National Space and Missile Materials Symposium
Madison, Wisconsin
June 27-30, 2011

Material Development of Faraday Cup Grids for the Solar Probe Plus Mission

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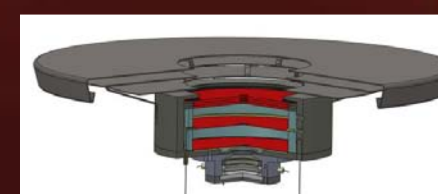
Solar Wind Electrons Alphas and Protons (SWEAP) for the Solar Probe Plus Mission



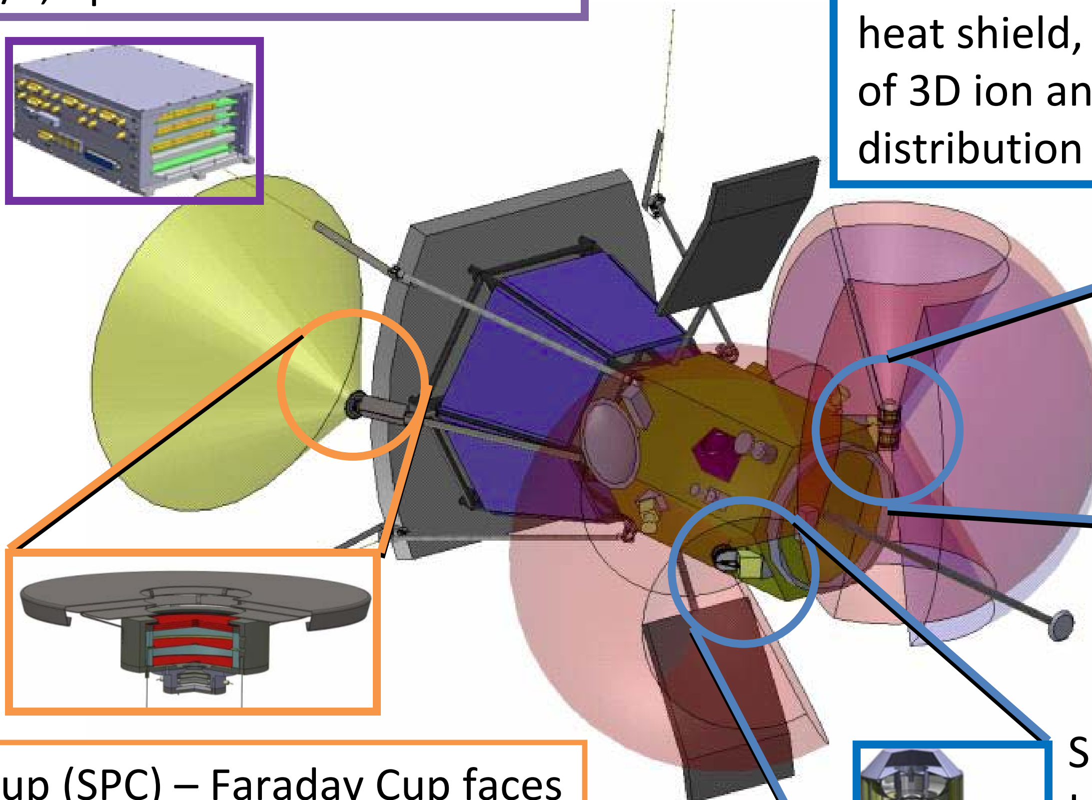
SWEAP Measurements

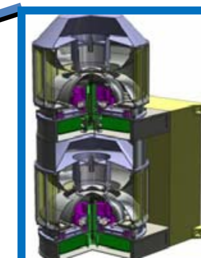
- SWEAP provides the observations of particle velocity distribution functions (VDFs) needed to understand coronal heating and solar wind acceleration
- SWEAP is a two-instrument suite that makes detailed measurements of the electrons, alpha-particles (fully ionized helium), and protons (fully ionized hydrogen) that make up 99% of the solar corona and solar wind
- SWEAP observations map out the number of particles moving at different velocities. These maps are then used to determine, e.g.:
  - Ion velocities, densities, temperatures, anisotropies
  - Electron temperature, anisotropy, heat flux
  - Interactions between particles and electromagnetic waves

The SWEAP Suite: SPC and SPAN

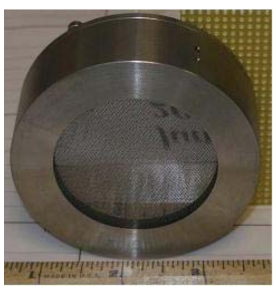
SWEAP Electronics Module (SWEM) – interface to s/c, operates SPC and SPAN

Solar Probe ANalyzers (SPAN) – Electrostatic Analyzers behind the heat shield, detailed measurements of 3D ion and electron velocity distribution functions

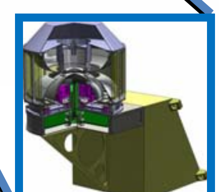




SPAN-A: Looks “ahead”, ions and electrons



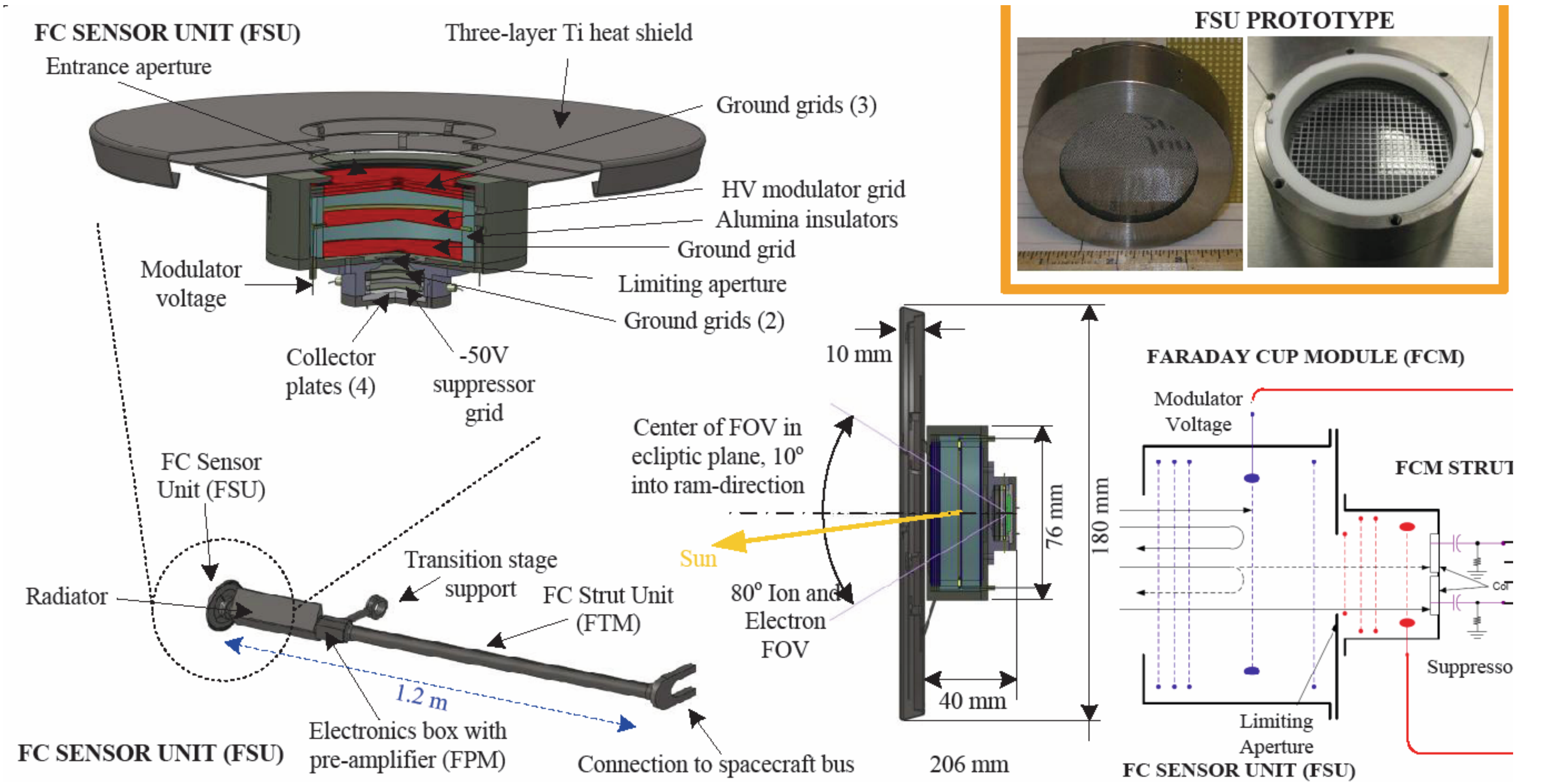
Solar Probe Cup (SPC) – Faraday Cup faces the Sun, high cadence (up to 128 Hz) bulk ion and electron measurements



SPAN-B: Looks “behind”, electrons

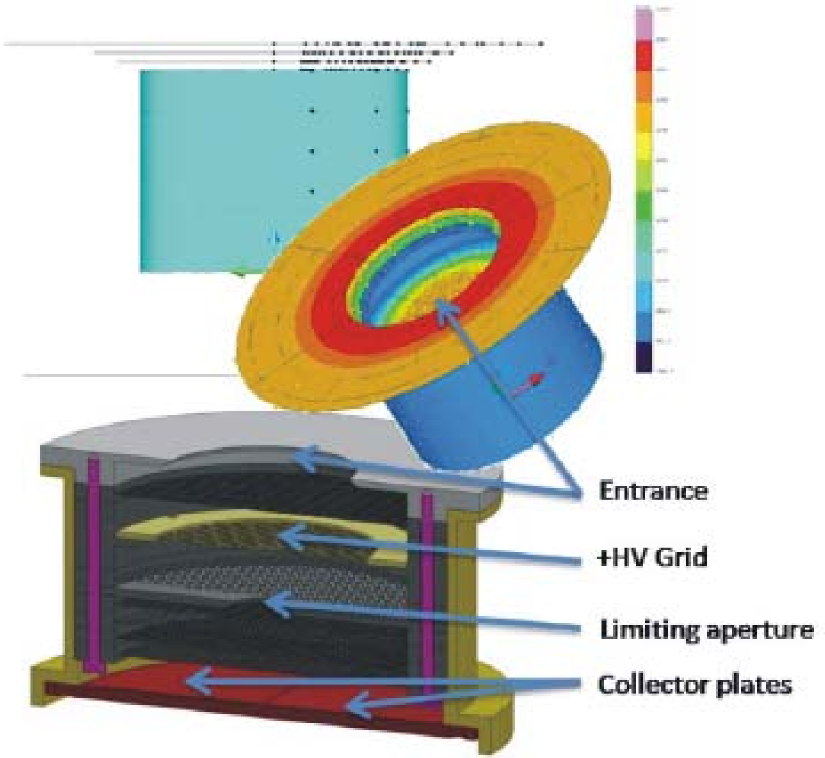
Themis

Solar Probe Cup (SPC) Block Diagram



SPC Grid Requirements

- Operate within 9.5 solar radii
- HV grids biased up to 10 kV
- Operate up to 1400 °C
- High melting temperature
- Low thermionic emission
- Resistance to sputtering
- Sufficient electrical conductivity
- First resonant frequency above 1.5 kHz
- Minimum 85% transparency
- Wire spacings on the order of 100 microns



Evaluation of Materials and Methods for SiC Grid Fabrication

Material options: sintered, chemical vapor conversion (CVC), chemical vapor deposition (CVD)

Processing options: form in final shape, machine, dry etch, wet etch

Several different methods were investigated to fabricate SiC grids

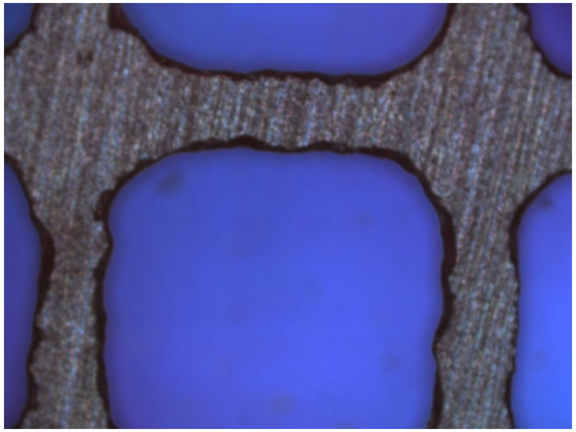
- SiC Hexaloy machining: rough grid pattern which may be too susceptible to fracture
- β-CVD SiC machining: Only partial machining possible through SiC before sample breaks apart
- Chemical Vapor Conversion Process: Not considered viable because of potential warpage and physical distortion of part.

✓ **β-CVD SiC dry plasma etching: successful etching of 500 micron deep vias**

Machining of SiC

SiC Hexaloy machining

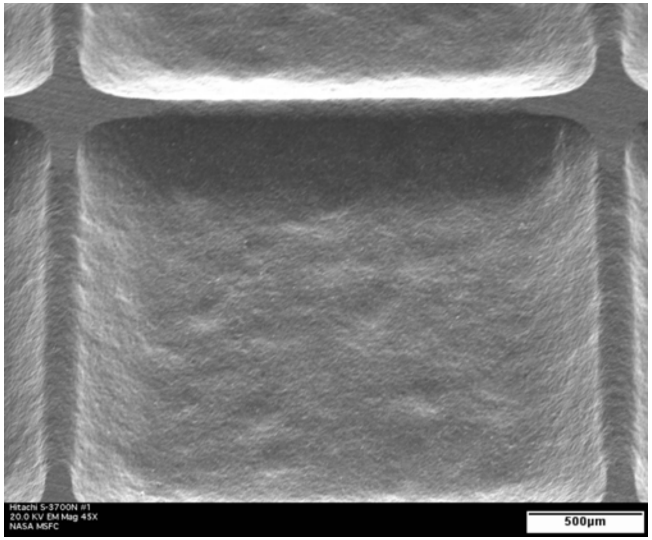
- sintered; non-crystalline
- possibly easier to machine than crystalline SiC
- high resistivity
- possibly more susceptible to sputtering
- could be machined but may be too rough and susceptible to fracture



Hexaloy SiC machined grid

CVD polycrystalline SiC machining

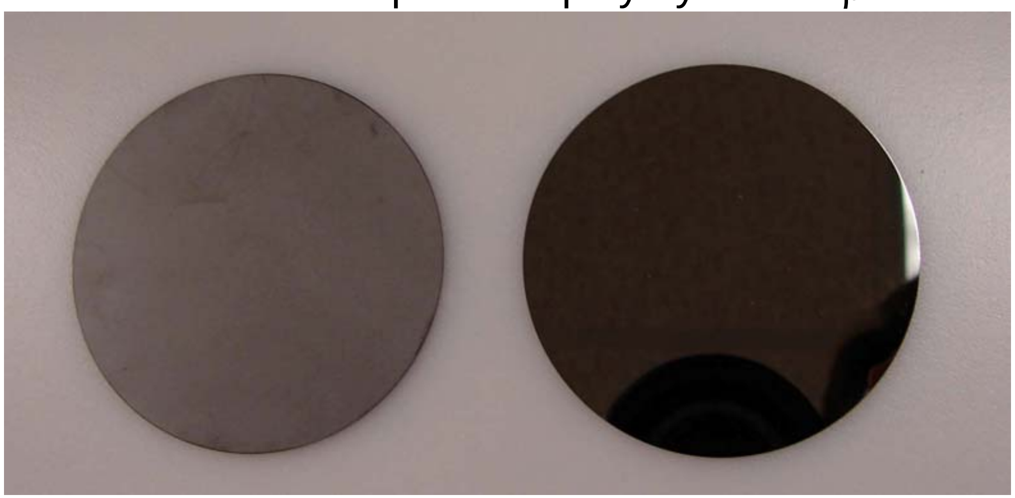
- unable to obtain straight and smooth walls
- Sample would break apart prior to machining all the way through



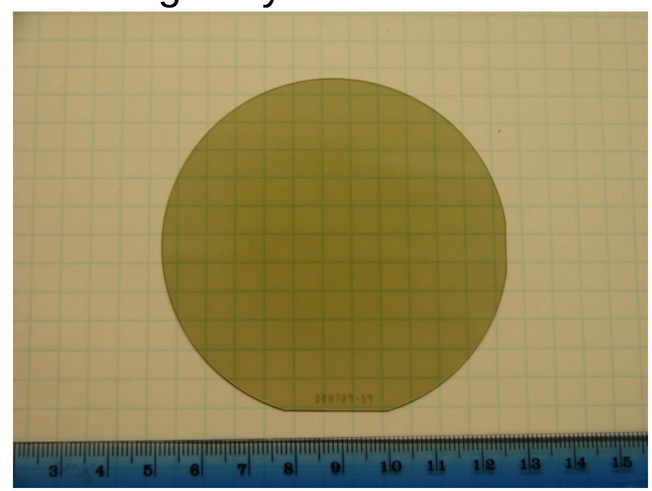
SiC Starting Material

- SiC received from four different vendors
- SiC type: polycrystalline β-SiC and single crystal SiC of the 4H polytype
- polished samples required in order to elucidate any changes that occur to the surface during the various testing phases

As-received and polished polycrystalline β-SiC



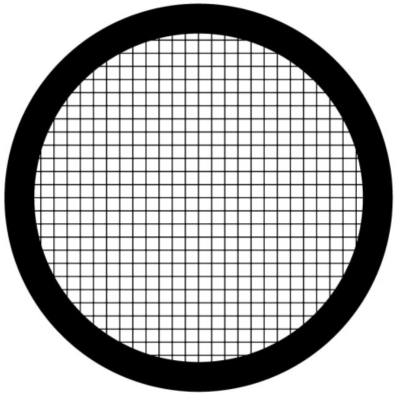
Single crystal 4HN SiC



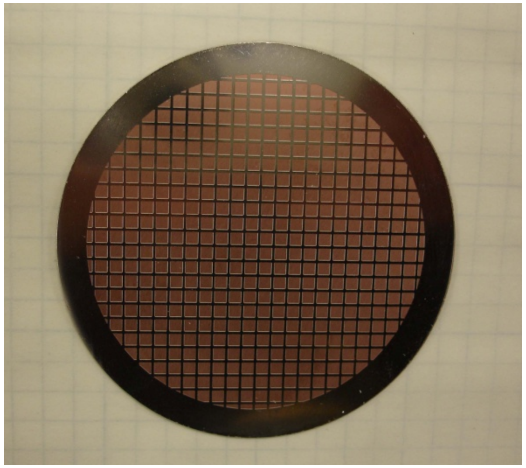
SiC Photolithographic Process

- Create a high-resolution, 50,000 dots/inch photomask
- Deposit metal layers onto the SiC to provide a surface on which the Ni mask will adhere
- Spin on the photoresist, expose the sample to UV through the mylar mask, and bake
- Electrodeposit Ni onto the exposed wires
- Remove Cu layer (and a thin portion of the Ni mask) with a wet etching process

Mylar mask plot



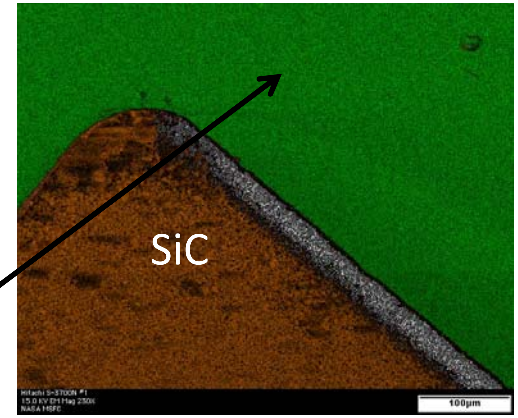
Post photolithography and electrodeposition of Ni



After wet etching

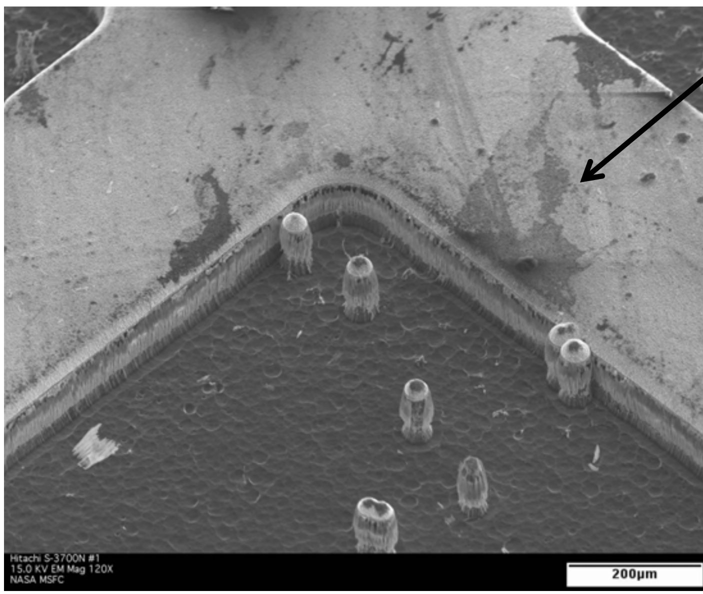
SiC Plasma-Etching Development

- Dry etching – STS Inductively Coupled Plasma (SF_6/O_2)
- Evaluated etching parameters such as chamber bias power and pressure
- Plasma etch rate = 0.5 microns/minute

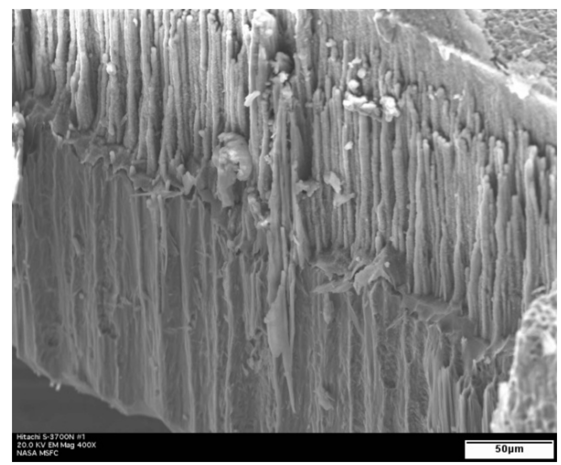


EDX map of partially etched SiC.

Ni mask

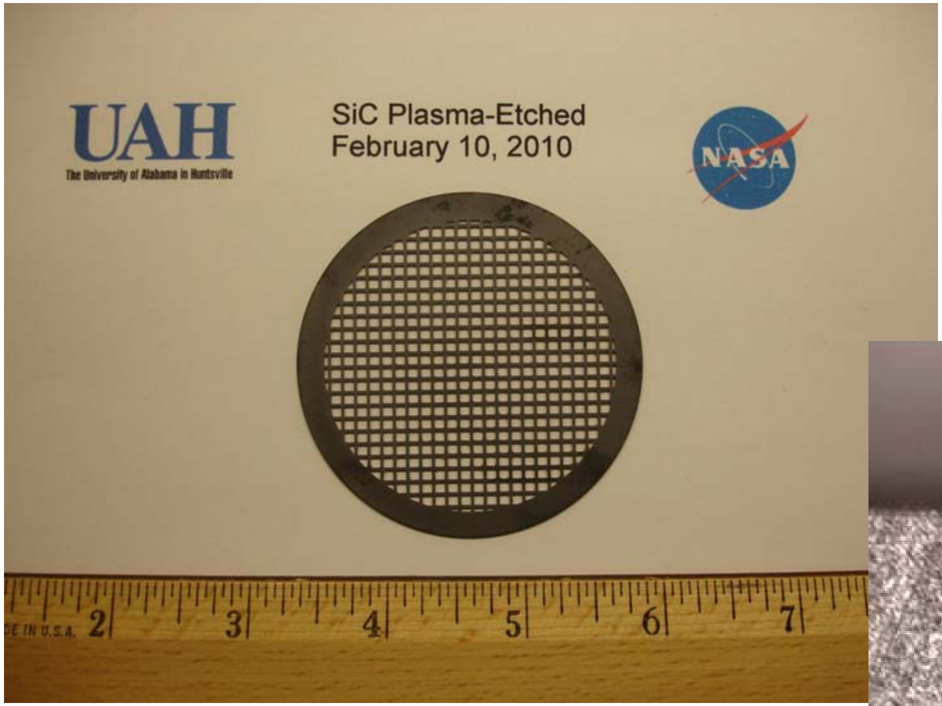


Partially etched SiC. The SiC columns result from pinprick holes in the photo-resist leading to islands of Ni masking.

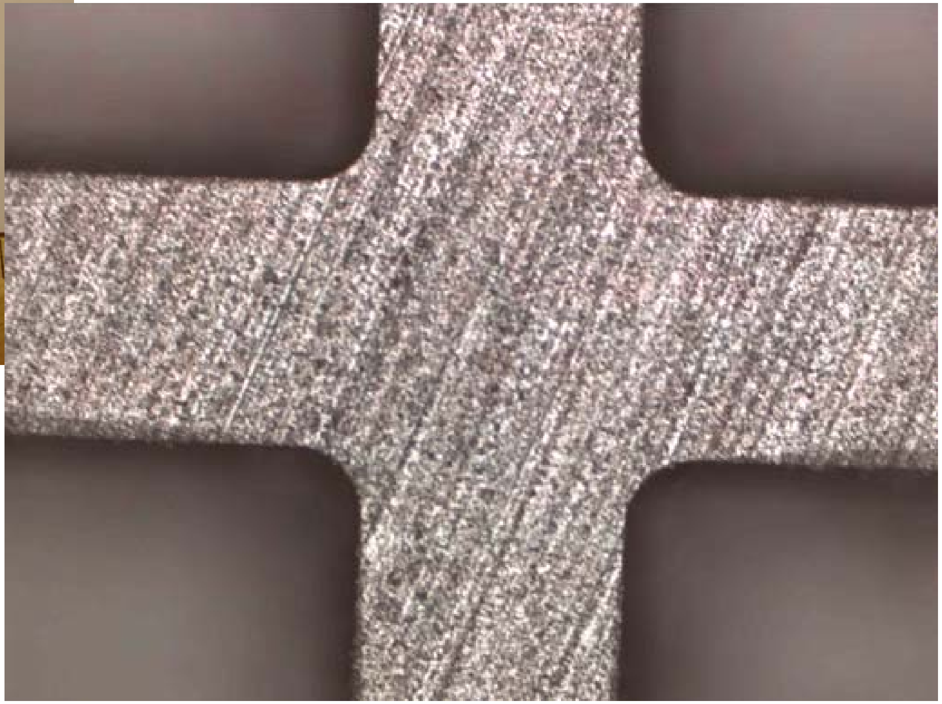


Wire sidewall etched under non-optimal conditions

SiC Plasma-Etching



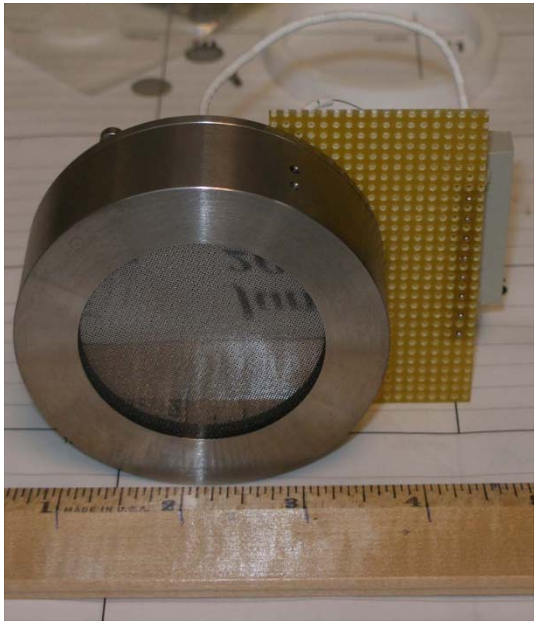
- 500 micron deep vias
- 65 mm diameter grid
- 400 micron wide wires
- 2 mm between wires



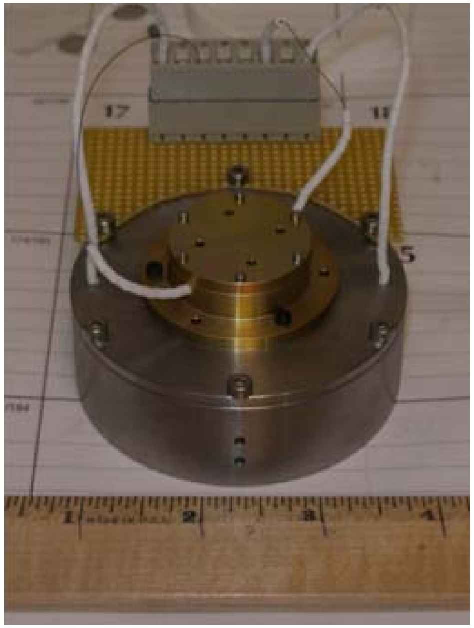
Prototype Faraday Cup Module

- Faraday Cup prototype constructed with tungsten grids
- Tungsten grids switched out with SiC grids for comparison

Faraday Cup prototype unit.
(a) entrance aperture
(b) collector side



(a)

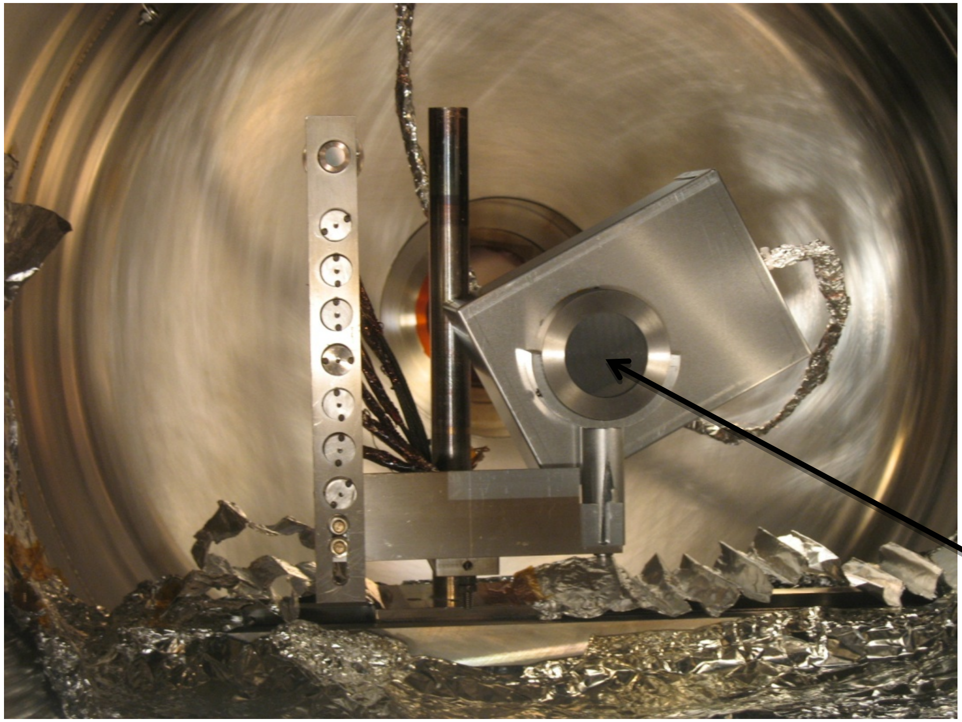


(b)

Solar Wind Testing at MSFC

Faraday Cup tested with protons, electrons, ultraviolet radiation and the combination of those beams

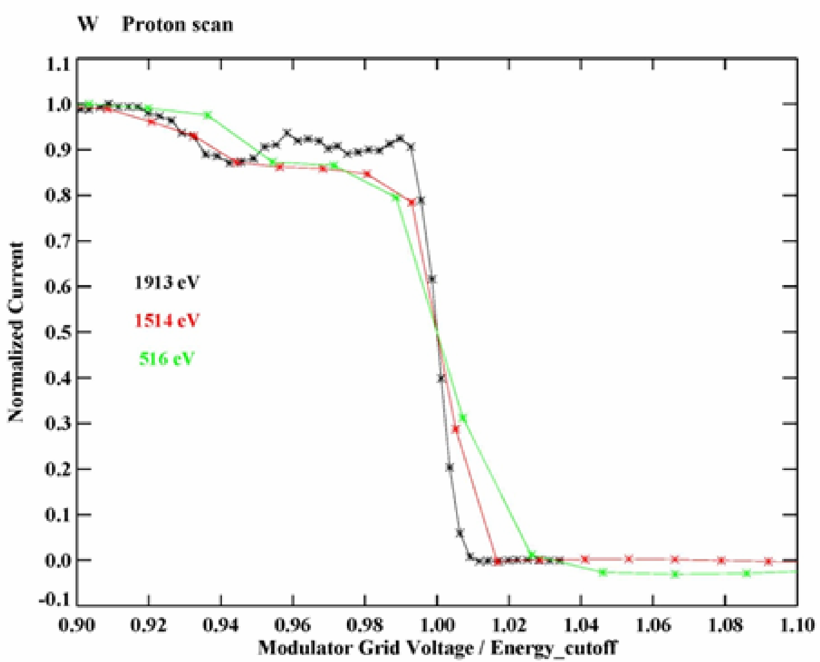
Faraday Cup with SiC grid in place

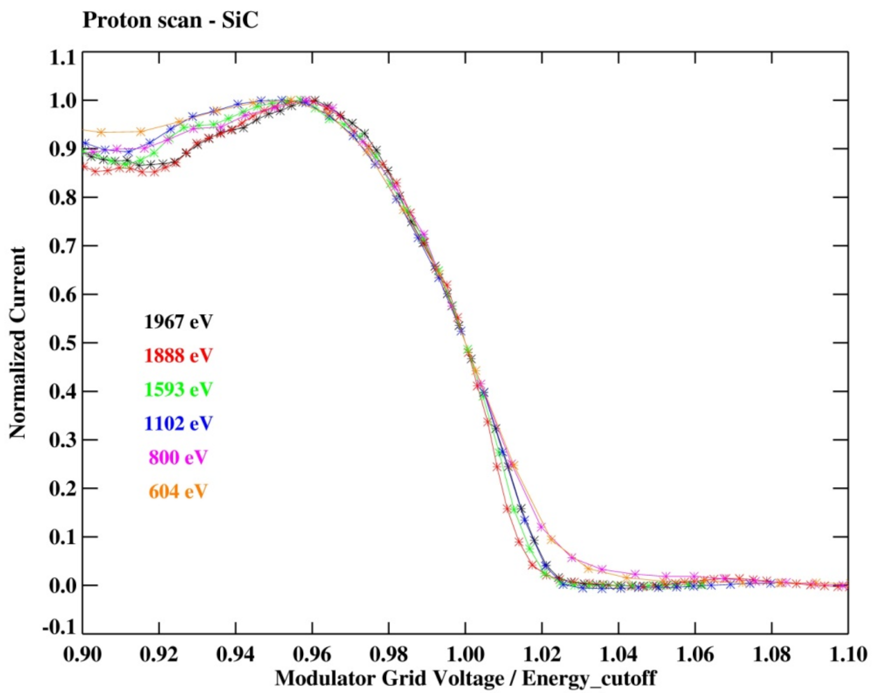


Interior of Solar Wind Test Chamber with FC placed in electronics box

Solar Wind Testing Results

- Both the W and SiC grids provide an acceptable energy cutoff
- The difference in cutoff is thought to be because of the larger grid spacing in the SiC grid.





Electrical Conductivity

Grids need to be sufficiently good electrical conductors so that:

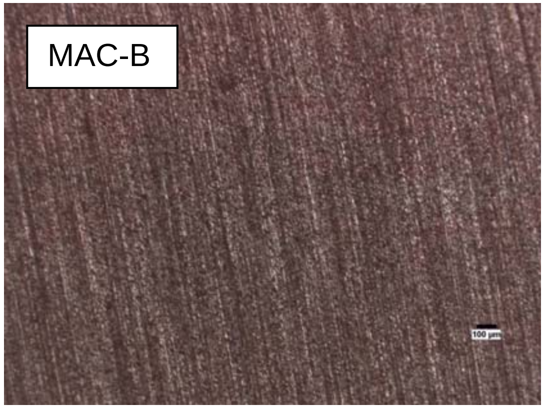
- Dissipation due to resistive loss within the grids when biased at up to 8KV does not affect the performance of the power supply (less than 1 mW)
- The voltage across the entire grid surface is uniform at better than 0.5% of the maximum voltage (so 4V RMS across the surface)
- Resistive loss does not interfere with the LC resonant circuit design
- Must be able to calibrate and test instrument at room temperature and to run far from Sun, so high conductivity needed for grids between -50C to + 1500C (TBC)

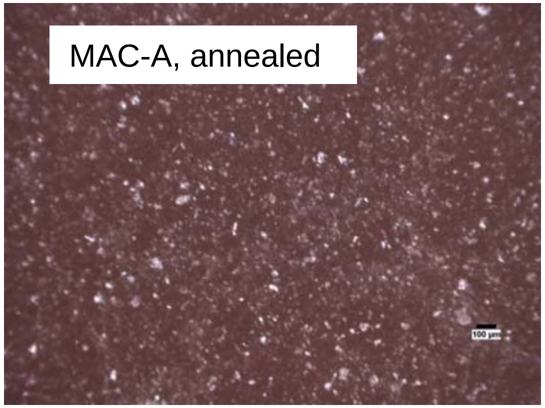
Testing

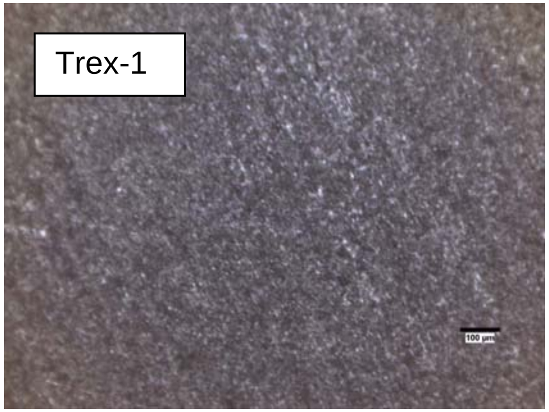
- SiC disks are electrically doped to provide appropriate level of electrical conductivity $O(1 \times 10^{-2}$ ohm cm)
- Testing required to determine if electrical conductivity could be maintained after exposure to vacuum at 1400 °C.
- SiC disks from 4 different vendors were measured using a 4-point probe technique.
- Results of testing showed that the SiC disks maintained their electrical conductivity values after thermal annealing at 1400 °C.

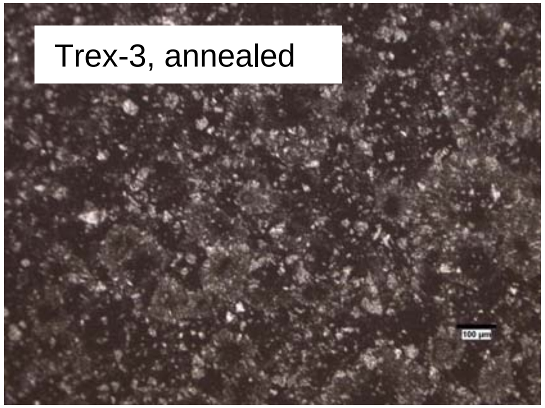
Thermal Annealing

- SiC disks from 4 different vendors, plus a tungsten grid, were annealed at 1400 °C under vacuum (10^{-6} torr)
- Apparent grain growth or solid-state recrystallization after annealing. Unclear if structure has stabilized or if there is any negative impact on performance as an electric grid material







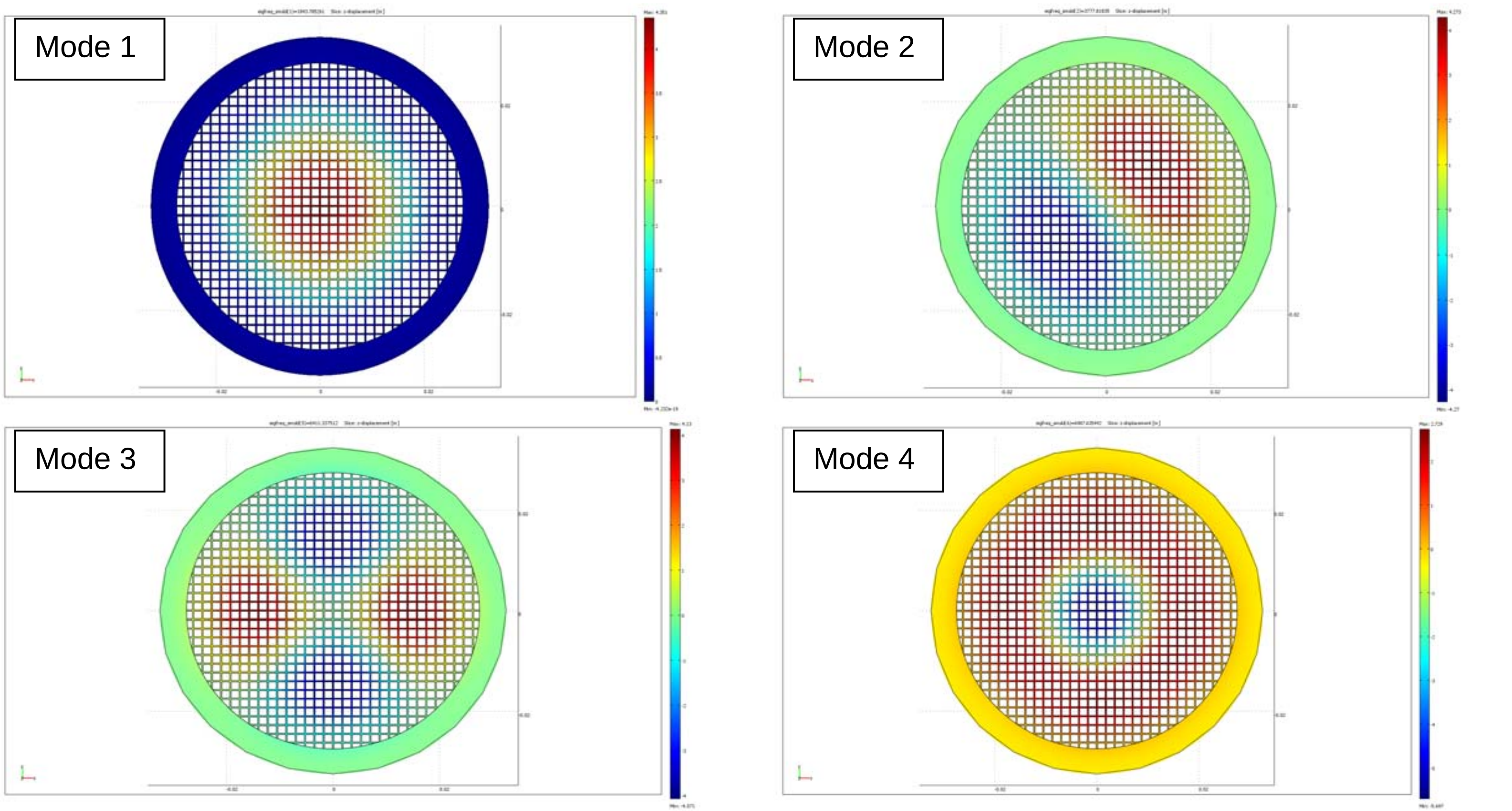


Mechanical Stiffness of Grids

- The goal is for the grid electrodes in the Faraday Cup to have their minimum vibrational frequencies high enough to avoid being excited by the 1280Hz HV modulator signal and interfering with the relatively small signal generated by the solar flux.
- The lowest frequencies of the grid electrodes have been numerically evaluated by using the commercial software COMSOL 4.0.
- To a good approximation, the vibrational frequency is inversely proportional to the square root of the density and linearly proportional to the thickness.

Mode	W Disk	SiC Disk	SiC Grid
1st mode frequency	1038.5 Hz	2588.3 Hz	2422.5 Hz
2nd mode frequency	2160.1 Hz	5386.5 Hz	4969.9 Hz
3rd mode frequency	3542.6 Hz	8835.8 Hz	7848.5 Hz
4th mode frequency	4039.7 Hz	10076.1 Hz	9124.7 Hz

Grid Vibrational Modes



Summary

- A prototype SiC grid has been manufactured using photolithography and a dry plasma-etching process
- Testing and analysis to date indicate that SiC grids meet the electrical, mechanical, and thermal requirements of the Solar Probe Cup
- The SiC grids provided an adequate energy cutoff based on Solar wind testing
- Single crystal SiC has more favorable properties and may be more stable than polycrystalline SiC
- The decision on which grids will be tungsten or silicon carbide will depend on future testing and analysis.