Substrate Charging Challenges and Mitigation Techniques for Electron Beam Lithography

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MAEBL Workshop

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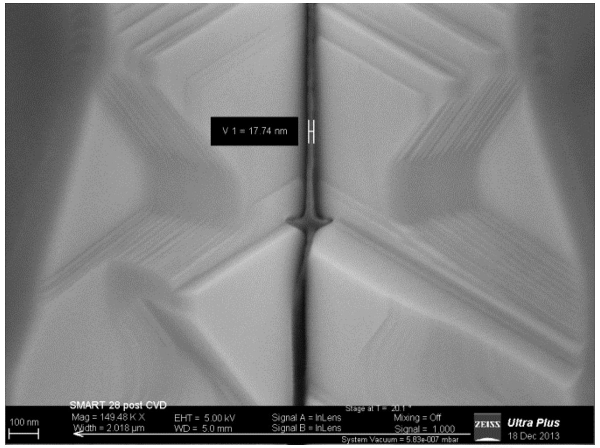
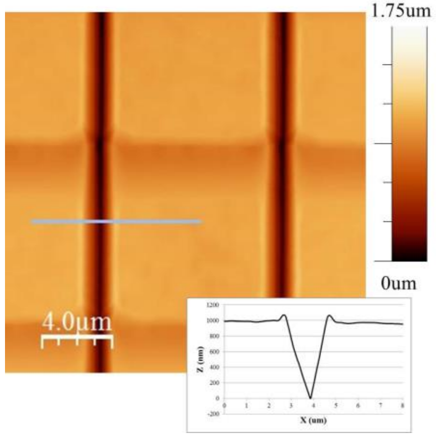
THE Ohio State University

Nanotech West Laboratory

Institute for Materials Research





Nanotech West At a Glance

nanotech.osu.edu

- **Ohio's largest comprehensive micro- and nanofabrication user facility**
- **Support academic and industrial research**
- **100+ R&D projects per year**
- **Over 150 users – mostly graduate students and small companies**

Cleanroom Highlights

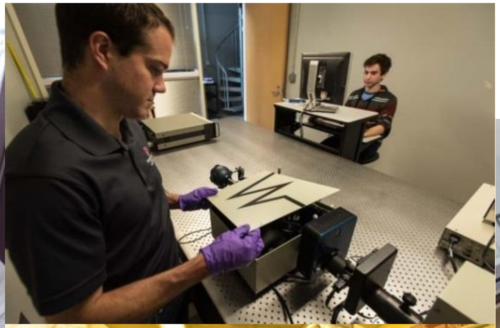
- 6,000 square feet of Class 100 cleanroom space
- 4 Bays with full 4" Semiconductor Processing Line
- Flexibility to work with exotic and state of the art materials
- Document system

Staff Highlights

- 9 engineers, 2 administrators, 8 undergraduate interns
- Technical backgrounds: electrical engineering, mechanical engineering, physics, chemistry, biology, electronics, military

Highlights

- 4,000 square foot BSL2 and Energy Storage Lab Space
- Infrared, FPA, and PV testing
- MOCVD Epitaxy (As, P, Sb)
- Materials Innovation Lab



The Ohio State University

EBL Experience at Nanotech West

- 2 Engineers with over 48yrs experience
- Academic and Industrial R&D, Manufacturing
- Gaussian and Shaped Beam Tools
- 5 Tool Platforms
  - ✓ EBPG 5000 (Ohio State)
  - ✓ EBPG 5HR (Penn State)
  - ✓ EBPG 4HR (Triquint/Qorvo)
  - ✓ Hitachi HL-700 and HL-800D (Triquint/Qorvo)

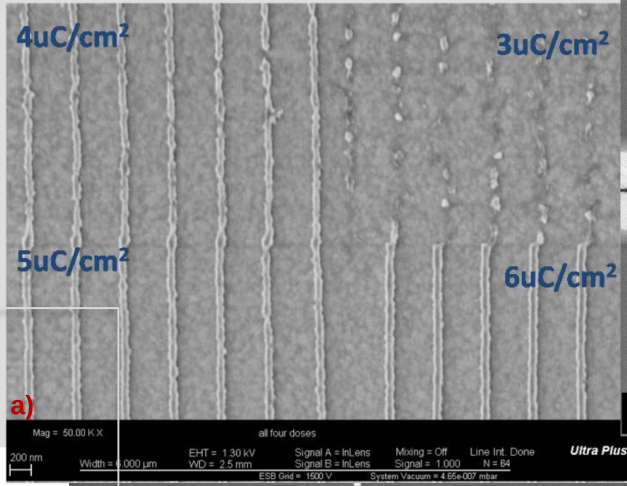
Lithography & Beams at Nanotech West

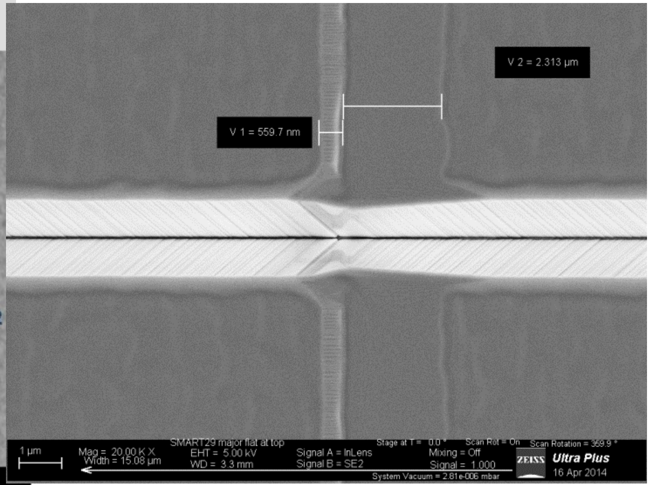
- **Electron Beam Lithography**
  - Vistec/Leica (now Raith) EBPG5000
  - 20, 50, 100kV Gaussian Beam
- **Photolithography – 4” wafer and flexible small pieces**
  - GCA 6100C i-line stepper
  - Two EVG 620 Contact Aligners
  - Karl Suss MJB3 Contact Aligner
- **Imaging**
  - Zeiss Ultra Plus 55 FE-SEM (charge compensation for insulators)
  - Hitachi S-3000H SEM
  - Bruker Icon 3 AFM
  - NanoScience Zeta-20 3D Optical Profilometer

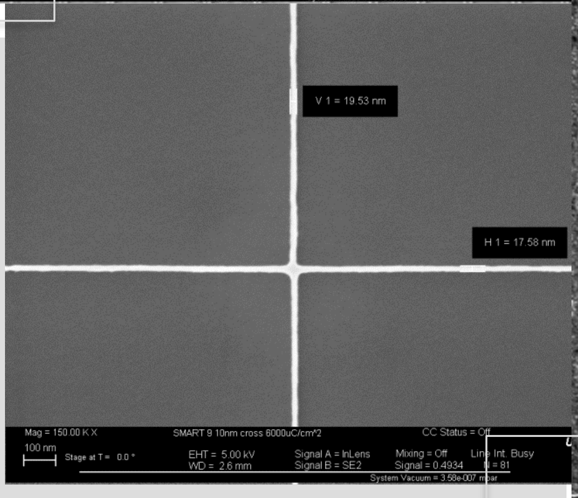
EBL at Nanotech West

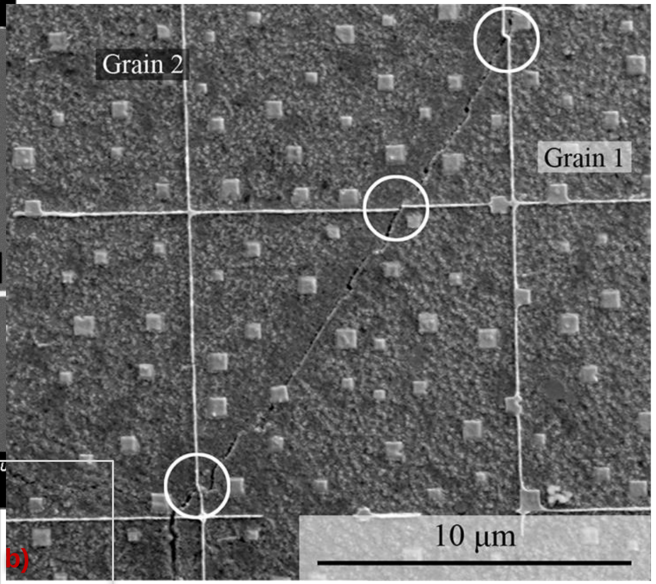
Supported Resists at Nanotech West (less is more)

- PMMA and MAA Copolymers
- SU-8 (R) and Standard
- maN2403
- HSQ (XR1541-4, -2)
- ZEP7000 on mask plates
- EBR9 on mask plates









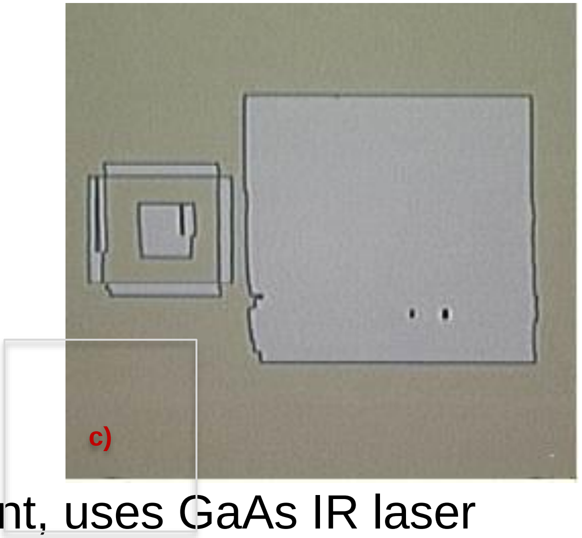
Typical User Requirements

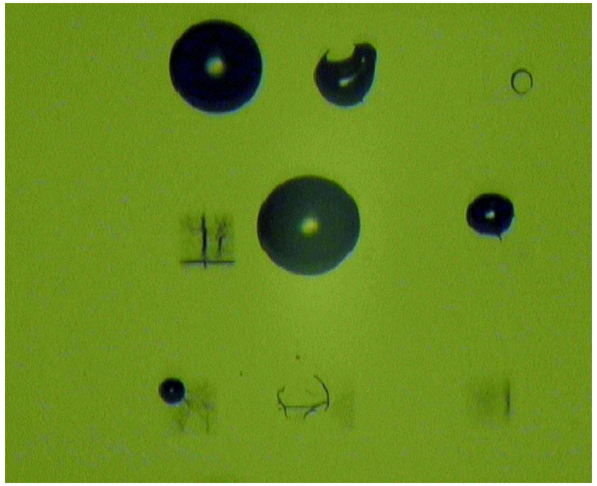
- Liftoff primarily, followed by ICP-RIE
- T-gates
- *Transparent and insulating substrates*
- Small pieces
- *Piezoelectric materials*
- 5” reticles and masks, 4” masks

a) Courtesy of G. Lafyatis A. Bross *J. Vac. Sci. Technol. B 27, 2602 (2009)*
b) Courtesy of M. Mills and J. Carter *Materials Science and Engineering: A Volume 605, 27 May 2014, Pages 127–136*

EBL on Insulating, Transparent, Piezoelectric Materials

"If it is difficult to pattern, we'll pattern it. Find a way."





Charging Concerns:

- ✓ Pattern displacement
- ✓ Distortion
- ✓ Poor overlay
- ✓ Stitching error

Transparent Substrates:

- ✓ EBPG requires height measurement, uses GaAs IR laser
- ✓ No/Bad height measurement results in poor focus and stitching error

Approach:

Charge dissipation layer above or below resist.

Exposure strategy.

Easier said than done sometimes …

c) "Interlayer and Intershot Charging Induced Pattern Distortion on GaAs Substrates Exposed with a High Throughput Shaped Beam Electron Beam Lithography System", A. Bross, R. Davis, T. Toyama, and J. Beene, Proceedings of the 2004 Conference on Compound Semiconductor Manufacturing Technology, Miami FL (2004)

Charge Dissipation Options

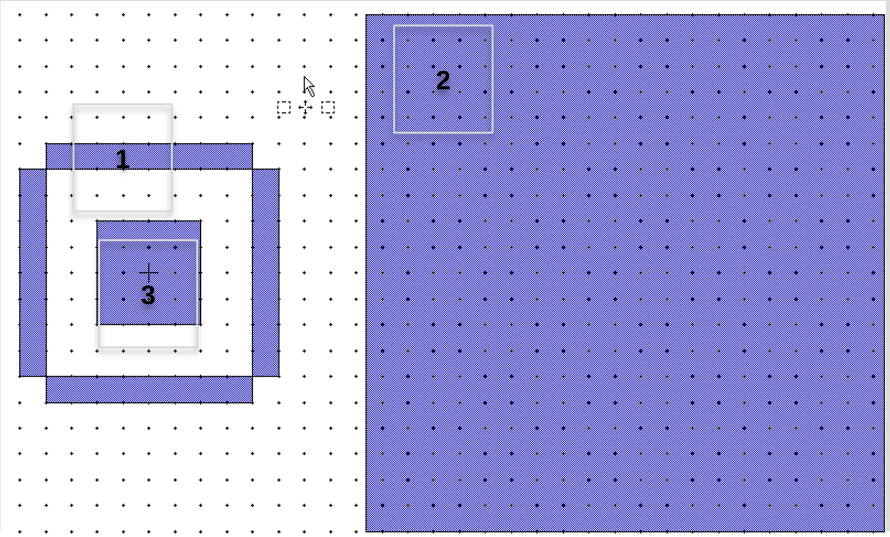
How to Dissipate Charge

Approach	Specifics	Pros	Cons	Other
Water Soluble Conducting Polymers	Espacer, AquaSave	• Straightforward on PMMA/ZEP • Water removal	• EXPENSIVE • Short shelf life (3 months) • Generates particles	
Metal Coings	Au, Al, Cr	• Readily available • Inexpensive • Straightforward	• Alters resist profile • Dose • Mixes with HSQ • Peeling at high beam current/doses • Process complexity	Must use thermal evap or sputter.
Exposure Strategy	Tool specific	No additional processing	SLOW	

Quantifying Charging in Your Tool Using Inspection/Tool Automation

Approach 1 – Test pattern for OSI Metra 2000 optical inspection tool

- Expose in order 1, 2, 3 (ring, large box, inner box)
- Vary substrate resistivity, dissipation approach, exposure strategy
- Automated optical inspection measurement

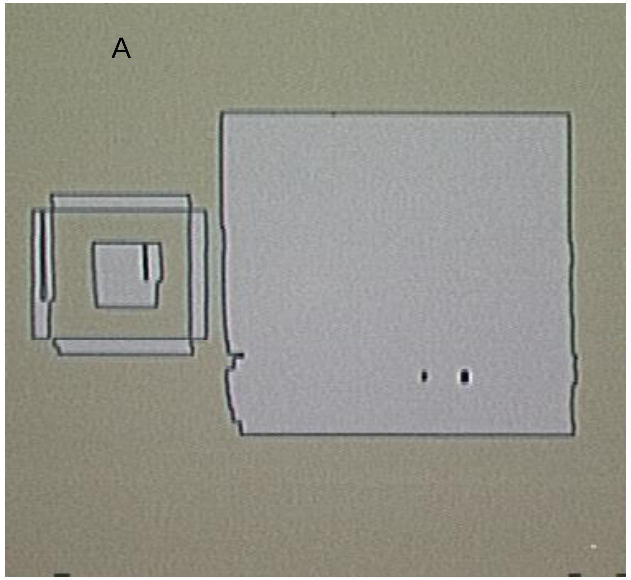


Process condition summary

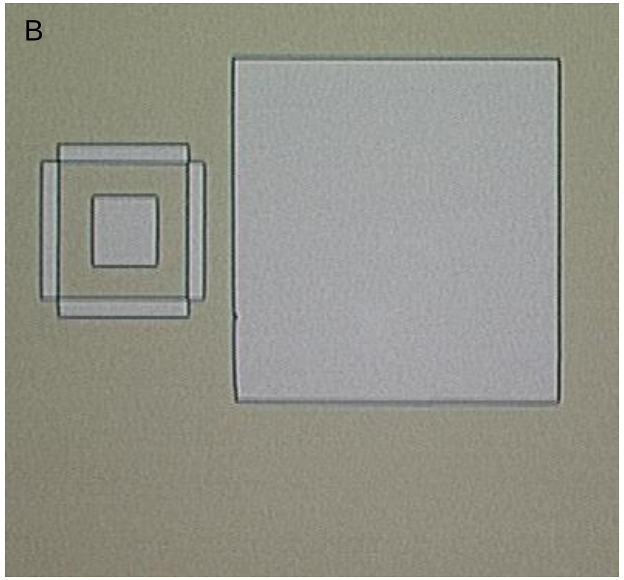
Pattern	GaAs Substrate	Sheet Resistivity (Ω/□)	Resist Thickness (Å)	Dose (μC/cm²)
Box-in-bar	Semi-Insulating	~10^{10}	2200	~300 & ~2300
Box-in-bar	Ion Implanted	300	2200	~300 & ~2300
Overlay	pHEMT	150	various	~300

Can Espacer Reduce Charge Sufficiently for GaAs?

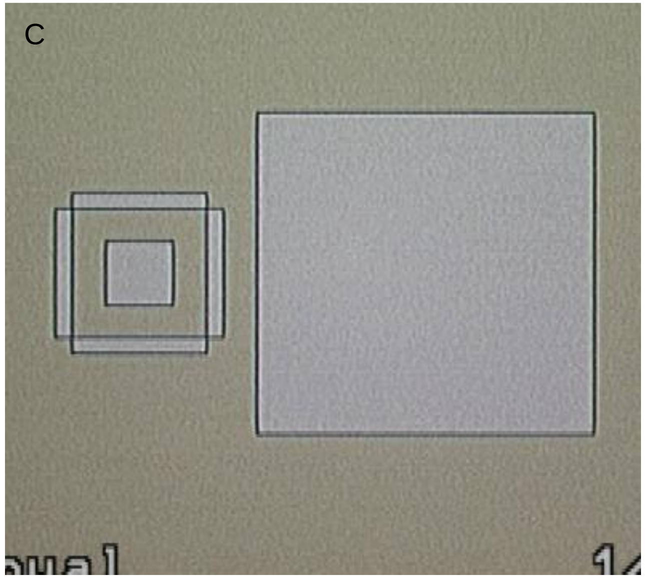
Furthest from ground
No Espacer



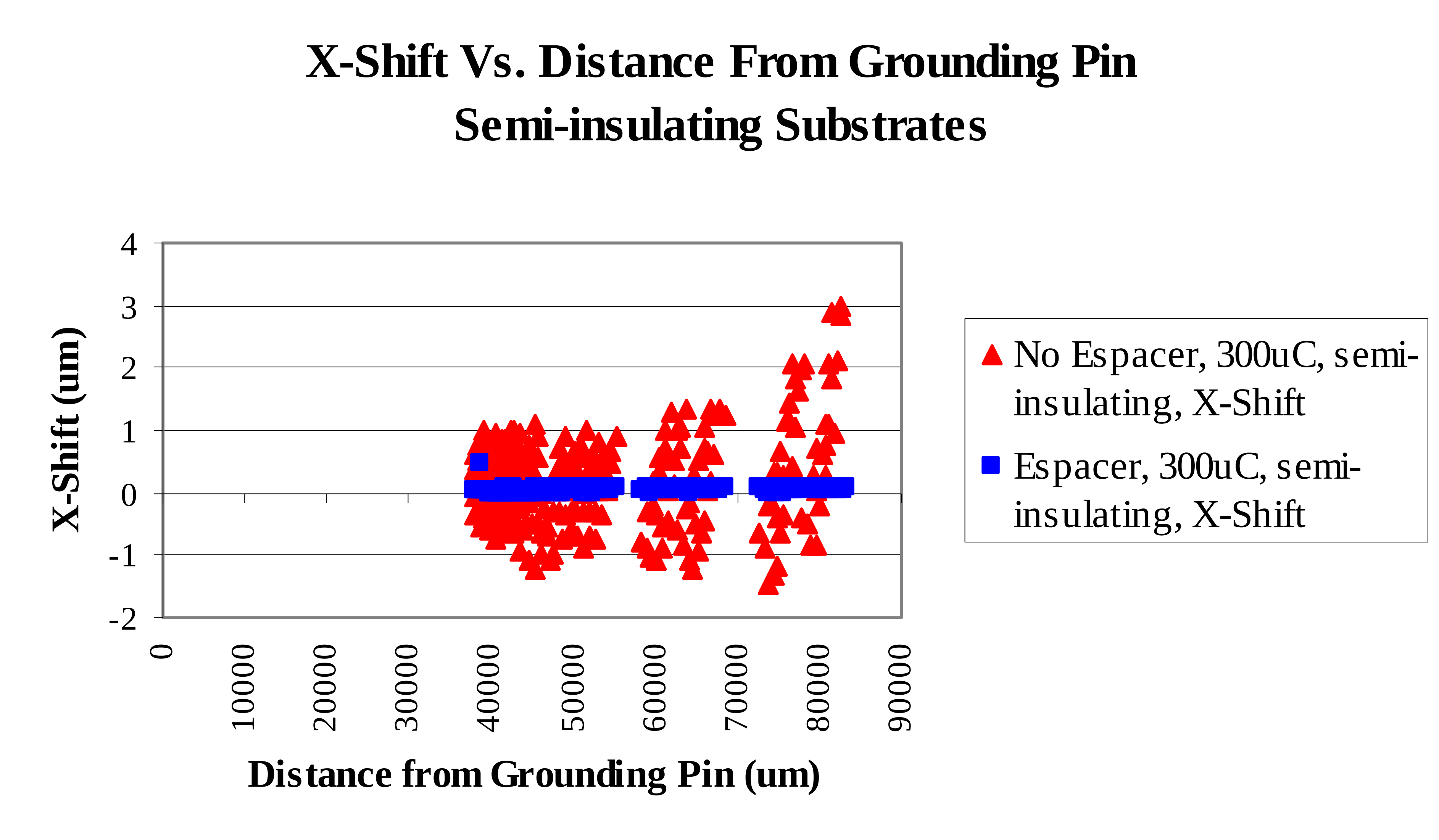
Closest to ground
No Espacer



Furthest from ground
Espacer



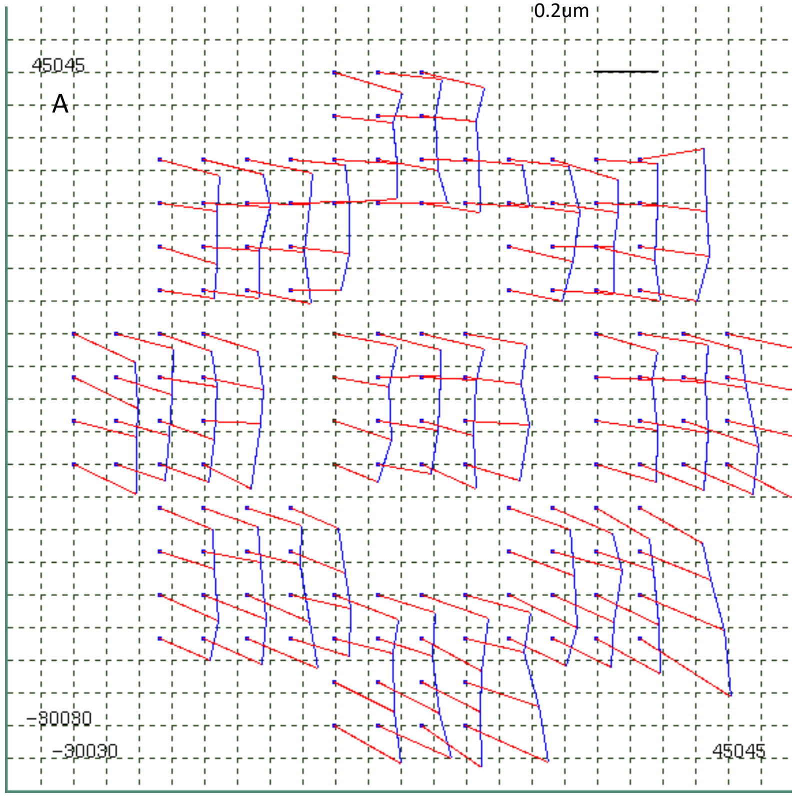
OSI Measurements



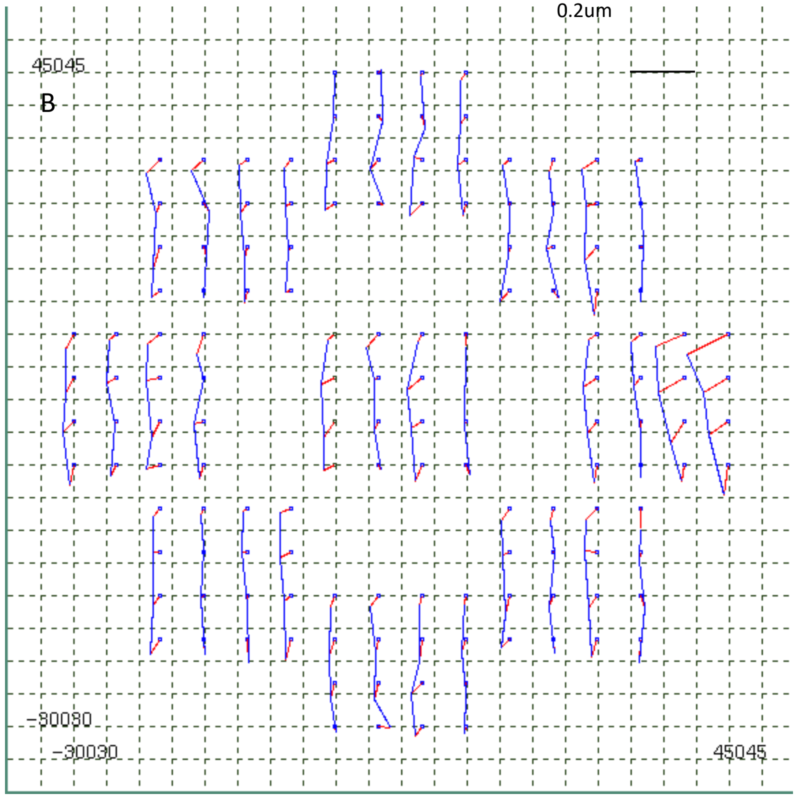
Approach 2 – Create tool specific overlay markers, use automated marker search

- ~~pHEMT (lower resistivity) GaAs~~
- Hitachi marks are crosses
- First half created by stepper (1)
- Second half by ebeam (2)
- Neglect overlay errors (<50nm)
- Measure markers with EBL
- Report error as layer
- (2) displacement vector from (1)

pHEMT GaAs 4” Wafers



No Espacer



Espacer

Summary of Approach 2 Results

Anti-charging Layer	Exposure Strategy	X-Displacement mean + 3 sigma (nm)	Y-Displacement mean + 3 sigma (nm)
None	Default	250	146
None	Right to left, with a delay between reticle columns	100	101
None	Left to right, with a delay between reticle columns	68	49
Espacer	Default	54	79
Espacer	Right to left, with a delay between reticle columns	77	84

Metal on Resist Dual Purpose

Metal Coatings – Both for conductivity and reflection for height reading/focus

Approach:

- Standard PMMA, deposit thin (20-50nm) metal on top
- Expose through metal, remove metal
- Au use KI3, Au use base like TMAH photodeveloper

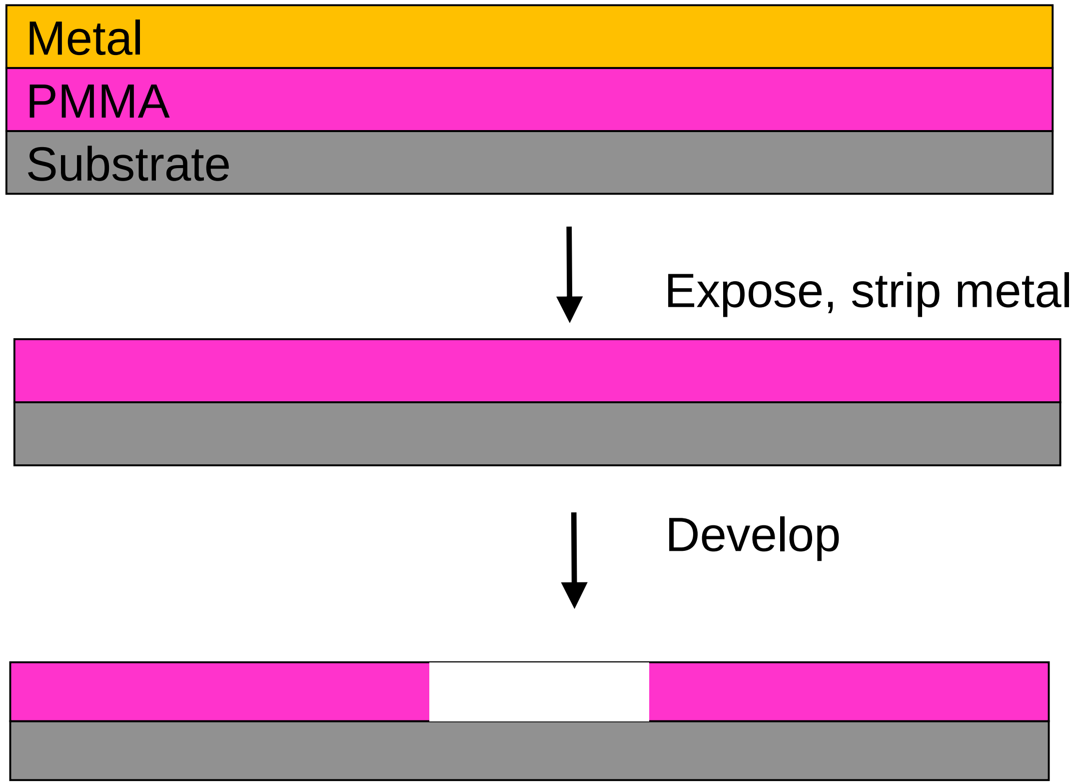
Considerations: Sputter, thermal evaporation, **no ebeam evap**

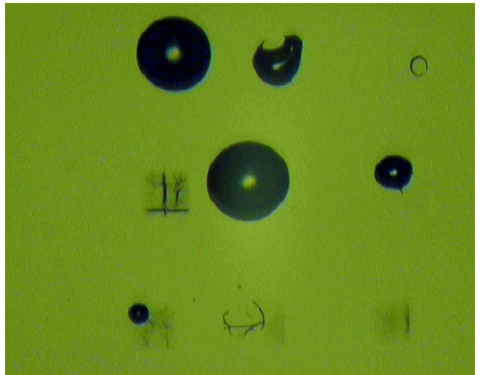
Problems:

At high doses some metal peels/bubbles

Changes profile, characterized by increased undercut profile

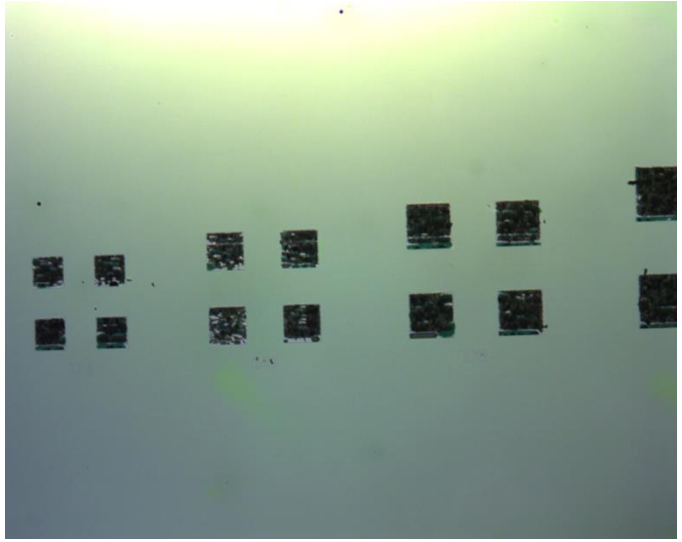
Ultimate resolution reduced



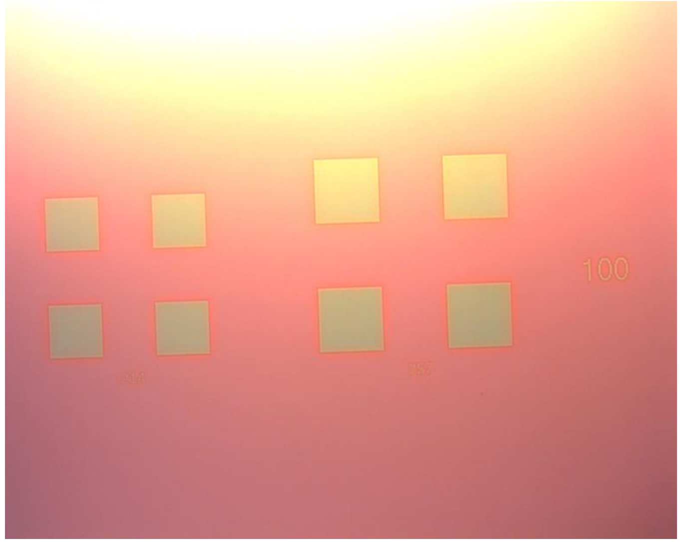


Metal Peeling at High Doses

Test exposure of Al and Au on bilayer resist, 2 mC/cm2, using 30, 50, 75, 100, 150 nA beam current.



Al peels @ all beam currents, down to 20 um features



Au does not peel, even at 150nA

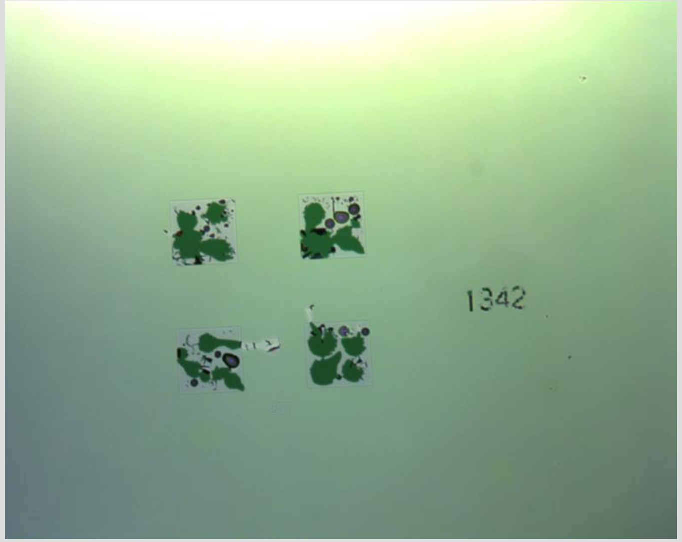
Peeling metal as a function of dose

100 nA, 100 kV

Aluminum fails at 1342 $\mu C/cm^2$

Gold fails at 3000 $\mu C/cm^2$

$\Rightarrow$ Gold wins



Slide courtesy of Michael Rooks Yale University

Resist Process Sensitive to Metal Coating

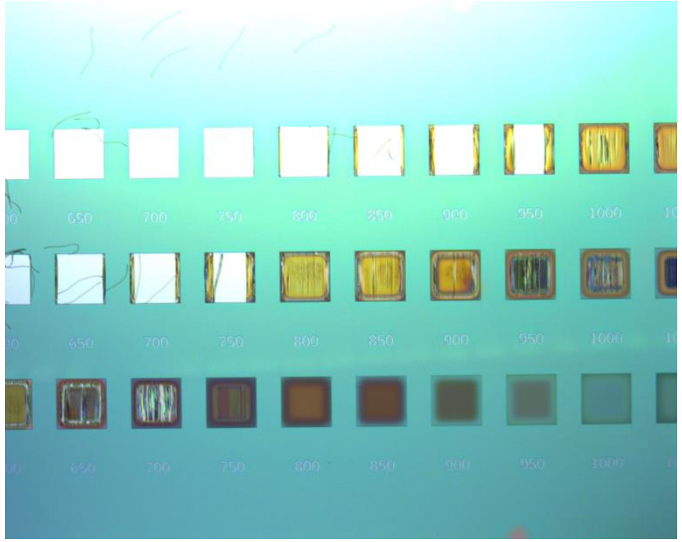
Au thickness at wafer center	Critical pitch = 2x undercut (± 25nm)
0	900 nm
10 nm	975 nm
20 nm	1025 nm
40 nm	1125 nm

Resist process sensitivity

Print gratings onto bilayer resist, using a range of pitch: 400 nm to 1200 nm.

At a critical pitch value, the resist lifts off.

Factor of 3 difference in gold thickness causes a difference in undercut ~50-100nm



Slide courtesy of Michael Rooks Yale University

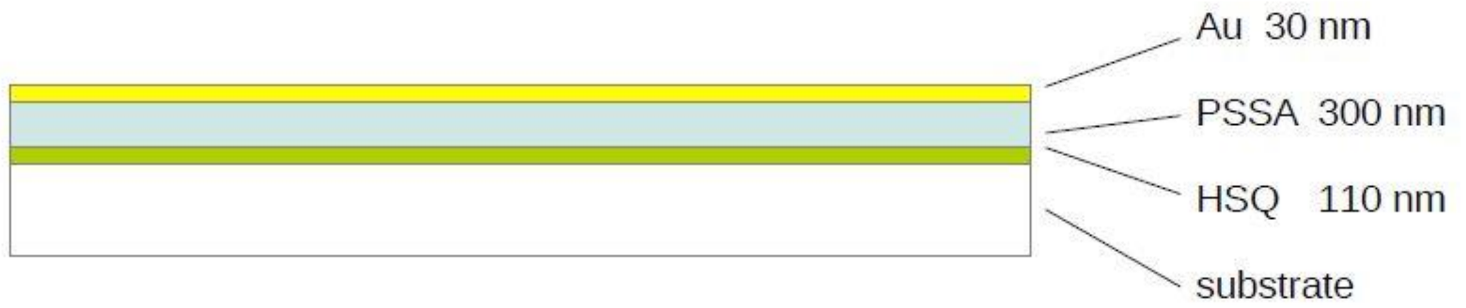
Metal on HSQ?

HSQ incompatible with metal directly on resist surface

Option: Coat HSQ with a water soluble conducting polymer, either PDOT:PSS or Espacer-300Z (Showa Denko Inc)

Next problem: Conducting polymers are unstable, have short shelf-life, and are outrageously expensive.

Do we really need a conducting polymer? No.
We just need a water-soluble layer to separate the metal from the resist.

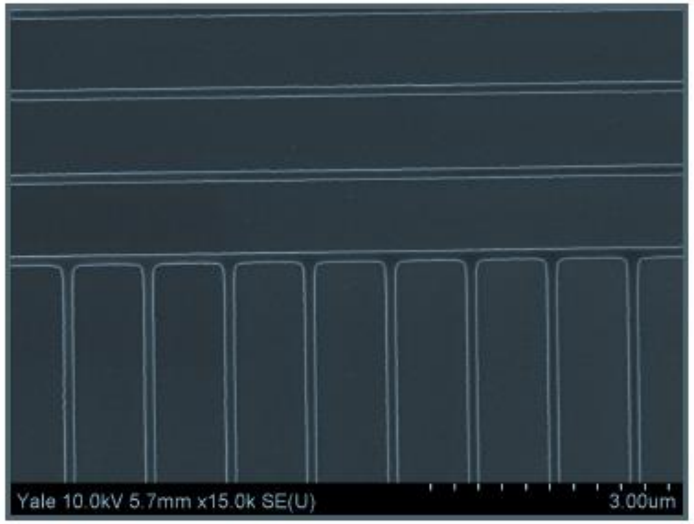


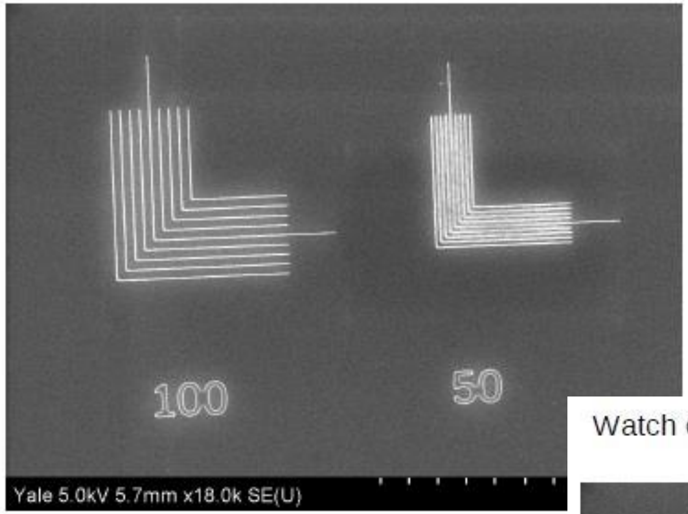
* poly(4-styrenesulfonic acid) diluted to 4.5% in water, Sigma-Aldrich 561223-500G

We tried PVA, starch,guar gum, soap, sugar, PEG, and PEO. Finally, we tried PSSA (aka PSS) Which is used to synthesize conductive coatings for solar cells. PSSA itself is an insulator.

Slide courtesy of Michael Rooks Yale University

PSS Interlayer Works

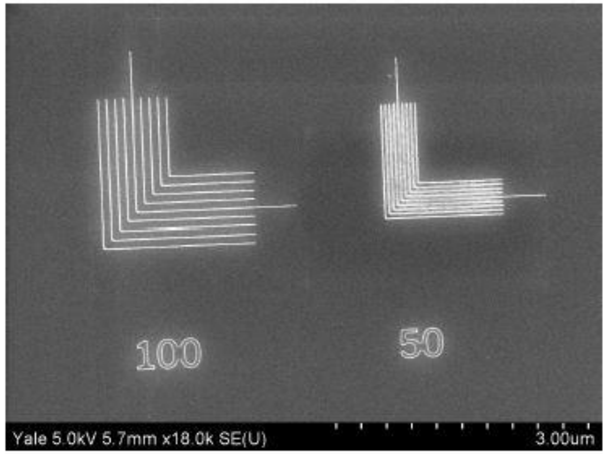


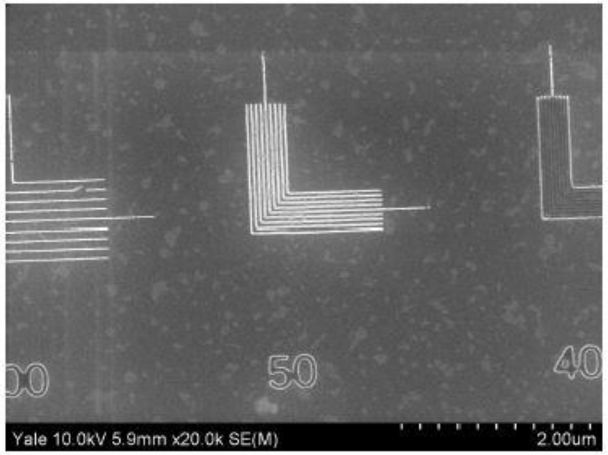


110 nm thick HSQ

30 nm thick HSQ

Watch out: Choice of surfactant is critical





Some Caveats
Use of PSSA increases line edge roughness
Choice of surfactant critical

PSSA surfactant:
Triton X100 (1%)

3M Novec 4200
Solution is unstable

Conclusions

- EBL Patterning on Insulators Possible with High Quality
- Requires Charge Dissipation Strategy
- ✓ Quantification Possible
- ✓ We choose metal deposition for “two for one” solution and cost concerns
- ✓ Conducting polymers are viable if not cost prohibitive. Necessary for very high resolution.
- Tool and substrate specific

Thank you!

Acknowledgements

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