Growth and Doping of α-Ga_2O_3 with Suboxide Molecular-Beam Epitaxy (*S*-MBE)

Cornell University | PARADIM
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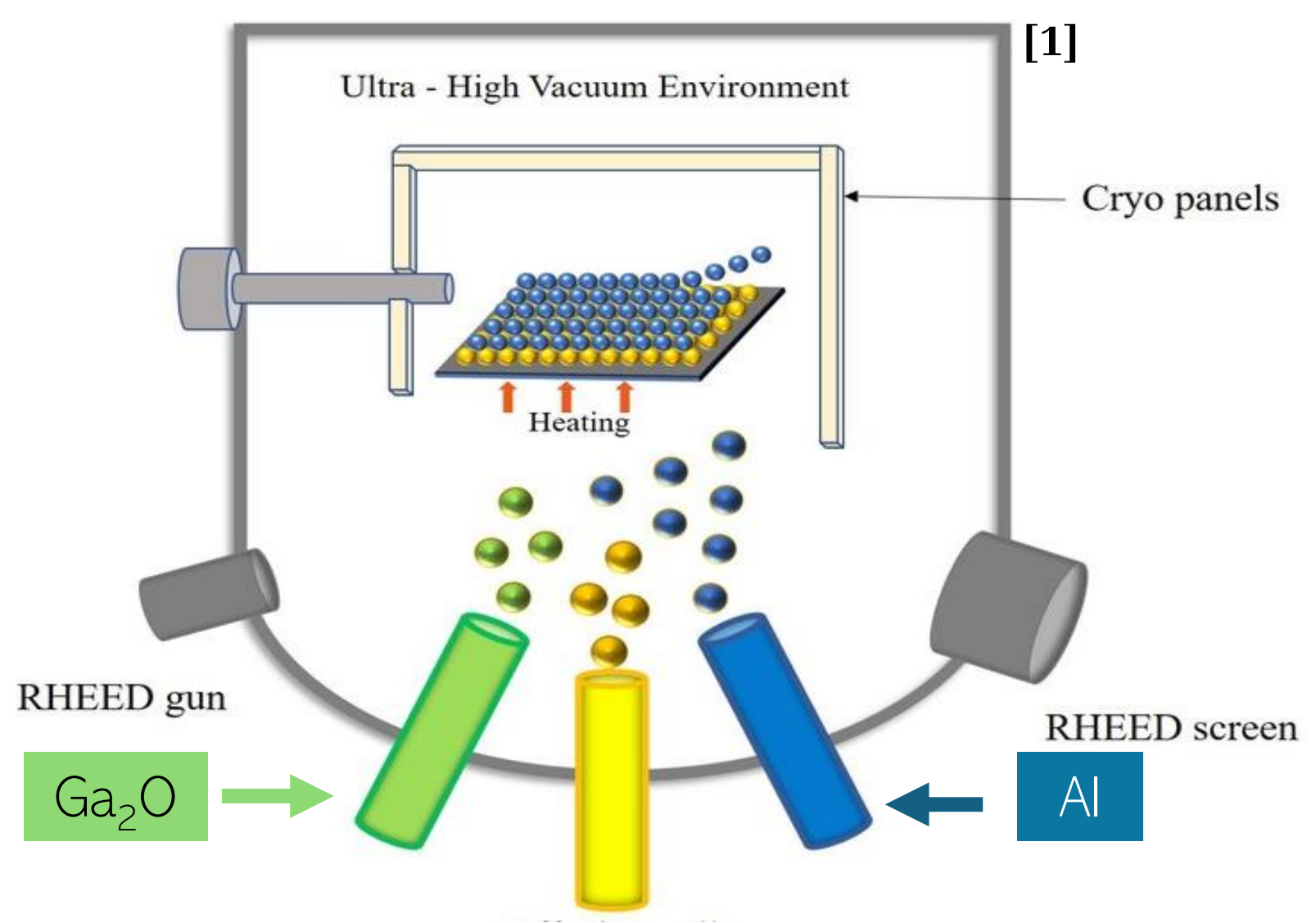
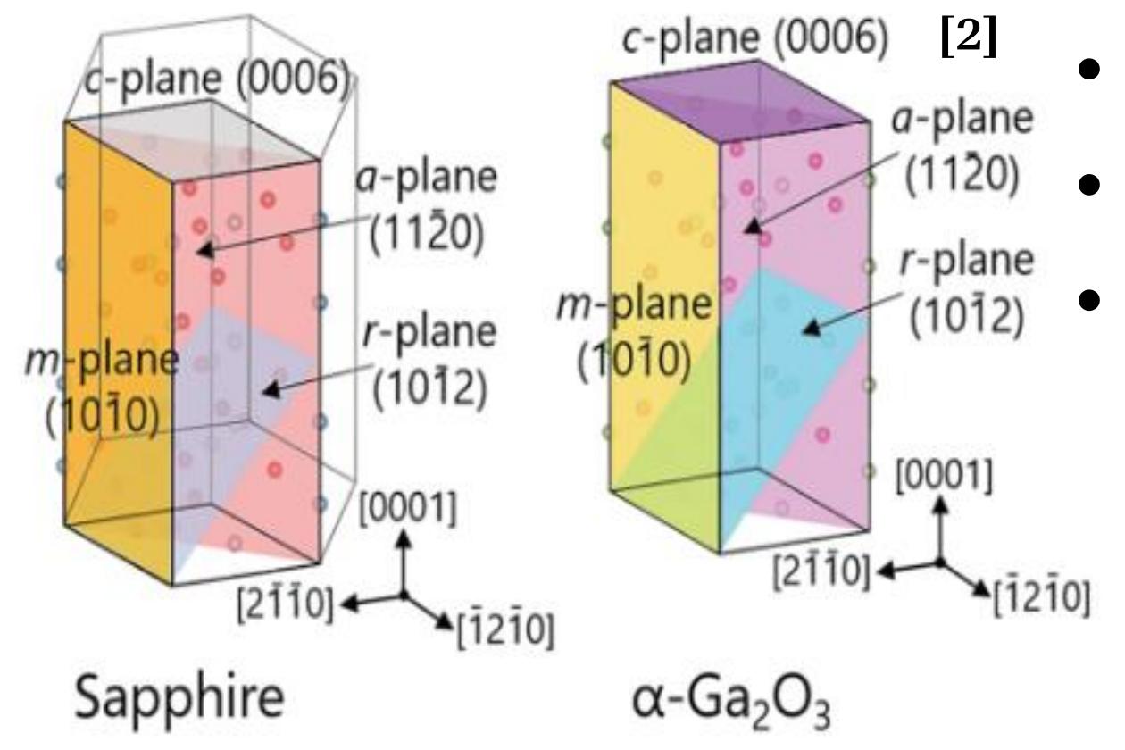
Introduction

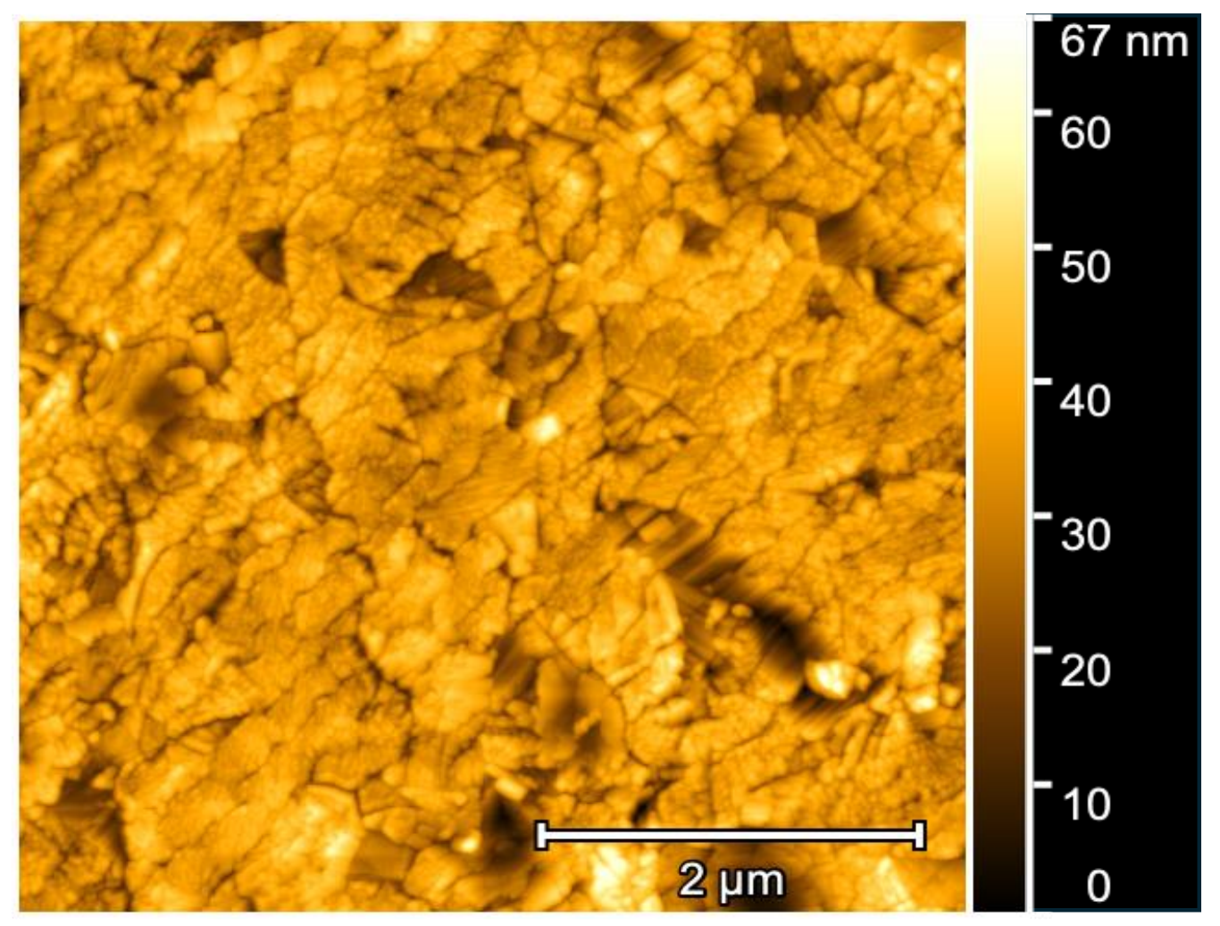


- MBE:
  1. $2Ga + ½ O_2 \rightarrow Ga_2O$
     - Rate limiting step
  2. $Ga_2O + 2O \rightarrow Ga_2O_3$
     - $Ga_2O_3 + Ga \rightarrow Ga_2O$
- *S*-MBE: more efficient
  1. $Ga_2O + 2O \rightarrow Ga_2O_3$
     - Increase growth speed

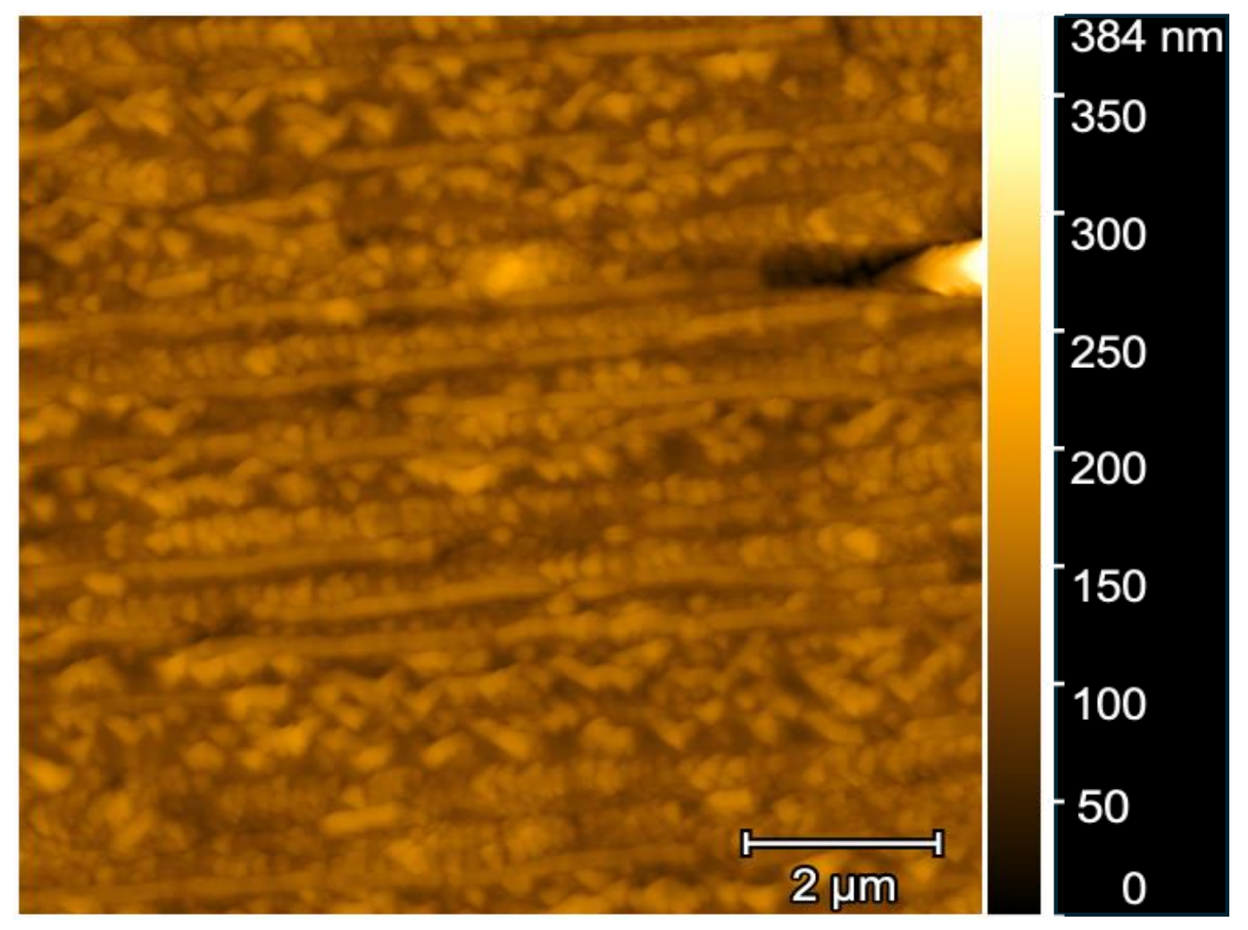


- Tunable lattice of 3.7-8.6 eV
- Higher intrinsic mobility than *β*-Ga_2O_3
- Electrically conducting + transparent up to 250 nm
  1. Transistors
  2. Solar-blind UV photodetectors
  3. Photocatalysts
- Sapphire & α-Ga_2O_3 are isostructural with 4% lattice mismatch

- α-Ga_2O_3 is more stable on m-plane sapphire (Al_2O_3) than a-plane
- Stepped m-plane sapphire → RMS of 7.6 nm, 360 nm thick
- Flat m-plane substrates → RMS of 24.5 nm, 436 nm thick
  - Directional conductivity, along cracks or streaks of *β*-Ga_2O_3
- Stepped substrates can't be produced in an efficient manner
  - Growth on flat substrates must be optimized



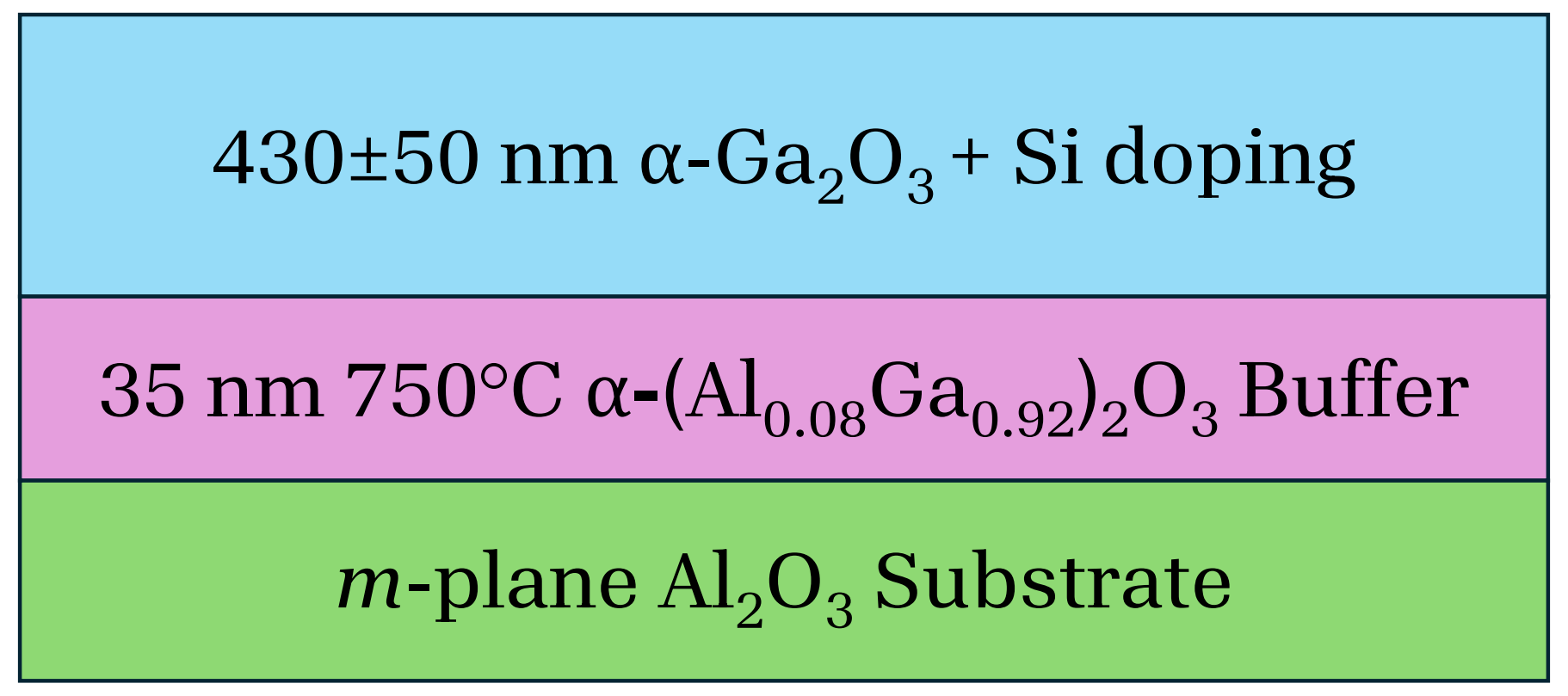
Stepped substrate growth AFM



Flat substrate growth AFM

Experimental

☐ **Phase 1:** Growth on *m*-plane, flat substrates with no steps
- High T α-$(Al,Ga)_2O_3$ buffer to fix directional conductivity by reducing lattice mismatch
  - Al prevents *β*-Ga_2O_3 as Al_2O_3 and α-Ga_2O_3 are isostructural



430±50 nm α-Ga_2O_3 + Si doping

35 nm 750°C α-$(Al_{0.08}Ga_{0.92})_2O_3$ Buffer

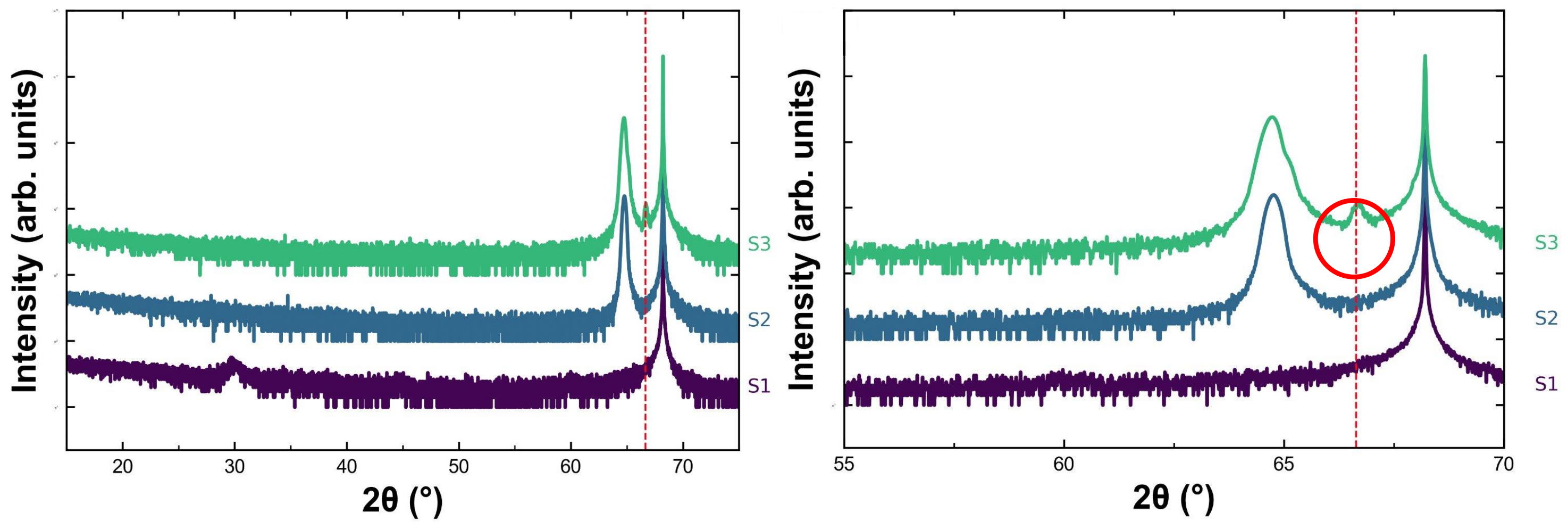
m-plane Al_2O_3 Substrate

☐ **Phase 2:** Match stepped substrate conductivity w/ flat substrates

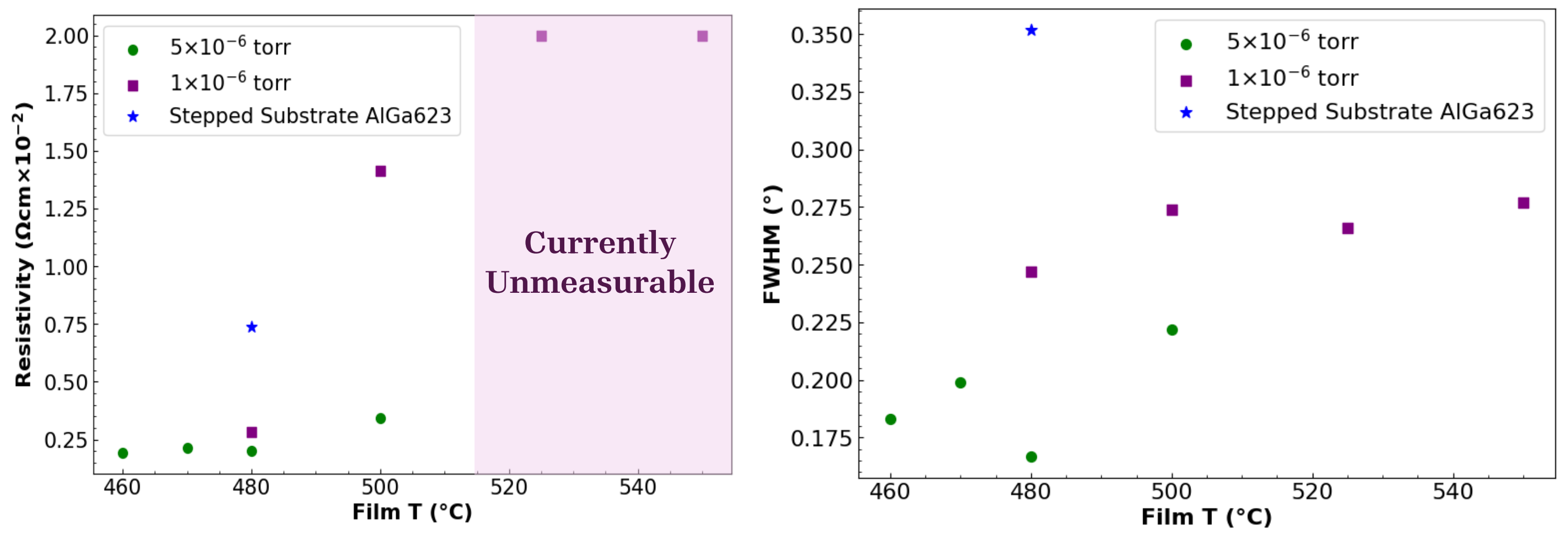
☐ **Phase 3:** Modulating carrier concentrations v. mobility
- Dislocation density estimations

Phase 1 Results

- S1: no buffer
  - **No α-Ga_2O_3**
- S2: α-Ga_2O_3
  - R: 64.2 Ω/□
  - μ: 61.6 $cm^2/(V·s)$
  - FWHM: 0.283°
- S3: α-$(Al,Ga)_2O_3$
  - R: **49 Ω/□**
  - μ: **78.8 $cm^2/(V·s)$**
  - FWHM: **0.167°**
  - **Hybrid peak** between film and substrate peaks, associated with high order
  - A buffer is clearly needed and adding aluminum increases mobility and lowers resistance



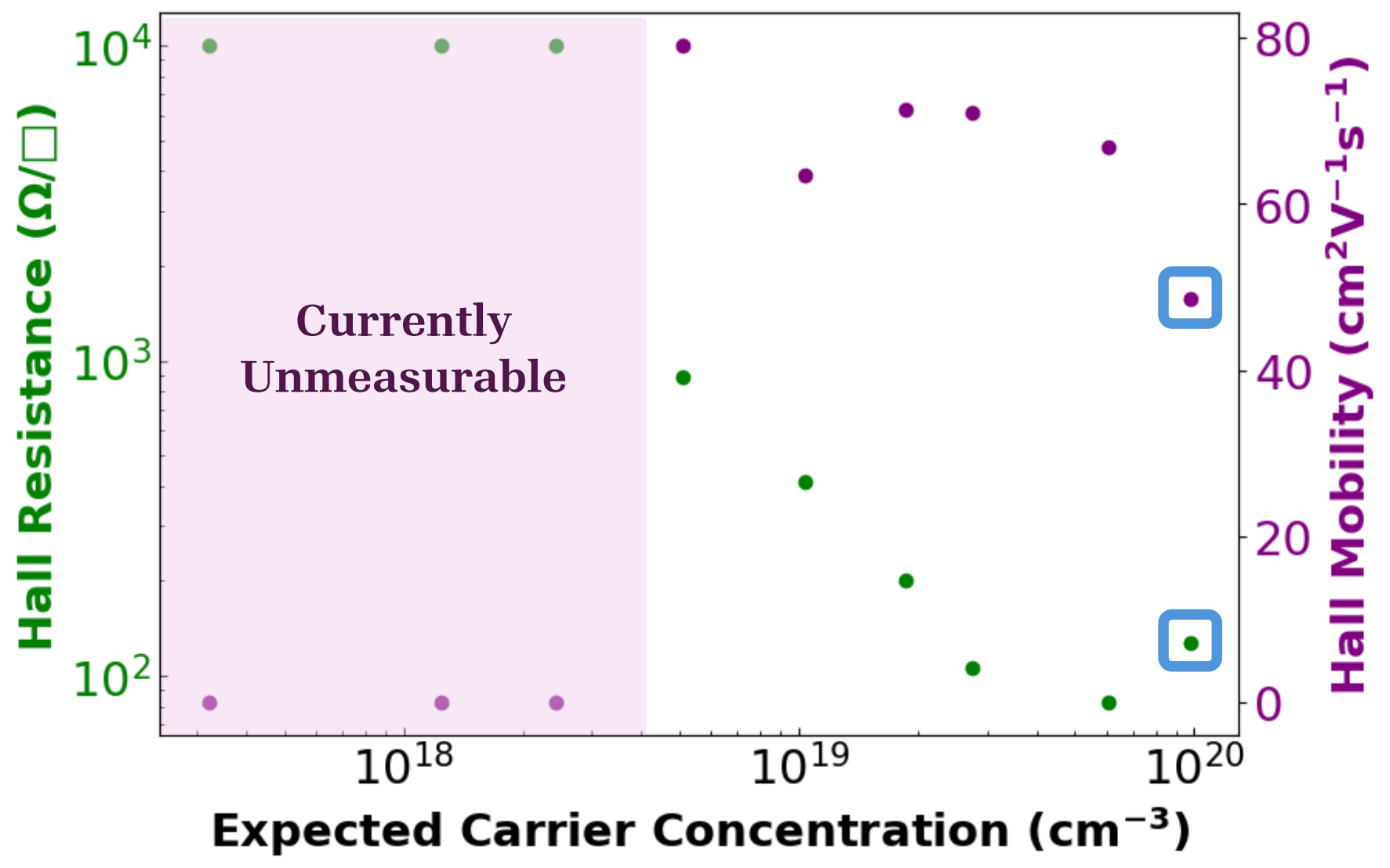
Phase 2 Results



- Best Stepped Film:
  - ρ: $7.4×10^{-3}$ Ωcm
  - FWHM: 0.352°
- Best Flat Film:
  - ρ: **$1.9×10^{-3}$ Ωcm**
  - FWHM: **0.167°**
- **High P_{O3} & low film *T*** results in better films than stepped substrates

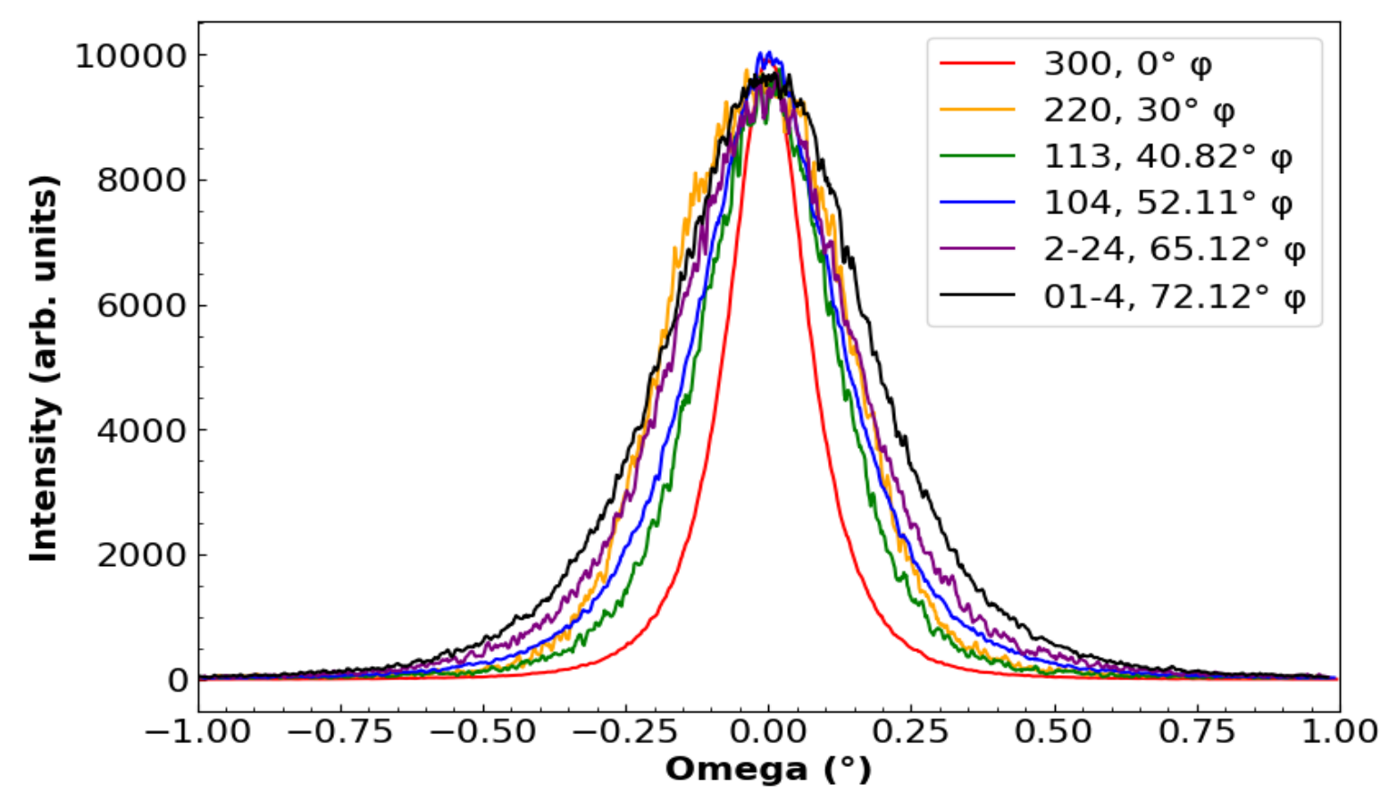
Phase 3 Results

- SiO_2 Source *T* varied from 1175-1400°C to control carrier concentration
- **Decreasing resistance** with increased carriers
  - Si activation 50% → 25% at 1400°C, leading to **higher resistance**
- High mobilities suggest our high structural quality caused **increased mobility with lower carriers**

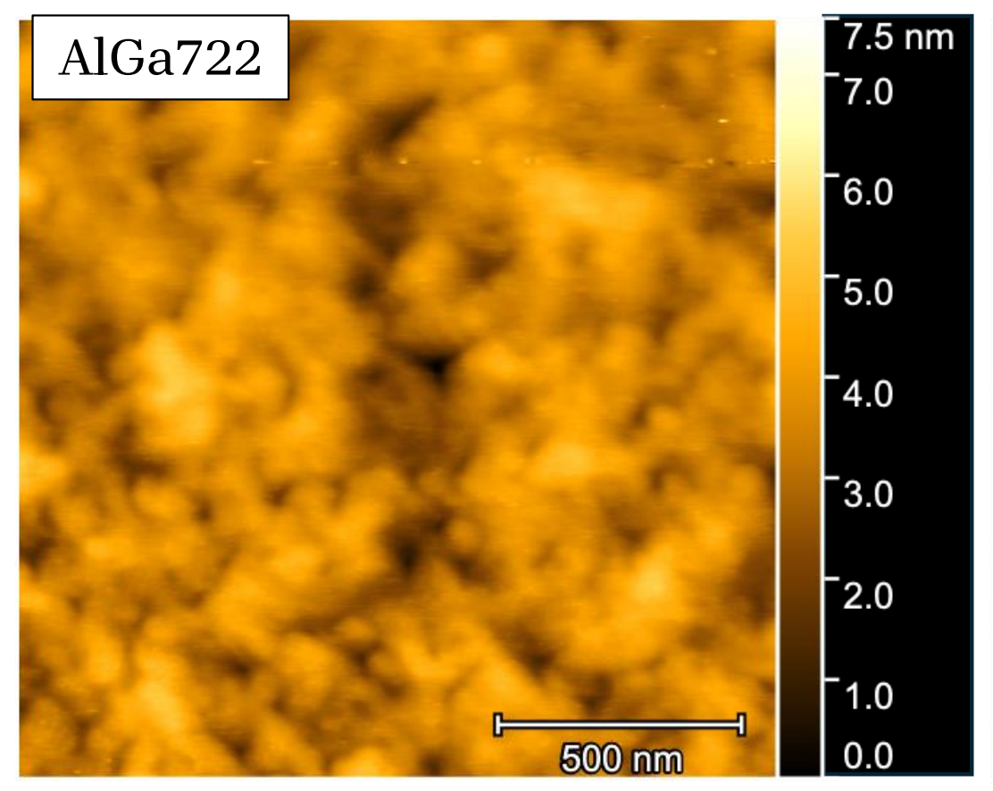


- Below is an analysis of our best films (AlGa722, AlG726) to current literature

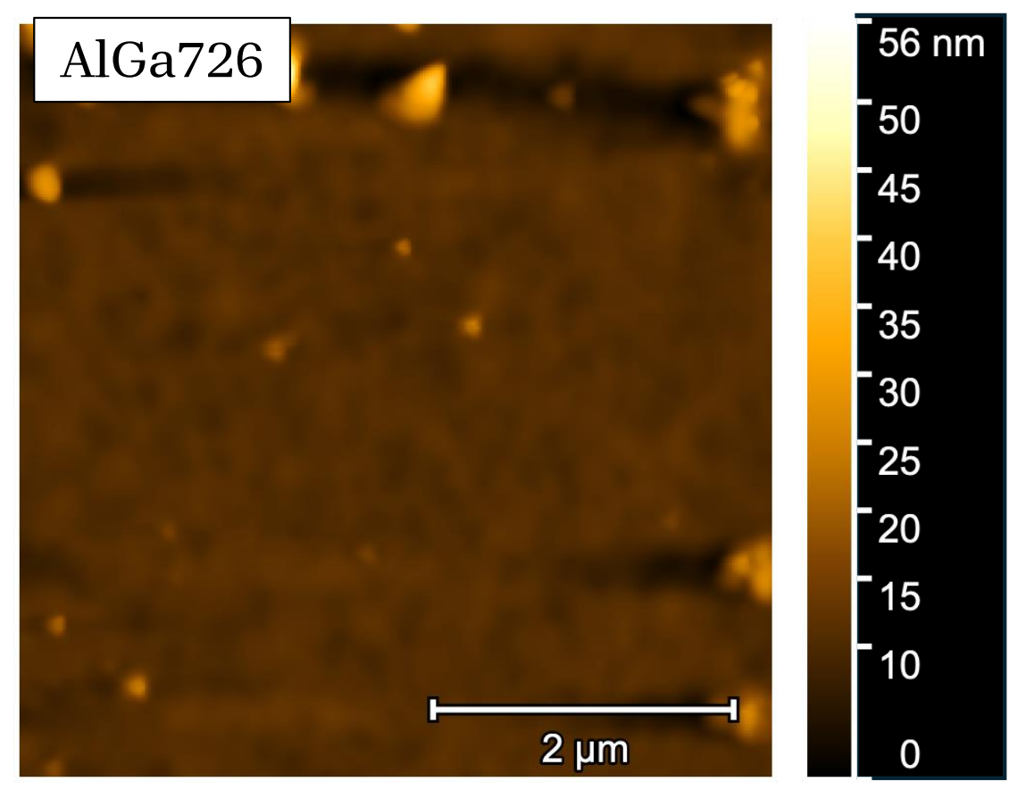
Parameter	Current Records	AlGa722	AlGa726
FWHM	0.27° [3]	0.167°	0.185°
Resistivity	$2.7×10^{-2}$ Ωcm [4]	$2.01×10^{-3}$ Ωcm	$1.67×10^{-3}$ Ωcm
Mobility	65 $cm^2V^{-1}s^{-1}$ [5]	78.8 $cm^2V^{-1}s^{-1}$	81.7 $cm^2V^{-1}s^{-1}$
Dislocation Density	10^{11}-10^{12} cm^{-2} [7, 8]	$3.72×10^8$ cm^{-2} [6]	$2.48×10^8$ cm^{-2}



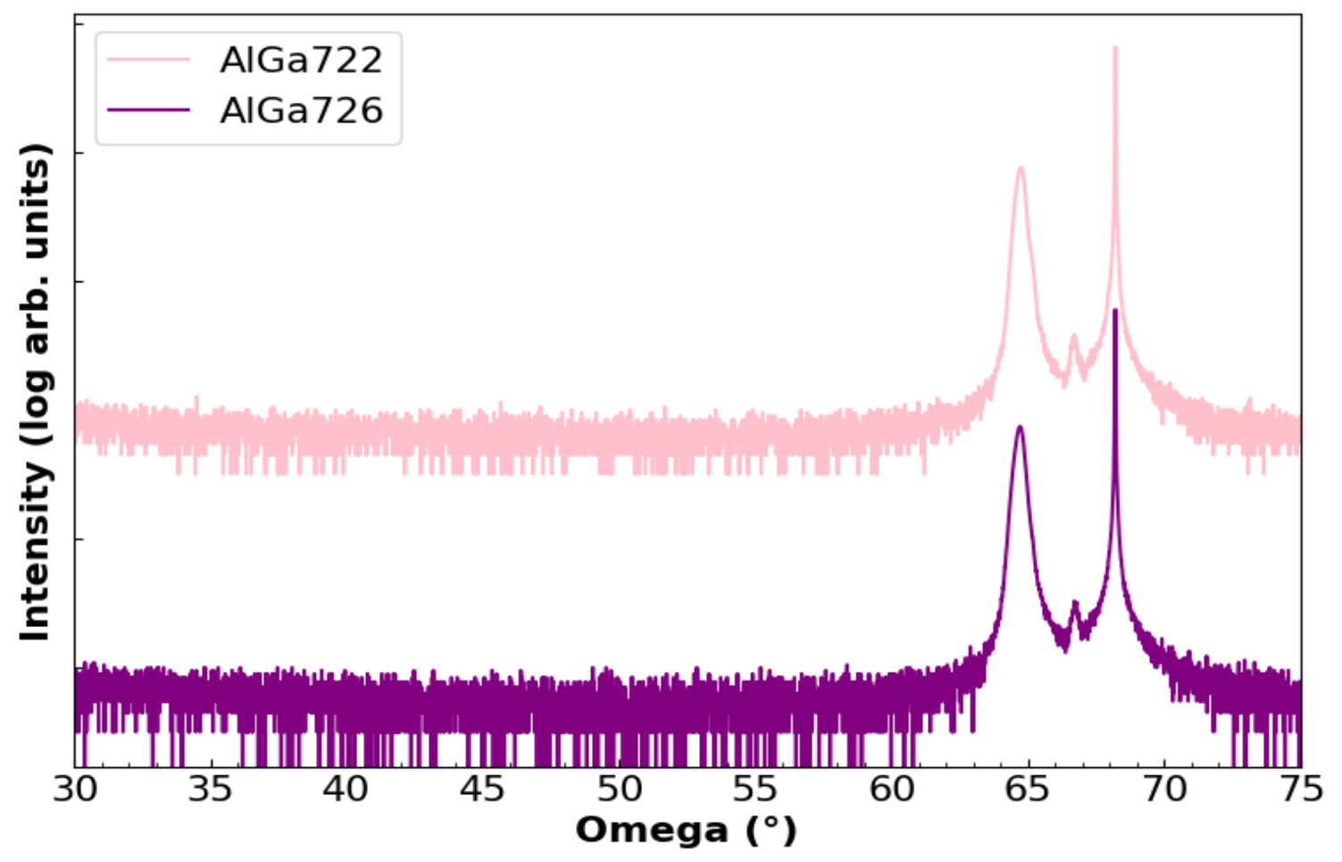
- AlGa722 FWHM widens w/ ψ due to edge dislocations from 0.167° to 0.402°
- **Hybrid peaks**, associated with high order, present in both AlGa722 and AlGa726
- AFM w/ **no cracks or *β*-Ga_2O_3 formation**, due to the high *T* buffer with aluminum



RMS: 0.695 nm, 410 nm thick



RMS: 0.664 nm, 485 nm thick

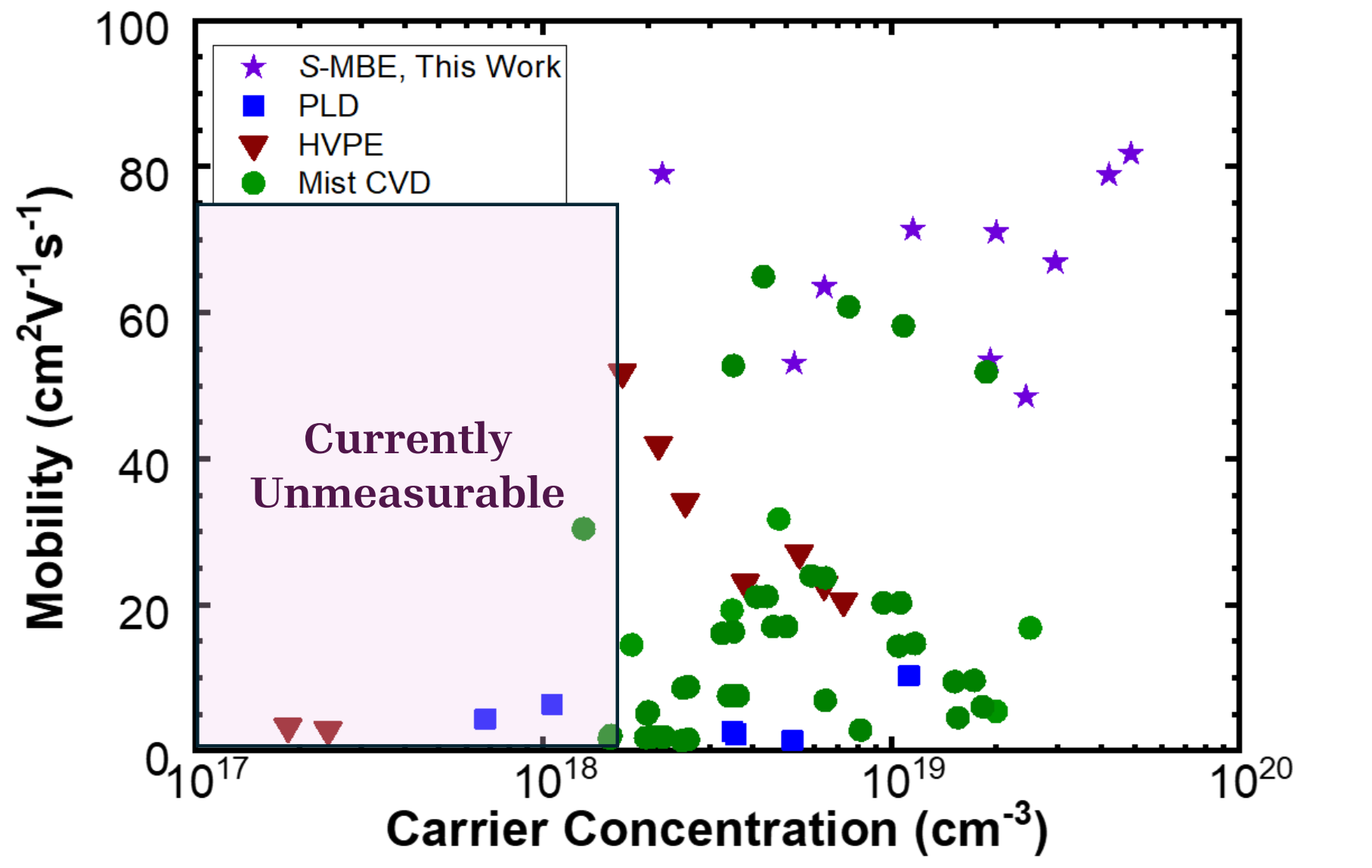


Conclusions

- ☑ **Phase 1:** Grew α-Ga_2O_3 on flat substrates with no steps
  - High *T* α-$(Al,Ga)_2O_3$ buffer with Al fixed directional conductivity and improved electrical properties
- ☑ **Phase 2:** Improved conductivity on flat substrates
  - Optimized film *T* and ozone *P*
- ☑ **Phase 3:** Plotted carrier concentrations v. mobility
  - Estimated dislocation density, broke current literature records

Future Work

- Optimizing **aluminum alloying** to increase bandgap
- Confirm dislocation density calculations with STEM
  - Determine which estimation methods are accurate for α-Ga_2O_3
- Liquid nitrogen Hall measurements
  - Lower *T* **decrease polar optical phonon scattering**
  - Shows extent of ionized impurities and dislocation scattering limits
- Annealing Ti/Au contacts to create **Ohmic contacts**
  - Allows us to measure mobilities at **lower carrier concentrations** currently unmeasurable due to high resistivity



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