Brookhaven National Laboratory

C-AD Machine Advisory Committee Meeting (MAC-20), Dec 19-21, 2023

U.S. DEPARTMENT OF ENERGY

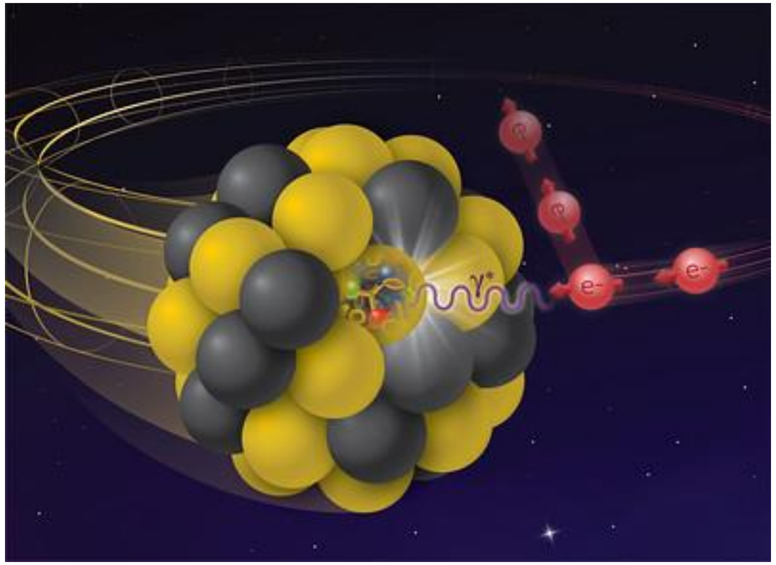
R&D for high intensity electron sources in support of EIC (ECA FOA)

Mengjia Gaowei on behalf of the collaboration
Collider Accelerator Department, BNL

Introduction: electron cooling for EIC

E-cooling in EIC

- High average current (100 mA)
- High bunch charge (up to 2nC)
- Long lifetime (>3days)
- Low emittance



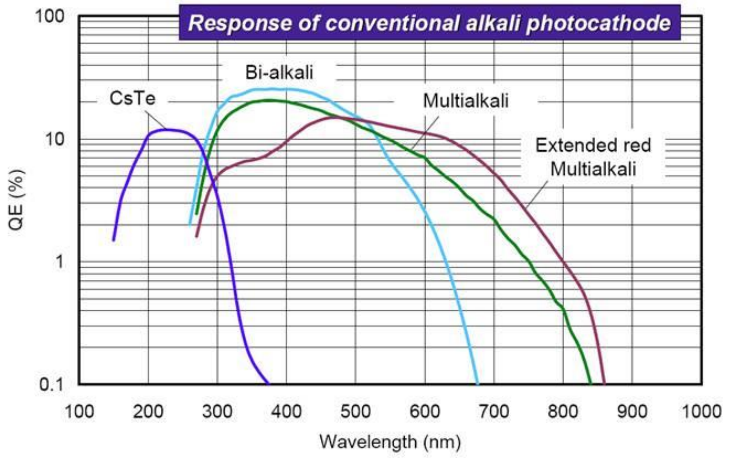
Electron cooling is a promising technique to improve the luminosity of the hadron beams by balancing emittance growth rates due to intrabeam scattering (IBS).

At RHIC, Both the low energy and high energy electron cooling project, LEReC and CeC, are currently using the bi-alkali antimonide photocathodes to generate electrons.

Current state-of-the-art/practice

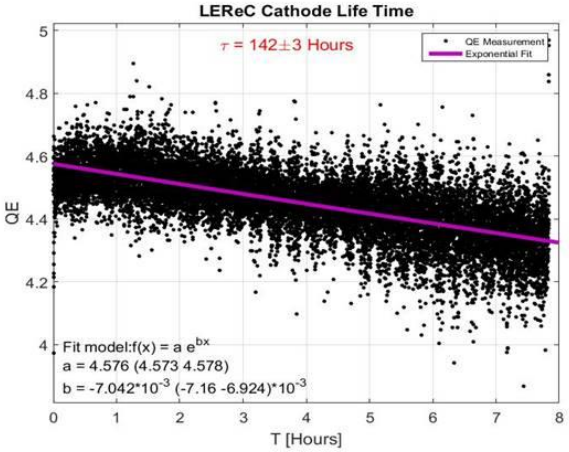
Excellent photocathode for electron cooling: good combination of properties

High quantum efficiency in visible light range
Less sensitive to vacuum than GaAs:Cs



Has been demonstrated in practice

Cornell University: 65 mA, 60 pC bunch charge for 2 days
LEReC @ BNL: 50mA for hours; 15~20 mA average current for weeks of operation, and 20K C charge lifetime

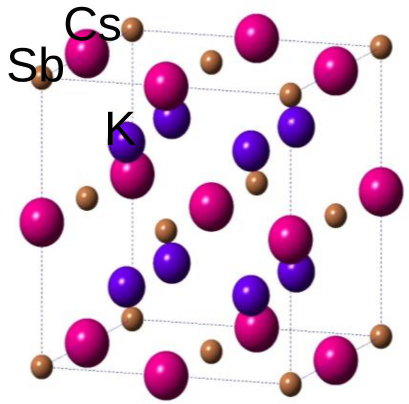


25 mA;
t = 142 h;
QE > 4%

For semiconductor photocathodes, material properties like stoichiometry, crystallinity and surface roughness determines the performance merits such as quantum efficiency and thermal emmitance. Our studies and experience show that our cathode material has a lot more to improve in terms of these properties.

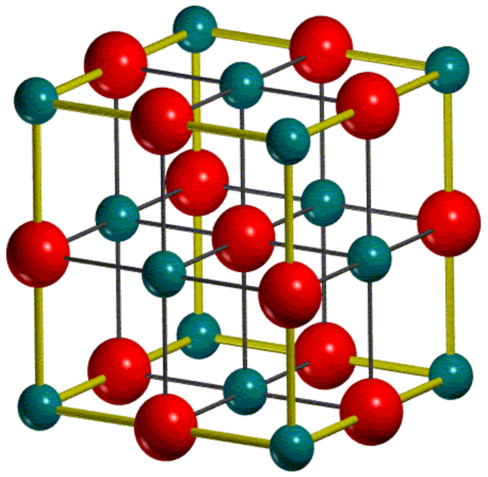
Epitaxial growth of alkali antimonide photocathode

- Epitaxy refers to the growth of a single crystalline film on a single crystalline substrate.
- Epitaxial Growth of Photocathode: Large grain or single crystal photocathode that has smooth surface; low scattering rate from reduced grain boundaries→ low mean transverse energy and high QE
- 2 key aspects to epitaxial growth: lattice matched substrates and co-evaporation.

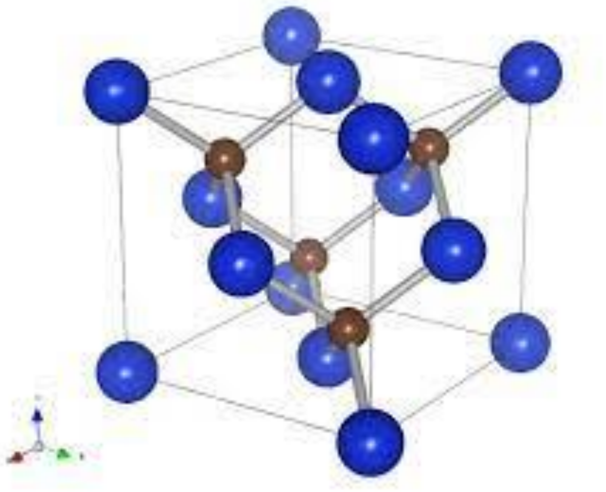


K_2CsSb unit cell

K_2CsSb, Cs_3Sb: b.c.c. crystal structure
Lattice parameter: 8.615 Å, 9.18 Å



MgO: f.c.c. crystal structure
Lattice parameter: 4.21 Å



3C-SiC: f.c.c. crystal structure
Lattice parameter: 4.35 Å

Research approach

Cathode Material development	Transfer system development	High current test
• Epitaxial growth of single crystal cathode material • Upgrade with RHEED • Bulk single crystal growth	• Existing design and experience	• High current test chamber • Gun test in tunnel • Material characterization for degraded cathodes

Project tasks and timeline

Tasks	Year 1				Year 2				Year 3				Year 4				Year 5			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Single crystal photocathode development	■	■	■	■	■	■	■	■	■	■	■	■								
Upgrade growth chamber with RHEED	■	■	■	■																
Incorporate in situ characterization with offline technique					■	■	■	■	■	■	■	■								
Measure the transverse emittance of the electron beam generated by the single crystal photocathode													■	■	■	■				
Compare emittance measurements with simulations																	■	■	■	■
Fabricate cathode transfer chamber between growth and analysis tools	■	■	■	■	■	■	■	■												
Commission the transfer chamber									■	■	■	■								
Lifetime test for single crystal cathode and the traditionally grown cathode under high current condition													■	■			■	■		
Characterize damaged cathodes in the analysis chamber and investigate recovering methods															■	■			■	■
Test synthesized bulk cathode under high current conditions															■	■	■			
Test cathodes with 2-D protective coating under high current conditions																		■	■	■

- Tasks year 1 (2021/8 ~ 2022/7)
  - Single crystal photocathode development
  - Upgrade growth chamber with RHEED
  - Fabricate cathode transfer chamber between growth and analysis tools (design stage)
- Tasks year 2 (2022/8 ~2023/7)
  - Single crystal photocathode development
  - Incorporate in situ x-ray characteristics with offline technique.
  - Fabricate cathode transfer chamber between growth and analysis tools

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Progress summary

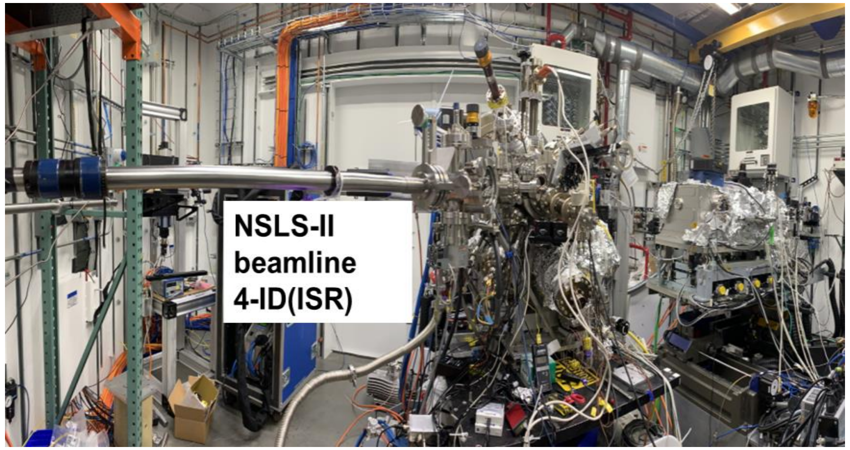
Hardware upgrade:

- **RHEED** system has been installed, commissioned on the cathode growth chamber. RHEED measurement was successfully performed during the NSLS-II beamline along with the x-ray characterization for the epitaxial growth of the photocathode material.
- Chamber was also upgraded to use **pulsed laser deposition (PLD)** as the growth method. Rotatable PLD target was installed and optics were build to introduce the excimer laser into the chamber.

Material development:

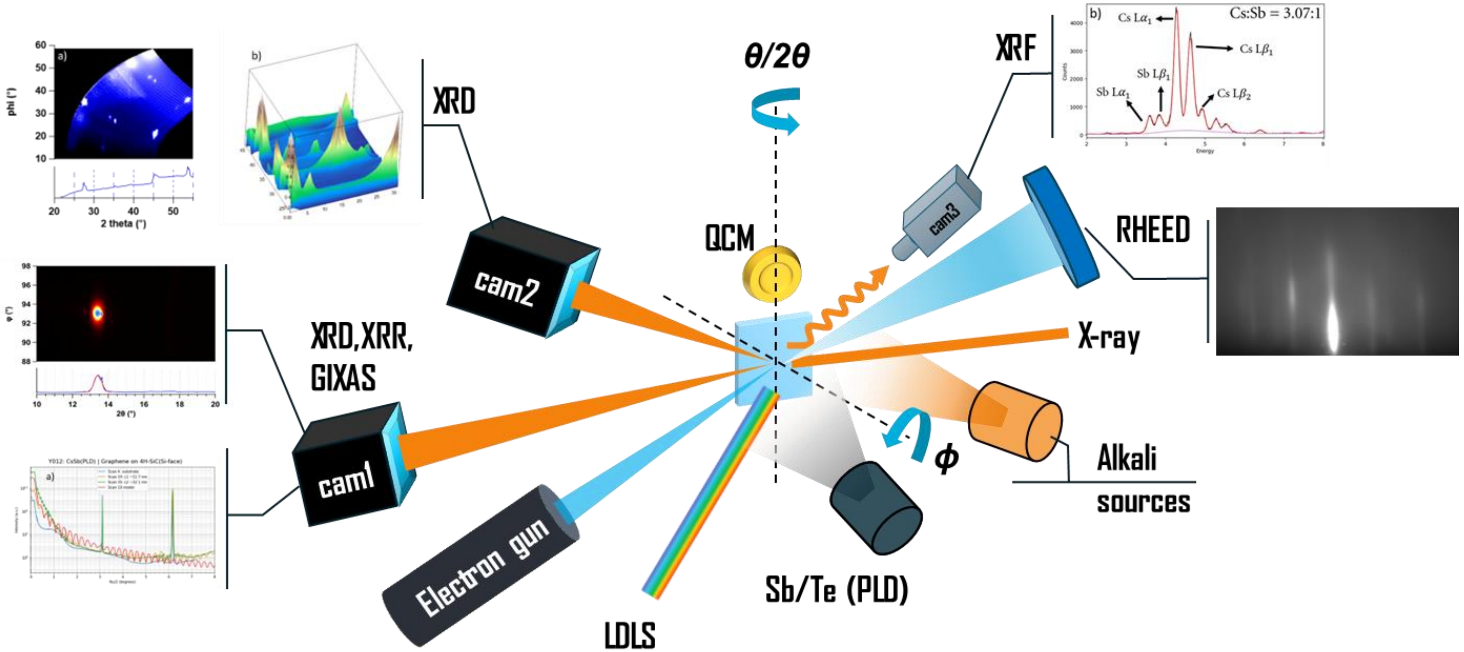
- **Epitaxial growth** of **K_2CsSb, Cs_3Sb and Cs_2Te** were performed on various lattice matched substrates. High quantum efficiency, ultrasmooth and epitaxial thin film photocathodes are achieved.

Experimental: characterization



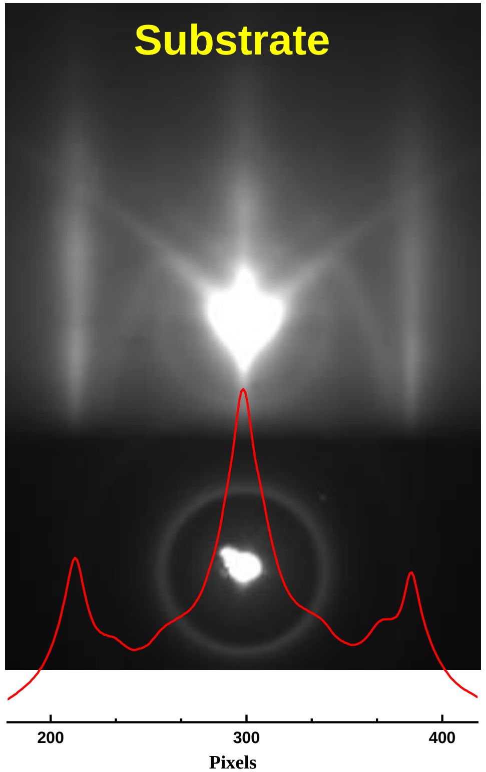
Evaporators:
- ❑ Thermal Sb/Te
- ❑ Alkali metals
- ❑ PLD Sb/Te

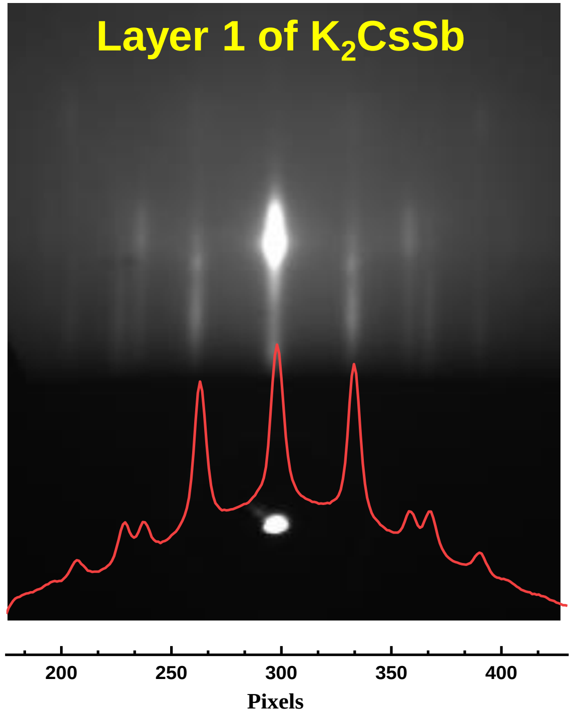
Characterization:
- ❑ QCM
- ❑ XRD
- ❑ XRR
- ❑ XRF
- ❑ QE
- ❑ RHEED

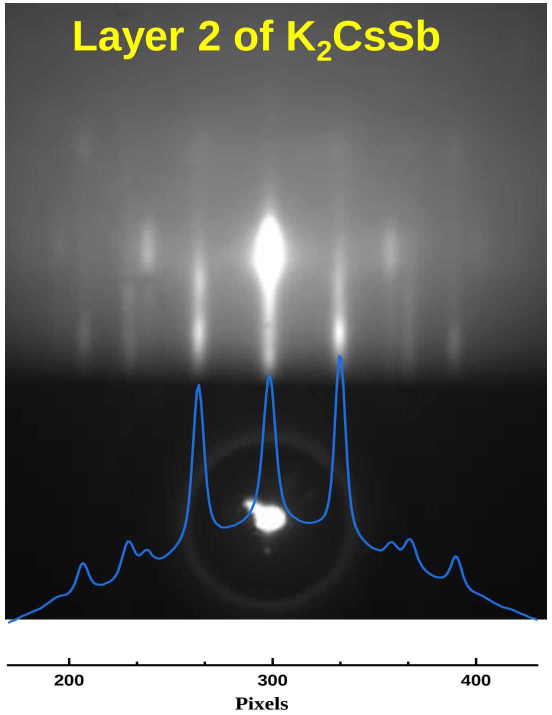


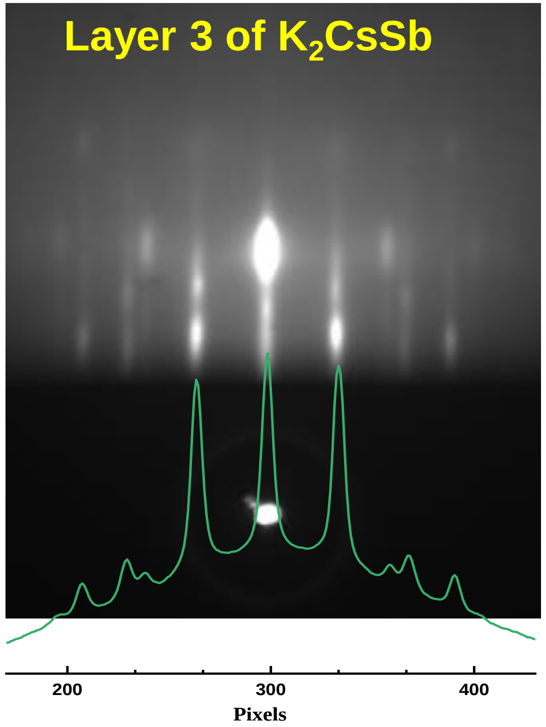
4-ID ISR NSLS-II National Synchrotron Light Source II

Epitaxial K_2CsSb: RHEED

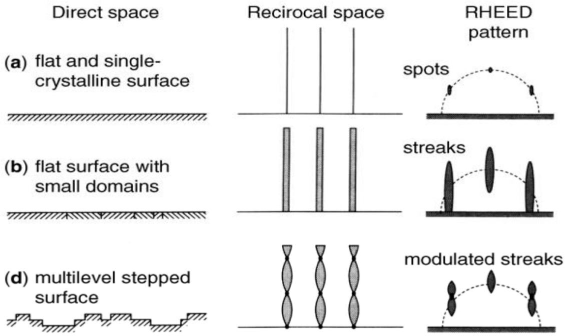




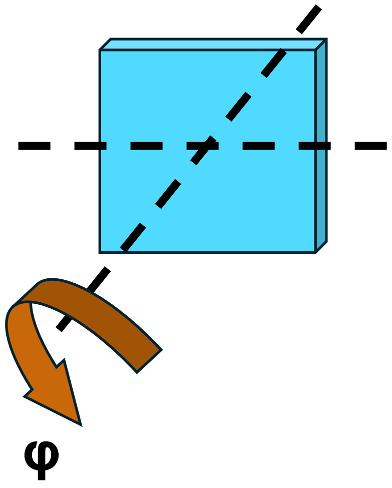




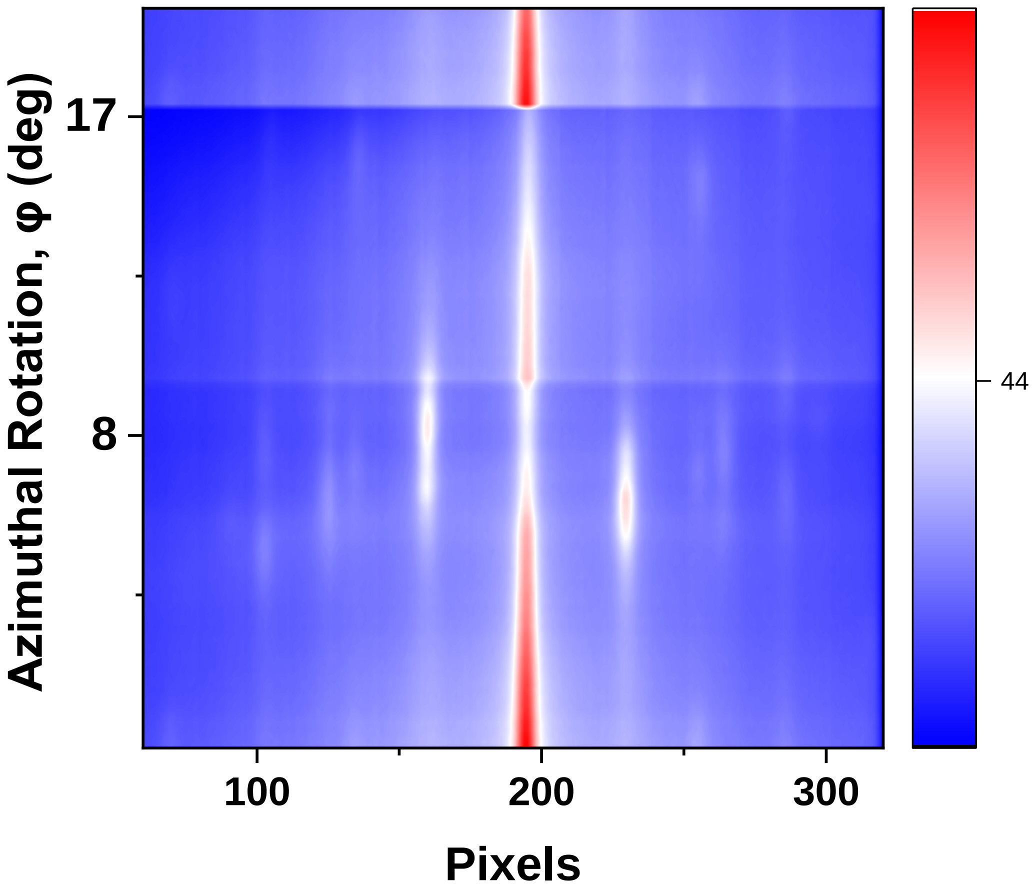
- ❑ Alignment with substrate peaks indicating epitaxy.
- ❑ Streaky pattern represent smooth surfaces with small domains.
- ❑ Multiple sets of streaks visible, indicating multiple grain orientations.
- ❑ Modulated streaks: roughness increases.

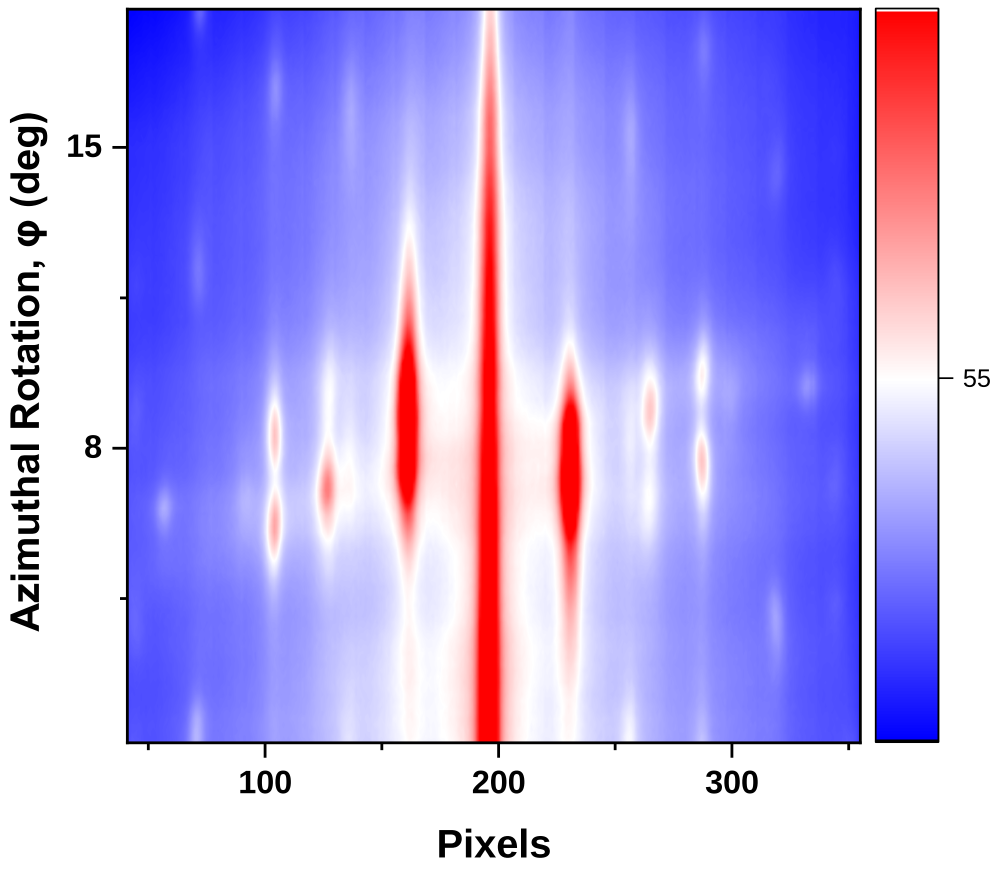


Epitaxial K_2CsSb: RHEED



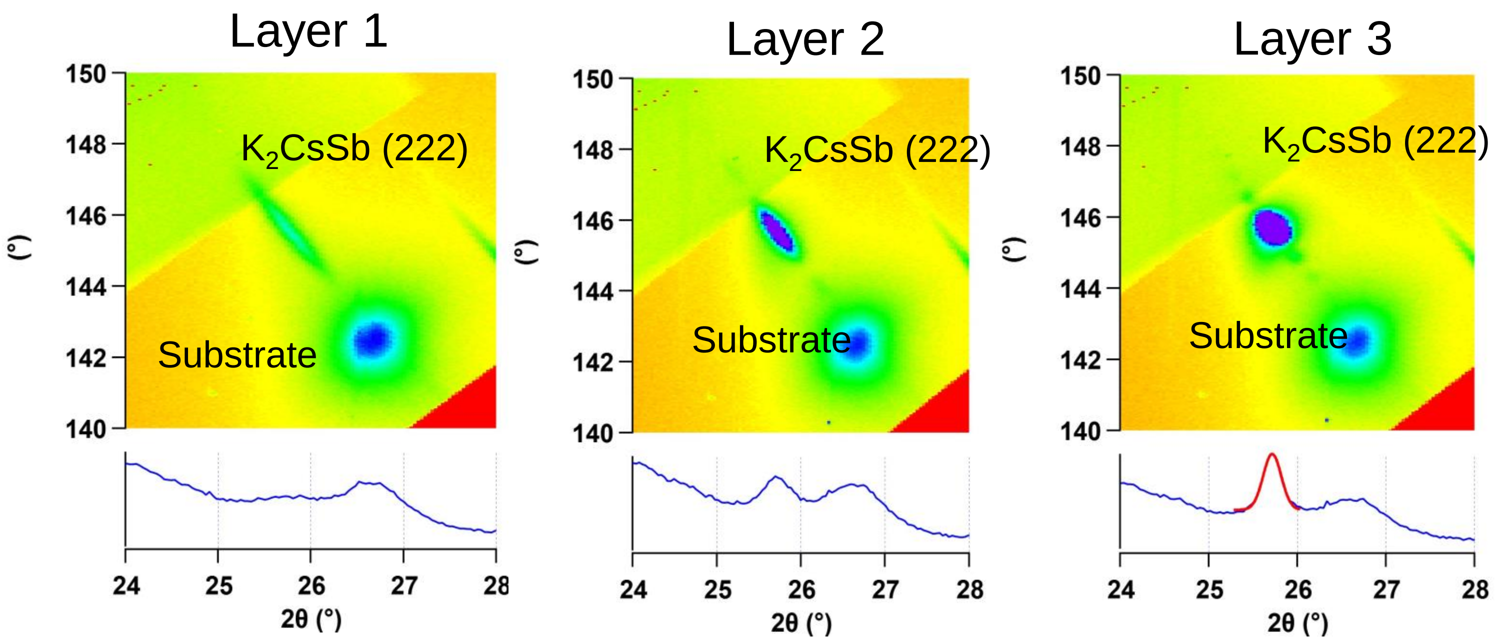
Schematic of azimuthal sample rotation



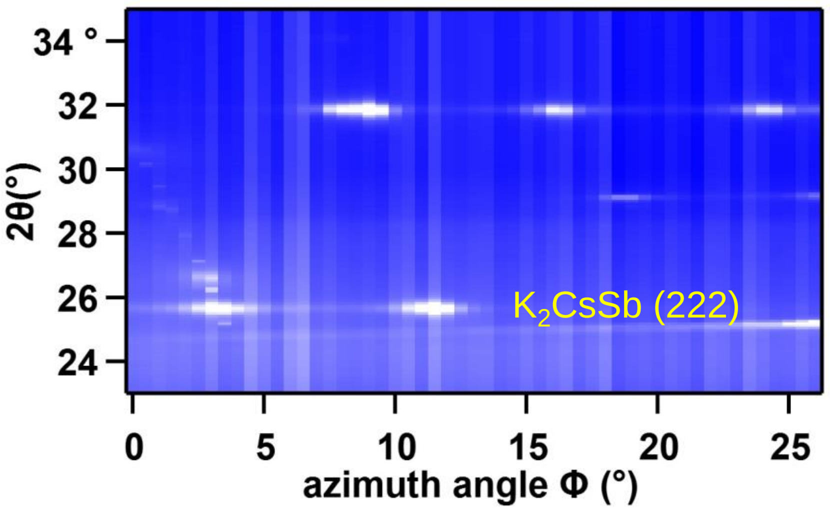


Azimuthal angular dependence in RHEED pattern are observed, indicating aligned crystalline domains are formed in the cathode film.

Epitaxial K_2CsSb: bulk crystallinity



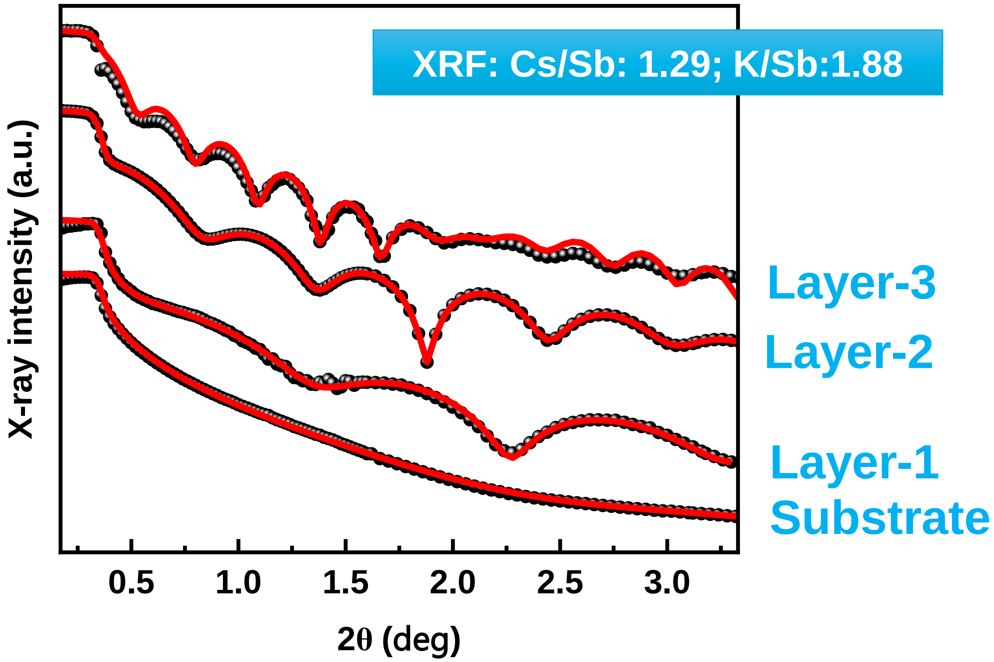
x0 =25.715 ± 0.00224
width =0.14515 ± 0.00415
Grain size: 411.30 nm
Film thickness Layer 3 : 20 nm

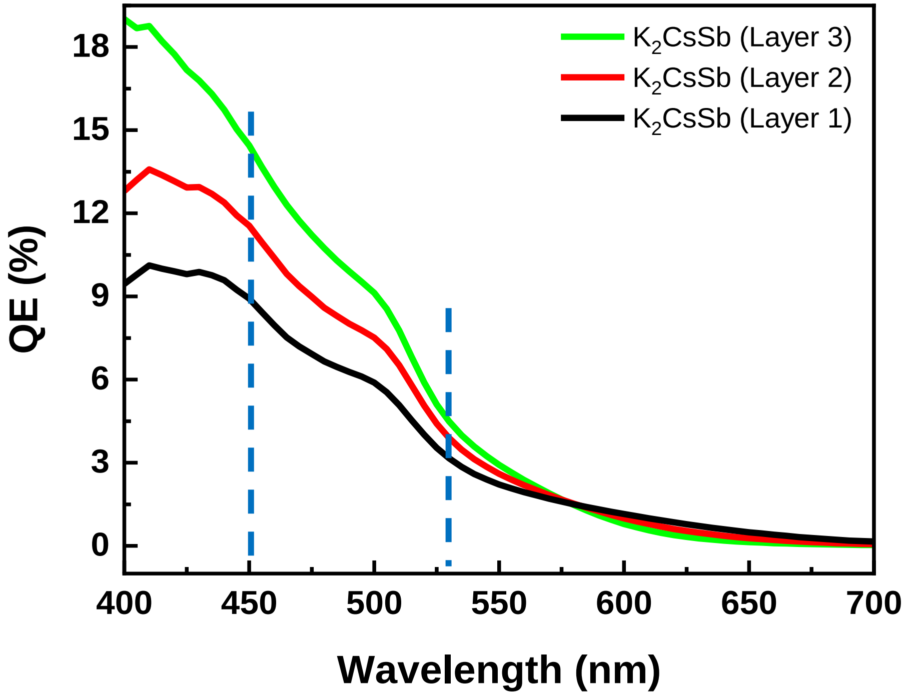


Diffraction image at Brag condition (222)
Elongation structure is from Mosaicity and strain of the film.
Grain size is >> film thickness; indicating the formation of large crystal domains.

Azimuthal angular dependence from XRD is observed, agrees with RHEED. Indicating the crystalline grains are aligned in orientation.

Film roughness and QE





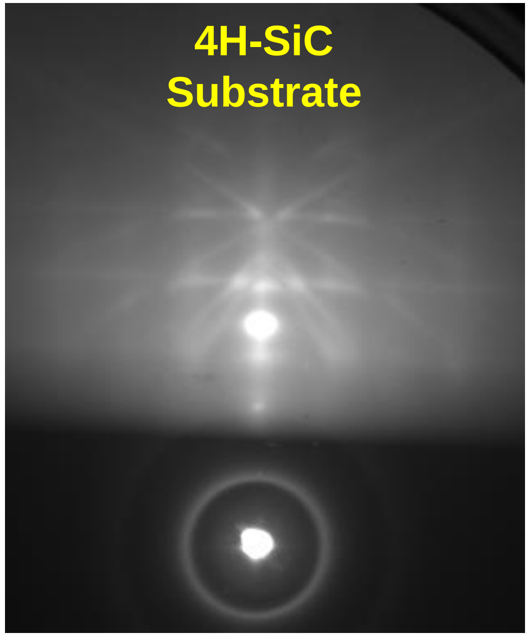
XRR	Thickness (nm)	Roughness (nm)
Substrate	NA	0.40
Layer 1	6	0.60
Layer 1+2	11	0.65
Layer 1+2+3	20	0.75

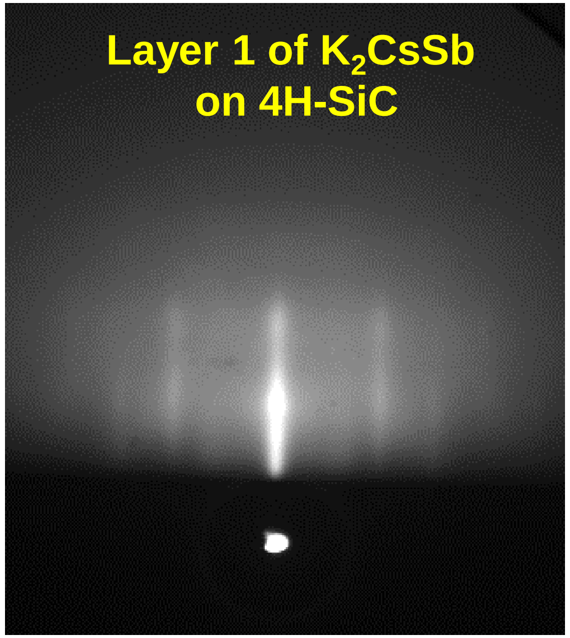
XRR of K_2CsSb Roughness increased with increasing thickness of photocathode thin film.

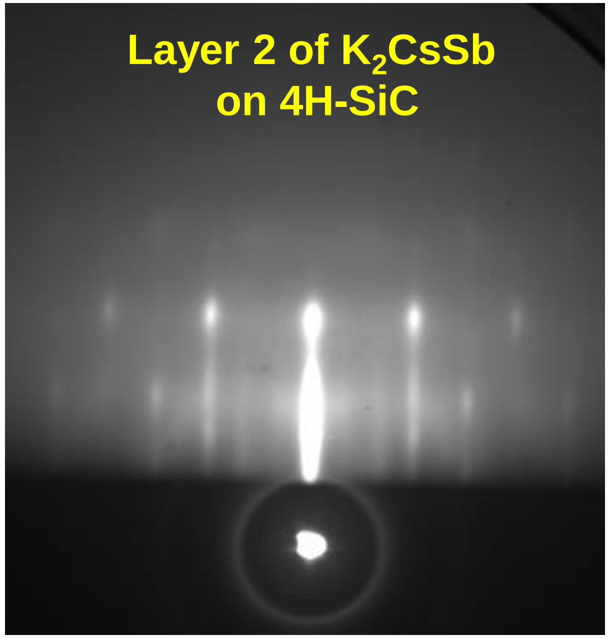
Wavelength (nm)	QE (%)		
	L1	L2	L3
450 (Blue)	8.9	11.6	14.5
530 (Green)	3.2	3.9	4.5

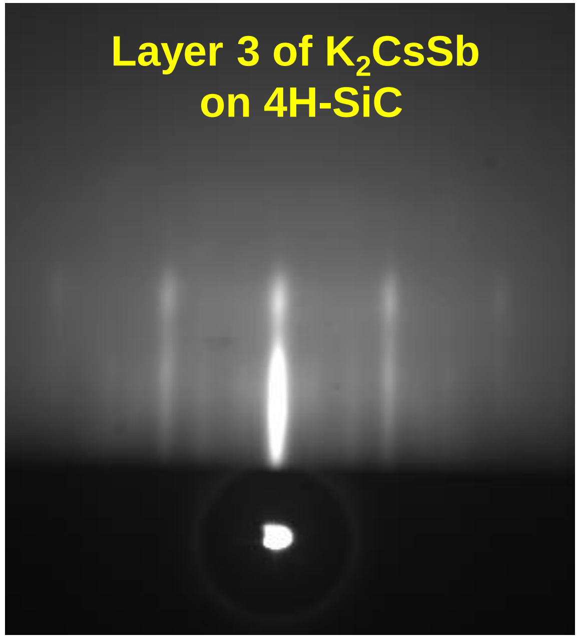
Offline test: K2CsSb growth on doped 4H/SiC

K_2CsSb/4H-SiC: RHEED



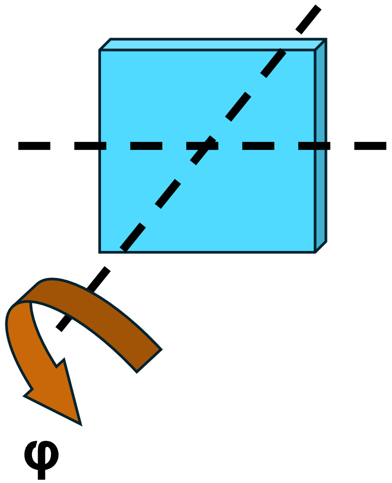




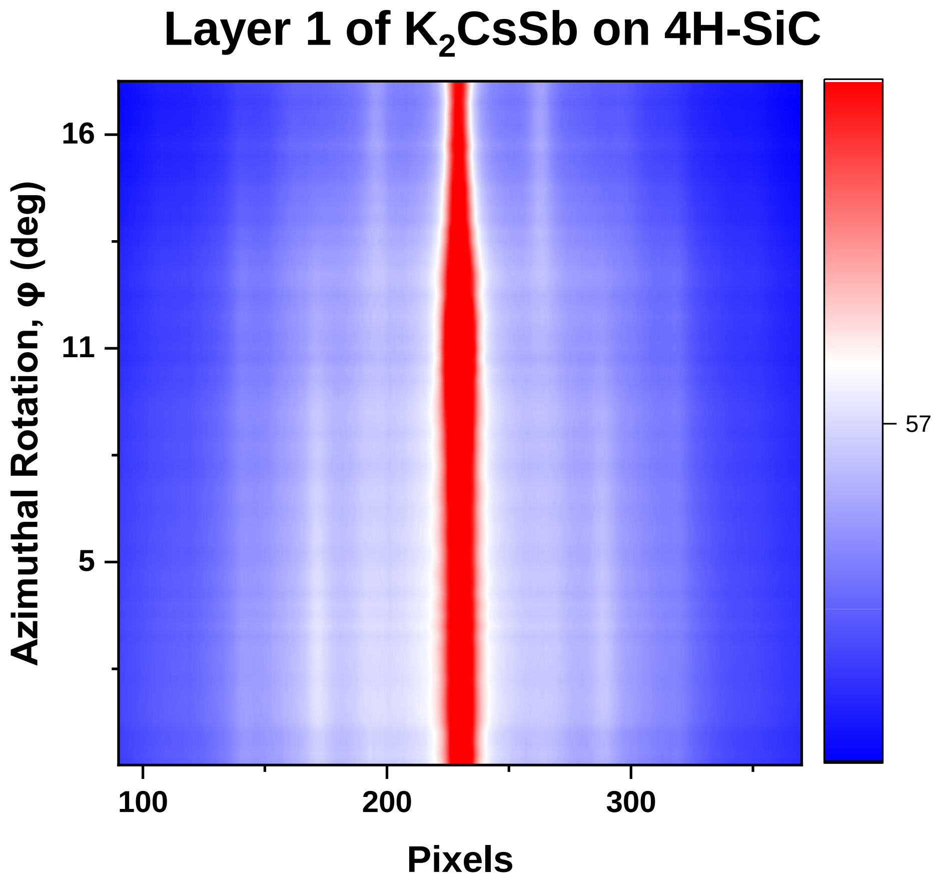


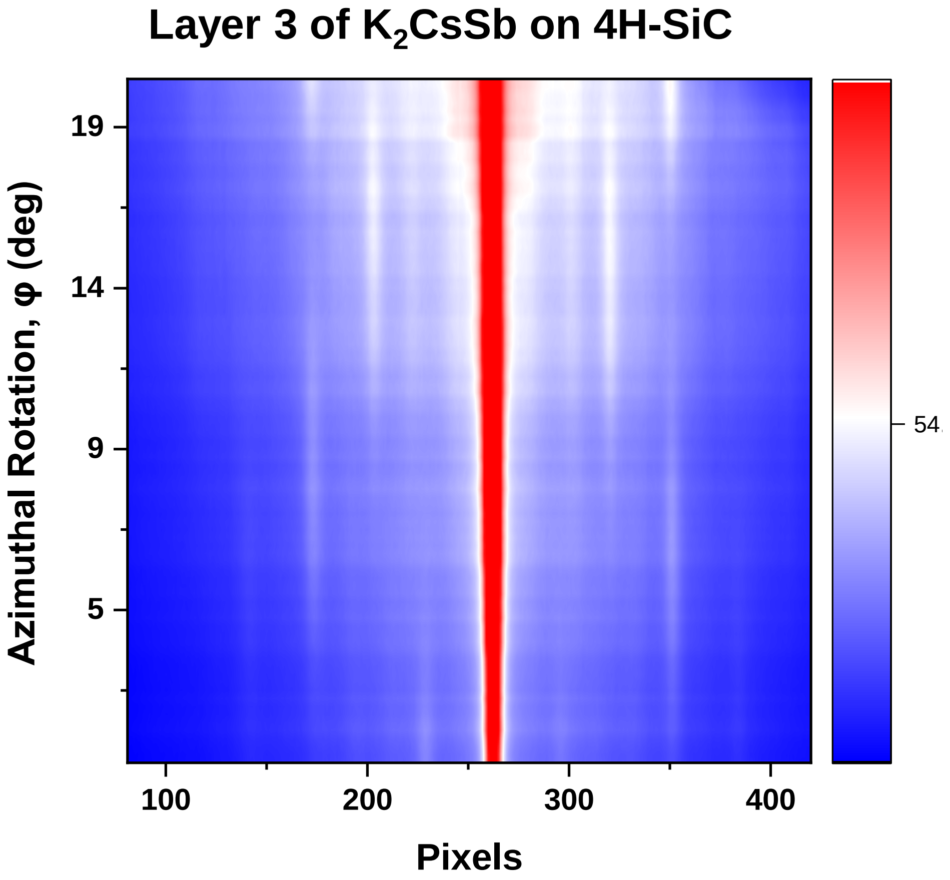
- Similar streaks to film in the x-ray experiment
- Streaky pattern represent smooth surfaces with small domains.
- Modulated streaks: roughness increases.

K_2CsSb/4H-SiC: RHEED



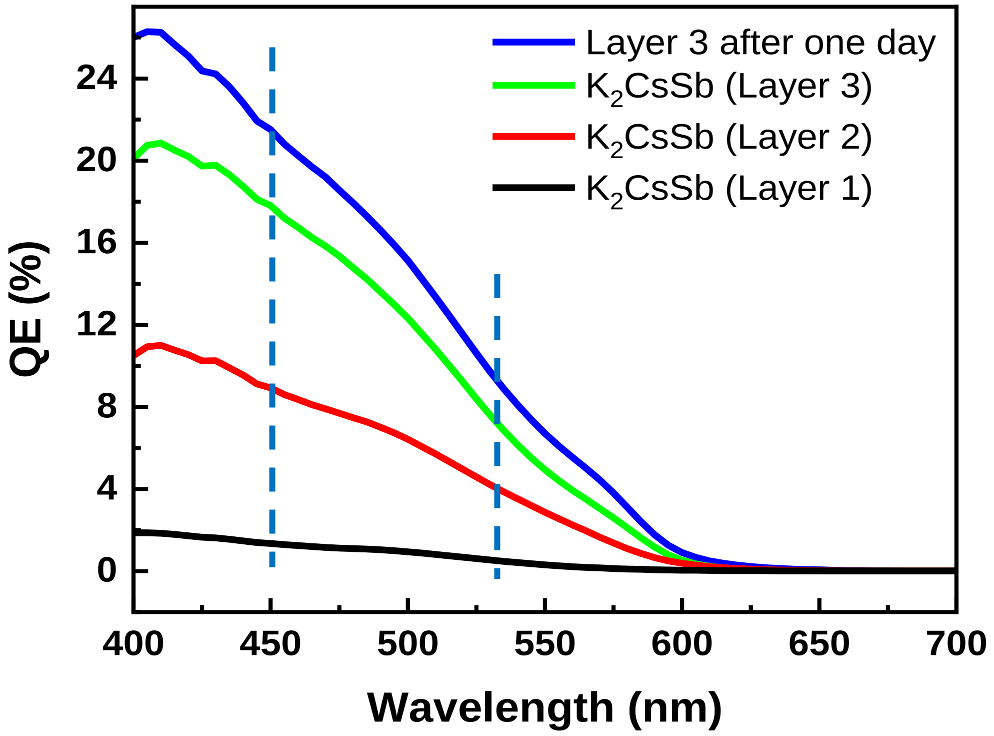
Schematic of azimuthal sample rotation

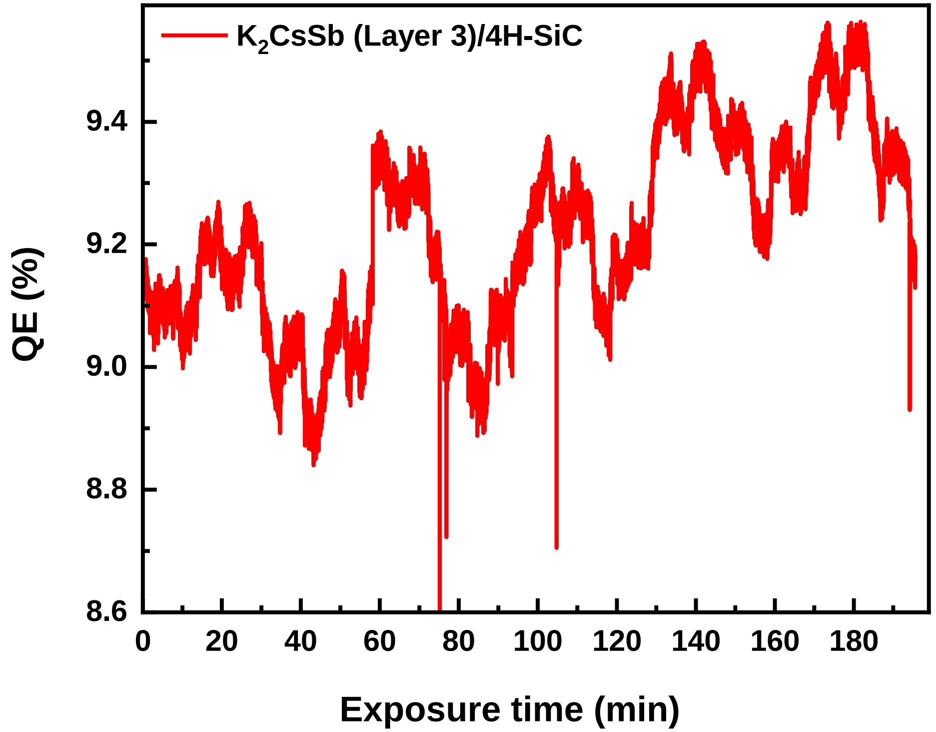




Azimuthal angular dependence observed!

Quantum Efficiency





Wavelength (nm)		Sample-3 QE (%)			
		L1	L2	L3	L3 after 1 day
Green laser		0.5	4.6	9.2	--
LDLS source	450	1.3	8.9	17.8	21.5
	530	0.5	4.2	7.6	9.7

- ❑ Green QE is > 9% !
- ❑ Measured QE after 3-4 days of growth, no decay
- ❑ Current draw is about 25 uA
- ❑ Fluctuations are likely from laser power

Summary/Plan forward

Epitaxial growth of multiple alkali-based photocathode materials are achieved. The cathode films are showing exceptional performance in crystallinity, surface roughness and QE in a varied thickness range.

The plan forward is to: complete the transfer chamber and the system for emittance measurement, measure the emittance for epitaxial K_2CsSb; gun test for high current performance; analysis for damaging mechanism to improve lifetime.

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Thank you very much! Suggestions and comments are appreciated!

Back up slides

Epitaxial growth of alkali photocathode

A reflection high energy electron diffraction (RHEED) system is a standard in-situ diagnostic that is mainly sensitive to the film surface structure, can provide qualitative information on the growth mode such as island nucleation, texture and crystallinity.

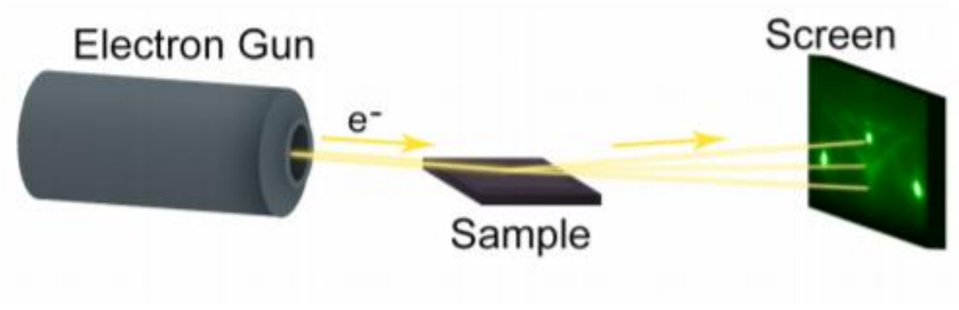
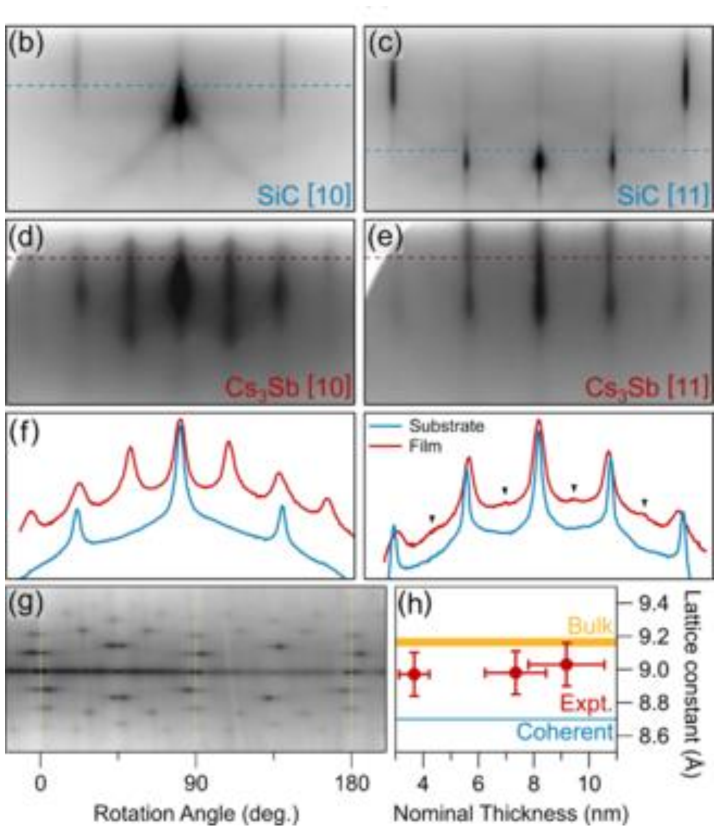


FIG. 1. The simplest RHEED set up includes an electron gun, a sample, and a fluorescence screen across from the gun.

RHEED: Cs_3Sb/3C-SiC

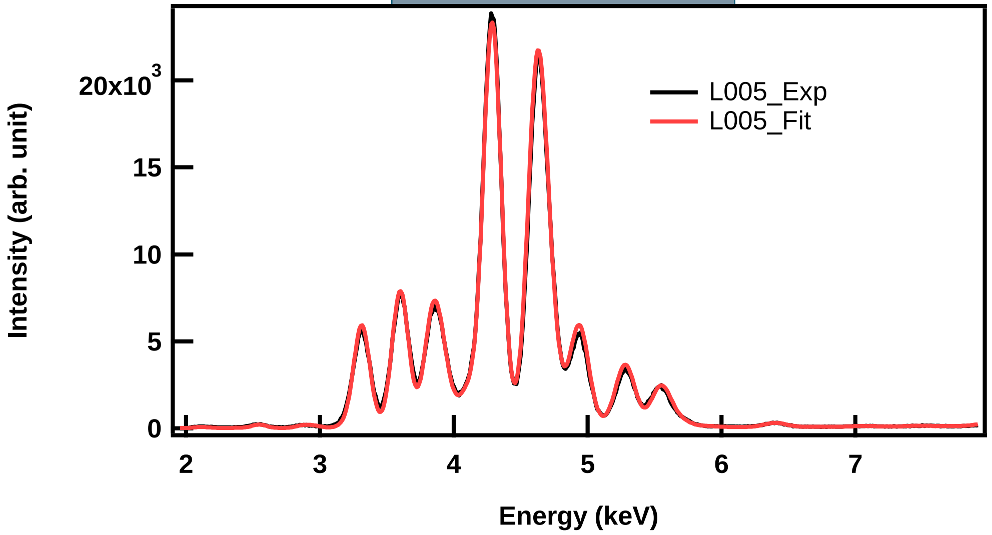


Reference:
Reflection High-Energy Electron Diffraction, Nassim Derriche et al, 2019
Shuji Hasegawa. Characterization of Materials (Second Edition), chapter Reflection High-Energy Electron Diffraction, pages 1925–1938. 2012.

C. T. Parzyck, et al
Phys. Rev. Lett. 128, 114801, 2022

Co-evaporation for epitaxial growth: stoichiometr
thin film growth in one ste

XRF analysis

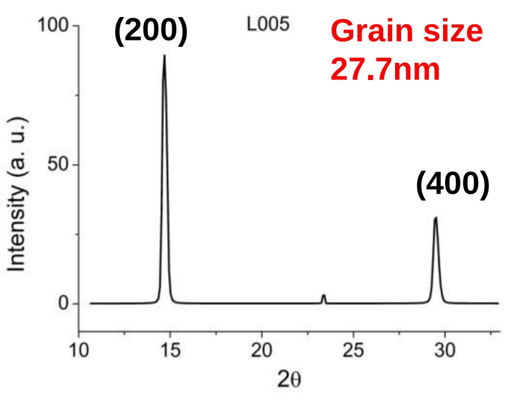


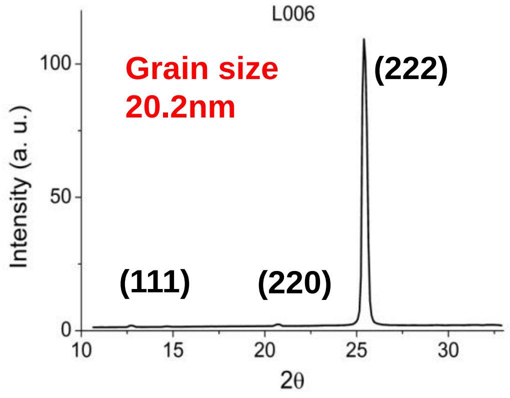
Calculated atomic compositions

	K	Sb	Cs
L005 Si	2.37	1.00	0.91
L006 Si	2.21	1.00	0.95
L011 Si	2.07	1.00	0.94
L012 MgO	1.98	1.00	0.88

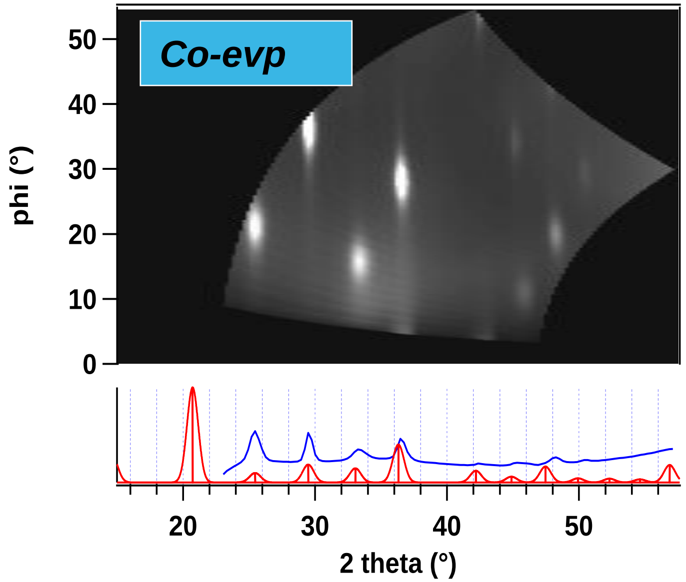
Good K/Cs/Sb ratio!

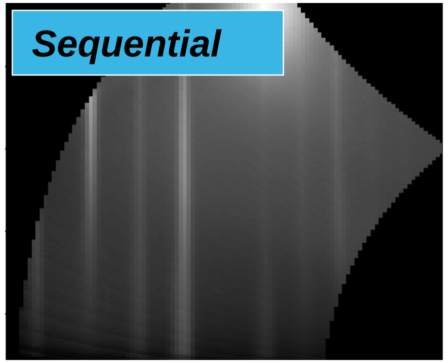
XRD: Camera 1



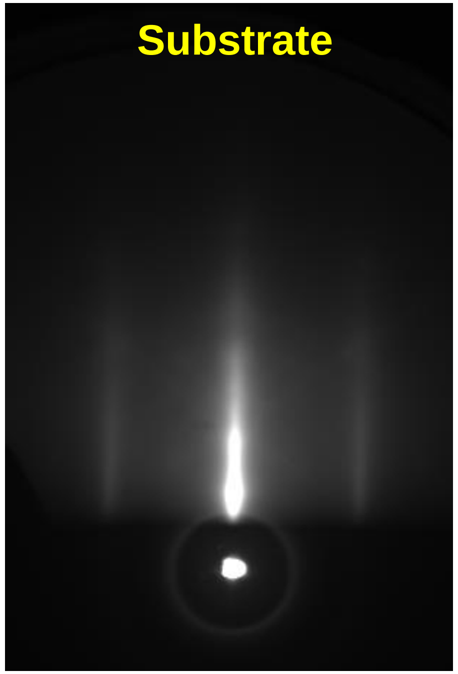


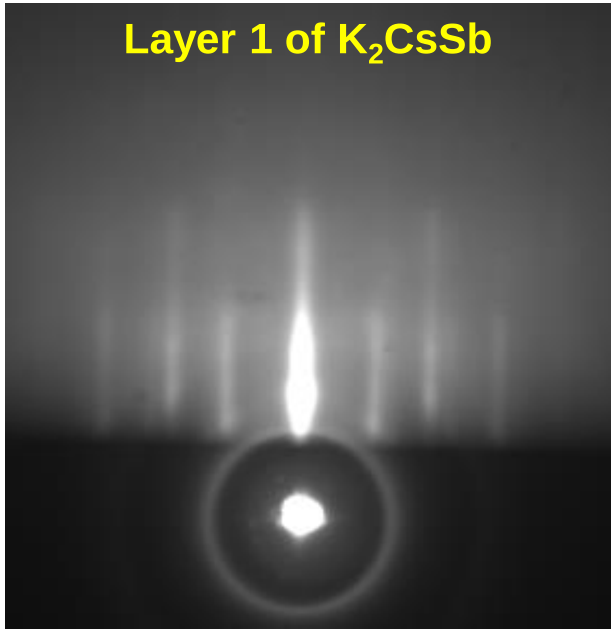
XRD: Camera 2

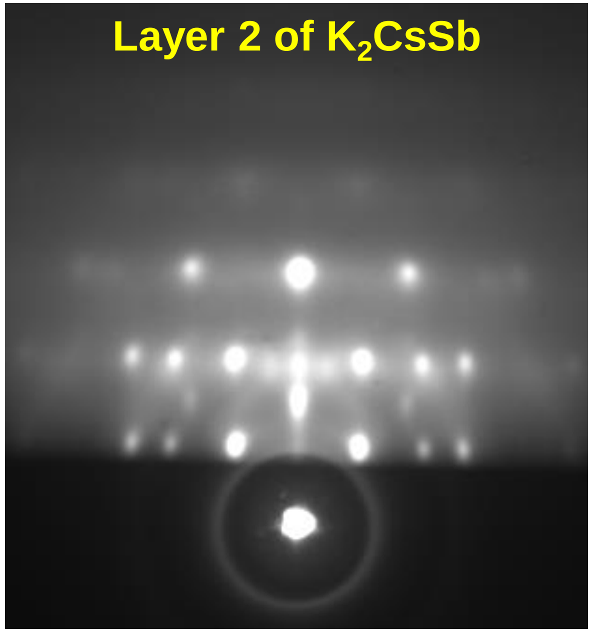


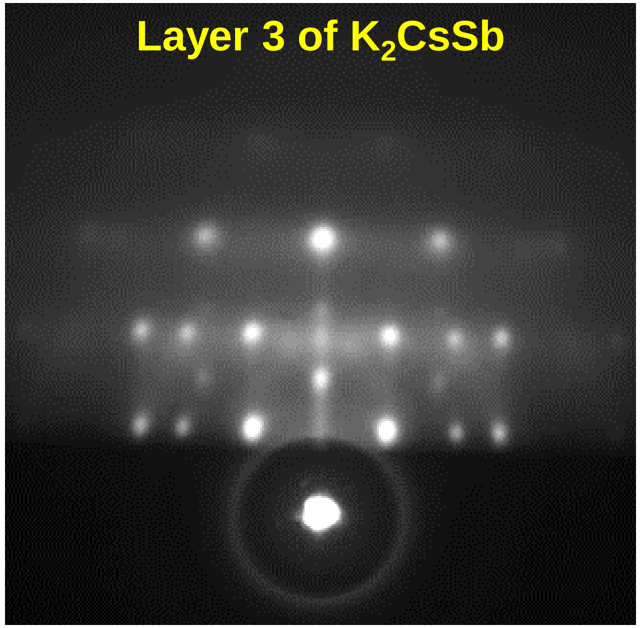


RHEED of K_2CsSb/New Substrate (Sample-2)







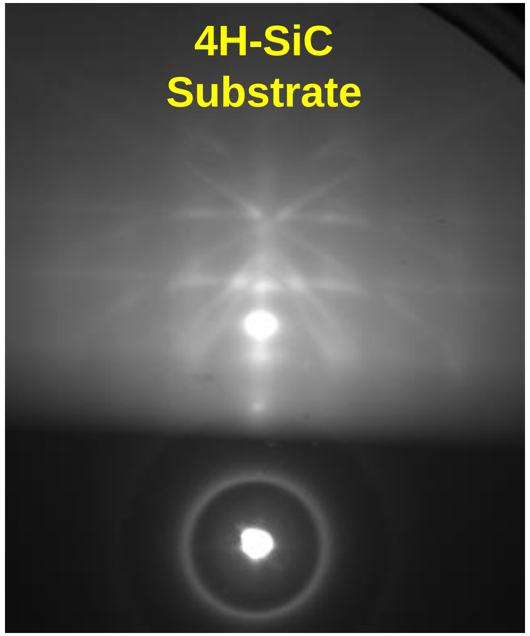


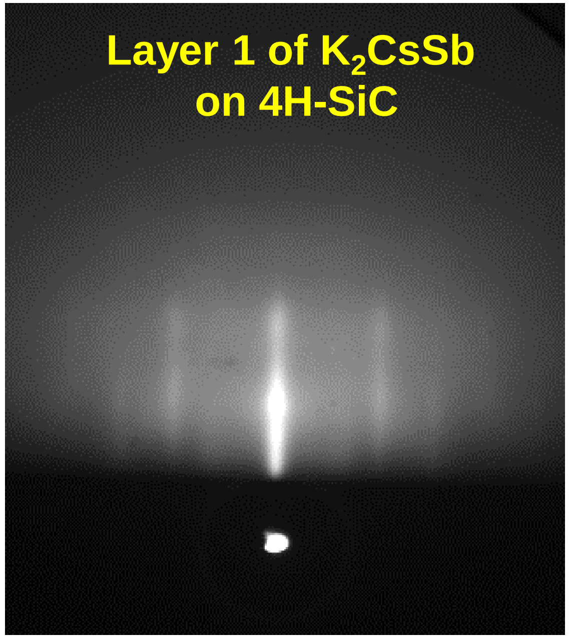
RHEED of K_2CsSb

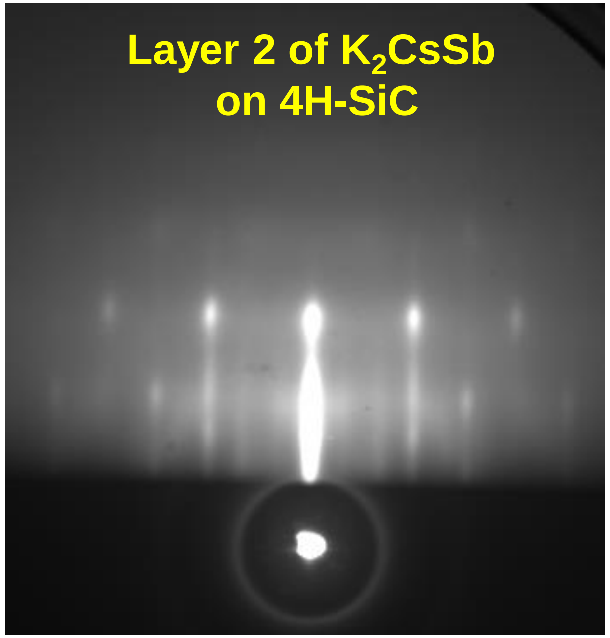
- ❑ RHEED image shows epitaxial growth.
- ❑ Streaks represent smooth surfaces with small domains.
- ❑ Dots represents 3D islands.

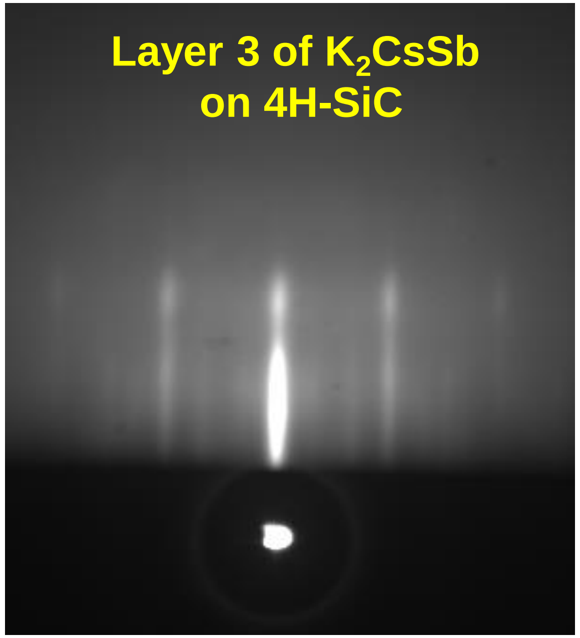
K_2CsSb on Substrate			
Peak # from center	D(pixel)	d (Å)	Close to Planes
1st	34.55	4.96	111
2nd	59	2.91	122
3rd	69.25	2.48	222
4th	90.4	1.90	133

RHEED of K_2CsSb/4H-SiC (Sample -3): Sb deposited using thermal evaporation









RHEED of K_2CsSb/4H-SiC

- ❑ RHEED image shows epitaxial growth.
- ❑ Streaks represent smooth surfaces with small domains.

K_2CsSb on 4H-SiC			
Peak # from center	D(pixel)	d (Å)	Close to Planes
1st	38.9	4.41	002
2nd	58.7	2.92	122
3rd	74.75	2.29	004
4th	89.15	1.92	133

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