed SC structure is largely controlled by absorptivity of the InGaN active layer; increase of the layer thickness is quite desirable for getting a higher absorptivity
- the SC performance seems to be rather tolerant to shortening of the non-radiative carrier life time, e.g. caused by strain relaxation in InGaN
- parasitic shunting of the SC p-n junctions may largely affect the conversion efficiency; to account for this factor, detailed understanding of the shunting mechanism and its relation to the materials properties and SC structure growth conditions is necessary for further improvement of the device performance