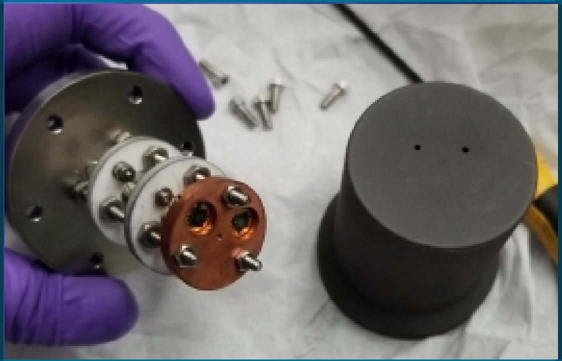
SAND2021-9602PE

Sandia National Laboratories

Development of rugged hydrogen sensors for measuring charge-exchange neutral flux at the wall and divertor



PRESENTED BY

Ryan Hood[1]

IN COLLABORATION WITH

R. Kolasinski[1], D. Truong[1], J. Whaley[1], D. Rudakov[2], T. Abrams[3], J. Watkins[1], A. Talin[1]

[1] Sandia National Laboratories, Livermore, CA

[2] University of California, San Diego, La Jolla, CA

[3] General Atomics, San Diego, Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. 2021

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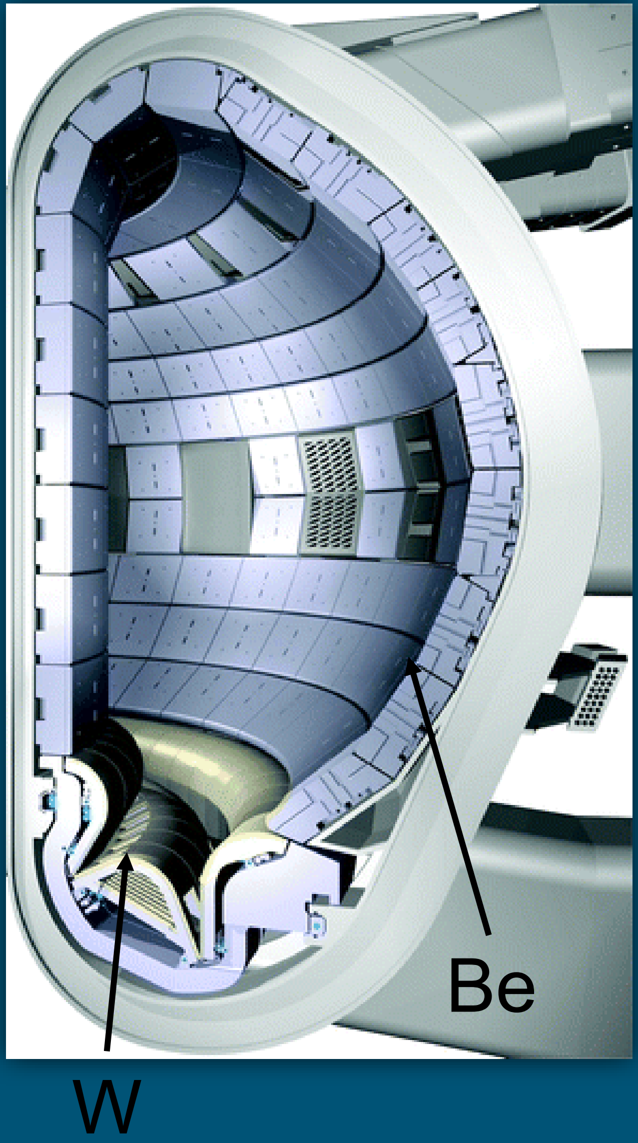
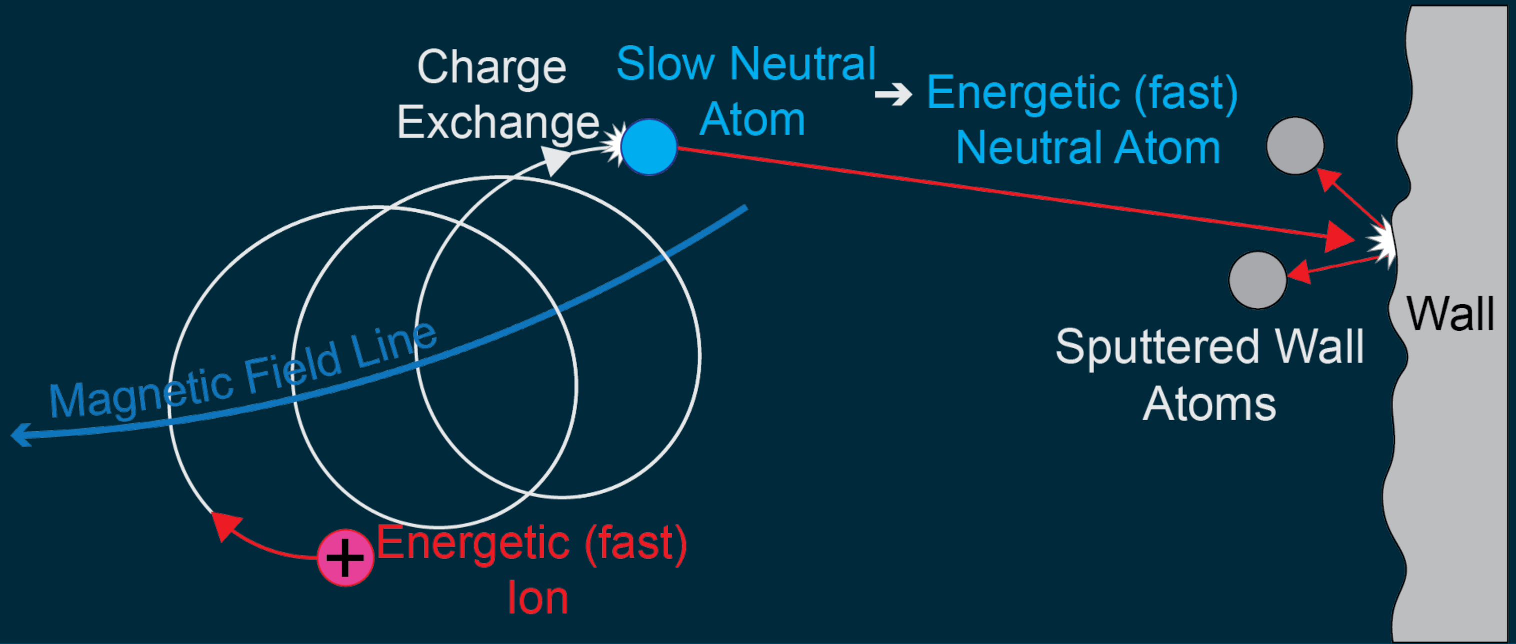
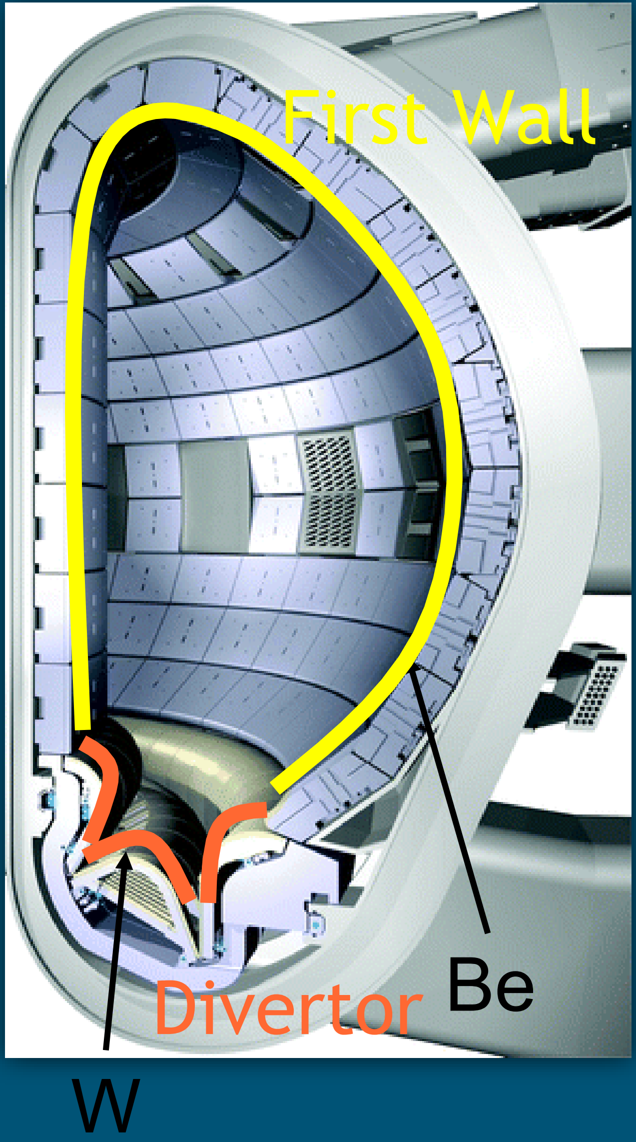
Materials are among the largest challenges for future tokamaks



Exposure conditions:
- High-flux D-T plasmas
- High-energy fusion products (14 MeV n, helium ash)
- Impurities
- Charge-exchange neutrals

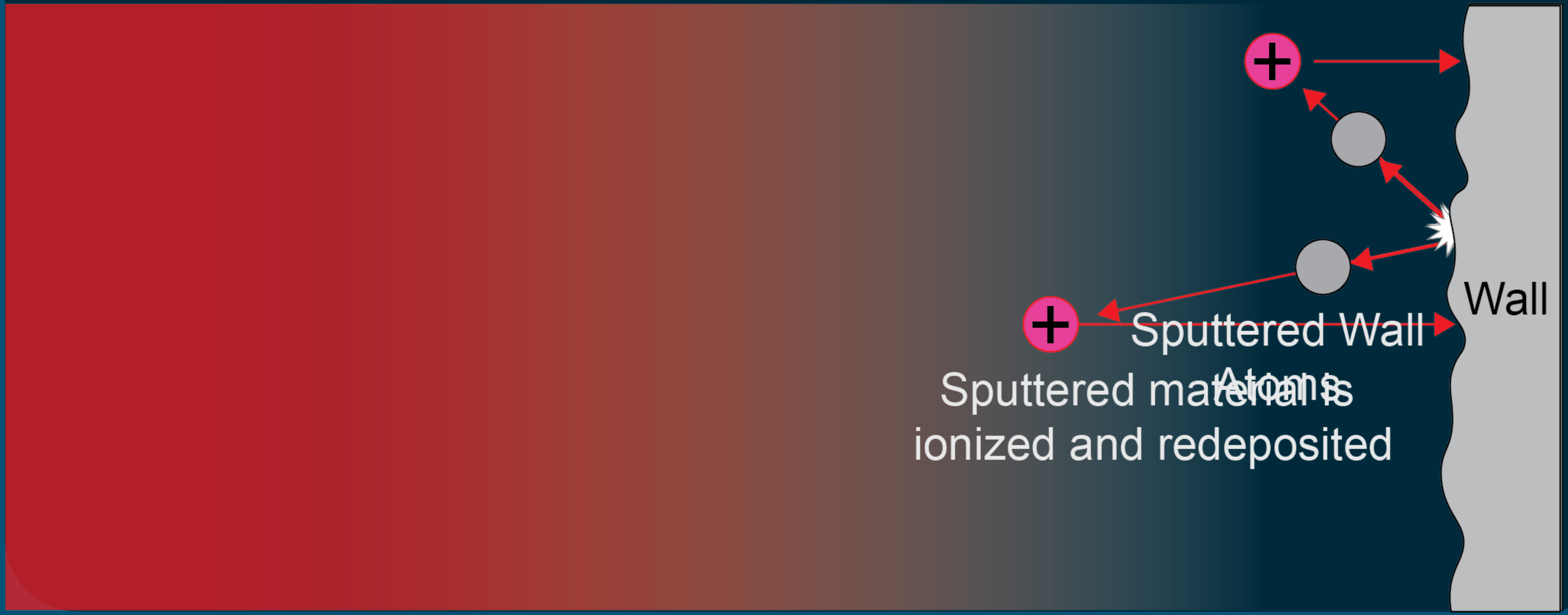


Result of sputtering depends on location



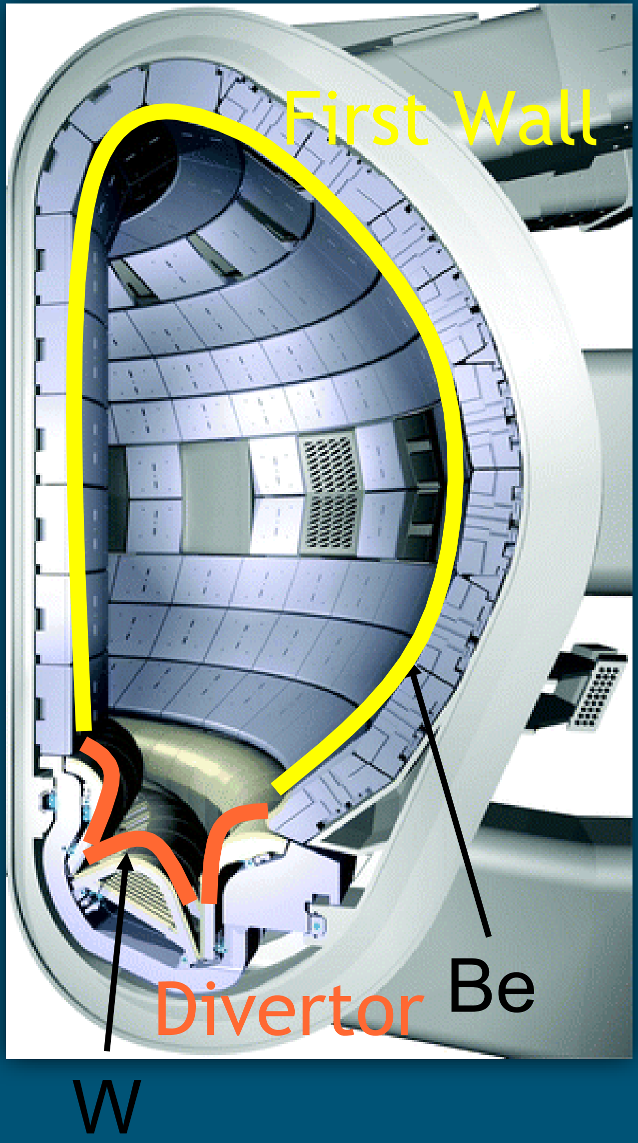
In divertor: high plasma density results in ionization and redeposition

- Sputtered material is ionized close to its origin and is redeposited locally
- Net erosion << Gross erosion [1]
  - A few nm/s for low-Z materials
  - Less than 1 nm/s for high-Z materials



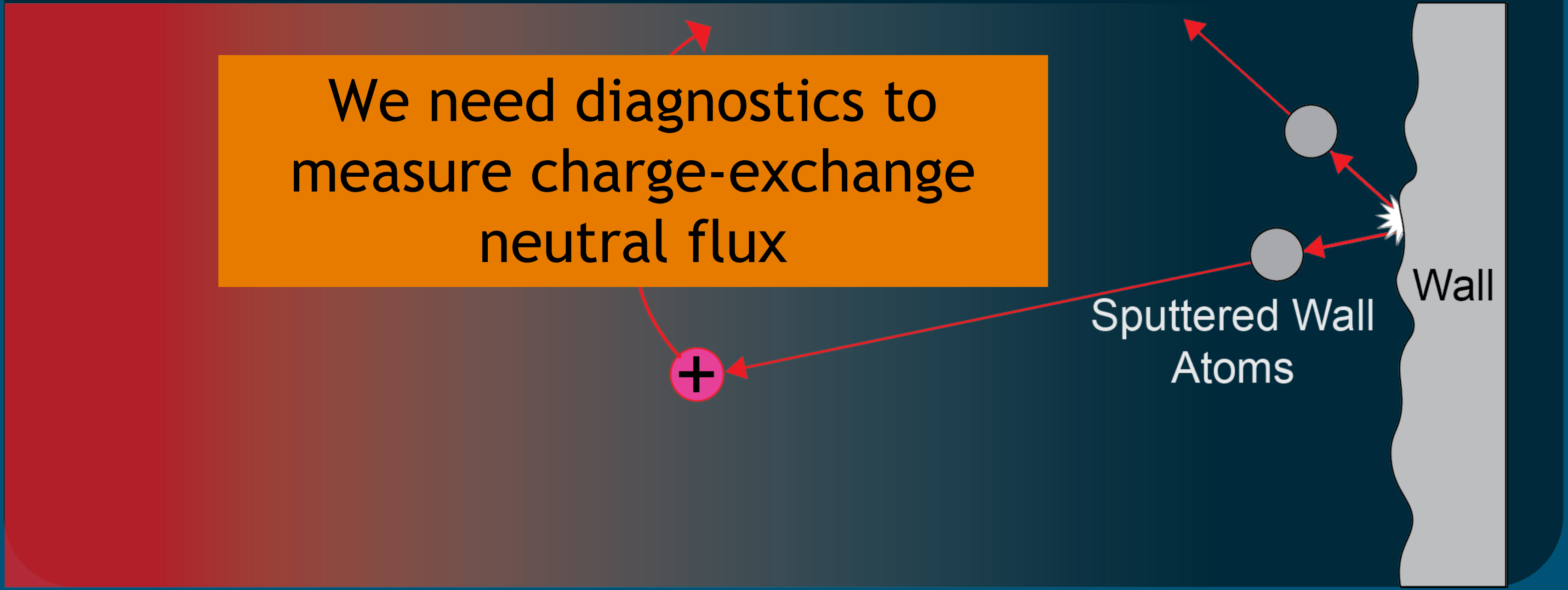
[1] D.G. Whyte, Fusion Sci. Technol. 48 (2005) 1096.

Result of sputtering depends on location



On first wall: plasma density will be orders of magnitude lower

- It is a concern that sputtered material may ionize on field lines connecting to more distant regions
- *Net* erosion ≈ *Gross* erosion [2]
  - 10's of kg/yr in ITER
  - 1000's of kg/yr in a power plant



[2] P.C. Stangeby, J. Nucl. Mater. 415 (2011) S278

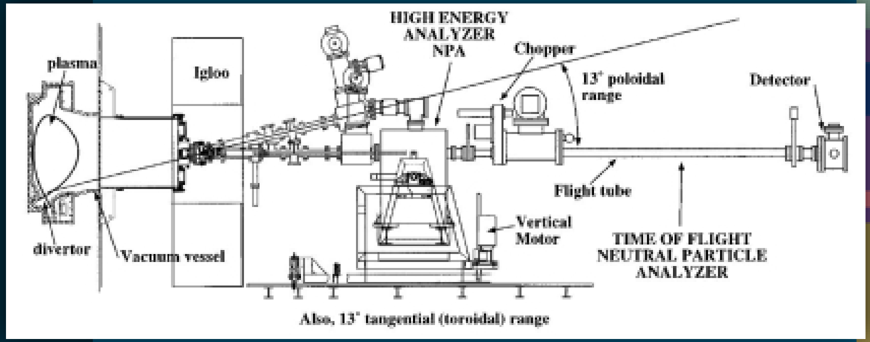
Past measurements

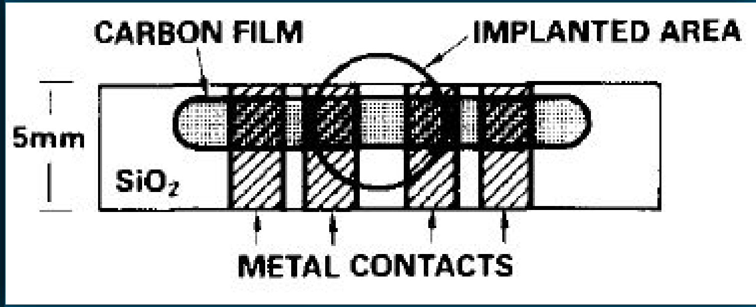
Although some studies were done in the 80's / 90's, characterization of c-x neutrals is presently lacking on US tokamaks

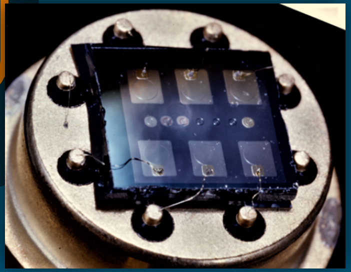
Diagnostics used:

- **Low Energy Neutral Analyzer (LENA)** - good time and energy resolution, but large and complex
- **Carbon Resistance Probe (CRP)** – compact and low power, but permanently saturate at 2 x 10^{15} H/cm^2
- **Pd-MIS H-sensors (Palladium Metal-Insulator-Semiconductor) -** same advantages as CRP **and** can be regenerated, but have lifetime limited by high energy particles

Rev. Sci. Instrum. **68**, 982 (1997); doi: 10.1063/1.1147731



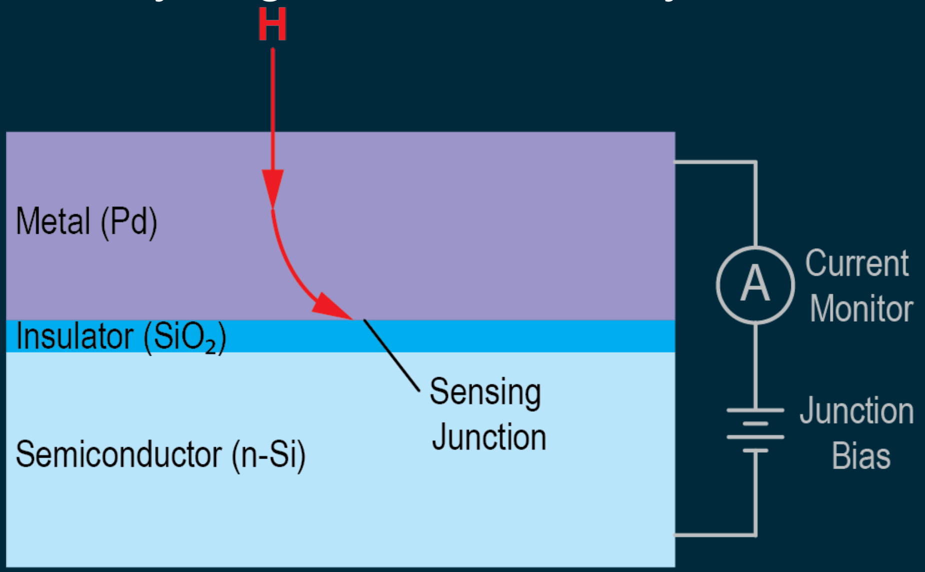


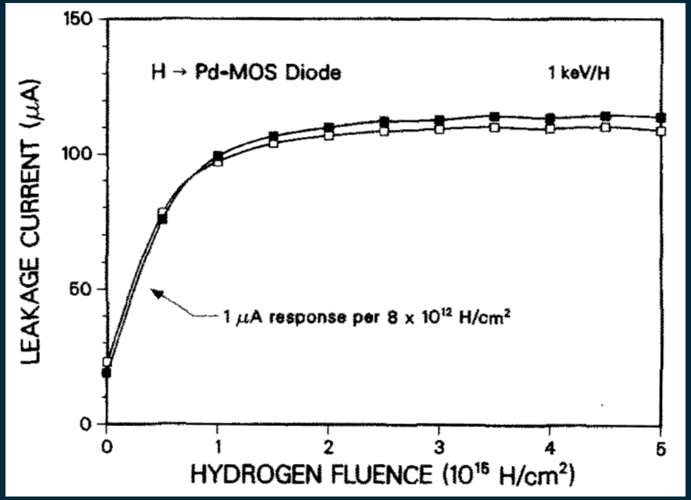


Pd-MIS H-sensor operating principle

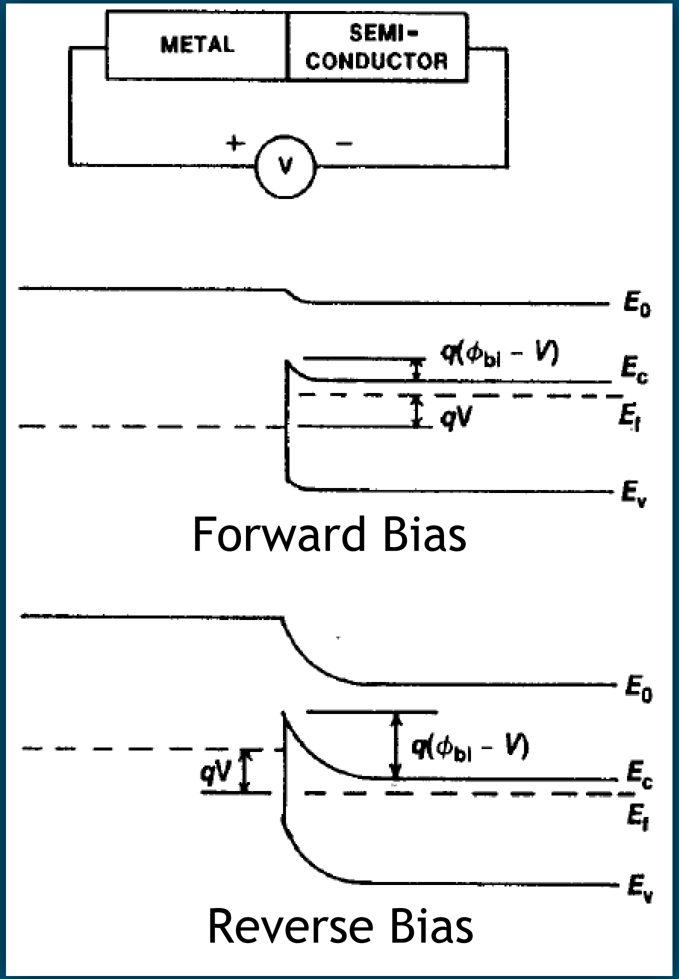
Metal – semiconductor junction forms a Schottky diode

- In reverse bias, leakage current is exponentially related to the barrier height
- Implanted hydrogen rapidly diffuses to the Pd-SiO_2 interface, where the hydrogen is weakly trapped changing the barrier height
- Hydrogen is detected by monitoring the reverse current





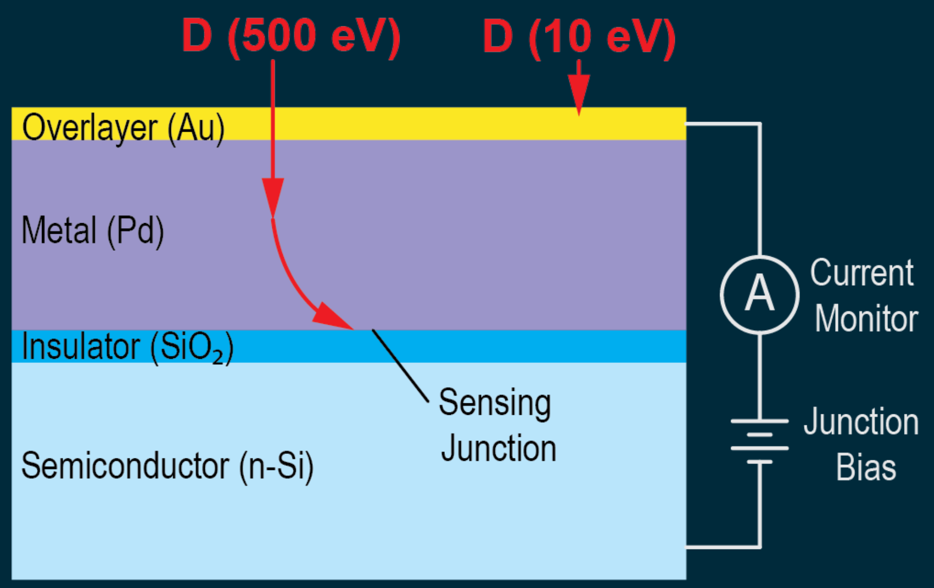
R. Bastasz, B.L. Cain, T.E. Cayton, R.C. Hughes, and D.N. Ruzic, J. Nucl. Mater. 162-164 (1989) 587



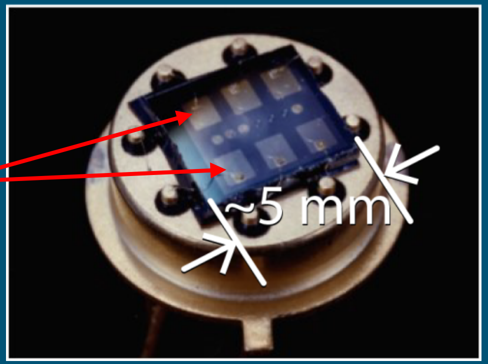
Metal-Semiconductor junction band diagrams shown in forward and reverse bias (oxide not shown for simplicity)

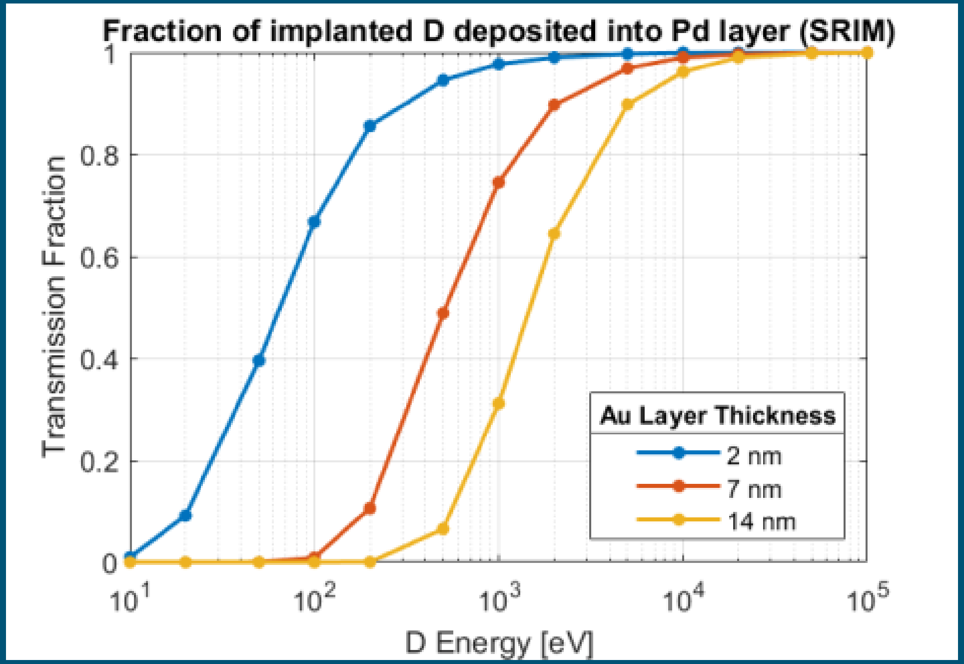
Energy resolution provided by gold overlayer

- Thin Au coatings can be deposited on different sensors to provide energy discrimination
- D_2 not penetrating the Au layer can not reach the SiO_2 interface
- Requires modelling to interpret (assume Maxwellian energy distribution + SRIM to estimate ion range)



Each of the 6 sensors has different Au thickness





Design modifications to improve ruggedness

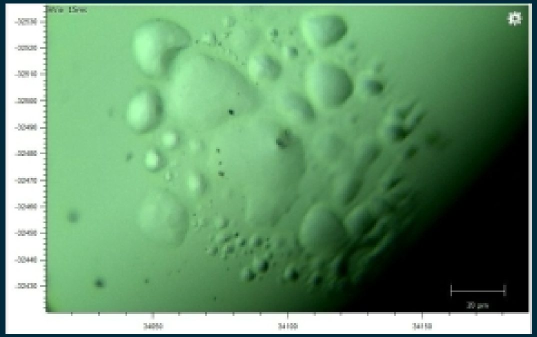
High energy particles result in charge accumulation in the oxide layer

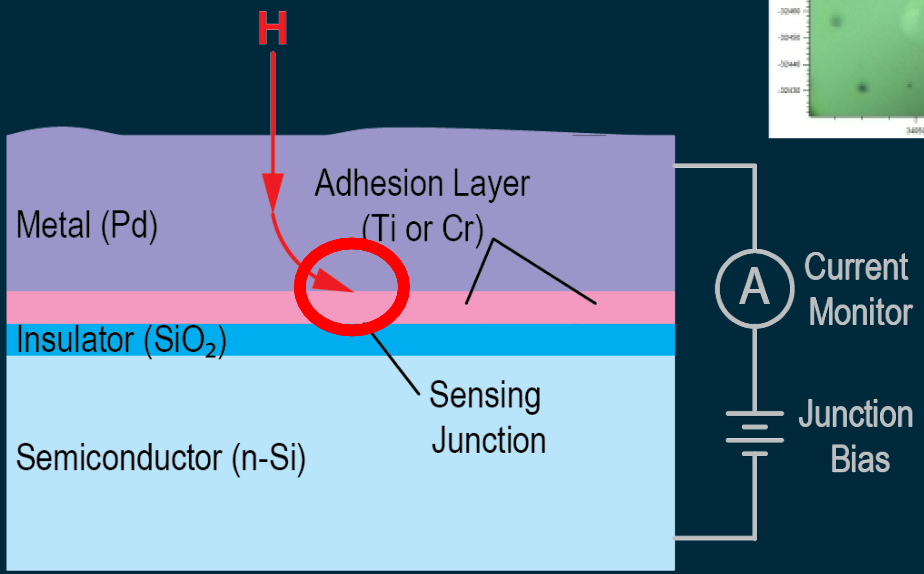
– This shifts the barrier potential making sensor calibration impossible

Remedies:

Minimize oxide thickness

- Must be grown slowly with careful surface preparation
- Done at Sandia MESA facility





Maximize metal layer thickness (~500 nm)

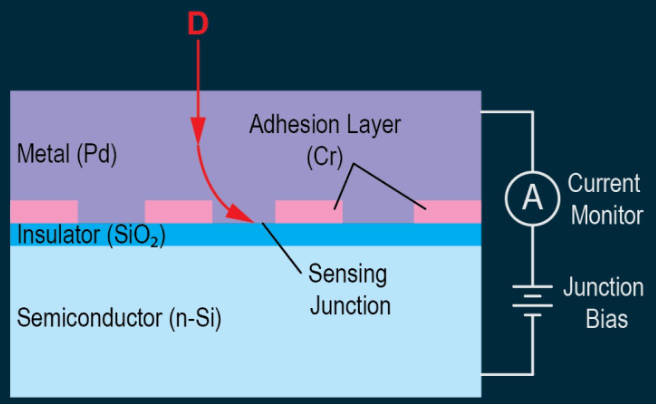
- Thick layers (greater than ~ 50 nm) result in poor fabrication yields
- Adhesion layer would typically be used in this situation (Ti/Cr), but this blocks H from reaching junction

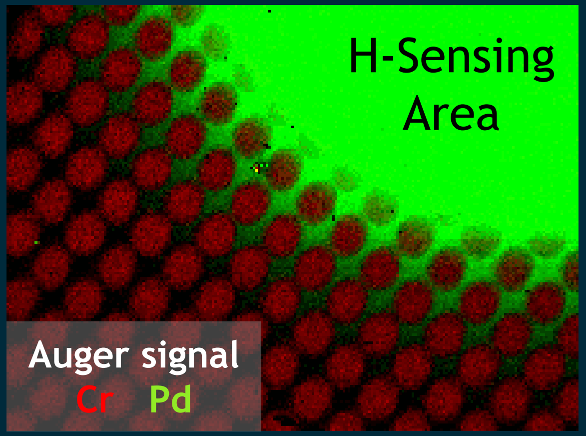
Maybe a compromise is possible?

Patterned adhesion layer enables H sensing with thick Pd layer

Adhesion layer is deposited through a fine hole pattern

- Hydrogen still has access to junction
- With improved bond between Pd and SiO_2

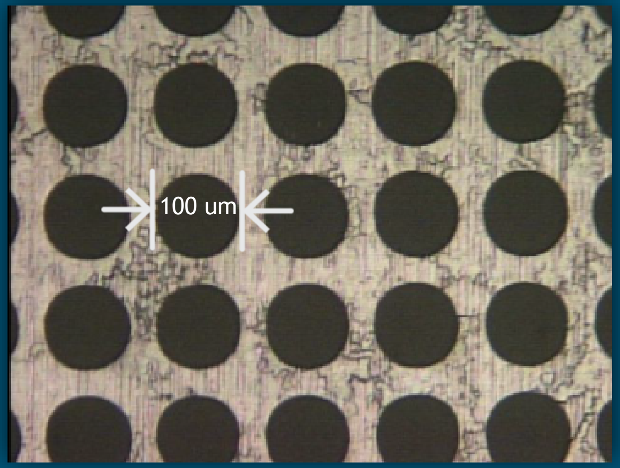


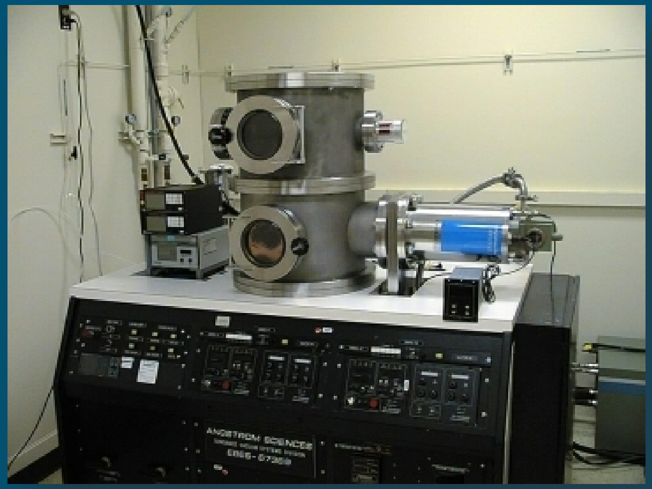


Newest sensors have 500 nm Pd

- Expected to withstand c-x energies up to ~50 KeV based on SRIM calculations (30x improvement)
- Have demonstrated excellent hydrogen sensitivity in laboratory testing at 340 eV/D and 1500 eV/D
- DIII-D piggyback experiment June 2021

Microscope image of shadow mask



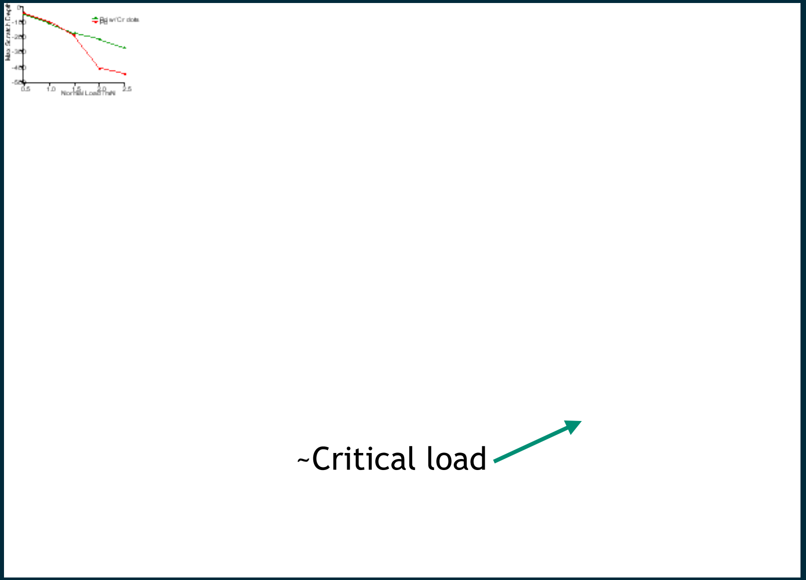


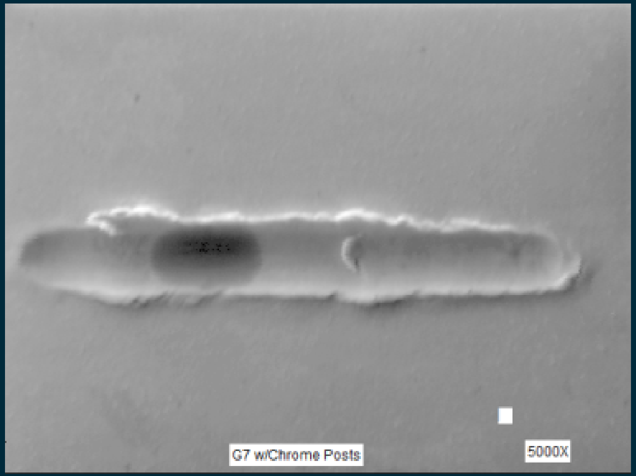
Dual e-beam evaporator located at Sandia Nation Laboratories

Nanoscratch testing shows improved adhesion with patterned Cr layer

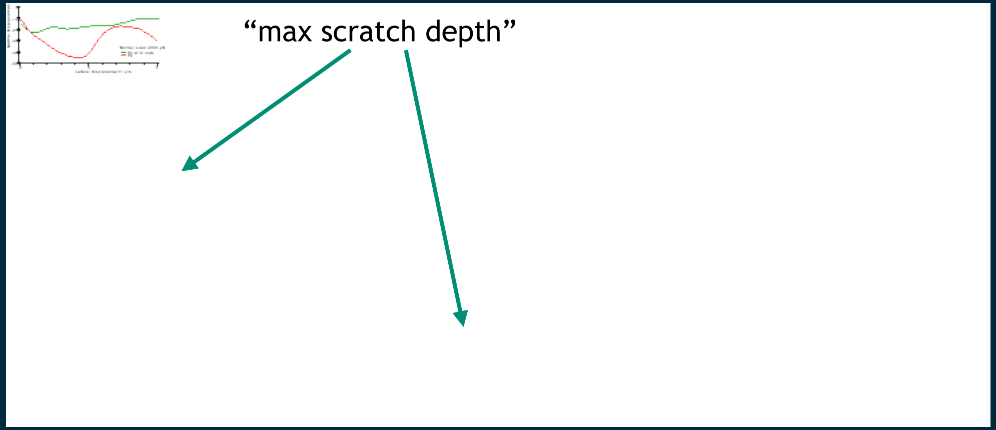
1 um radius diamond probe dragged across surface of sensor while maintaining normal force

- Pd layer appears to fail above 2 mN force without Cr
- Deeper scratches without Cr





SEM images from J. Whaley

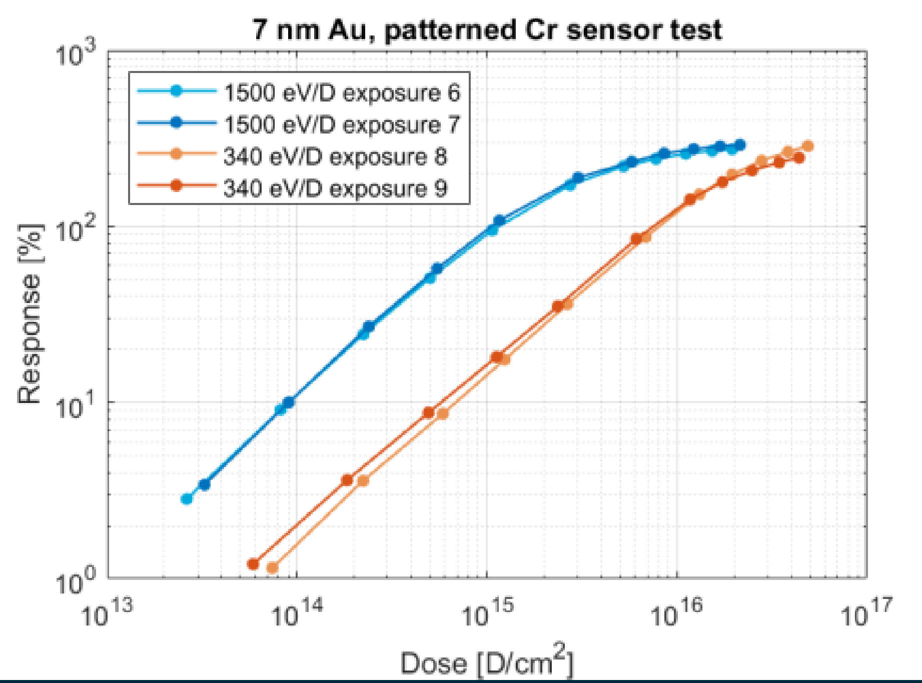


Nanoscratch testing by R. Friddle

Sensors conditioned using D ion beam before testing in DIII-D tokamak

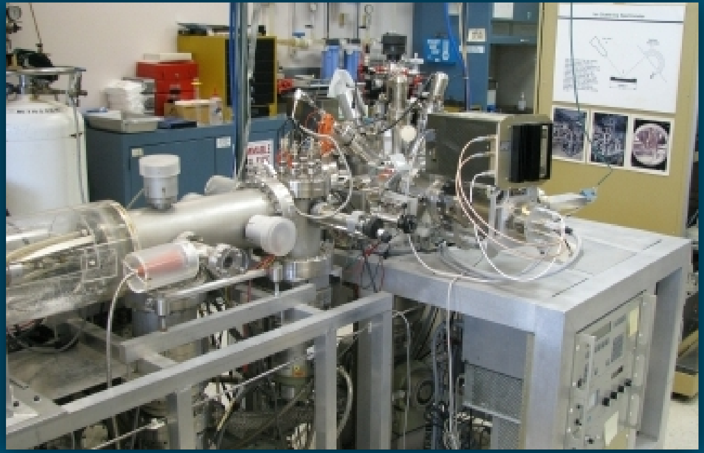
Conditioning performed using SIMS ion beam

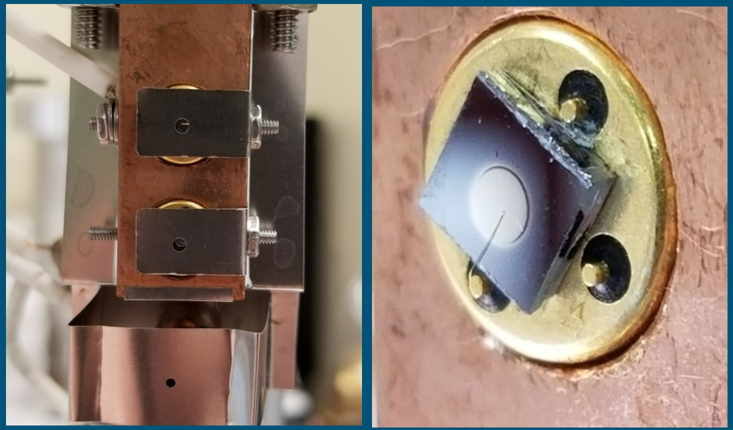
- Precision dosing by measuring collected ion current
- Control of beam energy and sensor temperature



- Strong response (~ 1-10 uA)
- Good sensitivity (~ 300%)
- Consistent response to dose after ~ 4 regeneration cycles

SIMS ion beam station at Sandia National Laboratories



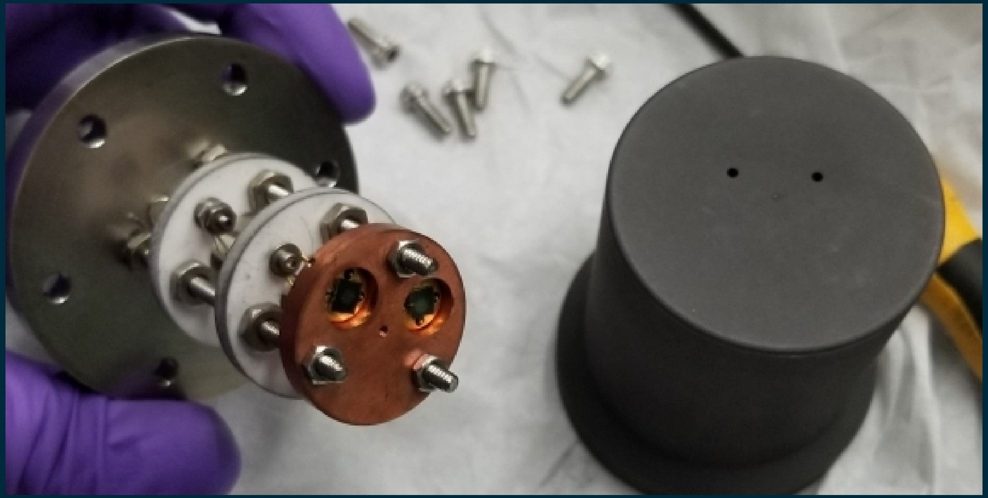


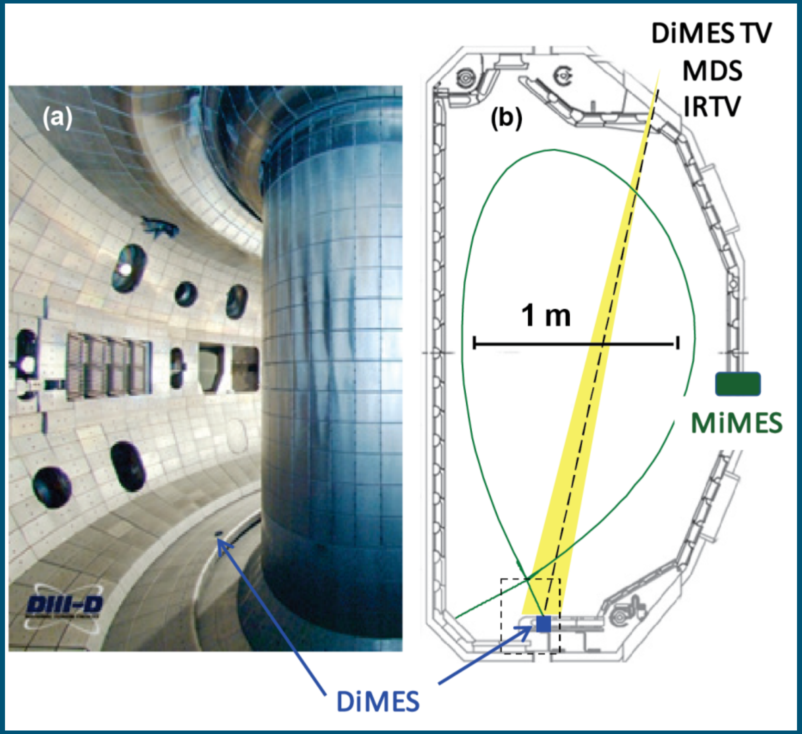
Sensors on TO-5 headers mounted for conditioning

Sensors were tested at DIII-D tokamak in piggyback experiments (June 2021)

Sensors were mounted in Divertor Material Evaluation System (DiMES) and tested over several days

- Test of sensors and data collection system in the tokamak environment
- Same gold thickness on each sensor (7 nm Au)



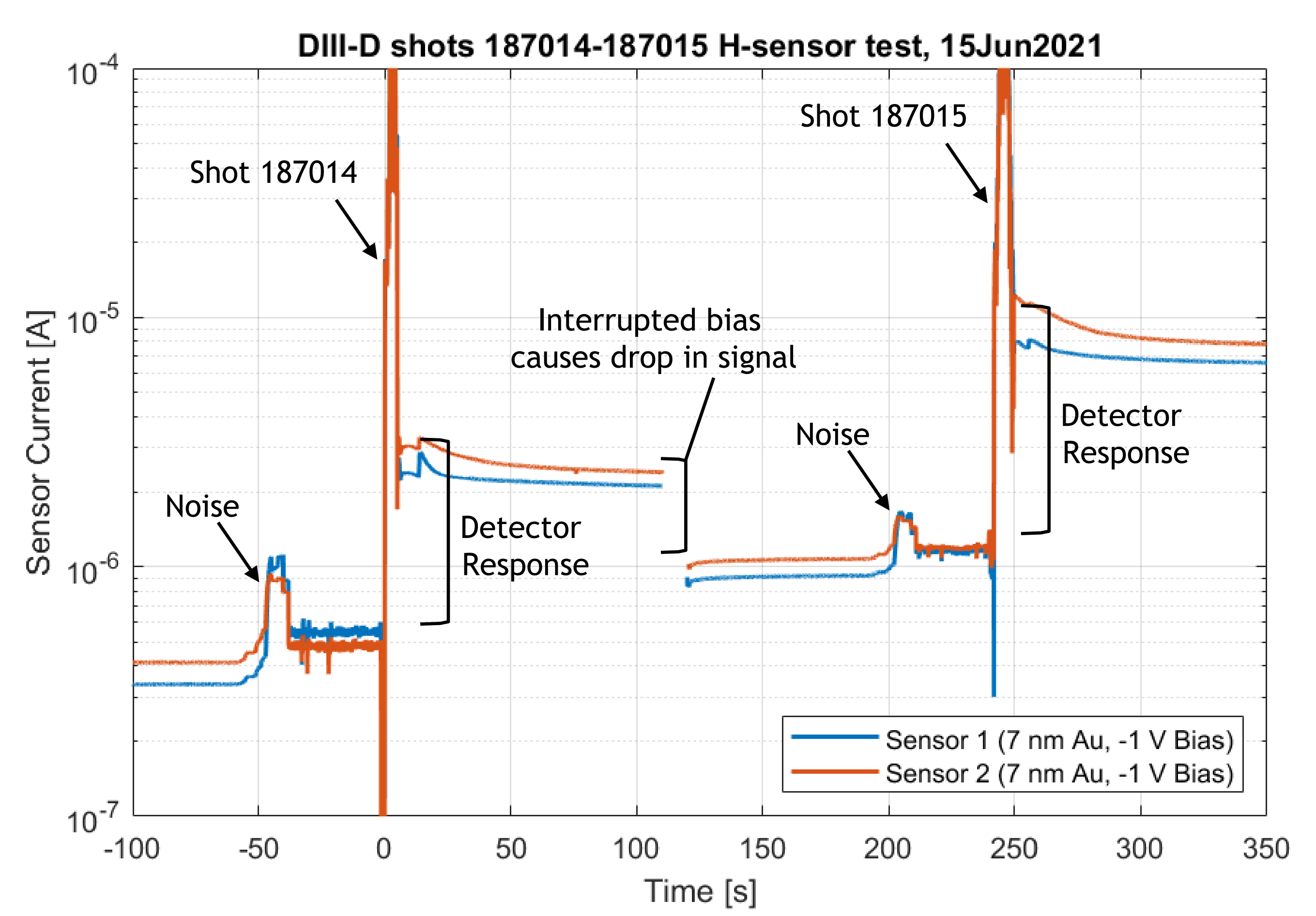


Adapted from: Rudakov D., Abrams T., Ding R., Guo H., Stangeby P., Wampler W., Boedo J., Briesemeister A., Brooks J., Buchenauer D., Bykov I., Chrobak C., Doerner R., Donovan D., Elder J., Fenstermacher M., Guterl J., Hinson E., Hollmann E., Lasnier C., Leonard A., McLean A., Moyer R., Nygren R., Thomas D., Unterberg E., Watkins J., Wong C. Fusion Eng. Des., 124 (2017), pp. 196-201

Sensors were successfully demonstrated in tokamak environment

Data collected from ~ 27 plasma shots over 2 days

- Saturation after ~ 4 shots in USN configuration
  - Strong signal!
  - Can be reduced with apertures or thicker gold layers
- Demonstrated sensor regeneration with thermal cycling
- Nearly identical response from pair of sensors in USN configuration before saturation
- Multiple gold thicknesses needed for fluence measurement

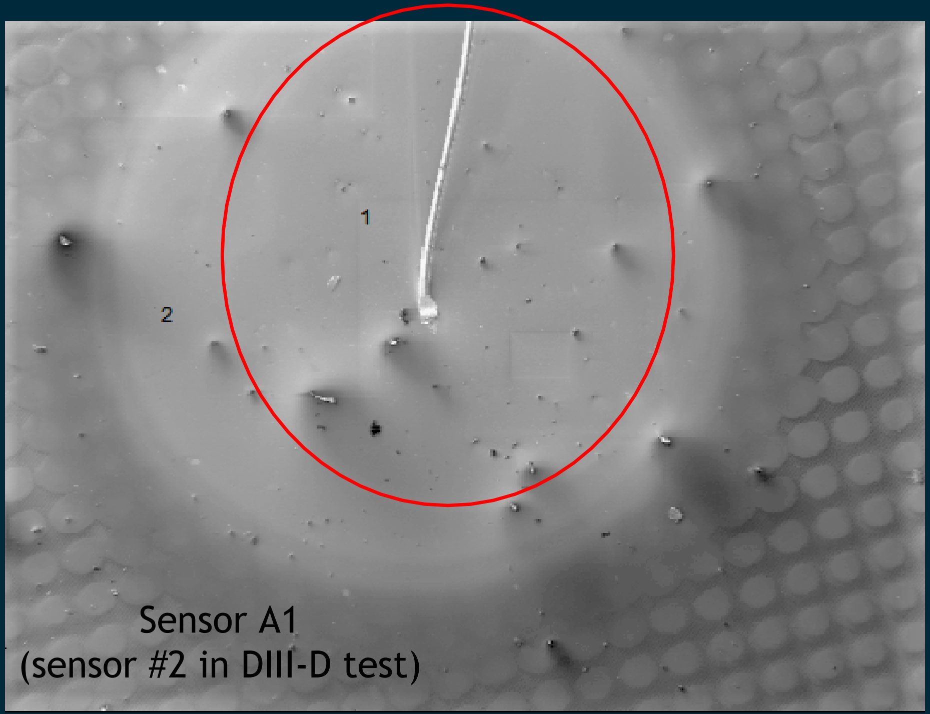


H-sensor data from consecutive USN plasma shots at DIII-D tokamak, starting from regenerated state

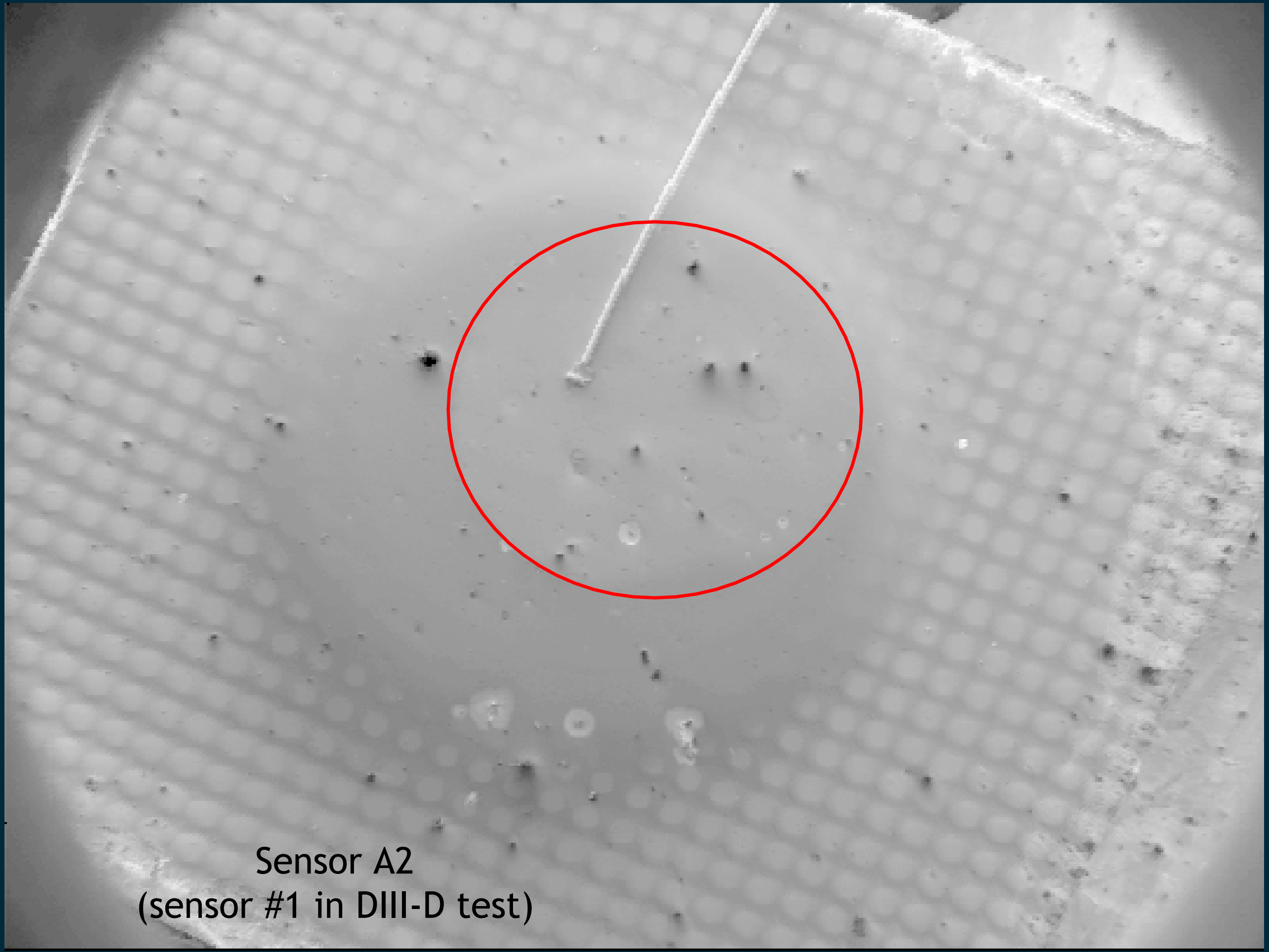
DiMES cap apertures visible in SEM and AES measurements

Sensors used in DIII-D seem to show erosion from neutrals and carbon deposits from sputtering

Dust is mostly from DIII-D system



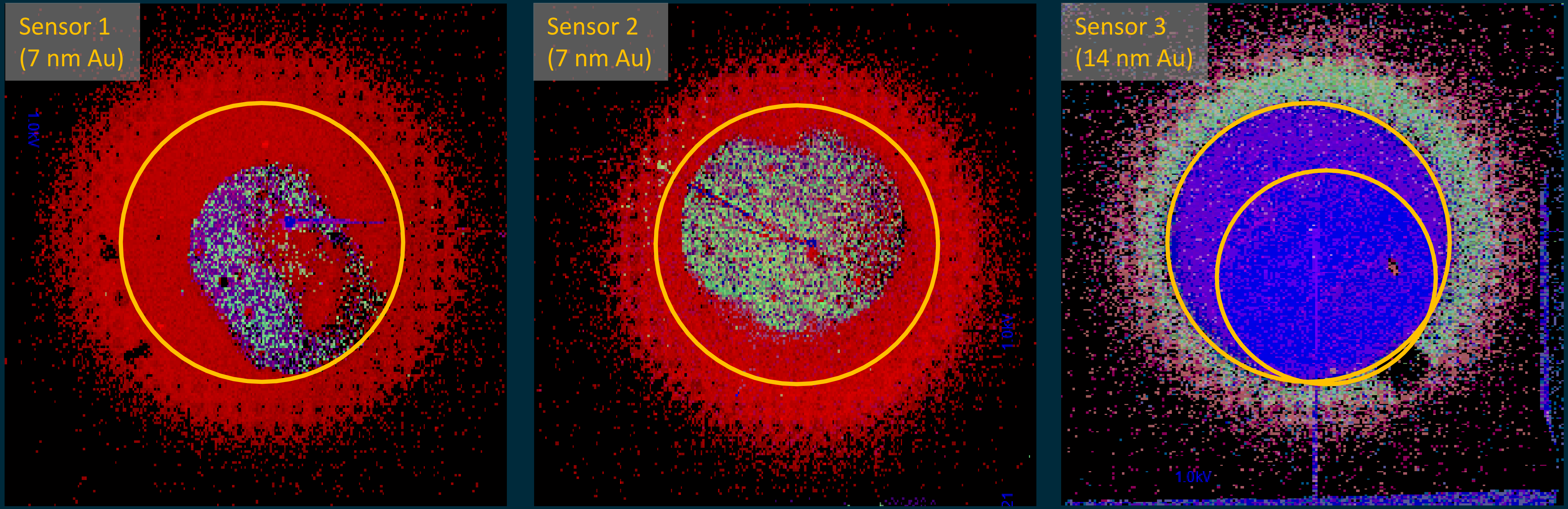
Sensor A1
(sensor #2 in DIII-D test)



Sensor A2
(sensor #1 in DIII-D test)

AES map of DIII-D sensors

- Carbon Palladium Gold
- Sensors 1 and 2 were tested in DIII-D and show significant carbon deposit and erosion
- Sensor 3 was only conditioned with 340 and 1500 eV D+ ion beam and shows slight erosion/cleaning



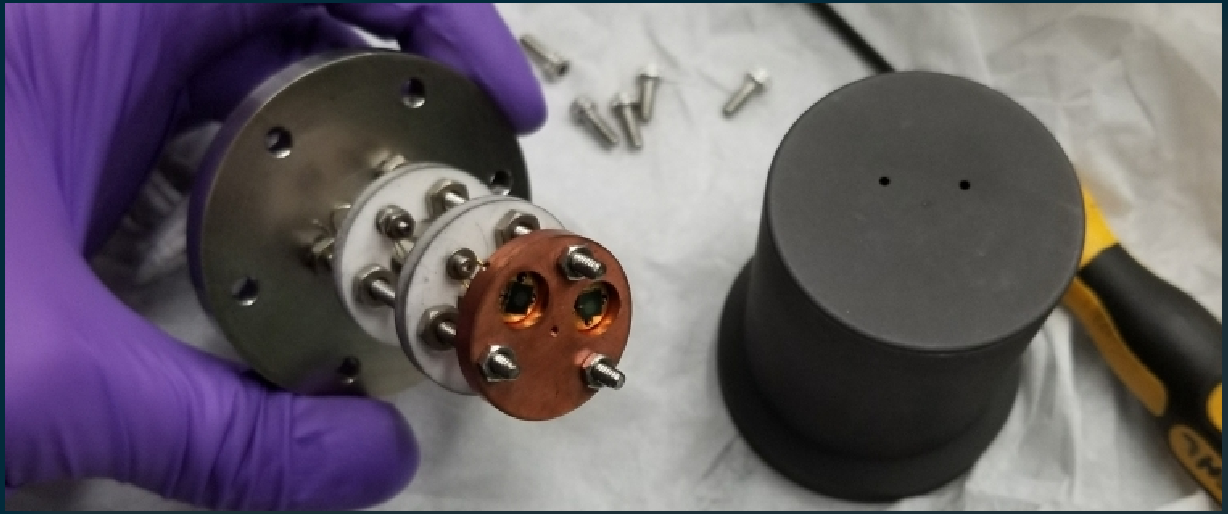
Future work

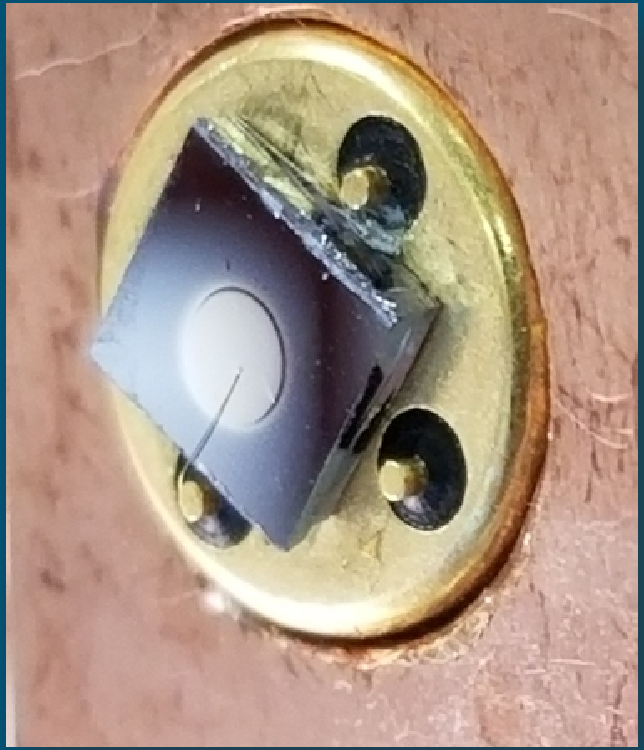
Explore optimization of adhesion layer (strength vs sensitivity)

Continue laboratory testing of sensors with thick Pd layer

- Calibrate hydrogen response
- Extract energy distribution from array of sensors

Further testing at DIII-D to measure shot-to-shot energy distribution and fluence





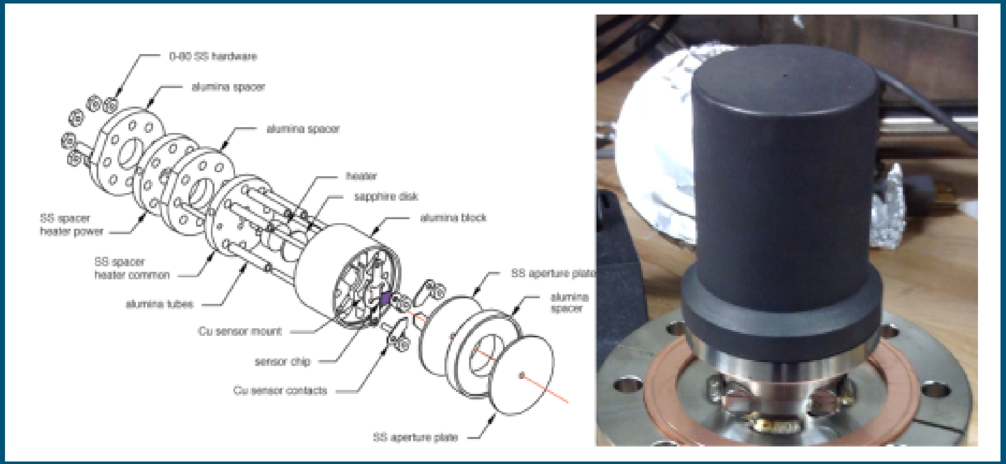
This work was funded by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences

Supplemental slides

Pd-MIS sensors have been tested in DIII-D (2018)

Legacy sensor tested in DiMES

- Demonstrated ability to function in Tokamak environment
- Successfully installed, run, and regenerated in-situ



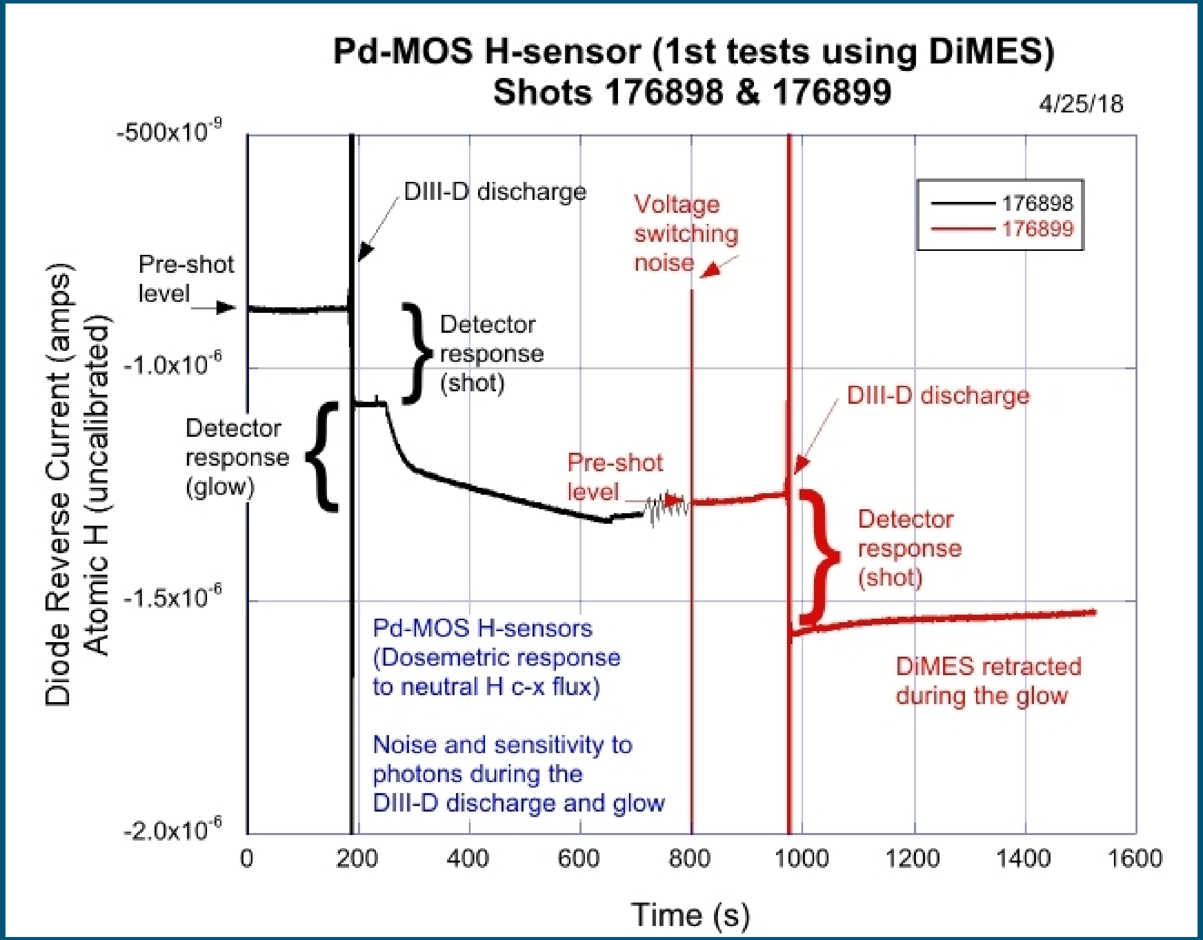
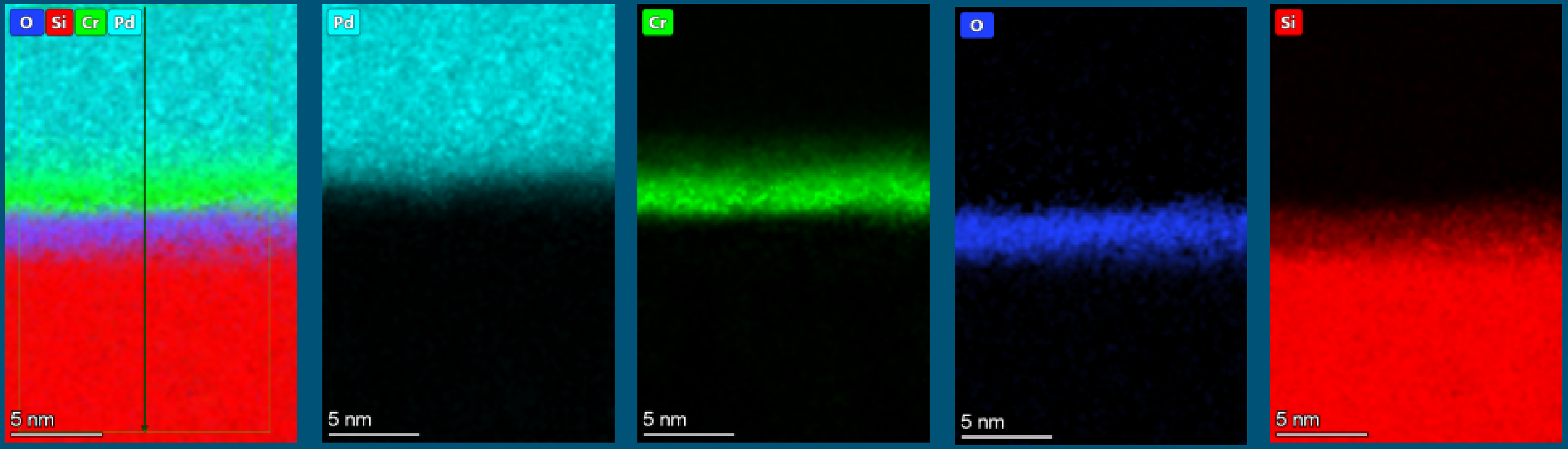
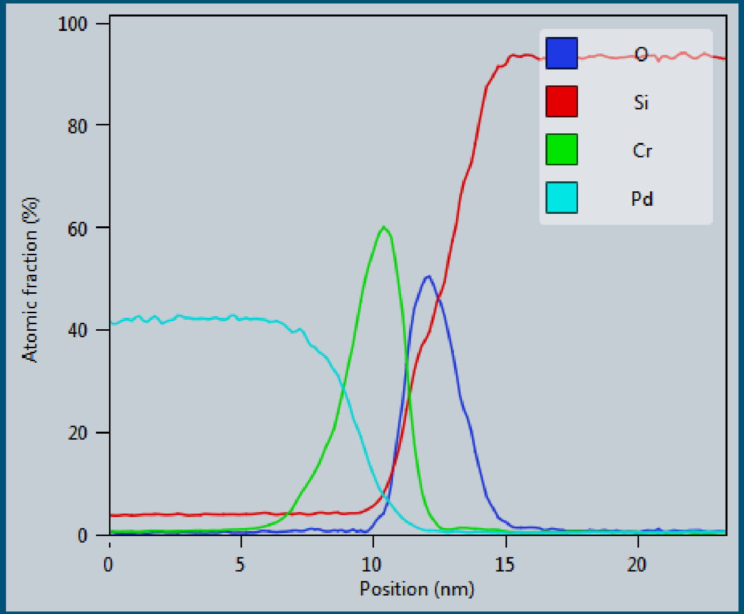


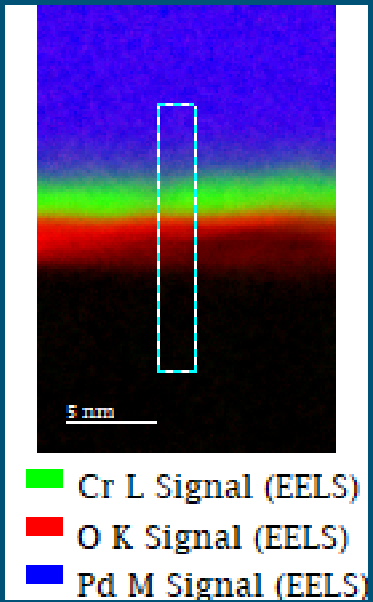
Figure courtesy of Dean Buchenauer

EDS and EELS measurements show minimal intermixing or oxidation of Cr

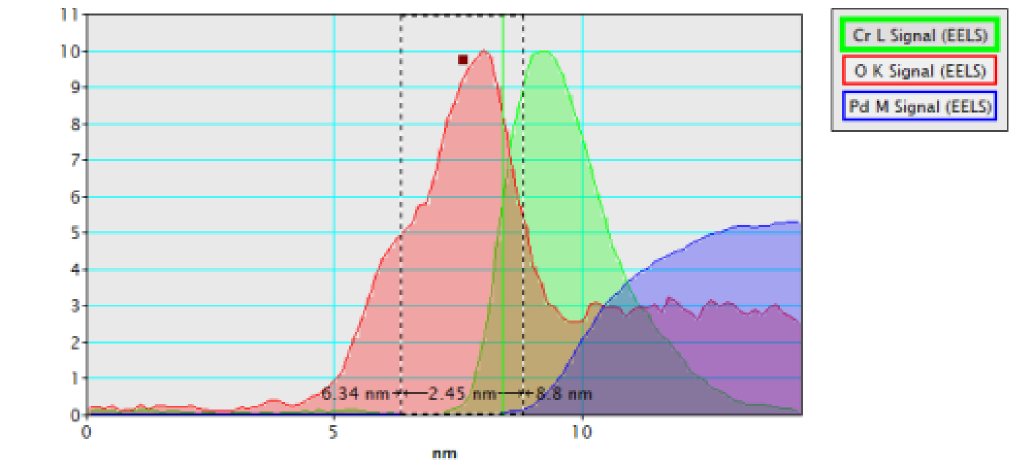


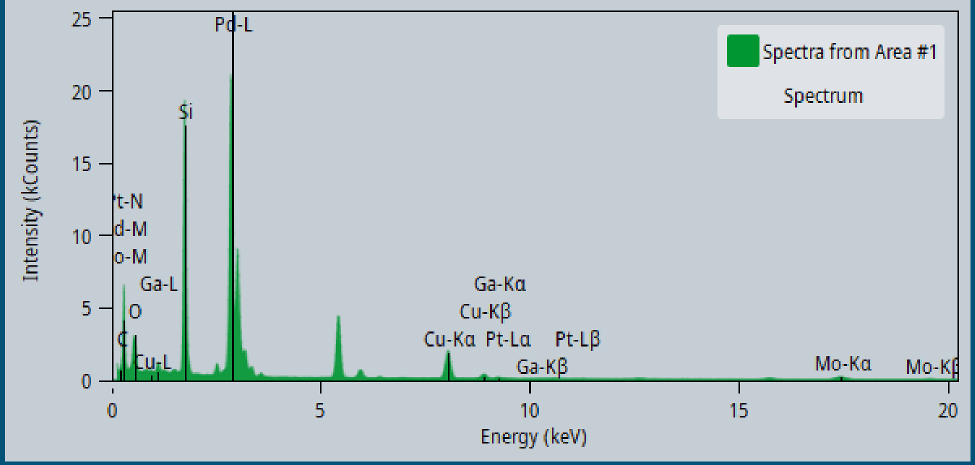


EDS measured 2.8 nm thick for Cr and 2.5 nm thick for oxide



EELS suggests something more like 2.5 nm for both the Cr and the O layer



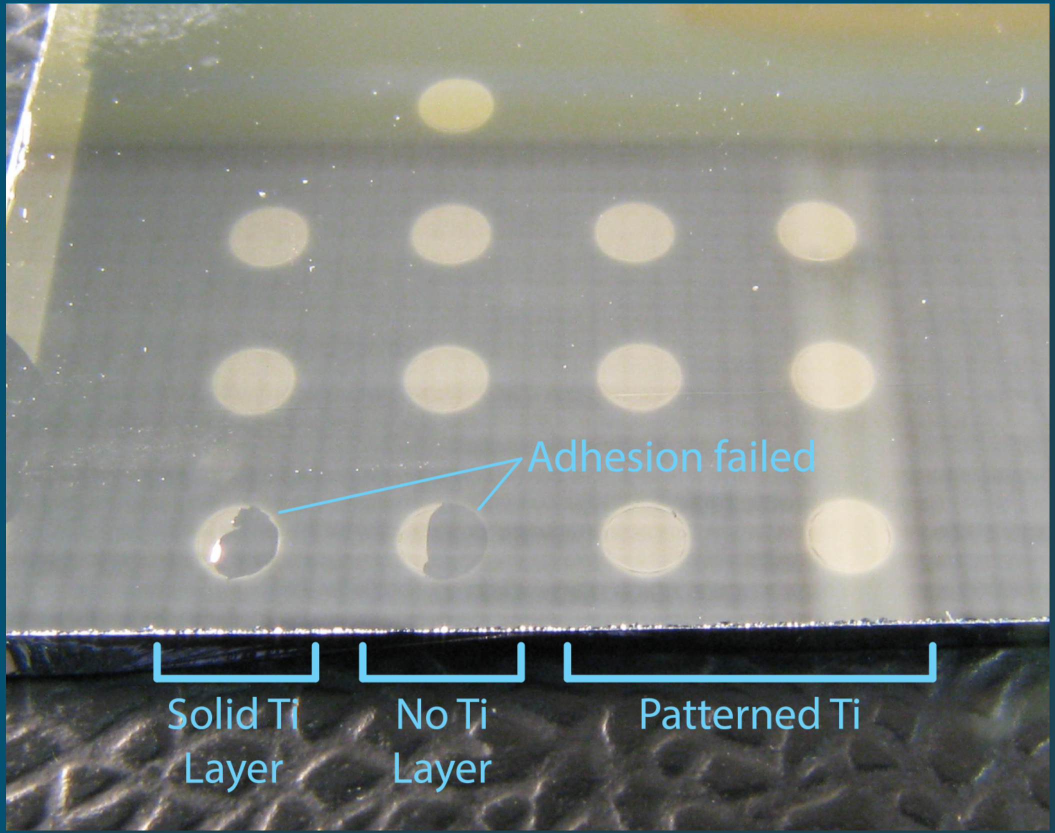


EDS and EELS measurements by J. Sugar

Adhesion testing of sensors with thick Pd

Adhesion testing “tape peel method” has shown promising results for Ti posts

- Overall good performance with patterned Ti
- Tape-peel method is highly variable though



Results of a tape peel adhesion test: sensors with patterned Ti out perform others in first test