# Polarization doping: new opportunities for III-nitride optoelectronics

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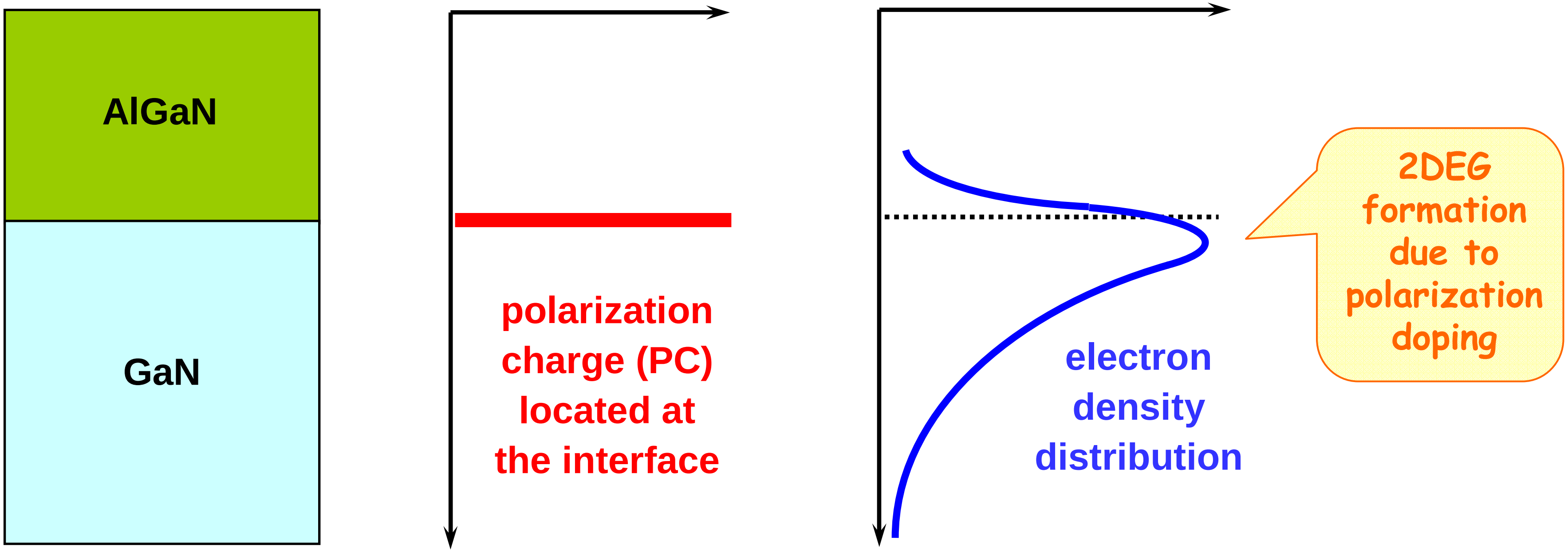
# Polarization doping for High-Electron Mobility Transistors

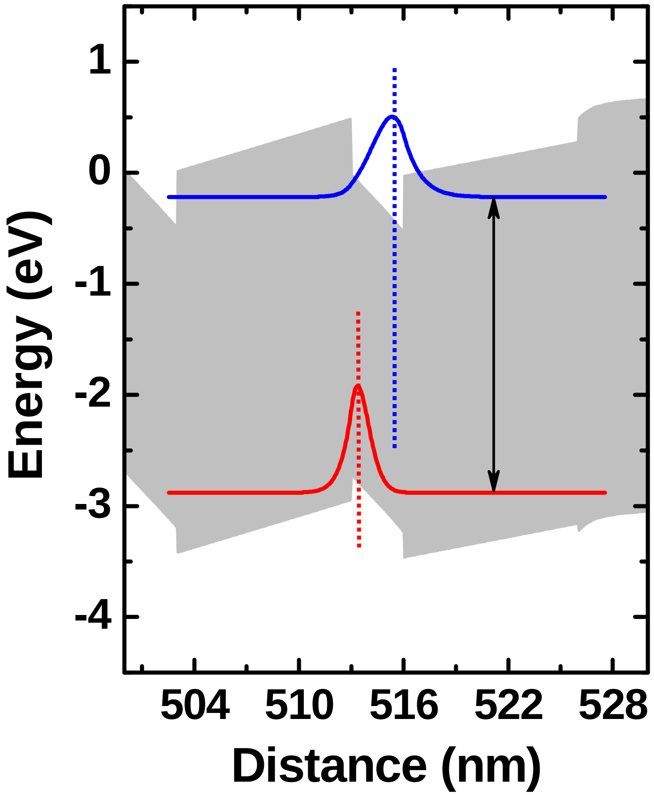



A. Bykhovsky et al., J. Appl. Phys. 74 (1993) 6734 – strong piezoeffect

F. Bernardini et al., Phys. Rev. B 56 (1997) R10024 – spontaneous polarization

at the moment, polarization doping is routinely exploiting in AlGaN/GaN and AlInN/GaN HEMTs, providing the sheet electron concentration in the range of ~$0.8-2.6\times10^{13}$ $cm^{-2}$

# Polarization impact on LED and laser diode performance

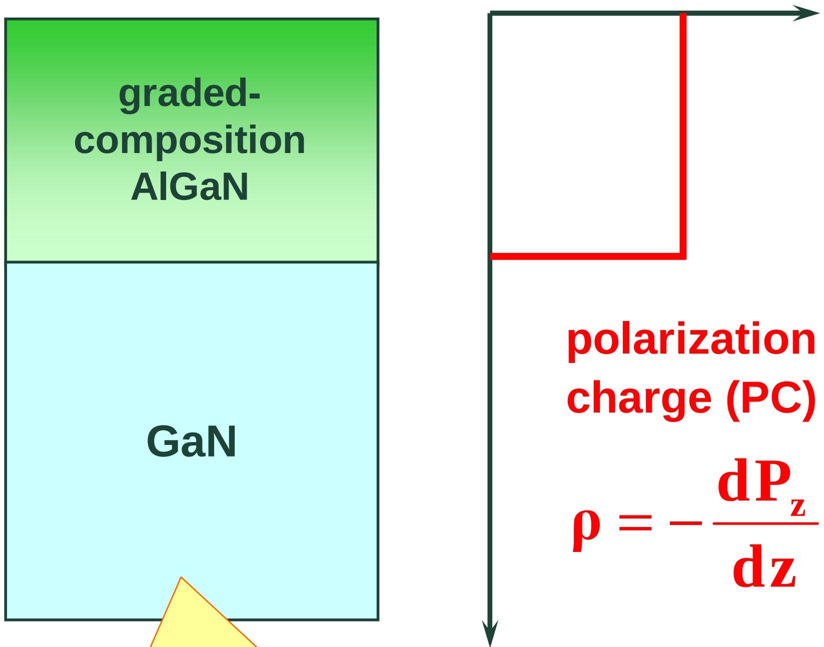



n-GaN / 5×(InGaN/GaN) / p-AlGaN / p-GaN LED structure

Negative impact of polarization charges on performance of [0001] LED and LD structures:

- interface polarization charges induce built-in electric field in InGaN QW resulting in a large separation of electron and hole wave functions; this leads to reduction of the photon emission rate and, eventually, in a lower IQE of the [0001] LED structure
- electric field induced in the MQW active region leads also to increased operation voltage of the LEDs
- polarization charges at the LED structure interfaces provide the conduction and valence band alignment favoring the electron leakage in the p-side of the heterostructure

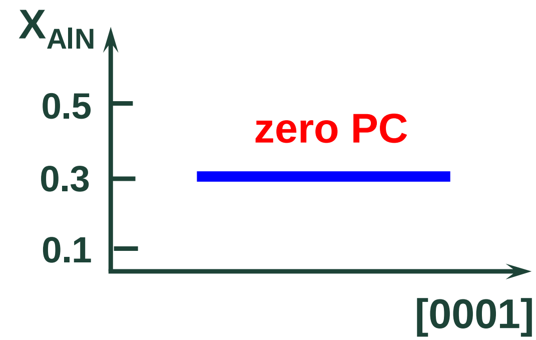
# Fundamentals of distributed polarization doping (DPD)



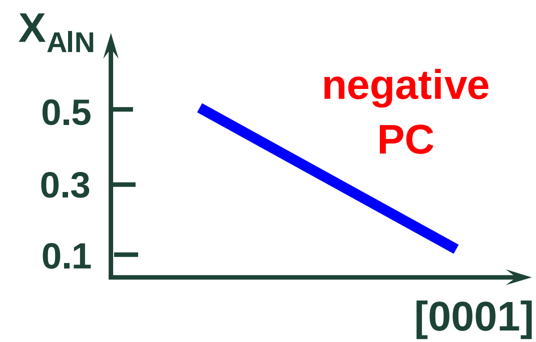

$$\rho = -\frac{dP_z}{dz}$$

Distributed polarization doping (DPD) has been initially proposed for III-nitride FETs

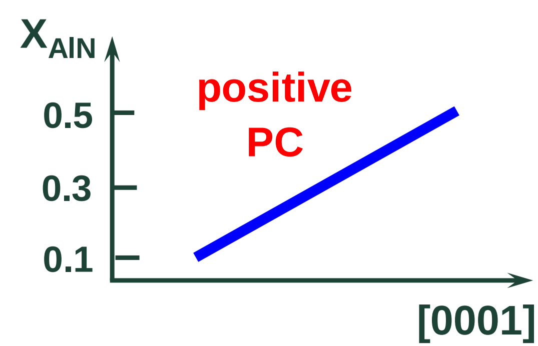
PCs are formed at interfaces only




p-type DPD inducing holes in the material



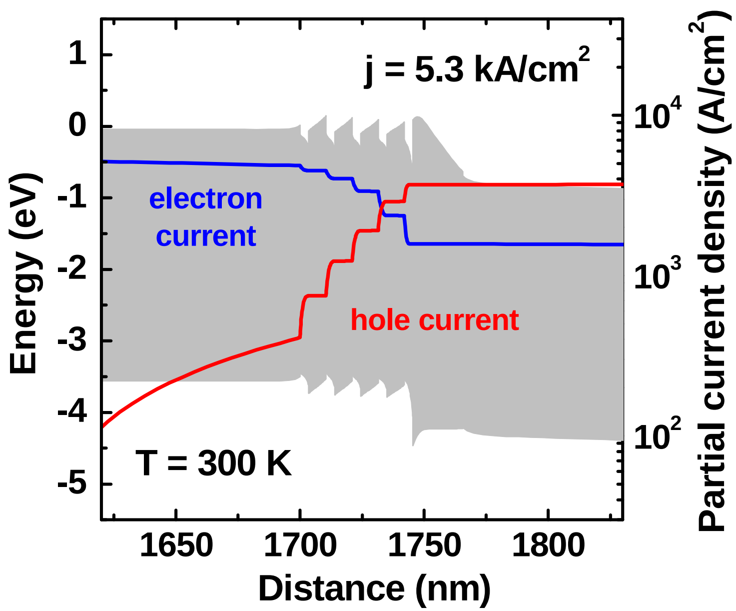

n-type DPD inducing electrons in the material

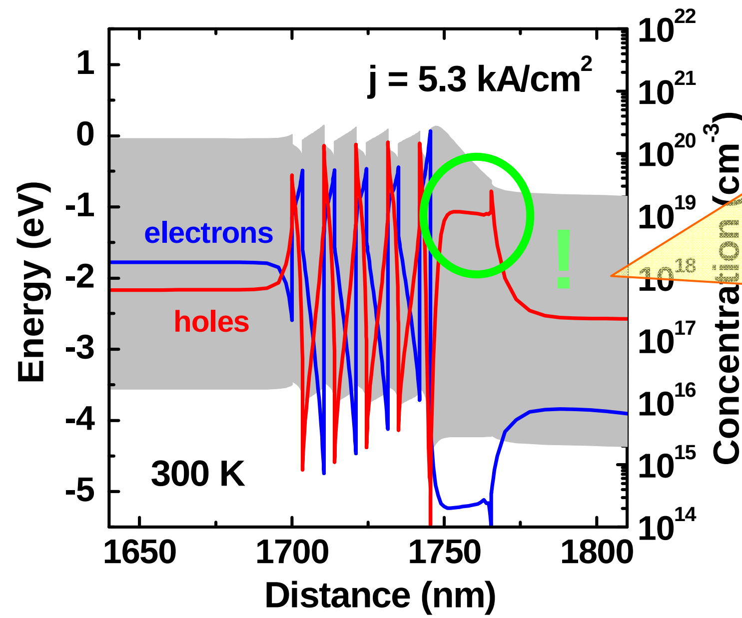



<u>Experiment:</u> D. Jena et al., Phys.Stat.Solidi (c) 0 (2003) 2339 – n-type DPD

# How to attain high hole concentration by DPD?

UV laser diode structure with graded-composition EBL



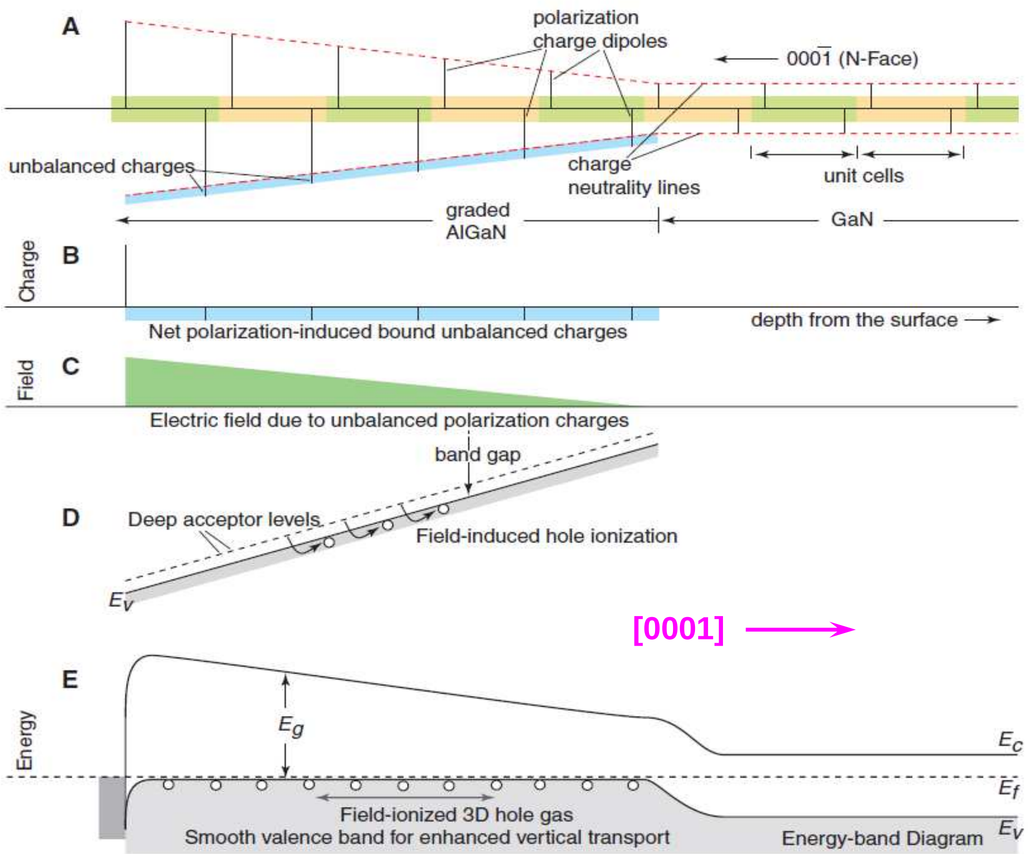



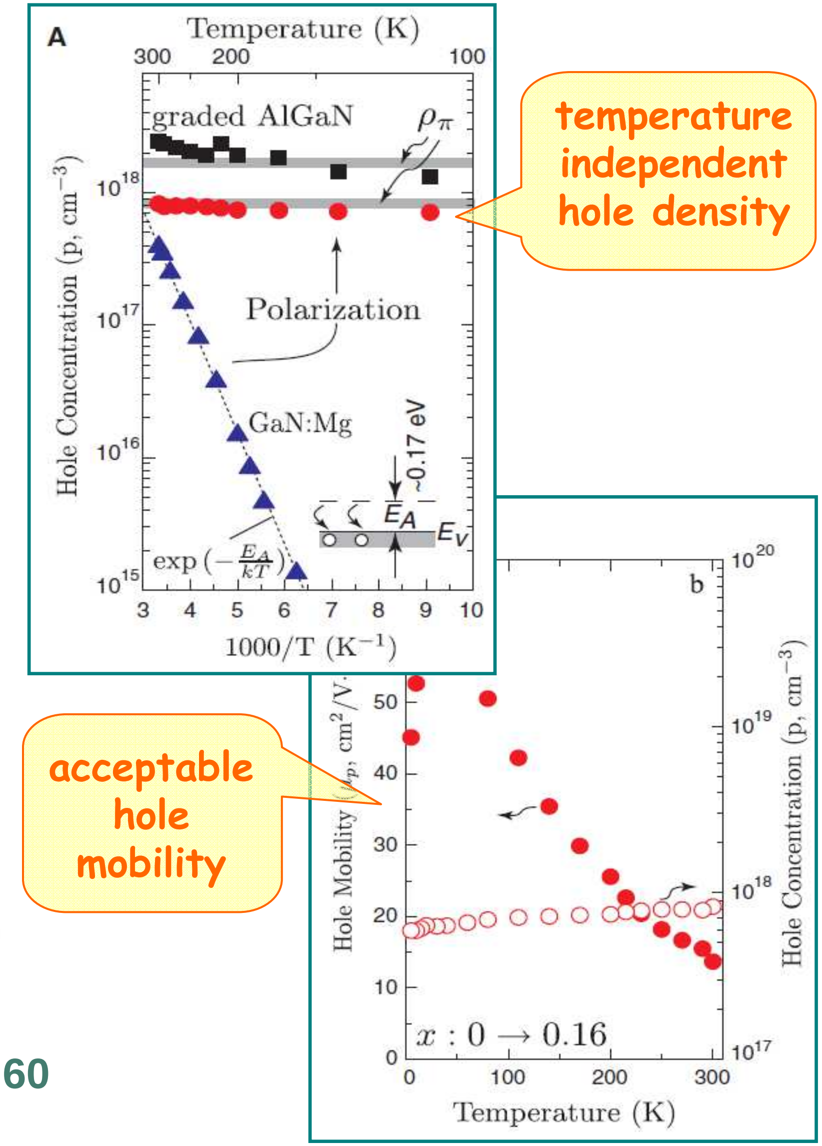

such a high hole density can never be obtained by conventional doping with Mg impurities

simulations of a UV laser diode operation have demonstrated a new way for achieving high hole concentration in graded-composition III-nitride alloys, which is quite promising for design of advanced optoelectronic devices

<u>Simulation:</u> K. A. Bulashevich et al., Proc. 3rd APWS, Jeonju (2007) 192

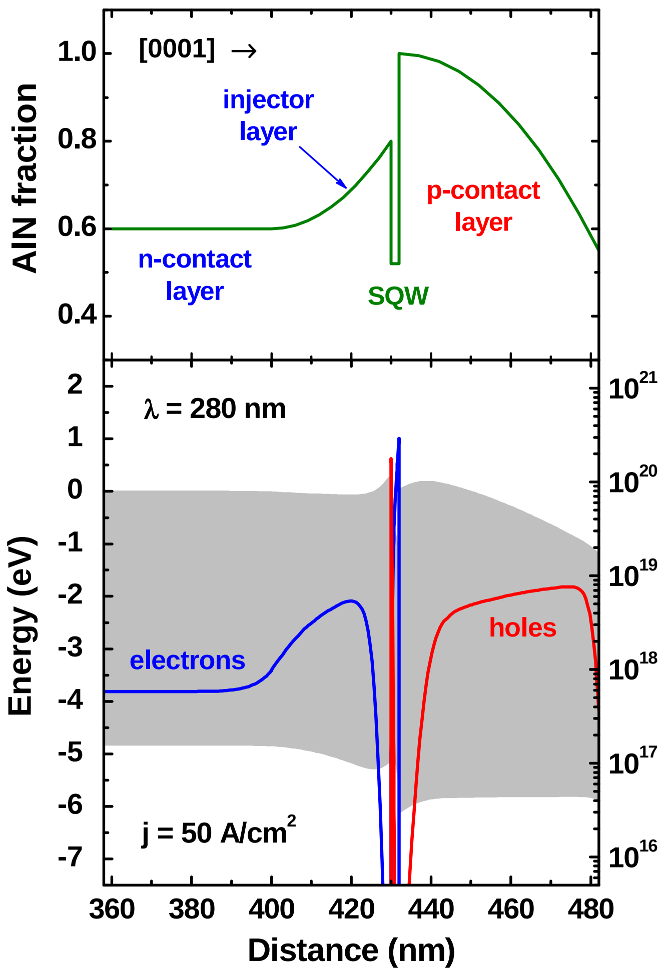
# Experimental confirmation of the *p*-type DPD concept

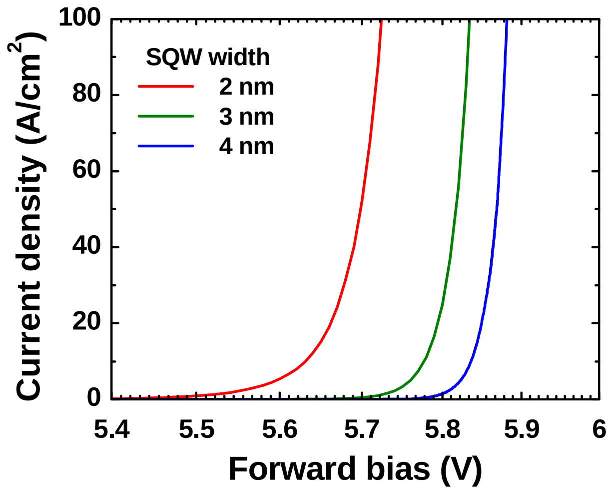


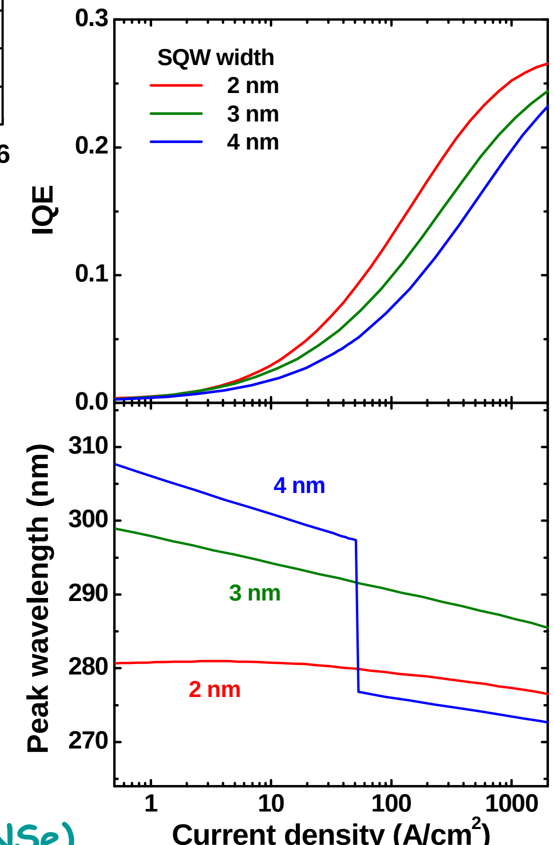

**Experiment:** J. Simon et al., Science 327 (2010) 60

# Acceptor-free deep-UV LED structure



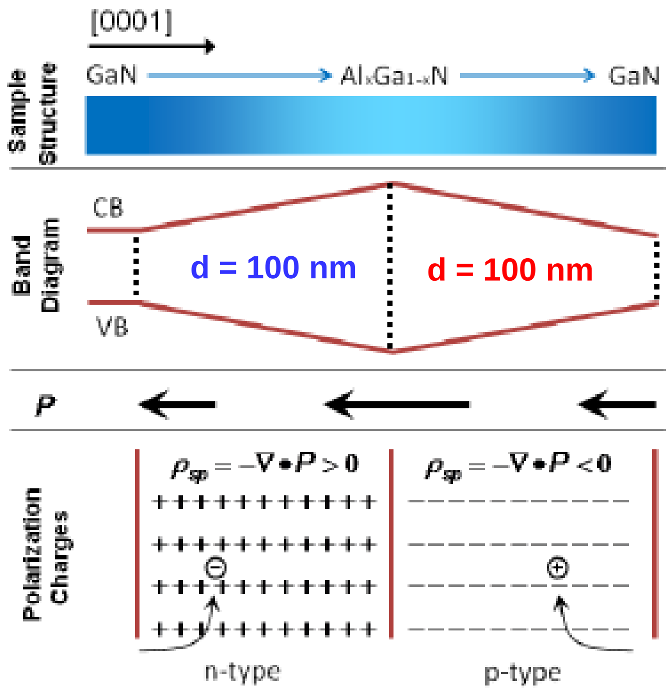

LED characteristics depend strongly on the SQW width



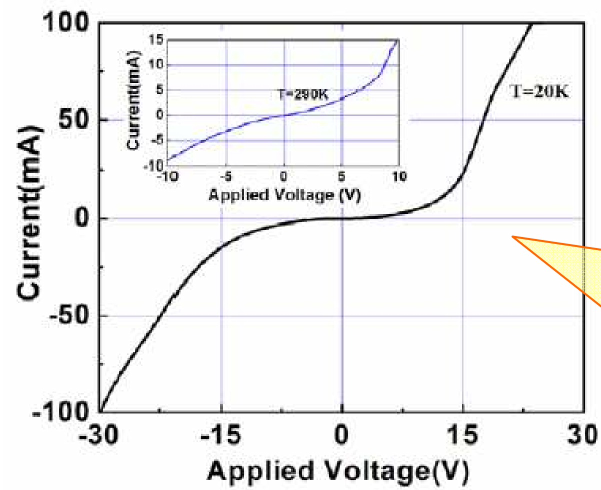

p-type DPD provides high hole density in the whole EBL/p-contact layer without using of Mg acceptors !

Simulation by SiLENSe 5.1 (http://www.str-soft.com/products/SiLENSe)

# Feasibility of polarization-doped *p-n* junction

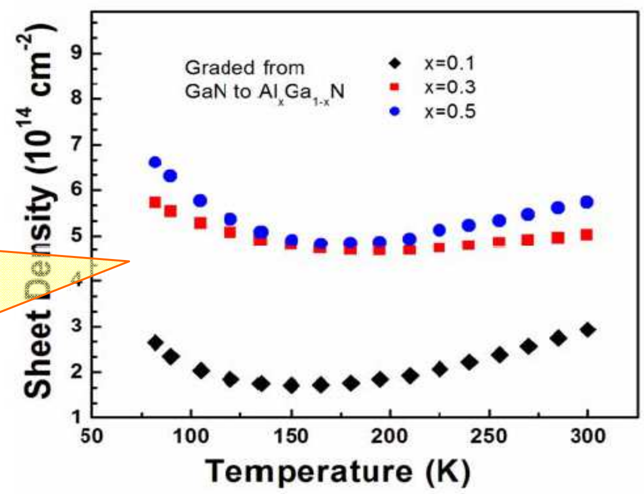



DPD p-n junction structure grown by PAMBE




diode characteristics has been demonstrated by DPD p-n junction

carrier density depends on the composition gradient in the AlGaN alloys

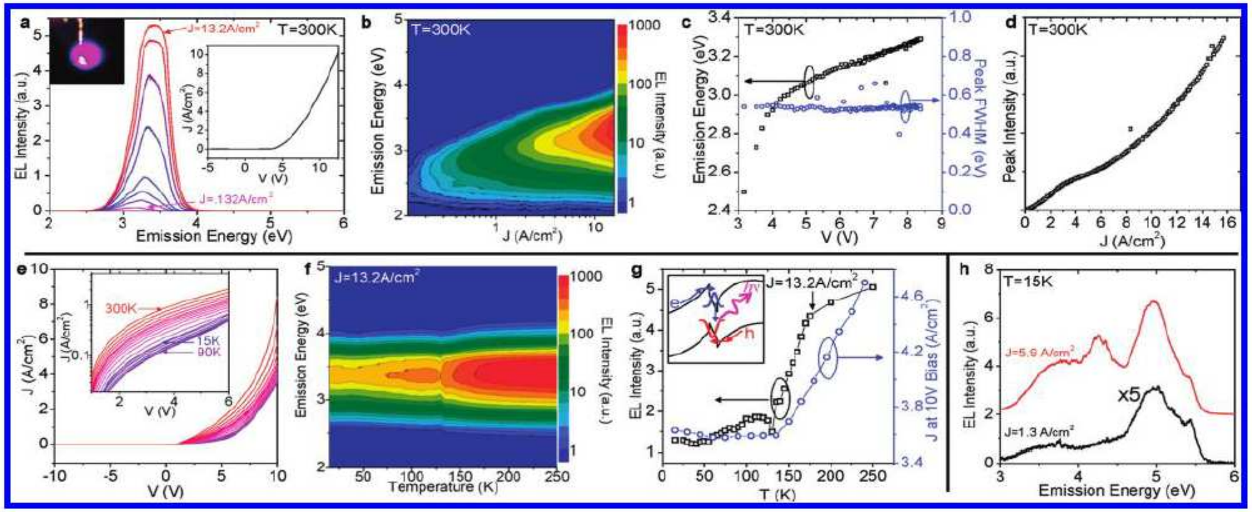


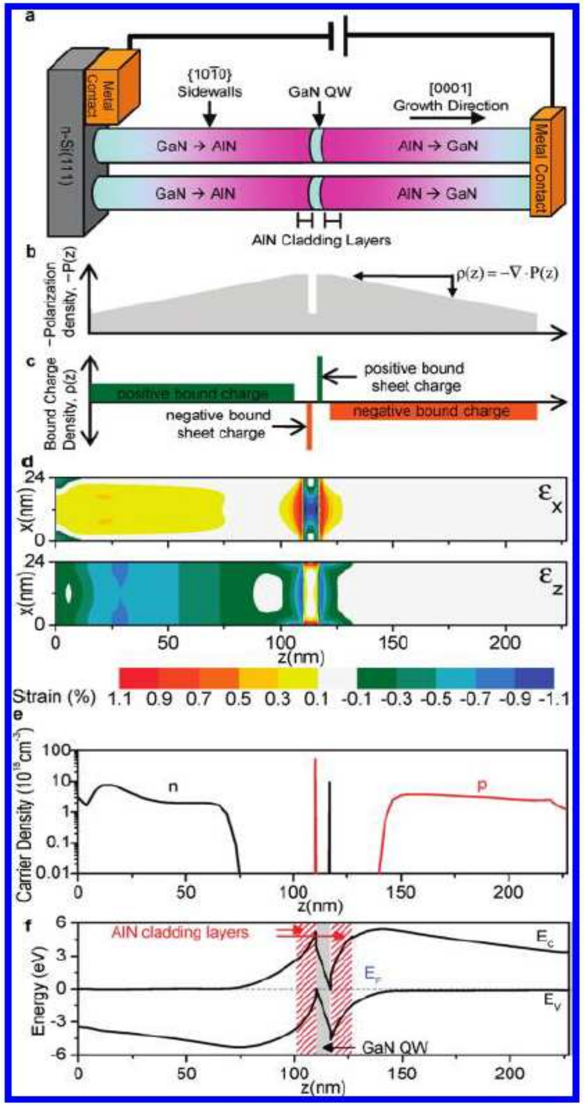

Experiment: S. Li et al., Phys. Stat. Solidi (c) 7/8 (2011) 2182

# Feasibility of polarization-doped UV LED structures

deep-UV nanowire LED structures with 7 nm GaN SQW and 110 nm DPD AlGaN claddings were grown be PAMBE (with the nanowire diameter of ~25 nm)

both SQW and DPD-AlGaN cladding designs were far from optimal ones

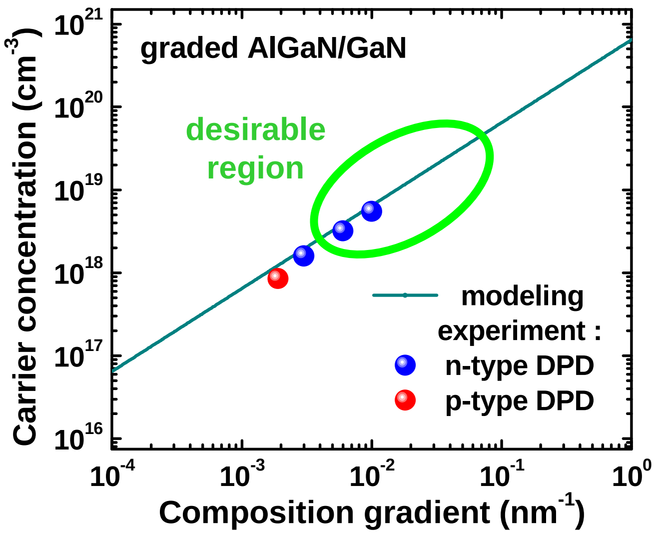


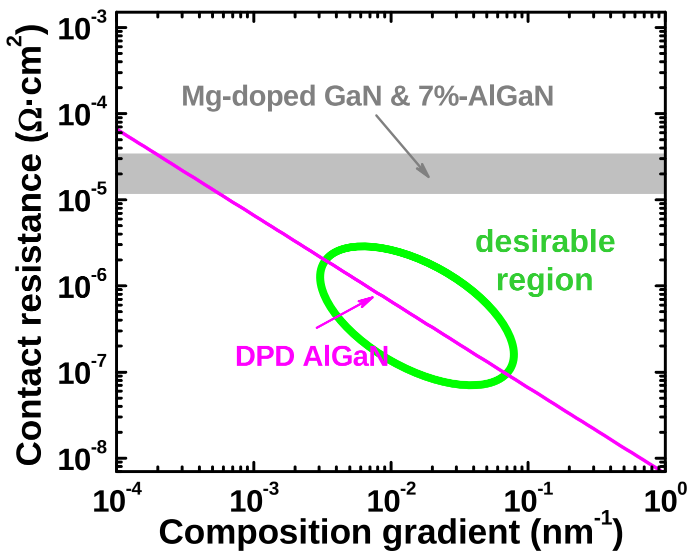


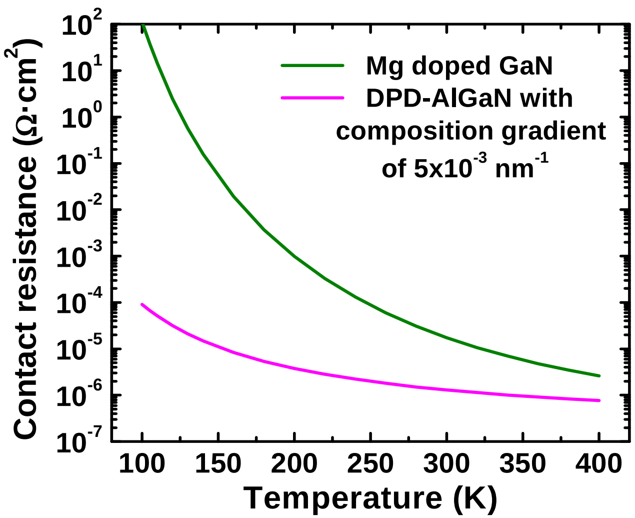
<u>Experiment:</u> S. D. Carnevale et al., Nanoletters 12 (2012) 915

# Low-resistance *p*-type Ohmic contact based on polarization doping

annealed Ni/Au contacts to graded AlGaN alloys with the Al content descending along the [0001] direction from a certain value to zero




$$\rho_c = \frac{kT}{q} \cdot \frac{\exp(\Phi_b/kT)}{\sum_{s=\mathrm{hh,lh,sh}} p_s V_s T_s^{\mathrm{av}}}$$

<u>Experiment and model:</u> S. Nikishin et al., Appl. Phys. Lett. 95 (2009) 164502

# Feasibility of Ohmic contacts formed to graded-composition AlGaN

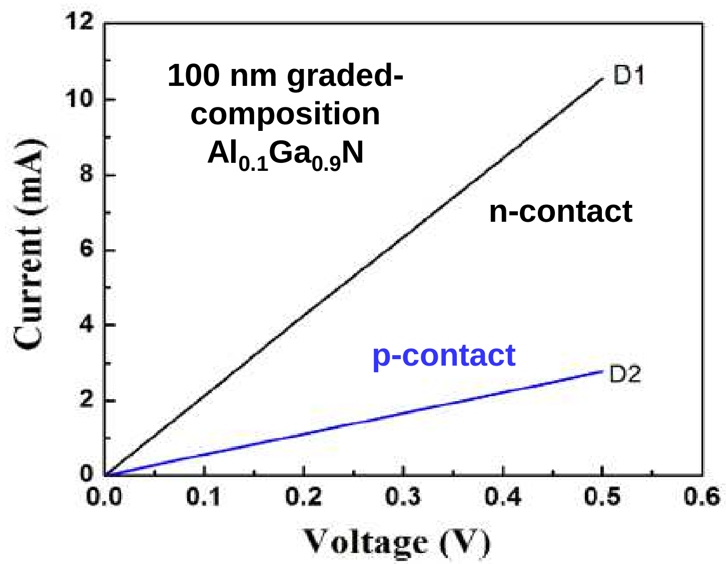



FIG. 1. Linear IV curves demonstrating ohmic contact for n- and p-type graded AlGaN layer. D1 is the IV curve for polarization induced n-type doping of a 10% graded $Al_xGa_{1-x}N$ ($x = 0.1$) film; D2 is the IV curve for polarization induced p-type doping of a 10% graded $Al_xGa_{1-x}N$ ($x = 0.1$) film. The RTP for n-type was at 800 °C for 30 s and 750 °C for 20 s for p-type.

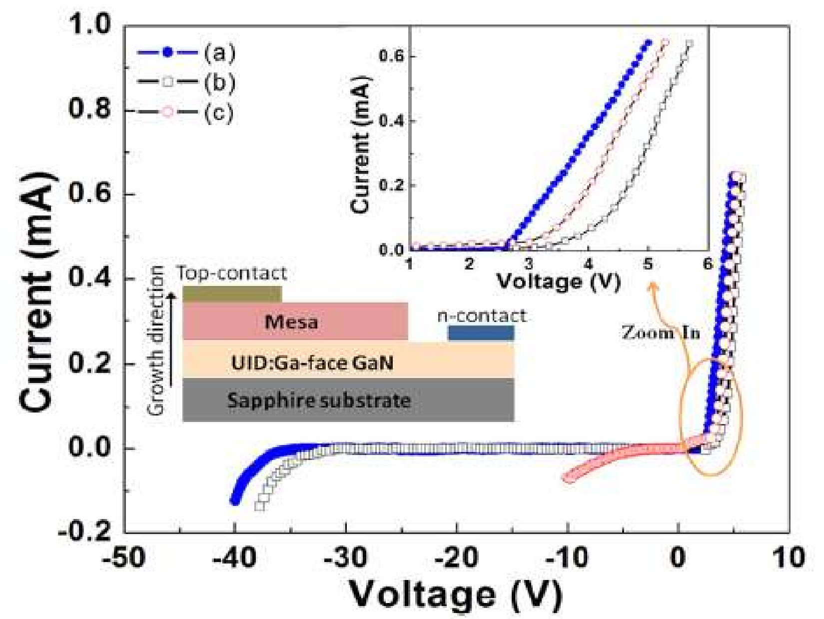



FIG. 4. Current-Voltage measurement for (a) regular doped GaN pn junction, (b) graded $Al_{0.1}Ga_{0.9}N$ pn-junction, and (c) Schottky diode. The mesa is Si and Mg doped GaN pn junction in a device (a); the mesa is graded $Al_{0.1}Ga_{0.9}N$ pn-junction in device (b); the mesa is undoped GaN film in device (c).

linear I-V characteristics is demonstrated for Ohmic contact to acceptor-free DPD AlGaN

diode characteristics of the DPD AlGaN *p-n* junction, impurity-doped GaN *p-n* junction, and GaN Schottky barrier

<u>Experiment:</u> S. Li et al., Appl. Phys. Lett. 1018 (2012) 122103

# Conclusions

- simulations show that the use of distributed polarization doping (DPD) provides new opportunities for design of advance optoelectronic devices like LEDs, laser diodes, and solar cells
- first experimental studies support the DPD concept in general but they do not utilize in full measure all its advantages, being carried out under conditions far from optimal ones
- a prototype of deep-UV LED structure is proposed and examined theoretically; it is found to be quite promising for improving the p-type conductivity in the heterostructure and forming low-resistance p-contacts to the LED
- implementation of the DPD concept in the device fabrication technology will require special approaches for precise control of the composition profile and strain relaxation in the device structures during their epitaxial growth