NREL Transforming ENERGY

GaAs Substrate Recycling Using *in-situ* Deposited NaCl Layers via Molecular Beam Epitaxy

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Introduction:
III-V Substrate Recycling

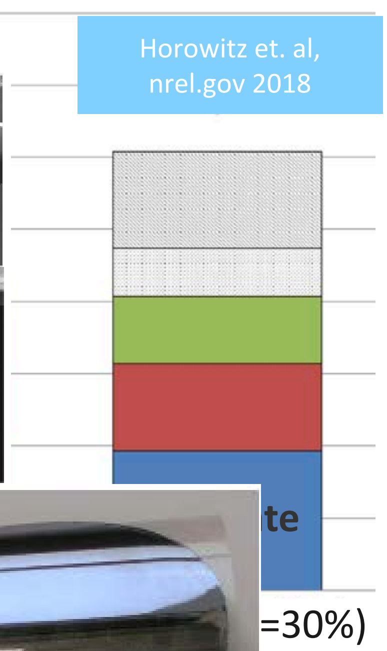
Substrate cost is large part of total cell cost

Existing methods of substrate reuse:

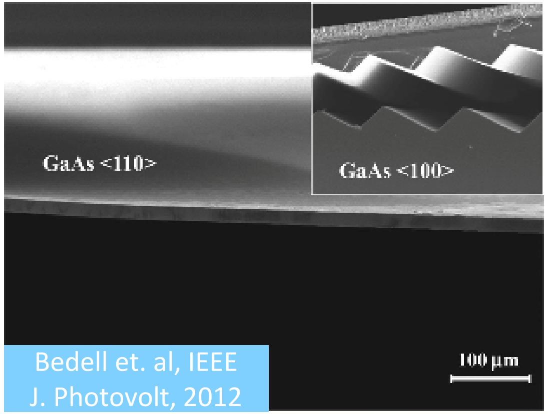
Mechanical exfoliation	Chemical wet etch
fast	smoother
rough	slower
	toxic
	Al selective

Other sacrificial layers? … NaCl?

- Highly water soluble
- Non-toxic
- NaCl has history in MBE



Horowitz et. al, nrel.gov 2018



Bedell et. al, IEEE J. Photovolt, 2012


Schermer et. al, Thin Solid Films, 2006

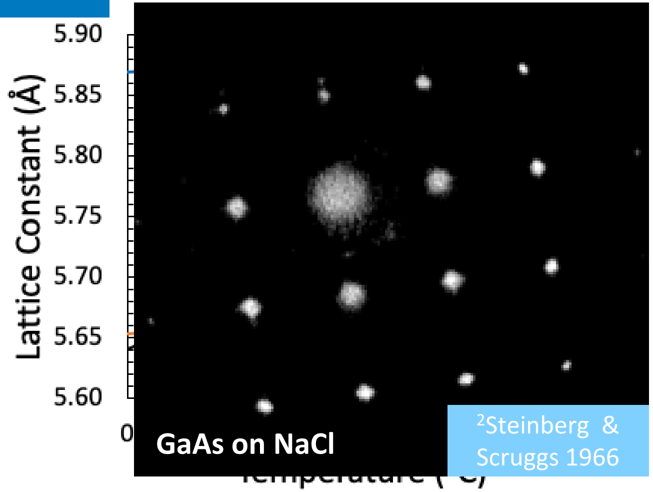
Previous Growth on NaCl

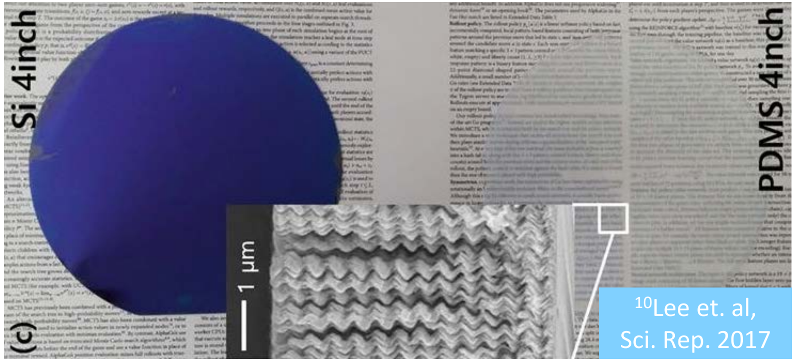
One of the first substrates for epitaxy of metals and semiconductors

- **III-V on NaCl first in 1960s in a bell jar[1,2]**
- **Si[3], Ge[4,5], SnS[6], CdS/InP[7]**

No reports of liftoff of true epitaxial single crystal overlayers on NaCl

NaCl and GaAs lattice matched at ~100°C





[1]Evans & Noreika Philosophical Mag 1966, [2]Steinberg & Scrubbs, J.Appl Phys 1966) [3]Shimoaka et al, JVSTB 1972, [4]Shimoaka et al, JVSTB 1971, [5]Barkai et al, Thin Solid Films 1980, [6]Wangperawaong et al, APL 2013, [7]Neelkanth et al,JVST 1980, [8]Tiwari et al, Prog. Photovolt: Res. Apply. 1999, [9]Tiwari et al, Prog. Photovolt: Res. Apply. 1999, [10]Lee et al, Sci Rep. 2017,

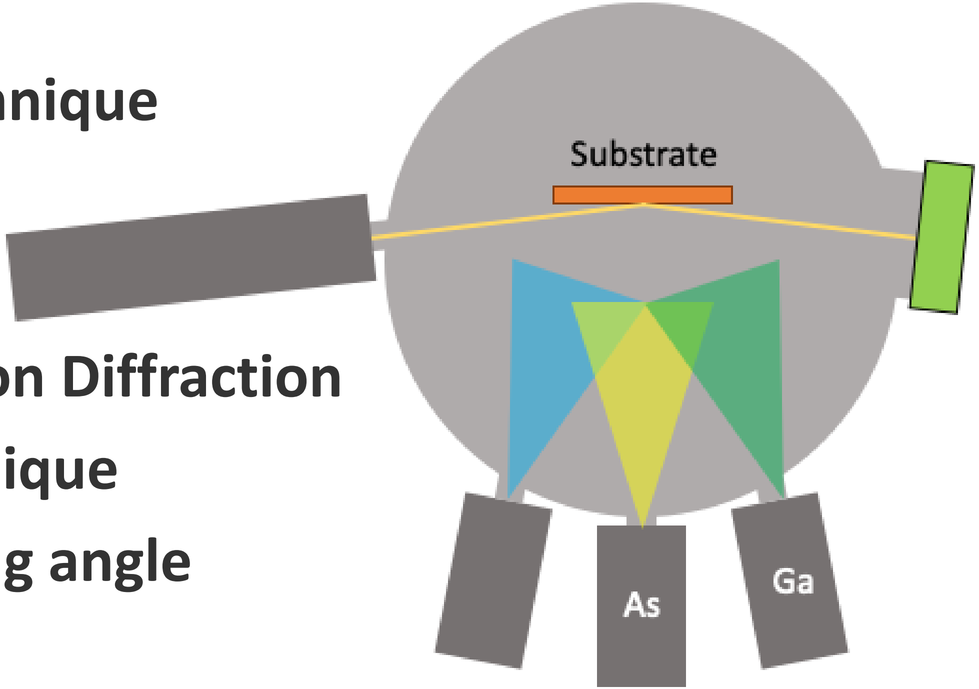
MBE and RHEED

Molecular Beam Epitaxy

- **High purity deposition technique**
- **Ultra-high vacuum**
- **NaCl compound source**

Reflection High Energy Electron Diffraction

- ***In-situ* measurement technique**
- **Surface analysis via glancing angle electron diffraction**



Reciprocal Space & RHEED Patterns

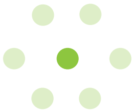
Atoms in reciprocal space: $k_x=2\pi/a$

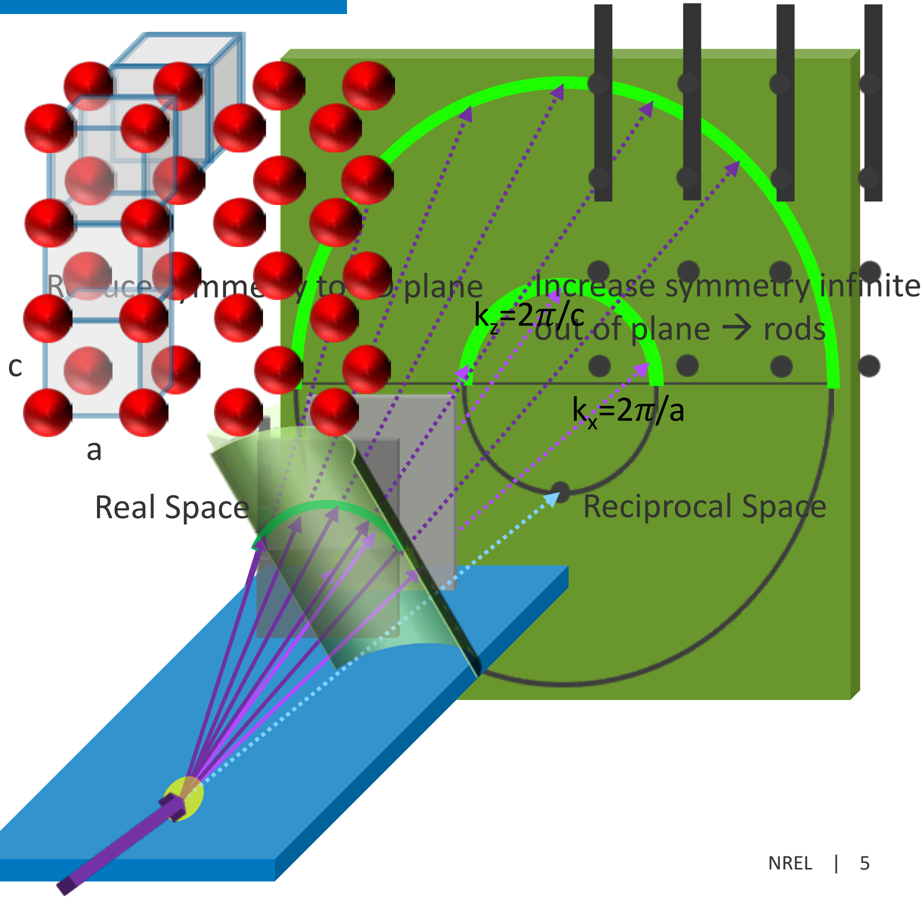
Diffraction conditions: Ewald Sphere

Typical surface patterns:

- **Real smooth surface → Streaks**
- **Rough surface → Spots**
- **Polycrystalline → Rings**

Additional patterns:

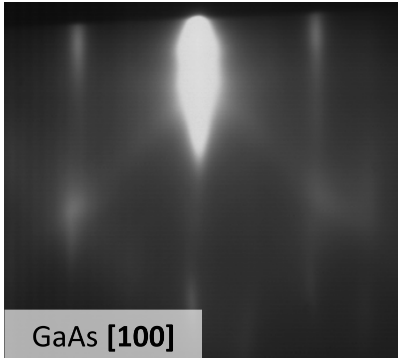
- **Faceted surface → Chevrons** 
- **Twins → Spot shadows** 



NaCl on GaAs: *In-situ Measurements*

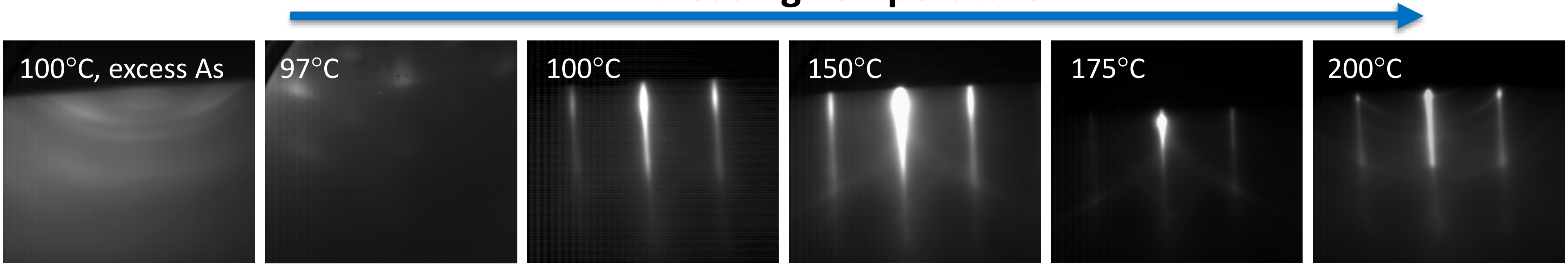
First step is to grow NaCl on GaAs (001)

- **~30nm of NaCl**
- **Growth rate of 3 nm/min**



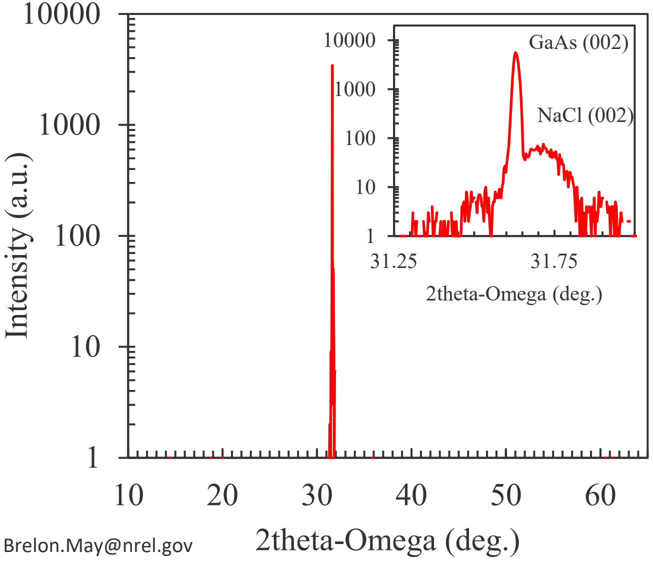
- **Important to have clean starting surface**
- **T_{sub}<100°C → 3D growth**
- **T_{sub}≥200°C → Polycrystalline**

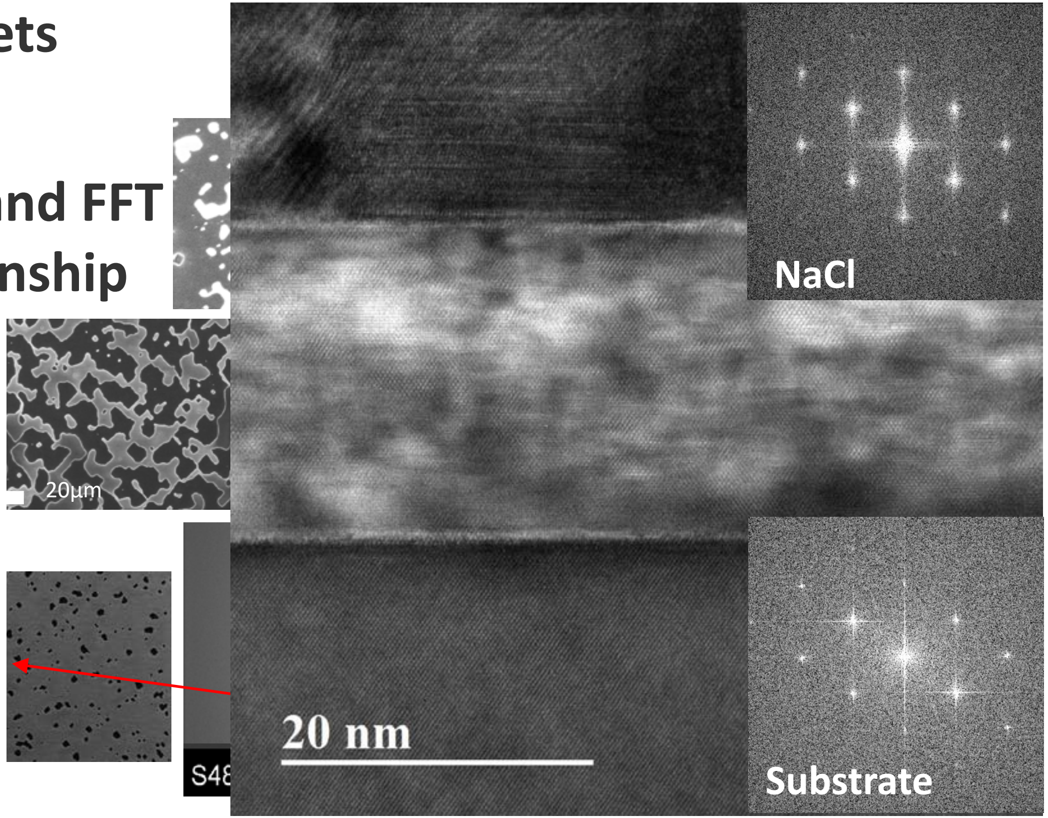
Increasing Temperature



NaCl on GaAs: *Ex-situ Measurements*

- **SEM shows NaCl with {100} facets**
- **XRD shows single phase**
- **TEM shows smooth interfaces and FFT patterns reveal epitaxial relationship**





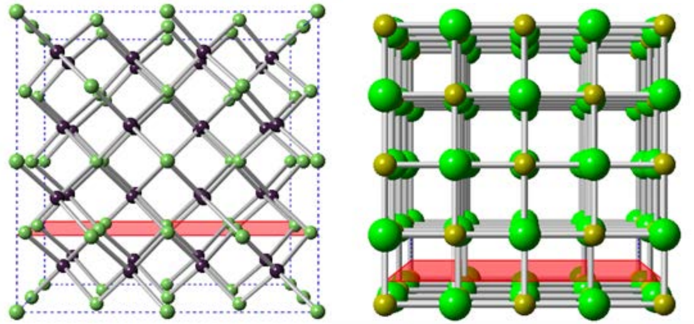
GaAs on Salt: The Problems

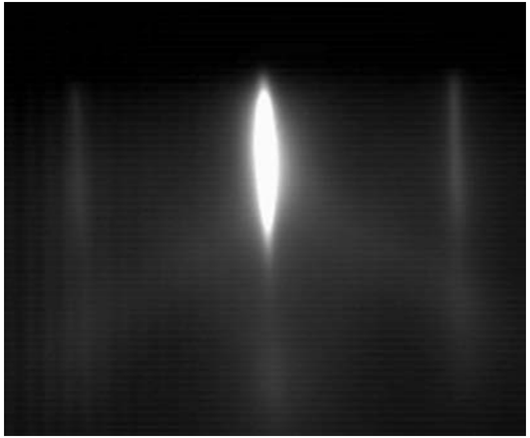
This is complicated chemically and structurally

- **Heterovalent interface**
    - NaCl – 6 ionic bonds
    - GaAs – 4 covalent bonds
- **Symmetry Mismatch → APDs & twins**
- **Not actually lattice matched**
    - GaAs typically grown at ~580°C → (+3%)

Initial 3D growth mode

→ Goes polycrystalline in minutes



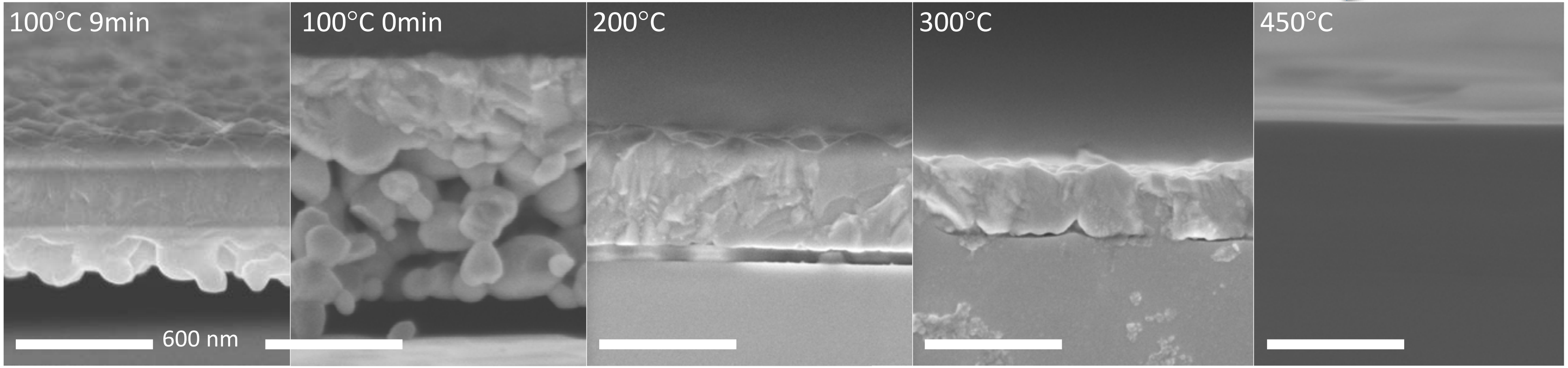


GaAs on Salt: Growth Temperature – Ramped

GaAs deposited on 30 nm thin NaCl layers at $T_{initial}$ → 580°C

- **$T_{initial}$ = 100°C → Porous interface + NaCl**
- **$T_{initial}$ = 200°C → Dense interface + NaCl**
- **$T_{initial}$ ≥450°C → Homoepitaxy + No NaCl**

Increasing initial deposition temperature

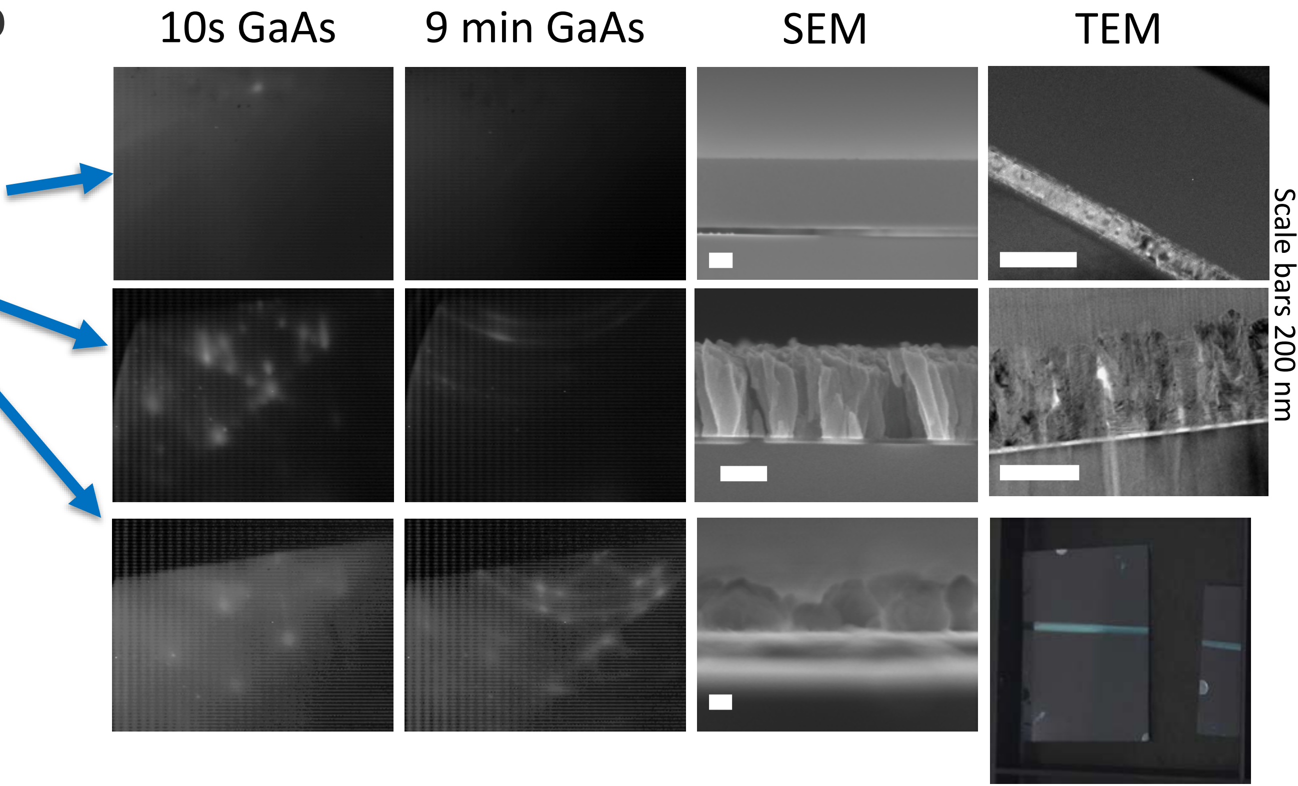


GaAs on Salt: Growth Temperature – Constant

Lower temperatures to ensure NaCl remains

- **100°C=amorphous**
- **250°C=columnar**
- **300°C=crystallites**

But the RHEED seems to be doing something to the sample



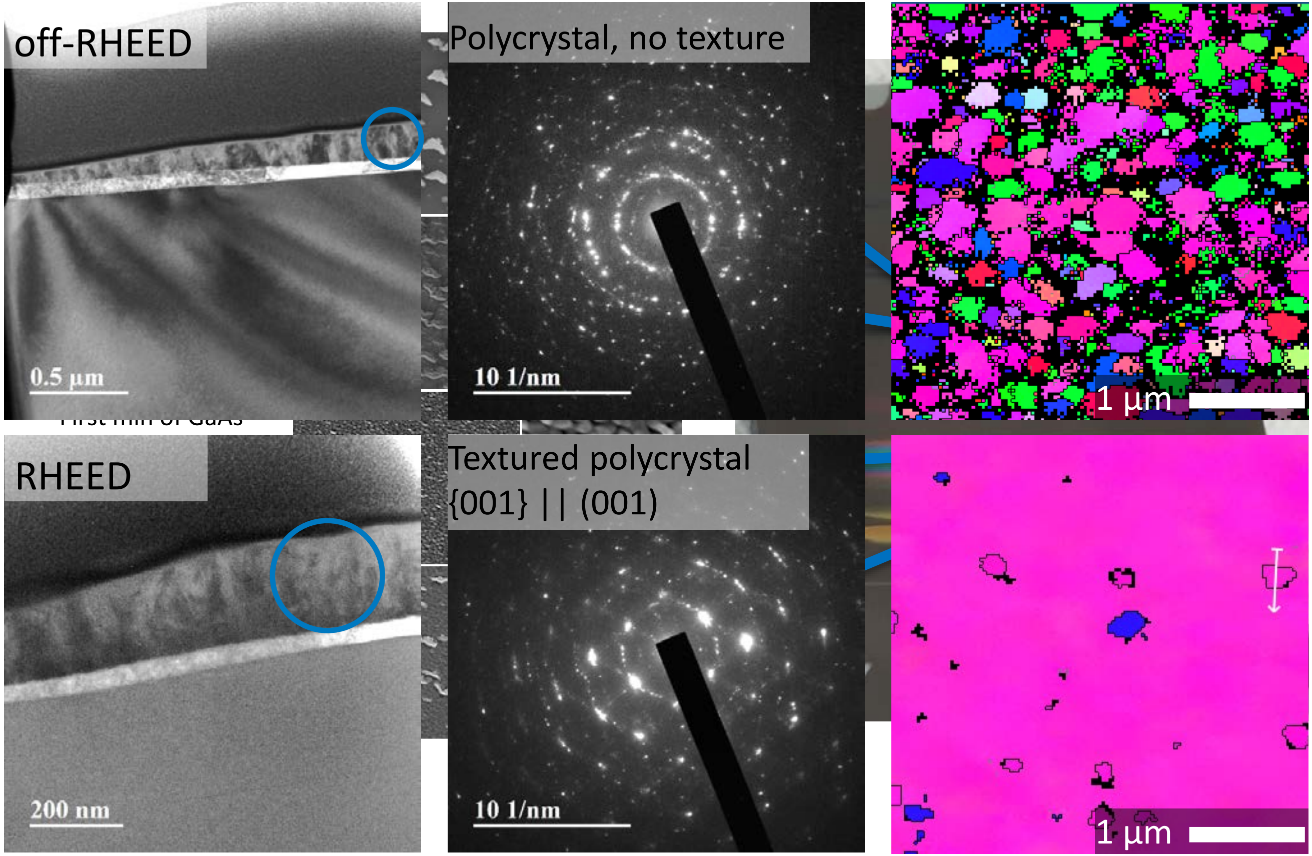
Effects of the RHEED Beam

TEM and EBSD

- **RHEED exposure = textured and larger grains**

15kV RHEED moved around during initial growth stages

- **Away from RHEED –** islands on smooth NaCl
- **90s pre-GaAs –** rough (not NaCl) underlayer, wavy islands
- **1st min GaAs –** 25nm features, no islands at all
- **2nd min GaAs –** wavy islands with featured surface



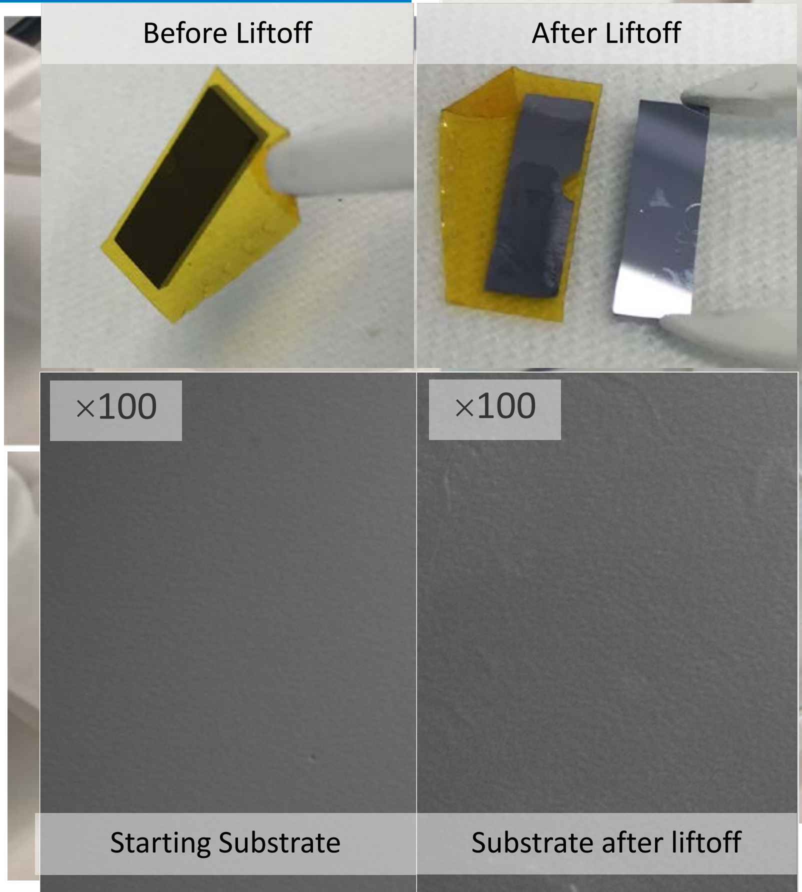
Liftoff of Overlayer in Water

Liftoff occurs quickly in water

- **Delaminates and curls without backing**
- **Kapton tape keeps overlayer from breaking/curling**
- **Can even be dry-peeled**

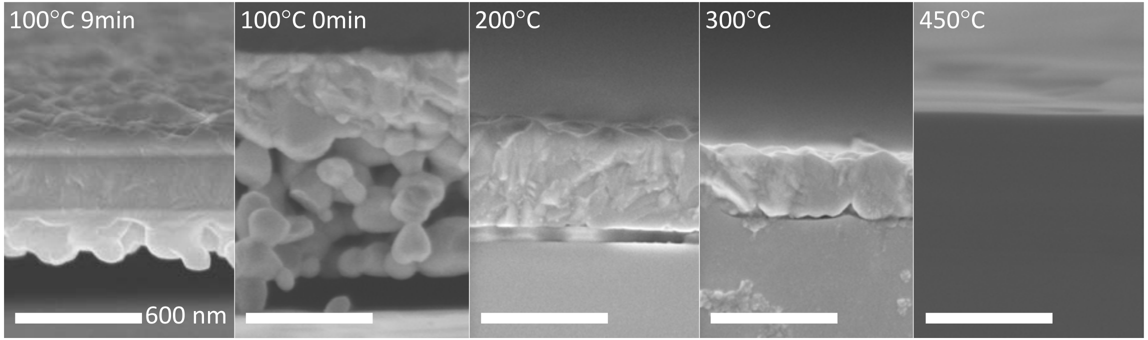
Comparable surface post-liftoff

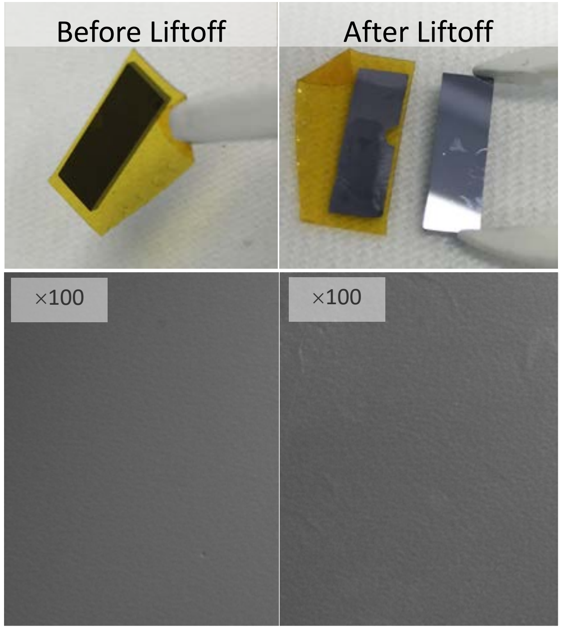
- **Regrowth should be possible**

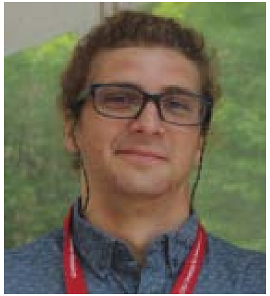


Conclusion

- Epitaxial NaCl thin films deposited on GaAs
- Highly temperature dependent GaAs overlayer crystallinity/morphology
- RHEED greatly affects initial growth of overlayer
- NaCl layer dissolves quickly in water facilitating liftoff



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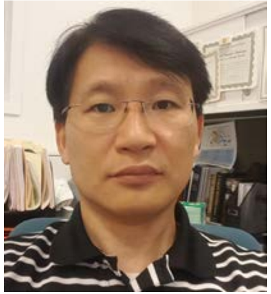
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Thank You

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