

# Transparent Conducting Contacts Based on Zinc Oxide Substitutionally Doped with Gallium

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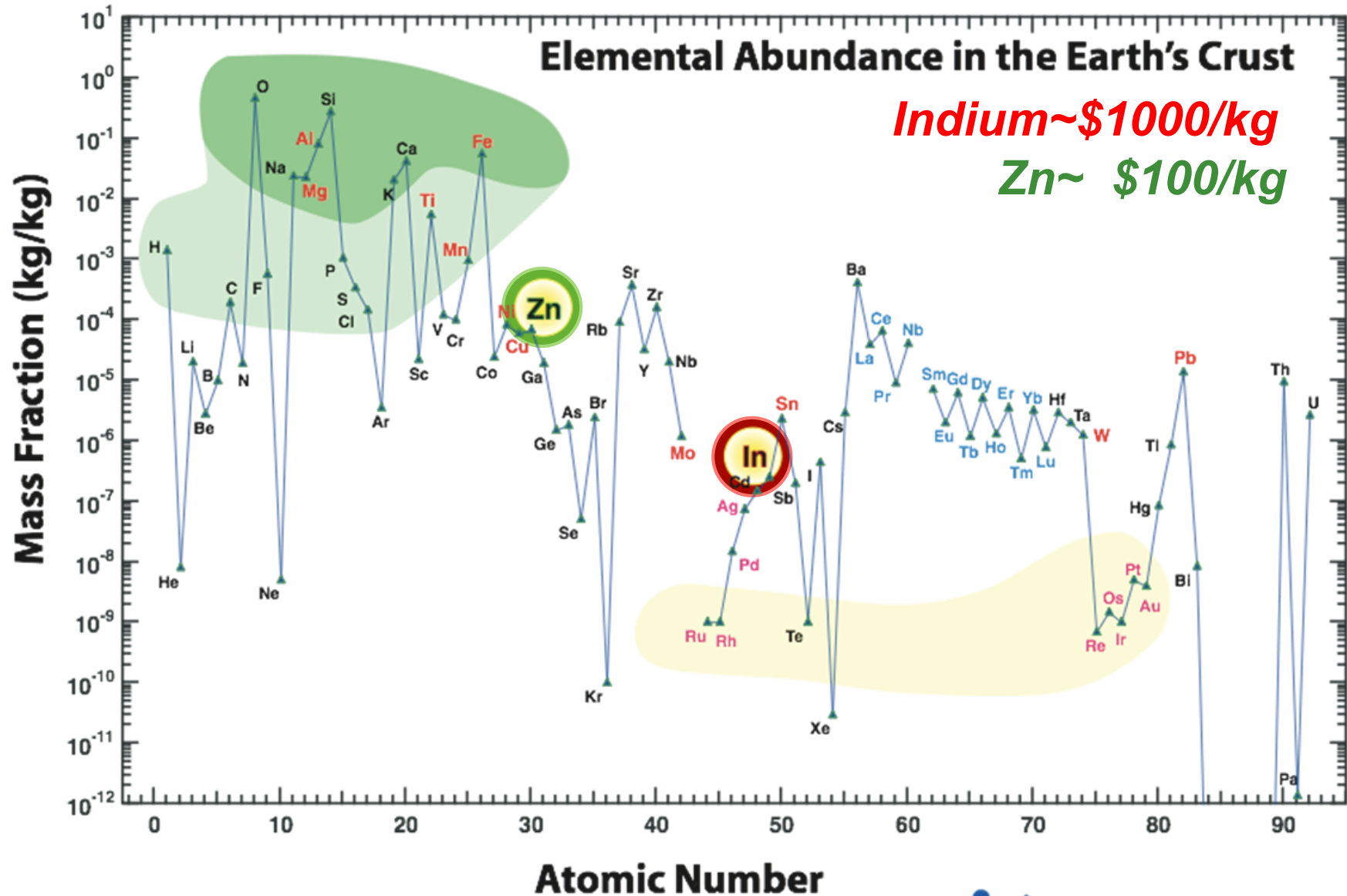
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NREL/520-43298

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# Motivation



# ZnO

- **Band gap Engineering**

- **Cd:ZnO**

- *Decreased gap*

- **Mg:ZnO**

- *Increase gap*

- **Doping**

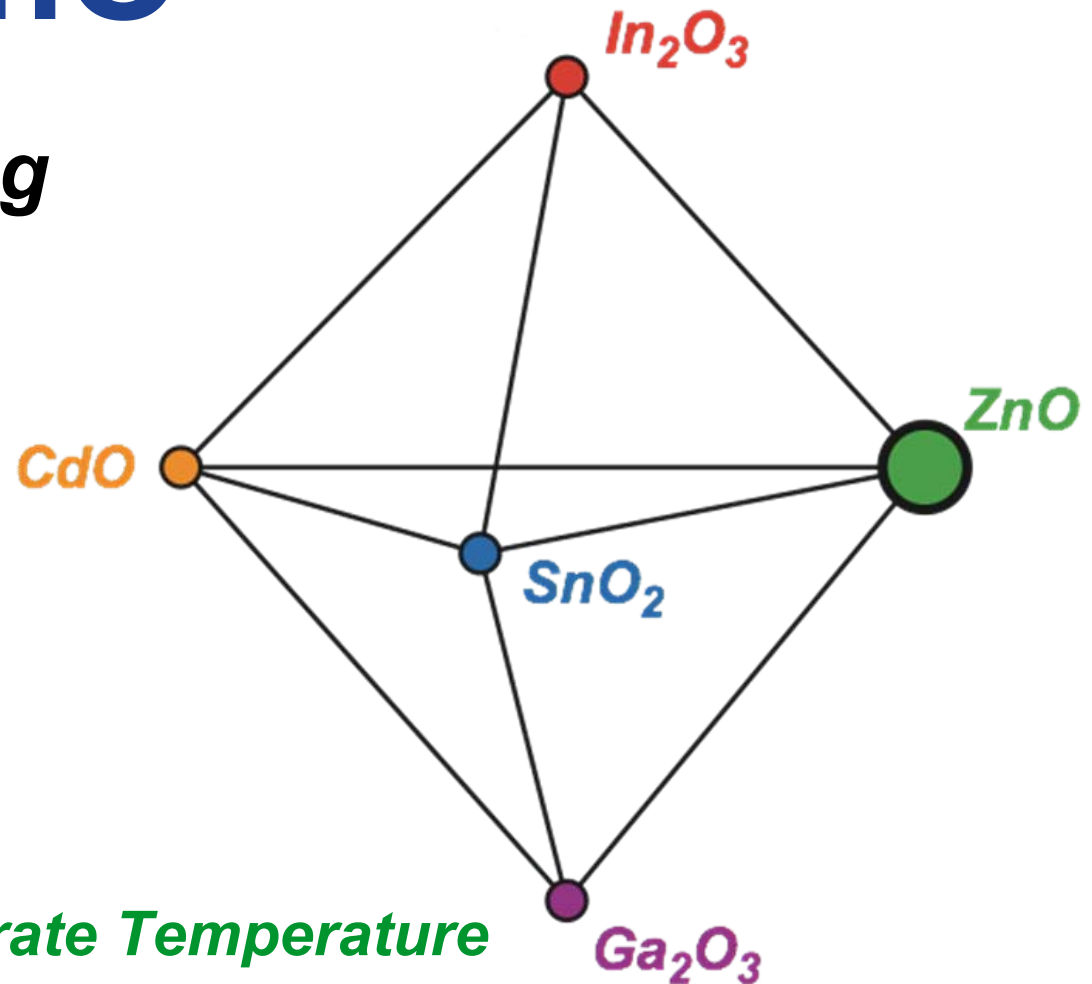
- **Al:ZnO**

- *Conventional*

- **Ga:ZnO**

- *Dependence on Substrate Temperature*

- *Optimization of Doping Level*

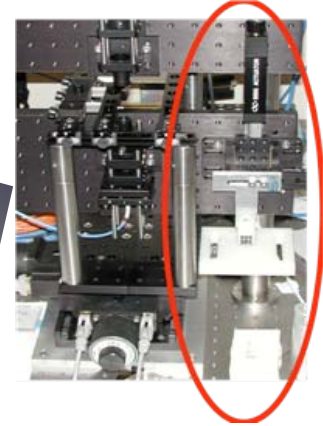


# Combinatorial Tools

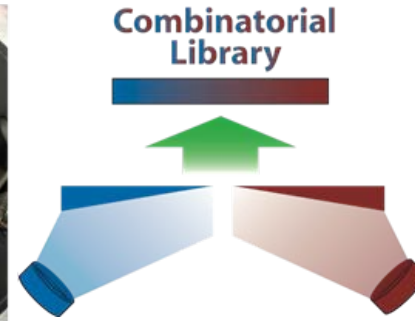
Chemical



Electrical



**Combi Deposition**  
(graded sputtering)



Co-sputtering

5 cm x 5 cm glass substrates

	0	1	2	3	4	5	6	7	8	9	A	
R0	+	+	+	+	+	+	+	+	+	+	+	R0
R1	+	+	+	+	+	+	+	+	+	+	+	R1
R2	+	+	+	+	+	+	+	+	+	+	+	R2
R3	+	+	+	+	+	+	+	+	+	+	+	R3
	0	1	2	3	4	5	6	7	8	9	A	



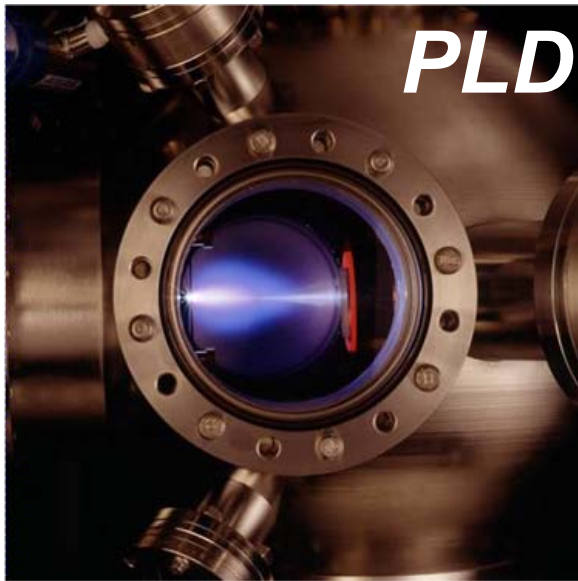
Optical



Structural



# Pulsed Laser Deposition



- ***Substrates:***

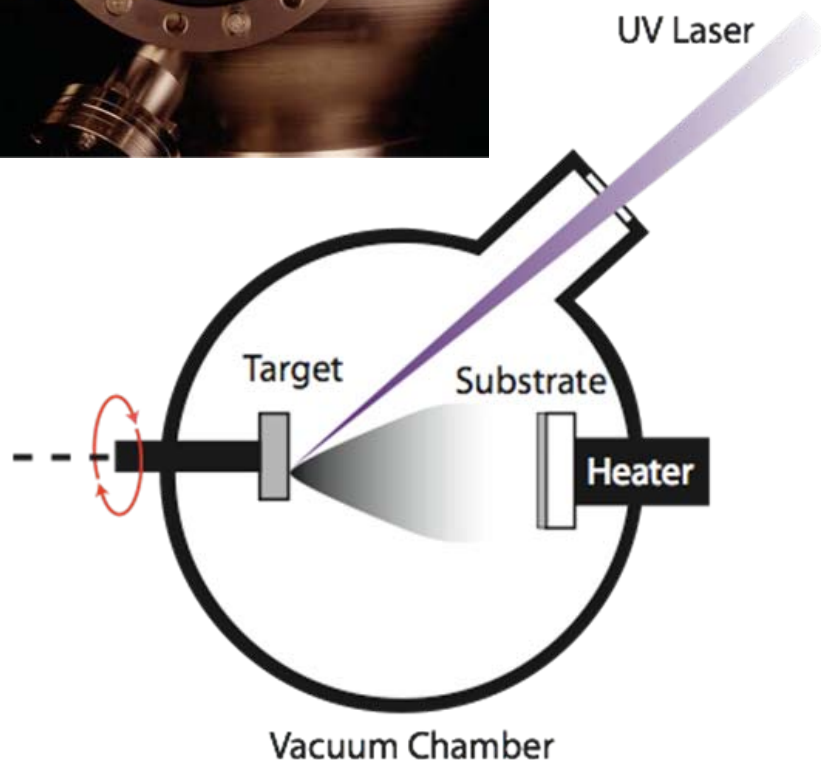
- Glass (Corning Eagle 2000)

- ***Deposition:***

- **Nominal Substrate Temperature:**
- **28-300 °C**

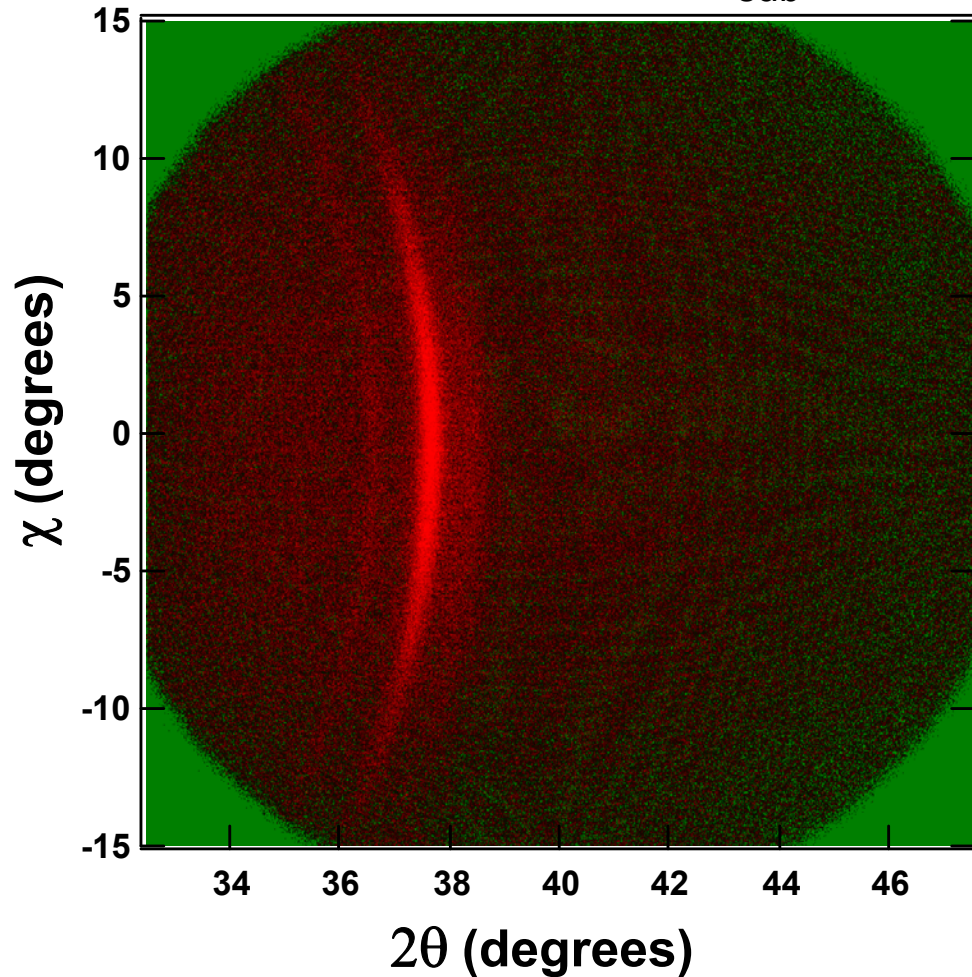
- ***Targets:***

- Ga:ZnO (Plasma Materials)
- **Ga composition 2, 5, 8 at.% (nominal)**

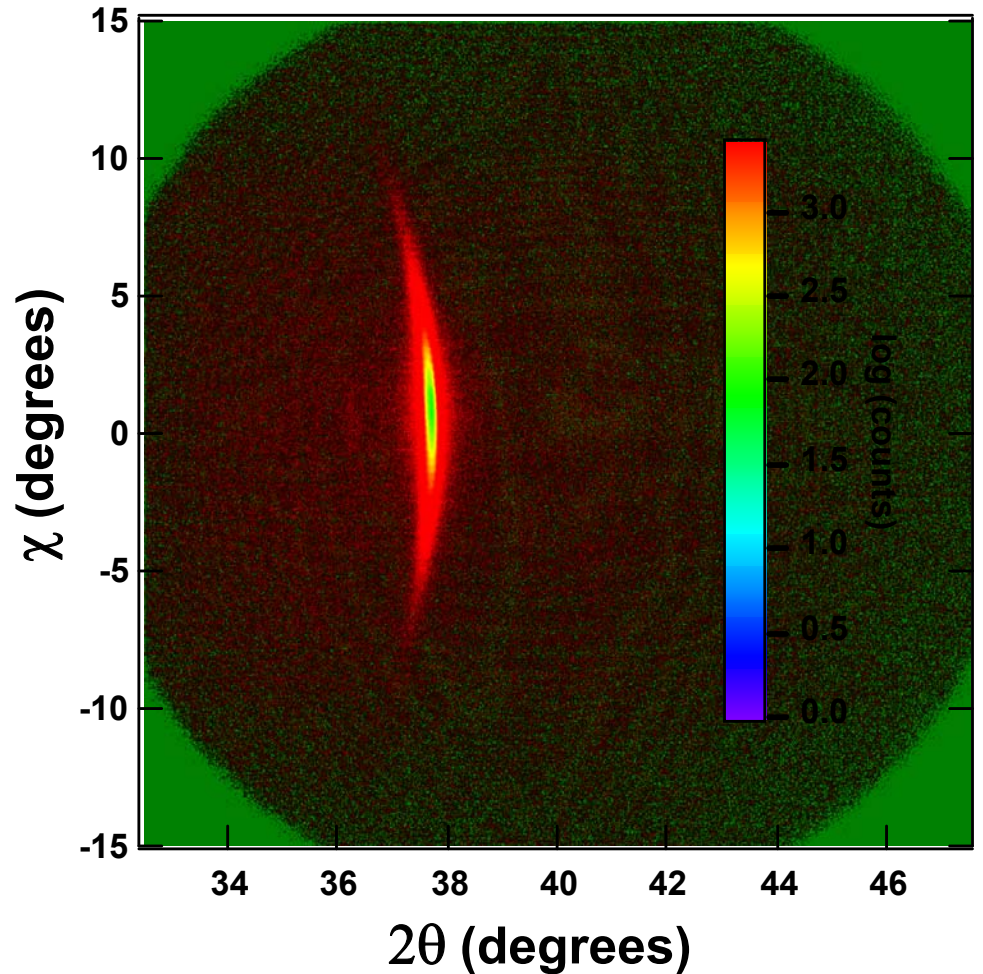


# Ga:ZnO Structural Properties

Ga:ZnO deposited at  $T_{\text{sub}} = 28^{\circ}\text{C}$



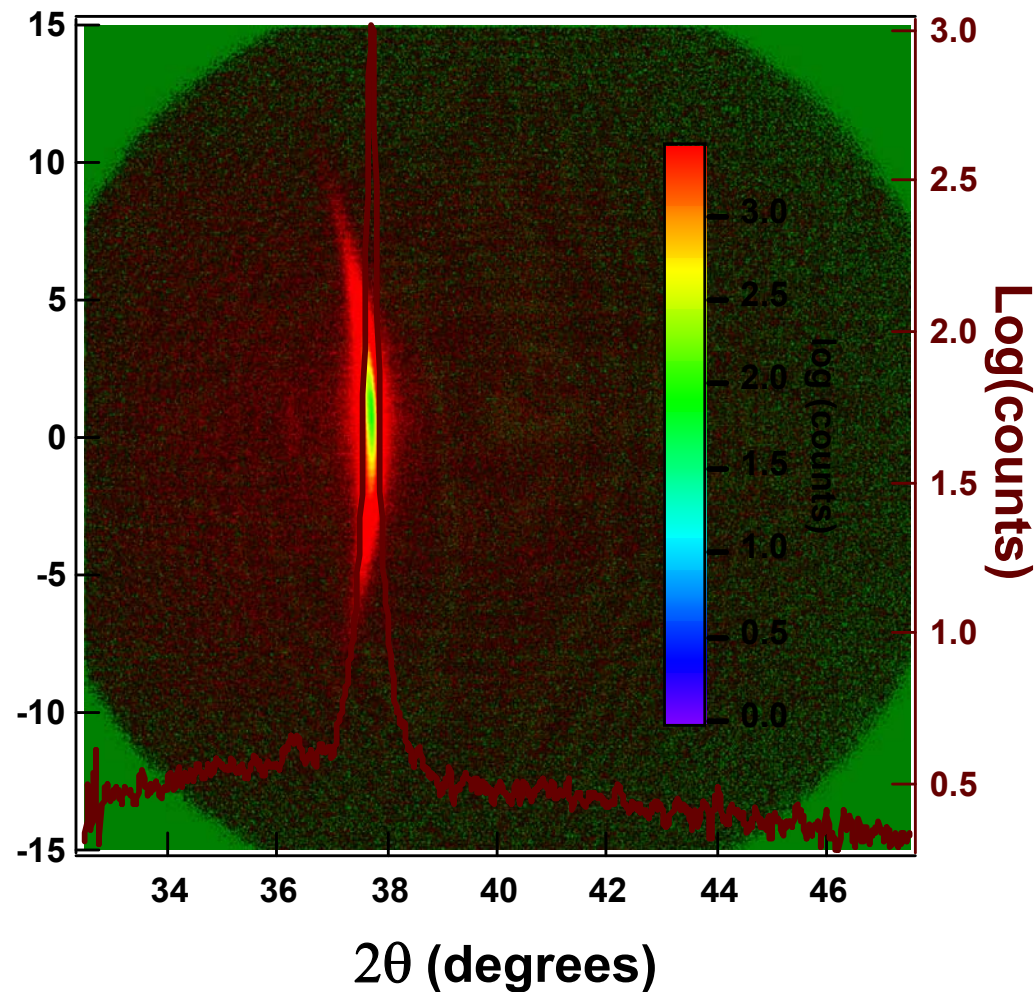
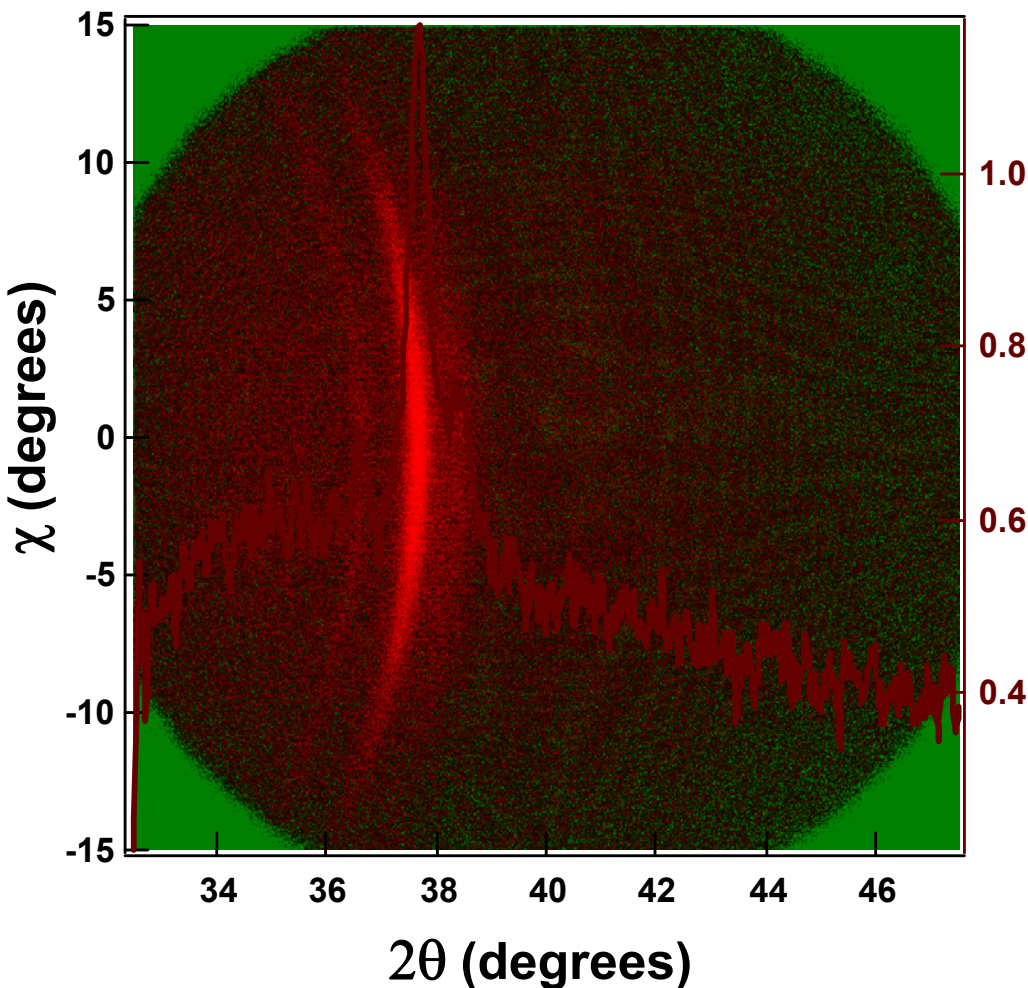
Ga:ZnO deposited at  $T_{\text{sub}} = 300^{\circ}\text{C}$



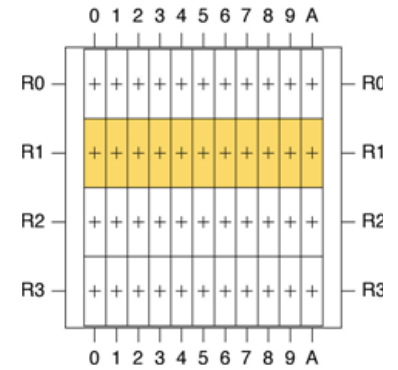
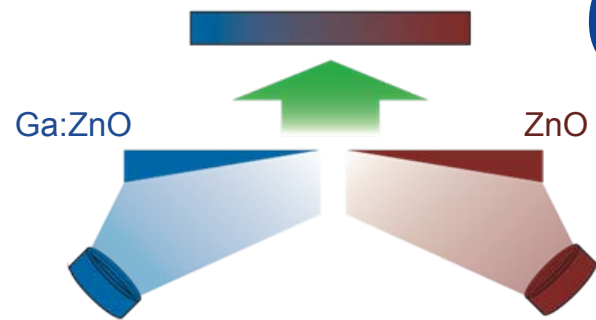
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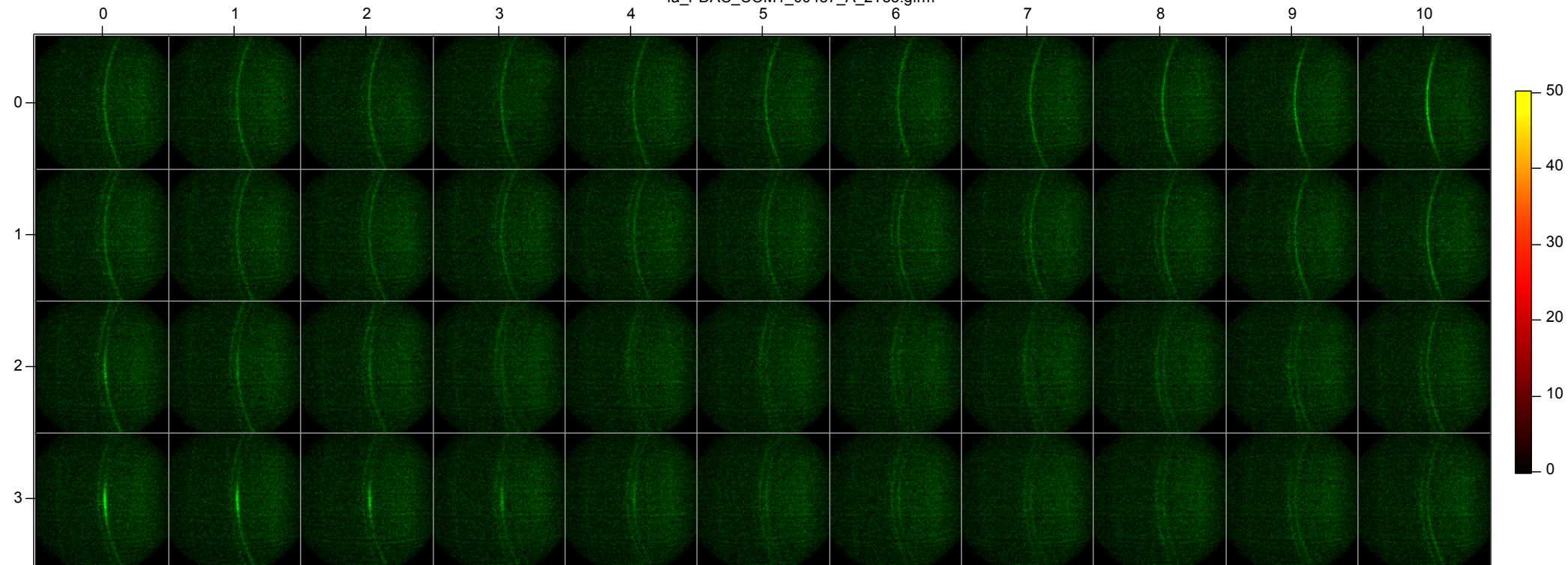
Ga:ZnO deposited at  $T_{\text{sub}} = 300^\circ\text{C}$



# Combinatorial XRD



fa\_PDAC\_COM1\_00487\_A\_2T35.gfrm

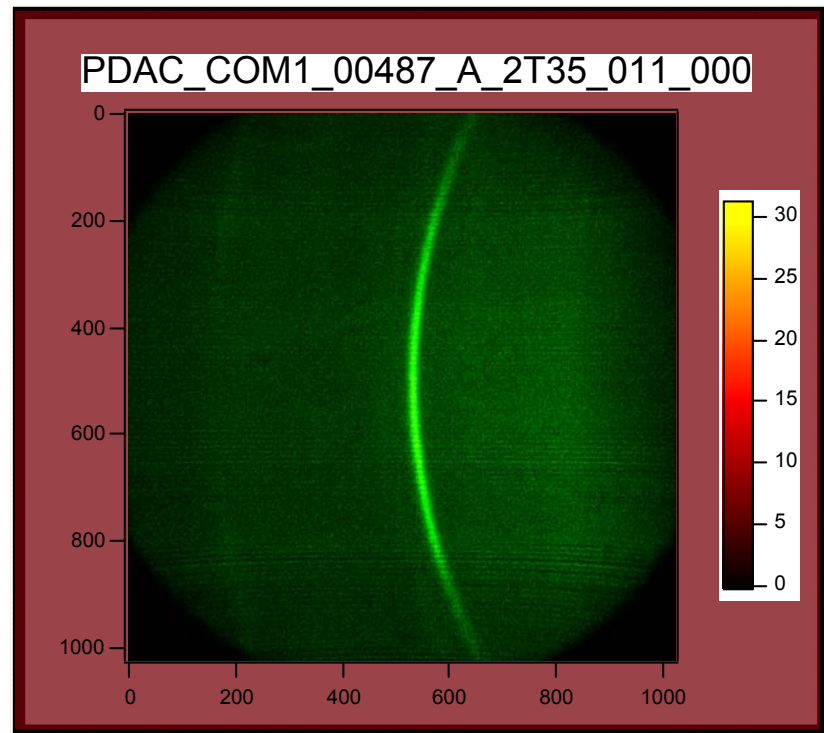
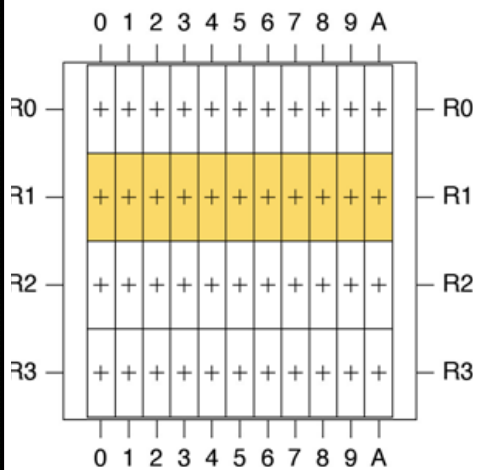
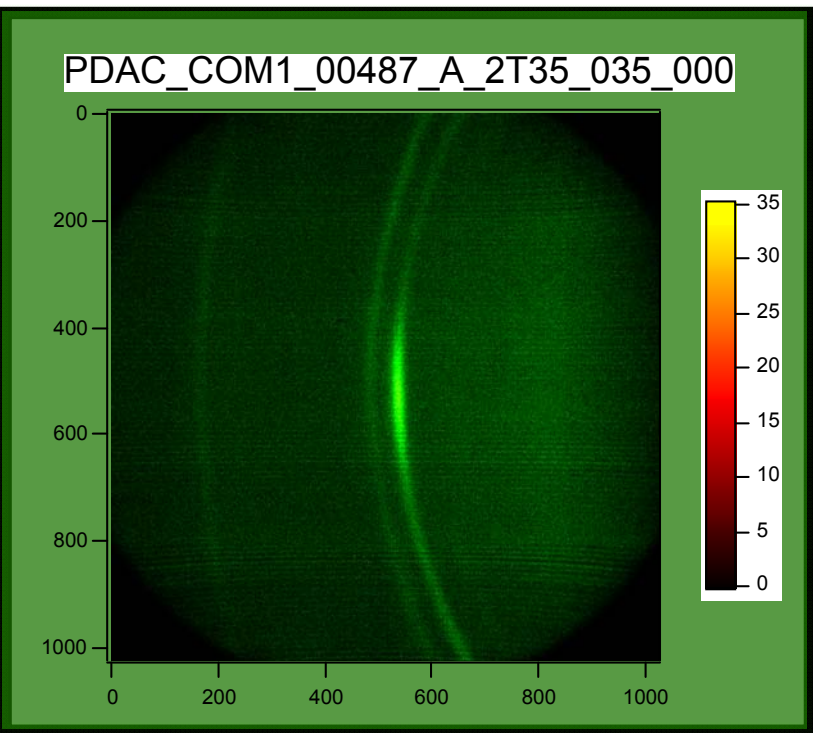
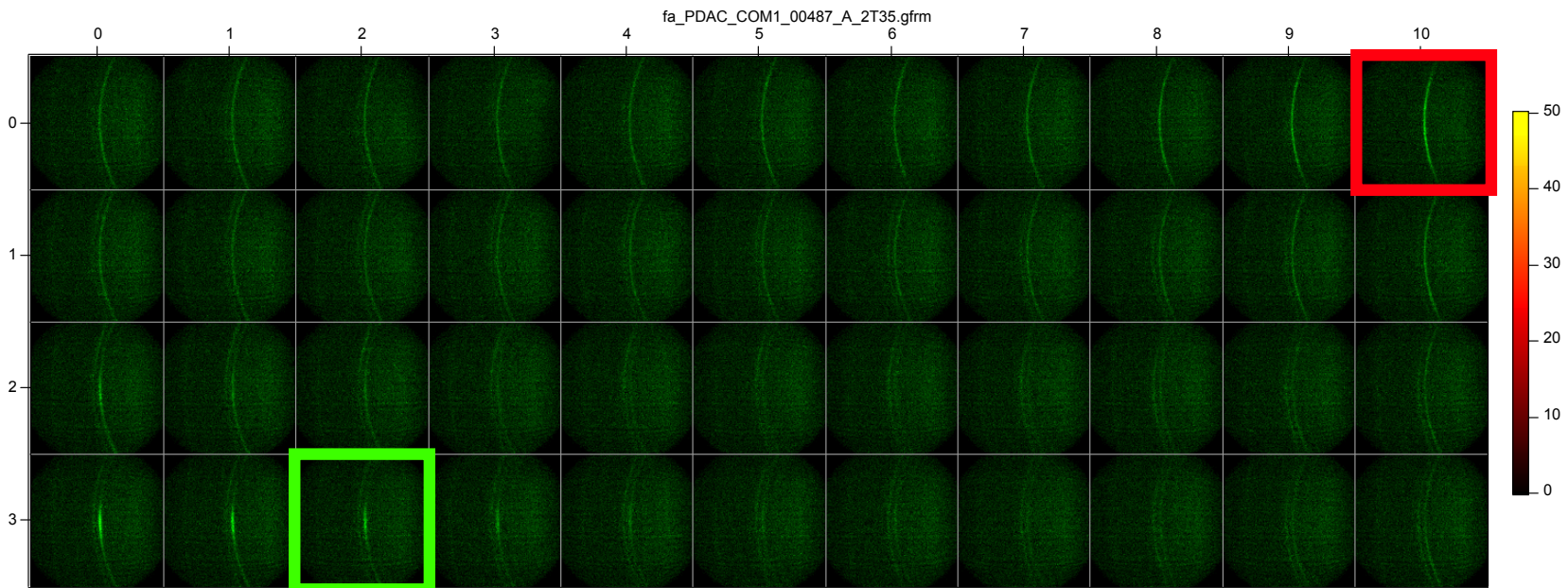


7 a.t.%

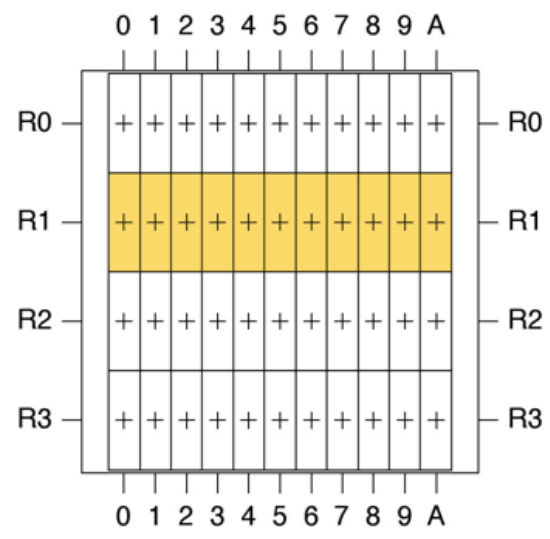
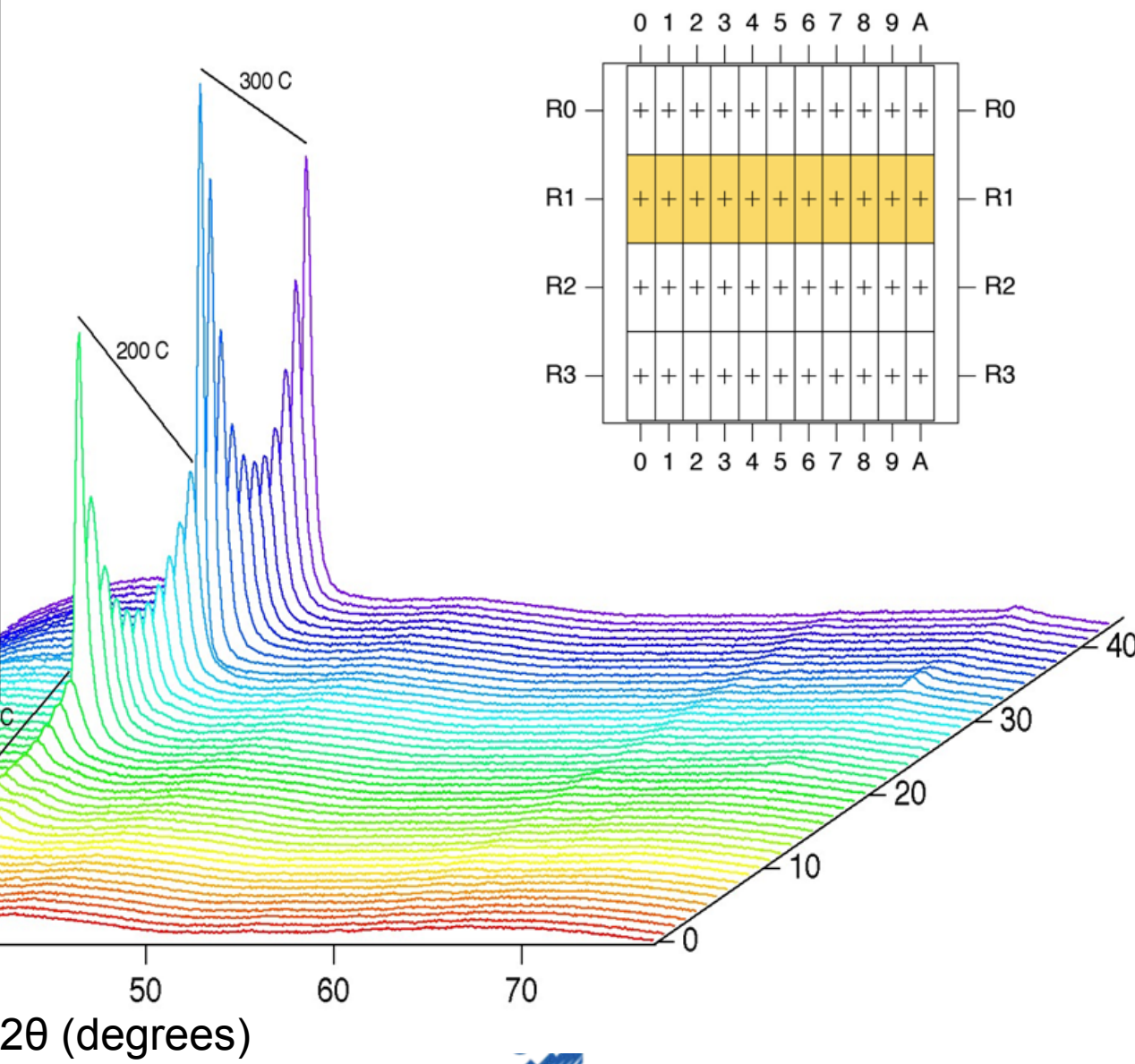
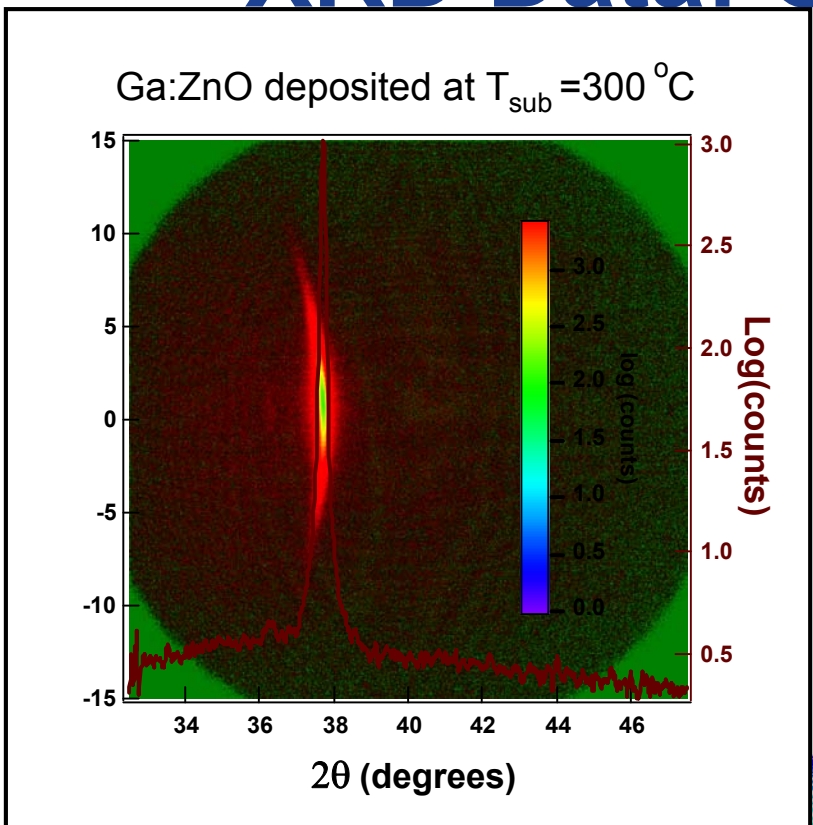
## Ga Content

4 a.t.%

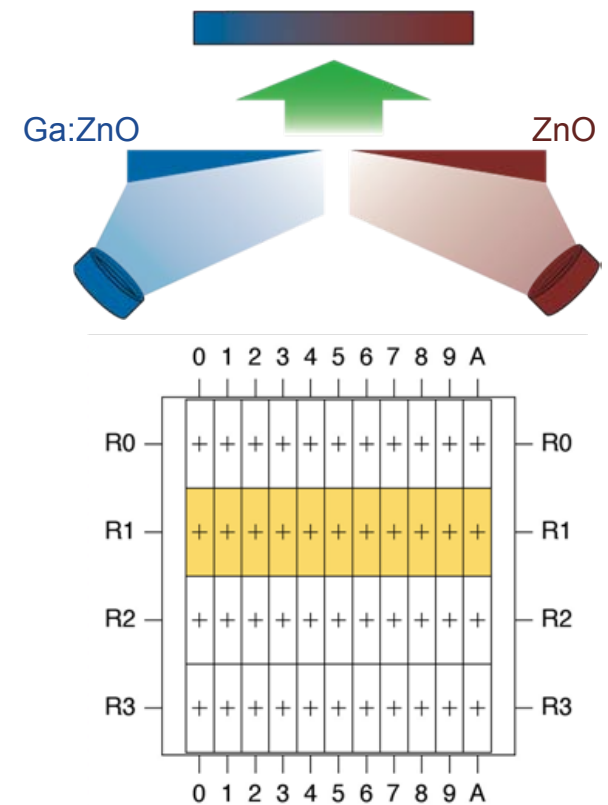
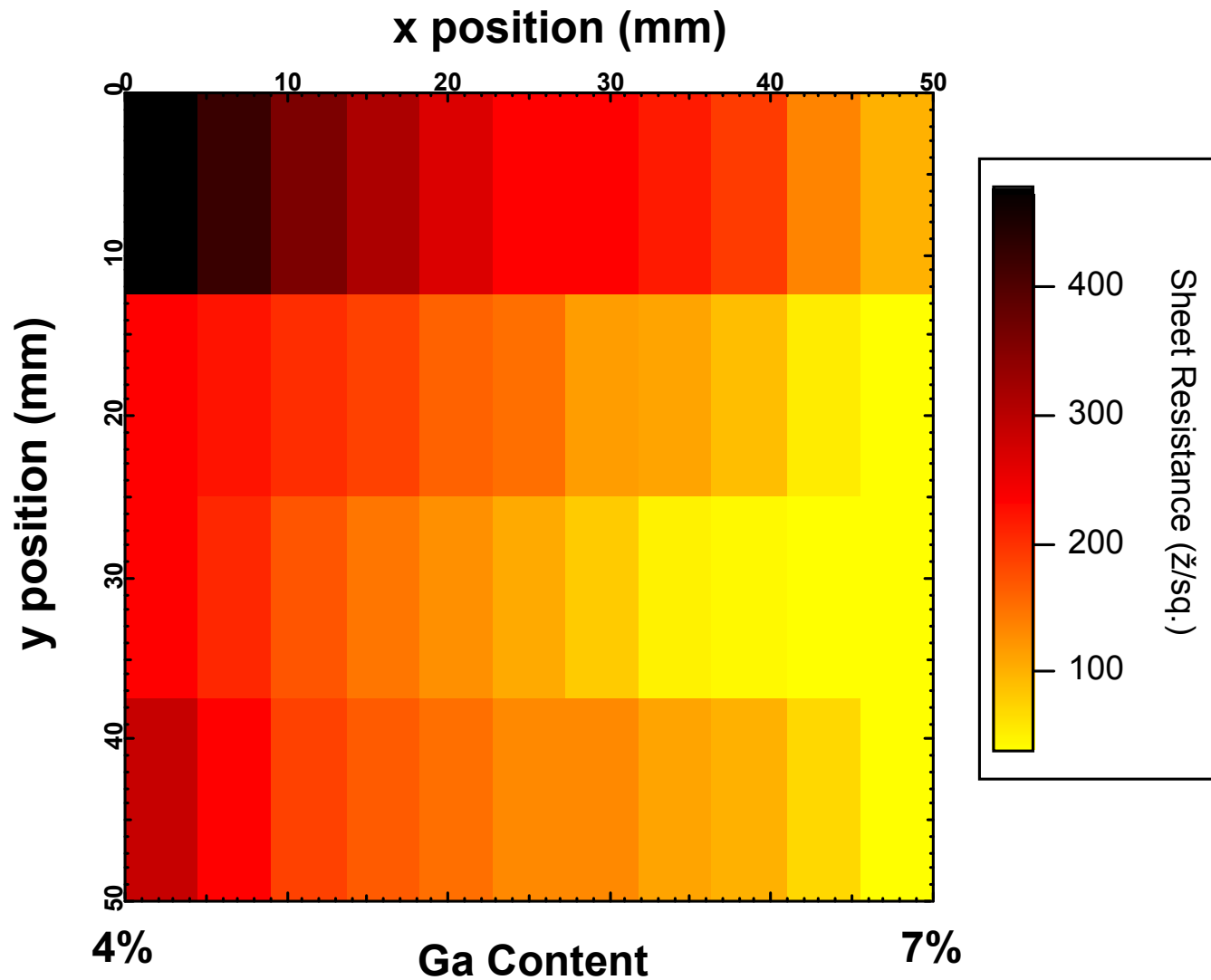




# XRD Data: Combinatorial Samples



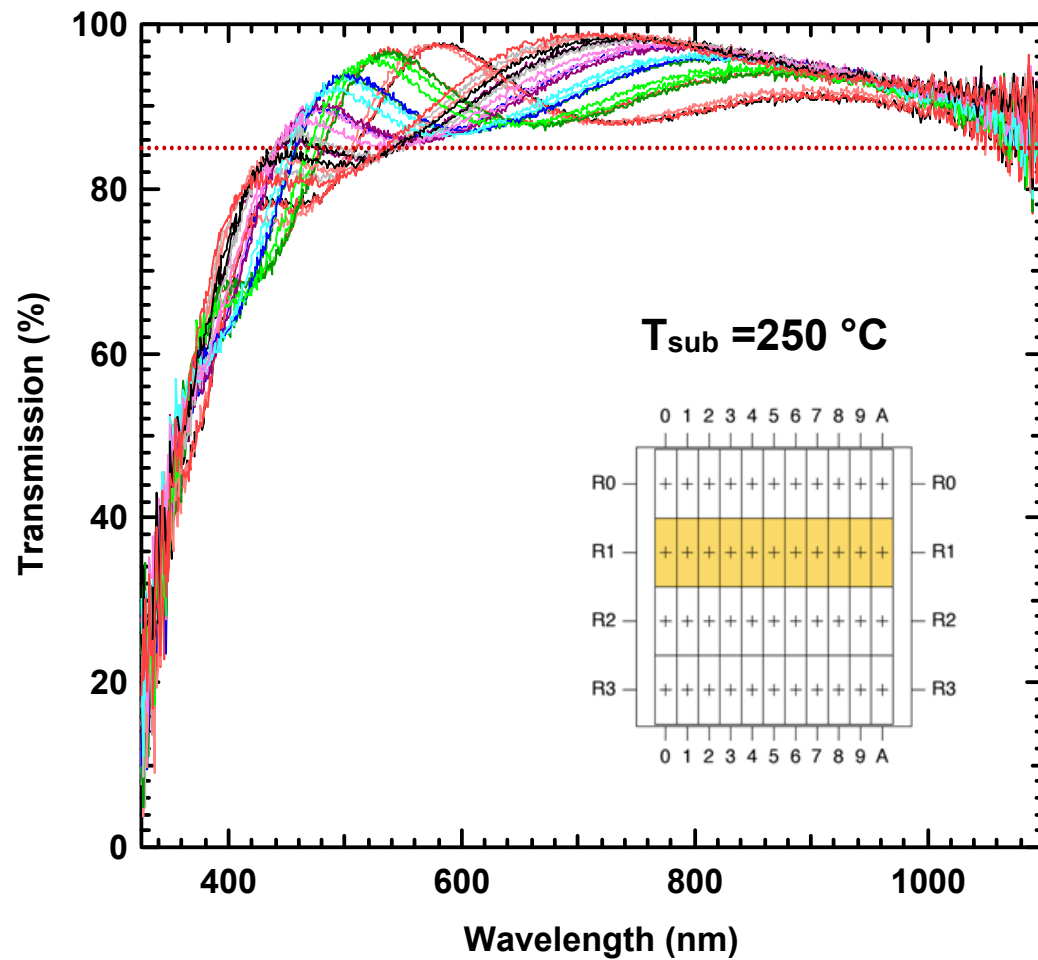
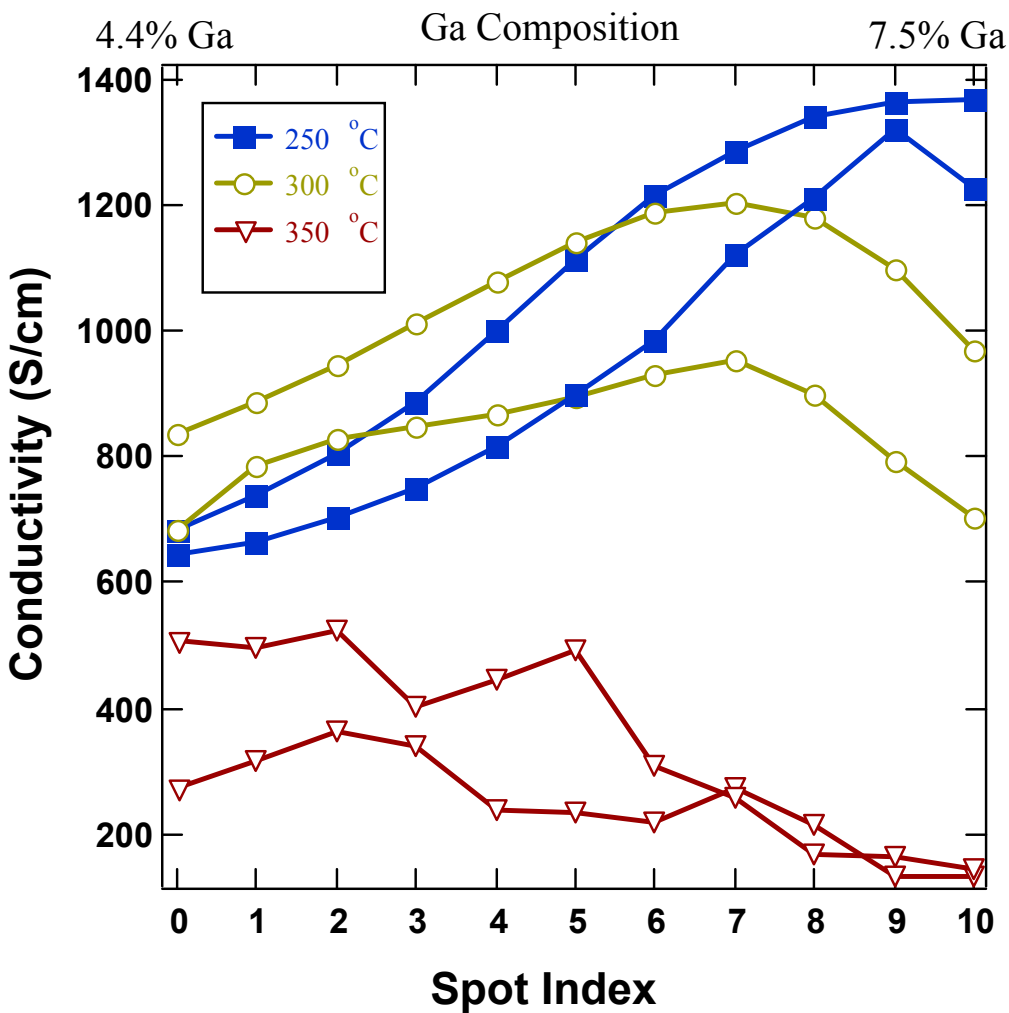
# Combinatorial GZO



$T_{\text{sub}} = 25^\circ\text{C}$   
 400  $^\circ\text{C}$  Anneal

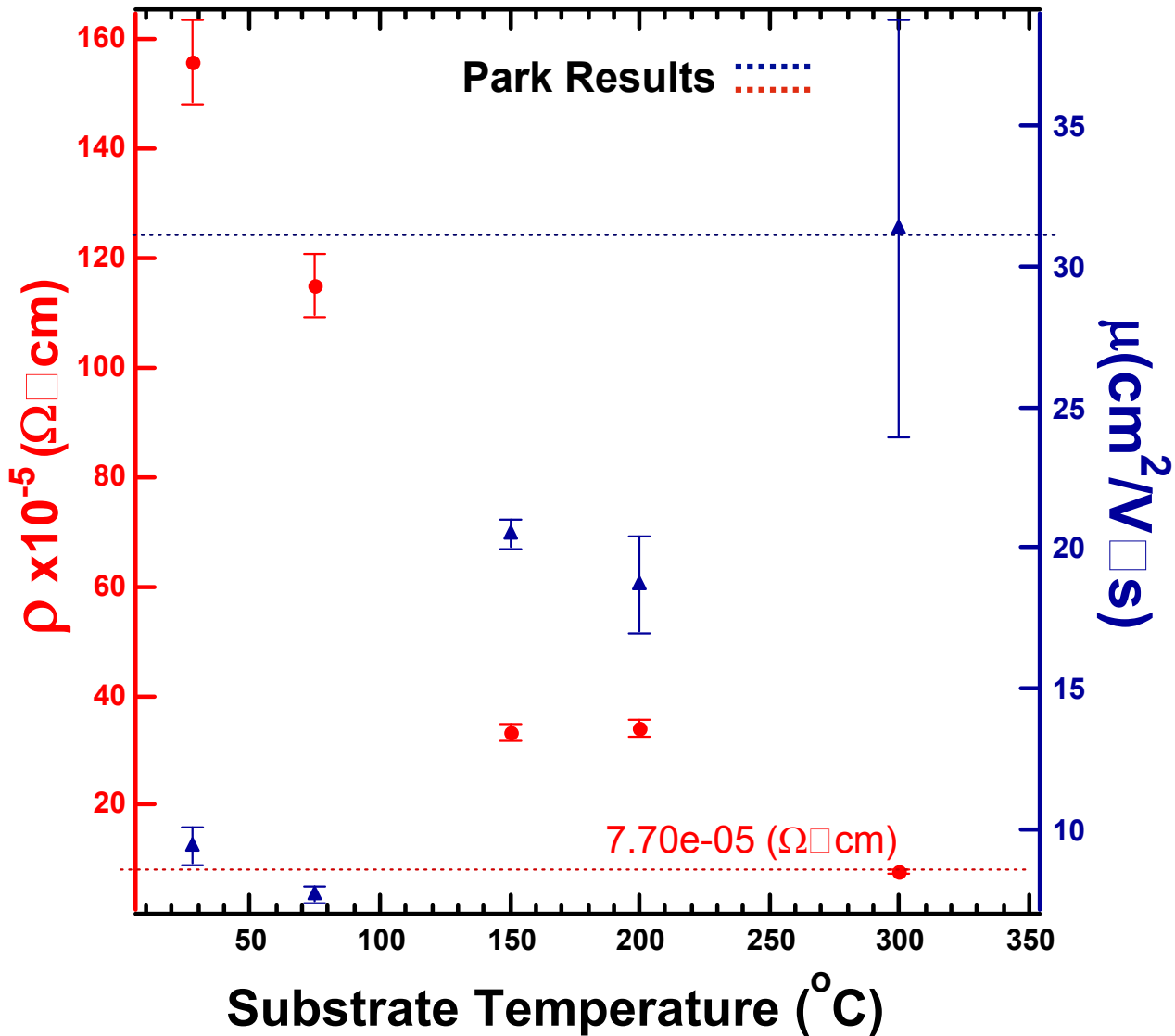


# Combinatorial GZO



Conductivity across center of several Ga:ZnO compositional libraries

# PLD Ga:ZnO Transport Properties



## Park Results

[Thin Solid Films, 513:90–94, 2006]

$$\rho = 8.12 \times 10^{-5} (\Omega \cdot \text{cm})$$

$$\mu = 30.96 (\text{cm}^2 \text{V}^{-1} \text{s}^{-1})$$

## NREL/PNNL

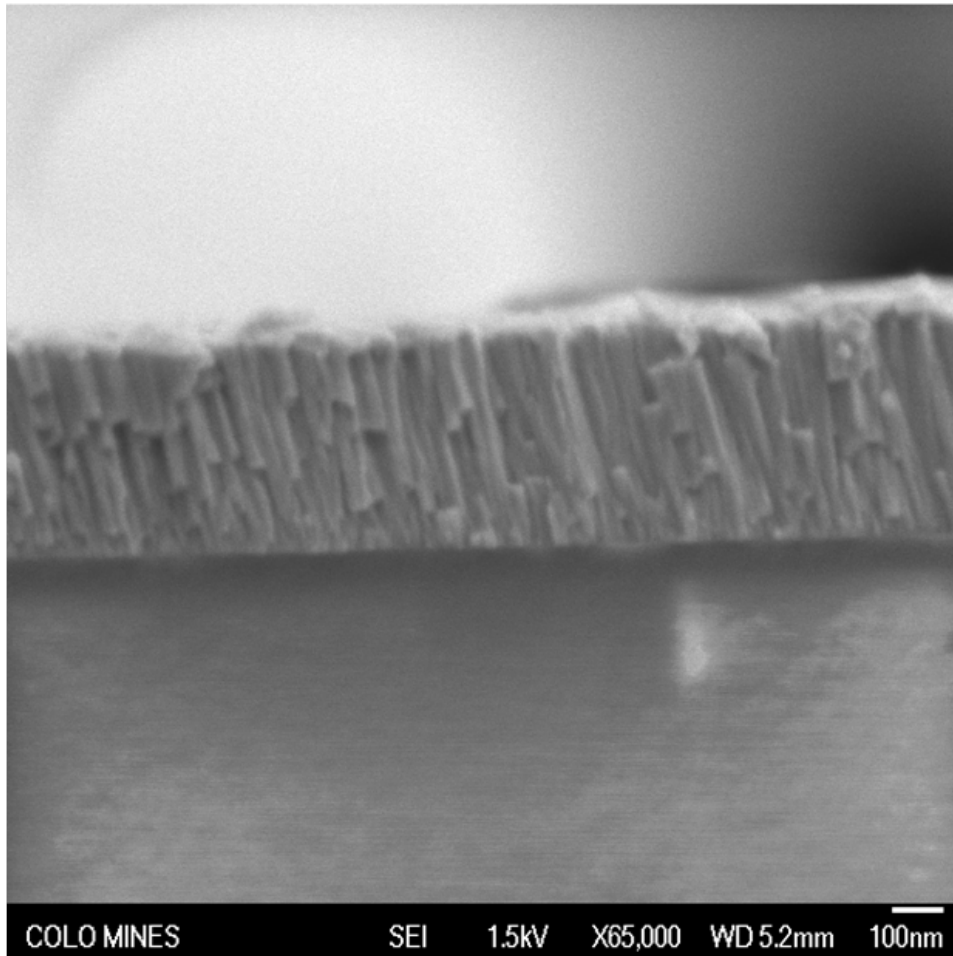
$$\rho = 7.7 \pm 0.5 \times 10^{-5} (\Omega \cdot \text{cm})$$

$$\mu = 31 \pm 7 (\text{cm}^2 \text{V}^{-1} \text{s}^{-1})$$

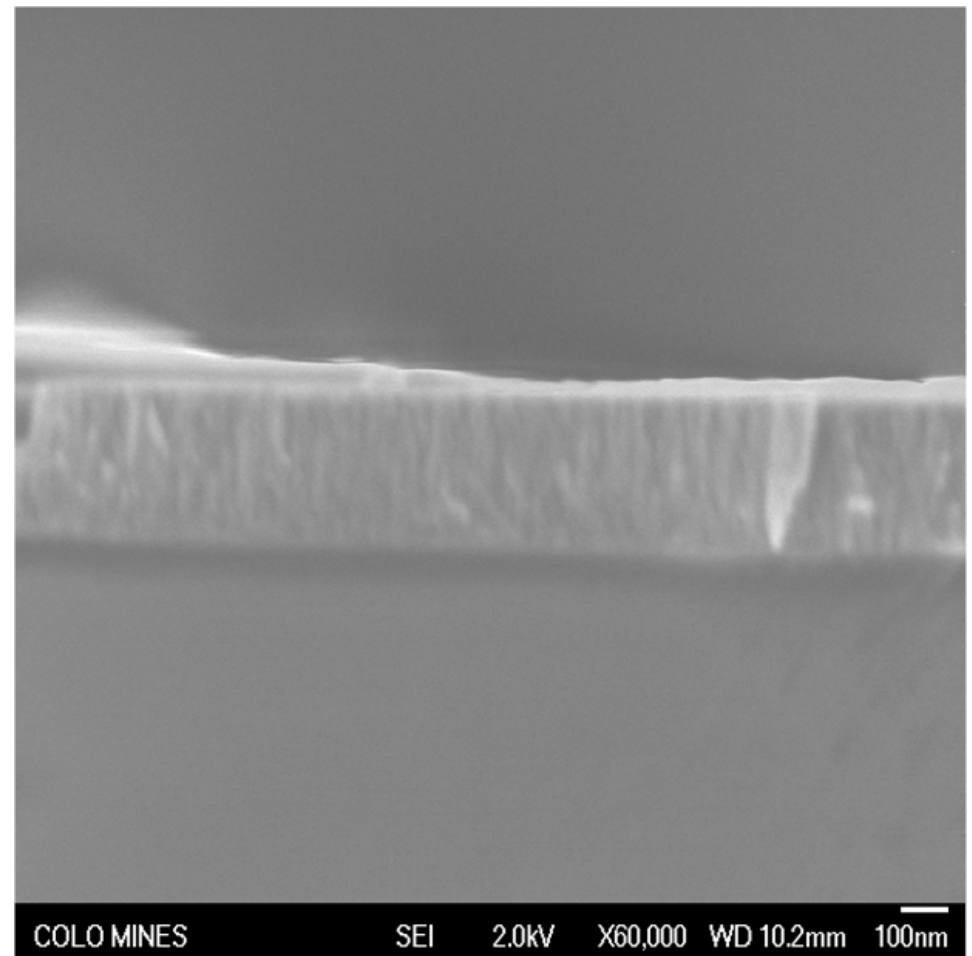
- › Base Pressure:  $<1.0 \times 10^{-6}$  torr
- › Deposition Atmosphere: 1.1 mtorr  $\text{O}_2$
- › KrF Laser ( $\lambda = 248$  nm)
- › Power Density:  $\sim 0.76$  J/cm<sup>2</sup>



# Sputtered GZO vs. PLD



*Sputtered Sample*



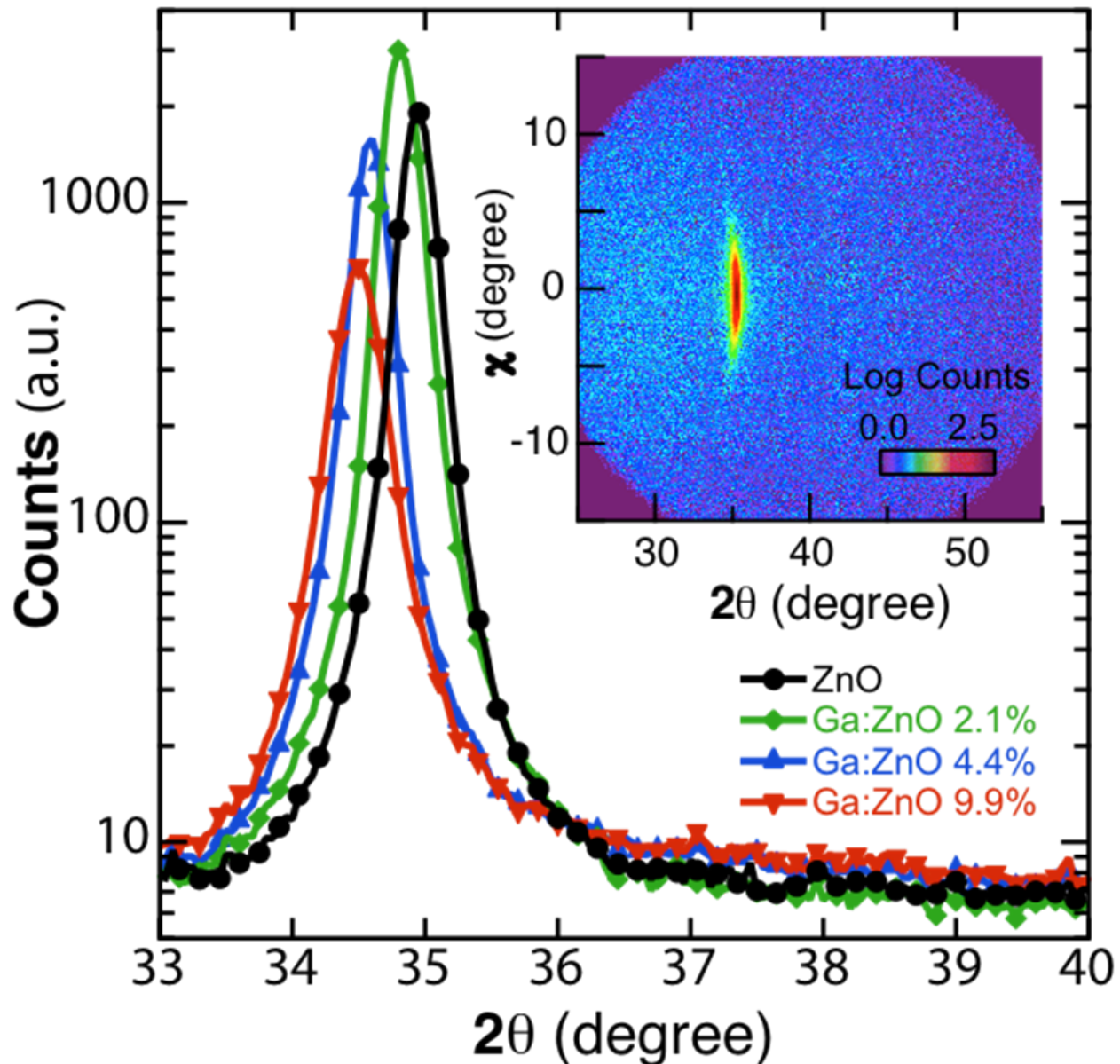
*PLD Sample*

# Promise & Future Directions

- *Ga:ZnO from PLD*
  - ›  $\sigma_{GZO} \equiv \sigma_{ITO}$
  - › *Scalability?*
- *Sputtered Material*
  - ›  $\sigma_{GZO} < \sigma_{ITO}$
  - › *More Optimization*
    - ›  $(\sigma, \mu, c.c.)$
- *Expand Combinatorial Studies*
  - › *Greater Range of Ga a.t.%*
  - › *Increased Temperature Range (550 °C)*
  - › *Tuned MgGaZnO for PV applications*
- *PLD*
  - › *Digital Alloys*
  - › *Interface Engineering*



# Ga:ZnO structure



- All deposition at:
  - $T_s = 300\text{ }^\circ\text{C}$
  - $1.1 \times 10^{-3}$  torr  $\text{O}_2$
- ***No  $\text{Ga}_2\text{O}_3$  segregation***
- ***All ZnO films are textured***
- ***Ga inclusion stretches lattice***

