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Office of Energy Efficiency & Renewable Energy

National Renewable Energy Laboratory
Innovation for Our Energy Future

Amorphous Transparent Conducting Oxides (TCOs) Deposited at T 100 ≤ °C

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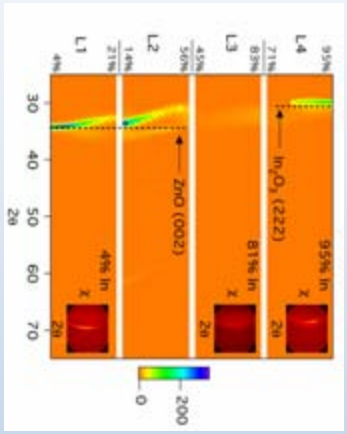
In-Zn-O (IZO), an Amorphous Mixed Metal Oxide Transparent Conductor

- Low Temperature Deposition ($T_S \leq 100$ °C)
- Smooth ($R_{RMS} < 0.5$ nm)
- Thermally Resilient
- Good Conductivity ($\sigma \approx 3000\ \Omega^{-1}\text{- cm}^{-1}$)
- High Mobility for Amorphous material ($\mu \approx 30\ \text{cm}^2/\text{V-s}$)

Combinatorial Approach
IZO: 5 - 95 %In with 4 depositions

Compositionally Graded Films



Chemical

Electrical

Optical

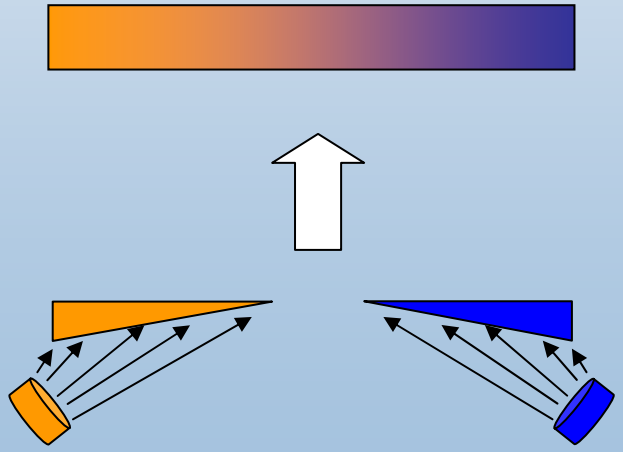
Structural

Film Deposition

Metal Oxide

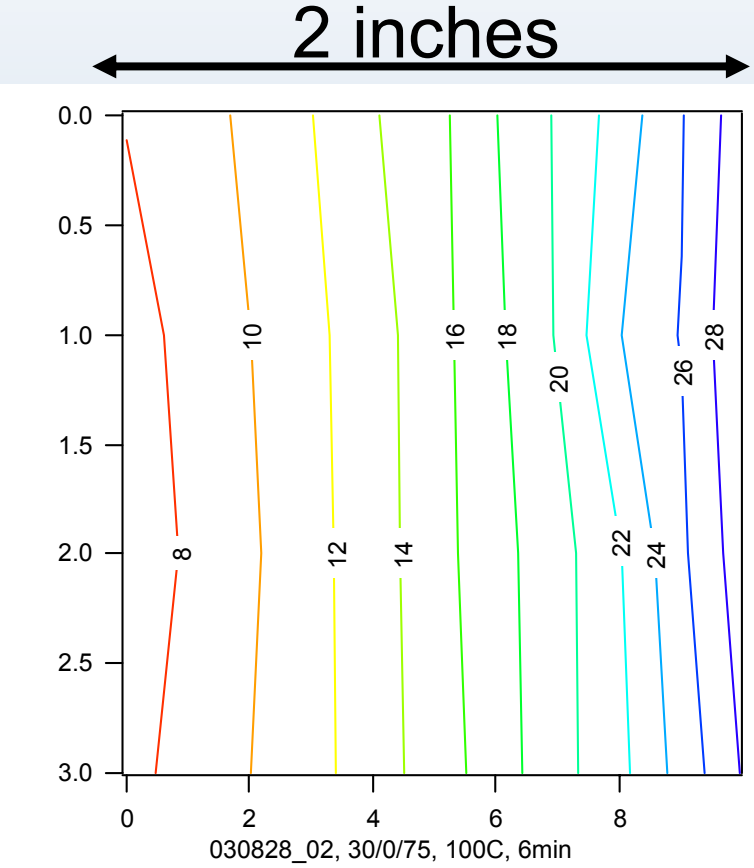
Co-sputtering

- 5cm x 5cm glass substrates
- 25°C - 550°C



ZnO, MoO_2, TiO_2 In_2O_3

Binary In-Zn-O Library
EPMA Analysis



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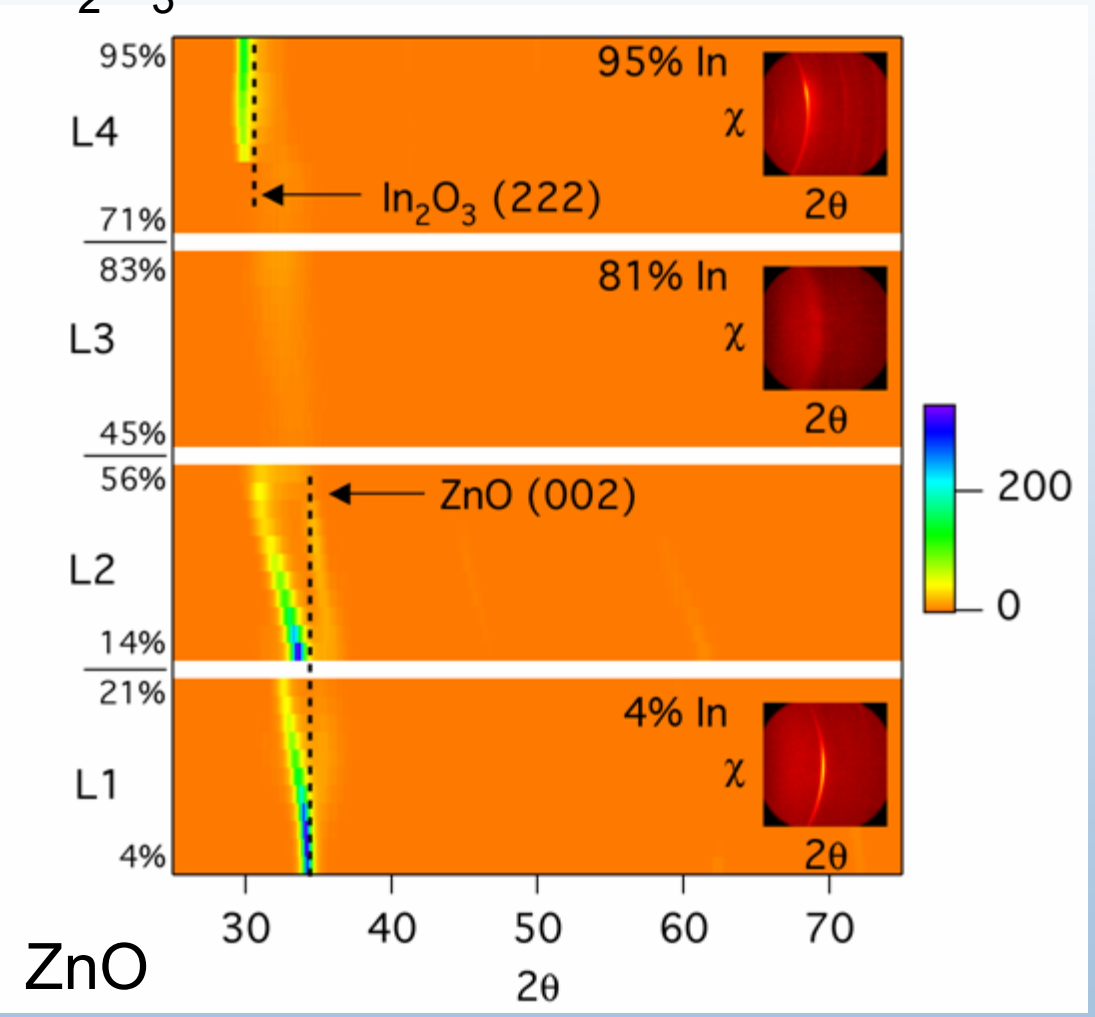
XRD for IZO Deposited at T_s = 100 °C

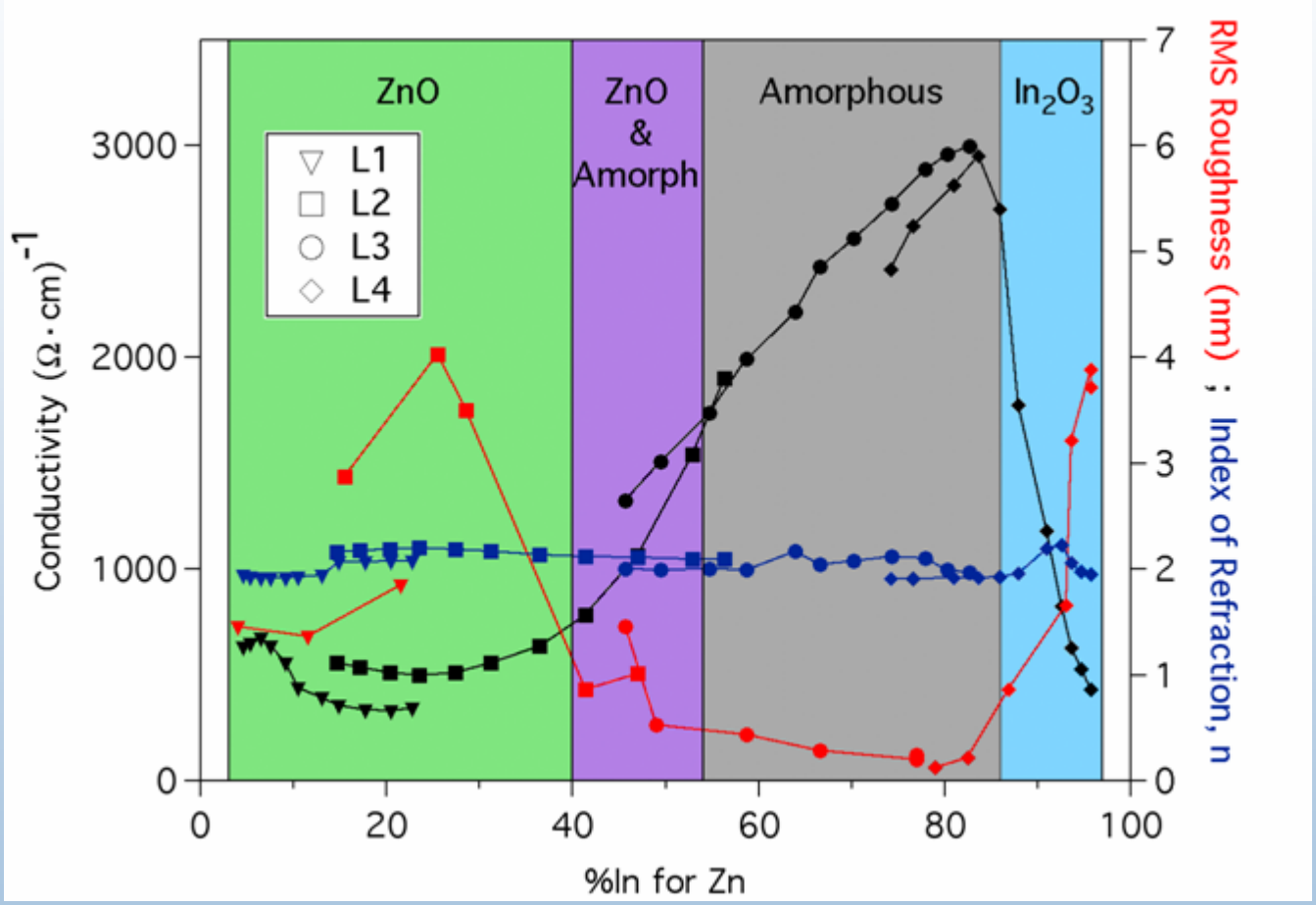
In_2O_3



ZnO

- Amorphous
  55 - 85 % In
- Crystalline Material
  Textured

As-dep IZO: Conductivity, Structure, Roughness & Refractive Index



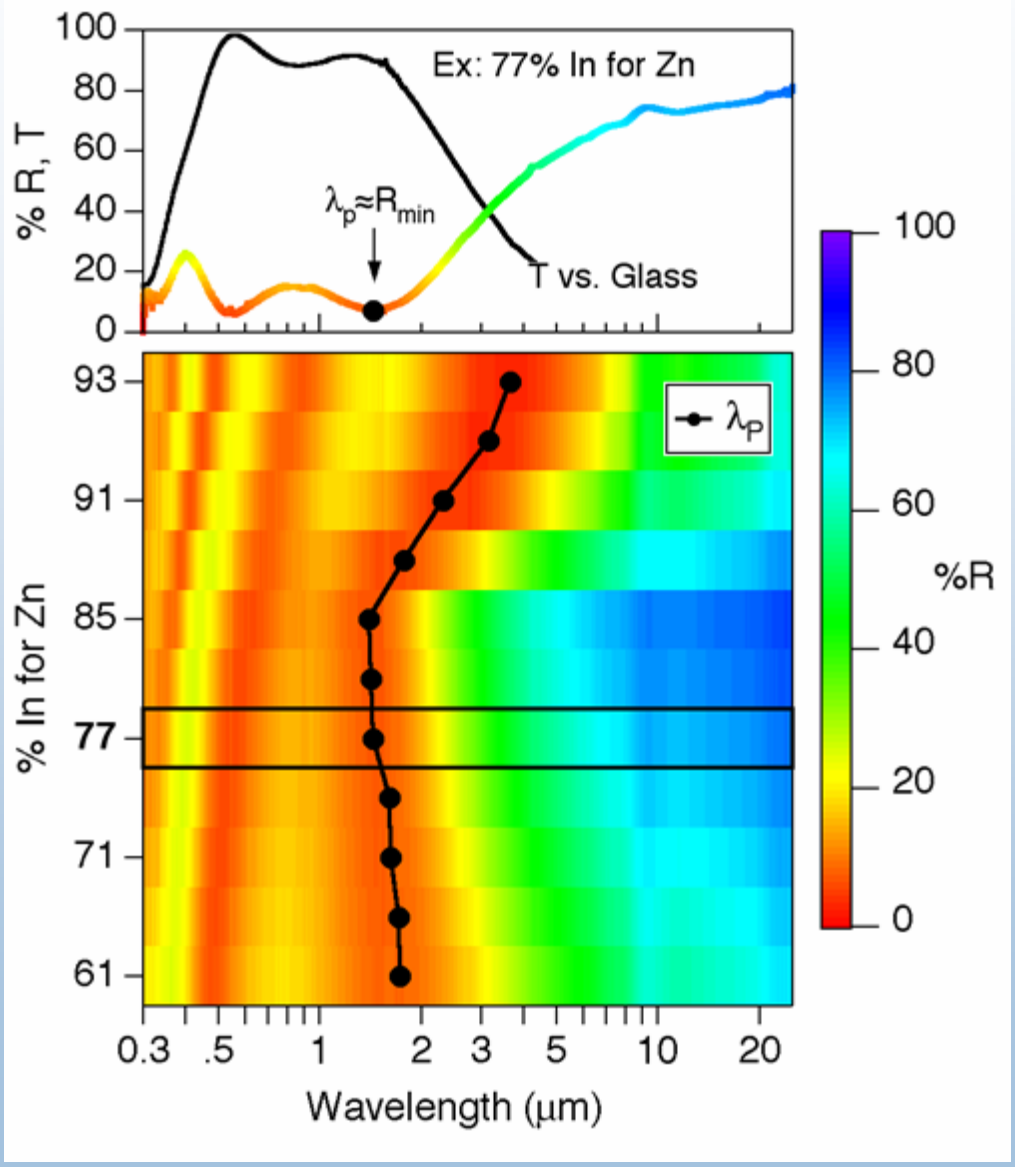
a-IZO (80/20)

$\sigma = 3000\ \Omega^{-1} - cm^{-1}$

$R_{RMS} < 0.5$ nm

Conductivity maximum occurs in smooth amorphous region.

As-deposited IZO Optical Properties



- Typical TCO (R, T)
- Fringes give thickness
- λ_p changes with %In
- Conductivity tracks λ_p.

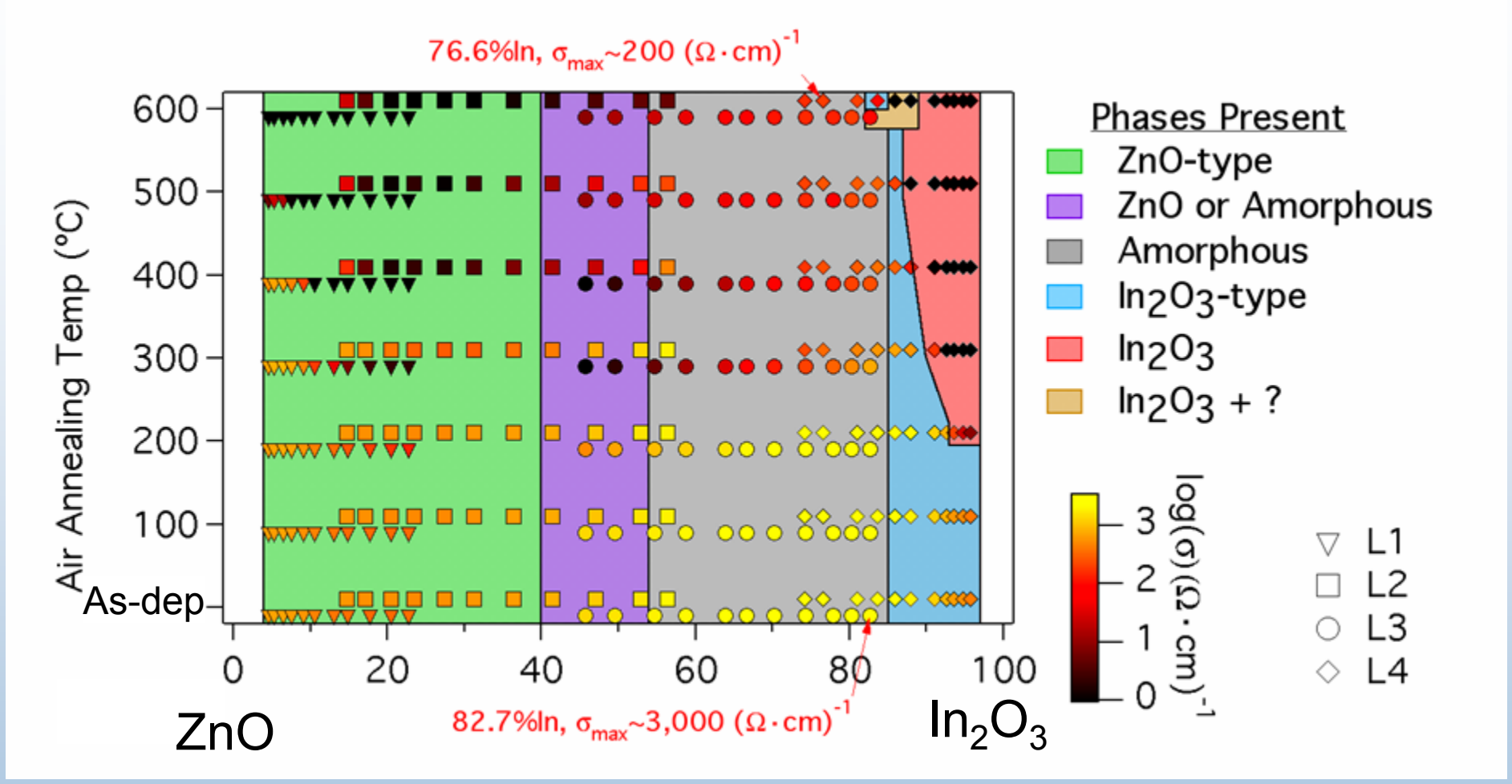
$$\sigma = Ne\mu$$

$$\lambda_p \propto 1/\sqrt{N}$$

Annealing of IZO Libraries

- Libraries annealed for 1 hour at target temperature
- Electrical, optical and structural properties evaluated
- Process repeated
  - 1 set of libraries annealed in air
  - 1 set of libraries annealed in argon

IZO Annealed in Air



- Amorphous IZO generally does not recrystallize for up to 1 hr @ 600 °C
- Conductivity drop for air-annealed a- IZO 80/20 much less than crystalline material.

Conductivity Drops Less for Argon Anneals

Air Anneal

Final Anneal:

σ_{max}~ 200 $(\Omega \cdot cm)^{-1}$

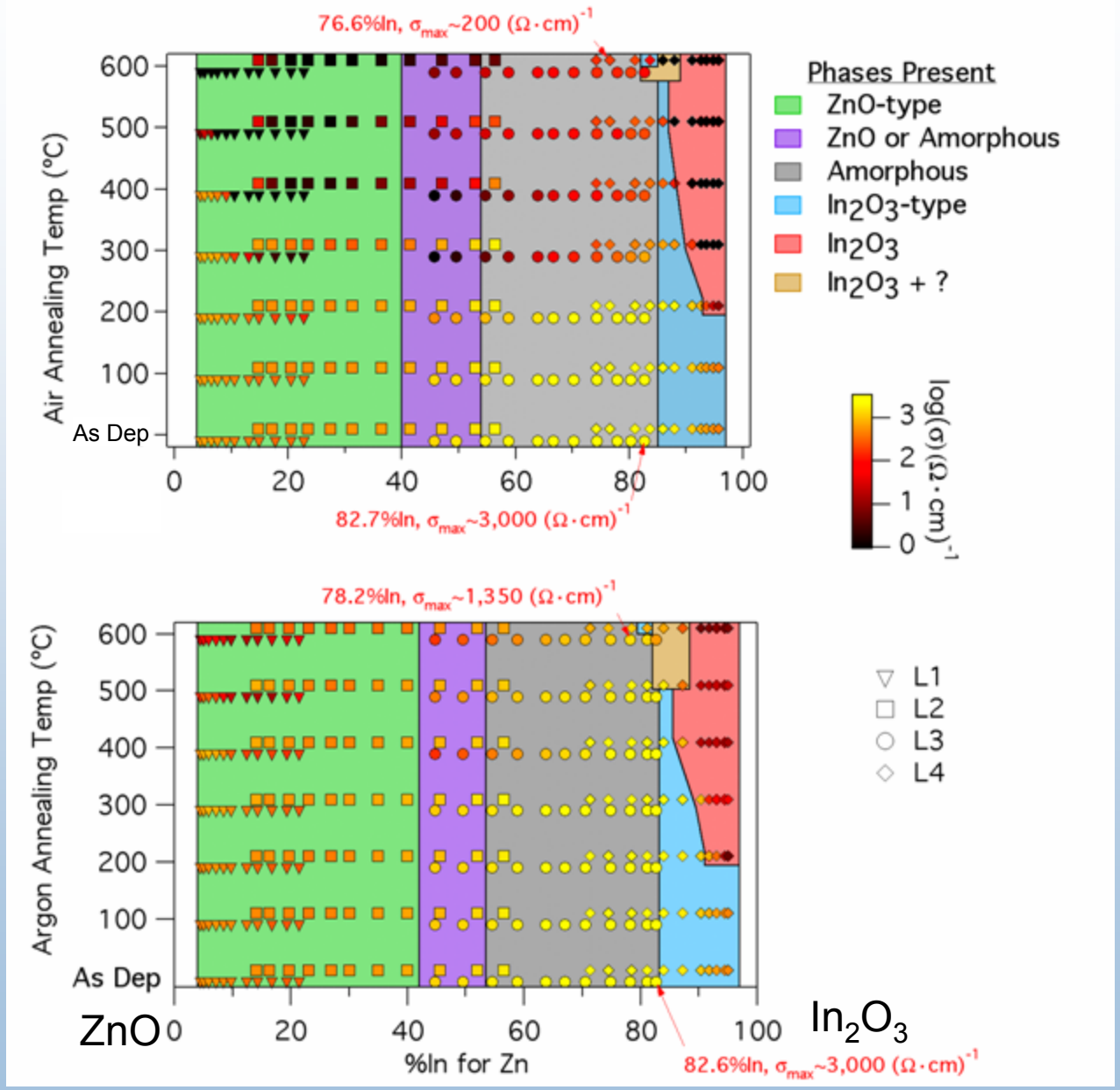
σ_{min}~ 0.04 $(\Omega \cdot cm)^{-1}$

Argon Anneal

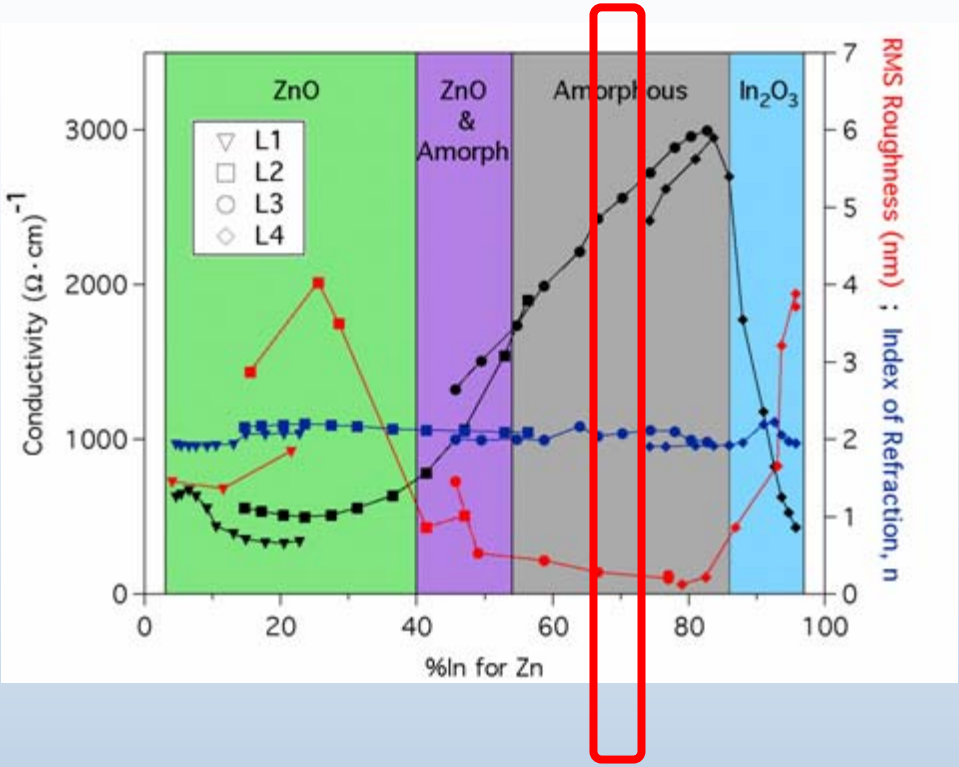
Final Anneal:

σ_{max}~ 1,350 $(\Omega \cdot cm)^{-1}$ [1]

σ_{min}~ 6 $(\Omega \cdot cm)^{-1}$

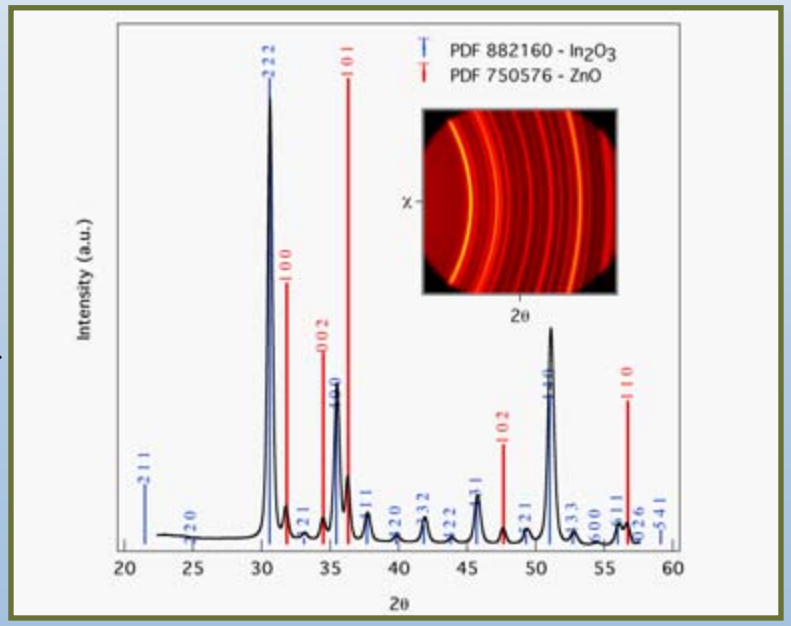


IZO 70/30: Center of Amorphous Region



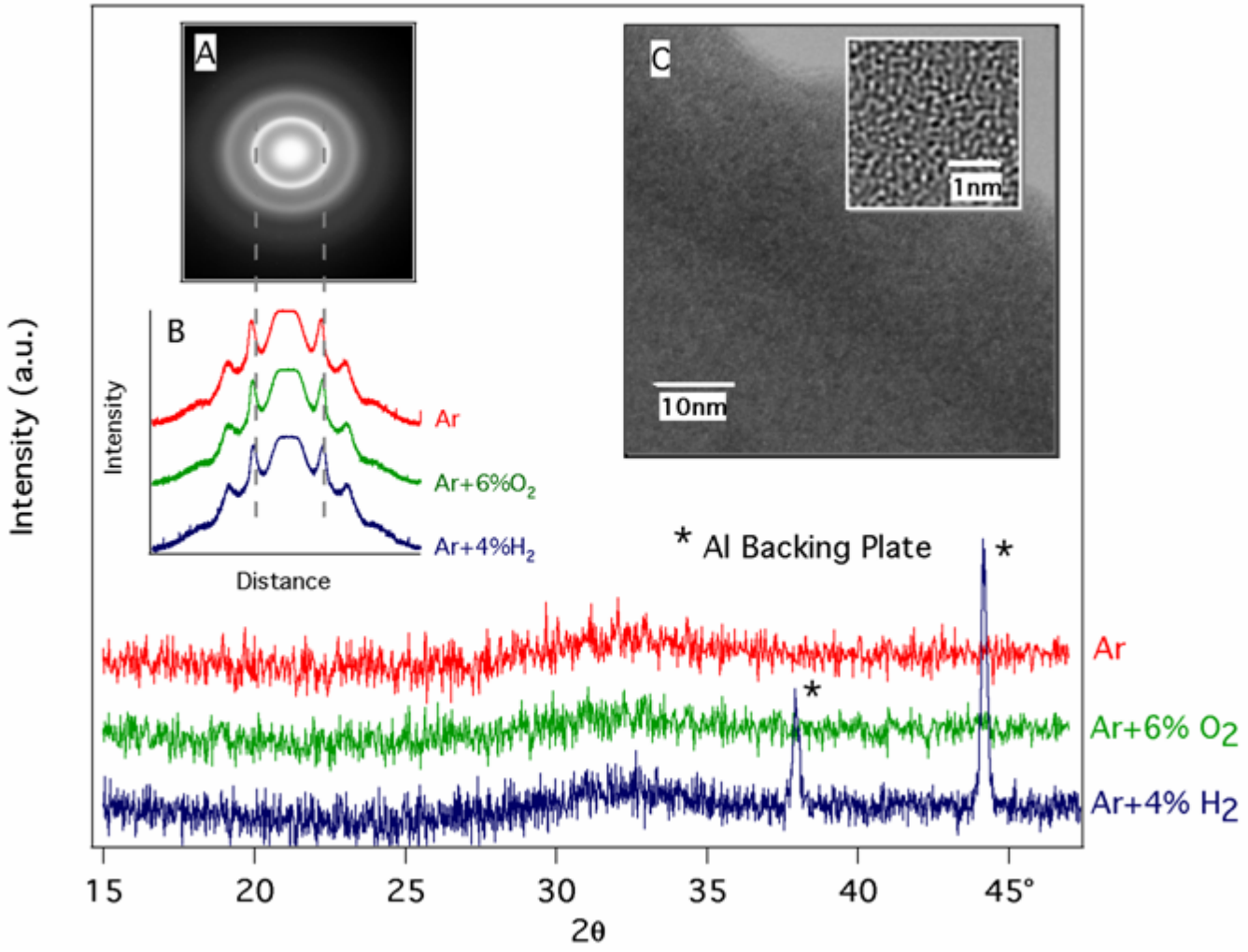
2" Single Composition Target

- Pressed at 25,000psi
- Sintered in air 800°C, 24hrs
- Two Phases: ZnO, In_2O_3

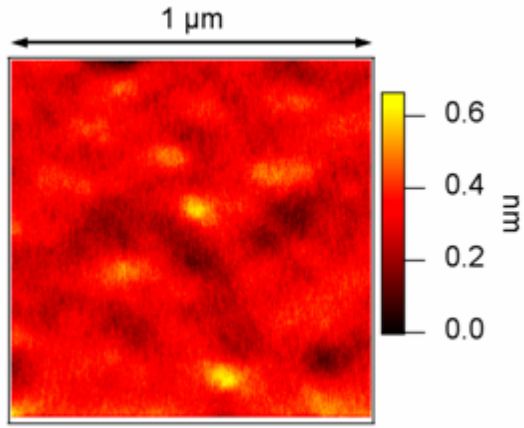


RT Sputtered IZO 70/30 is Amorphous and Smooth

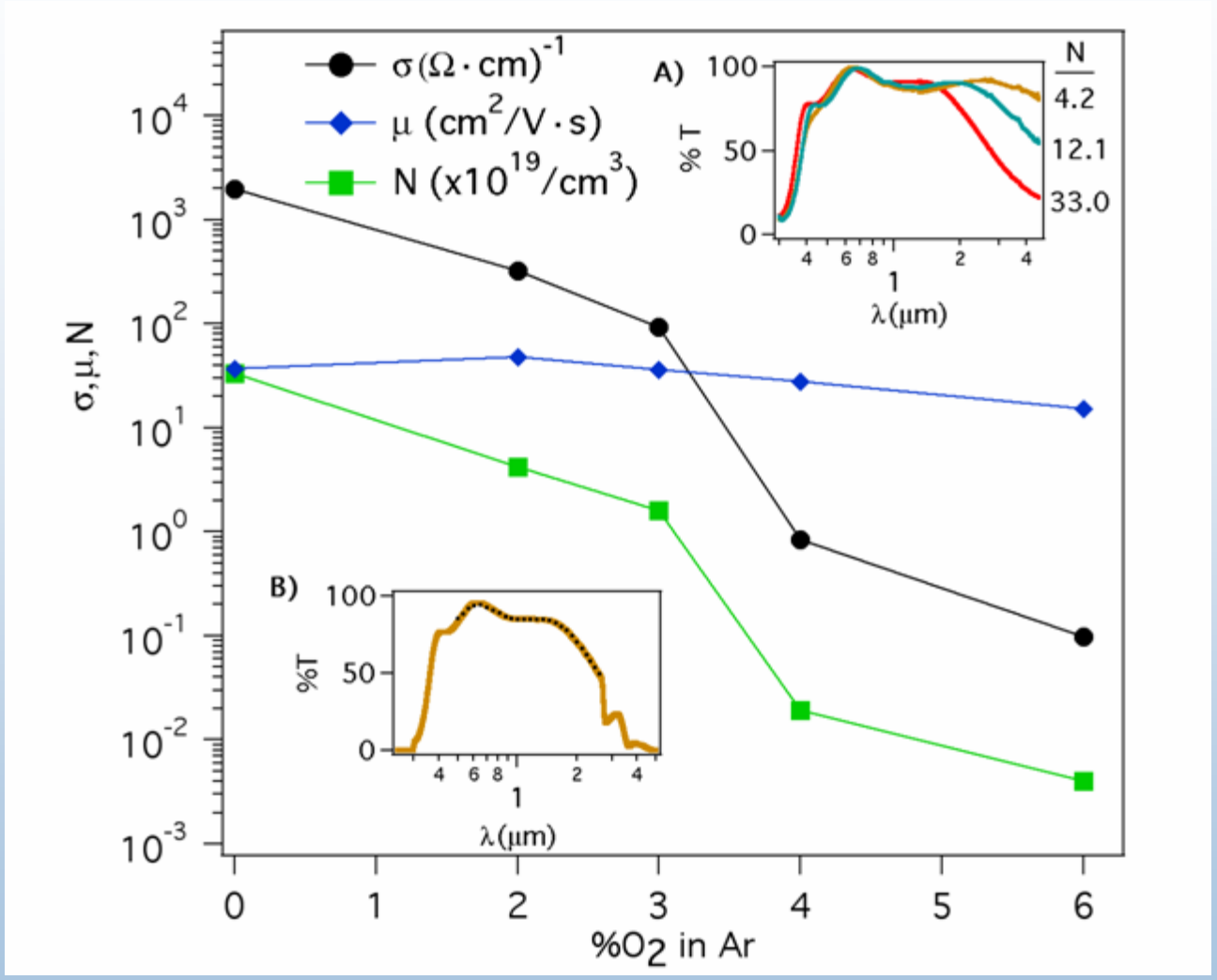
XRD, TEM



AFM

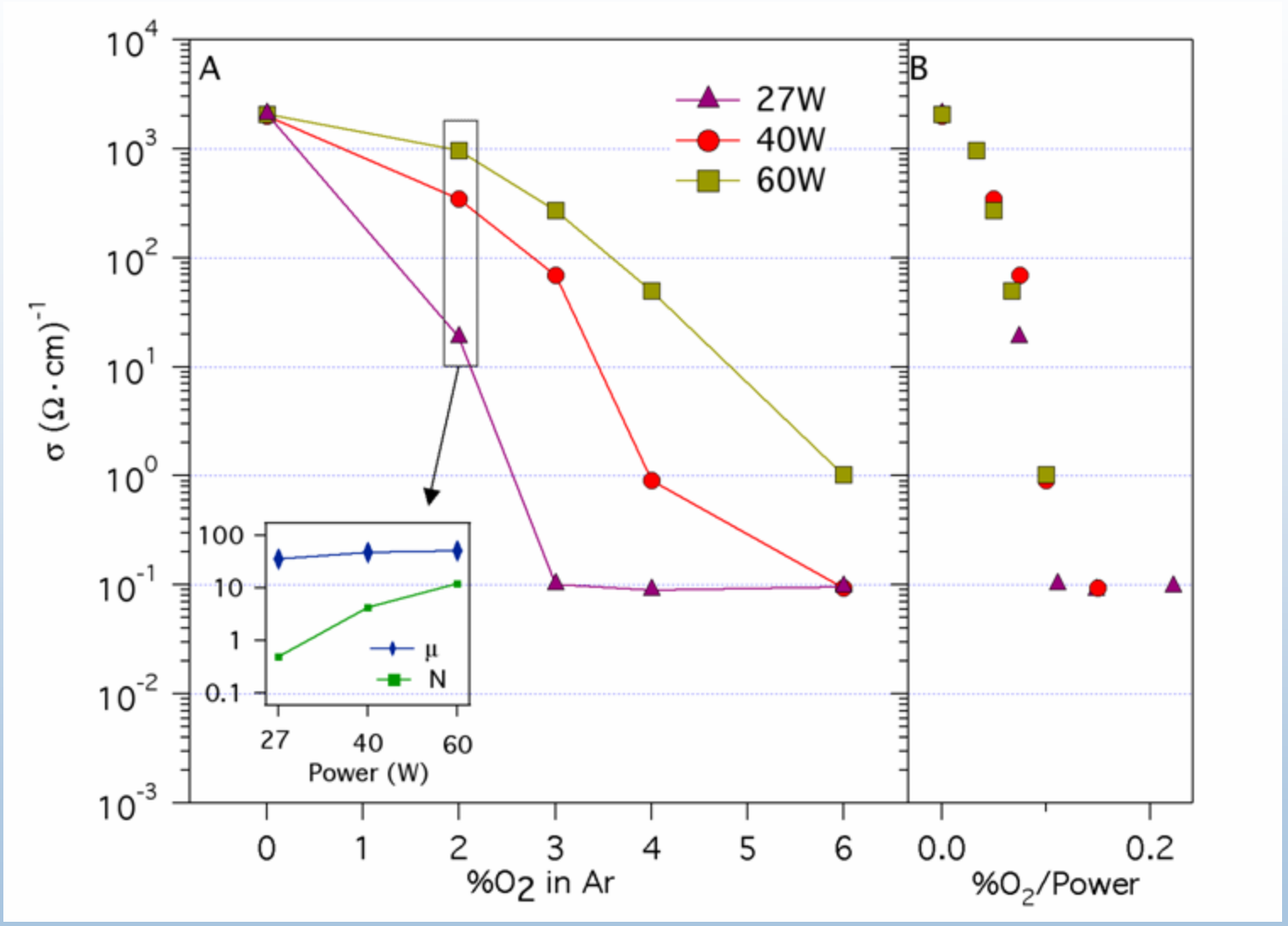


O_2 in Sputter Gas Reduces Conductivity



- N strongly effected by O_2
- μ nearly constant
- μ ≈ 30 cm^2/V-s

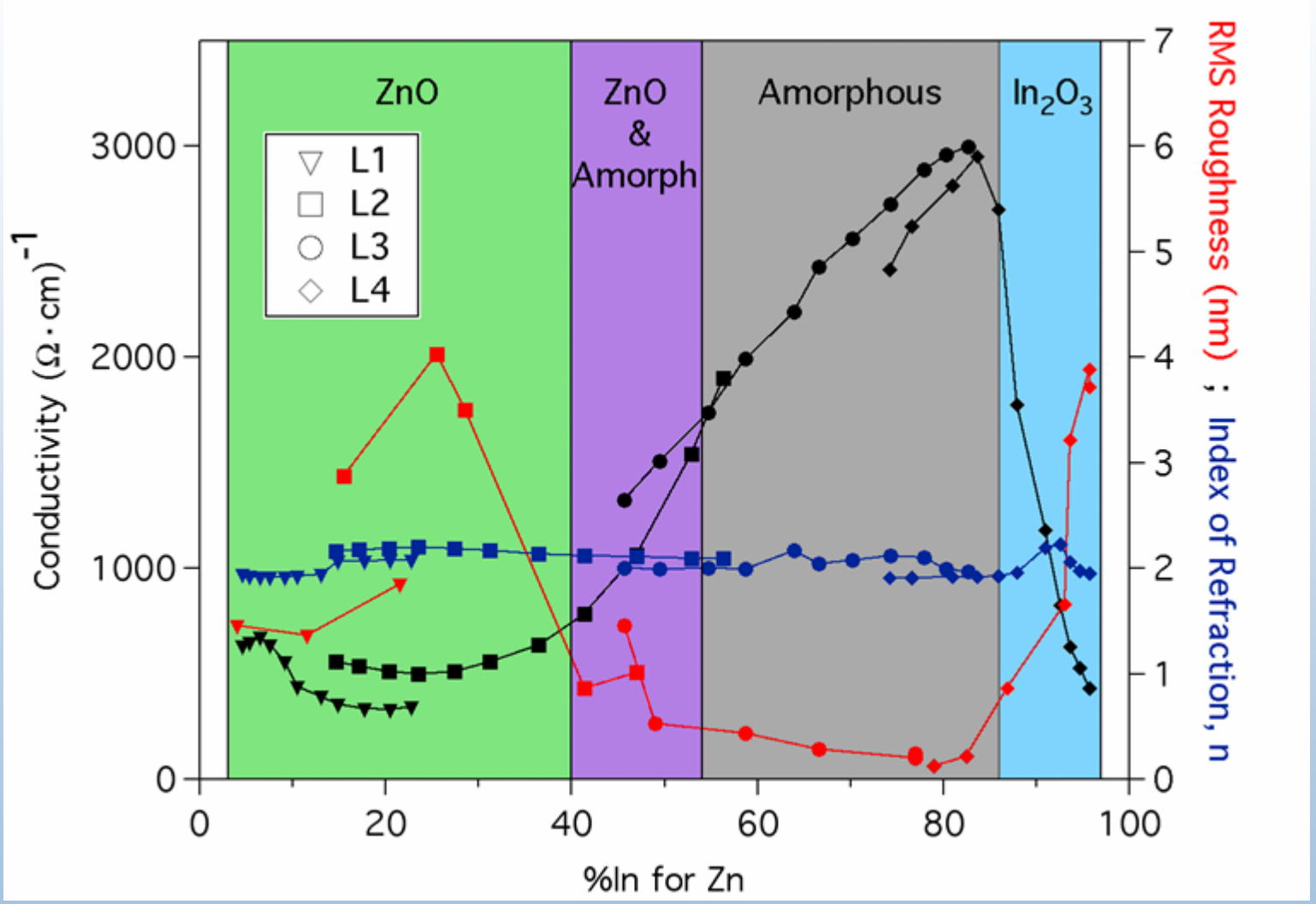
Effect of O_2 Scales with Sputter Rate



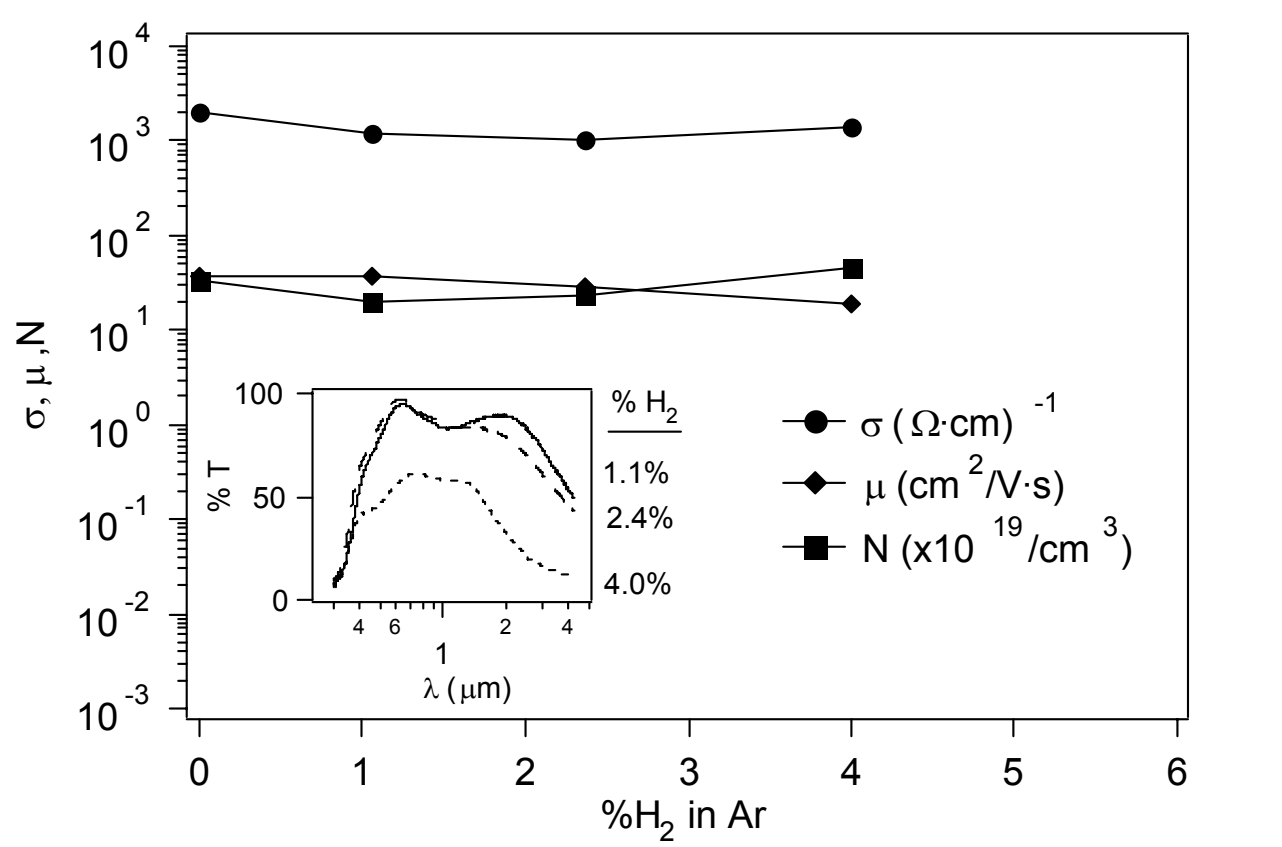
Summary

- Amorphous InZnO (a-IZO) is a very versatile TCO with:
  - Low process temperatures (~ 100 °C)
  - Easy to make by sputtering
  - Excellent optical and electronic properties
  - Very smooth etchable films
  - Remarkable thermal processing stability

In-Zn-O (IZO): as-dep @ T_s = 100 °C



IZO: H_2 in Sputter Gas



- Overall, mot much effect
- No increase in carrier concentration (N)
- Sample gray for 4% H_2