Floating c-Si Thin Films for Solar Cells

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NCCAVS 2012

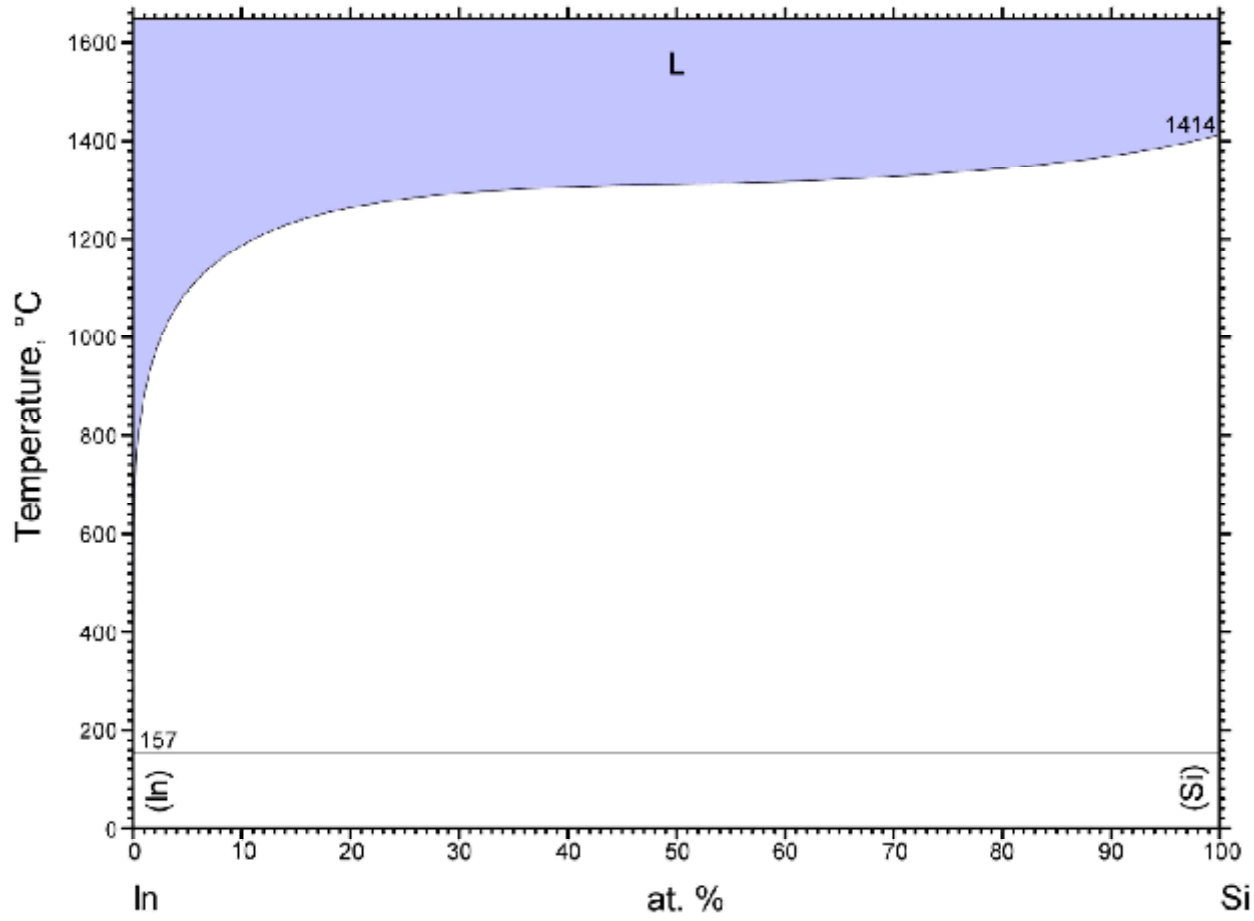
February 22, 2012

FFG CONCEPT

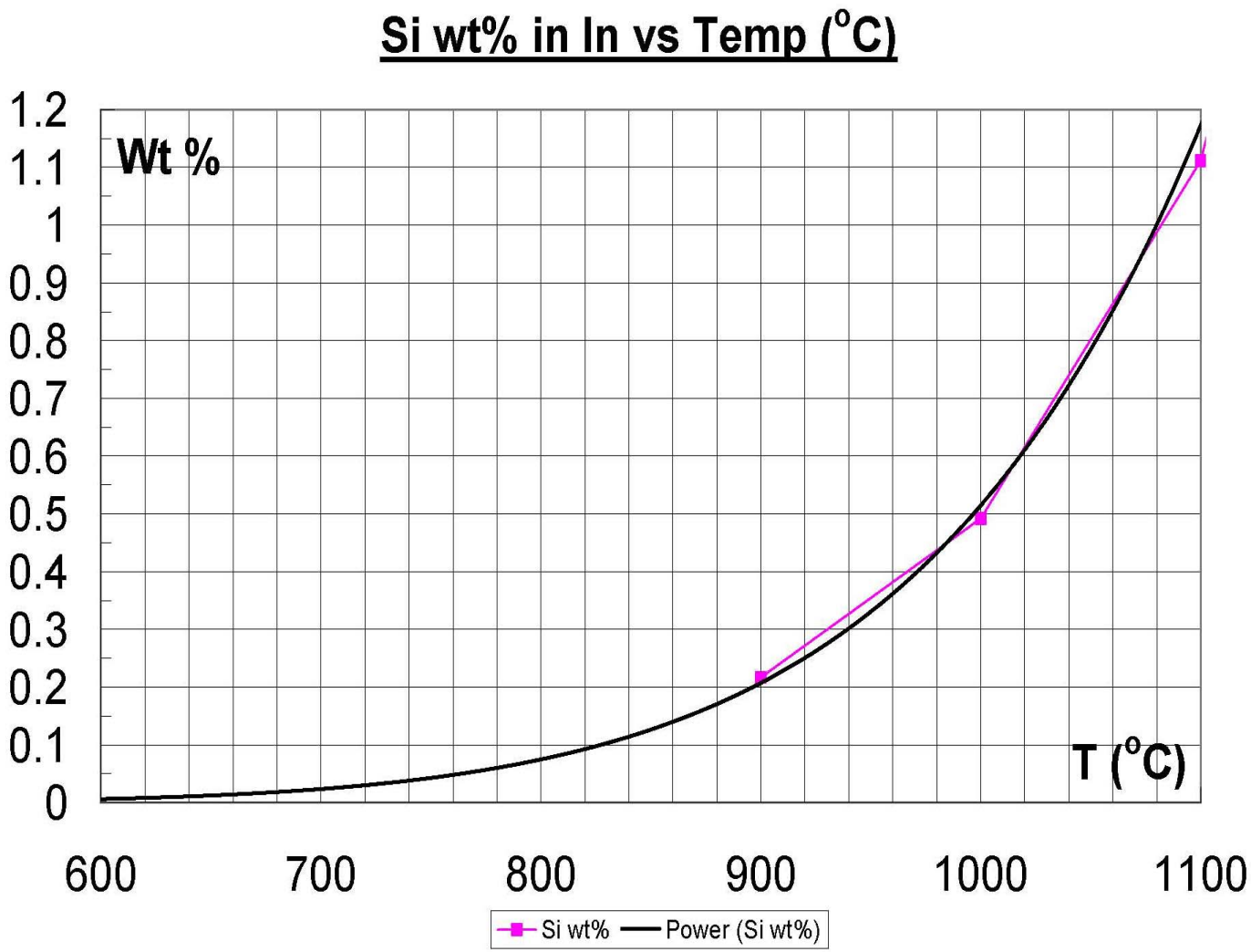
- Dissolve Si-source in molten In or Sn bath at T_2, where 800ºC ≤ T_2 ≤ 1,000ºC
- Cool molten bath to T_1, where T_1«T_2
- Due to lower solubility of Si at T_1 than at T_2, Si separates (or is driven) out of solution, and
- Due to lower density of Si than that of the molten bath, Si floats to the top surface of the molten metallic bath
- During cooling, Si grows as a floating Si-foil, along the direction of its thickness
- Growth at the Interface is free of interfacial stress (like space growth), producing extra large grains (or single crystalline) flat and smooth Si-foil essentially free of dislocations

In-Si Phase Diagram

Indium-Silicon Binary Alloy Phase Diagram (based on 1990 Olesinski R.W.)



Partial In-Si Phase Diagram



FFG RIBBON CONCEPT

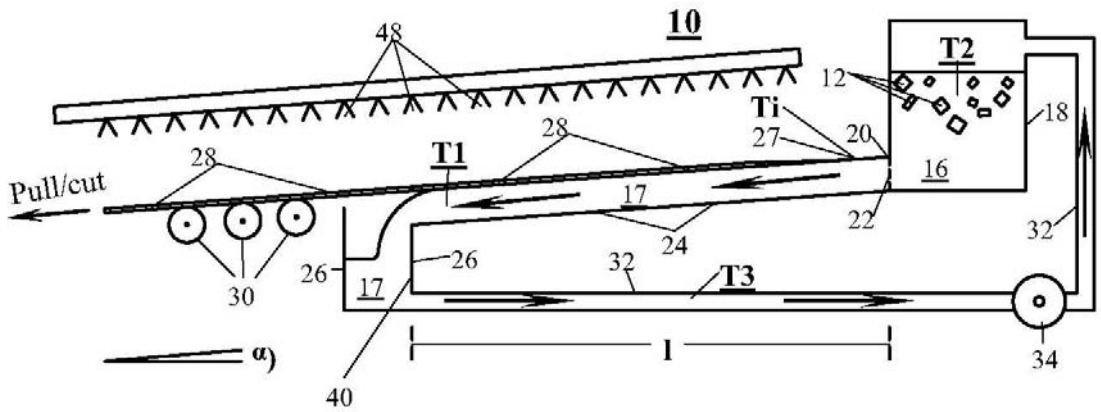


Figure 1A

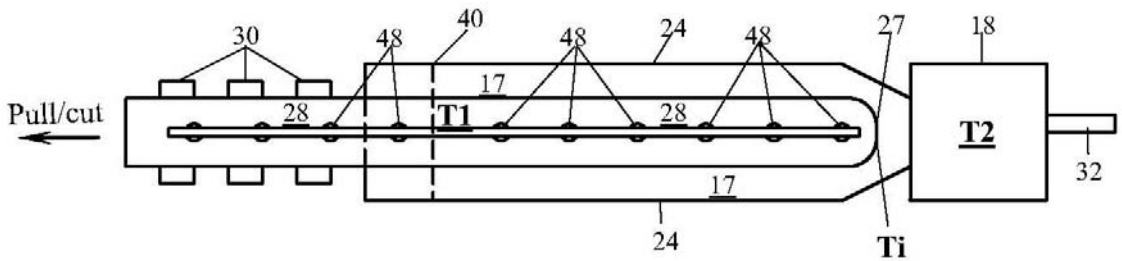


Figure 1B

FFG PANEL (SHEET) CONCEPT

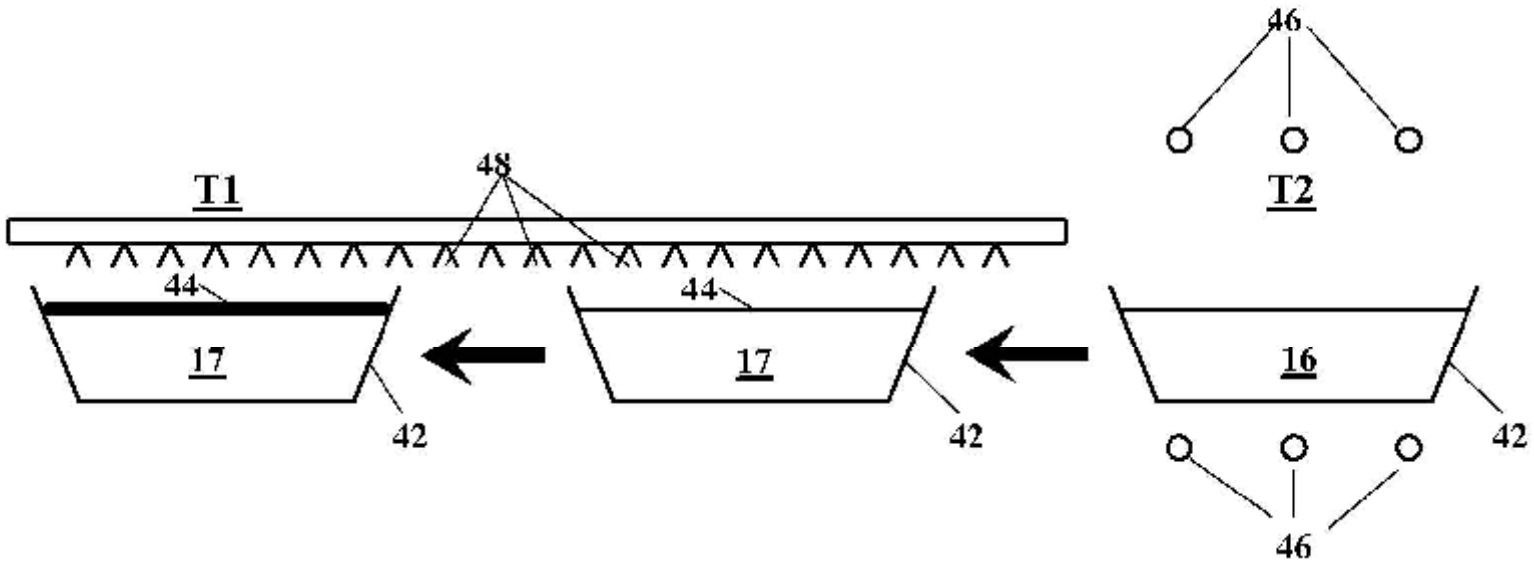


Figure 3

PROSPECTS

- **Since growth of FFG Si-foil takes place across the entire foil/bath interface, in the direction of the foil thickness, foil production rate can be exceptionally high *10-50 m^2/hr* (in a single line).**
- **The authors are not aware of any physical limitations on the width and length of FFG Si ribbons or panels.**
- **Si ribbons or panels with thickness between 50-100μm, width ≥ 1 meter, and length of several meters are anticipated in production**
- ***Si material costs and energy savings are estimated at >80%* compared with conventional sliced wafers.**
- **FFG process is inherently self-purifying, enabling the use of lower grade Si source.**

Proof of Concept Goals

- **Demonstrate growth of a continuous sheet of floating Si-foil from In and/or Sn melt solution**
- **Demonstrate continuous Si-foil on the frozen In and/or Sn melt**
- **Demonstrate separation of the Si-foil from the molten bath**
- **Criteria for success:**
  1. **verify that precipitated Si floats as a continuous Si-foil on top of molten In or Sn**
  2. **grain size ≥10μm**

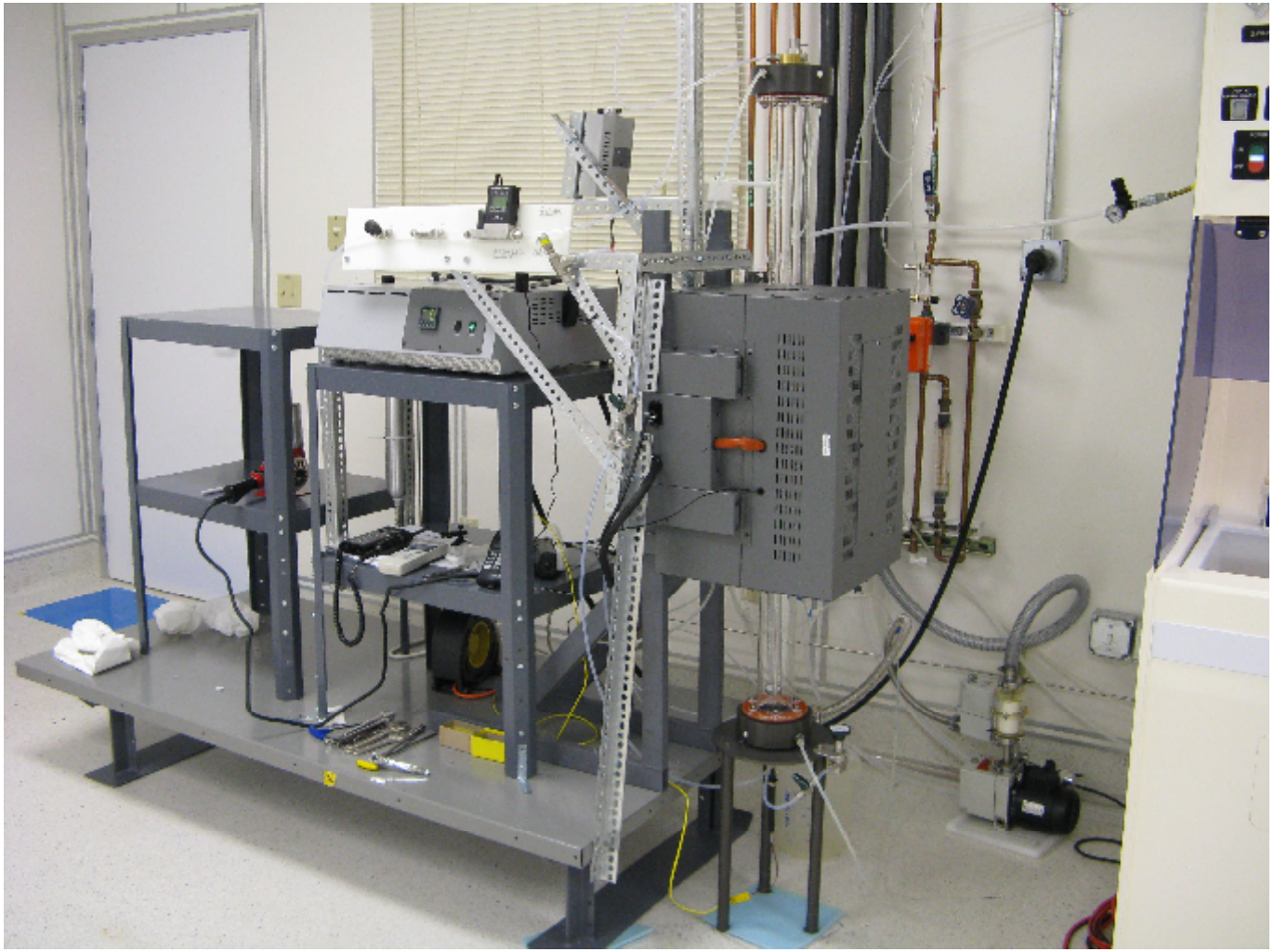
Proof of Concepts Goals (2)

3. **Separate Si-foil from In and/or Sn melt**
4. **Si-foil thickness 50-200μm**
5. **Si-foil purity: ≤ 1000 ppm In or Sn in Si-foil**
6. **Si-foil minority lifetime: ≥ 1.0 μsec, and/or**
7. **Carrier mobility: ≥ 10 $cm^{-2}V^{-1}s^{-1}$**

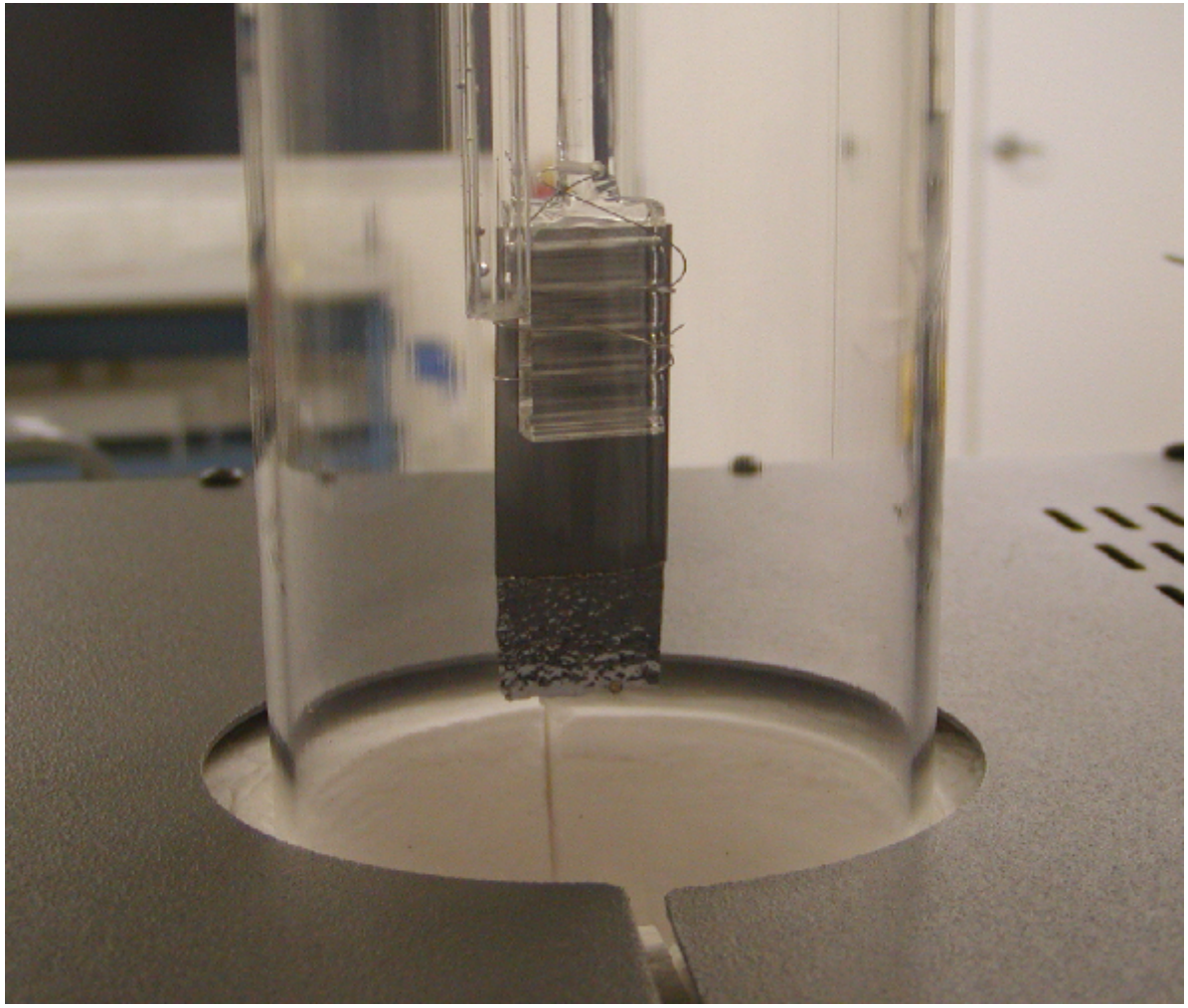
Results

- **Accomplished most of the goals:**
  1. **Demonstrated continuous Si-foil on frozen In bath**
  2. **Demonstrated grain-size ≥ 1000µm (up to 7.4mm)**
  3. **Separated Si-foils using a quartz strainer**
  4. **Demonstrated Si-foil thickness 50-200µm**
  5. **Si-foil purity: In impurities ~14ppb, other impurities < 0.1ppm, oxygen ~1.8ppm, carbon below detection limit (< 50ppb)**
  6. **Mobility: Minority lifetime: > 10 µsec**
  7. **Si-foil properties suitable for solar cell applications**

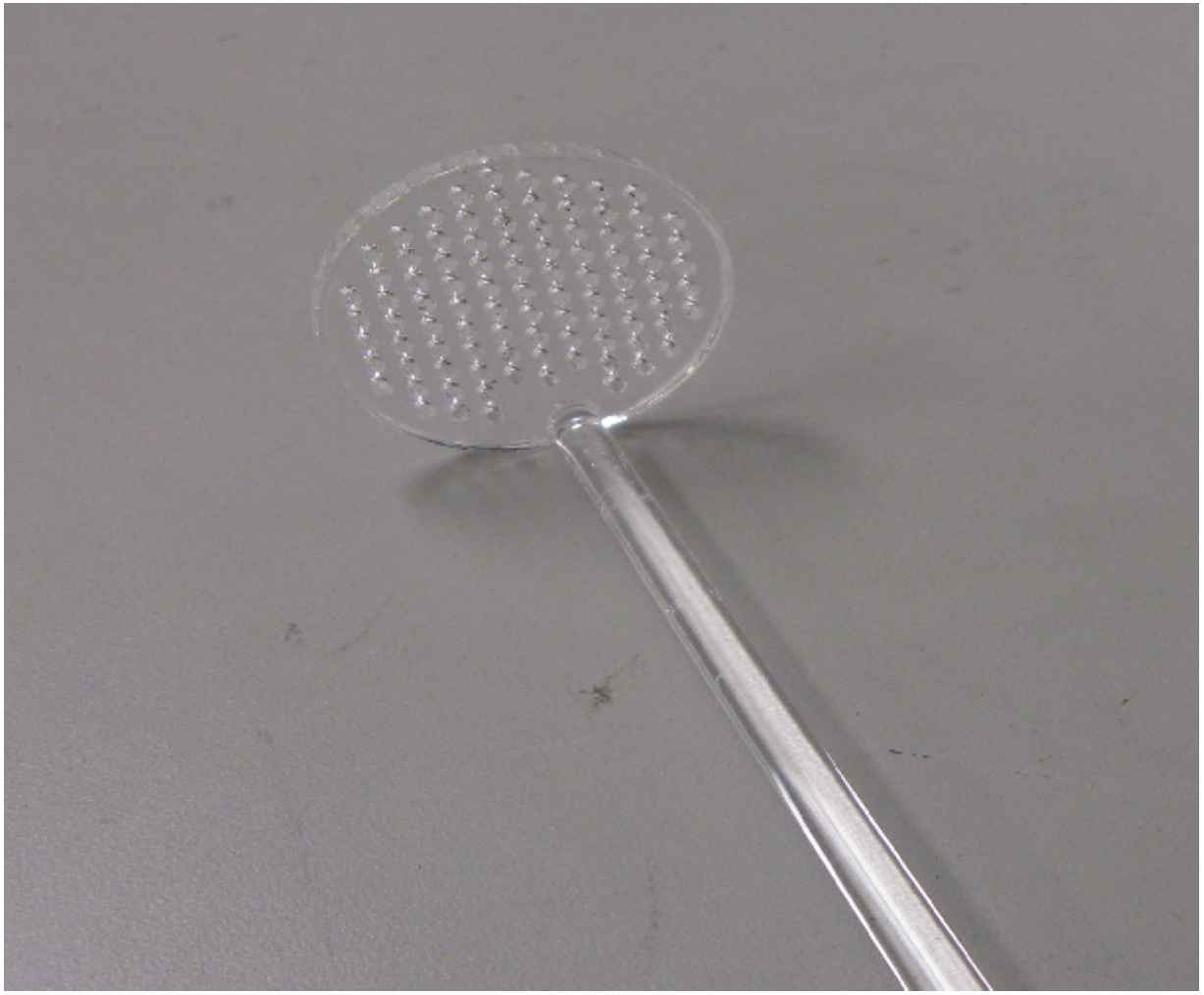
Experimental Set-Up



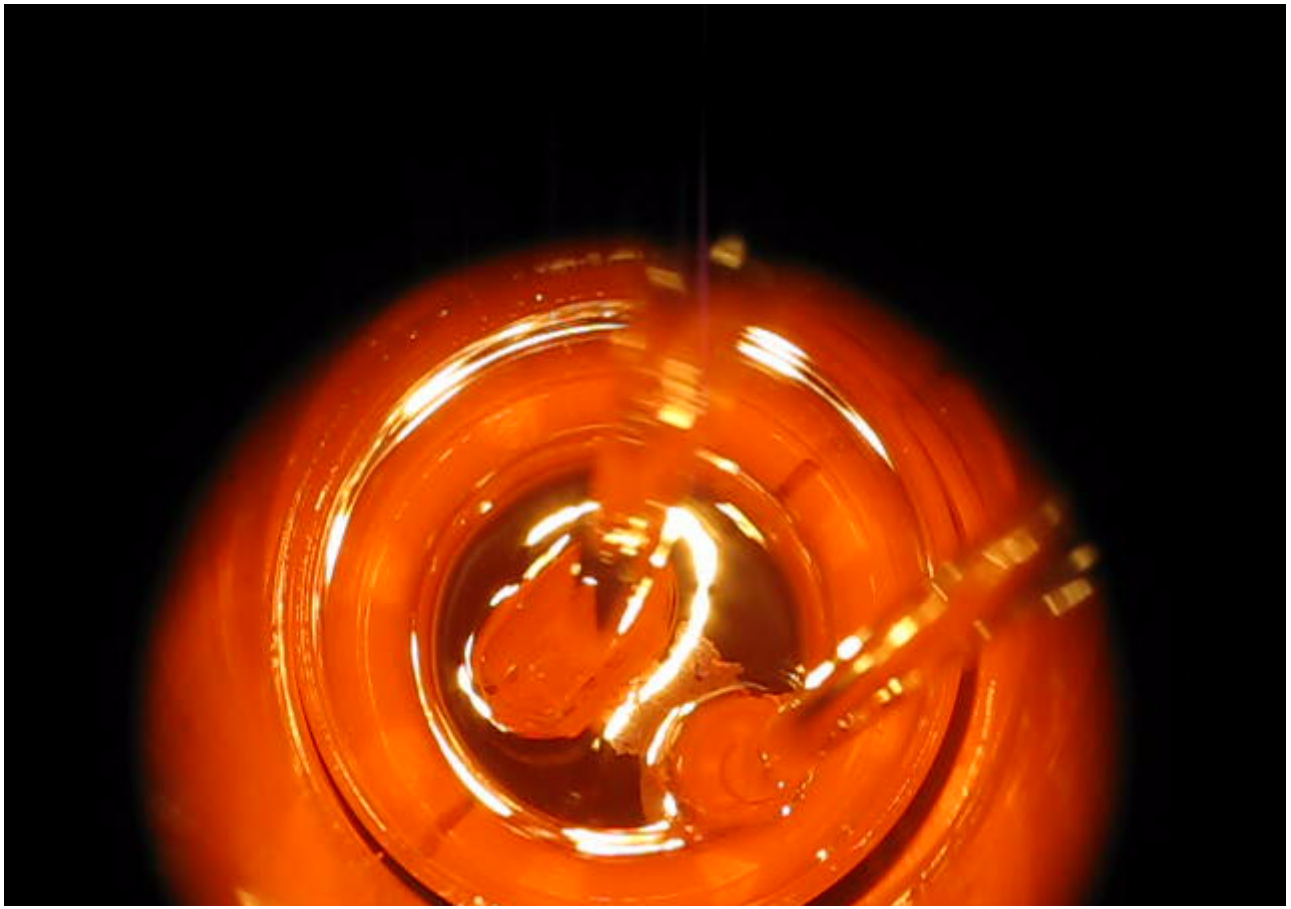
Si-Source



Quartz Strainer

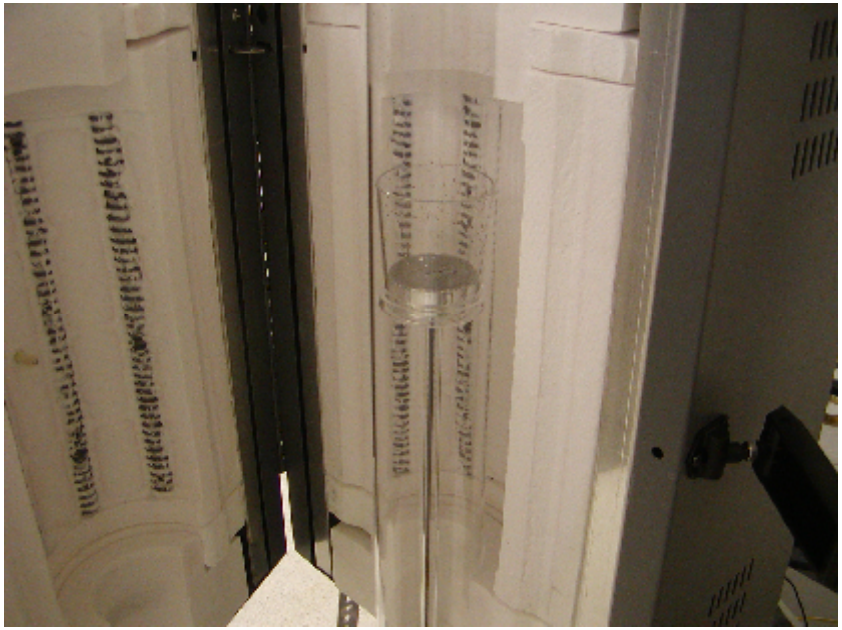


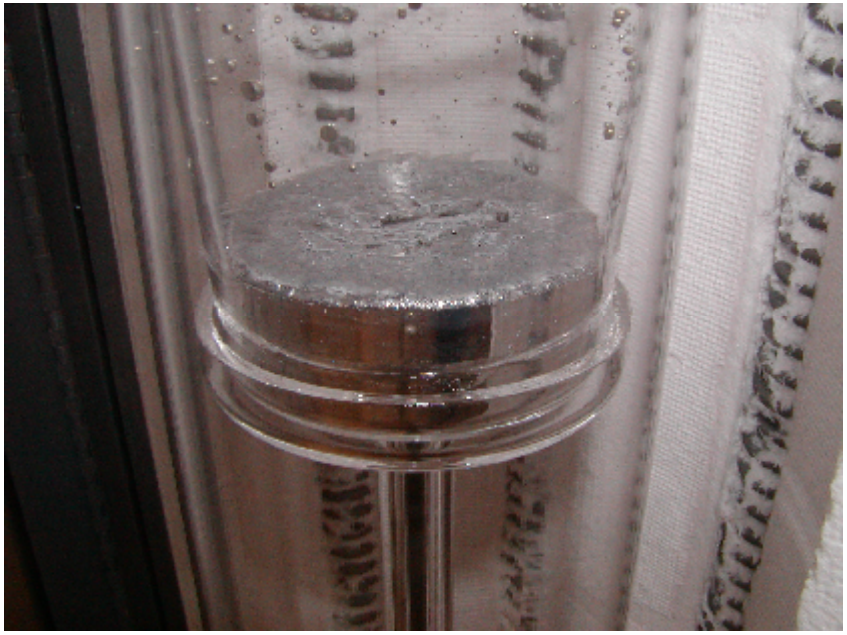
Experiment #150



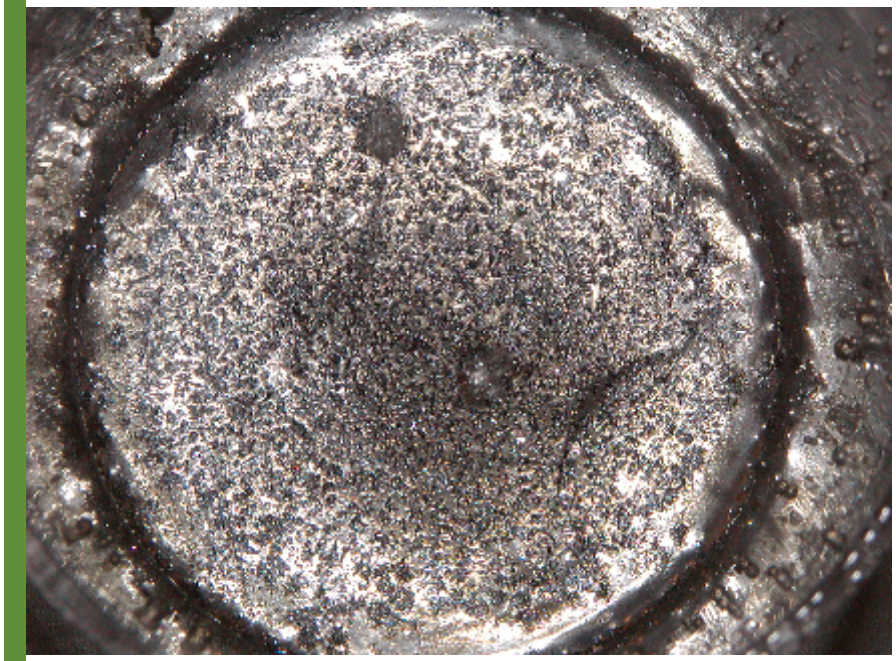
1,000°C; end of Si-source dissolution in In melt. Feb. 27, 2009.

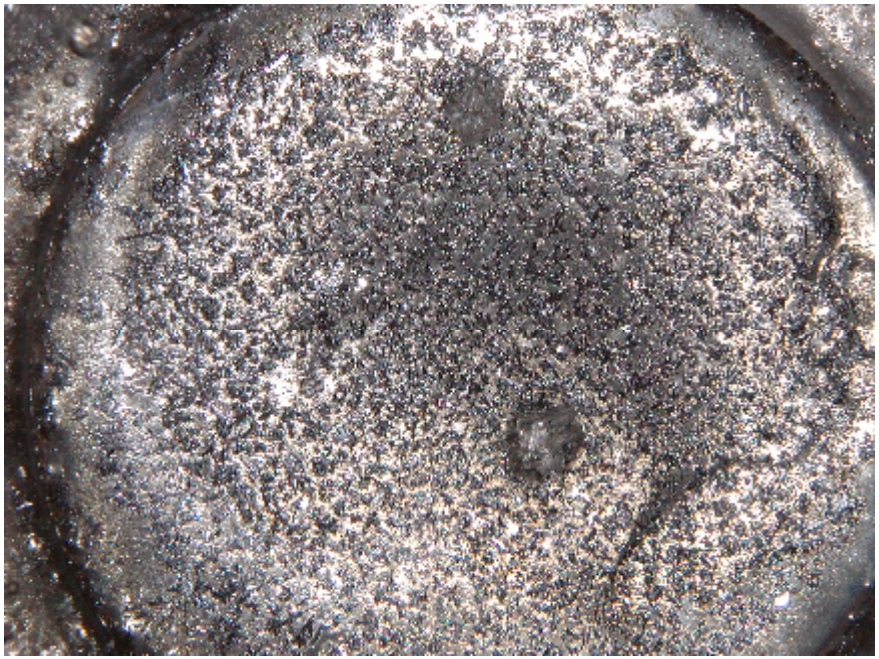
Crucible after Run #07



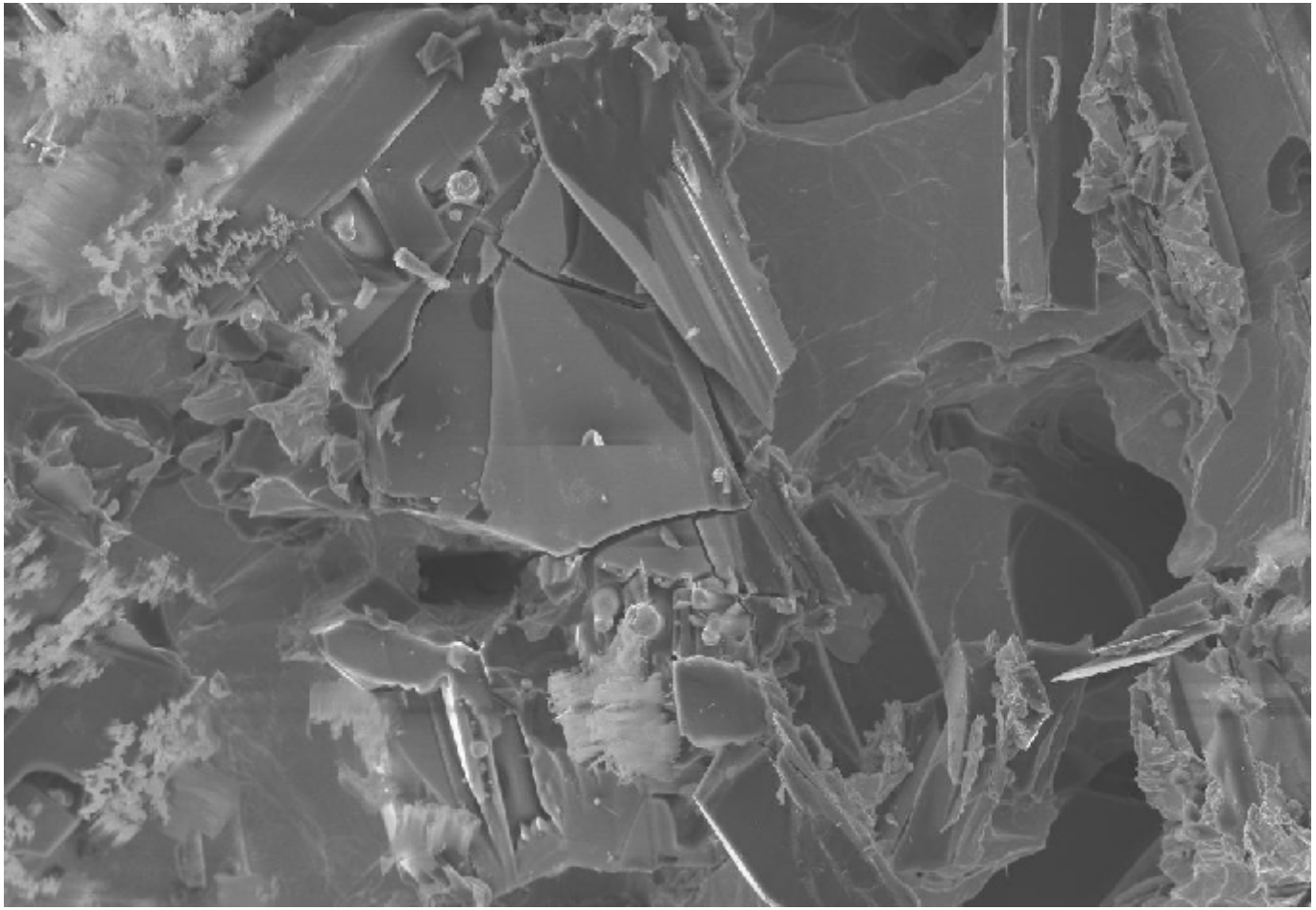


Crucible after Run #07



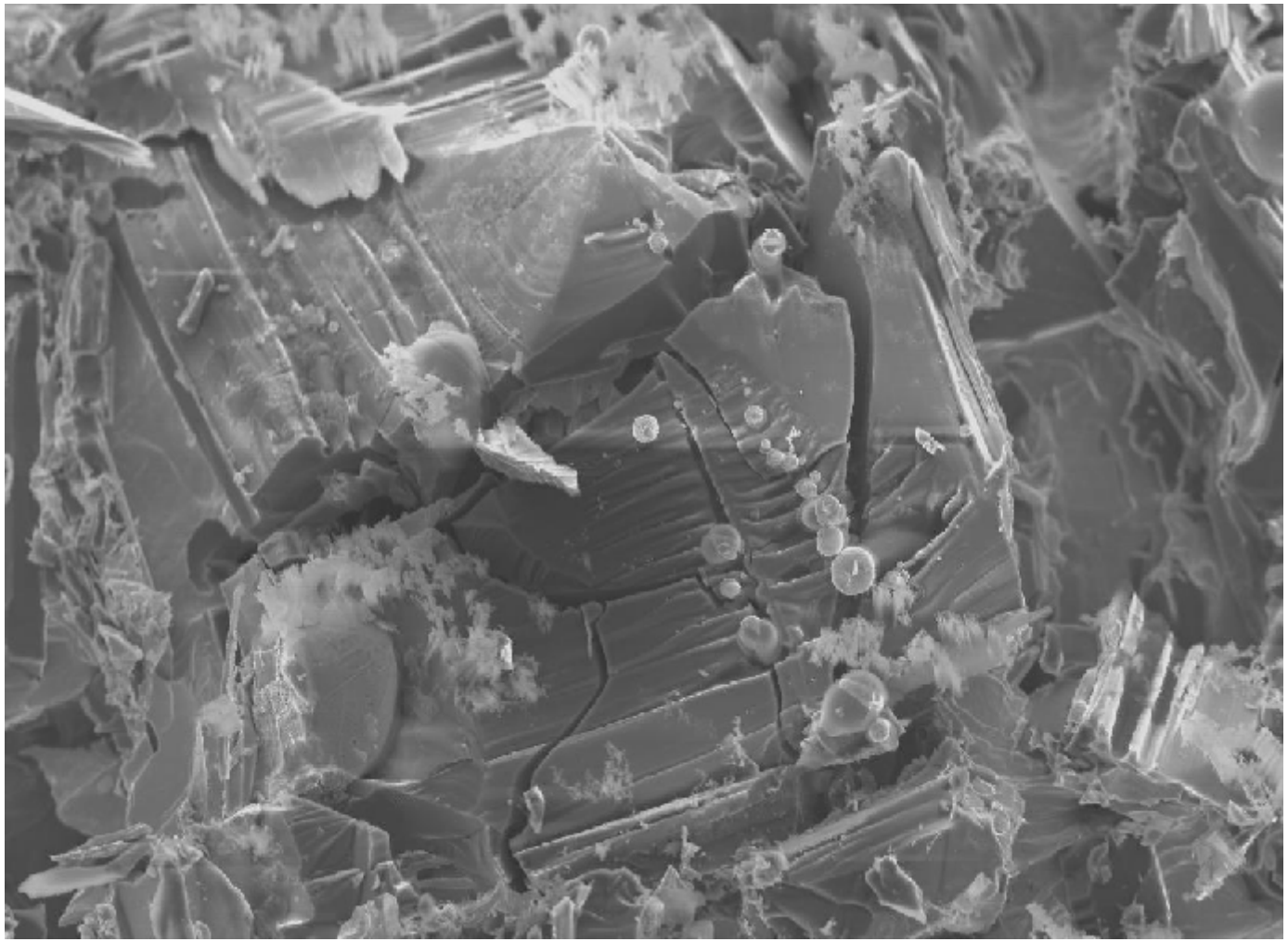


Scrapped Spot 1, Run #07



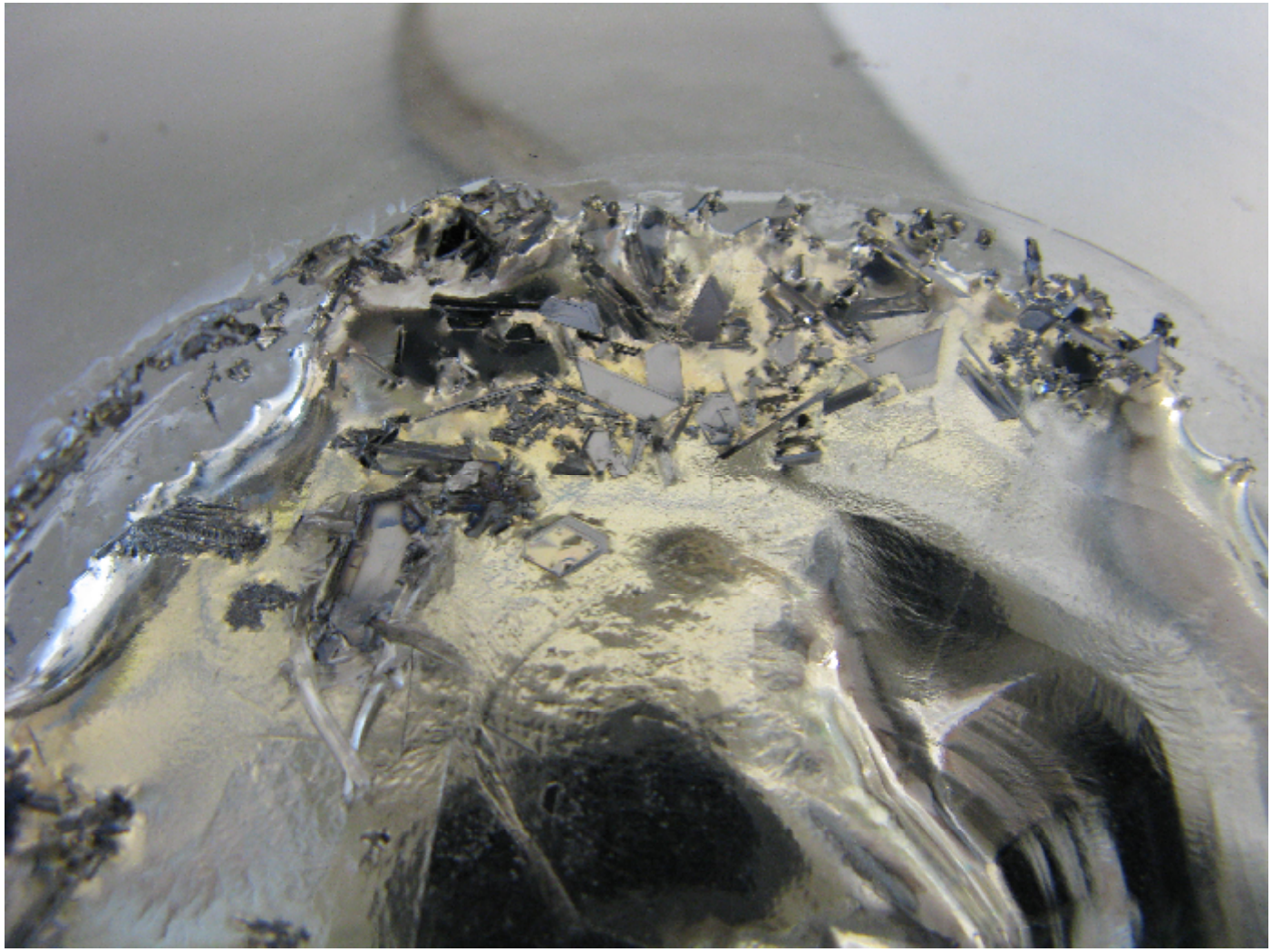
50µm

Scrapped Spot 1, Run #07

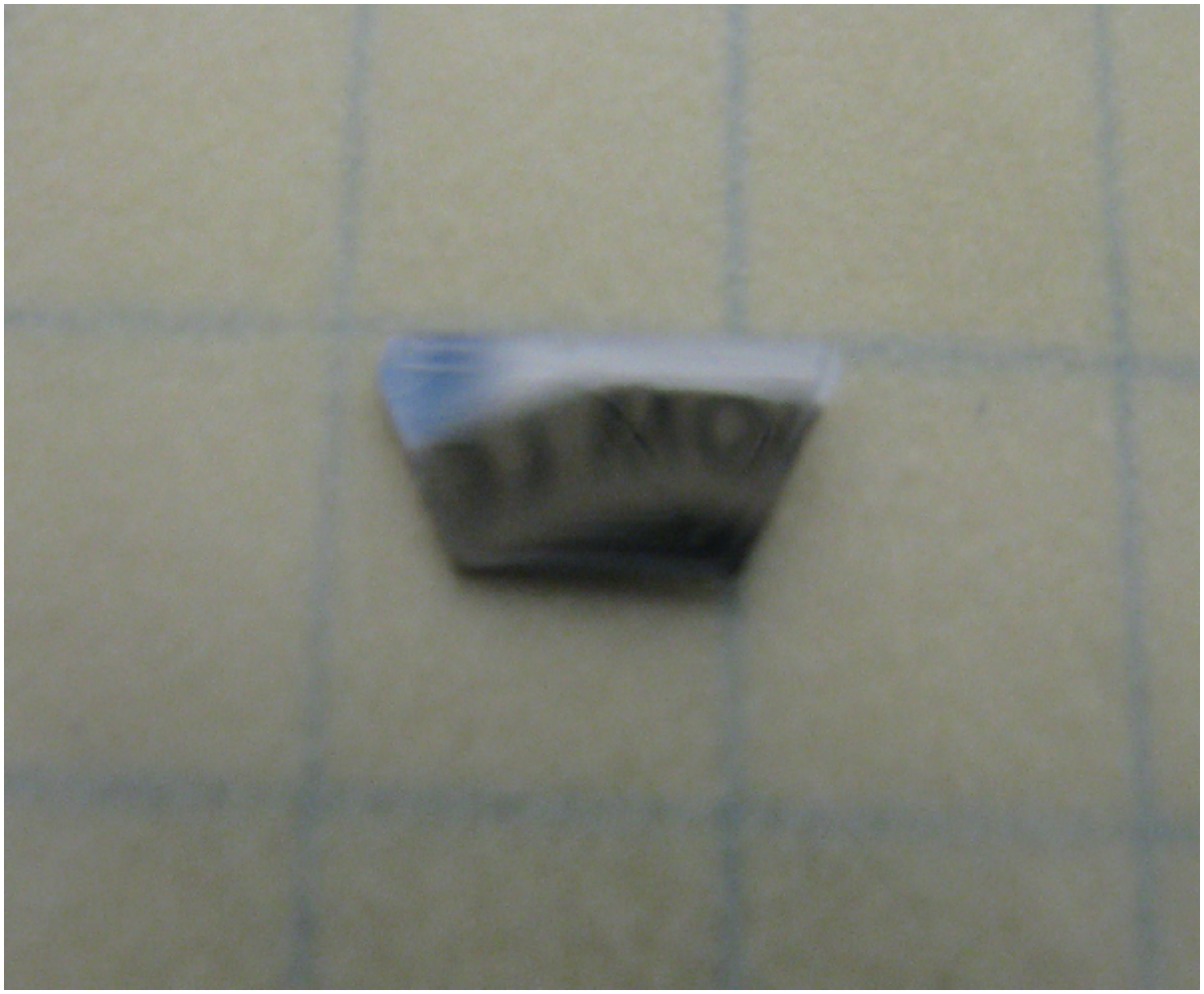


Loc A; 200X

Top View of Crucible Run #120



Run #120



Flat crystal: ~7.4mm long; area ~ 0.18cm^2; ~75µm thick; grid lines 0.25” apart.

LA-ICPMS Elemental Analysis #123

Table 1. Trace elemental concentrations found in silicon sample #123 RTL-123.

Element	Concentration (ppm wt)	Element	Concentration (ppm wt)
Li	< 0.1	In	* Interference
Be	< 0.1	Sn	< 0.1
B	< 0.1	Sb	< 0.1
Na	< 1	Te	< 0.1
Mg	< 0.1	Cs	< 0.1
Al	< 0.1	Ba	< 0.1
Si	Matrix	La	< 0.1
P	< 10	Ce	< 0.1
K	< 1	Pr	< 0.1
Ca	< 1	Nd	< 0.1
Sc	< 0.1	Sm	< 0.1
Ti	< 0.1	Eu	< 0.1
V	< 0.1	Gd	< 0.1
Cr	< 0.1	Tb	< 0.1
Mn	< 0.1	Dy	< 0.1
Fe	< 1	Ho	< 0.1
Co	< 0.1	Er	< 0.1
Ni	< 0.1	Tm	< 0.1
Cu	< 0.1	Yb	< 0.1
Zn	< 0.1	Lu	< 0.1
Ga	< 0.1	Hf	< 0.1
Ge	< 0.1	Ta	< 0.1
As	< 0.1	W	< 0.1
Se	< 0.1	Re	< 0.1
Rb	< 0.1	Os	< 0.1
Sr	< 0.1	Ir	< 0.1
Y	< 0.1	Pt	< 0.1
Zr	< 0.1	Au	< 0.1
Nb	< 0.1	Hg	< 0.1
Mo	< 0.1	Tl	< 0.1
Ru	< 0.1	Pb	< 0.1
Rh	< 0.1	Bi	< 0.1
Pd	< 0.1	Th	< 0.1
Ag	< 0.1	U	< 0.1
Cd	< 0.1		

* Unable to determine value due to contamination from previous testing.

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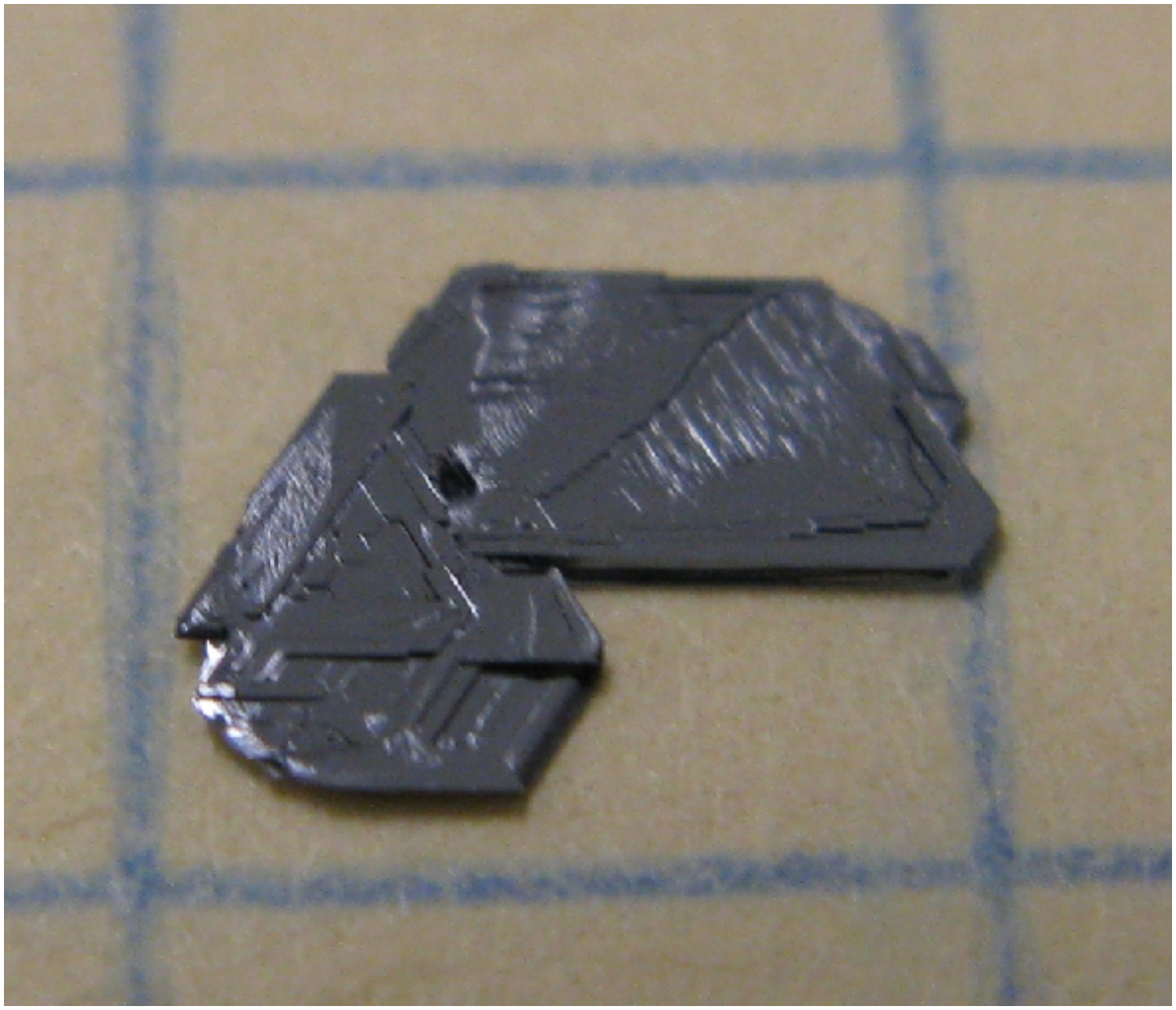
Sample #150 Top Surface

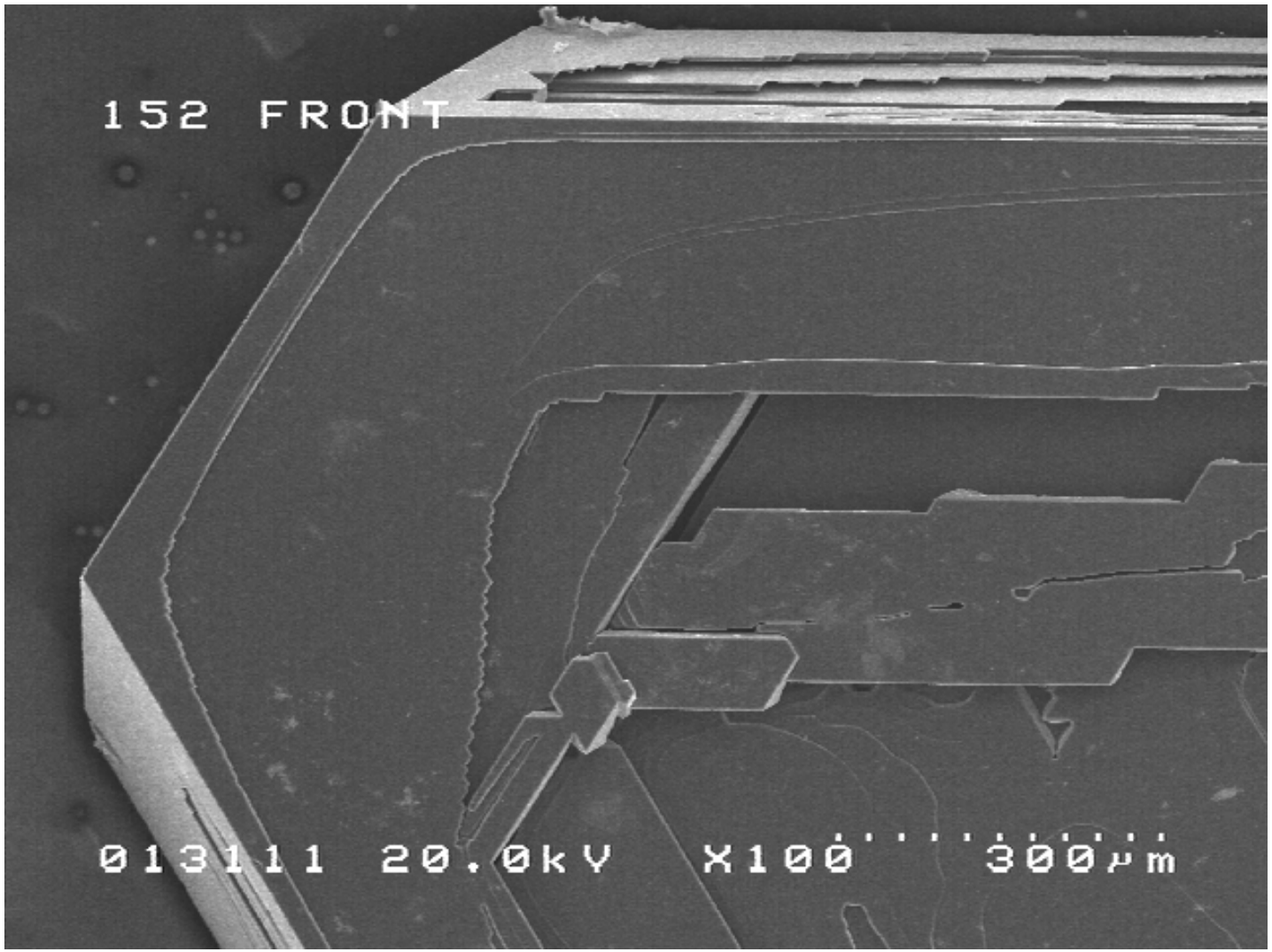
Flat bicrystal: ~7.0mm long; area ~ 0.26cm^2; ~96µm thick.

Sample #150 Bottom Surface

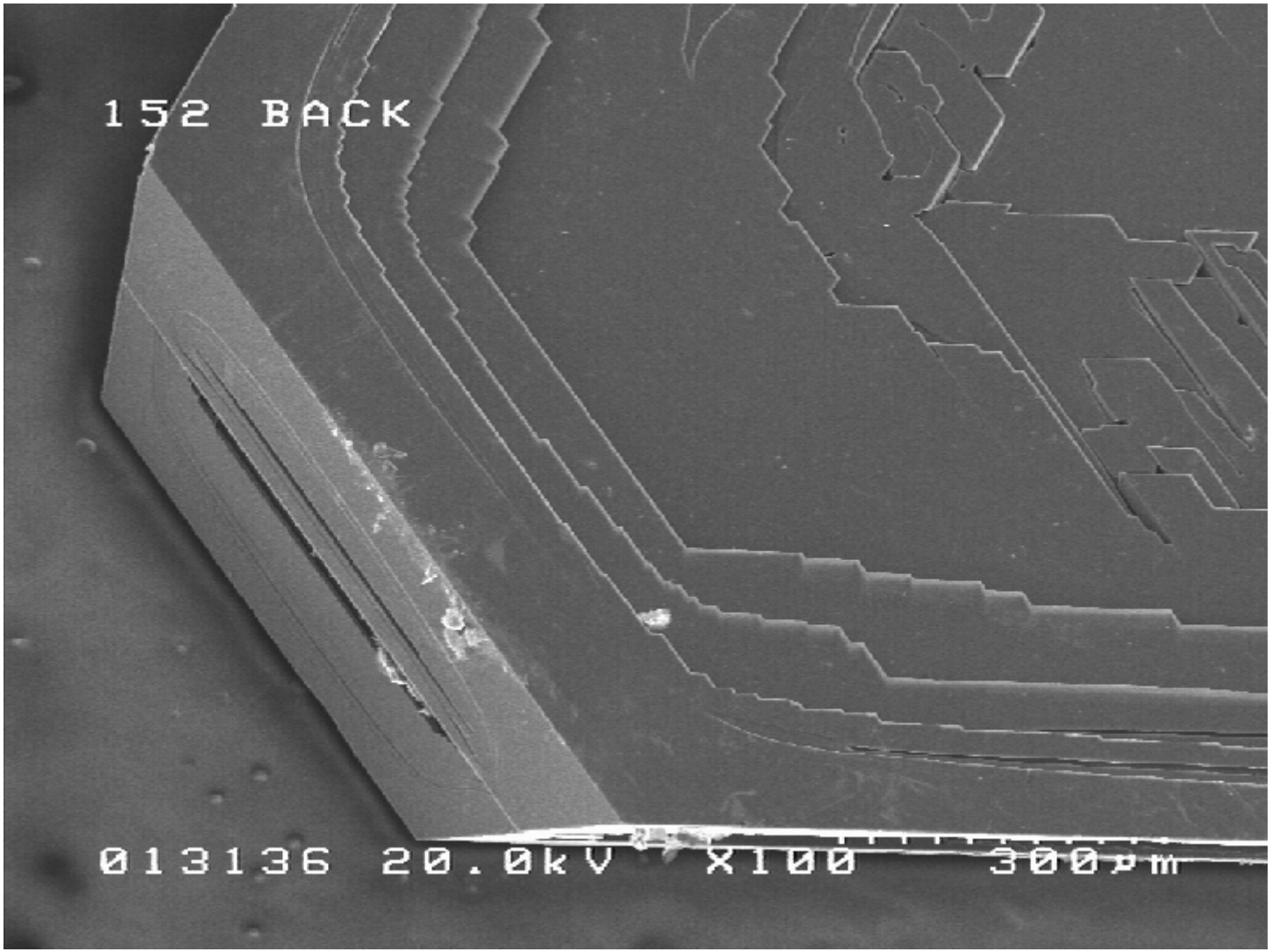


Flat bicrystal: ~7.0mm long; area ~ 0.26cm^2; ~96µm thick.

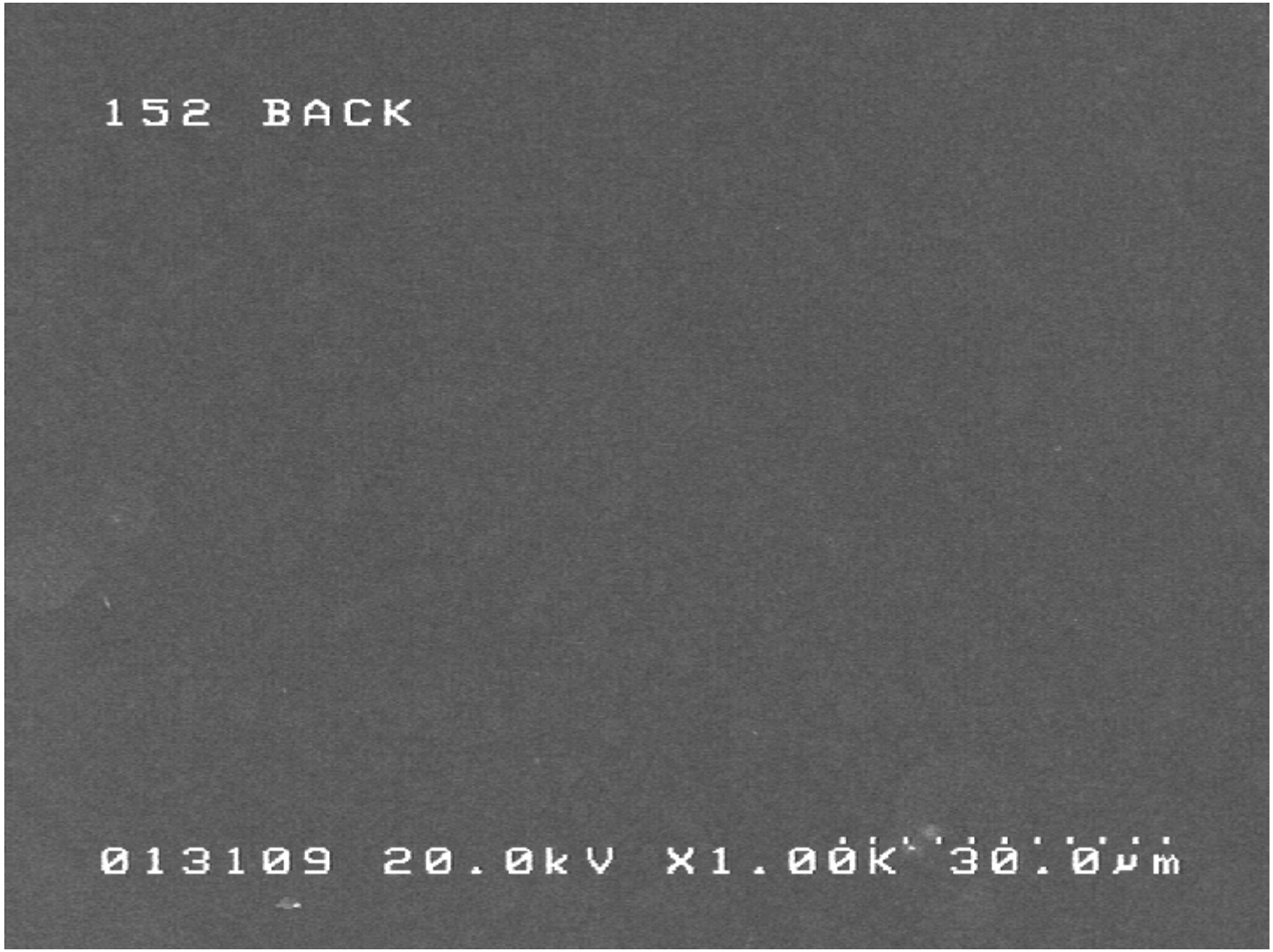
Sample #152 Top Surface



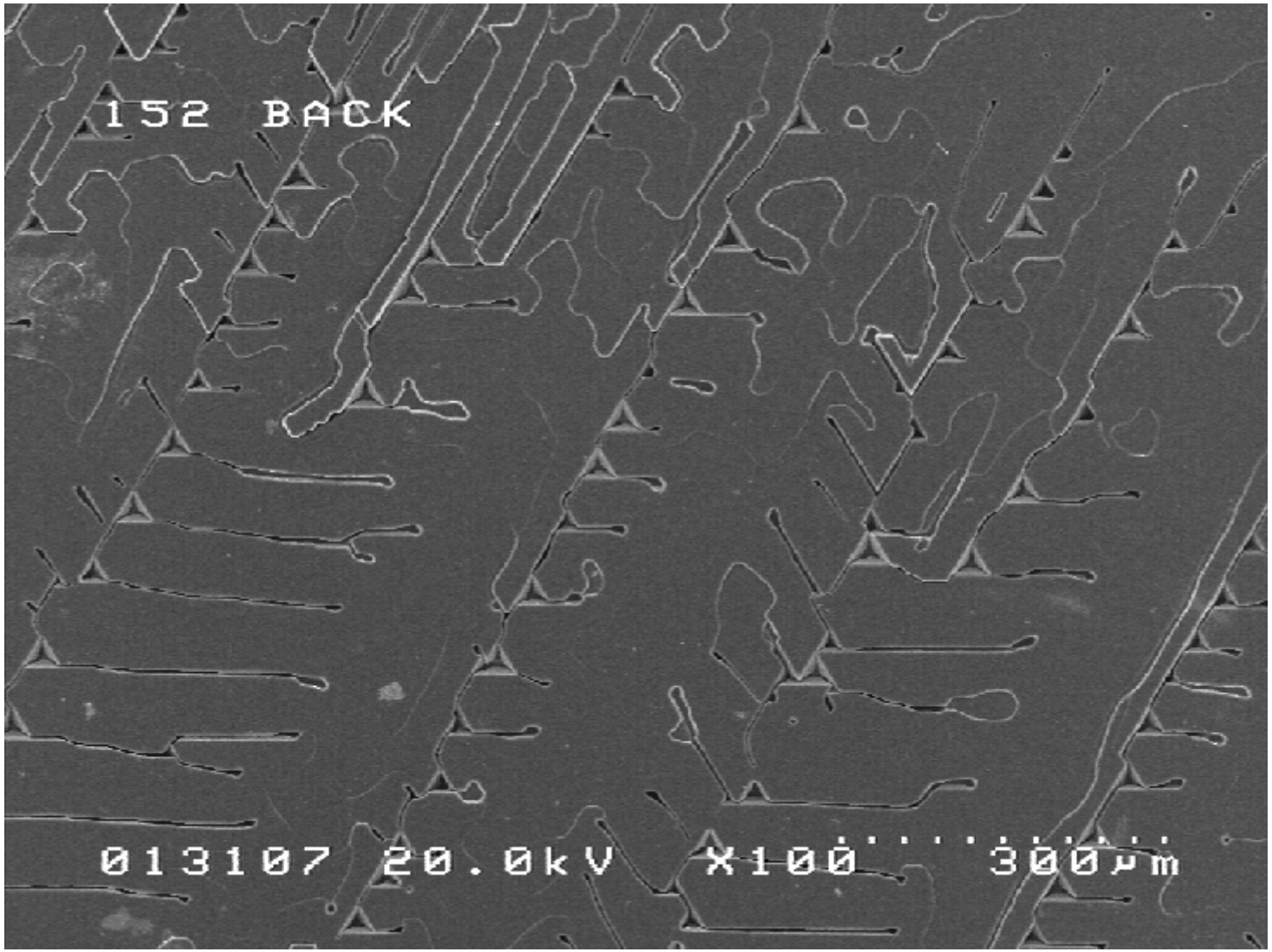
Sample #152 Bottom Surface



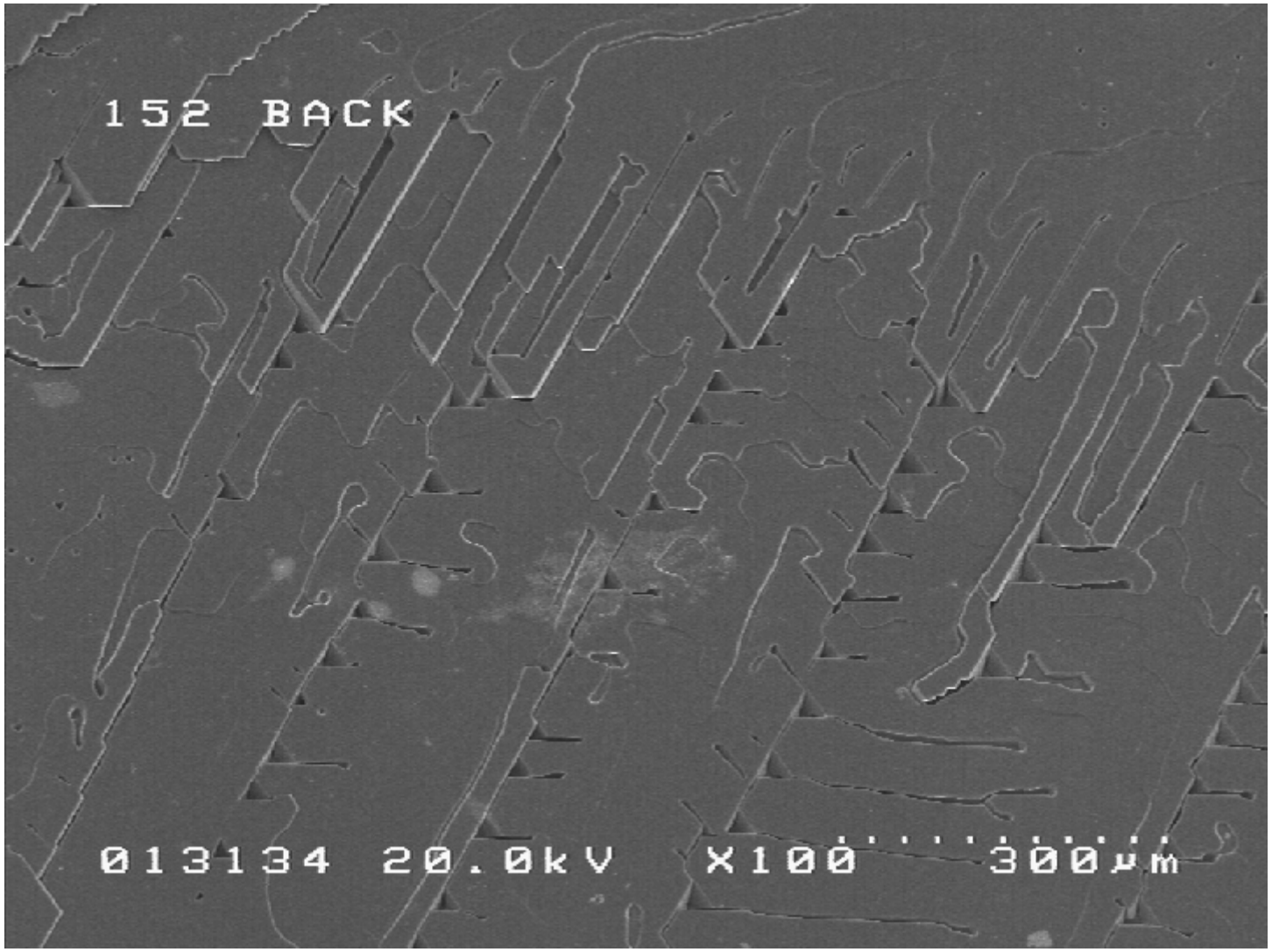
#152 Smooth Bottom Surface



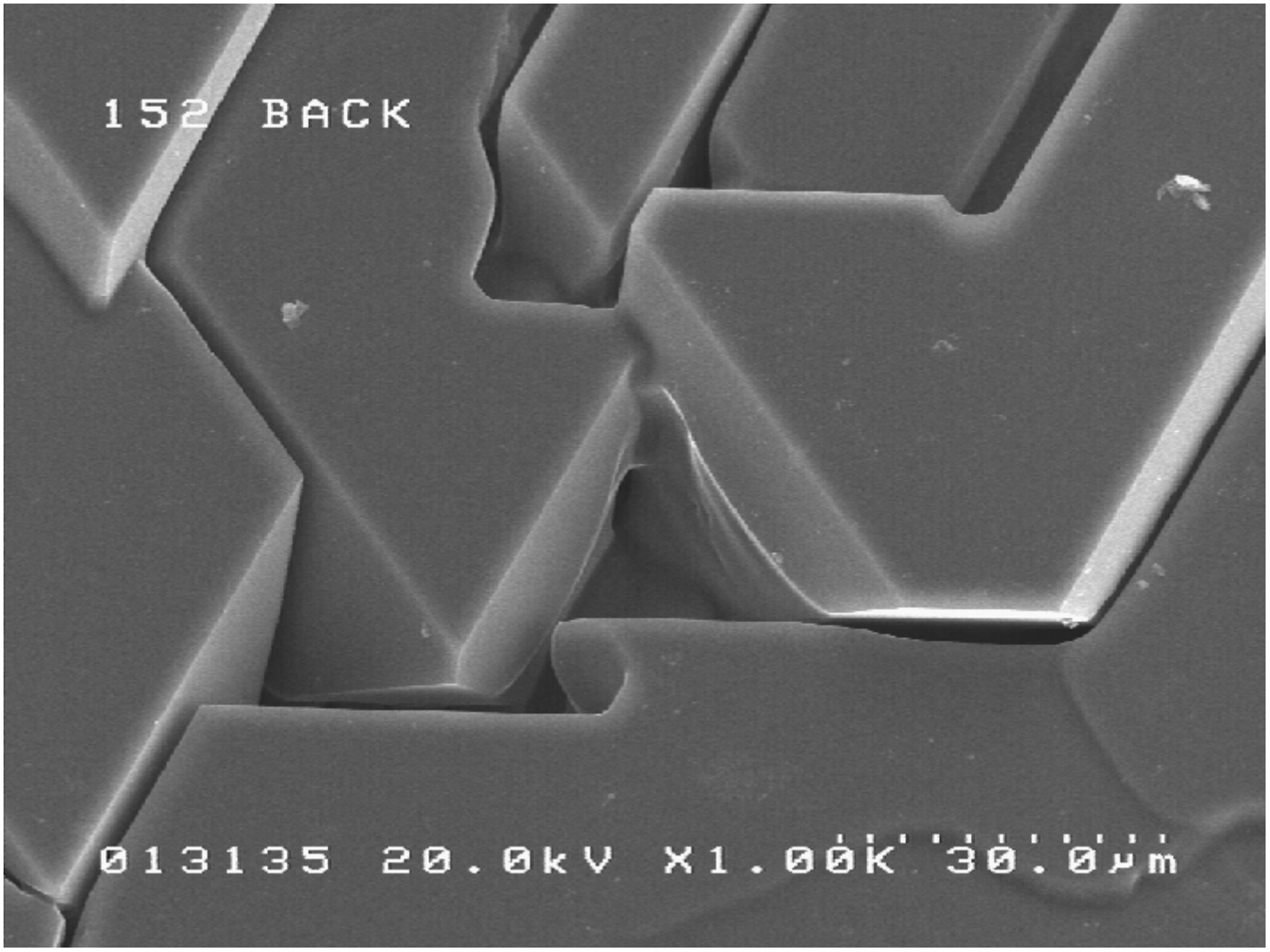
#152 Center Bottom Surface



#152 Center Bottom Surface



#152 Center Bottom Surface



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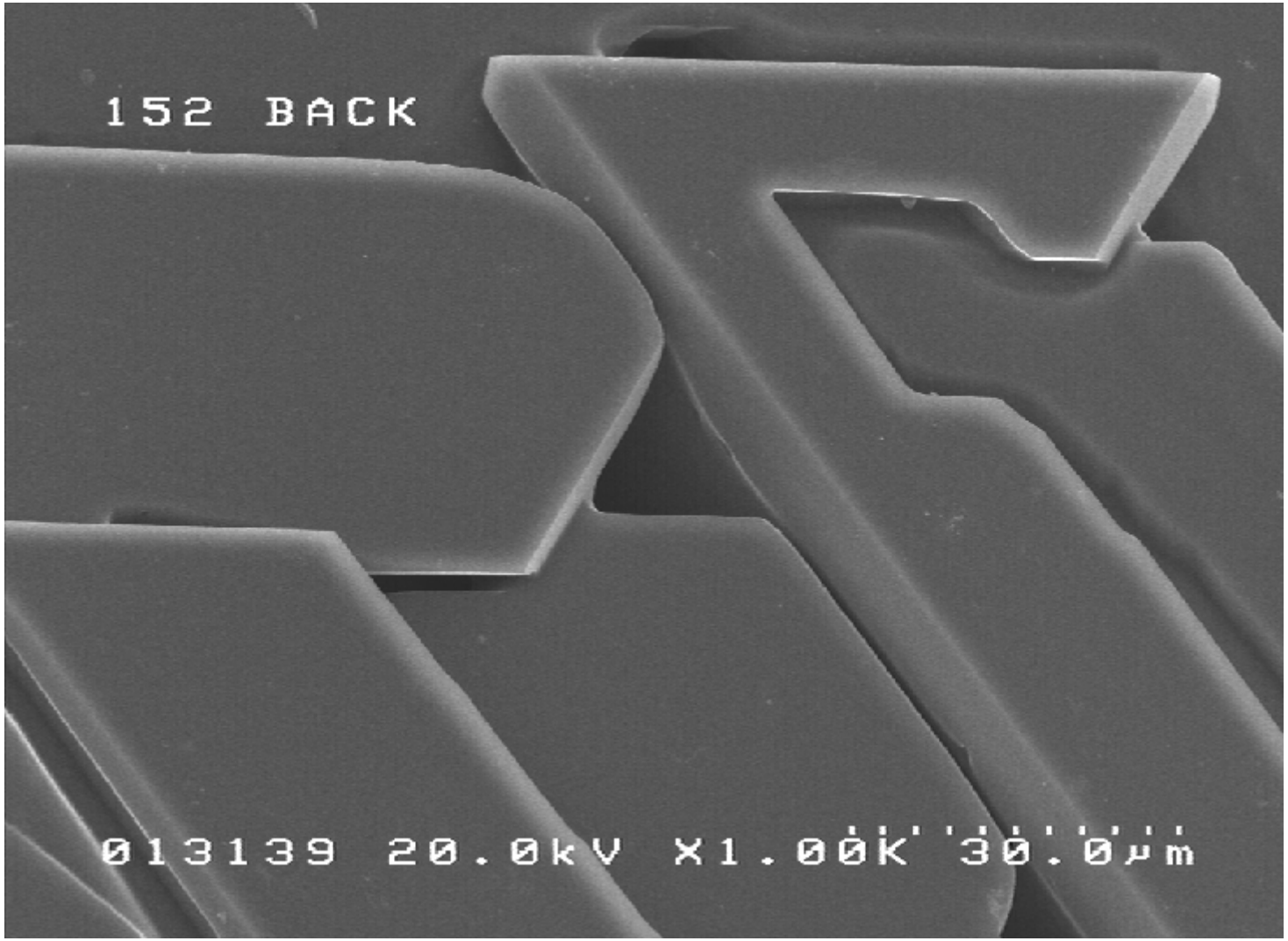
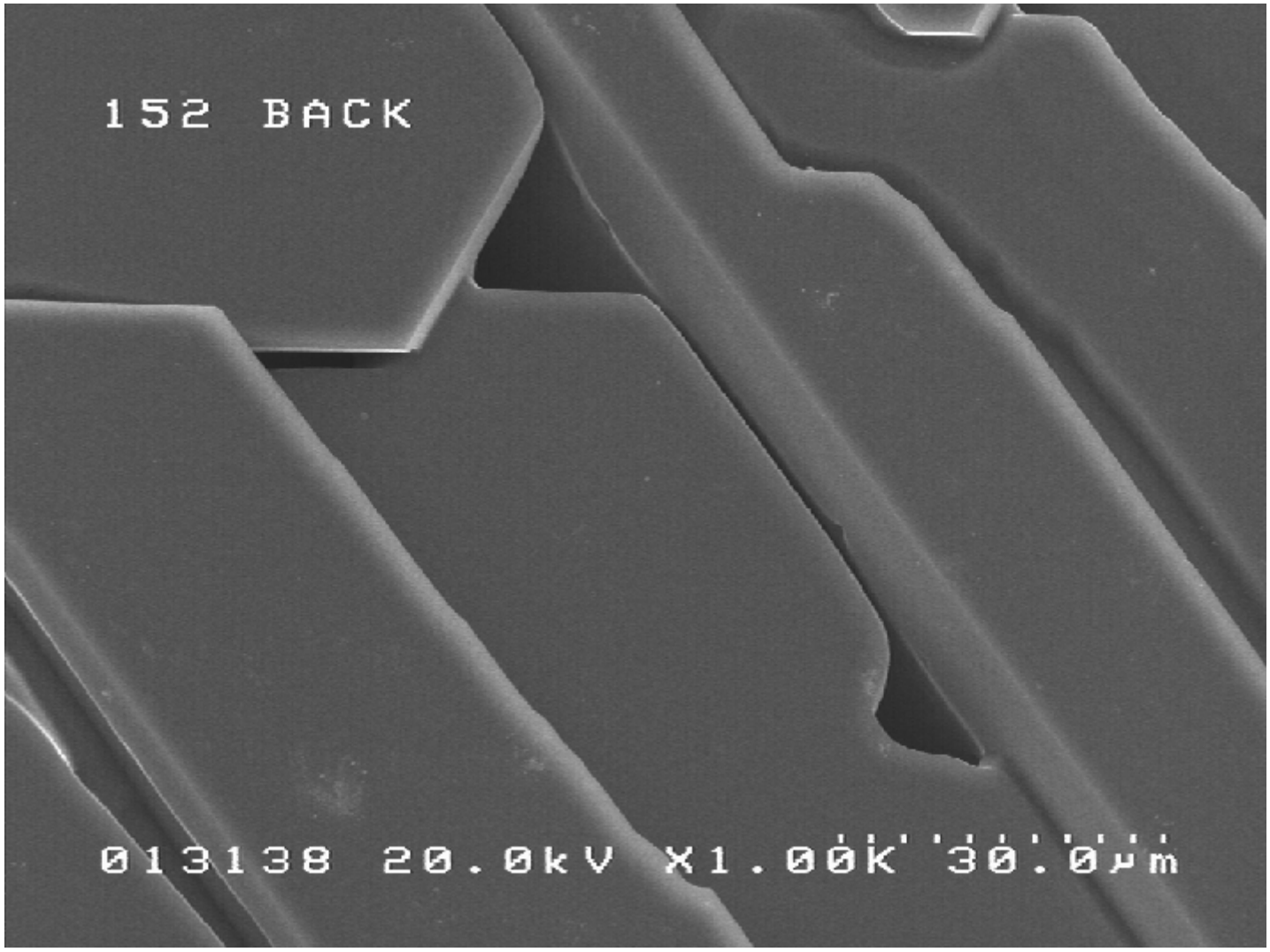


#152 Center Bottom Surface



Summary

- **Continuous floating Si-foils on In melt, of ~30mm diameter size, were demonstrated. Foil thickness was about 50-200μm.**
- **Flat Si crystals > 7mm size were obtained.**
- **EDX and LA-ICPMS analyses indicate very high purity Si material, with most metals Impurity level below 0.1ppm.**
- **SIMS analysis indicates In impurity level as low as 14 ppb! Oxygen ~1.8ppm; C < 50ppb.**
- **Measured minority lifetime > 10 μsec.**
- **The demonstrated Si quality and purity meet requirements for solar cell applications.**

ACKNOWLEDGMENTS

- **This work was done at Ribbon Technology LLC, which is no longer in business.**
- **The authors thank Dr. Richard Swanson, President of SunPower Corporation, for his interest and help.**

REFERENCES

1. U. Cohen, Patent Pending.
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3. ASM Alloy Phase Diagrams, Diagram No. 901409 (Olesinski 1990), ASM International, 2006.
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