Deep Level Analysis of Homoepitaxial ZnO Doped with N

A. Kurtz, A. Hierro, L. Gura, E. Muñoz
ISOM and Dept. Electrical Eng., Technical Univ. Madrid, Spain
J. M. Chauveau
CHREA-CNRS, Valbonne, France

Contact email: adrian.hierro@upm.es

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Introduction

What blocks the full development of oxides? p-type doping

- High intrinsic carrier concentration (n-type)
- Efforts to reduce this effect:
  - Homoepitaxy[1]
  - Non-polar orientations
- Similar samples exhibit residual doping as low as ~10^{14} cm^{-3} (2)

The path to p-type doping

- Many dopants proposed
- N is a promising candidate
  - Simple N_O is a deep level
  - Complex levels have shallower energies
- N-related levels observed near the VB by many groups
  - Energies between 130 meV and 160 meV from VBM

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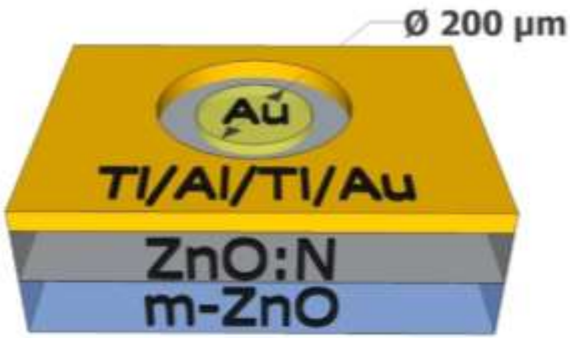
[1] **Lautenschlaeger et al., *J.Cryst.Growth* 312, (2011)**

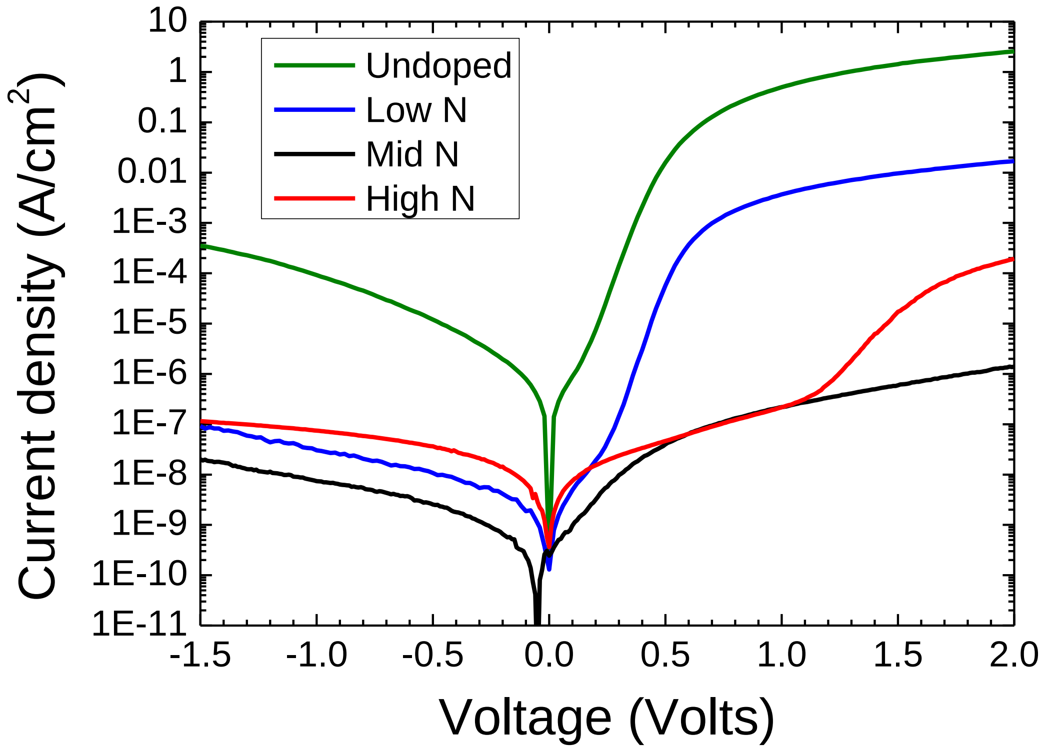
[2] **Taïnoff et al., *Appl.Phys.Lett. 98,* 131915, (2011)**

Sample description

Sample	Ideality factor	Barrier height (eV)	Rs (Ω·cm^2)	Rc (Ω·cm^2)	Thickness (µm)
Undoped	1.3	1.0	0.4	$9.5 \cdot 10^7$	1.5
Low N	1.2	1.2	61.5	$4.2 \cdot 10^9$	1.3
Mid N	3.3	1.2	$4.8 \cdot 10^5$	$1.1 \cdot 10^{10}$	1.5
High N	-	-	-	-	1.8

- Grown by MBE on m-plane ZnO
- Doped with N[1]
- Semitransparent 100 Å-thick Au Schottky diodes
- Surface treated with H_2O_2

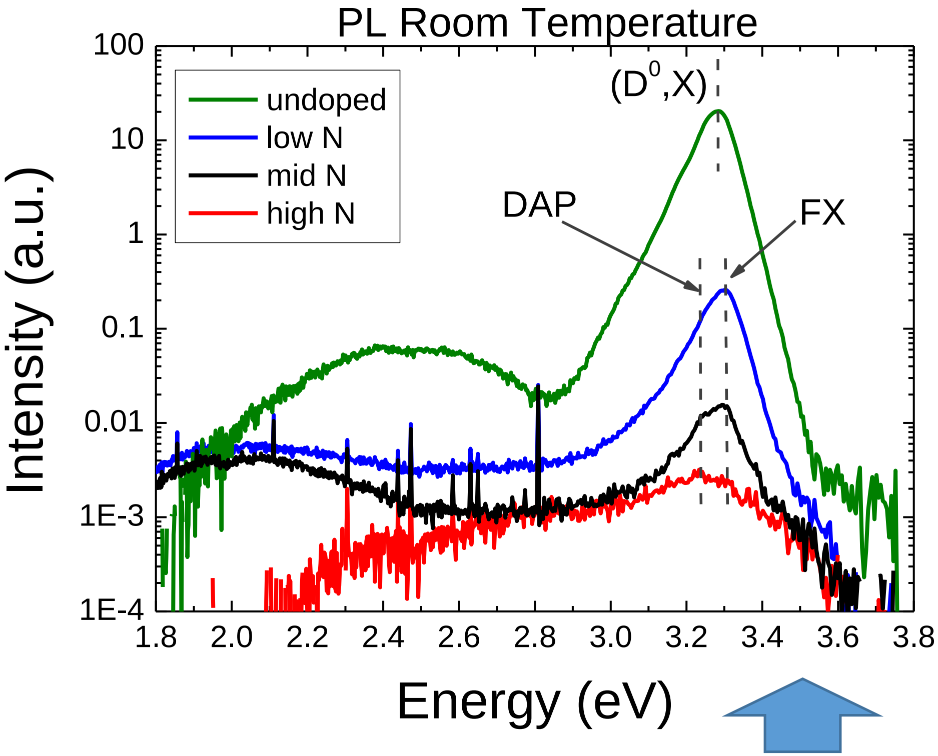


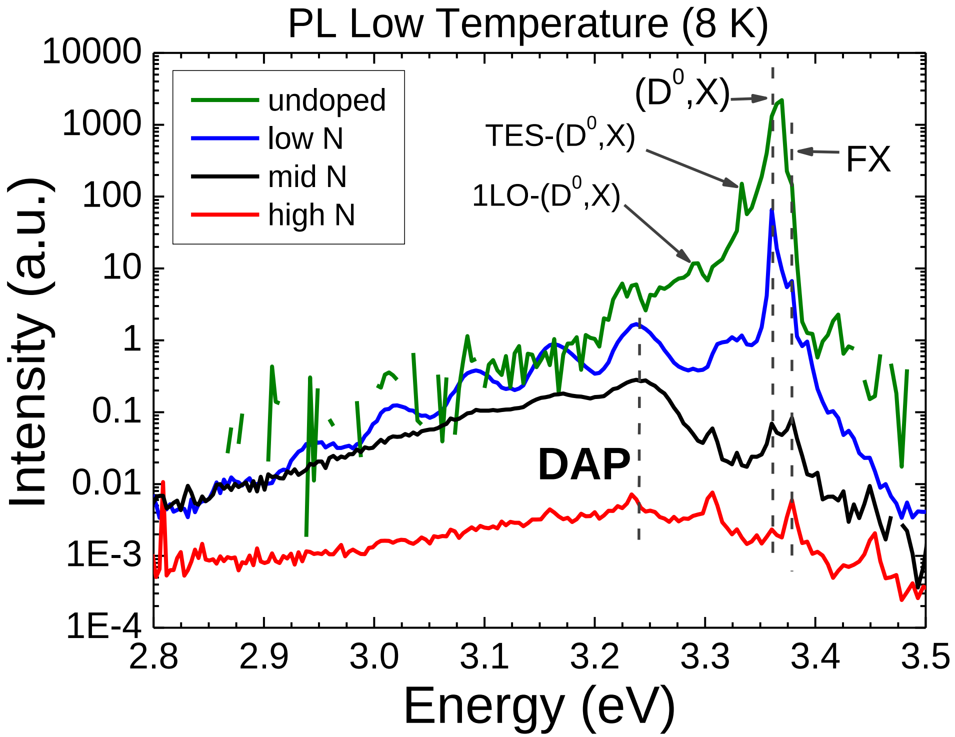


[1] Taïnoff et al., *Appl.Phys.Lett. 98,* 131915, (2011)

Photoluminescence (PL)

- DAP at low T observed, similar to previous results[1]
- [N]~10^{19} cm^{-3} in mid N sample [1]





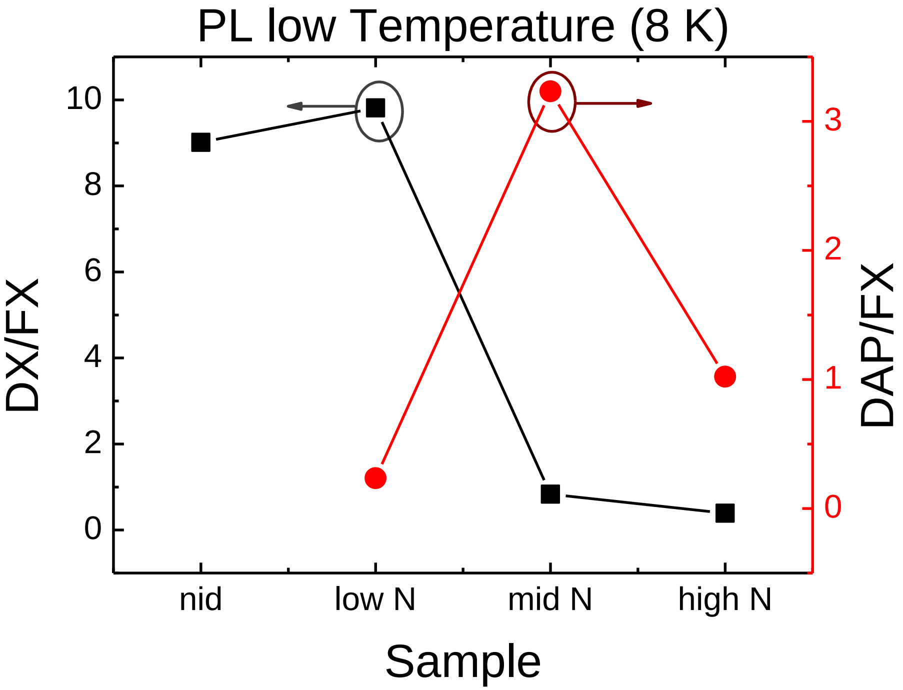
RT-DAP at 0.12 eV below E_g=3.37 eV

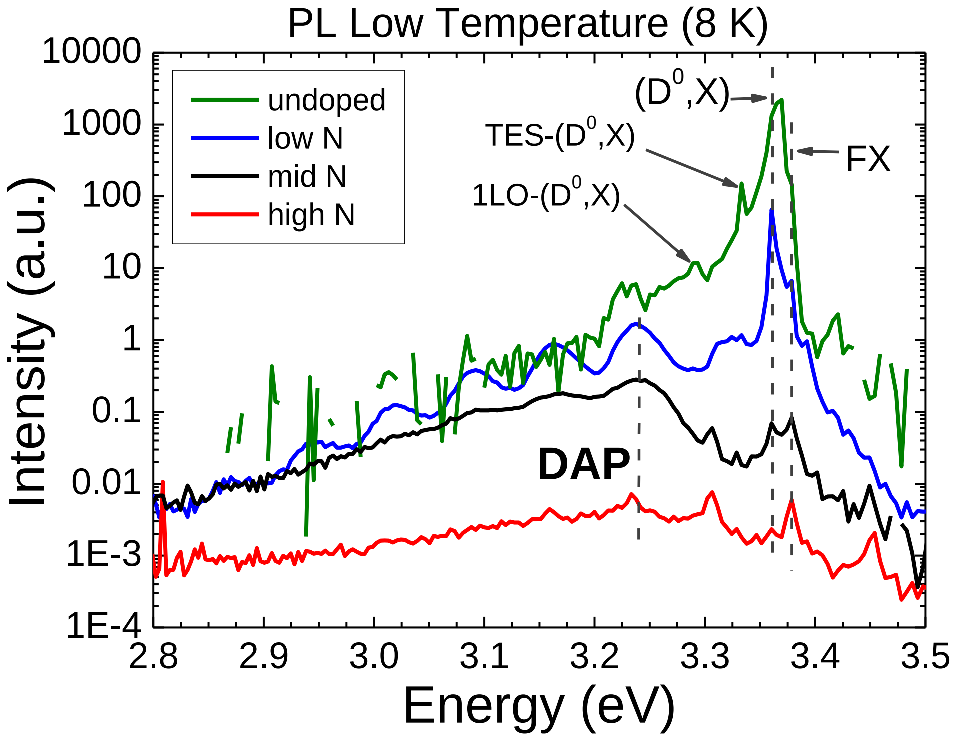
High crystalline quality: FX, D^0X, TES- D^0X, LO- D^0X observed

[1] Taïnoff et al., *Appl.Phys.Lett.* 98, 131915, (2011)
[2] H. Morkoç, U. Özgür, Zinc Oxide Fundamentals, Materials and Device Technology, Wiley (2009)

PL analysis

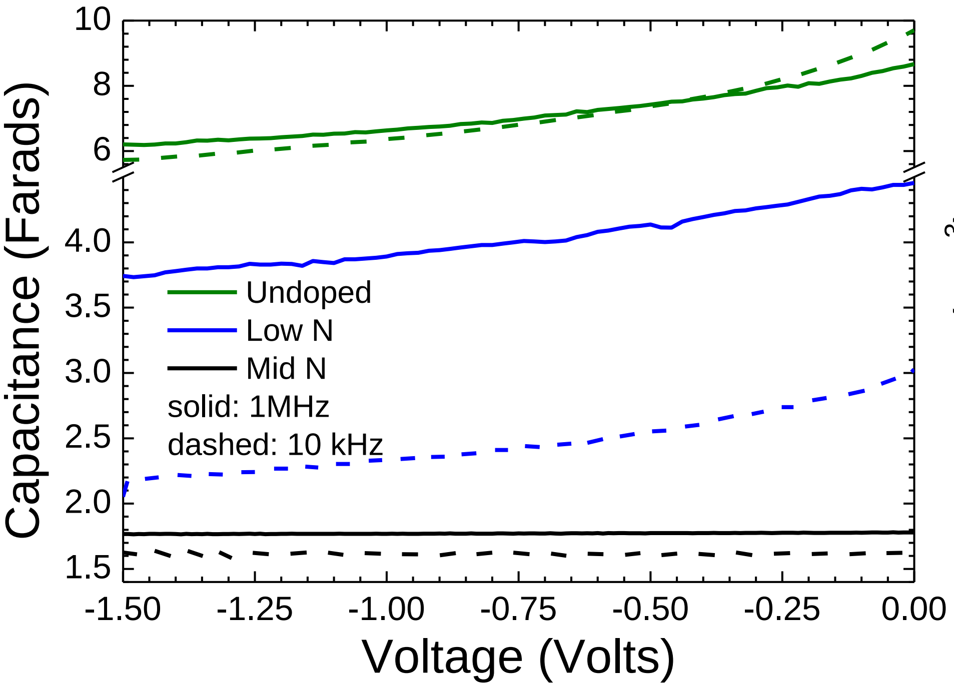
- Donor-bound exciton (D^0,X) decays with N concentration and FX remains → N incorporation reduces the donor concentration ?
- Donor-acceptor-pair (DAP) appears with N and dominates → Acceptors incorporated

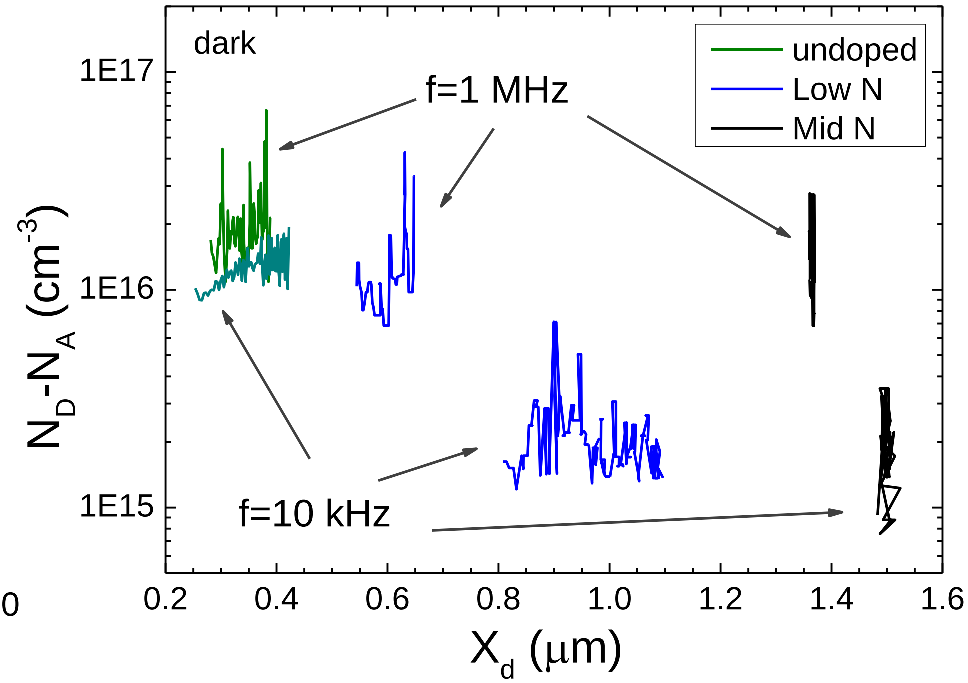




DAP dominates for increasing N concentration

Capacitance-Voltage (CV)



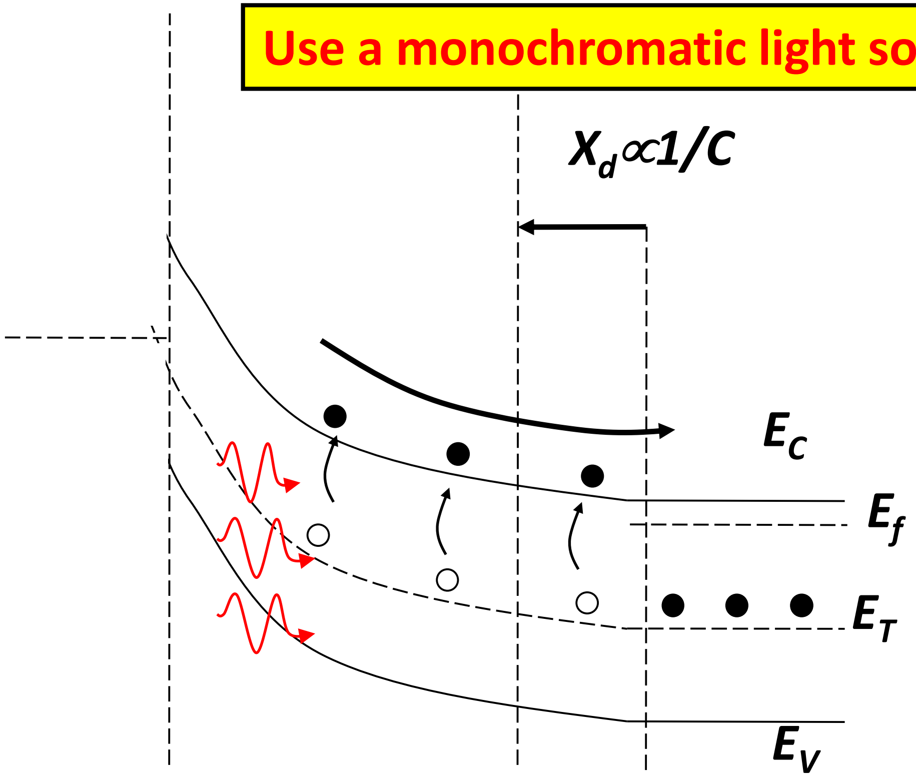


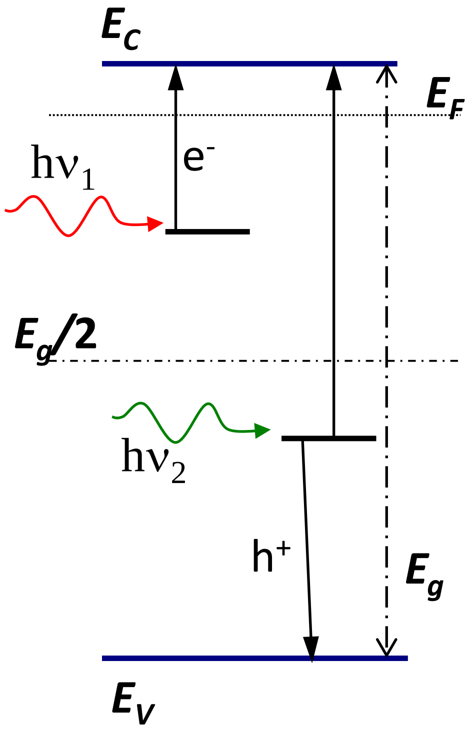
- Measurements done in the dark
- High N sample completely depleted → Not measurable

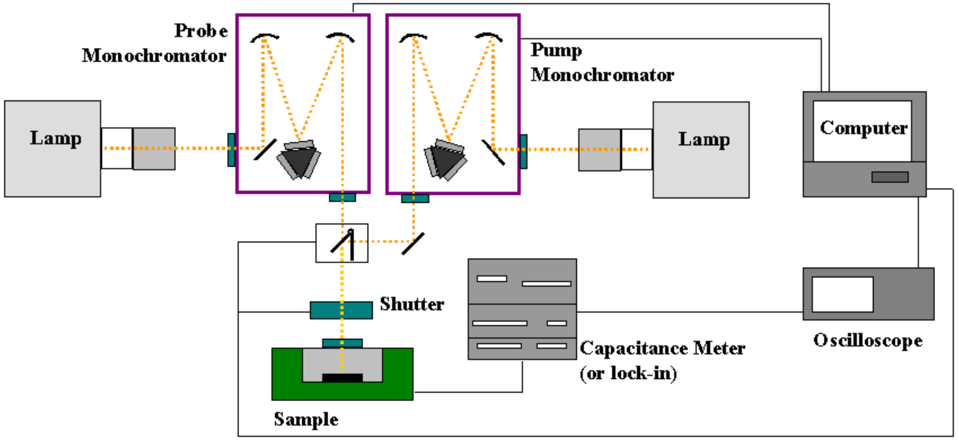
- Mid N sample heavily compensated in the dark
- N-type even under illumination
  - ➢ Tested using lighted-CV (not shown)
- Change in CV with frequency
  - ➢ Low efficiency of the compensating agent

Deep level optical spectroscopy (DLOS)

Use a monochromatic light source to scan throughout the bandgap



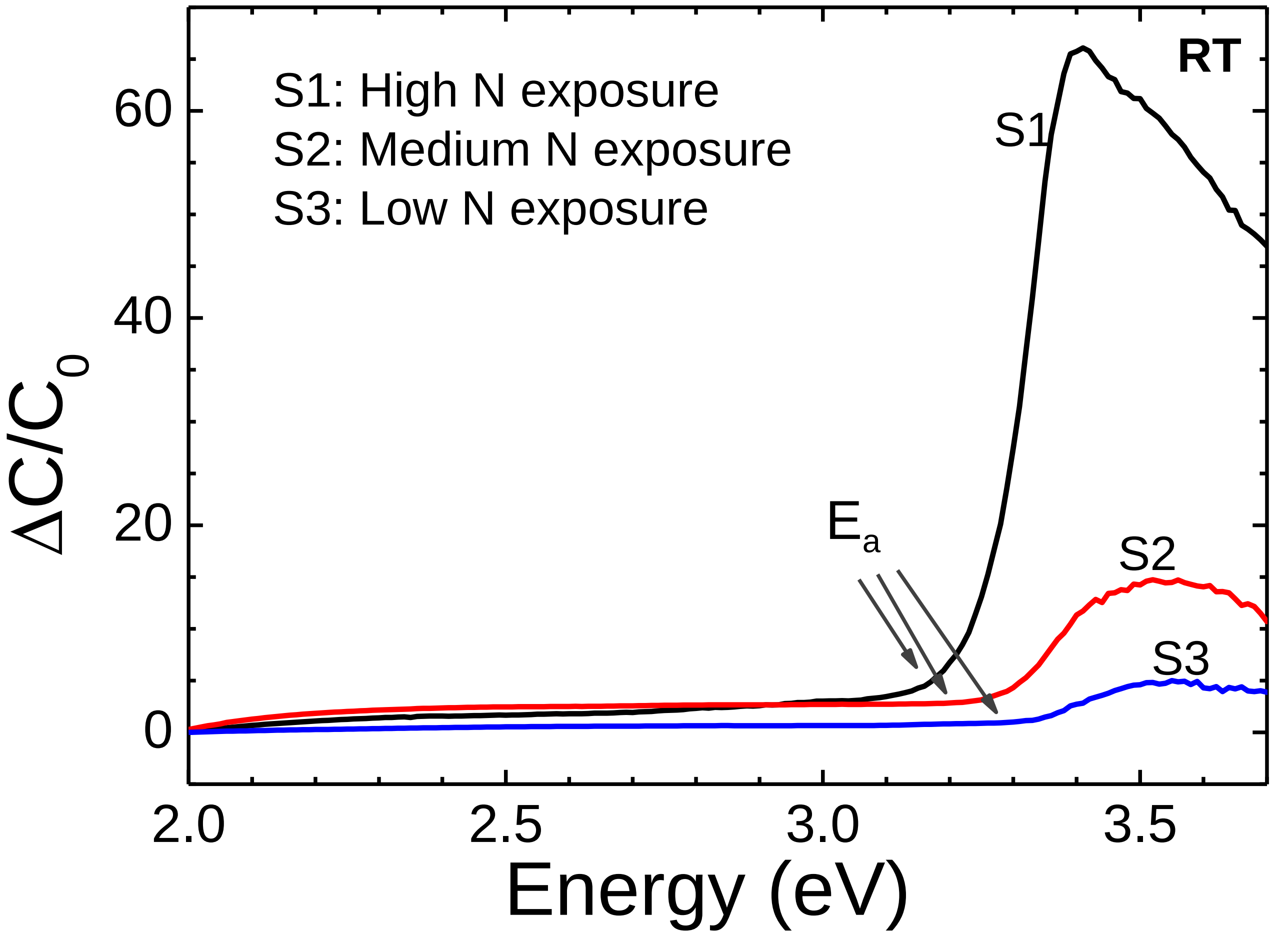




- Onset in ΔC gives deep level energy
- Concentration depends on ΔC magnitude
- $N_T = 2 \times (N_D^+ - N_A^-) \times \frac{\Delta C}{C_0} \quad (cm^{-3})$

DLOS – Example spectra

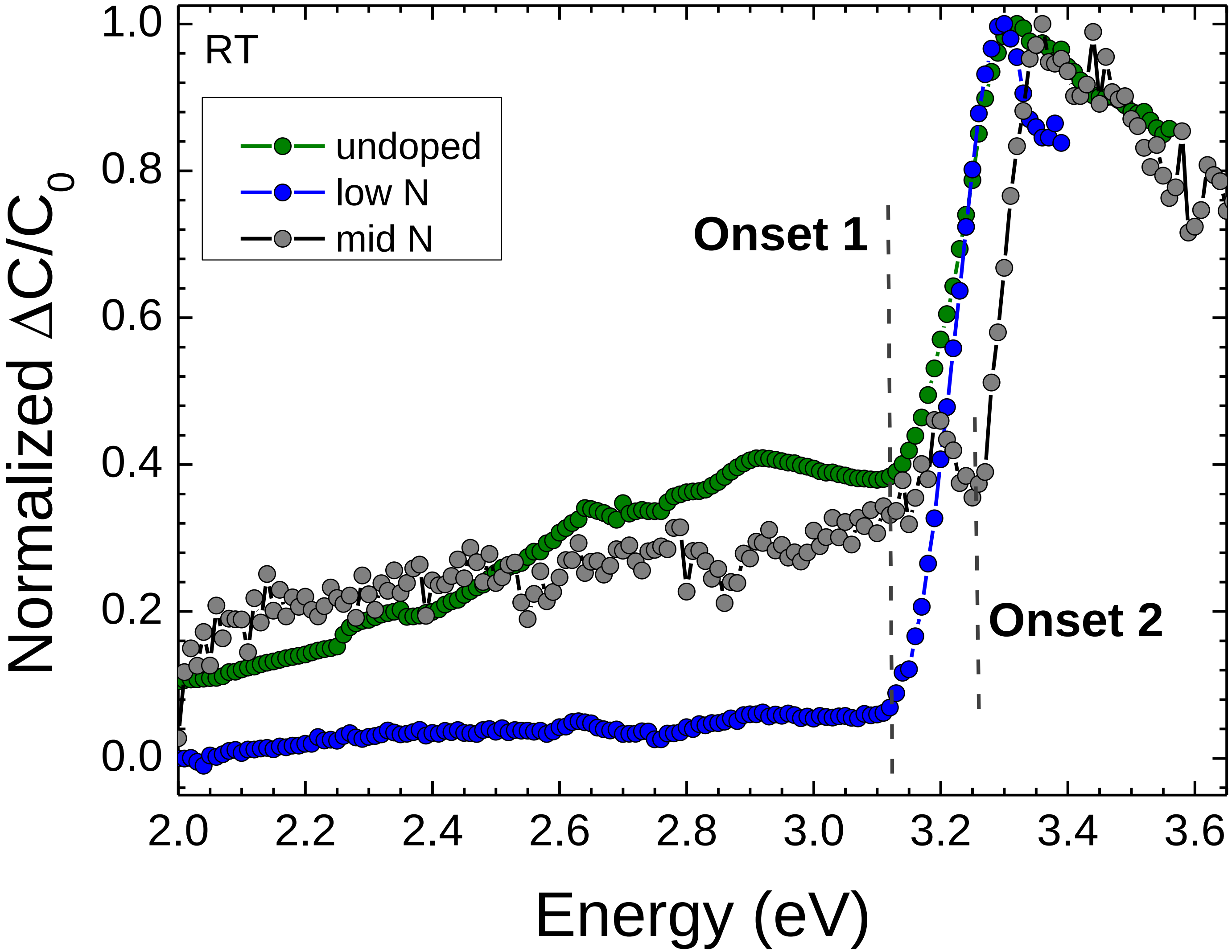
ZnMgO:N grown by RPE-MOCVD at SU



- Levels are referenced to VB in n-type material
- E_a is calculated subtracting the onset to the gap energy (E_g)
- Capacitance rises till gap or excitonic absorption → Q-factor degradation

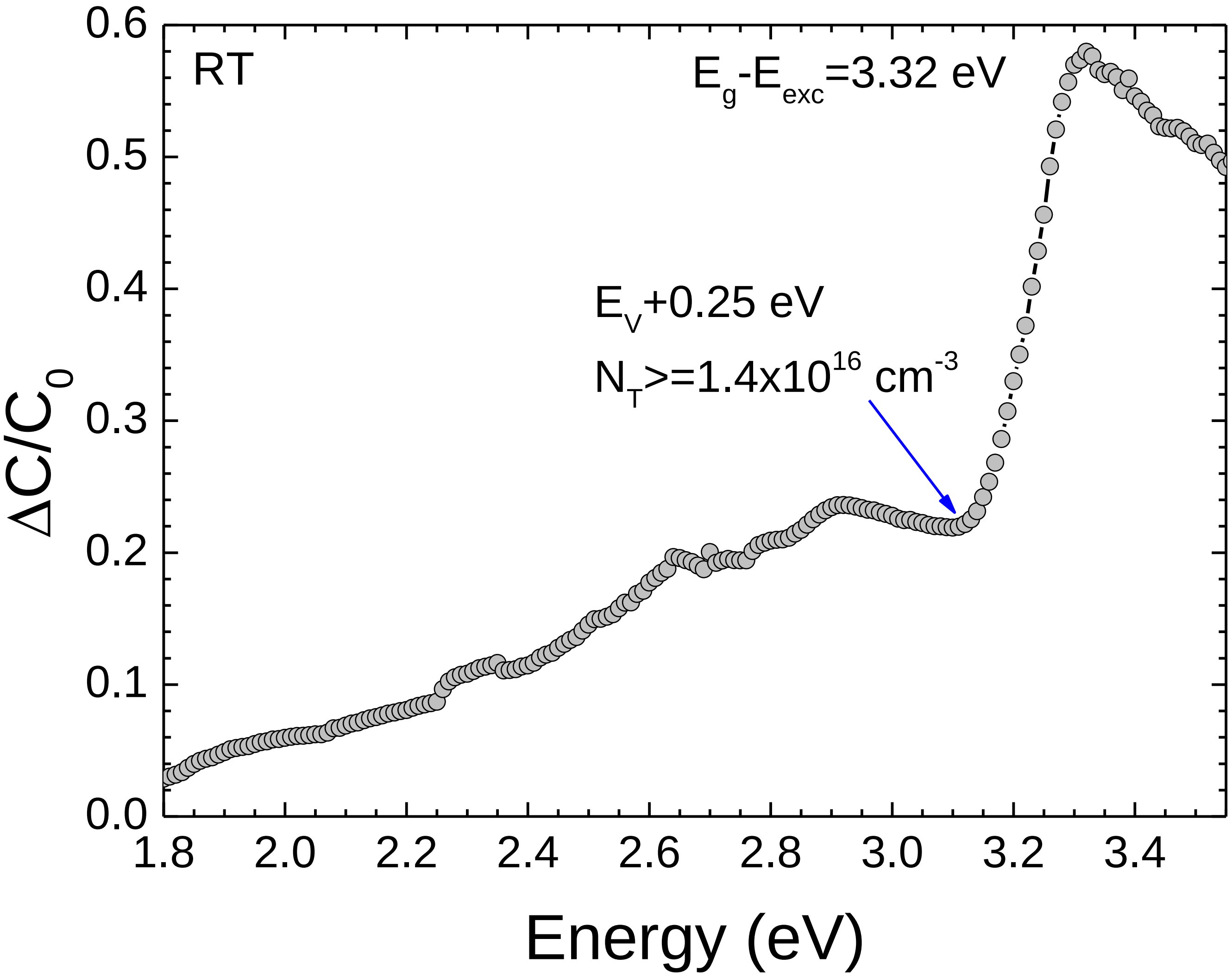
Kurtz et al., *Appl.Phys.Lett.* 104, 081105, (2014)

DLOS for all samples (1MHz)



- Undoped and low N samples very similar near bandgap → Different in mid-gap
- Mid N sample changes deep level distribution

Undoped ZnO

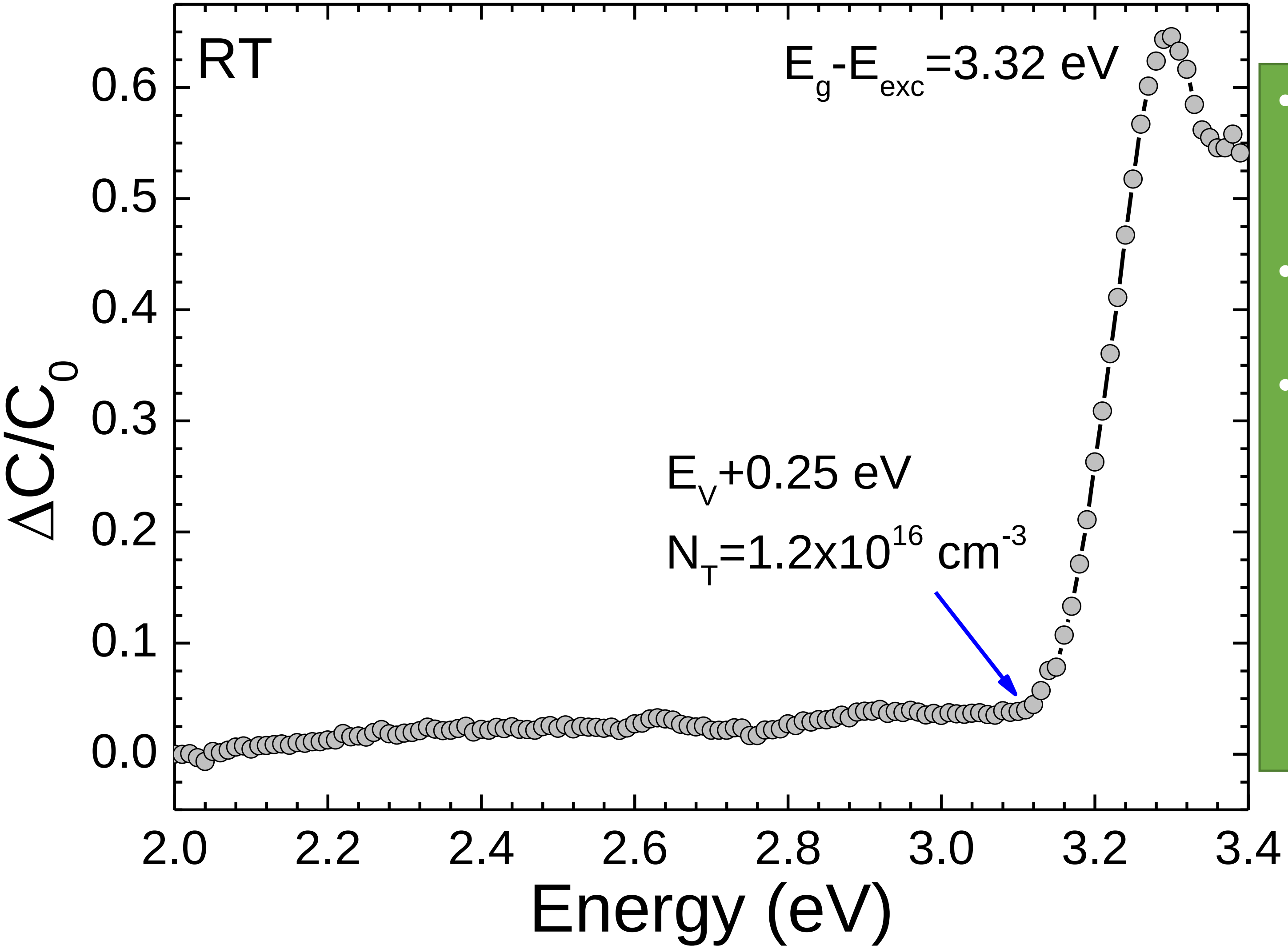


- Dominant level at E_V+0.25 eV
- Capacitance degrades when resonant with the exciton → Increase in conduction[1]
- Concentration is a lower bound

Sample very sensitive to lamp features and filter changes
→ Difficult to determine traps deep in the bandgap

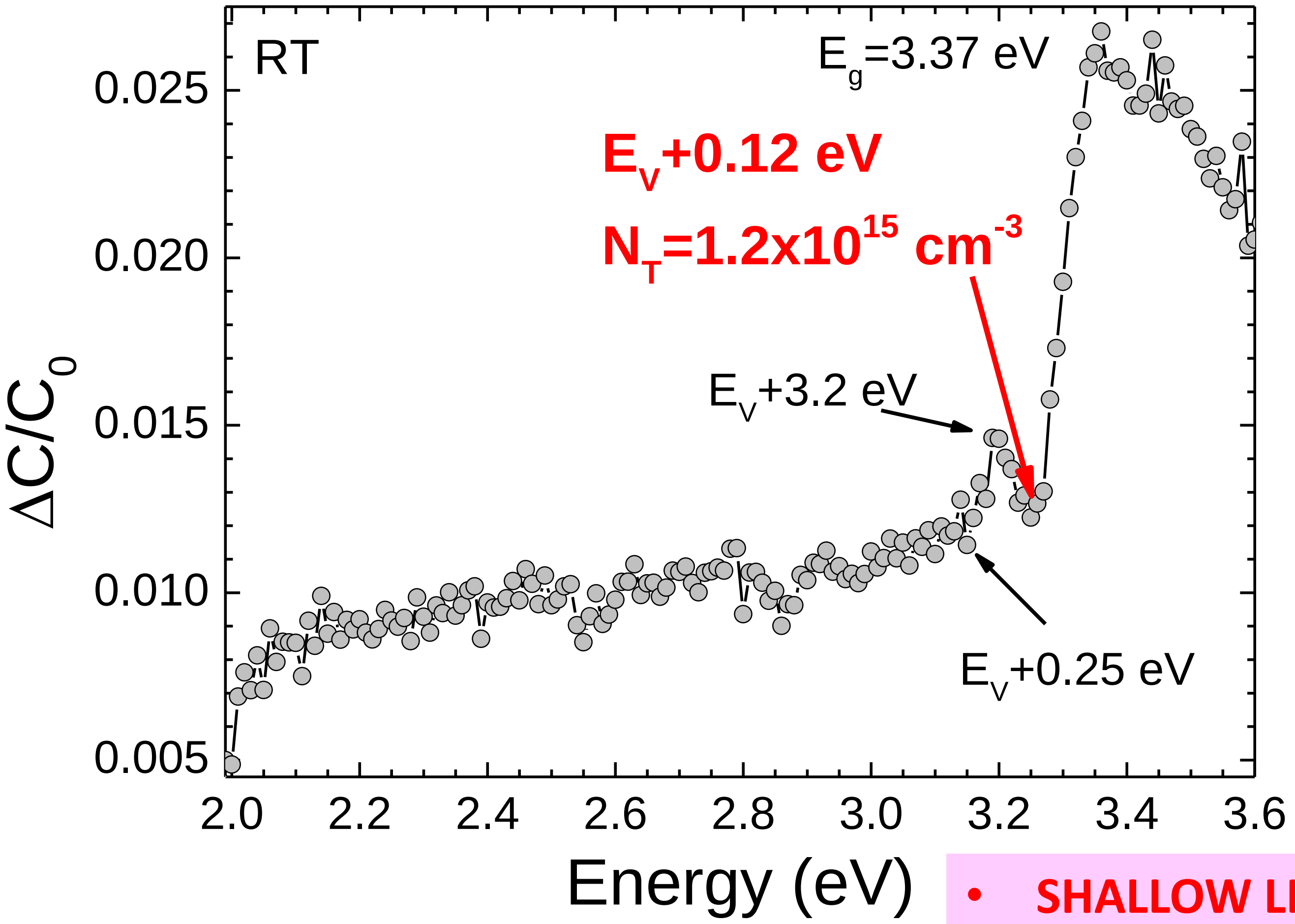
[1] Shown in a later slide

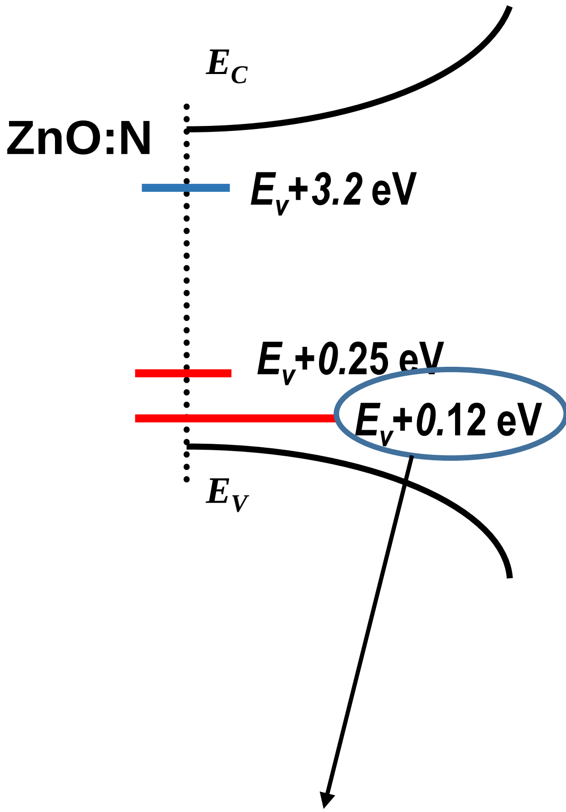
Low N ZnO



- Same level at E_V+0.25 eV as in undoped sample
- Similar concentration
- No significant ΔC variation until high energies → Reduction in levels deep in the band

Mid N ZnO

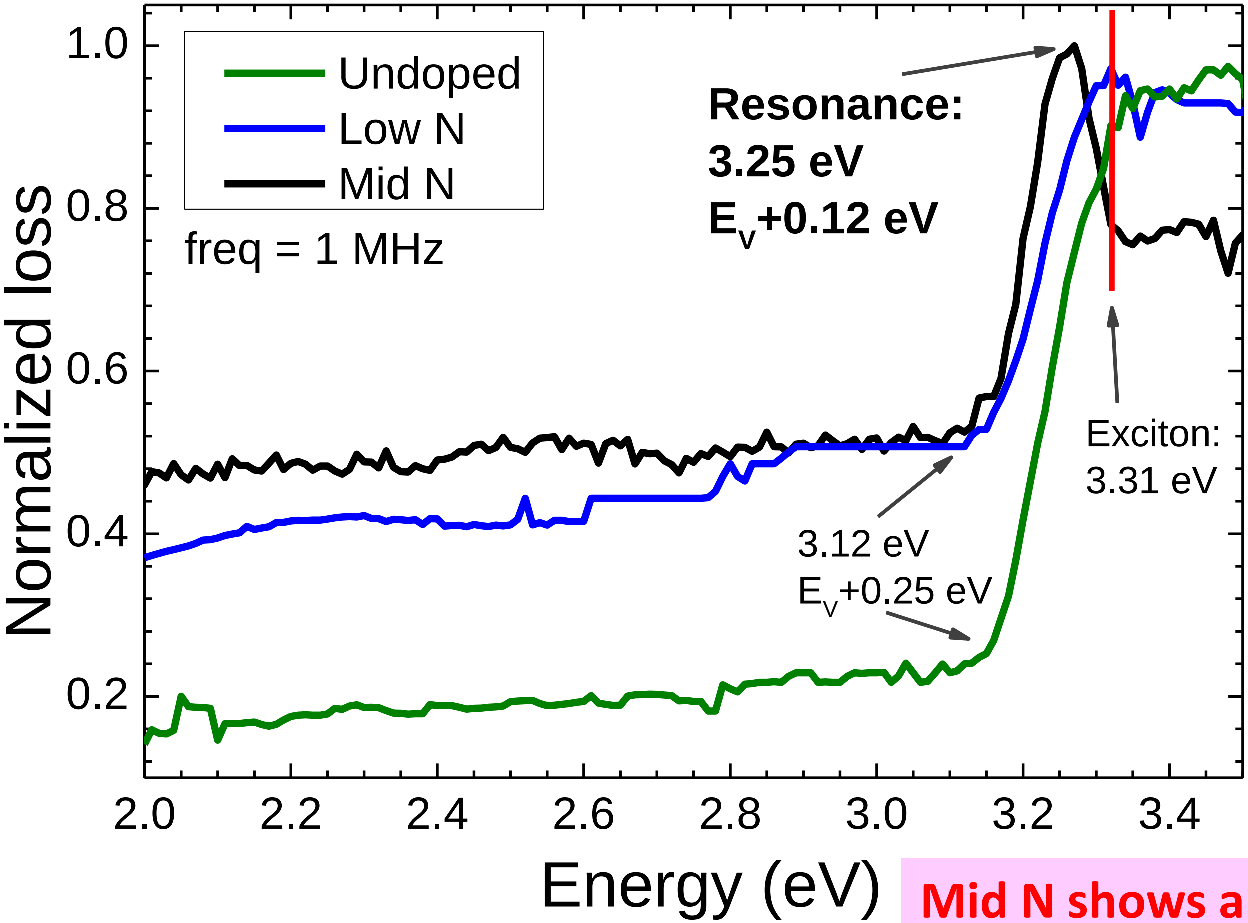




- **SHALLOW LEVEL introduced by N**
- **Matches perfectly DAP from RT-PL**

- Level at E_v+0.25 eV is not responsible for the capacitance change
- New donor-like level appears at E_V+3.2 eV (E_C-0.17 eV)

Losses at 1 MHz



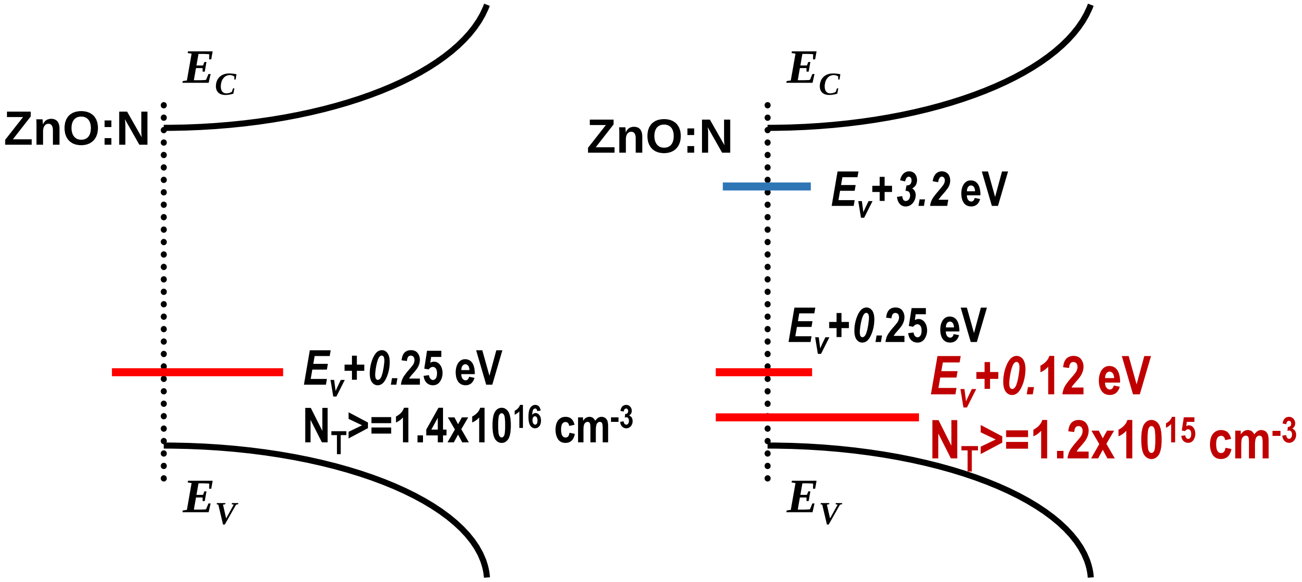
- Losses = Conductance at 1MHz
- Modulated photocurrent
- Measures free charge at high freq.

Mid N shows a resonance at E_V+0.12 eV
→ Trap being emptied: Matches ΔC/C

- All samples start rising at 3.12 eV → Modulation
- Undoped and low N samples rise up to exciton energy

Conclusions

Undoped and Low N **Mid N**



- E_V+0.25 eV present in all samples
- N-related level at E_V+0.12eV → Agrees with report by Muret[1]
- Donor-like level at E_V+3.2 eV only visible with high N concentration

- **N introduces an acceptor level at E_V+0.12 eV ($N_T=10^{15}$cm^{-3})**
- **E_V+0.12 eV level matches well donor-acceptor-pair (DAP)**

[1] **Muret et al., *Appl.Phys.Lett.* 101, 122104, (2012)**

THANK FOR YOUR ATTENTION!!!