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Growth of Single-crystal Al Layers on GaAs and Si Substrates for Microwave Superconducting Resonators

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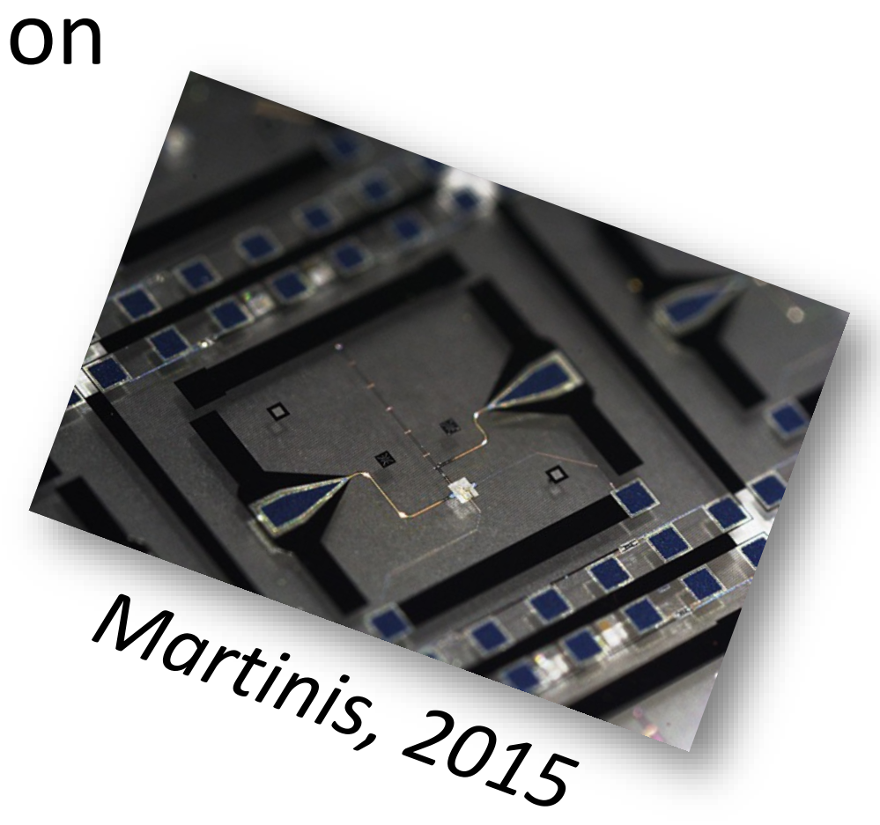
Motivation

Optimizing the epitaxy of aluminum (Al) on semiconductor surfaces is pivotal for the fabrication of high quality factor superconducting resonators[1], fundamental components of quantum computing systems. Losses in the resonators are suspected to emerge from defects in the crystalline structure and the incorporation of contaminants at the metal-substrate interface[2], both of which must be therefore minimized. Here we report on the epitaxy of single crystalline Al layers of atomic smoothness on GaAs and Si substrates.

Applications

- Single photon detection
- Quantum buses
- Qubit state read-out
- UV-NIR plasmonics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Challenges

- Significant lattice mismatch
- High diffusivity of Al (0.97cm^2/s at 30°C)
- Low temperature epitaxy
- Reproducibility of the obtained orientations for growth on GaAs[3]

Experimental details

- Epitaxy in the GEN10 MBE system (Veeco Instruments Inc.)
- Epi-ready GaAs(001), Si(001) and Si(111) wafers loaded in class 100 clean room conditions
- Short-period AlAs/GaAs superlattice buffers grown on GaAs substrates
- Slow cool down to -10°C with shielded substrate to prevent in-situ contamination
- 110nm Al layers deposited at 0.5Å/s
- **Multi-azimuth** RHEED (Staib) monitoring on rotating substrate (kSA400 and kSA RMAT, k-Space Associates, Inc.)
- *Ex-situ* analysis: XRD (D8 ADVANCE, Bruker Corp.), AFM (di-Innova, Veeco Instruments Inc. and Nanoscope Analysis, Bruker Instruments Corp)

References

[1] Appl. Phys. Lett., 100(11):113510, 2012.
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[3] J. Appl. Phys., 59(9):3189{3195, 1986.

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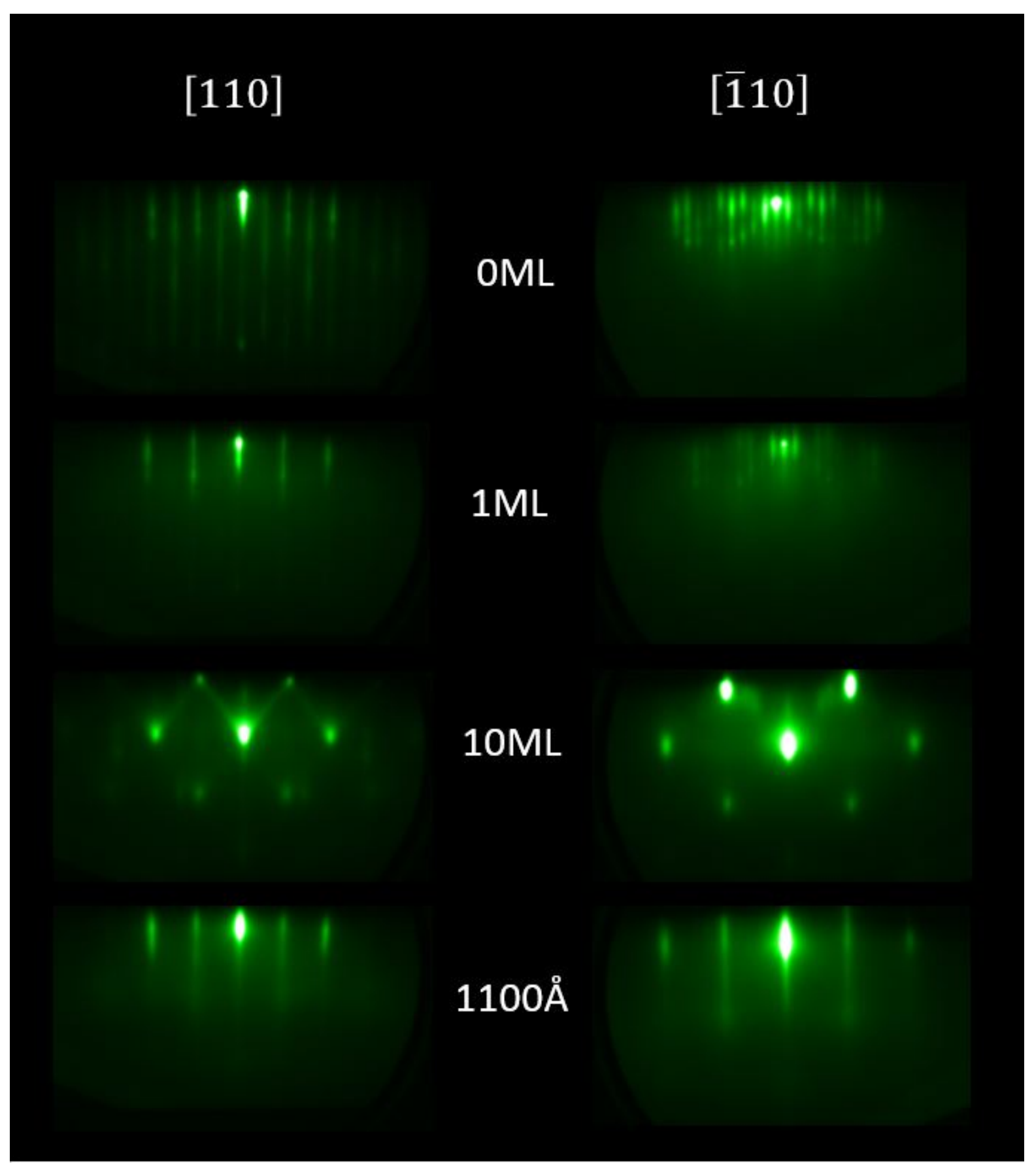
Results

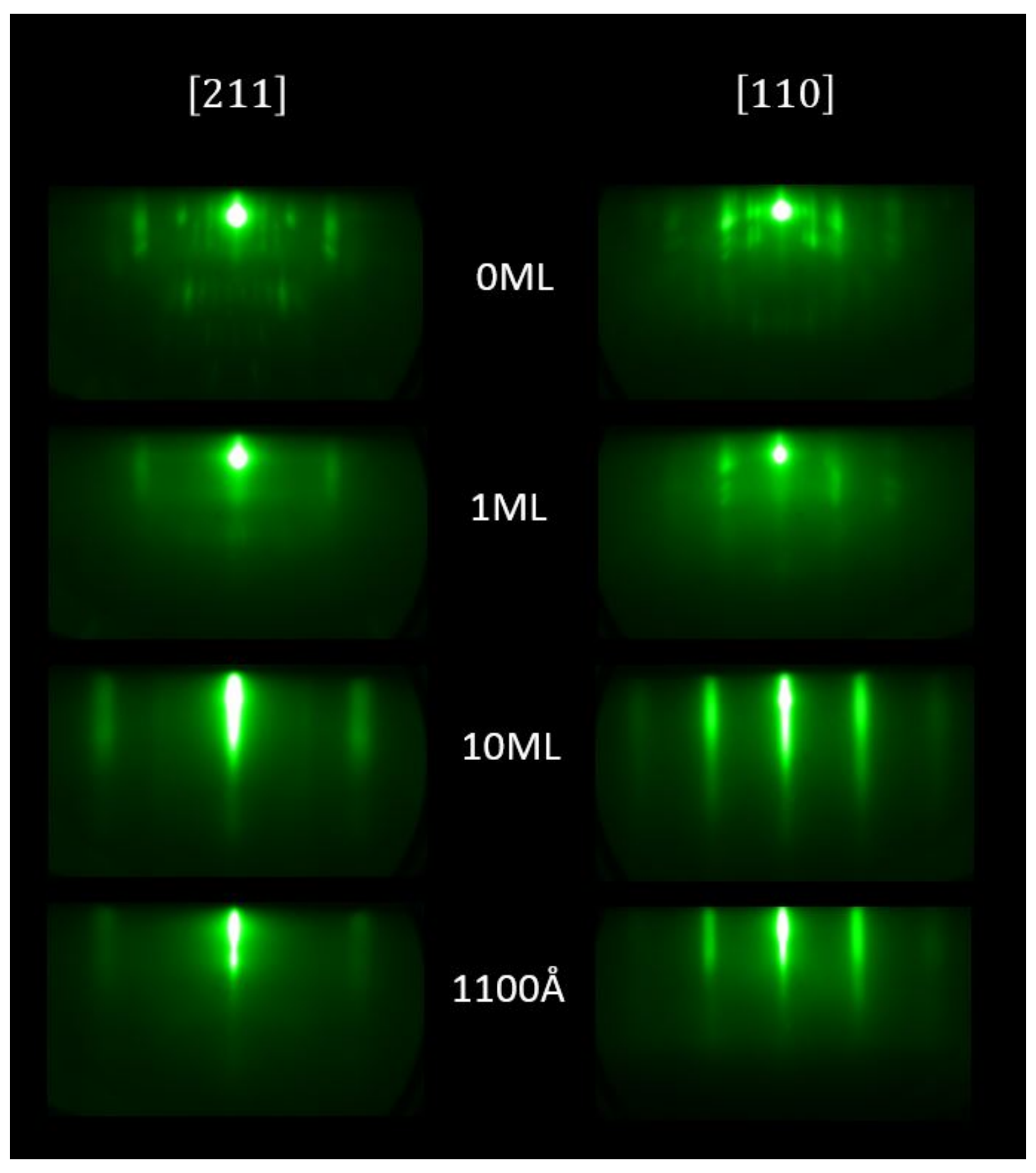
Crystalline aluminum layers of atomic smoothness were obtained, with best results for GaAs(001)-(2x4) and Si(111) starting surfaces. Aluminum epitaxy on GaAs(001)-(4x4) reconstructed surfaces led to the formation of polycrystalline materials of inconsistent composition. All samples showed low level of defects under microscope observation.

Starting surface	Crystalline orientation	Growth mode	Defects level	RMS
GaAs(001)-(2x4)	Al(110)	SK[a]	Low	0.324nm
GaAs(001)-(4x4)	Al(111)+Al(100)+Al(110)	SK[a]	Low	0.916nm
Si(111)-("1x1")	Al(111)	FV[b]	Low	0.487nm
Si(111)-(7x7)	Al(111)	FV[b]	Low	0.519nm
Si(001)-(2x1)	Al(110) bicrystals	VW[c]	Low	0.724nm

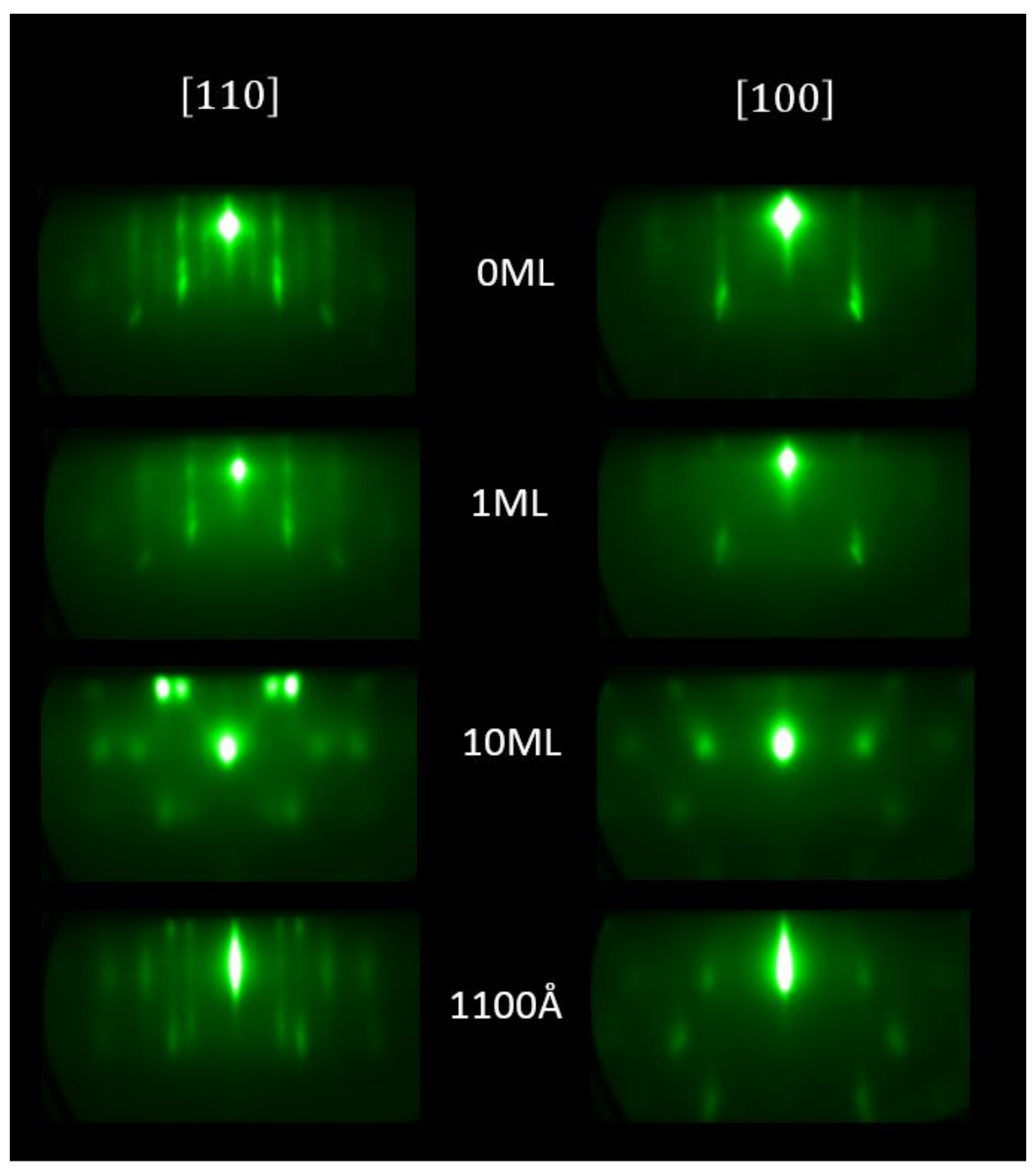
(a) Stranski-Krastanov (b) Frank-Van der Merwe (c) Volmer-Weber



RHEED patterns changes during epitaxy of Al on GaAs(001) [(a)]

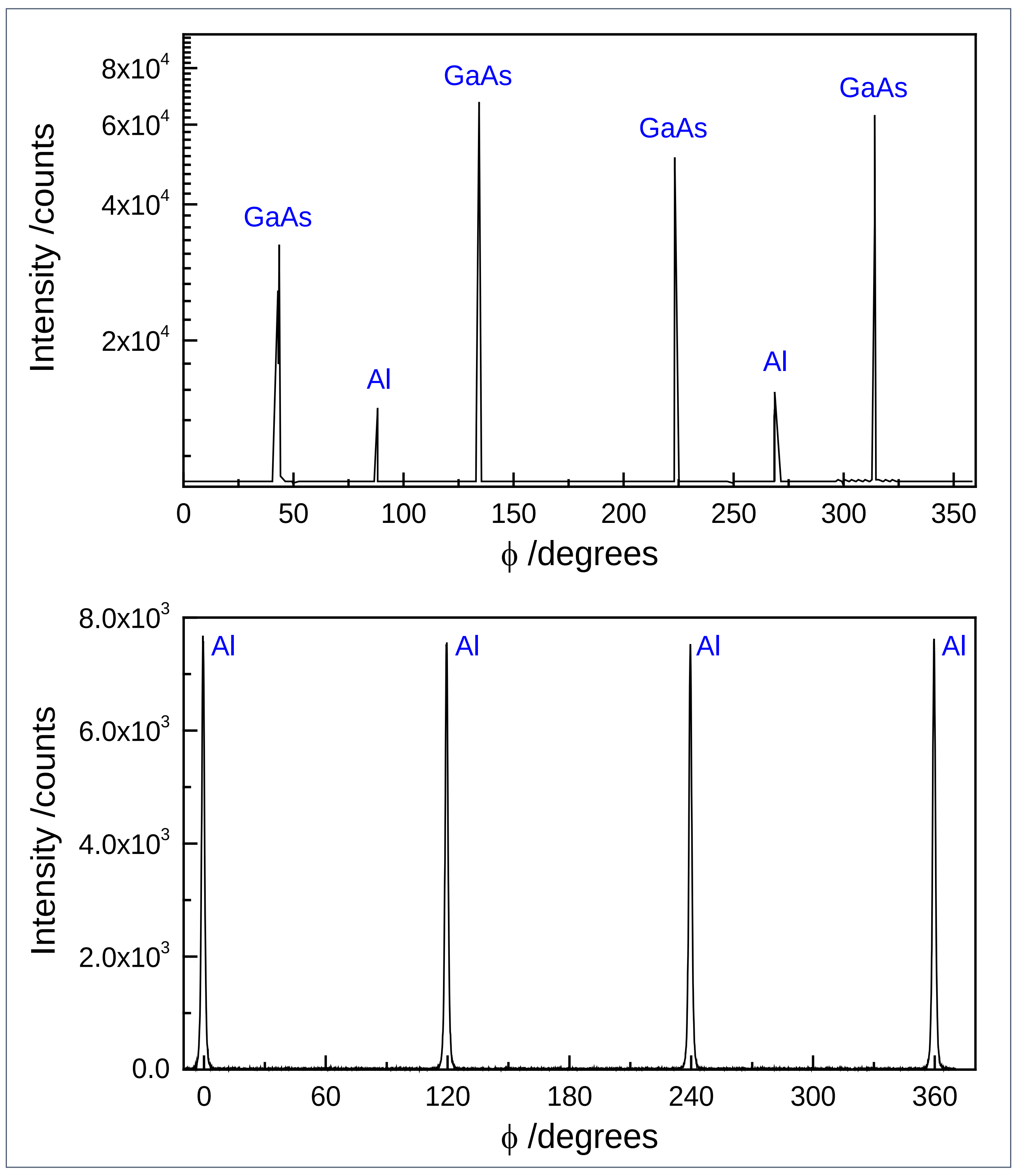


RHEED patterns changes during epitaxy of Al on Si(111) [(b)]

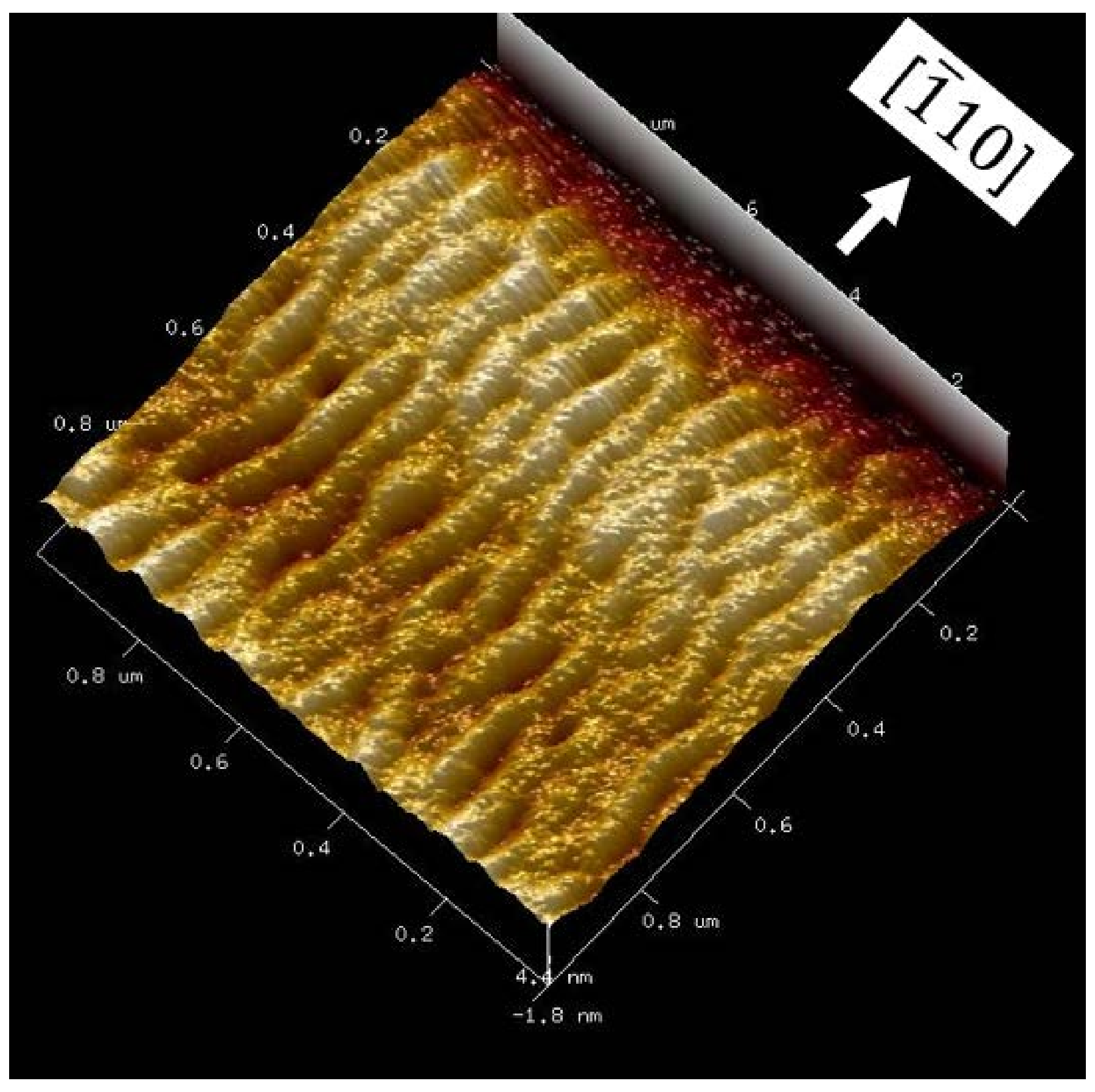


RHEED patterns changes during epitaxy of Al on Si(001) [(c)]

Different growth modes were observed: Stranski-Krastanov for the epitaxy on GaAs(001), Frank-Van-der-Merwe on Si(111) and Volmer-Weber on Si(001). In the case of GaAs(001)-(2x4), 3D islands coalescence happened at different rates along $[\bar{1}10]$ and $[110]$ directions, showing an increased mobility of Al along the $[\bar{1}10]$direction. This led to the elongated pattern observed on the surface at the end of the growth as shown below. The samples were further studied *ex-situ* by HRXRD, AFM and DIC microscopy.



XRD ϕ scans, set at $\omega - 2\theta = 44.72°$ corresponding to Al(200), of the Al(110) layers on GaAs(001) (top, $\Psi = 45°$) and of the Al(111) layers on Si(111) (bottom, $\Psi = 54.73°$) confirm their single crystalline nature.



AFM of Al on GaAs reveals an atomically smooth layer with elongated pattern in the $[\bar{1}10]$ direction. Complimentary Nomarski microscopy studies showed very low level of point defects.

Summary and outlook

High quality single crystalline and atomically smooth Al layers were grown on both GaAs and Si substrates. Ongoing and future work include:

- Patterning of resonators (in process)
- Comparative study of *ex-situ* cleaning techniques for further improvement of the device quality.

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