Strain relaxation and dislocation annihilation with graded α-$(Al_xGa_{1-x})_2O_3$ layer for high quality epitaxial α-Ga_2O_3 thin films

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Outline

Introduction

- ✓ Issue of power devices & wide band gap materials
- ✓ Ga_2O_3 material properties

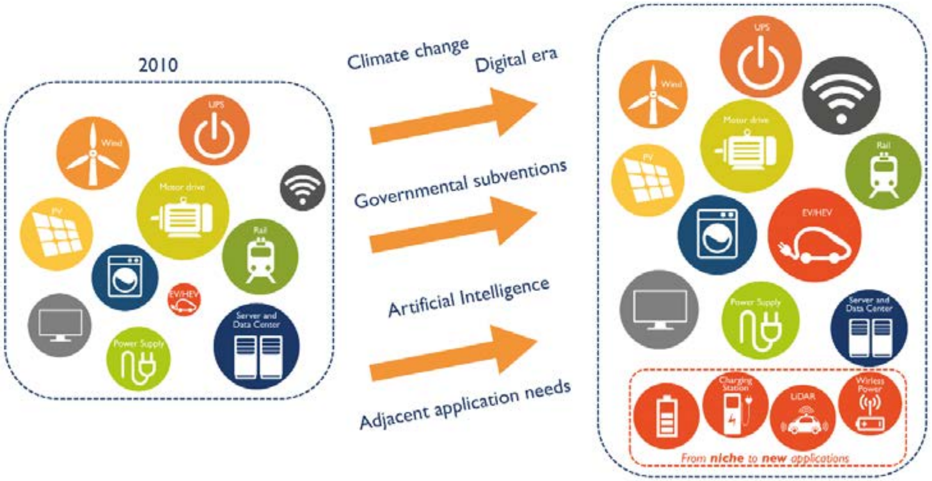
Experiment & results

- ✓ Hetero-epitaxial growth of α-Ga_2O_3 / α-$(Al_xGa_{1-x})_2O_3$ on sapphire substrate
- ✓ Structure properties of α-Ga_2O_3/ α-$(Al_xGa_{1-x})_2O_3$ / c-sapphire hetero structure
  - Strain state & dislocation annihilation in α-$(Al_xGa_{1-x})_2O_3$ / c-sapphire
  - Threading dislocation density in α-Ga_2O_3 layer

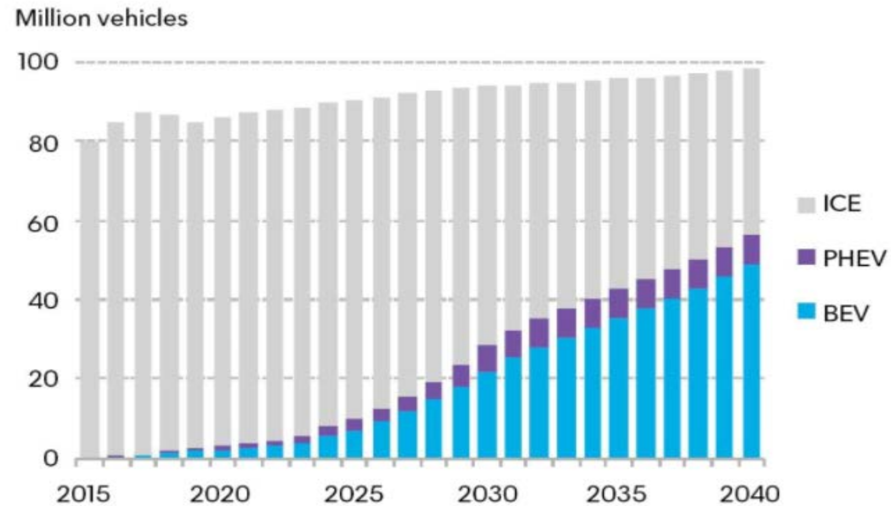
Summary

Issue of power device

- **Expansion of power electronic field**

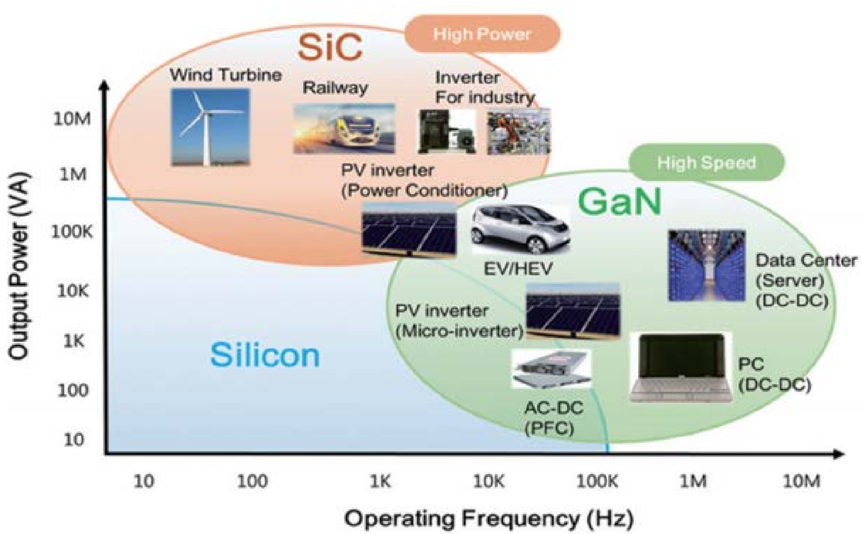


- **Global long- term vehicle sales market**

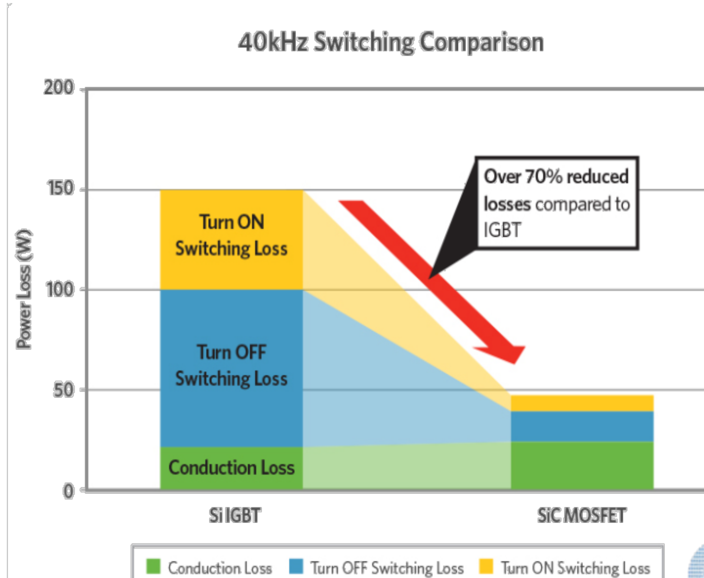


BloombergNEF

- **Challenge of silicon-based power devices**



Yole Development (2017)

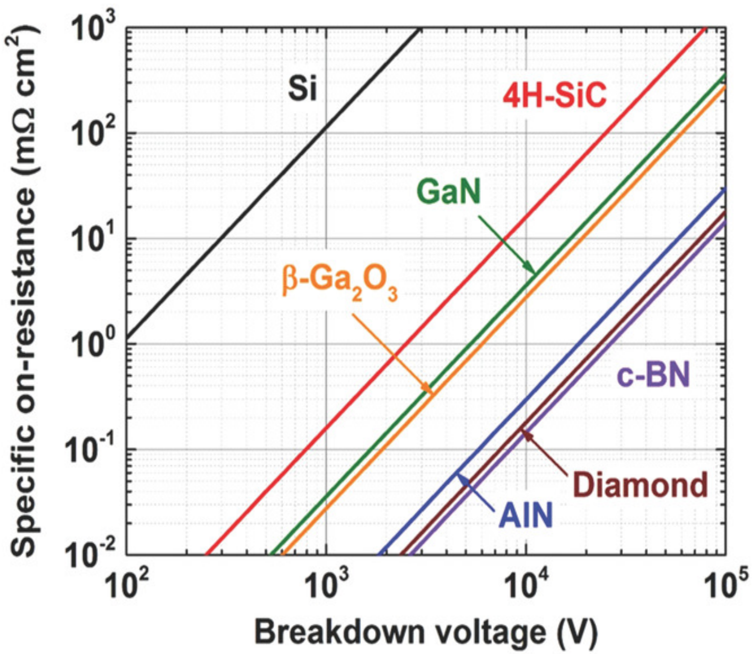


Wide bandgap semiconductor

- **Candidate materials for power semiconductor**

Name of materials	Si	SiC	GaN	β-Ga_2O_3	α-Ga_2O_3
Band gap (eV)	1.1	3.3	3.4	**4.8**	**5.3**
Mobility (cm^2/VS)	1400	1000	1200 2000 (2DEG)	**200~300 1000 (2DEG)**	**200**
Breakdown field (MV/cm)	0.3	2.5	3.3	**6.5**	**9.5**
Relative dielectric constant	11.8	9.7	9	**10**	**10**
Baliga's FOM	1	340	870	**1231**	**3844**

- **Baliga figure of merit(BFOM) : V_{BR}^2/ R_{on}** (V_{BR}^2 : Break down voltage R_{on} : specific on-resistance)



✓ **The higher the Baliga figure of merit(BFOM)**

→ The higher the voltage the device can block at off state.

→ The higher its conductance per unit area at on state.

✓ **Ga_2O_3 has merit in availability native substrate compare to other materials.**

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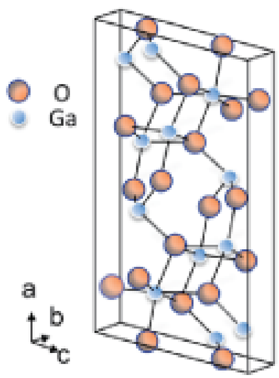
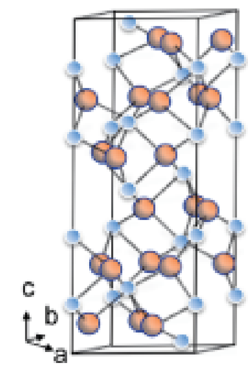
Gallium oxide

- **Comparison between material properties & technological maturity of β, α-phase**



Monoclinic
β-Ga_2O_3

	β-phase (stable state)	**α-phase (meta-stable state)**
Crystal structure	**Monoclinic**	**Corundum**
E_g (Band gap)	4.8 ev	5.0 ev
Electron mobility	300 cm^2/Vs	200 cm^2/Vs
E_{br}	6.5 MV/cm	9.5 MV/cm
Substrate	β-Ga_2O_3 (melt-grown)	Sapphire
n-type doping	Si, Ge, Sn	Si, Sn
p-type doping	No report	No report
Hetero junction _ $(Al_xGa_{1-x})_2O_3$	$x < 18\%$ (phase segregation)	$x < 90\%$ **(This work)**
Epitaxial growth technique	MOCVD, PLD,MBE,HVPE (Homo-epi) (Hetero-epi)	**Mist-CVD**, HVPE (Hetero-epi)
Application	**SBD, FET, Photo detector**	**FET, SBD**



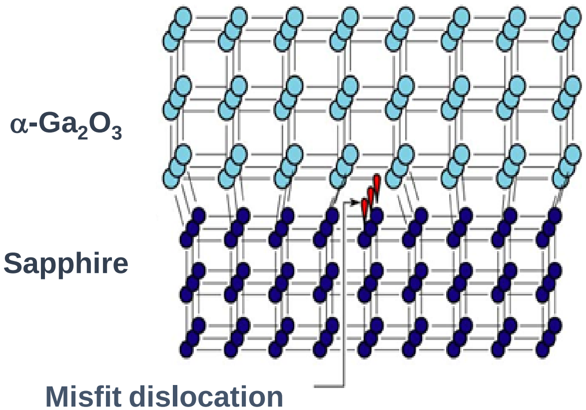
Hexagonal structure
α-Ga_2O_3 (Corundum)

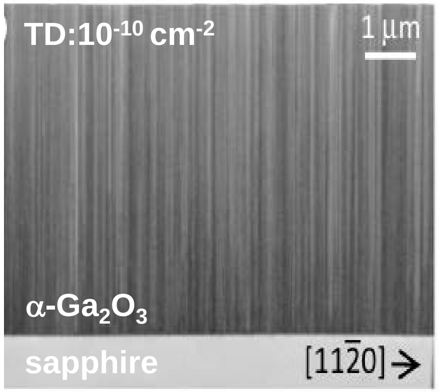
- ✓ **The availability of the bulk substrate is main advantage of β- phase over α- phase.**
  → Native β-Ga_2O_3 substrate cost is very expansive. (cost limitation)
- ✓ **The advantage of α- Ga2O3 is corundum structure which allows band gap engineering (3.8ev ~ 8.8ev) with α-Al_2O_3 and α- In_2O_3.**

Issues on Heteroepitaxial growth α-Ga_2O_3 on sapphire

- α-Ga_2O_3/sapphire lattice mismatch: 4.6%

  → High threading dislocation density (TDD)

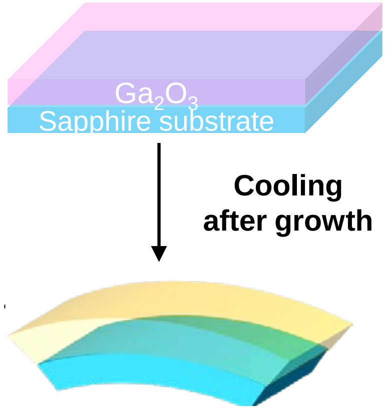


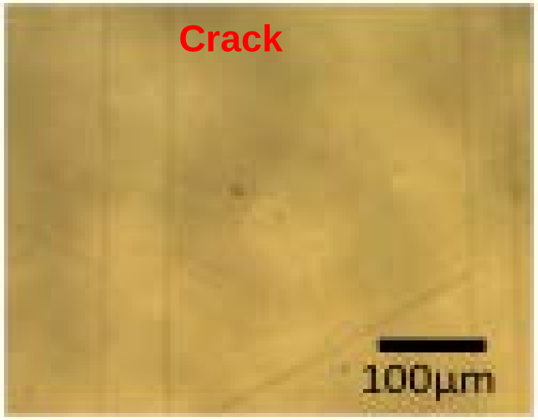


T.C.Ma *et al*., Appl. Phys. Lett. **115**, 182101 (2019)

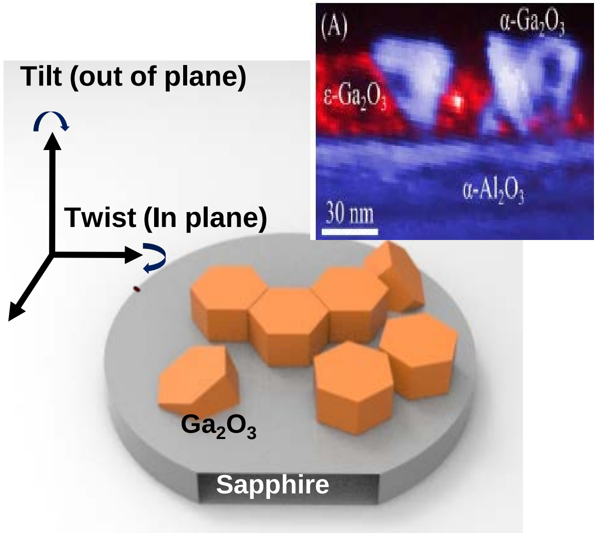
- Difference in thermal expansion coefficient

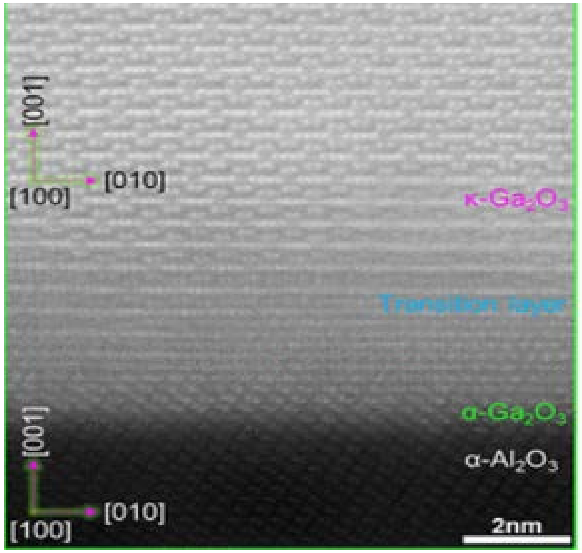
  → Thermal stress , wafer bow



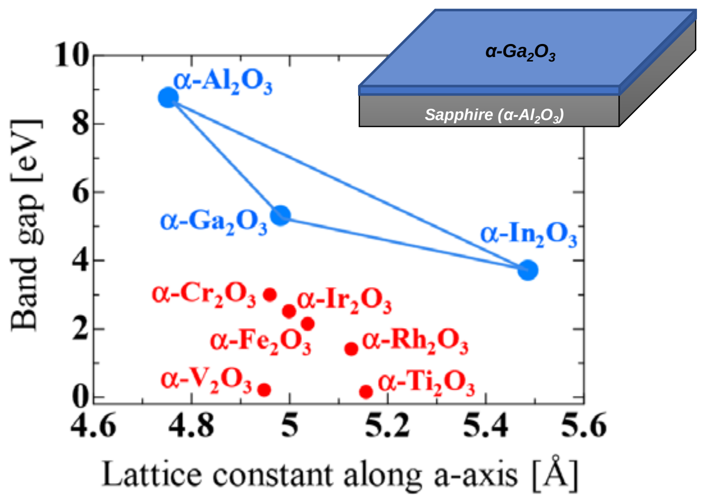


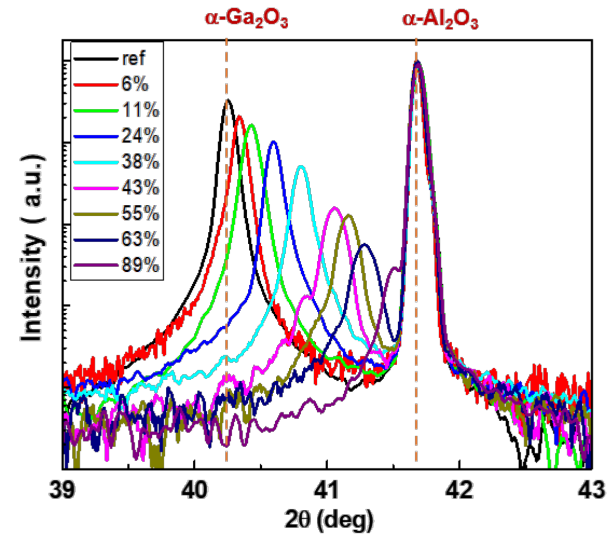
- Metastable phase epitaxy



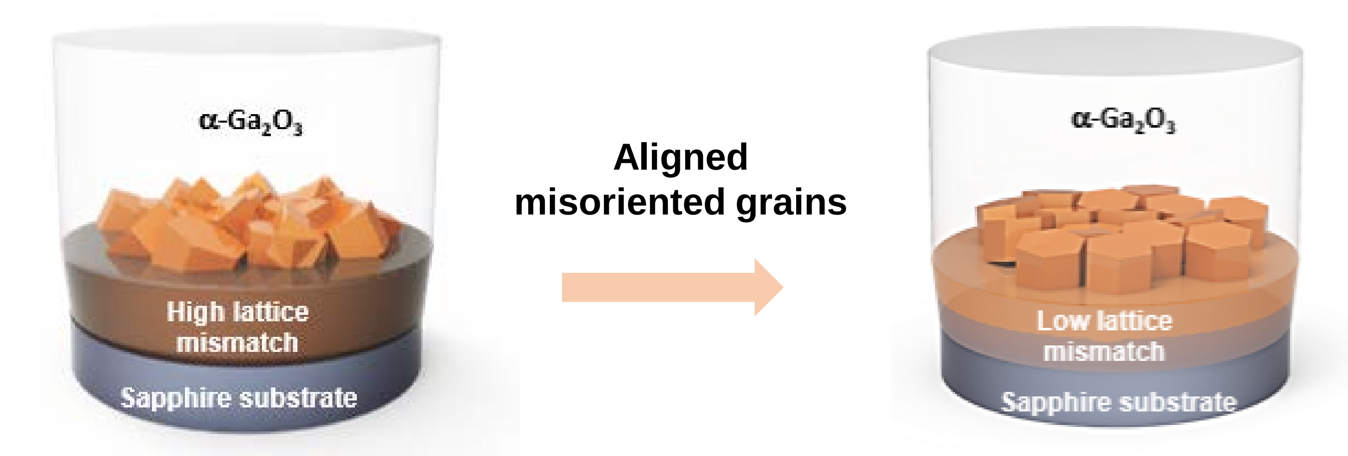


Epitaxial grown α-$(Al_xGa_{1-x})_2O_3$ buffer layer



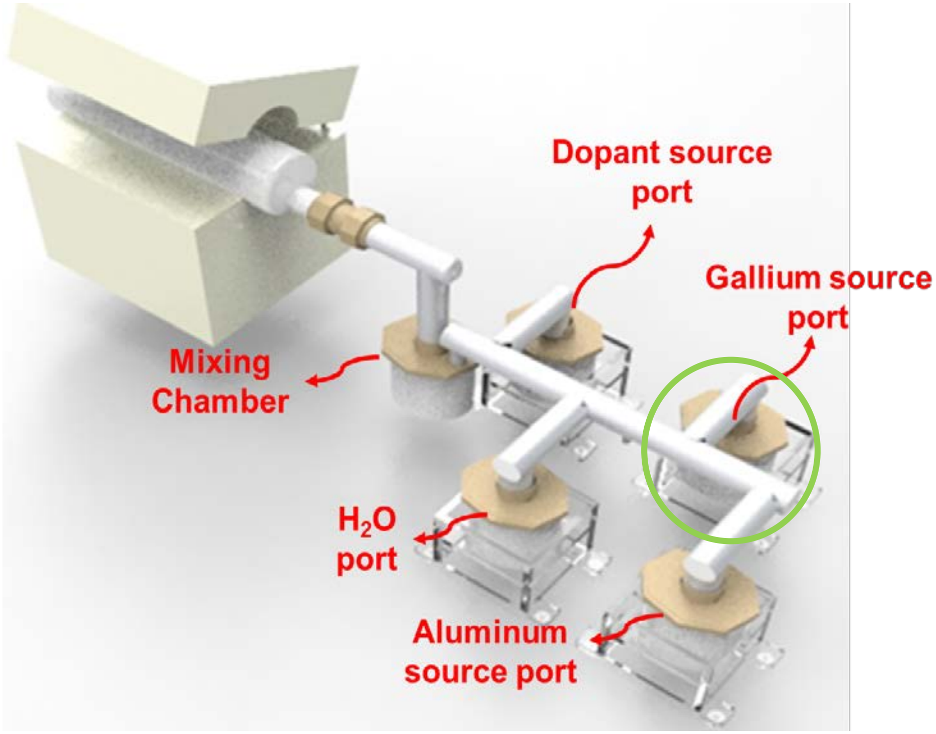


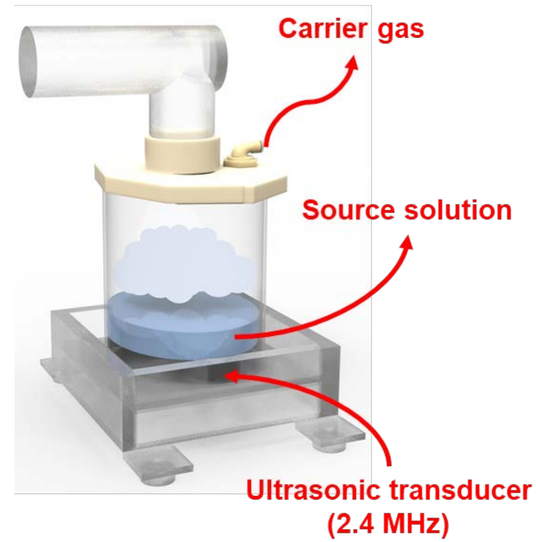
✓ α-$(Al_xGa_{1-x})_2O_3$ lattice constant is intermediate between α-Ga_2O_3 (4.98(Å)) and α-Al_2O_3(4.76(Å)).



✓ Epitaxial α-Ga_2O_3 with reduced TD density could be demonstrated in graded α-$(Al_xGa_{1-x})_2O_3$ layer on c- sapphire hetero structure.

Mist chemical vapor deposition (Mist- CVD)



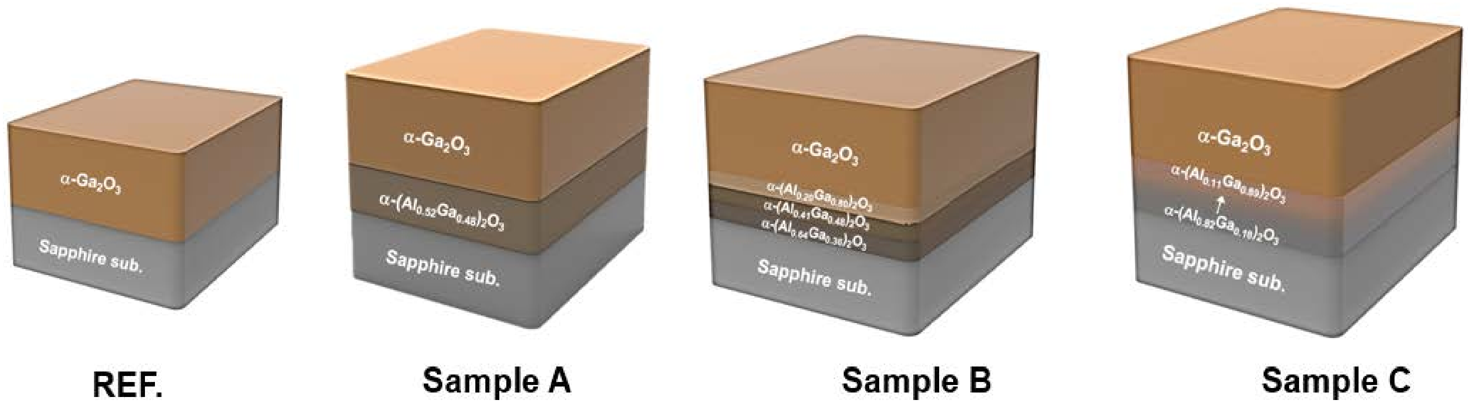


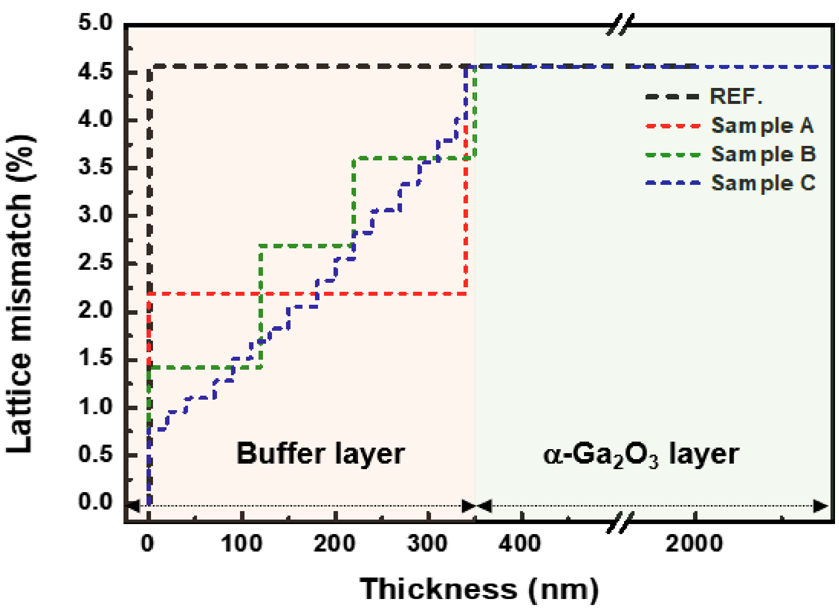
Source		substrate	Carrier gas	Flow rate (carrier/dilution)
$GaCl_3$	$Al(acac)_3$	Half of 2-inch sapphire	N2	3slm/0.5slm

✓ **Liquid solution of precursors is ultrasonically atomized to form aerosol particles, and these mist are transferred onto heated substrates.**

Experiments & structure properties

- Schematic α-Ga_2O_3 /α-$(Al_xGa_{1-x})_2O_3$/ c- sapphire hetero structure



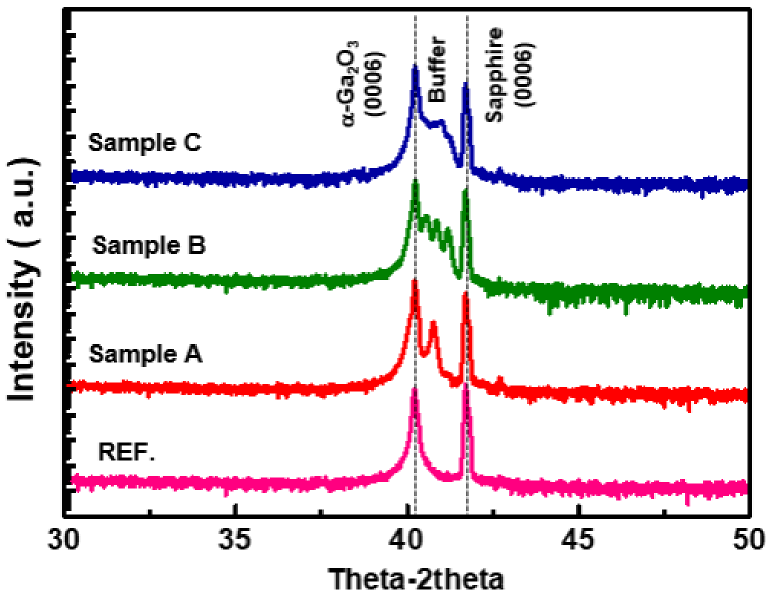


- Growth conditions of α-Ga_2O_3 /α-$(Al_xGa_{1-x})_2O_3$

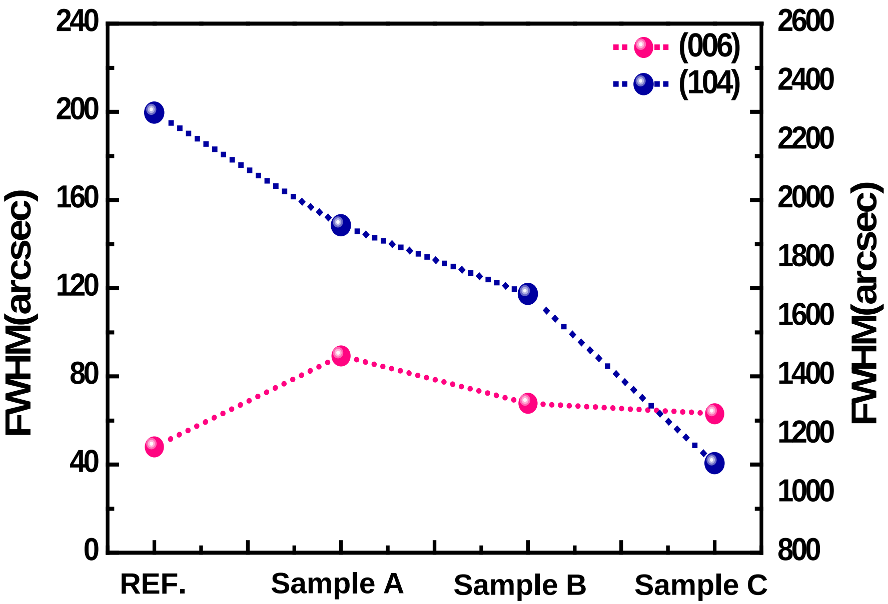
	α-$(Al_xGa_{1-x})_2O_3$	α-Ga_2O_3
Al composition (%)	11~ 82	0
Thickness (um)	0.35	2
Growth temp. (^oC)	525	500
Carrier gas	N_2	N_2

Structure properties_ XRD analysis

- **Omega-2theta scan profile**



- **FWHMs of w- rocking curves**

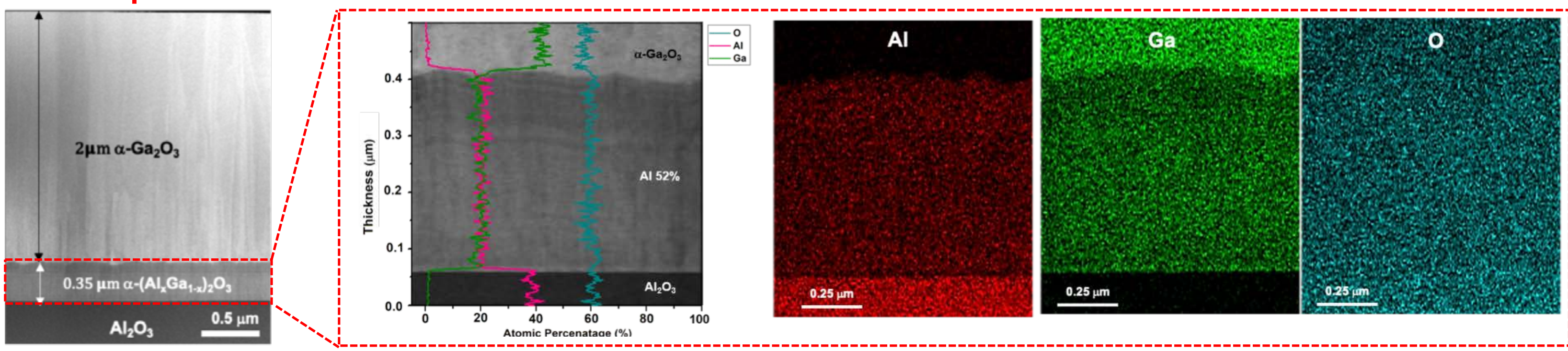


	Buffer layer (0.35 μm)			α-Ga_2O_3 layer (2 μm)	
				ω - rocking curve FWHM (arcsec)	
	Buffer configuration	Al composition (%)	In-plane misfit (%)	Symmetric plane (0006)	Asymmetric plane $(10\bar{1}4)$
REF	-	-	~ 4.6	48.06	2286.43
Sample A	1-layer	52	~ 2.4	89.31	1913.57
Sample B	3-layer	64,41,20	~ 0.92	67.72	1499.97
Sample C	Graded layer	82→60→52→24→11	~ 0.5	62.97	1174.28

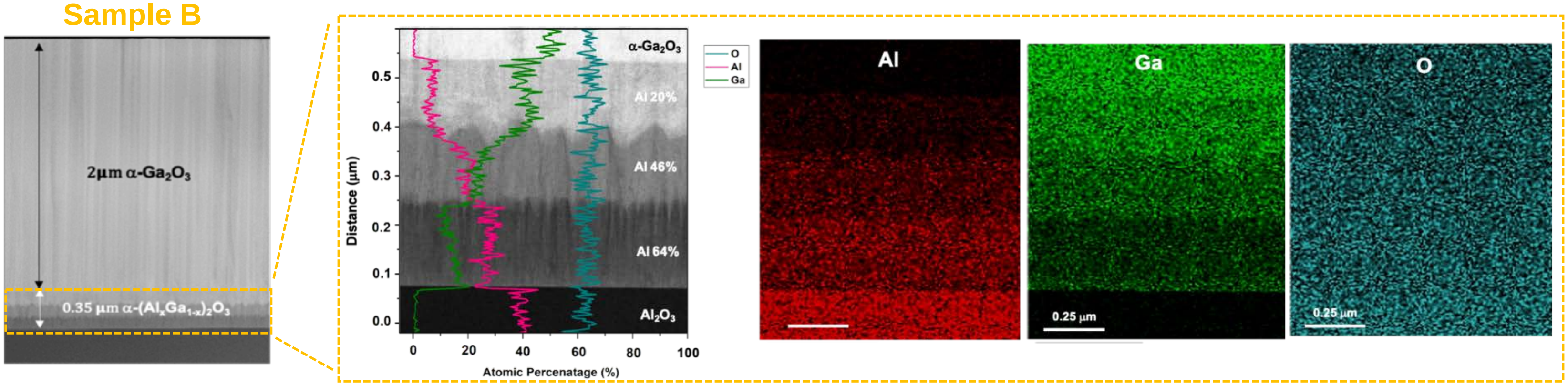
Reduced by 42%

Structure properties_ TEM & EDS analysis

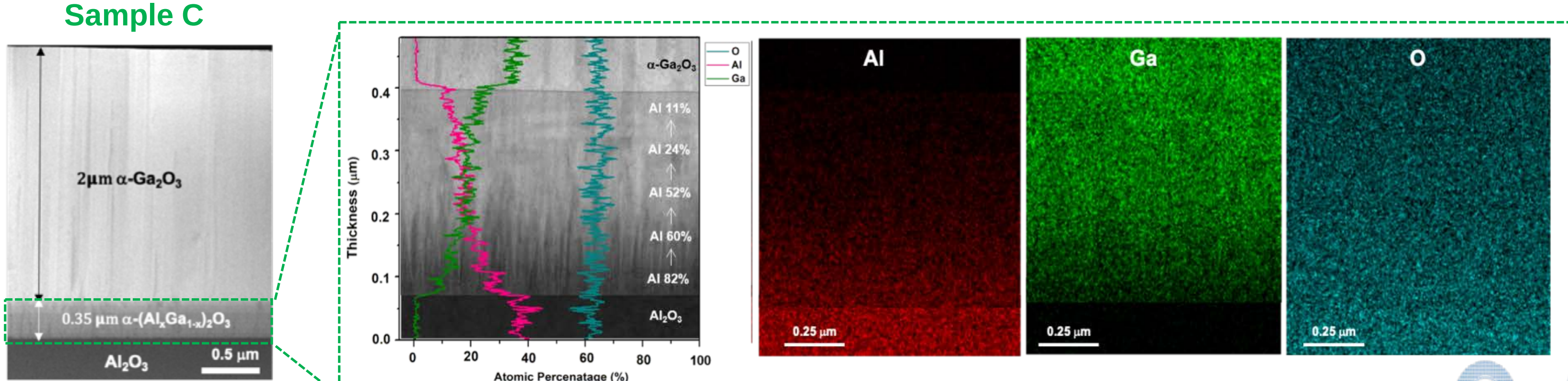
Sample A



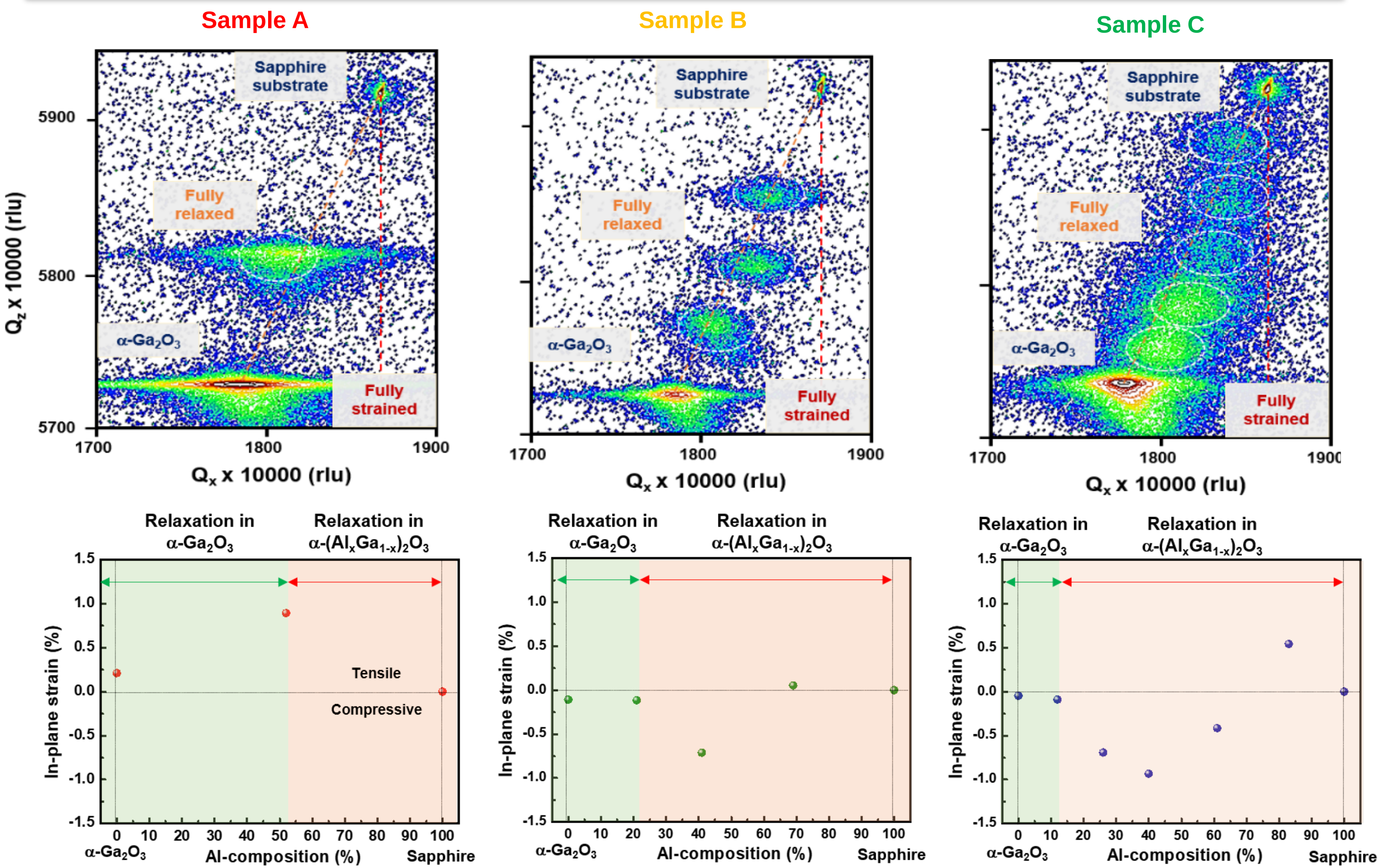
Sample B



Sample C



Strain relaxation in α-Ga_2O_3 /α-$(Al_xGa_{1-x})_2O_3$ hetero structure

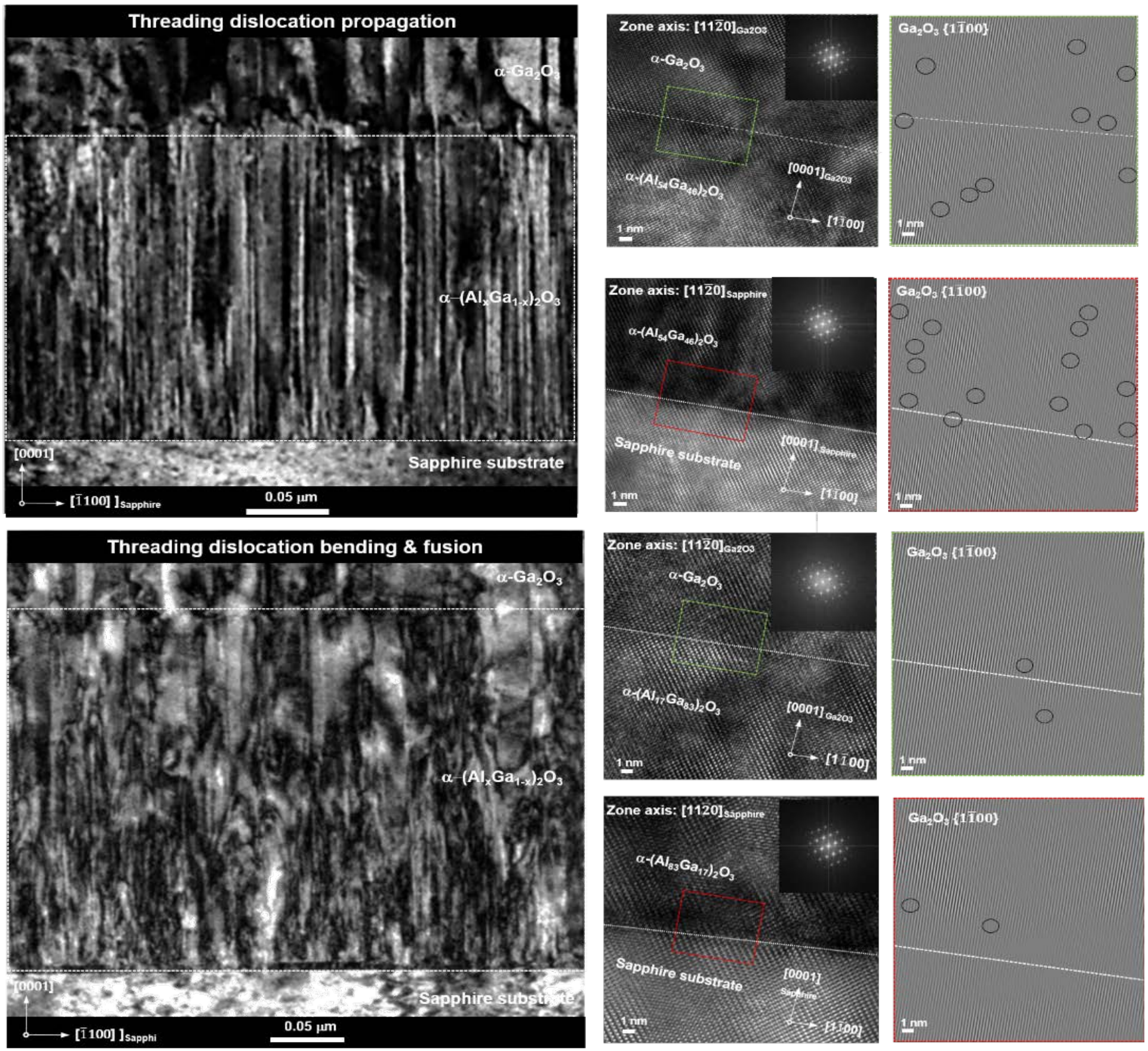


Evolution of dislocation evolution in α-$(Al_xGa_{1-x})_2O_3$ layer

Cross-section TEM | HR-TEM | SAED

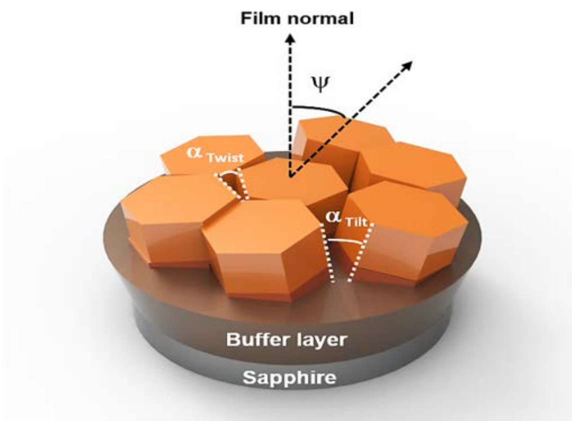
Fully-relaxed state

Gradually strain state

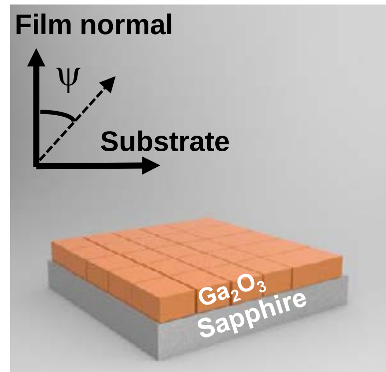


Treading dislocation density in α-Ga_2O_3 layer

- **Mosaic tilt, twist angle calculation**



Srikant model fitting



$$W(\Psi) = \left\{ \left[W^{tilt}(\Psi) \right]^n + \left[W^{twist}(\Psi) \right]^n \right\}^{1/n},$$

$$W^{tilt}(\Psi) = \cos^{-1}\left[\cos^2(\Psi)\cos(W_{out}) + \sin^2(\Psi) \right],$$

$$W^{twist}(\Psi) = \cos^{-1}\left[\sin^2(\Psi)\cos(W_{in}) + \cos^2(\Psi) \right],$$

Tilt angle

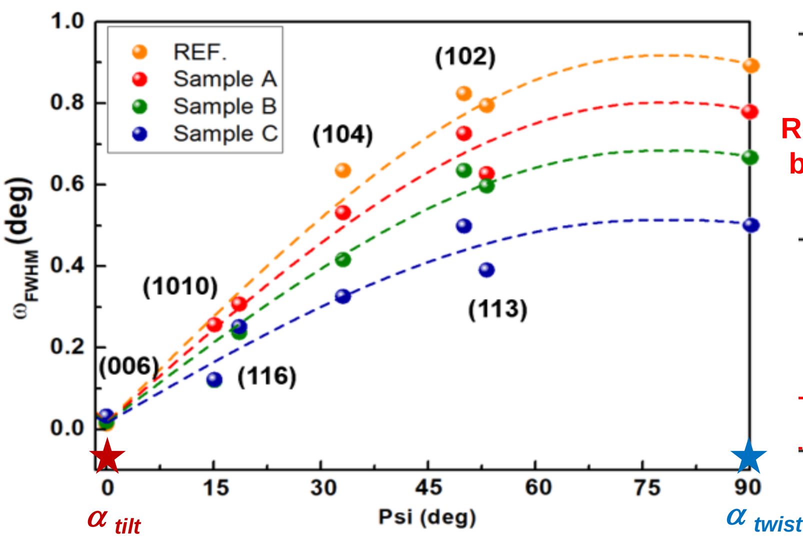
$$N_S = \frac{\alpha_S^{\,2}}{4.35 b_S^{\,2}}$$

Twist angle

$$N_E = \frac{\alpha_E^{\,2}}{4.35 b_E^{\,2}}$$

b_s= <0001> $b_e = \frac{1}{3}$ $<2\overline{11}0>$

- **Threading dislocation density**



Reduced by 43%

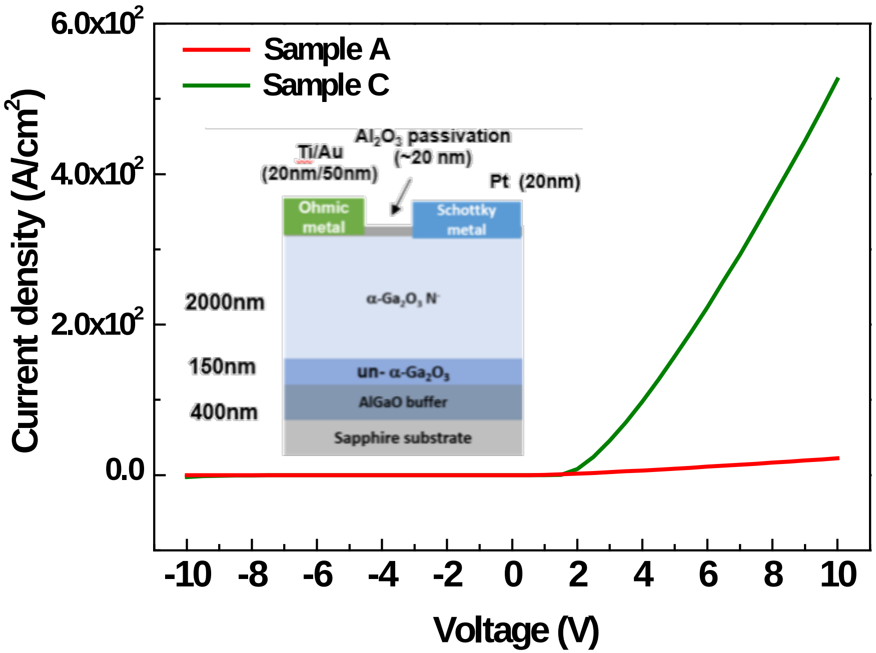
	Crystalline distortion		Dislocation density	
	α_{tilt} (deg)	$\alpha_{twisted}$ (deg)	Screw- dislocation density (cm^{-2})	Edge-dislocation density (cm^{-2})
REF	0.013	0.896	1.91 X 10^6	2.08 X 10^{10}
Sample A	0.024	0.783	3.54 X 10^6	1.13 X 10^{10}
Sample B	0.018	0.669	2.69 X 10^6	9.68 X 10^9
Sample C	0.032	0.503	4.68 X 10^6	7.29 X 10^9

Reduced by 1 order

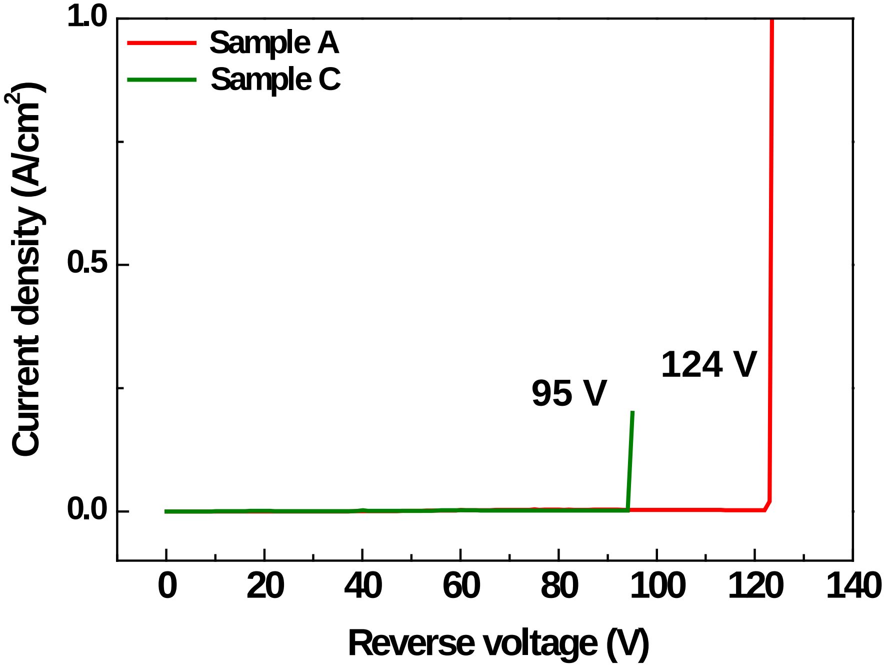
✓ **The threading dislocation density of α-Ga_2O_3 grown on graded α-$(Al_xGa_{1-x})_2O_3$ was reduced by 1 order magnitude compared to that on singe α-$(Al_xGa_{1-x})_2O_3$ layer**

Electrical properties of α-Ga_2O_3 /α-$(Al_xGa_{1-x})_2O_3$ hetero structure

- On-resistance



- Breakdown voltage



- **Baliga figure of merit(BFOM) : V_{BR}^2/ R_{on}** (V_{BR}^2 : Break down voltage R_{on} : specific on-resistance)

	TDD (cm^{-2})	R_{on} (Ω cm^2)	V_{BR} (V)	Figure of merit V_{BR}^2/ R_{on} (mw/cm^2)
Sample A	1.13 x10^{10}	0.148799	123	733.709
Sample C	7.29 x10^9	0.019017	95	4274.577

✓ **The figure of merit for the α-Ga_2O_3 Schottky diode on graded α-$(Al_xGa_{1-x})_2O_3$ is almost six times large than that on singe α-$(Al_xGa_{1-x})_2O_3$ layer**

Summary

- ✓ Epitaxial α-Ga_2O_3 / α-$(Al_xGa_{1-x})_2O_3$ hetero structure were successfully grown on c-sapphire substrate by mist–CVD.
- ✓ Compressive strained α-$(Al_xGa_{1-x})_2O_3$ layer suppressed the propagation of treading dislocation from lattice mismatch.
- ✓ Threading dislocation density were calculated based on mosaic structure with tilt and twist angle.
- ✓ Epitaxial α-Ga_2O_3 with reduced TD density could be demonstrated in graded α-$(Al_xGa_{1-x})_2O_3$ layer on c-sapphire hetero structure.
- ✓ The figure of merit for the α-Ga_2O_3 Schottky diode on graded α-$(Al_xGa_{1-x})_2O_3$ is almost six times larger than that on singe α-$(Al_xGa_{1-x})_2O_3$ layer

THANK YOU FOR LITENING