MOTH-EYE ANTIREFLECTION FOR SMALL SATELLITES

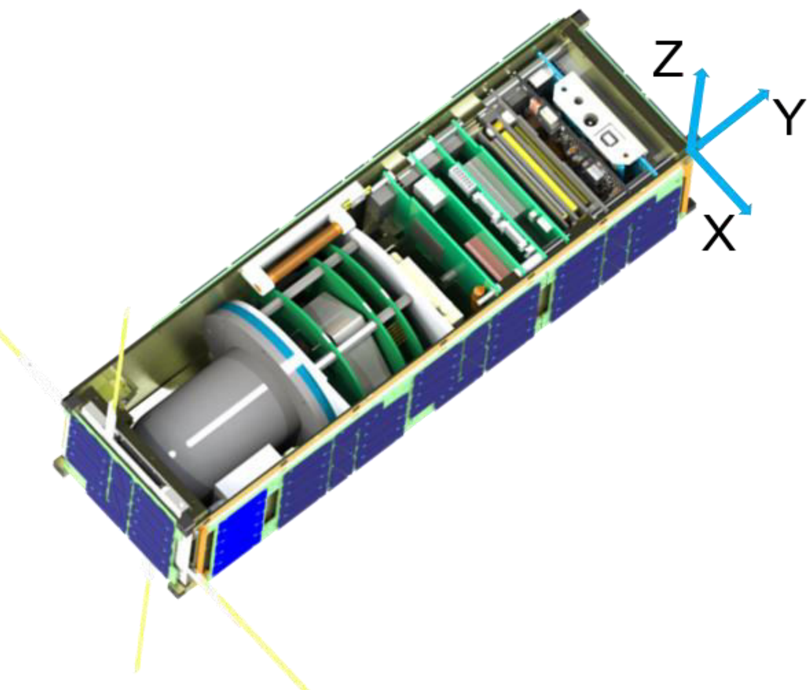
SMALL SAT CONFERENCE 08/11/15

HUGH PODMORE
REGINA LEE

OUTLINE

- Introduction to Moth-Eye Antireflection (MEAR)
- Design and Fabrication of MEAR surfaces for CubeSats
- Characterization of MEAR surface and implications for CubeSats
- Conclusions, contributions and future work

MEAR FOR CUBESATS



CAD model of 3-U SIGMA CubeSat operated by Kyung-Hee University

- High-quality science requires large power budgets.
- CubeSat volume constrains power:
  - Small surface area for light collection
  - Adding arrays possible, but difficult
  - Small surface, high incidence
- Many CubeSats adhere their own coverglass. Can this glass be improved to increase transmission at high angles of incidence?

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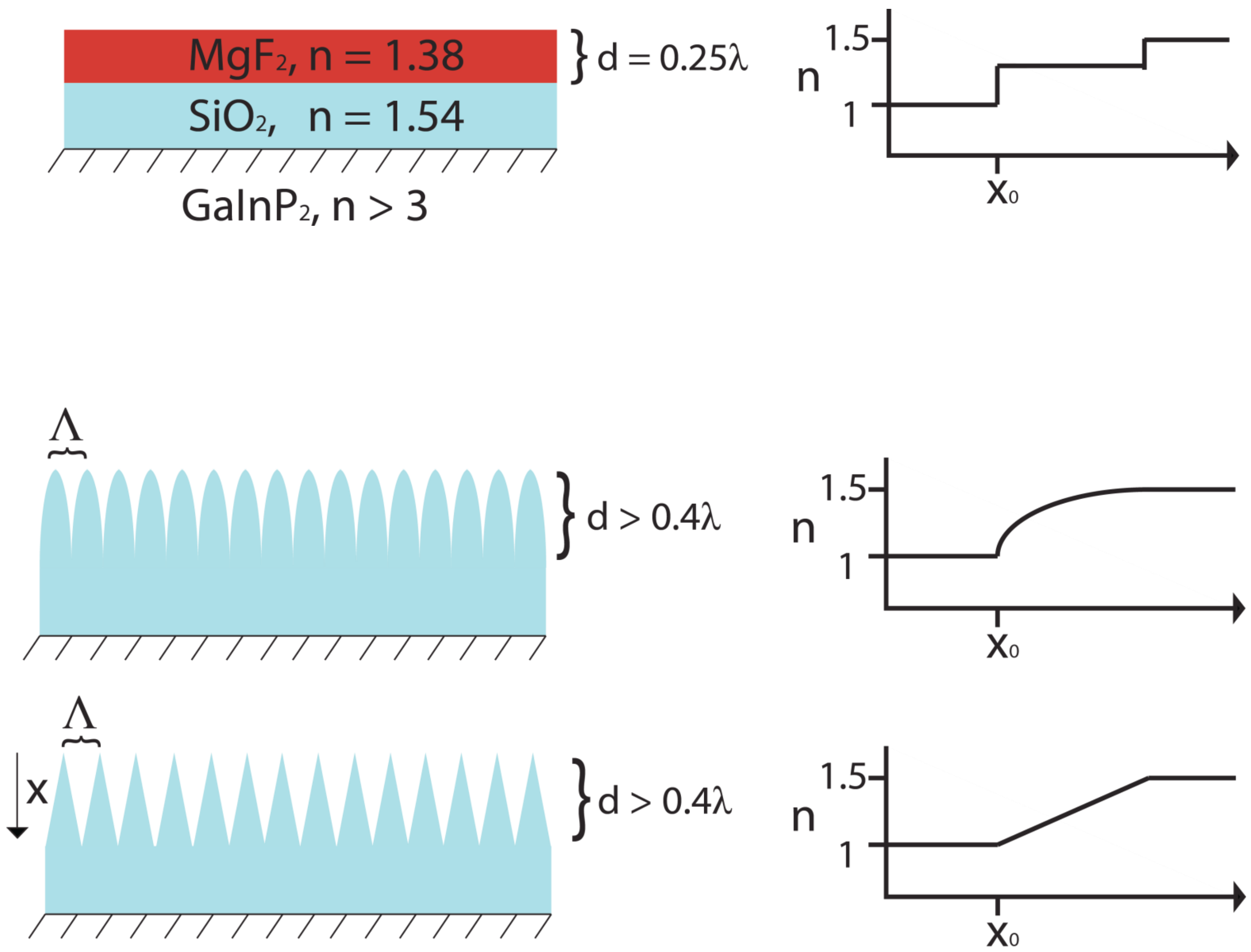
MEAR THEORY



- Components 180° out of phase
- Interference reduces impedance

- Infinite boundaries → Infinite reflections
- Infinite reflections → Total destructive interference

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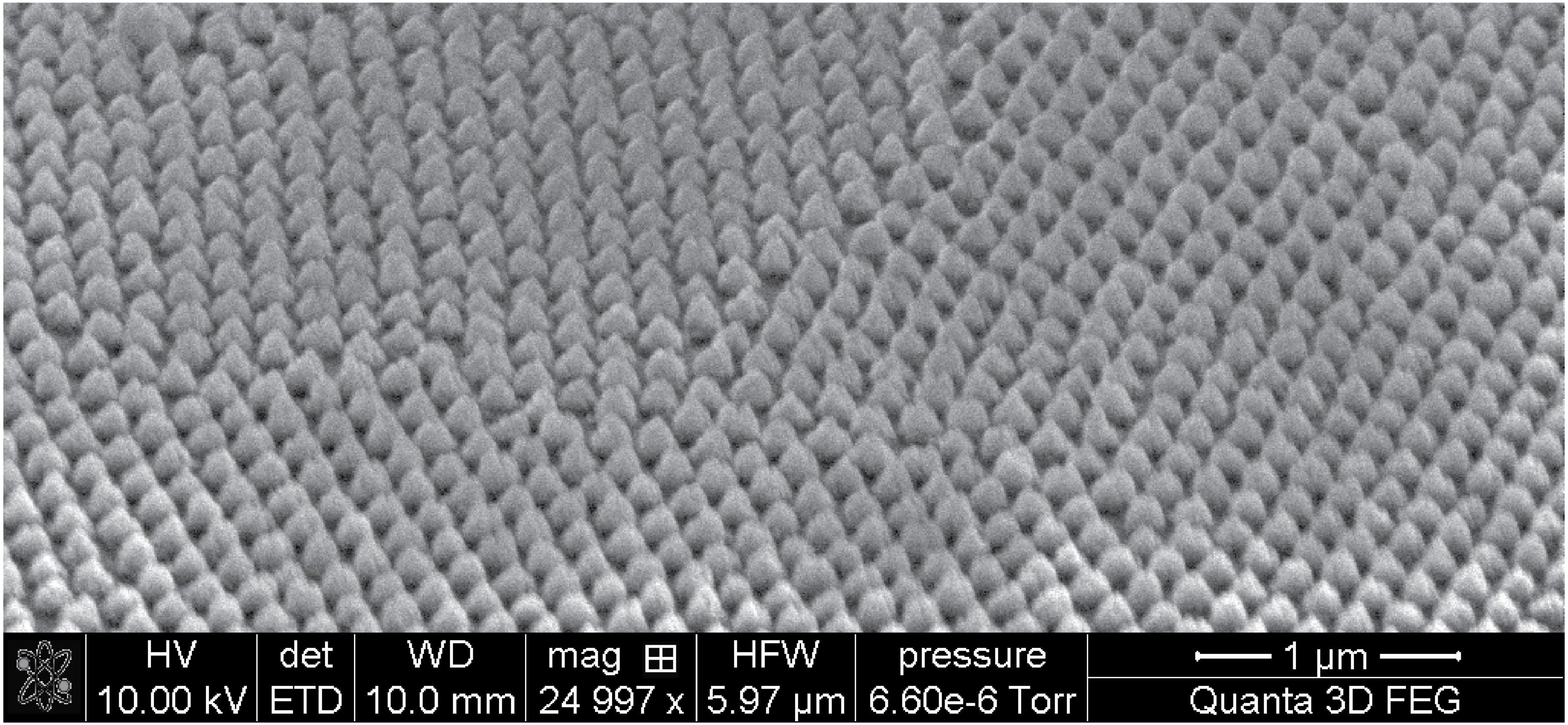
MEAR THEORY



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MEAR THEORY

- Nanostructured surfaces reduce reflection by subwavelength antireflection (MEAR-effect)

- MEAR conditions:
  - Maximum pitch: $\Lambda < \lambda_{min}/2n$
  - Minimum height: $h > 0.4\,\lambda_{max}$

- Profile is important: index changes as a function of the fill factor.
  - "Klopfenstein tapers" (5-th order poly, sine curve) are ideal but not necessary provided index is graded

- MEAR surfaces provide strong antireflection even at high incidence

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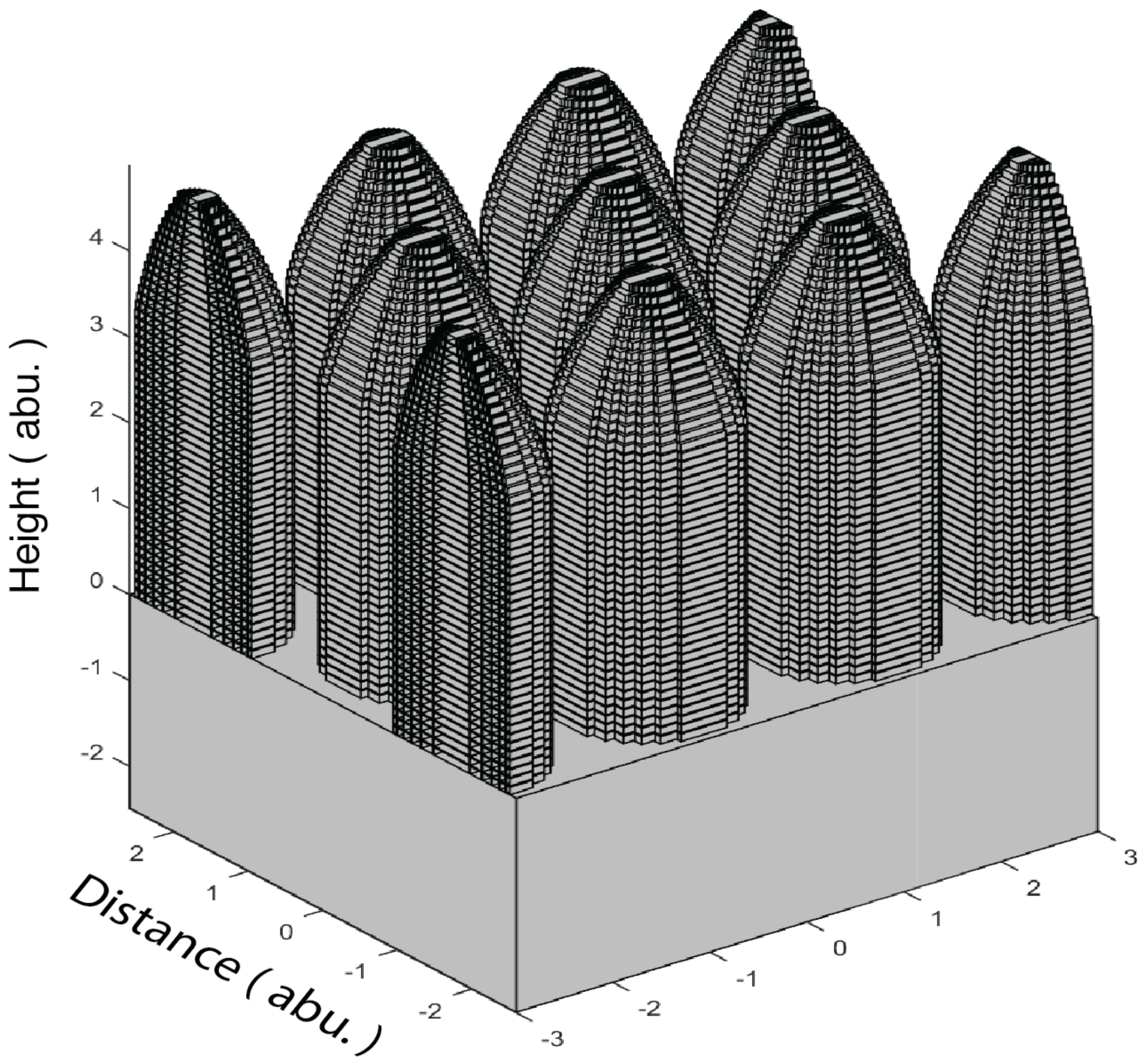
MOTH EYE DESIGN



- Simulate transmission using Rigorous Coupled Wave Analysis (RCWA)
  - GD-CALC, MPB, S^4
- Determine transmittance
- Convolve with EQE & Spectra, integrate across wavelength to get $P(\theta)$
- Comparison with attitude data yields power production

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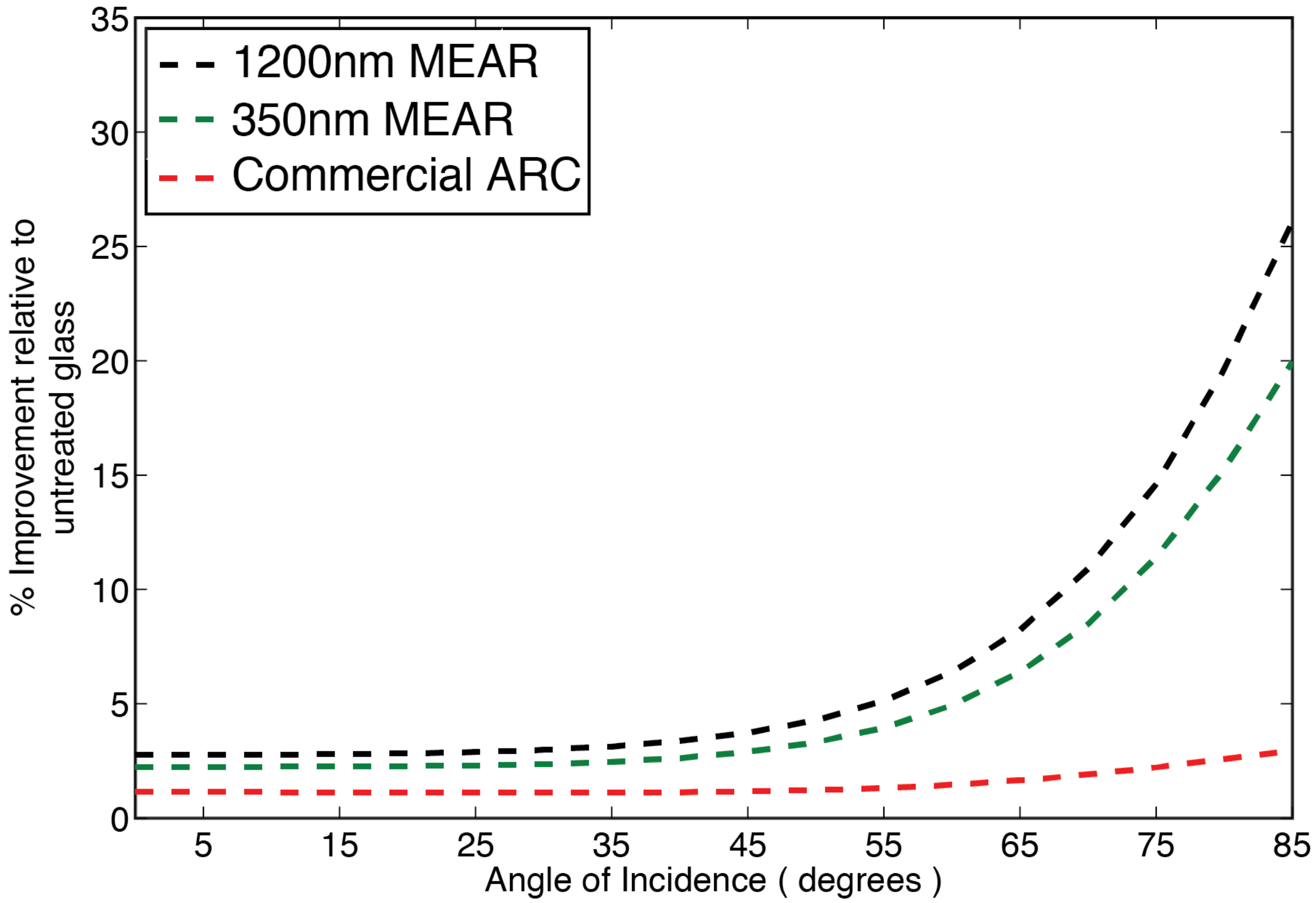
MOTH EYE DESIGN



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MOTH EYE FABRICATION OBJECTIVES

- Feature height,
  - EMT-TMM suggests diminishing returns at h > 500nm
  - RCWA optimization gives h = 1204nm

- Spacing Λ < 150nm

- Pyramidal or 5th order polynomial profile

REALITY

- Feature height, spacing and profile highly dependent on fabrication process

- "You can't coat a CubeSat in gold."

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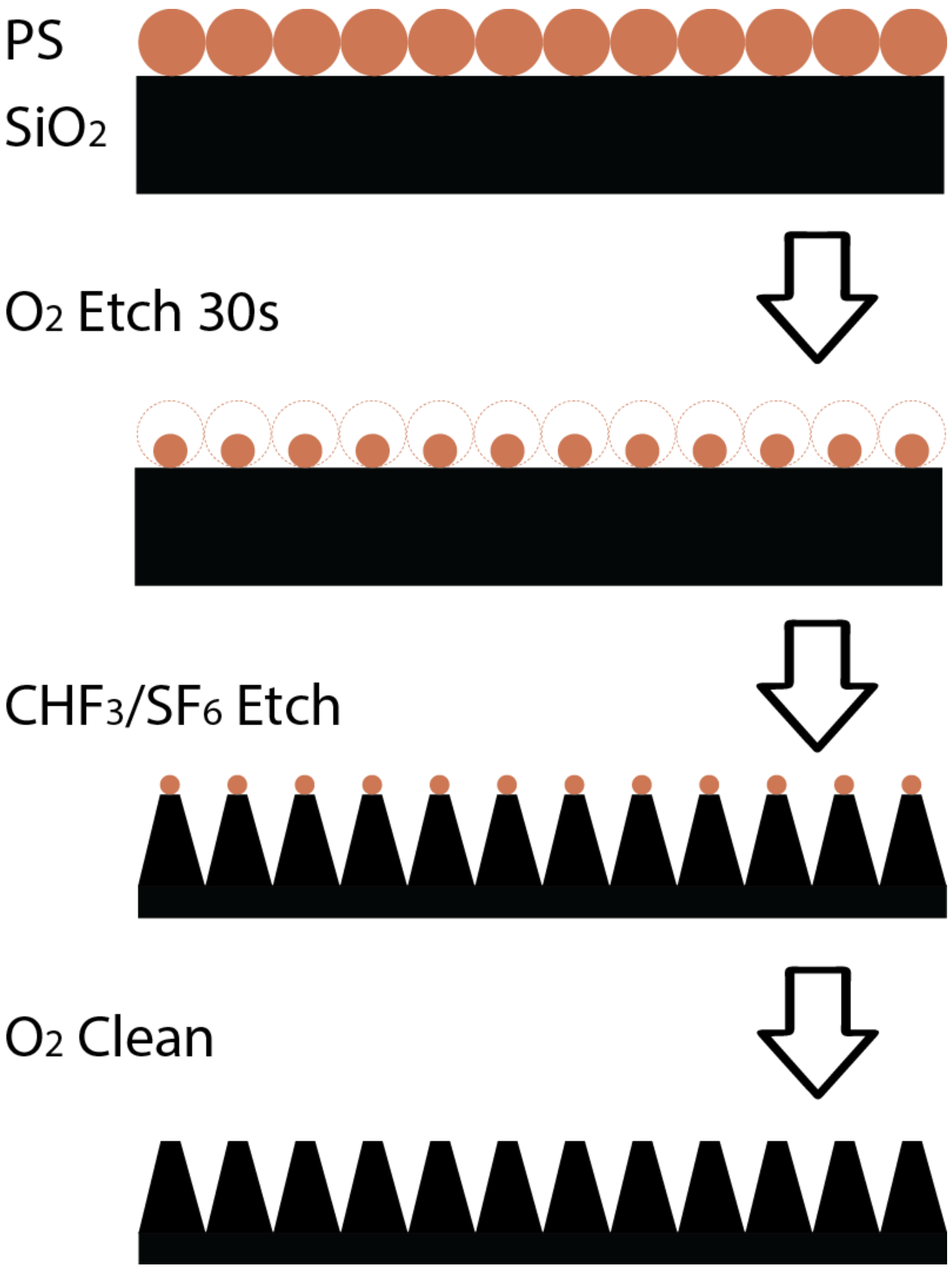
MOTH EYE FABRICATION



- Nanosphere Lithography (NSL)
- Assembly of etch mask by colloidal self-assembly
- RIE in CHF3/SF6 Plasma
- Etch mask made of PS Nanospheres
- Cheap & Simple, produces aspect ratio 5:1

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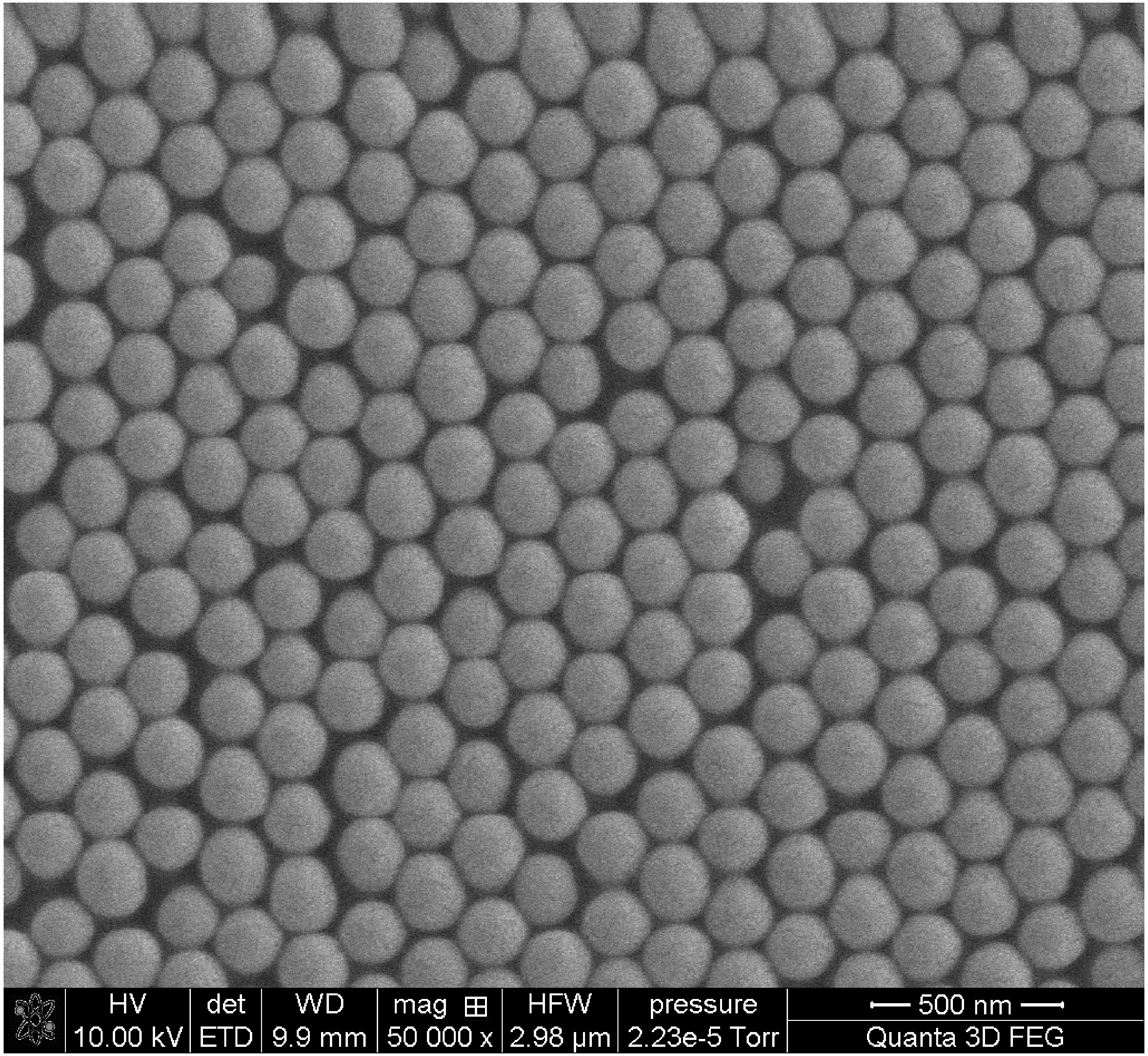
NANOSPHERE LITHOGRAPHY



- Produces monolayer in hexagonally close packed (HCP) configuration.
- Defects at small scale due to particle size.

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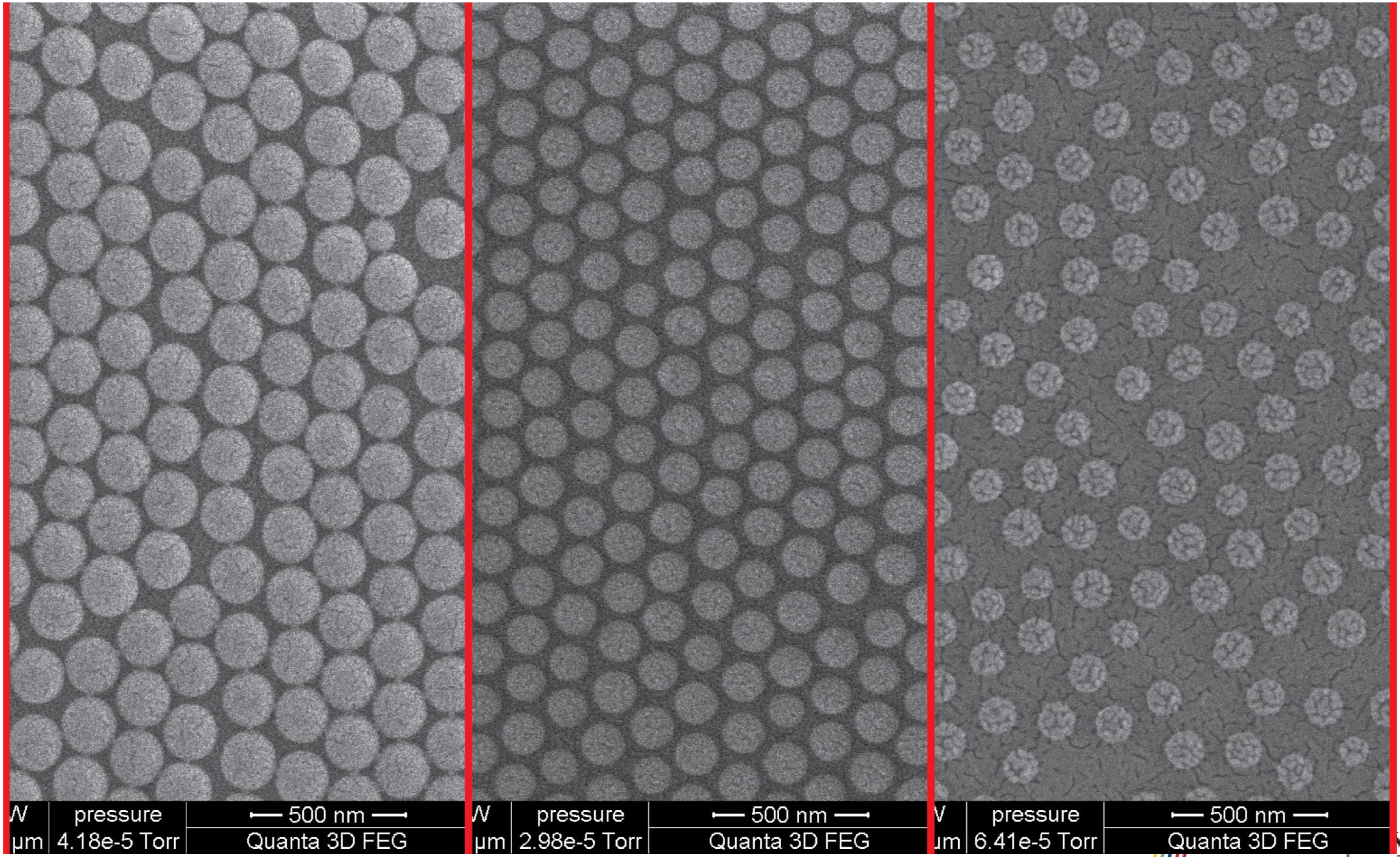
SIZE REDUCTION



15s, 30s, 45s

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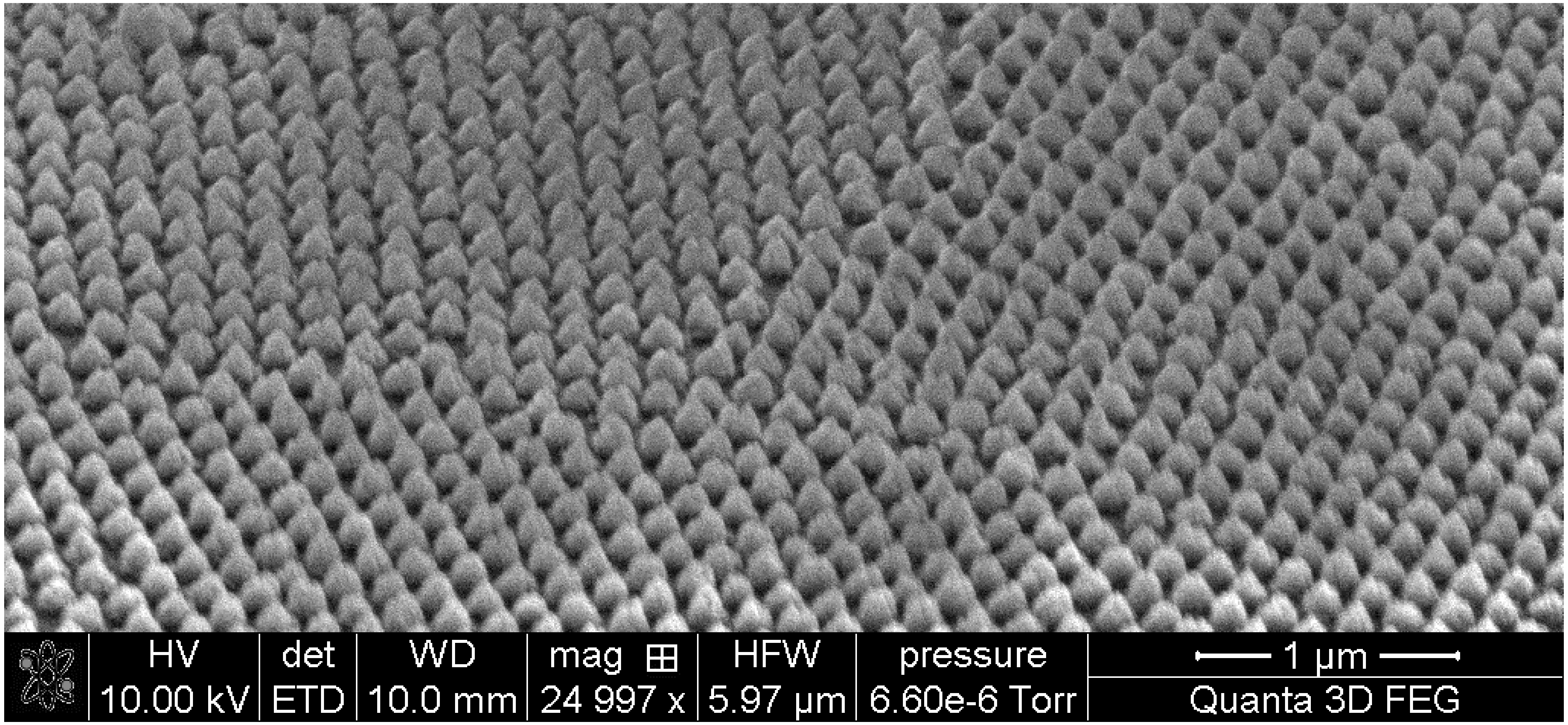
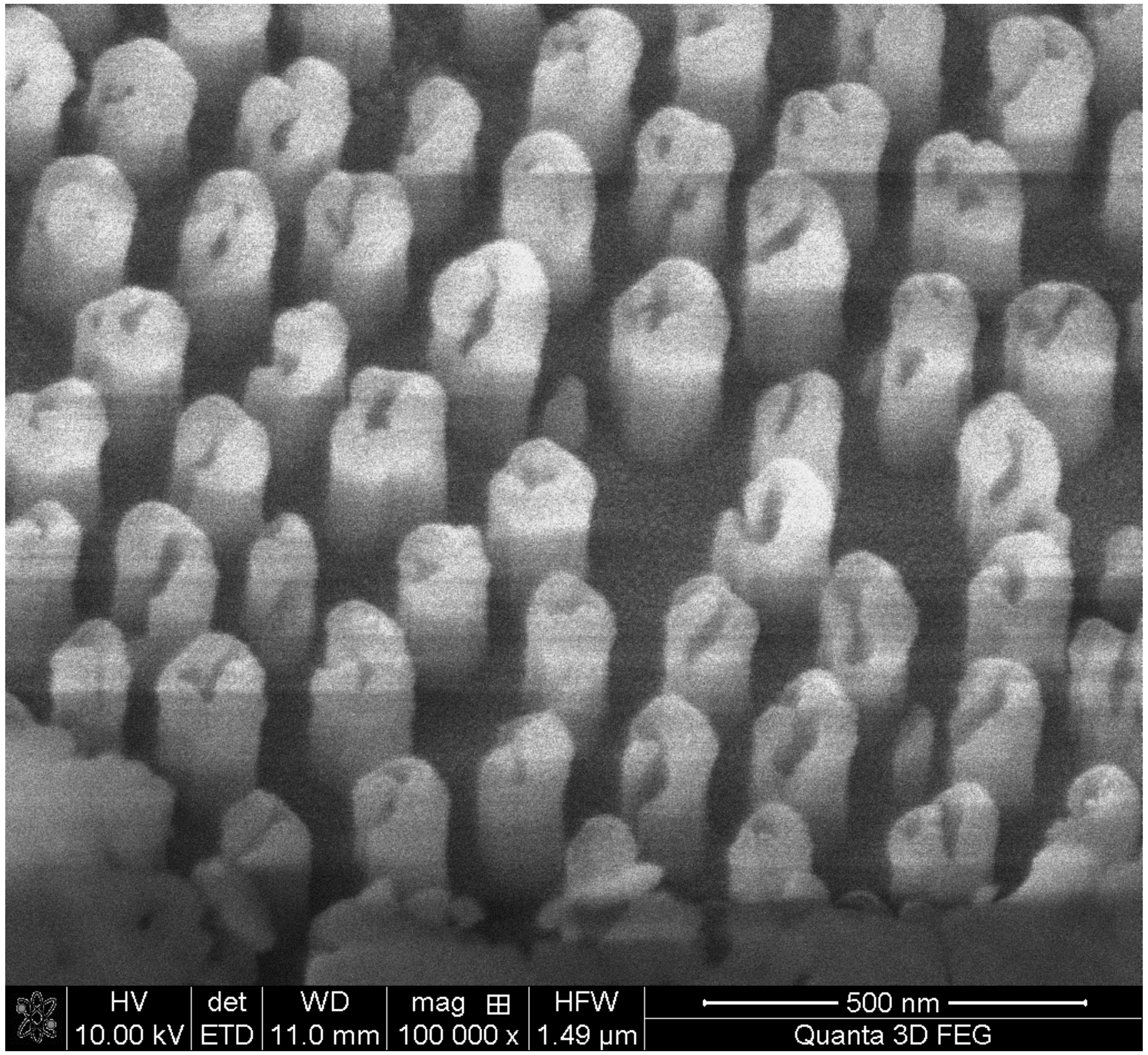
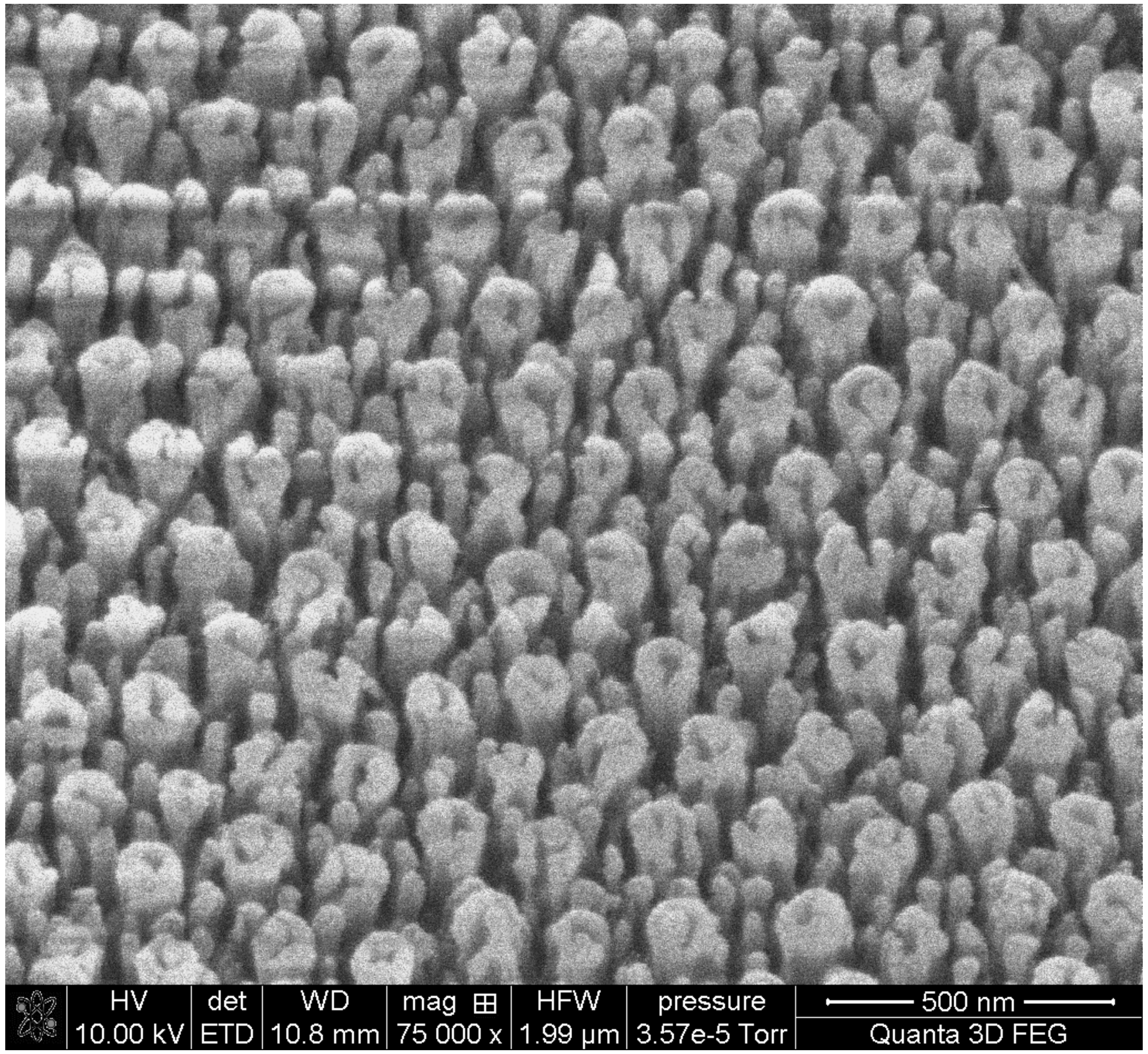
RIE ETCHING



- Previously obtained well-ordered structures, unable to achieve high aspect ratios

RIE ETCHING





- More recently obtained higher aspect ratio structures.
- Structures ordered with inter-particle columns

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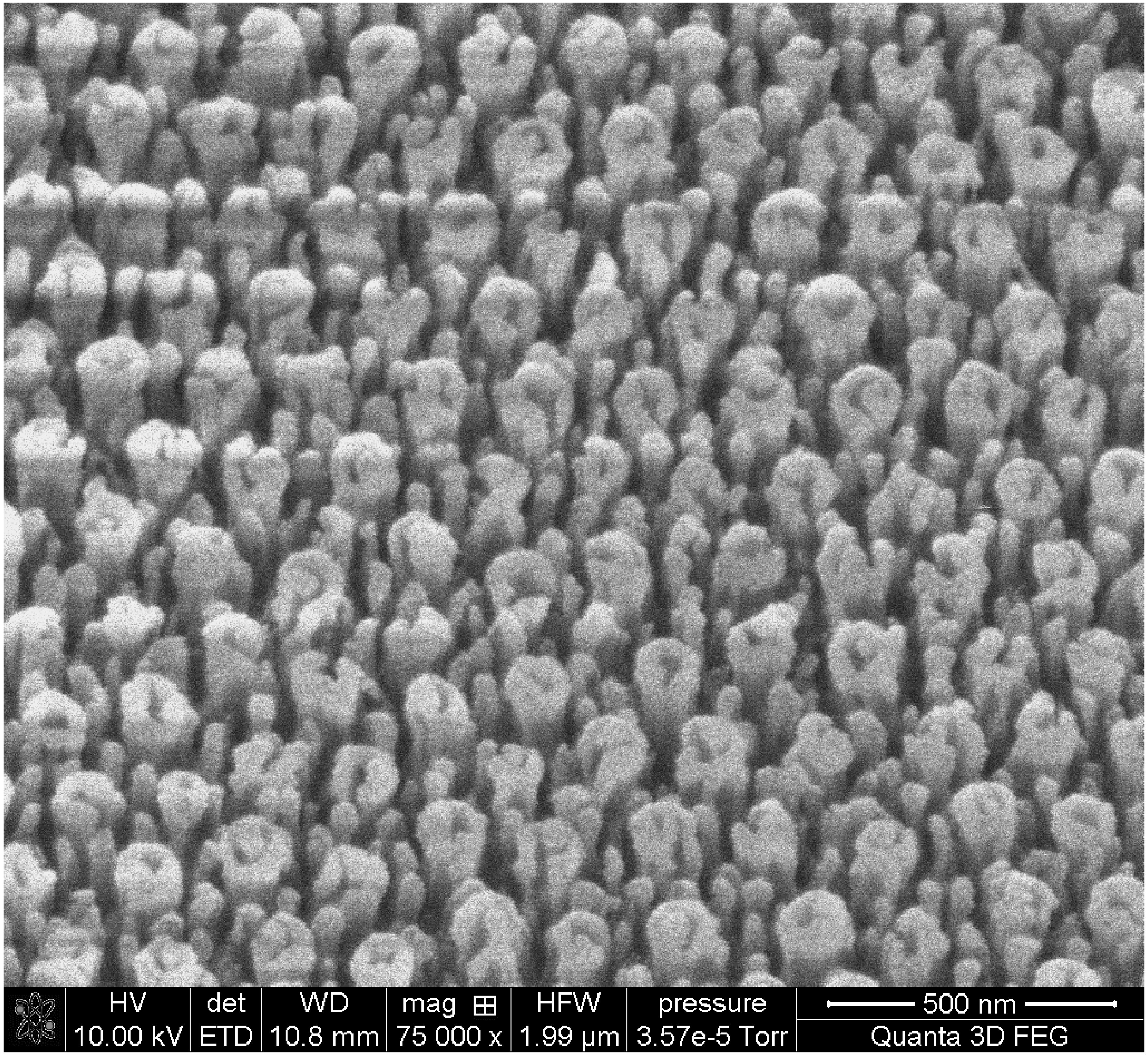
RIE ETCHING



- Inter-particle structures the result of micromasking
- “RIE-Grass” or Glass grass
- MEAR structures with no mask?

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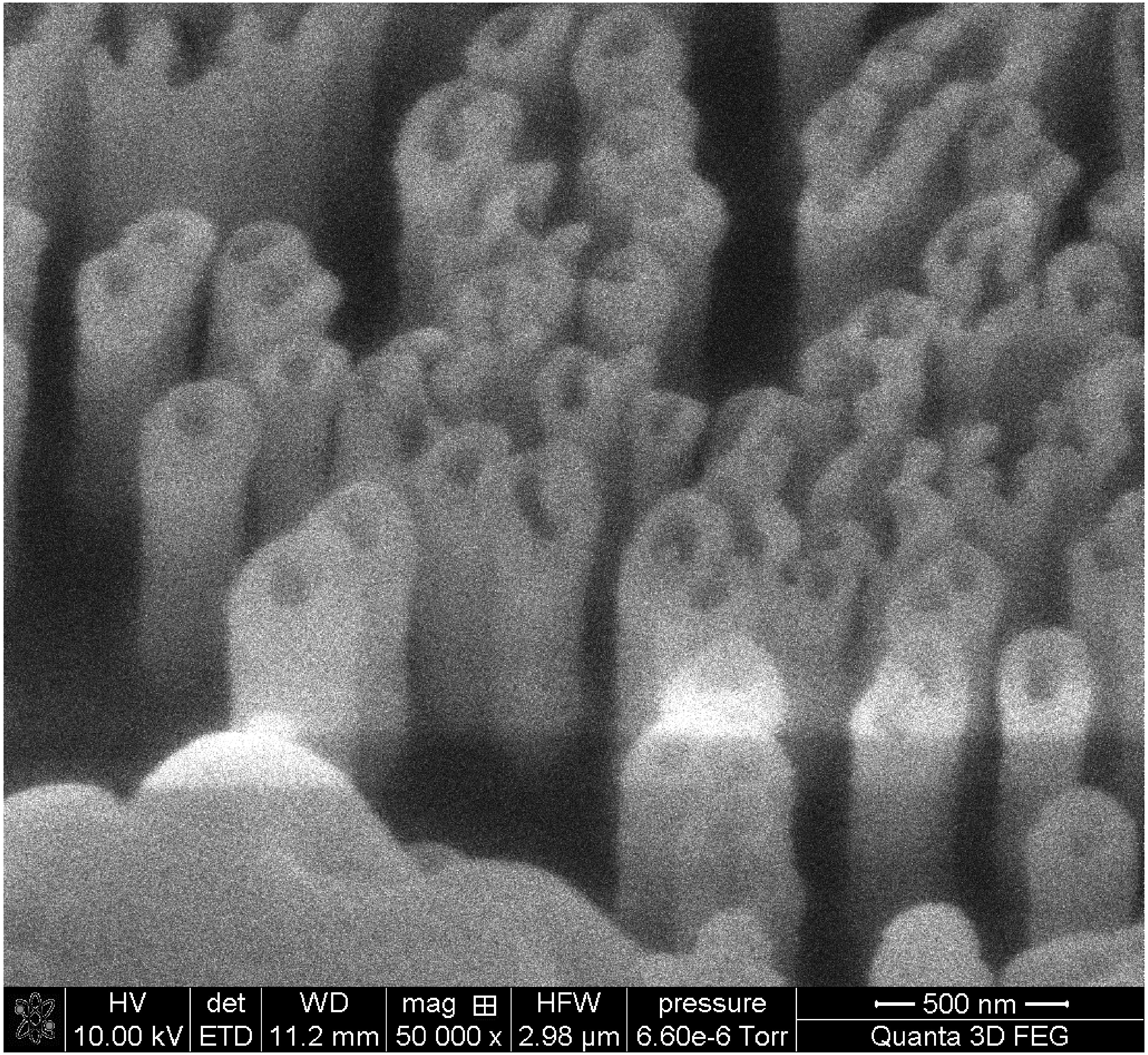
RIE ETCHING



- 1177nm height
- Spacing 130nm
- Tube-like appearance consistent with literature
- Do these structures exhibit MEAR?

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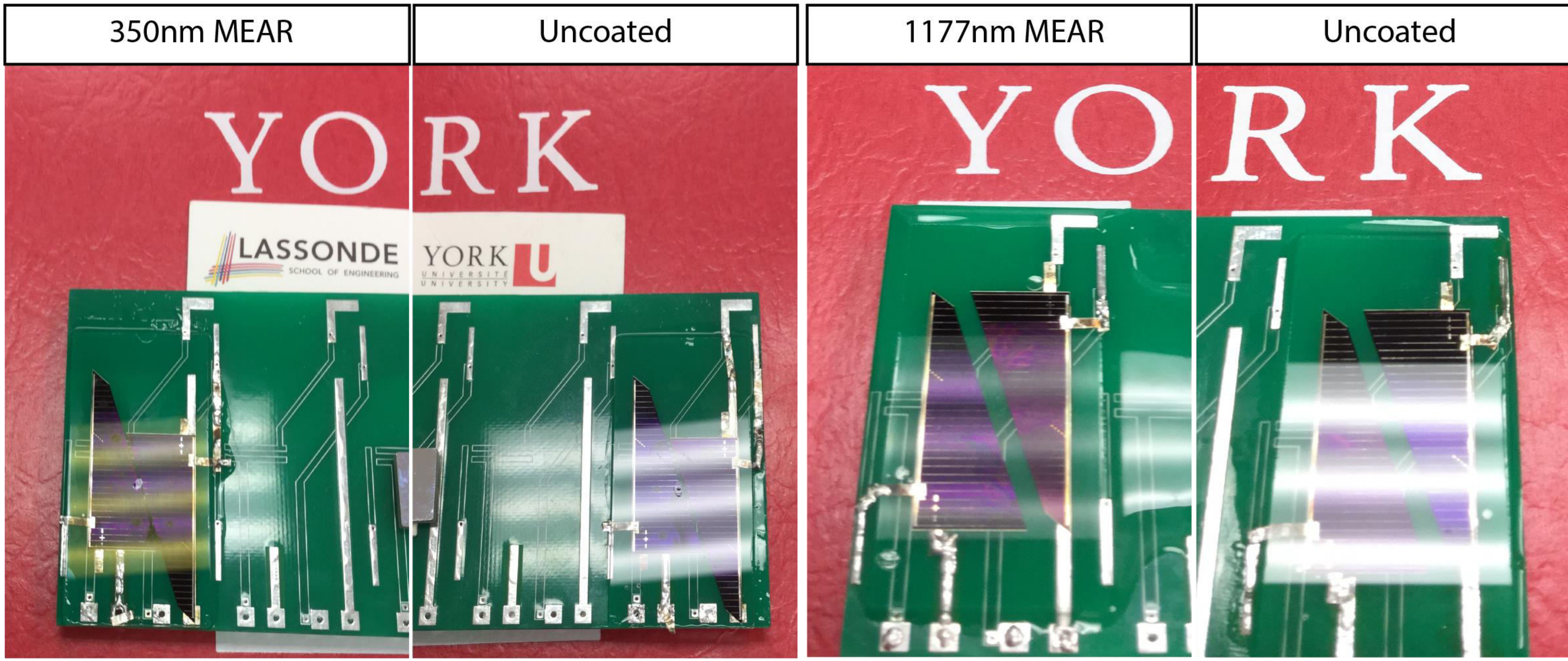
TESTING AND CHARACTERIZATION



- Left – NSL Fabrication
- Right – Maskless, single step fabrication

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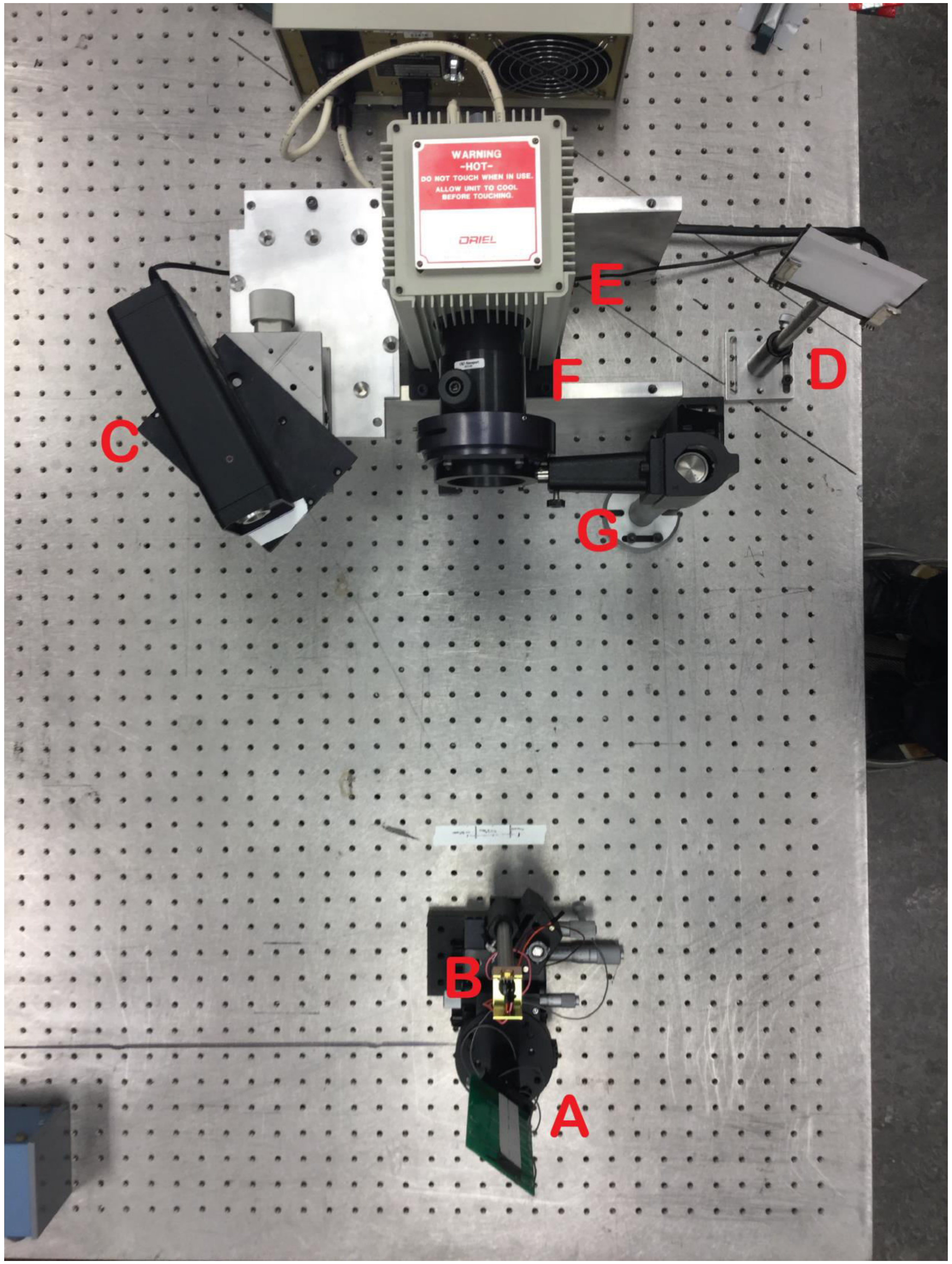
TESTING AND CHARACTERIZATION



A) Solar cell panel on rotator & translators.

B) Beam power sensor

C) Alignment laser

D) Imaging screen

E) 75W Xenon arc lamp

F) 33mm diameter collimator

G) Shutter

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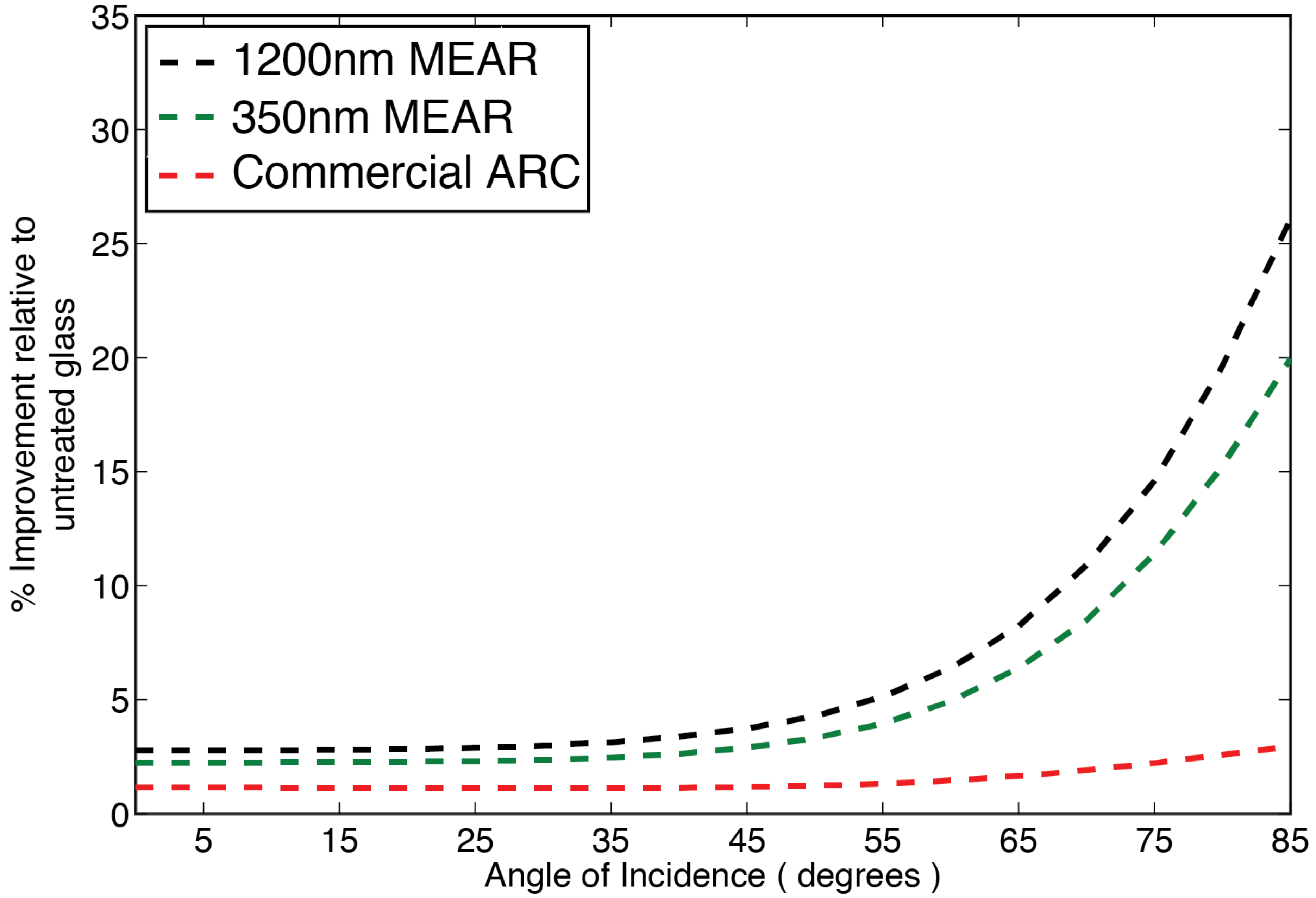
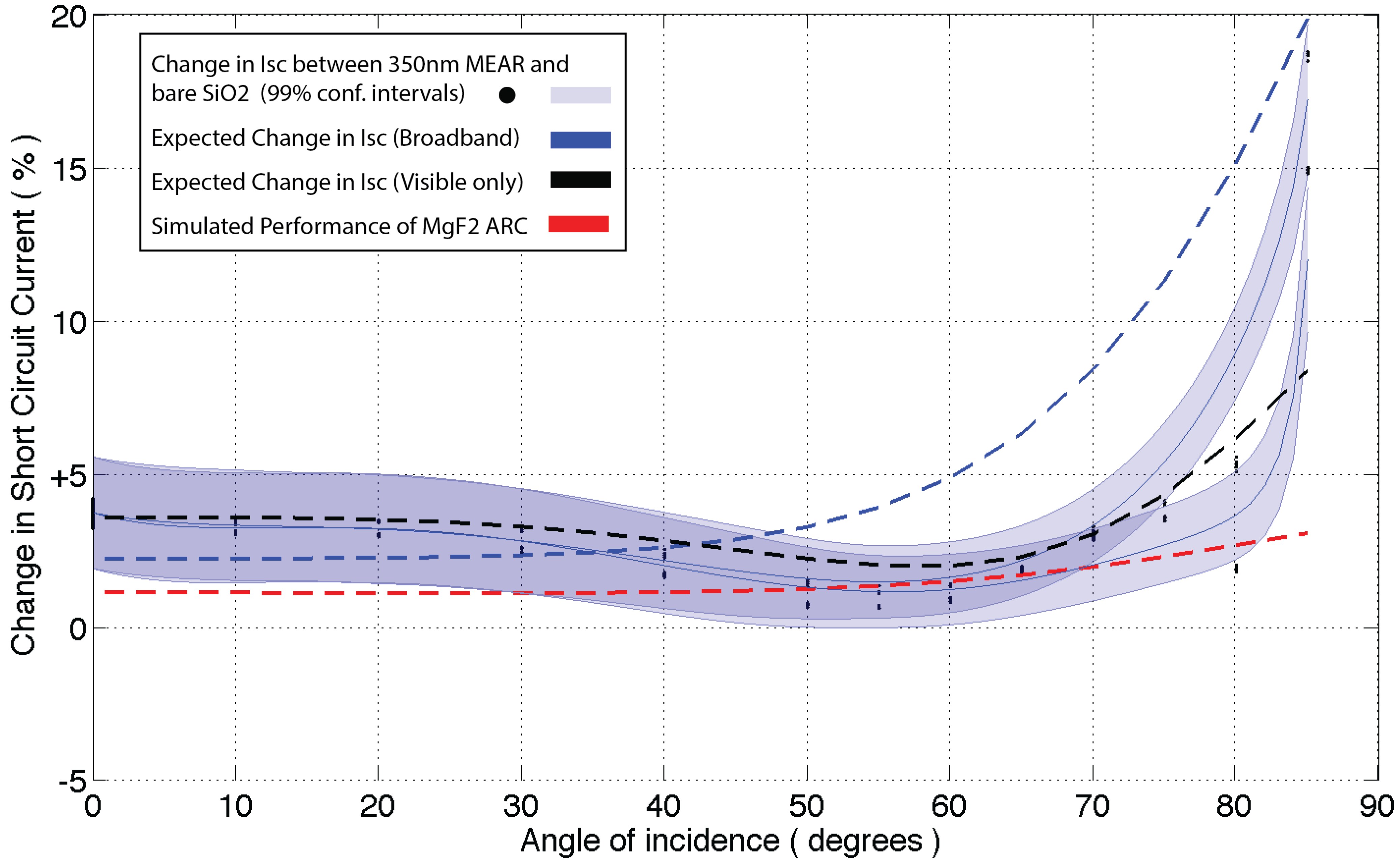
TESTING AND CHARACTERIZATION

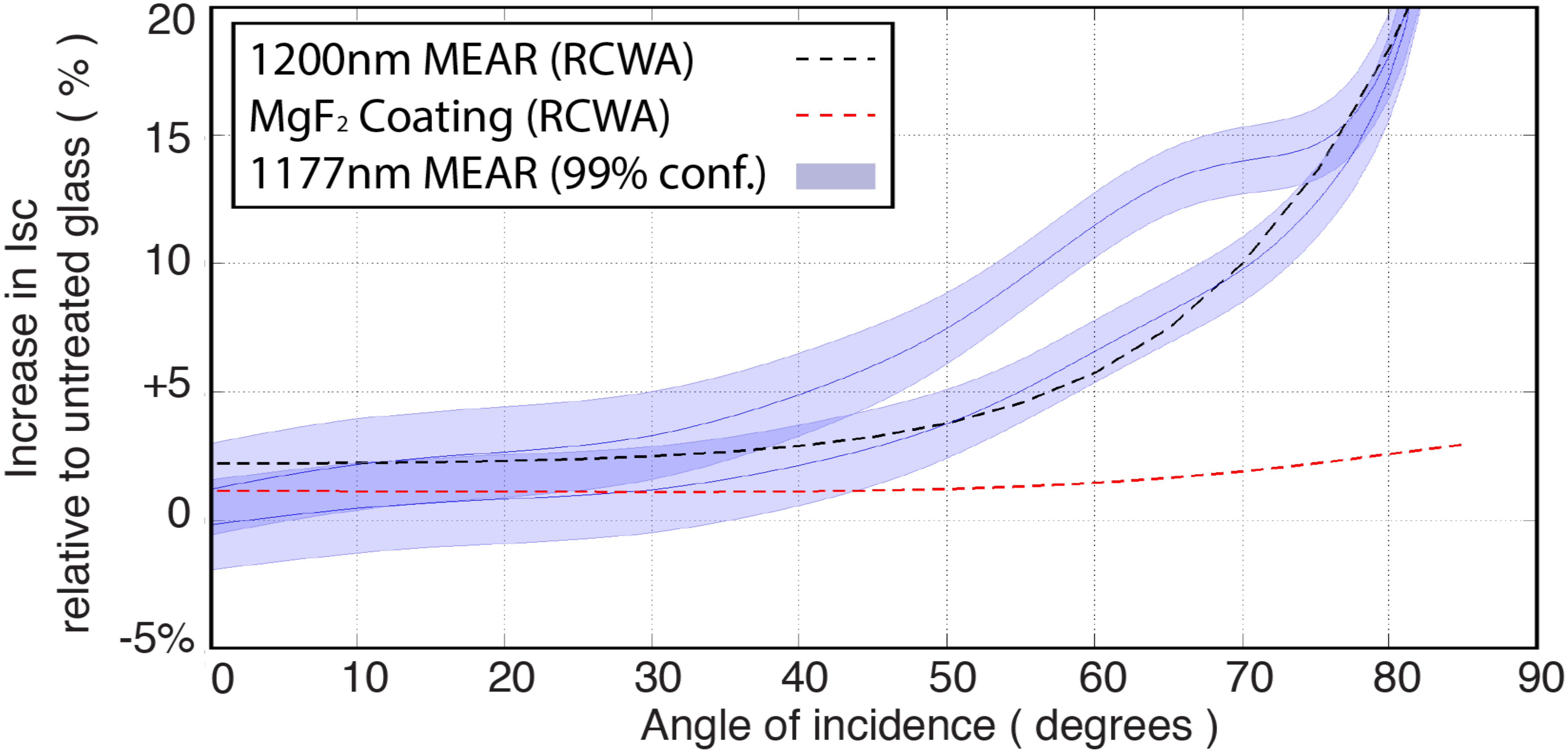


TESTING AND CHARACTERIZATION



- 350nm MEAR shows poor improvement, esp. at high incidence, poor AR in infrared due to low height

TESTING AND CHARACTERIZATION



- 1177nm MEAR shows significant improvement at high incidence, well beyond commercial ARC

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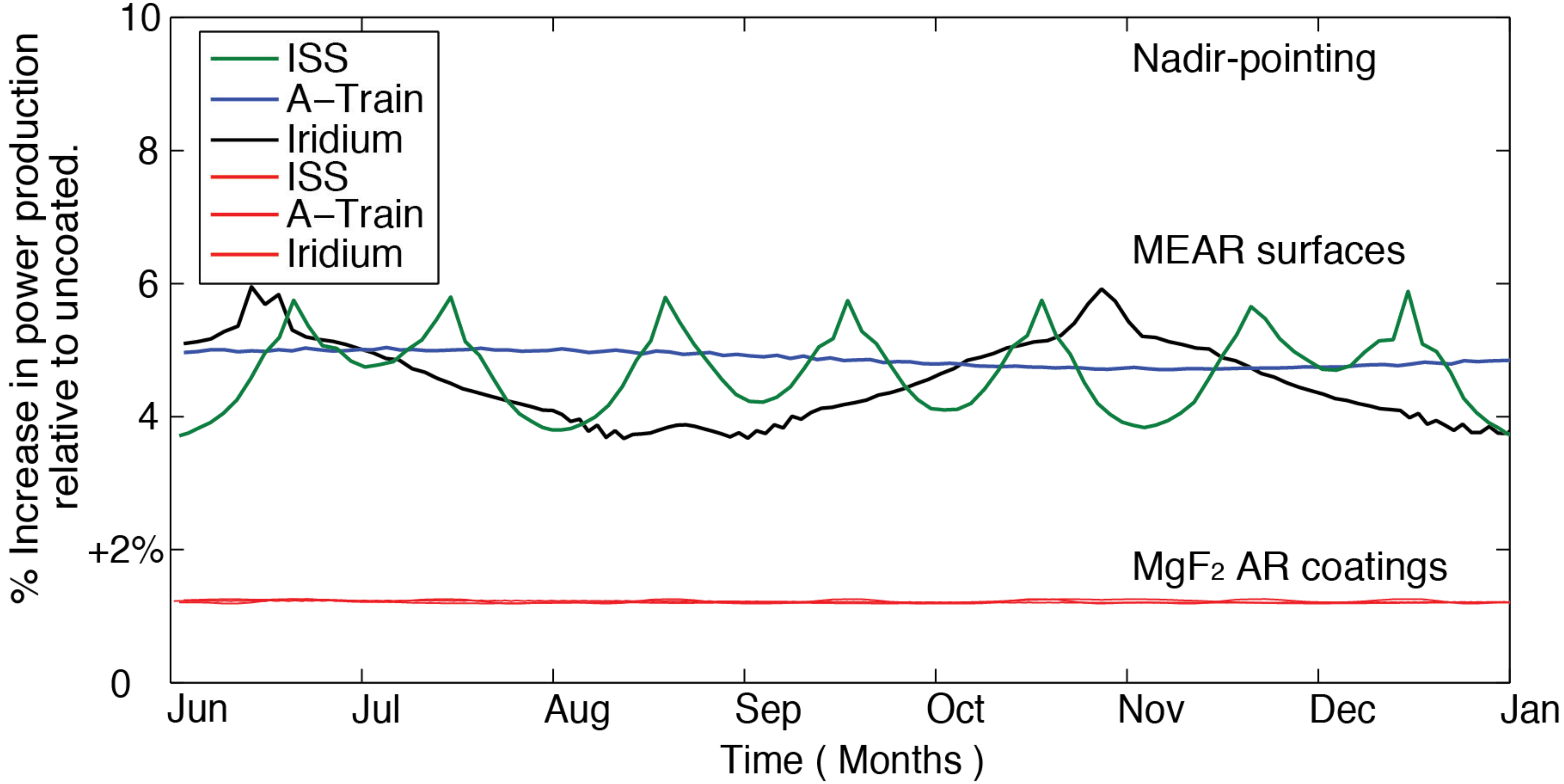
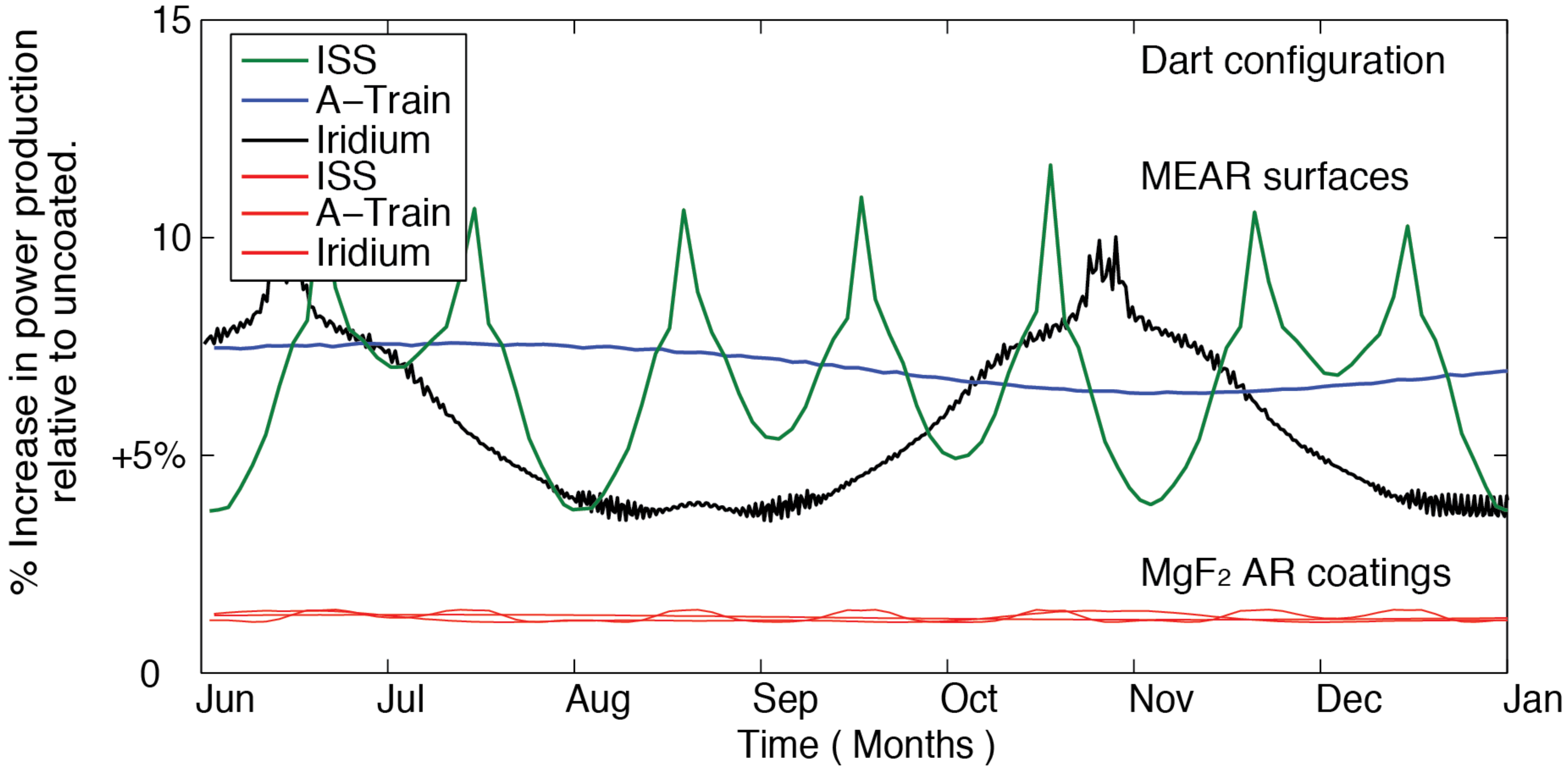
TESTING AND CHARACTERIZATION



Orbit	Mean	Maximum	Minimum
A-Train	4.9%	5.0%	4.7%
Iridium	4.5%	6.0%	3.7%
ISS	4.6%	5.9%	3.7%
A-Train (MgF_2)	1.2%	1.2%	1.2%
Iridium (MgF_2)	1.2%	1.3%	1.2%
ISS (MgF_2)	1.2%	1.3%	1.2%

TESTING AND CHARACTERIZATION



Orbit	Mean	Maximum	Minimum
A-Train	7.0%	7.6%	6.4%
Iridium	5.5%	9.4%	3.7%
ISS	6.5%	11.7%	3.7%
A-Train (MgF_2)	1.3%	1.3%	1.2%
Iridium (MgF_2)	1.2%	1.4%	1.2%
ISS (MgF_2)	1.3%	1.5%	1.2%

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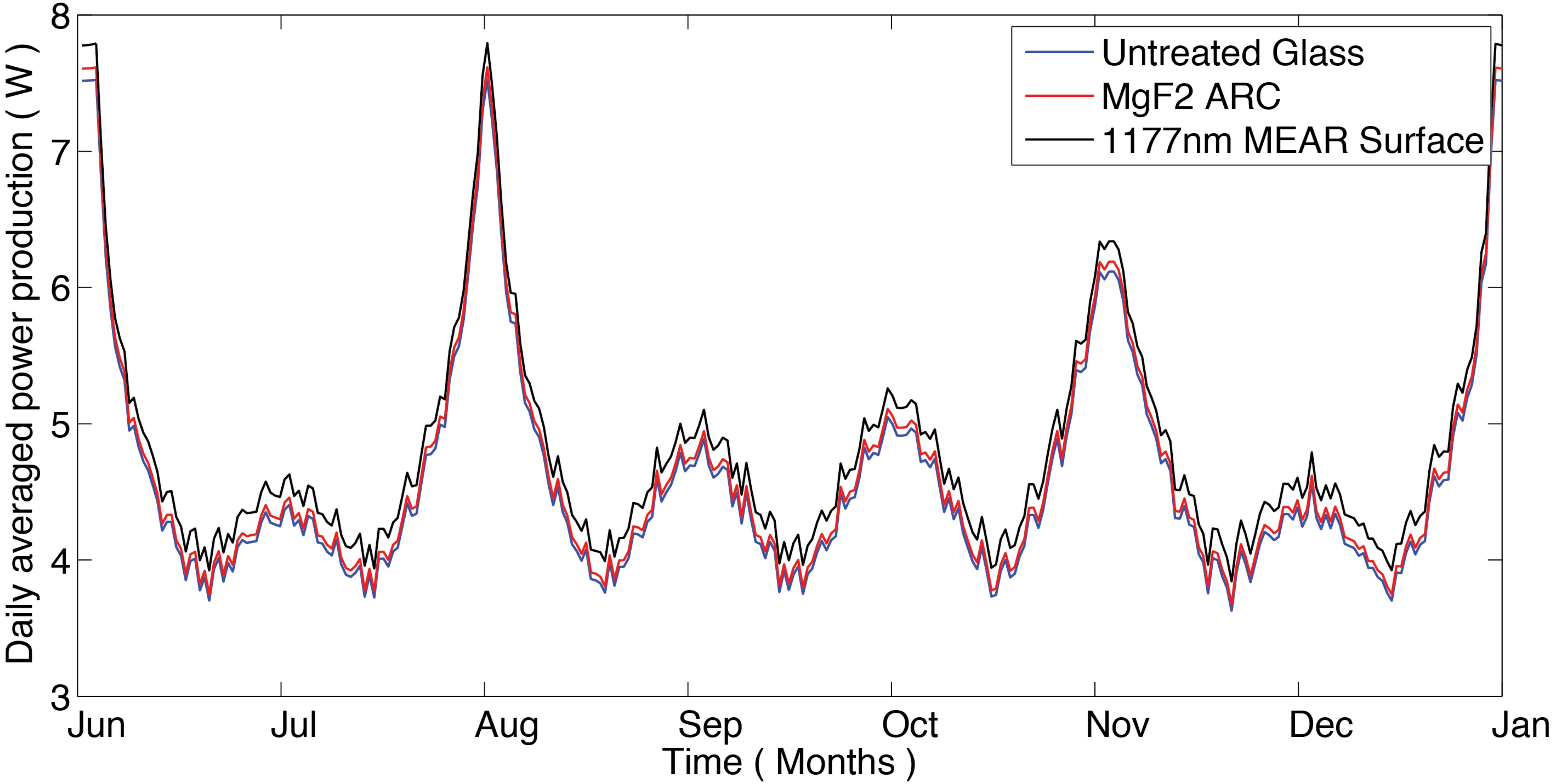
TESTING AND CHARACTERIZATION



- Equivalent to an extra 3.5-4.0W h / day
- Effect is enhanced during low-illumination

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RESULTS

Orbit	Mean	Maximum	Minimum
	1177nm MEAR Surfaces		
A-Train	4.9%	5.0%	4.7%
Iridium	4.5%	6.0%	3.7%
ISS	4.6%	5.9%	3.7%
A-Train - DART	7.0%	7.6%	6.4%
Iridium - DART	5.5%	9.4%	3.7%
ISS - DART	6.5%	11.7%	3.7%
	MgF_2 AR Coatings		
A-Train	1.2%	1.2%	1.2%
Iridium	1.2%	1.3%	1.2%
ISS	1.2%	1.3%	1.2%
A-Train – DART	1.3%	1.3%	1.2%
Iridium – DART	1.2%	1.4%	1.2%
ISS – DART	1.3%	1.5%	1.2%

- 3.5-4.0W h / day
- Effect enhanced during low light
- MEAR surfaces realized in single step fabrication

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SUMMARY & CONCLUSIONS

- MEAR Surfaces for CubeSats designed using RCWA.
  - Ideal height found to be 1204.1nm, pitch <150nm
- MEAR Surfaces fabricated by NSL and single-step "grass growth"
- MEAR Surfaces characterized in solar simulation environment
- Average expected power increase on orbit 4.7% for Nadir pointing, 6.3% for Dart.
  - Equivalent to increasing base cell efficiency 28.3% → 30.1%

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FUTURE WORK

- Adapt fabrication procedure for CMO glass
  - MEAR effect is geometry based, similar AR expected
- Continue to investigate the effect of applying MEAR surface to rear of coverglass
- Design 1-U test panel to fly as hosted payload
- Investigate applications to micro-rovers

ACKNOWLEDGEMENTS

CENTRE FOR RESEARCH IN
EARTH AND SPACE SCIENCE

NSERC
CRSNG

TNFC

CANADENSYS

- Research assistant & microfabrication trainee Juan Guzman

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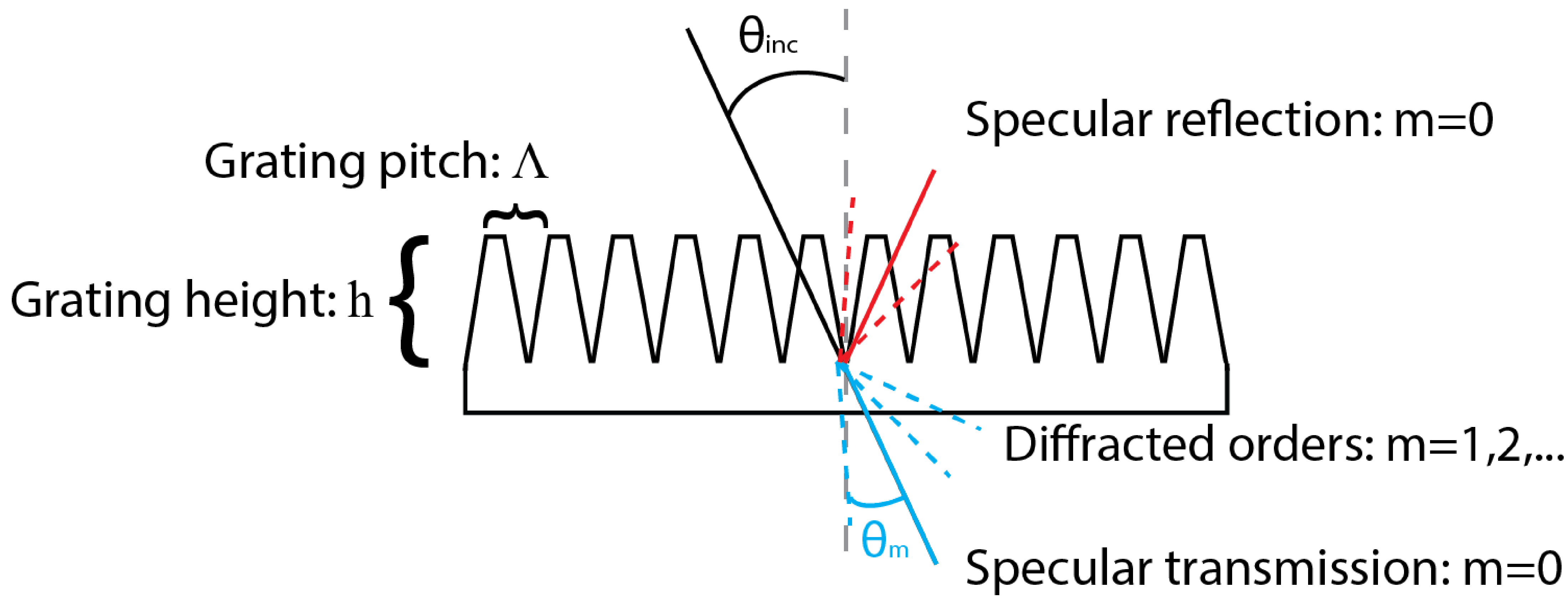
SUPPLEMENTAL: MEAR THEORY



$$\theta_m = \arcsin\left(m\frac{\lambda}{n\Lambda} - \sin(\theta_i)\right)$$

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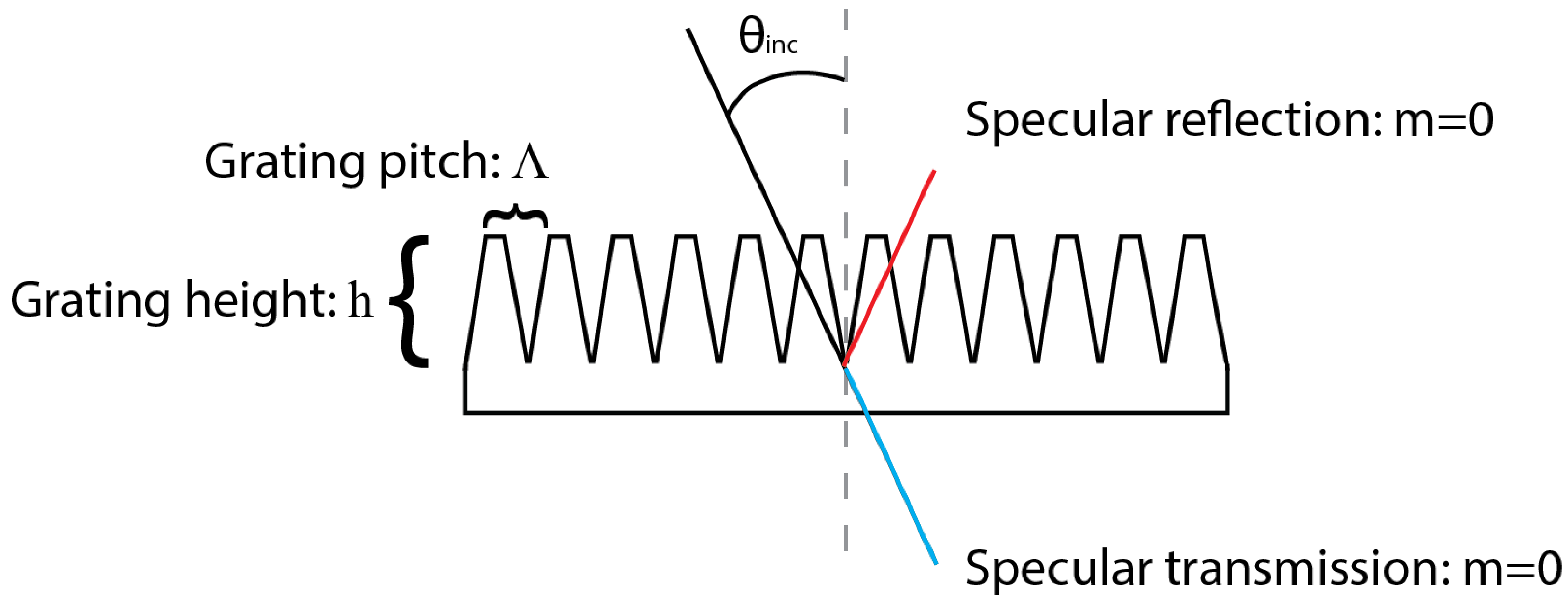
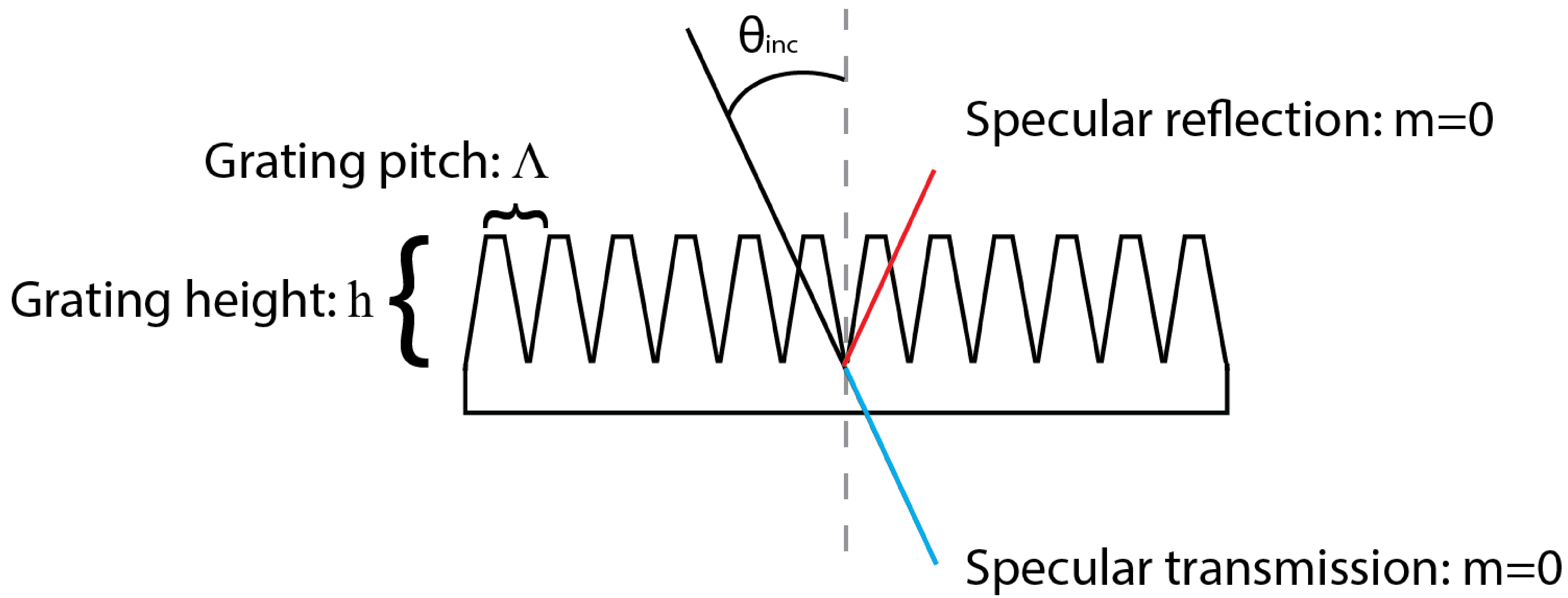
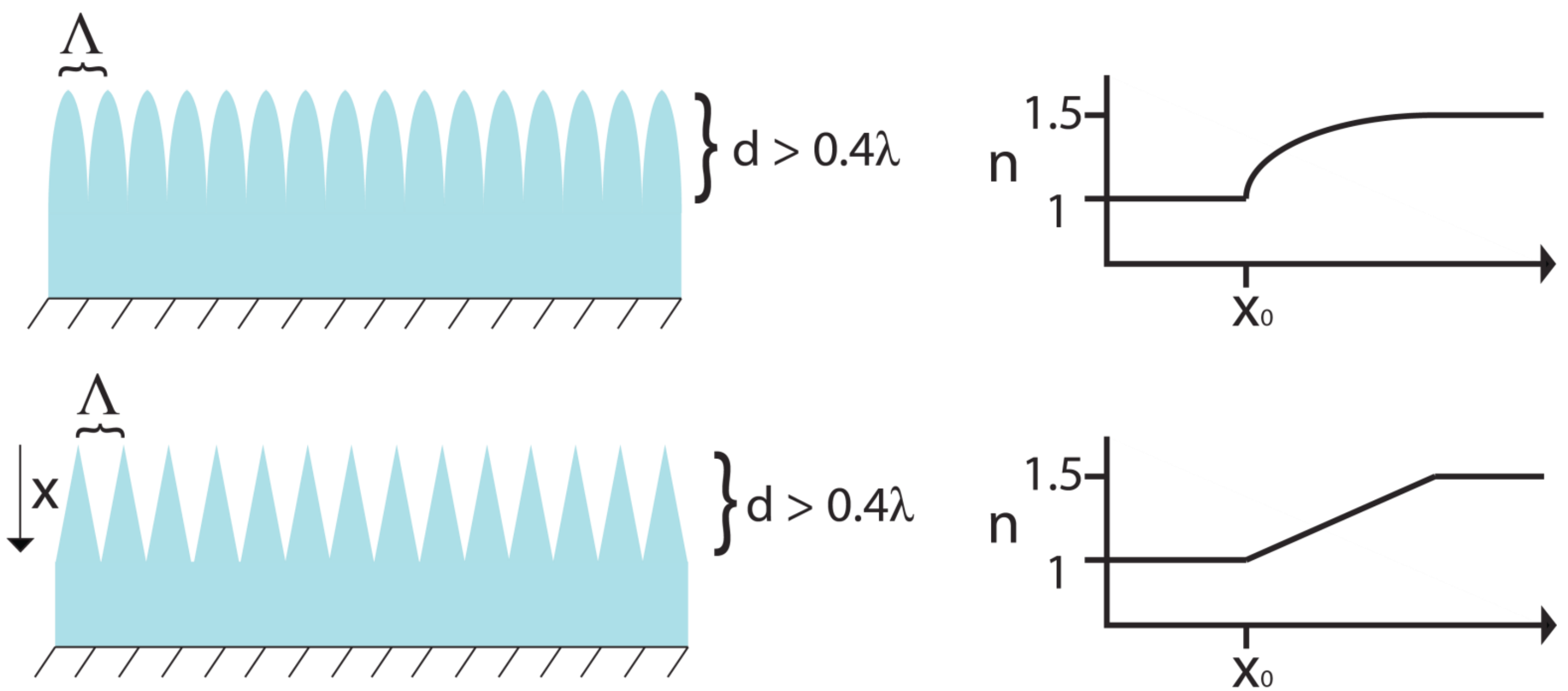
SUPPLEMENTAL: MEAR THEORY



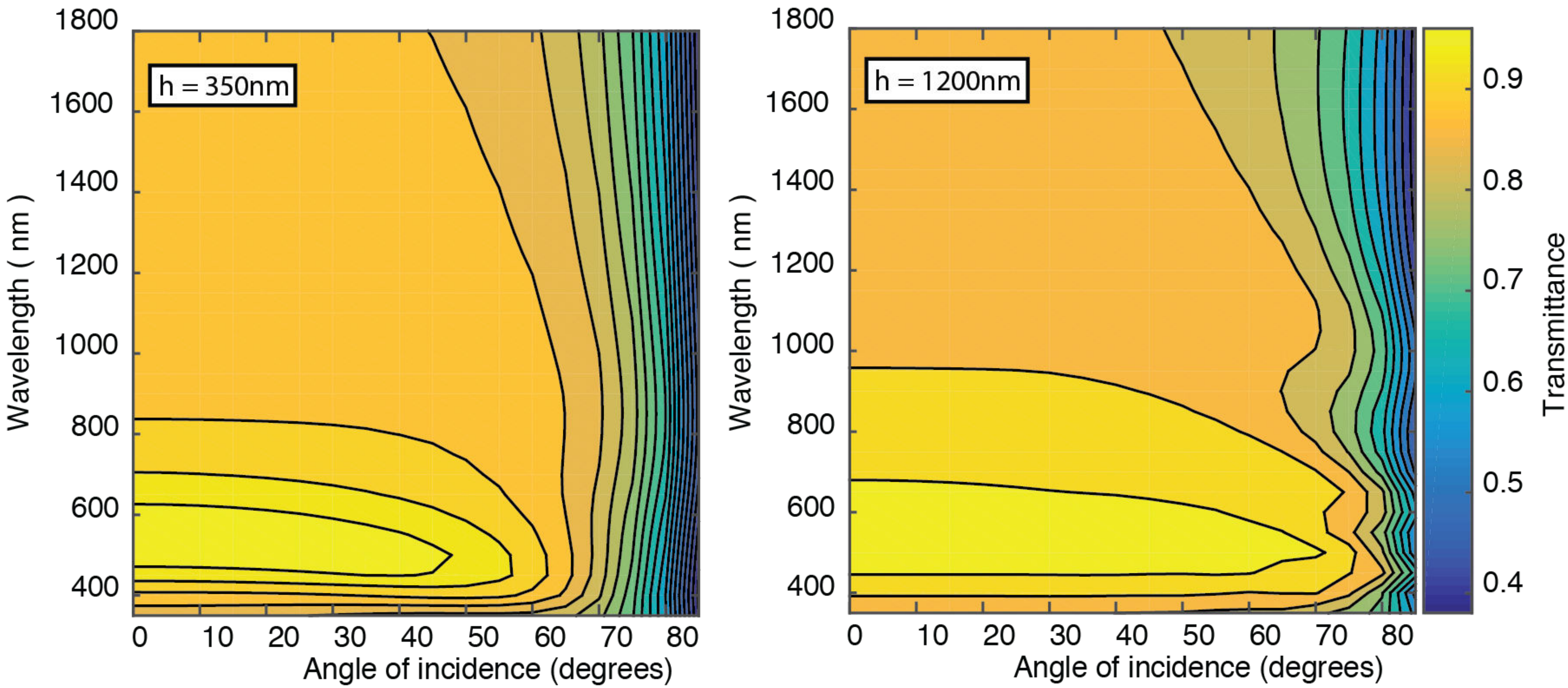
$$\theta_m = \arcsin\left(m\frac{\lambda}{n\Lambda} - \sin(\theta_i)\right)$$

SUPPLEMENTAL: MEAR THEORY





SUPPLEMENTAL: MOTH EYE DESIGN



- Height is most "free" parameter
- Pitch is limited by subwavelength condition

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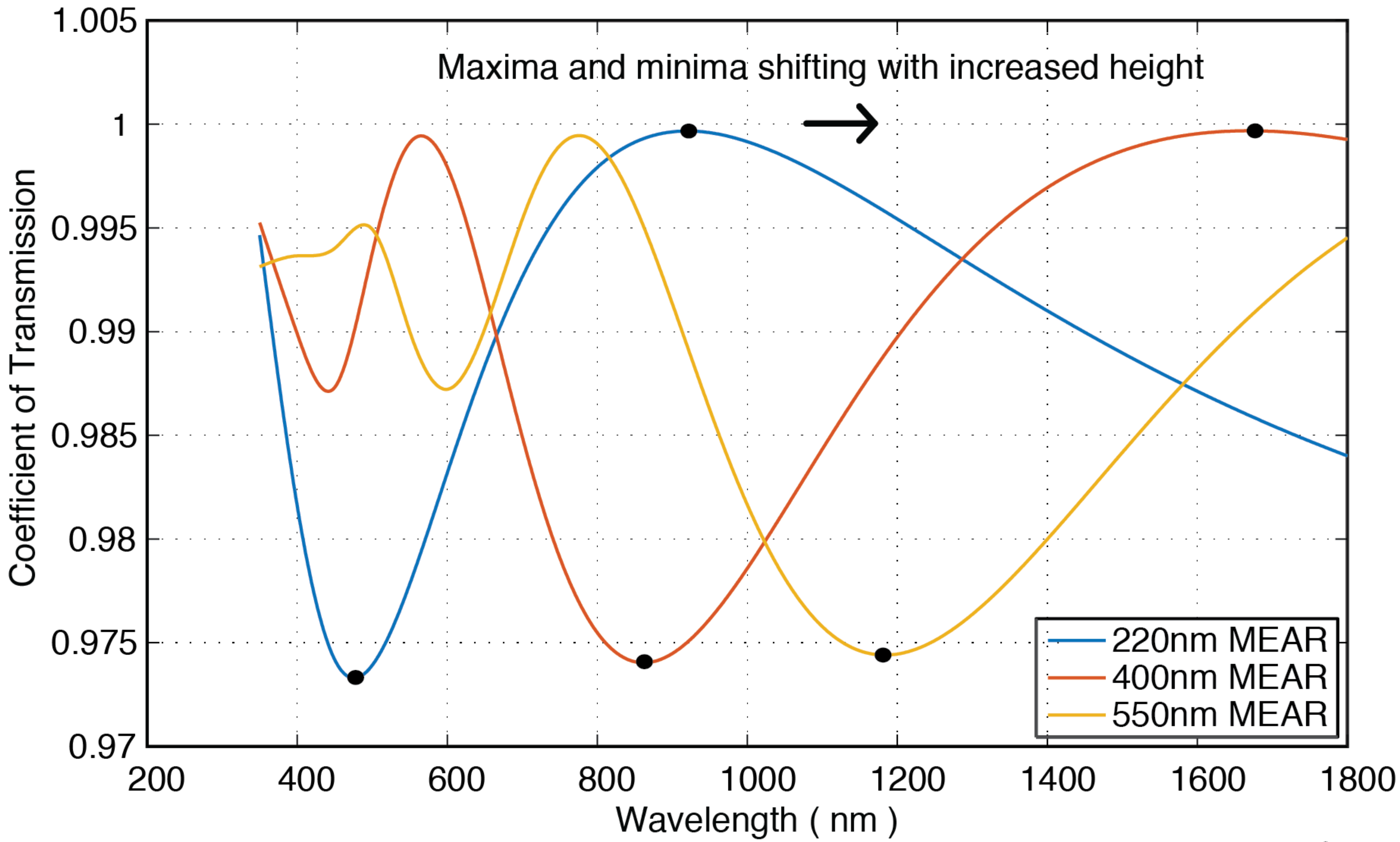

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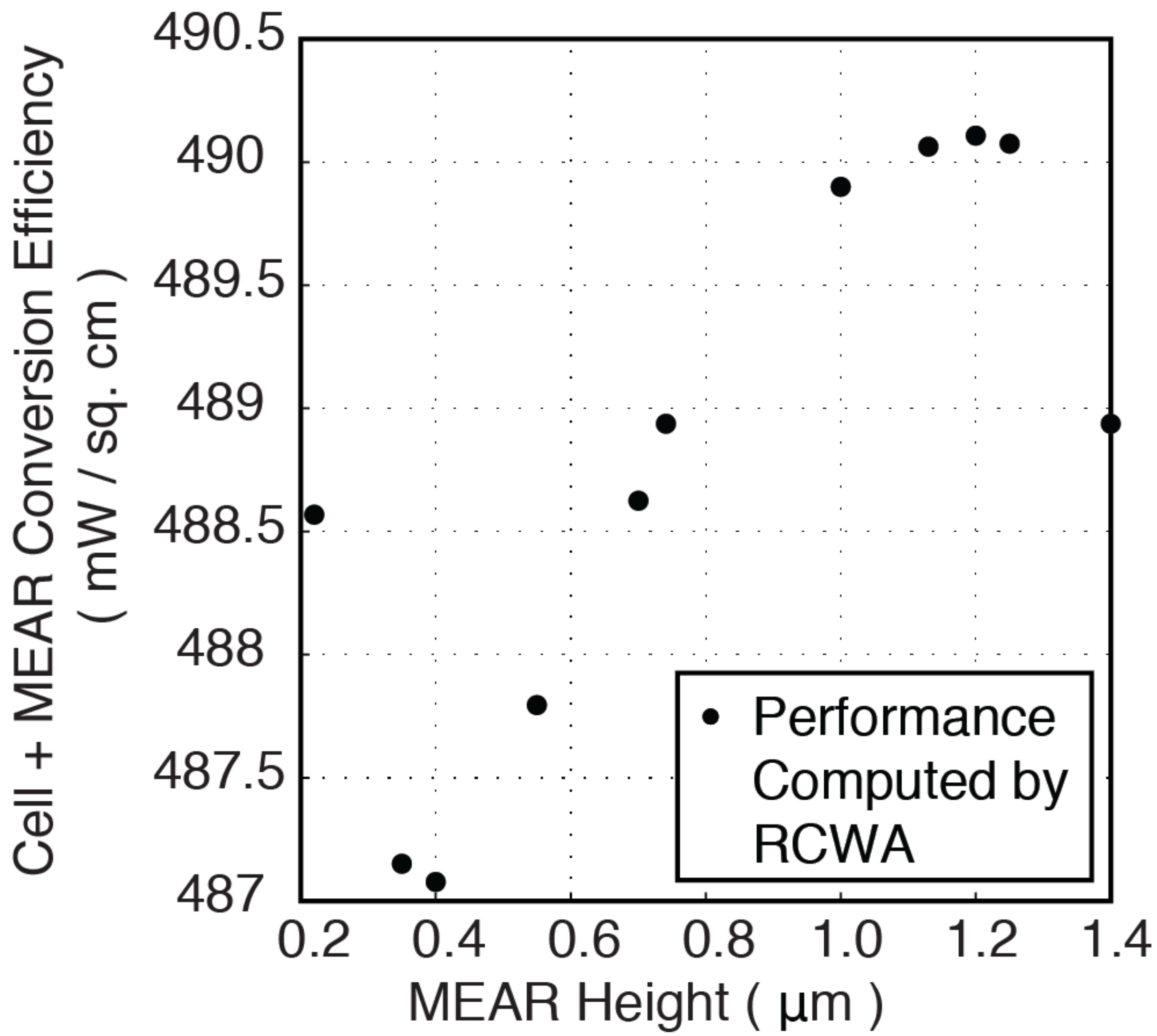

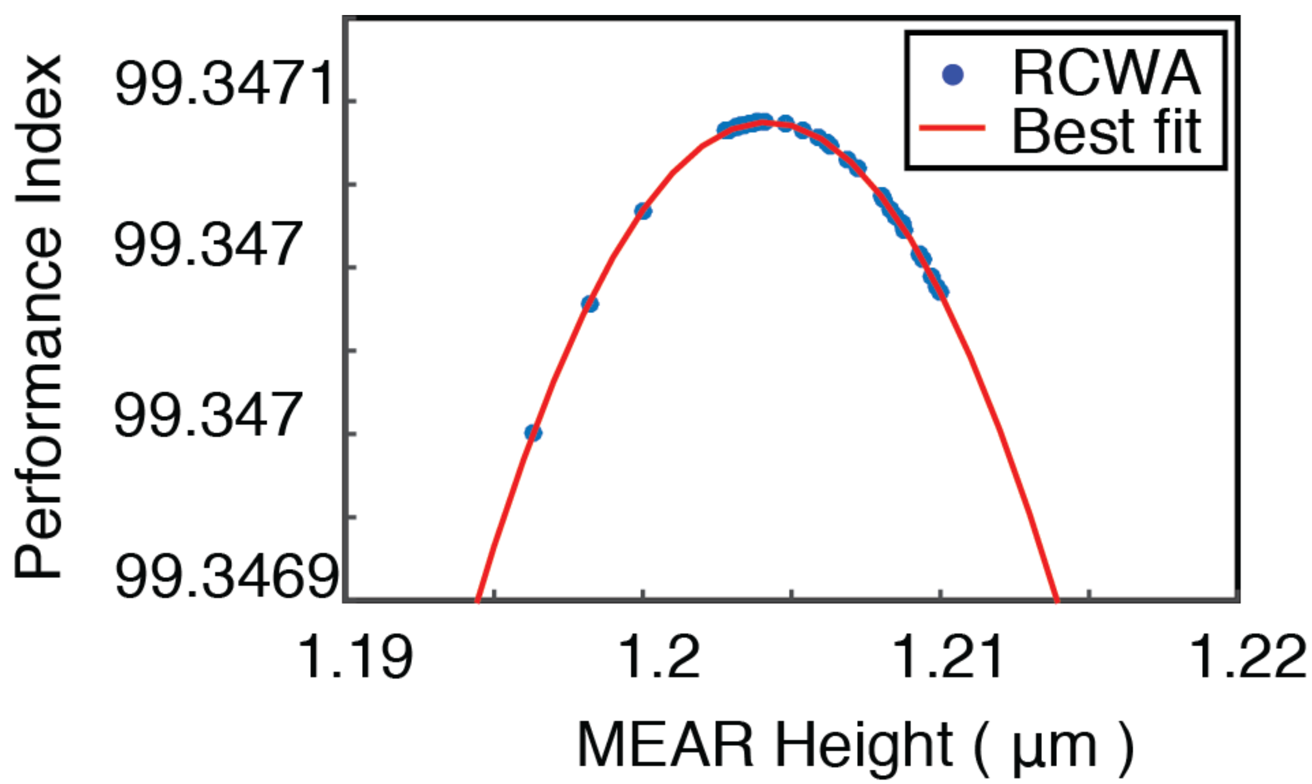

- h = 1204.1nm ± 15.1nm
- Constrained to 130nm pitch

- Height is most “free” parameter
- Pitch is limited by subwavelength condition

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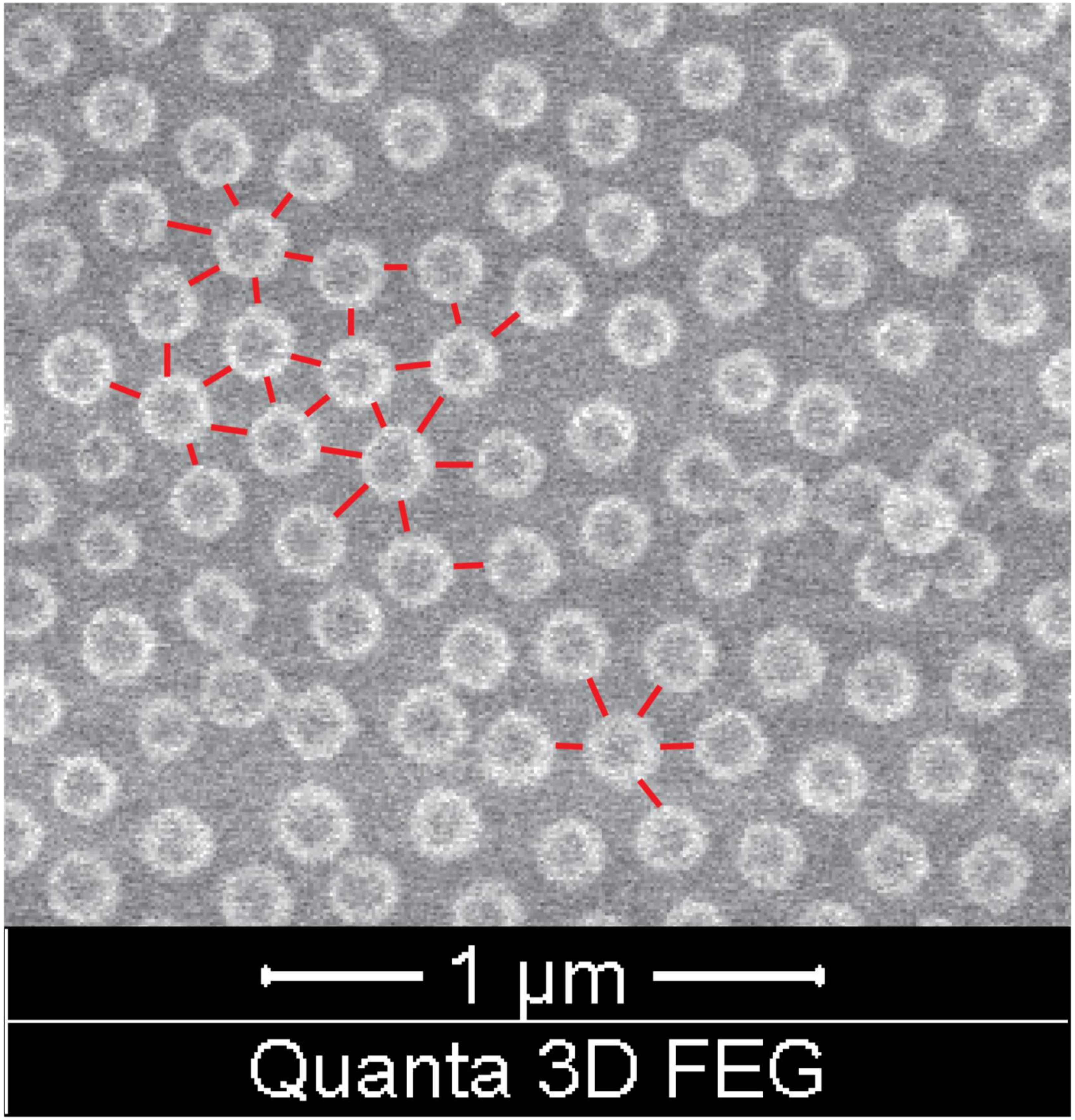
SUPPLMENTAL: SIZE REDUCTION



- O_2 etch yields etch rate of ~60nm/min.

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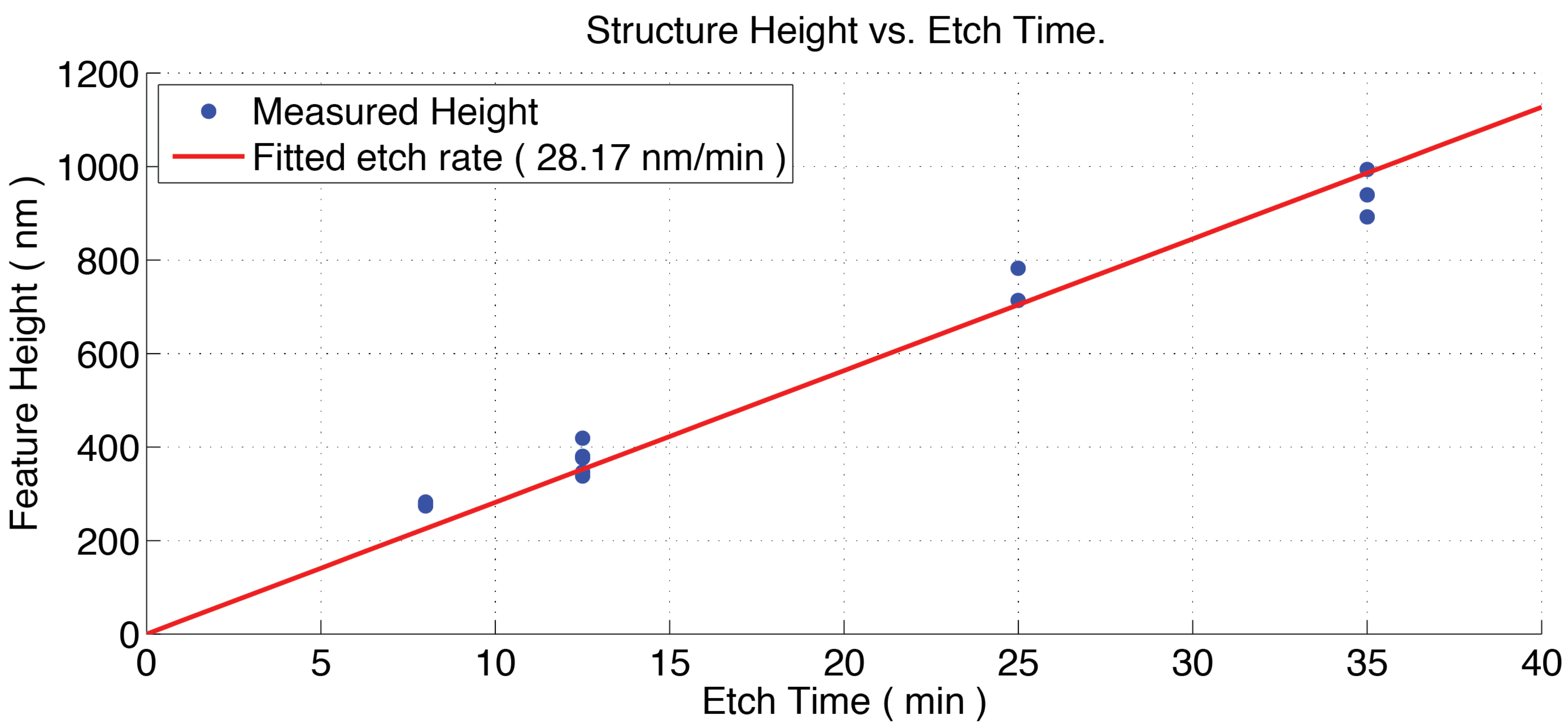
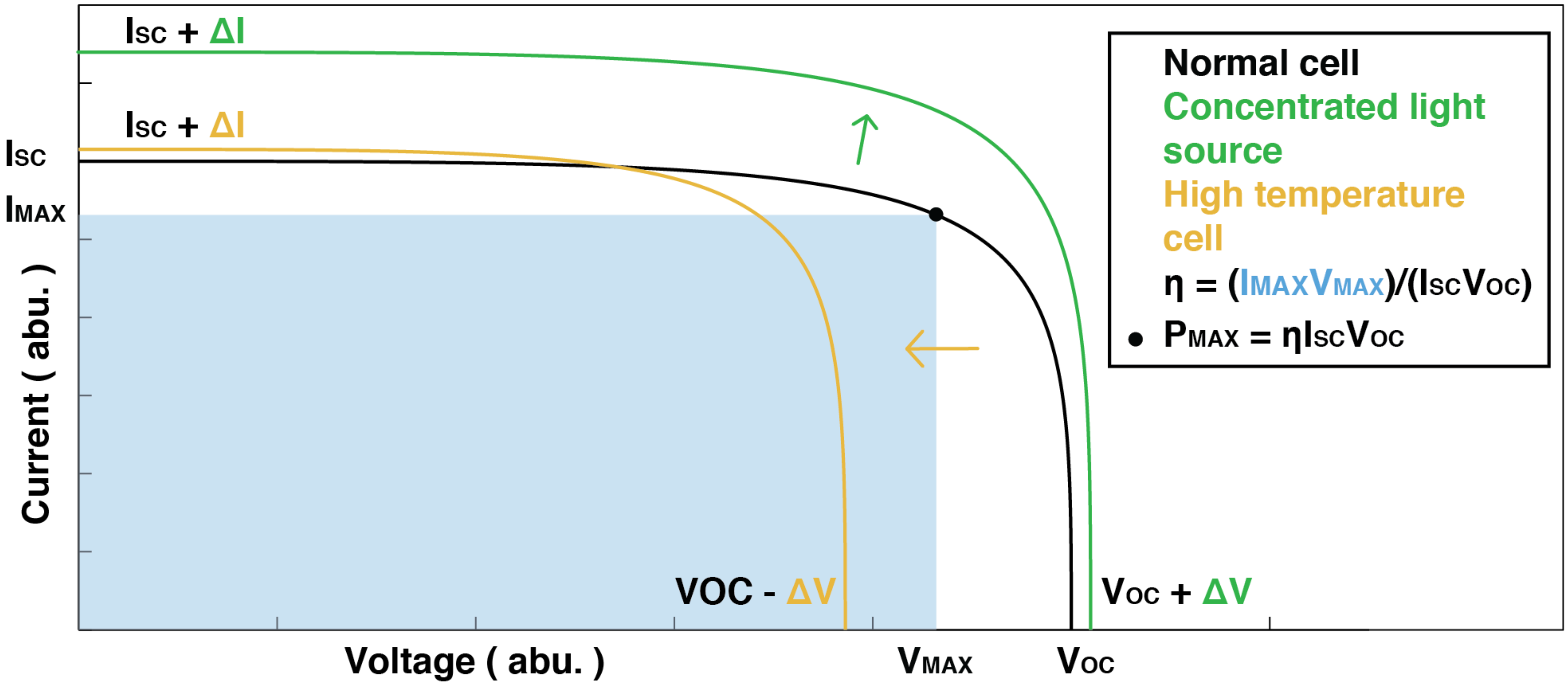
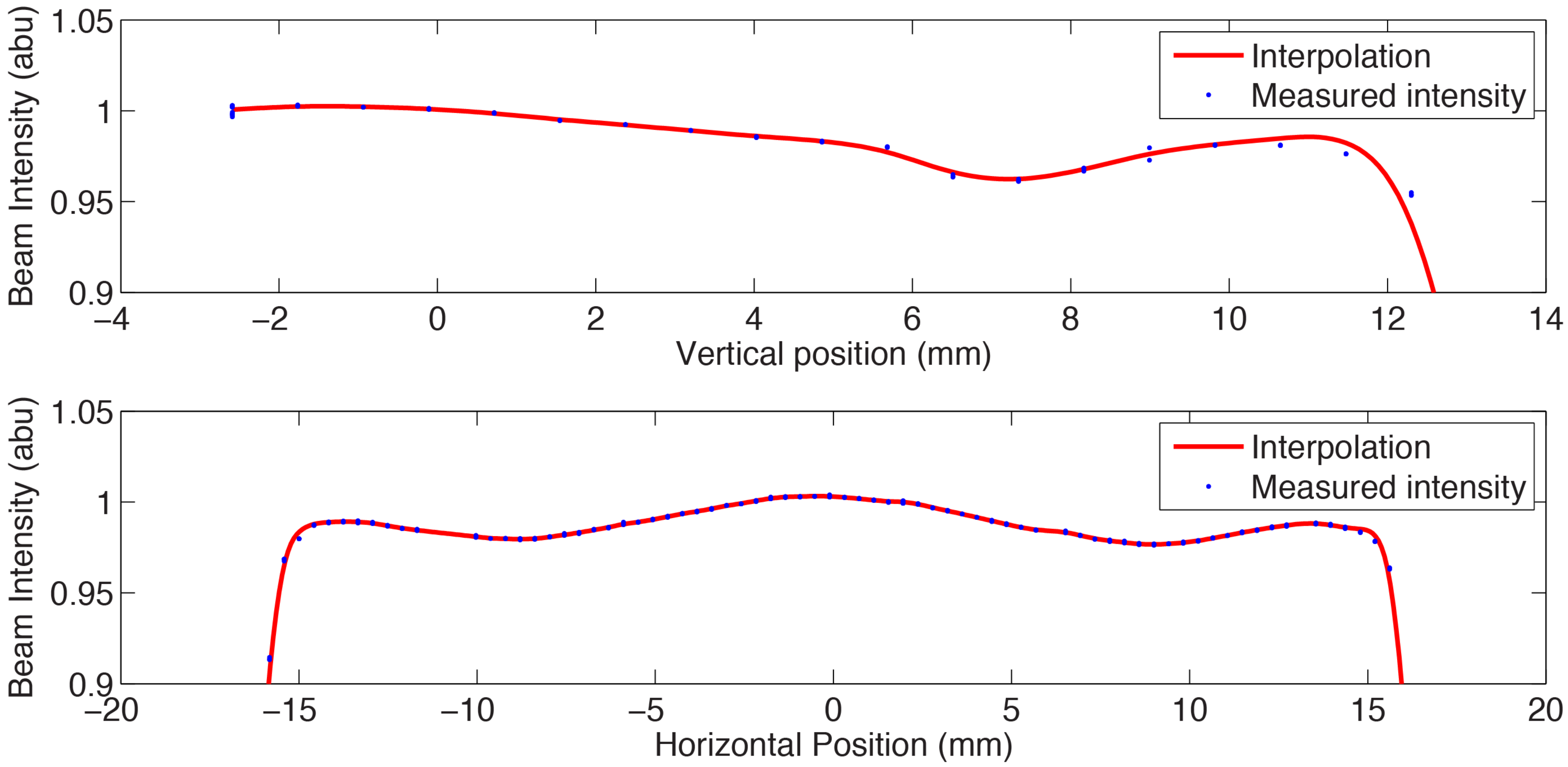
SUPPLMENTAL: ETCH RATE



SUPPLEMENTAL: MEASUREMENT RATIONALE



SUPPLEMENTAL: BEAM CHARACTERIZATION



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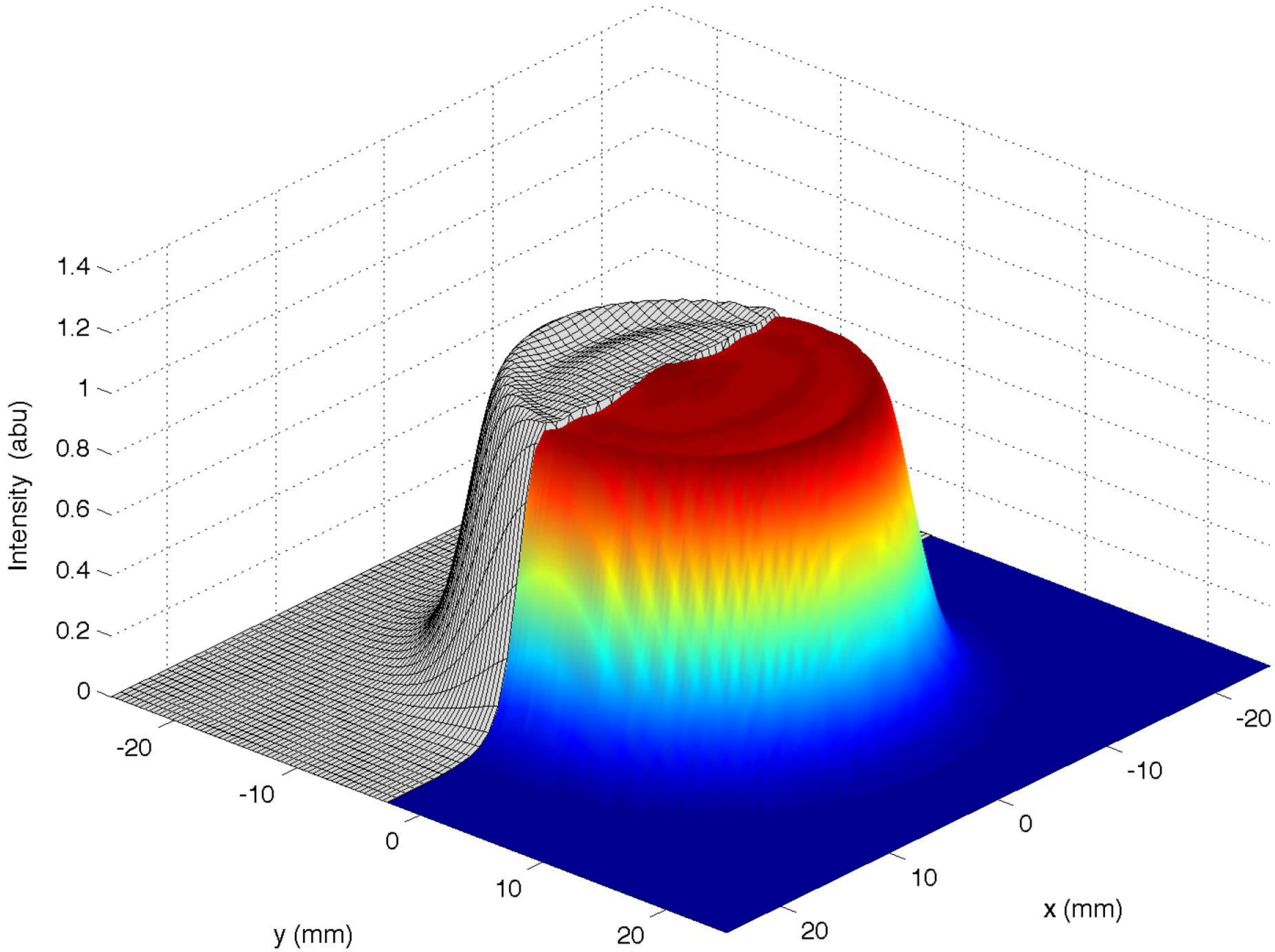
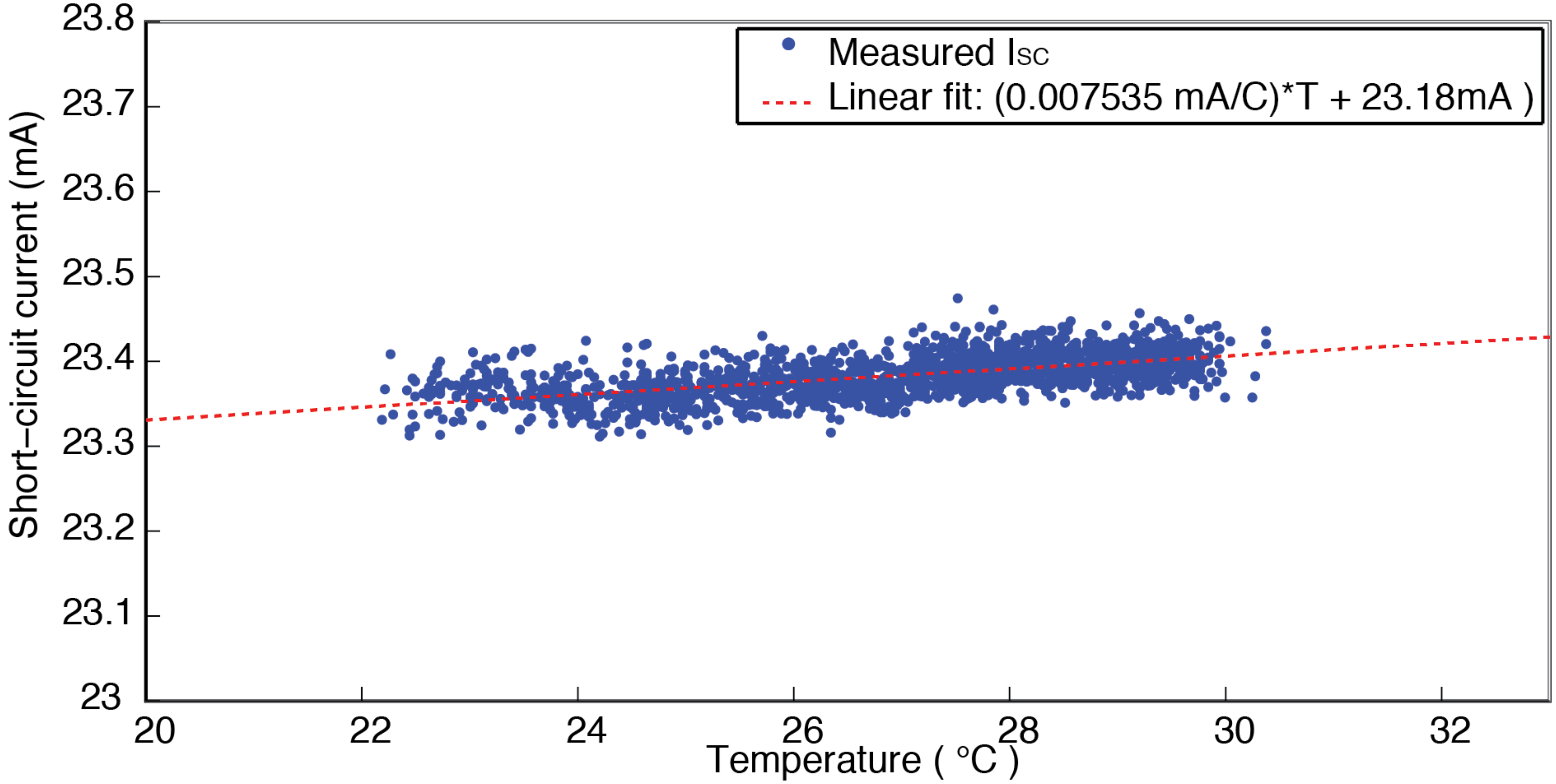
SUPPLEMENTAL: BEAM CHARACTERIZATION



- Beam profile smooth.
- Appears as an extended Airy disk.
- Cells are not positioned below 3mm mark.

SUPPLEMENTAL: TEMPERATURE



5m exposure
~0.3% I_{SC} shift

- Very low temperature response in I_{SC}, V_{OC} a different matter.
- Relative measurements → identical electrical heating

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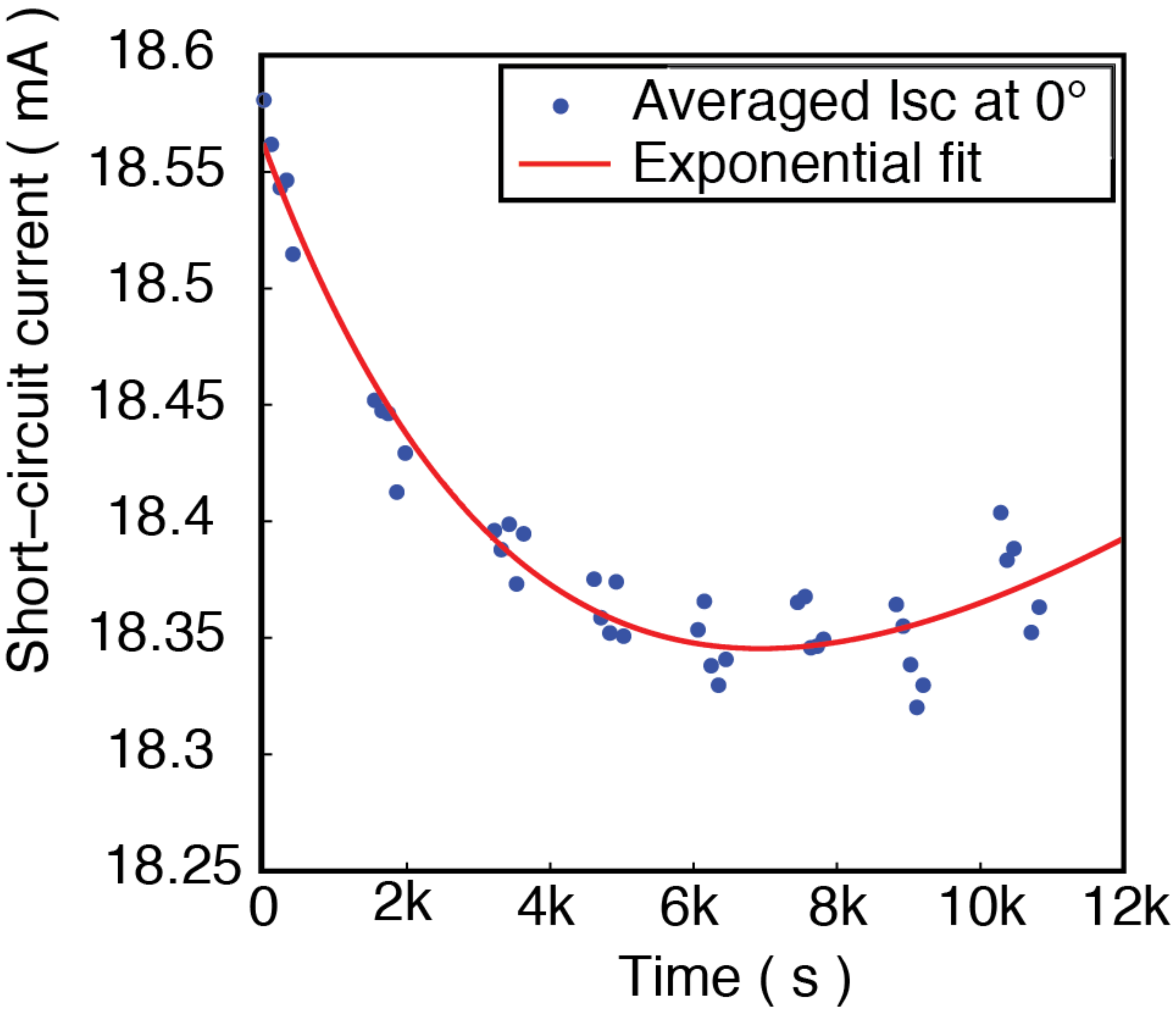
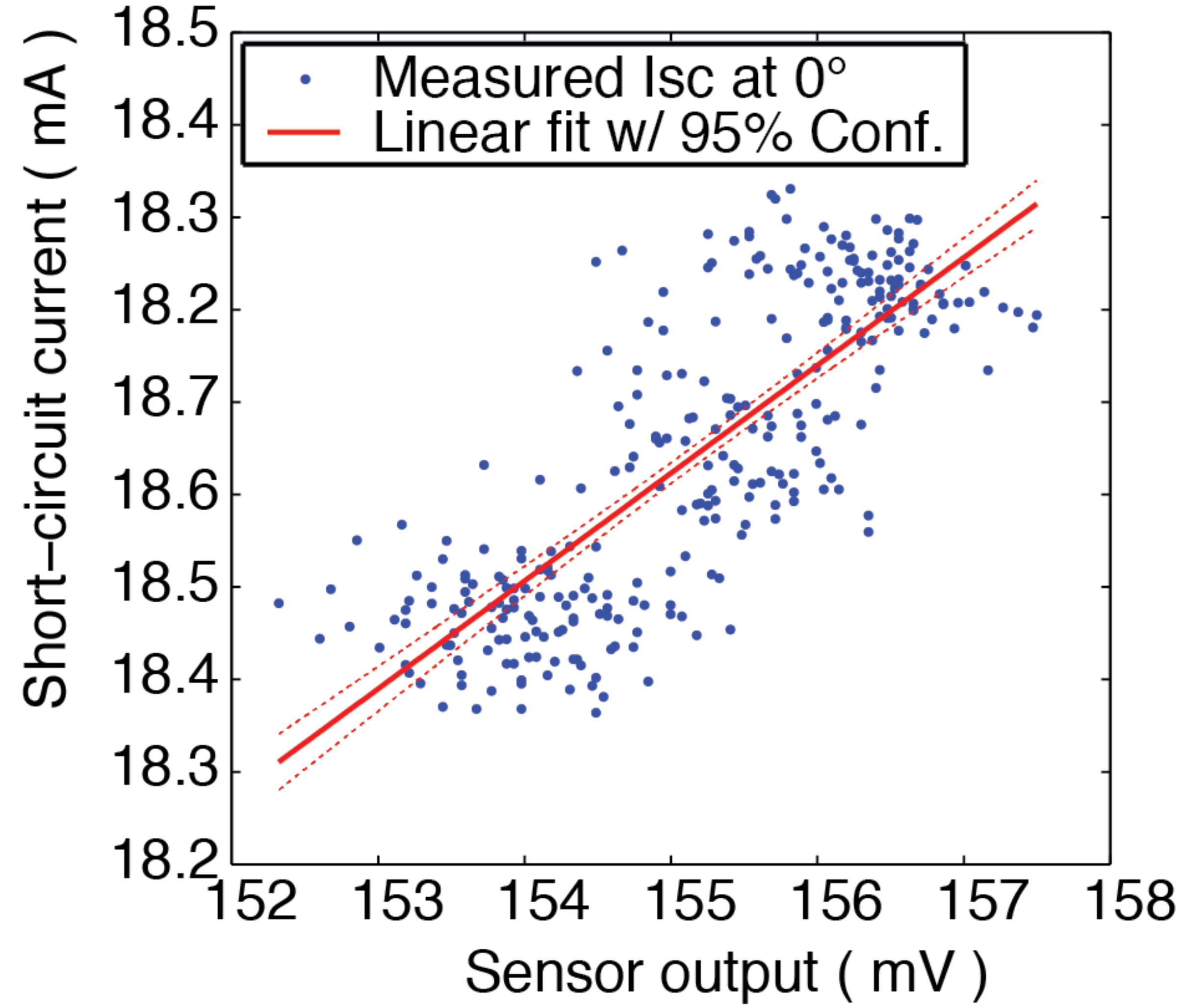
SUPPLEMENTAL: DRIFT





- Beam drift immediately following ignition
- May be accounted for by linear relationship with photodiode

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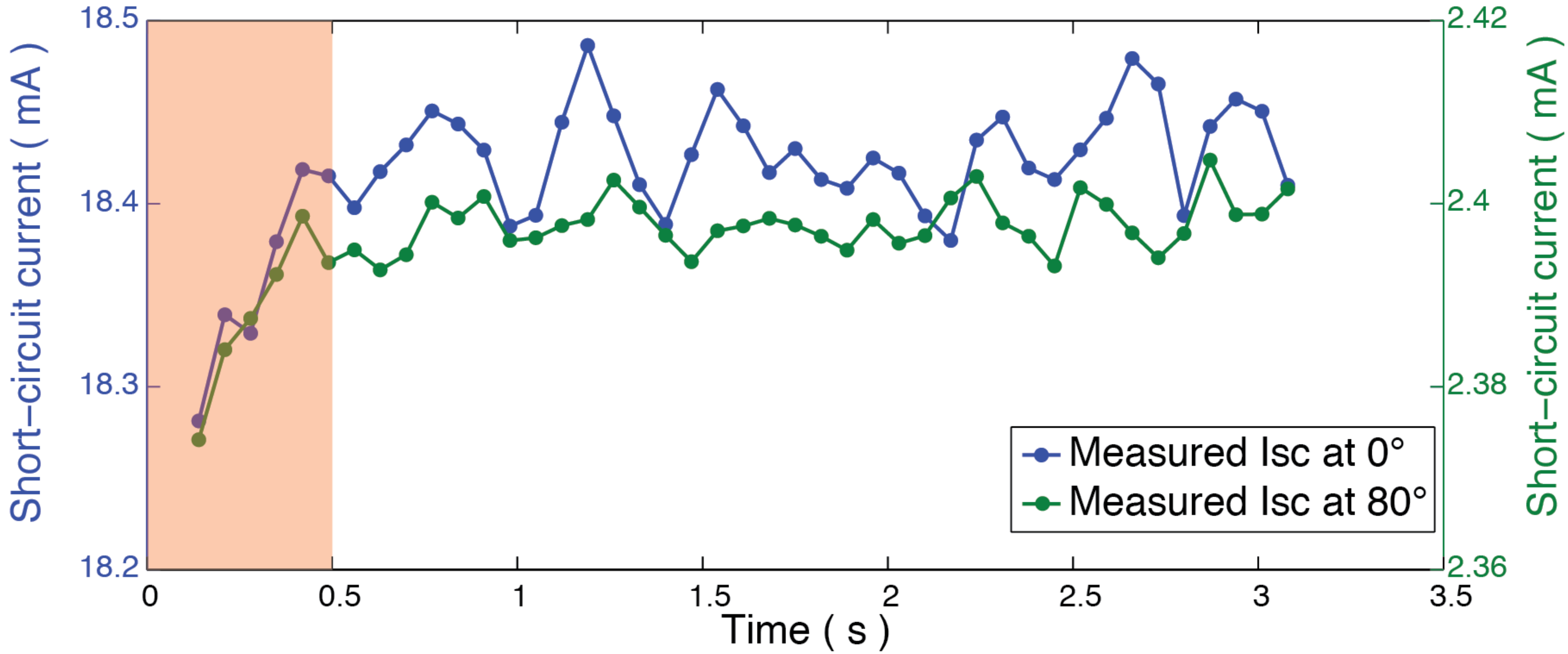
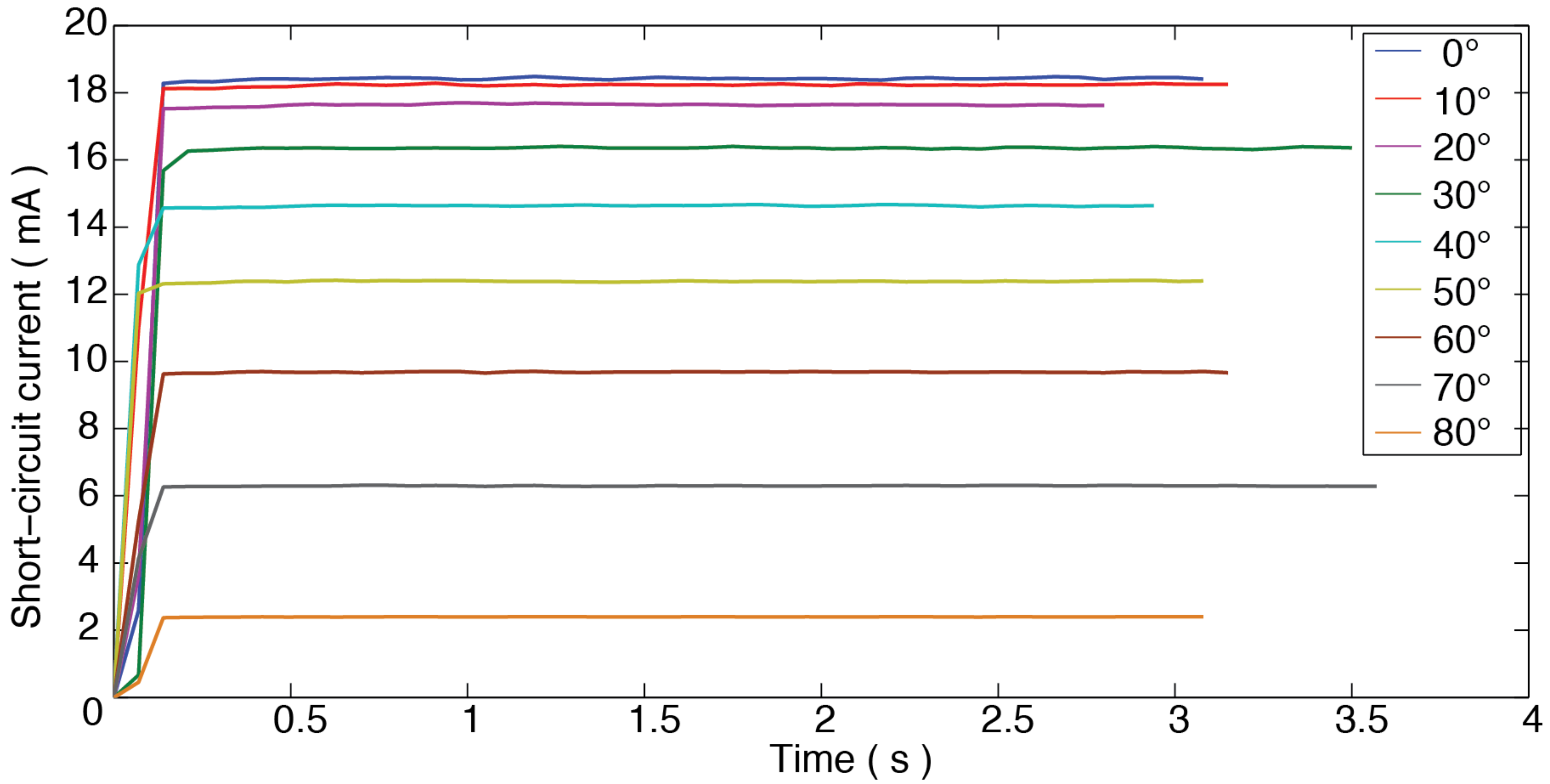
SUPPLEMENTAL: RC-LAG



- RC-Lag in the circuit
- 5% of final value
- First 0.5s of signal following crossover

SUPPLEMENTAL: RC-LAG



- RC-component not significant.

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SUPPLEMENTAL: EXPECTED UNCERTAINTIES

Parameter	Symbol	Value (3σ)	Value as %
I_{SC} readout	σI_{SC}	0.00432 (mA)	< 0.385
Power sensor	σB_{λ}	---	0.161
Position of cell on PCB (at 0°)	σX_R	0.1mm	0.484
Horizontal position of PCB (at 0°)	σX_0	0.1mm	0.489
Vertical position of PCB (at 0°)	σY_0	0.1mm	0.006
Incident angle (at 0°)	$\sigma \theta_0$	1.25 arcmin	0.00002
Position of cell on PCB (at 85°)	σX_R	0.1mm	0.004
Horizontal position of PCB (at 85°)	σX_0	0.1mm	0.036
Vertical position of PCB (at 85°)	σY_0	0.1mm	0.006
Incident angle (at 85°)	$\sigma \theta_0$	1.25 arcmin	0.832
Total uncertainty in relative Transmission (T_1/T_2)	σ_T	**< 0.021**	**---**

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