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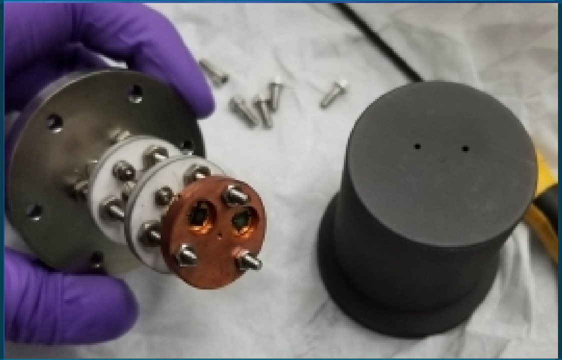
SAND2021-13686C

Sandia National Laboratories

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



Ryan Hood[1], 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, CA

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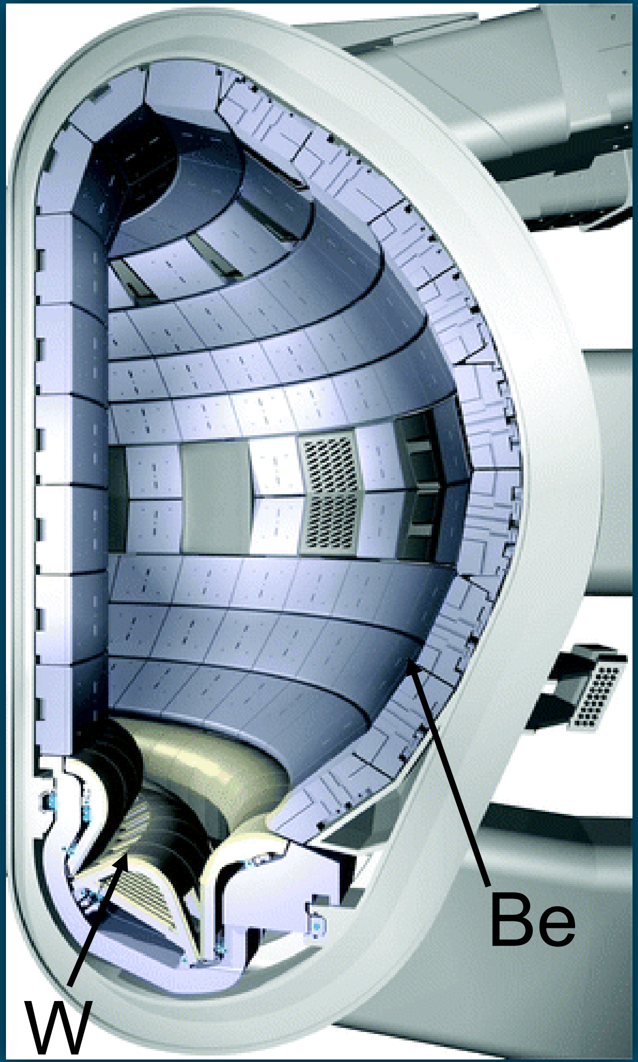
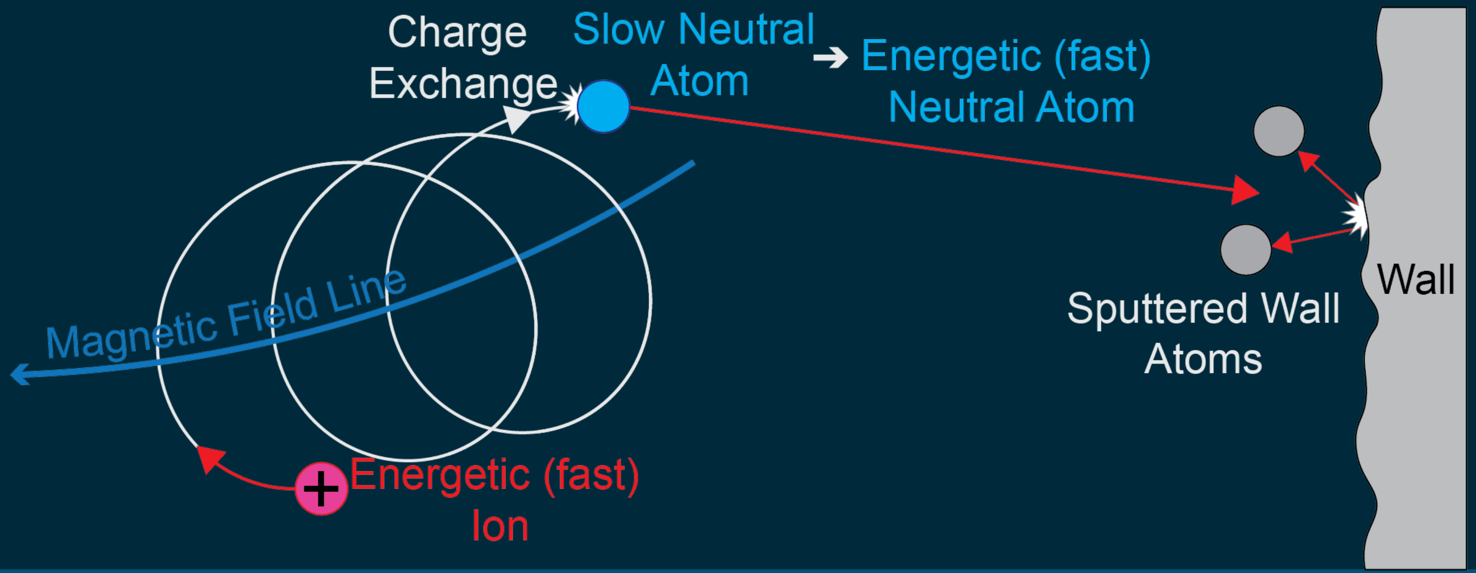
Materials will be a significant challenge for future tokamaks



Exposure conditions:

- High-flux D-T plasmas
- High-energy fusion products (14 MeV n, helium ash)
- Impurities
- Charge-exchange neutrals
  - Diagnostics are presently lacking on US Tokamaks
  - In past, low energy neutral analyzers and carbon resistance probes have been used
  - Pd-MIS style sensors may be better choice – compact and can be regenerated [1]

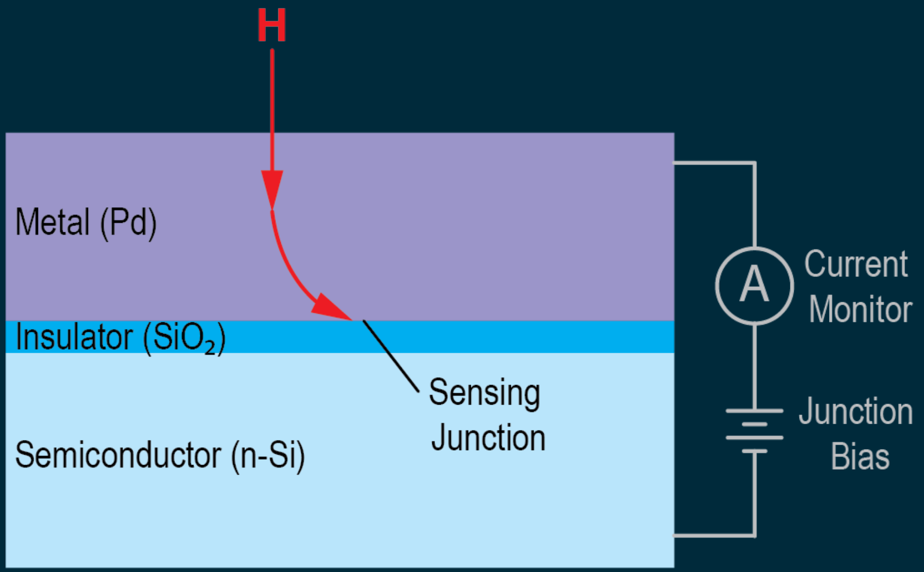


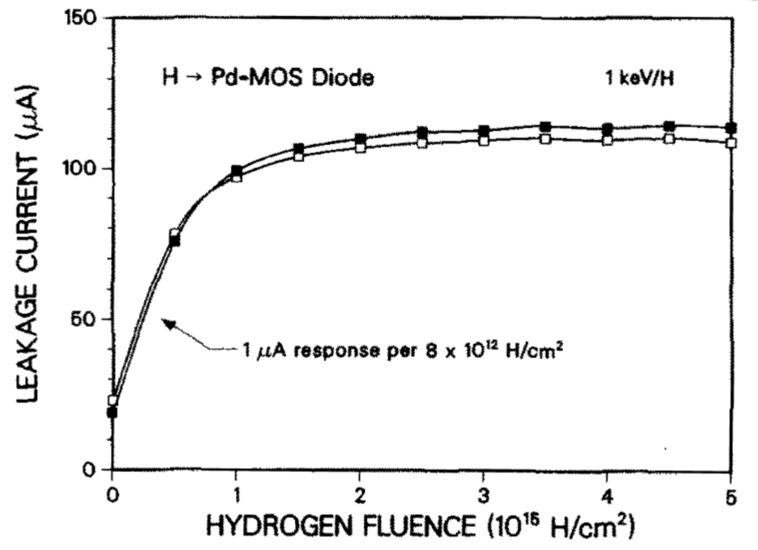
[1] R. Bastasz, B.L. Cain, T.E. Cayton, R.C. Hughes, and D.N. Ruzic, J. Nucl. Mater. 162-164 (1989) 587

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

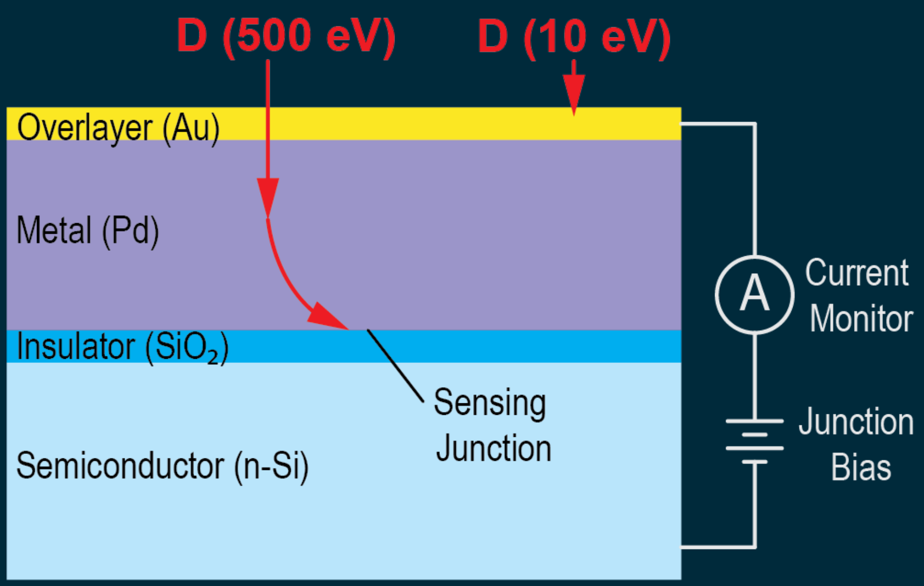




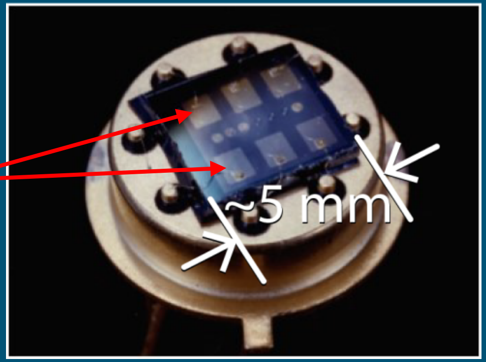
R. Bastasz, B.L. Cain, T.E. Cayton, R.C. Hughes, and D.N. Ruzic, J. Nucl. Mater. 162-164 (1989) 587

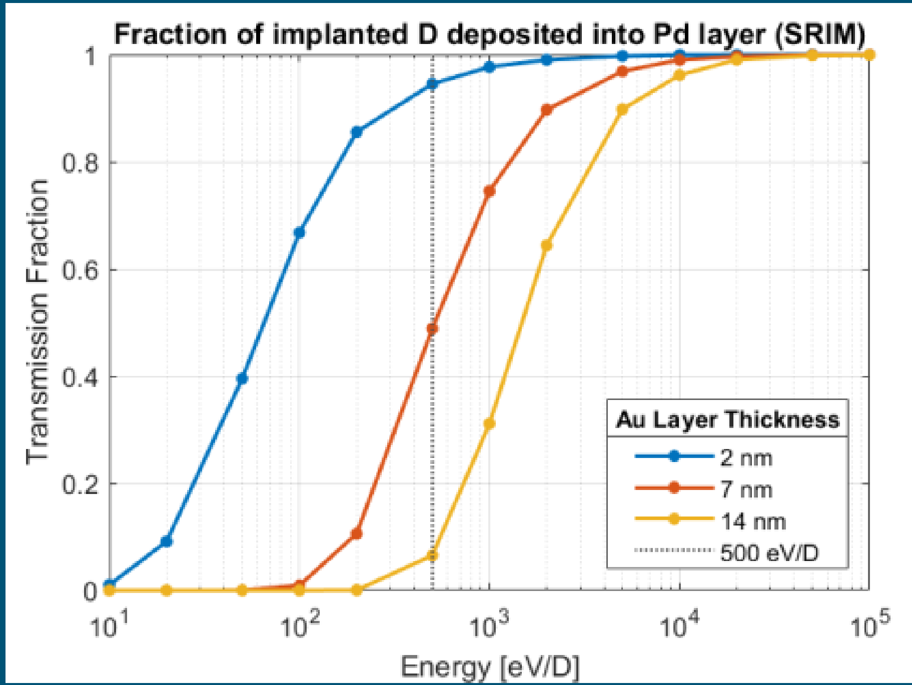
Energy resolution provided by gold overlayer

- 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





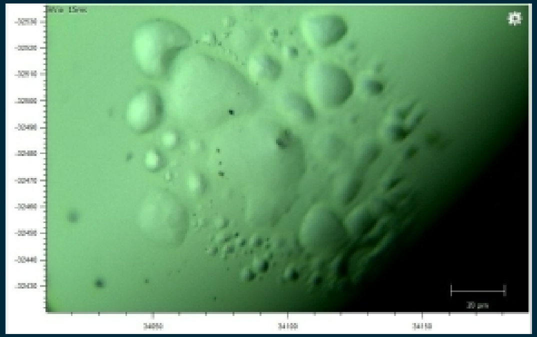
Design modifications to improve ruggedness

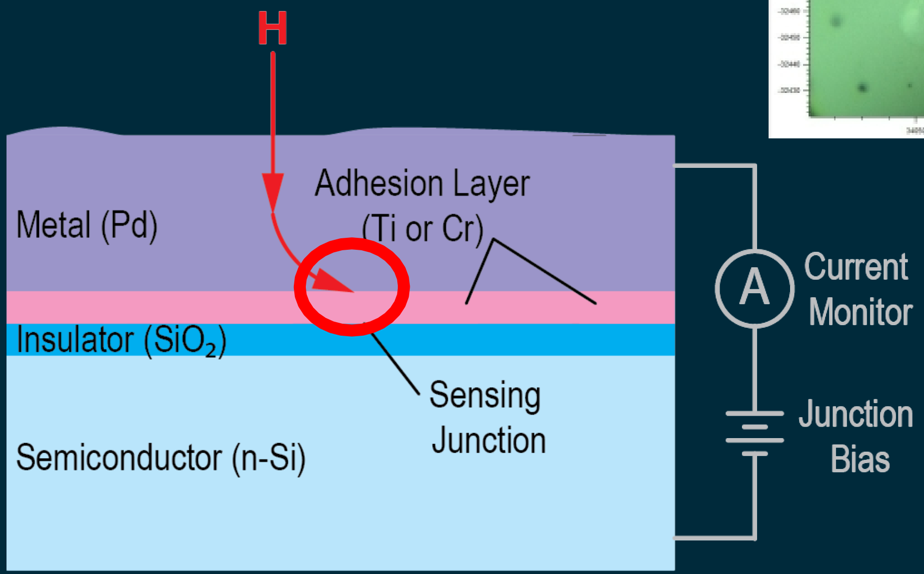
High energy particles result in charge accumulation in the oxide layer
– This shifts the barrier potential making sensor calibration impossible

Remedies:

Minimize oxide thickness

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





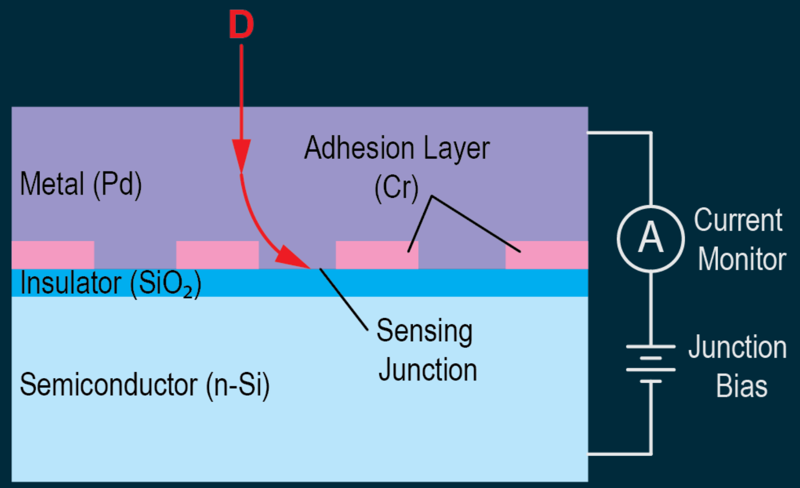
Maximize metal layer thickness (~500 nm)

- 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

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

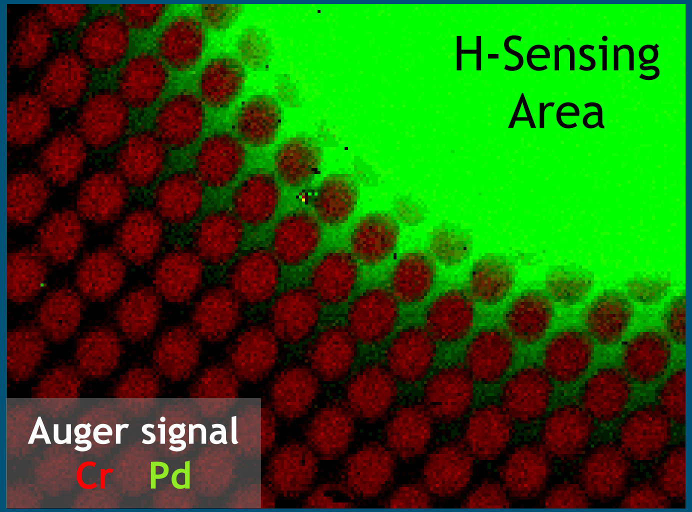


Newest sensors have 500 nm Pd

Expected to withstand c-x energies up to ~50 keV based on SRIM calculations (30x improvement)

Good compromise

	No adhesion layer	Patterned Cr layer	Continuous Cr layer
H Sensitivity	Great	Very Good	Poor
Film Adhesion	Poor	Good	Very Good

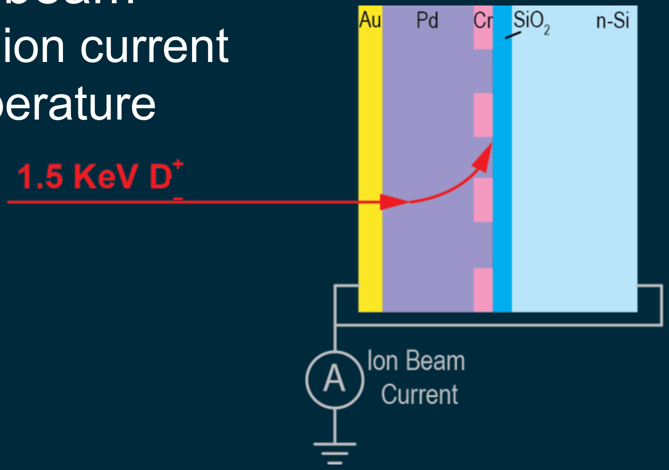


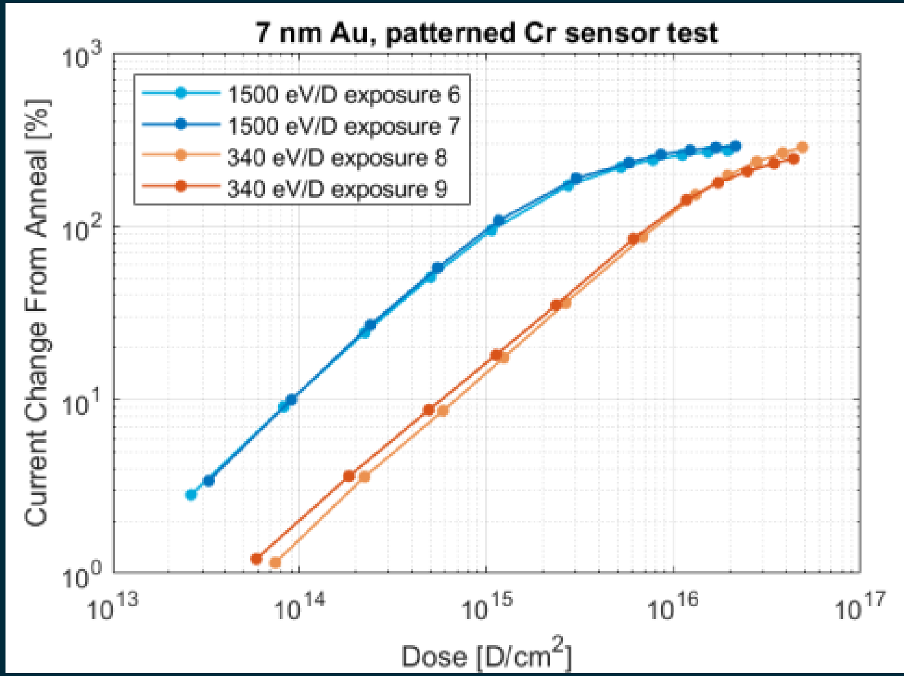
Auger electron microscopy map showing elemental composition on surface

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

Conditioning performed using SIMS ion beam

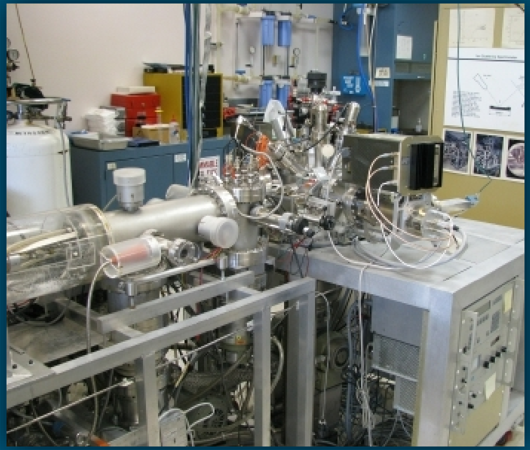
- Precision dosing by measuring collected ion current
- Control of beam energy and sensor temperature





- Strong response (~ 1-10 uA)
- Consistent response to dose after ~ 4 regeneration cycles
- Different ion energies give different response
  - Fewer ions penetrate gold layer at lower energy
  - More reflected ions at lower energy

SIMS ion beam station at Sandia National Laboratories

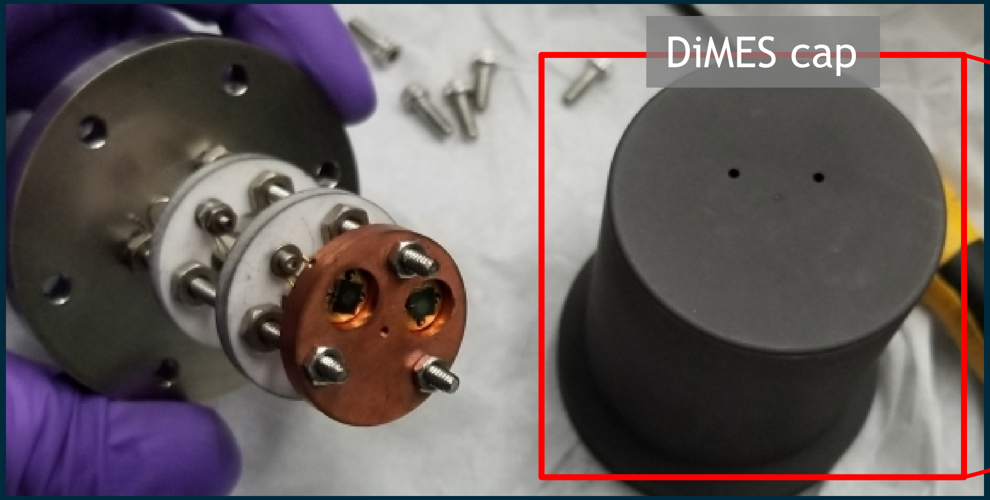


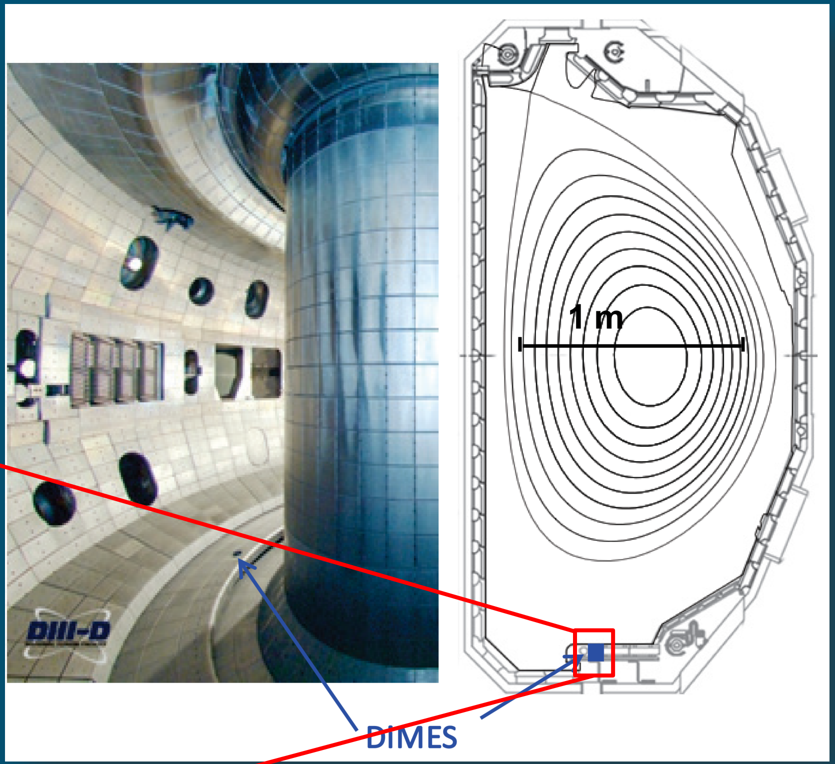
TO-5 mounted sensor

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., et al., Fusion Eng. Des., 124 (2017), pp. 196-201

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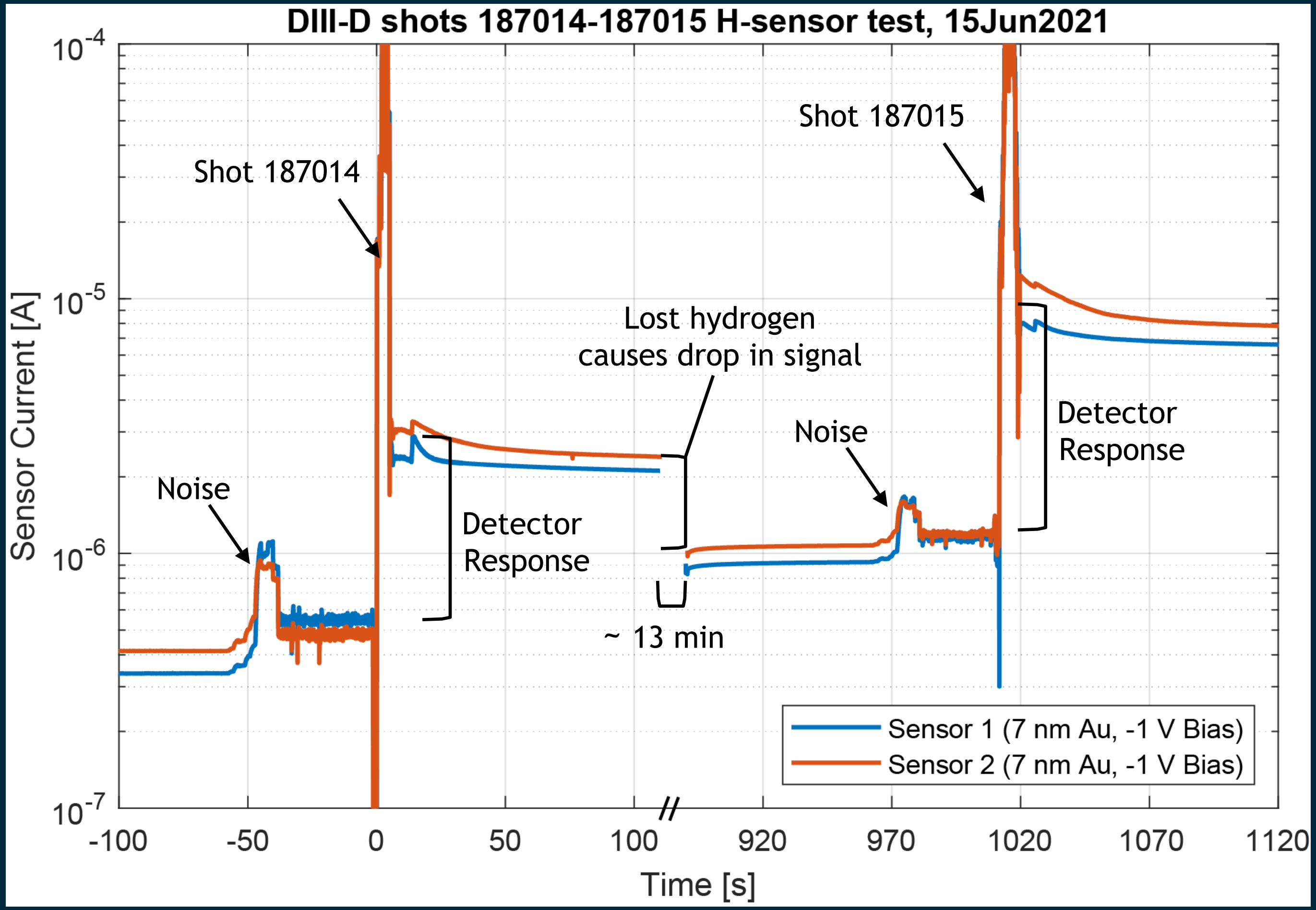
Sensors were successfully demonstrated in tokamak environment

Sensors exposed to ~ 27 plasma shots over 2 days*

- Saturation after ~ 3 H-mode shots in USN configuration – strong signal!
- Demonstrated sensor regeneration with thermal cycling
- Nearly identical response from pair of sensors in USN configuration before saturation

If we assume 500 eV thermal c-x particles:
~ 5 x 10^{14} D/cm^2 s



H-sensor data from consecutive USN plasma shots in DiMES, starting from regenerated state

* Special thanks to Huiqian Wang for allowing us to piggyback during his experiment

Post-exposure analysis shows dust and signs of erosion

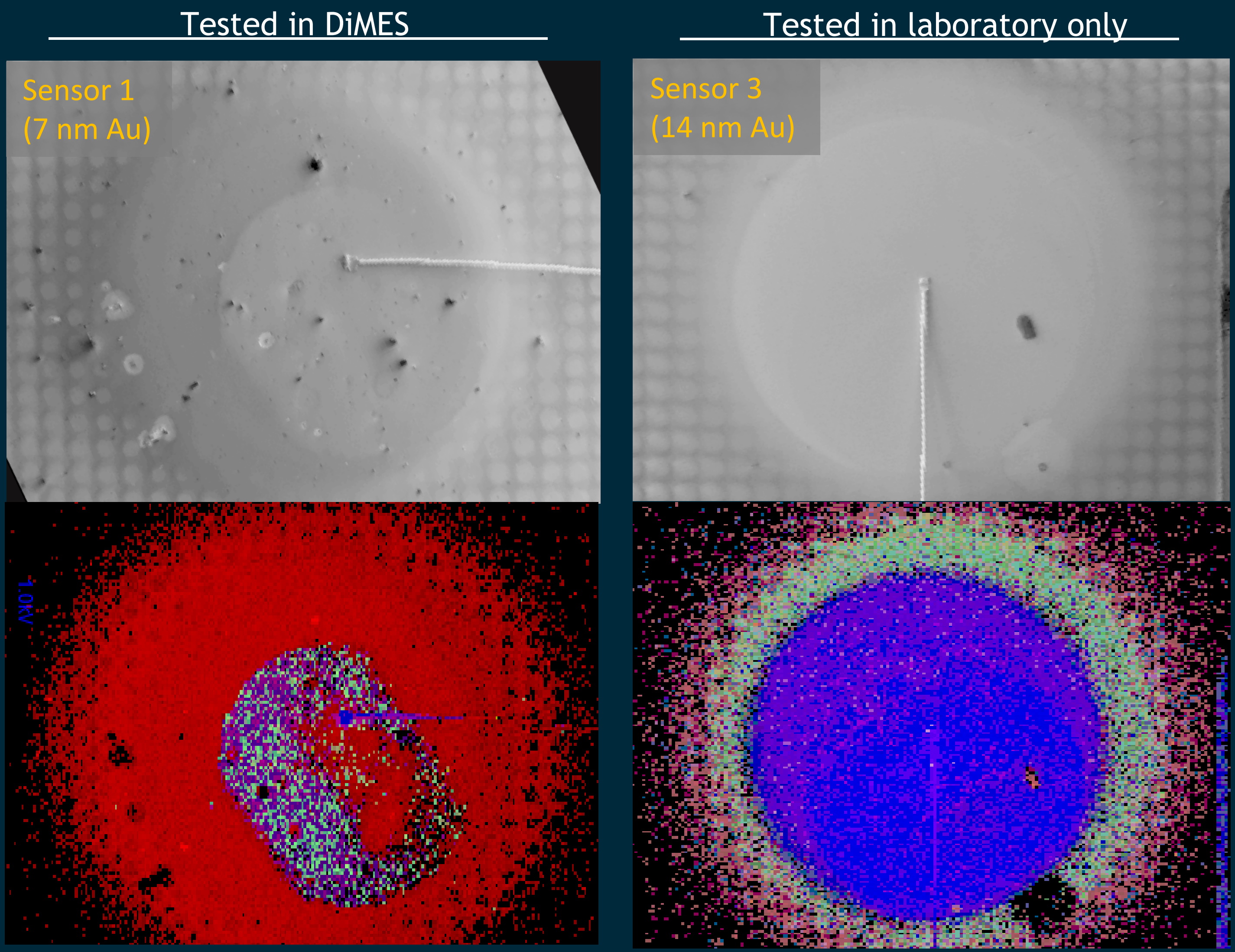
Scanning electron microscope images

- Sensors exposed in DiMES show dust and mark where aperture was aligned
- Sensors only tested in lab are nearly blemish free

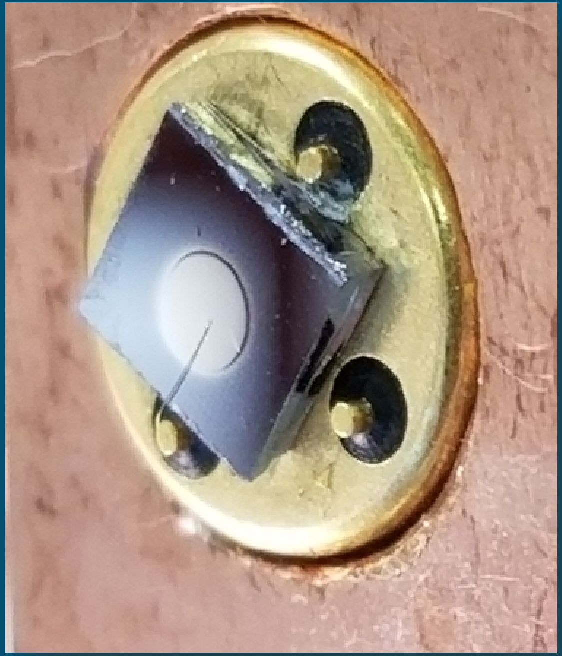
Auger electron microscopy maps show elemental composition on surface (~0.4 – 5 nm)

Carbon Palladium Gold

- Sensors exposed in DiMES are covered in carbon from cap except under aperture
- Sensors only tested in lab look as expected



Successful demonstration at DIII-D paves way for future development and testing

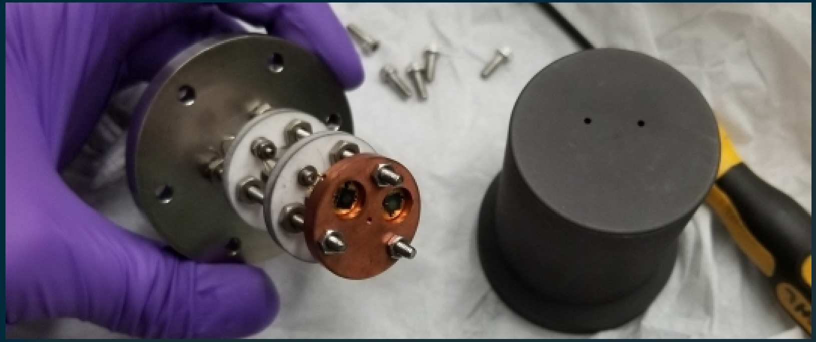


Summary

- Ruggedized H-sensors have been developed with thin oxide and thick Pd for resilience to high energy particles
- Sensors were demonstrated in DiMES at the DIII-D Tokamak withstanding ~27 plasma shots

Future Work

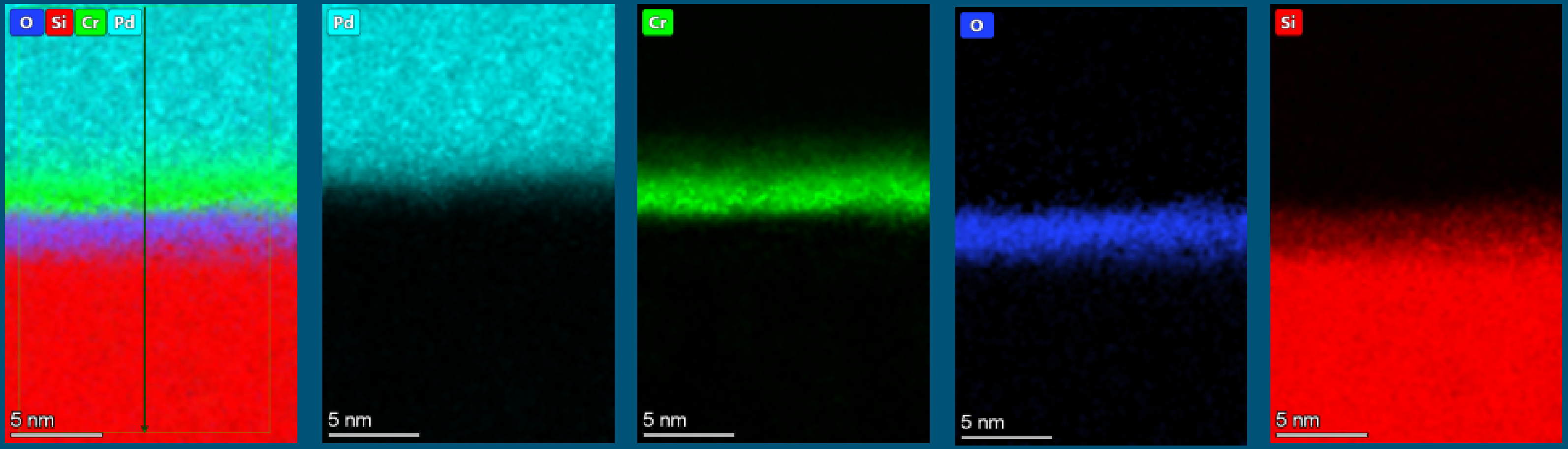
- Explore optimization of adhesion layer
- Continue laboratory testing of sensors
- Further testing at DIII-D
  - Measurements of shot-to-shot energy distribution and fluence using multiple gold thicknesses
  - Resolve poloidal distribution of c-x flux using multiple sensors with angled apertures
  - Integration into WITS wall station

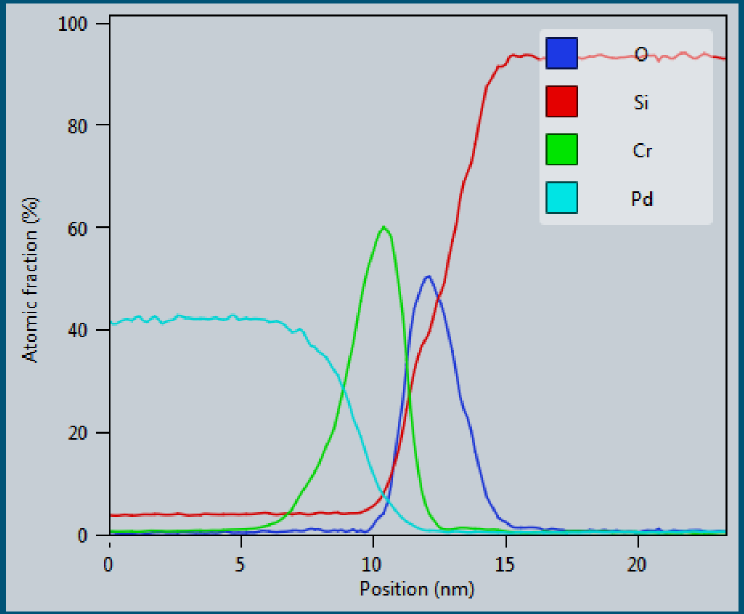


This work was funded by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences

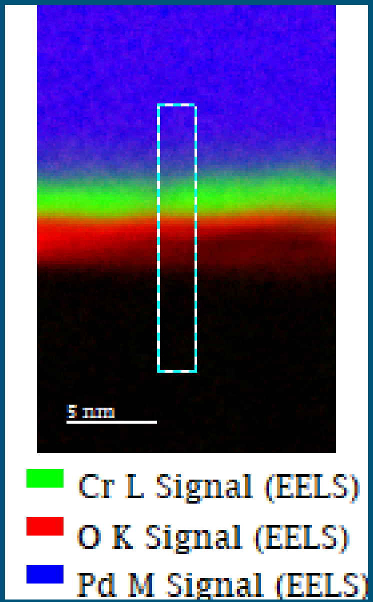
Supplemental slides

EDS and EELS measurements show minimal intermixing or oxidation of Cr

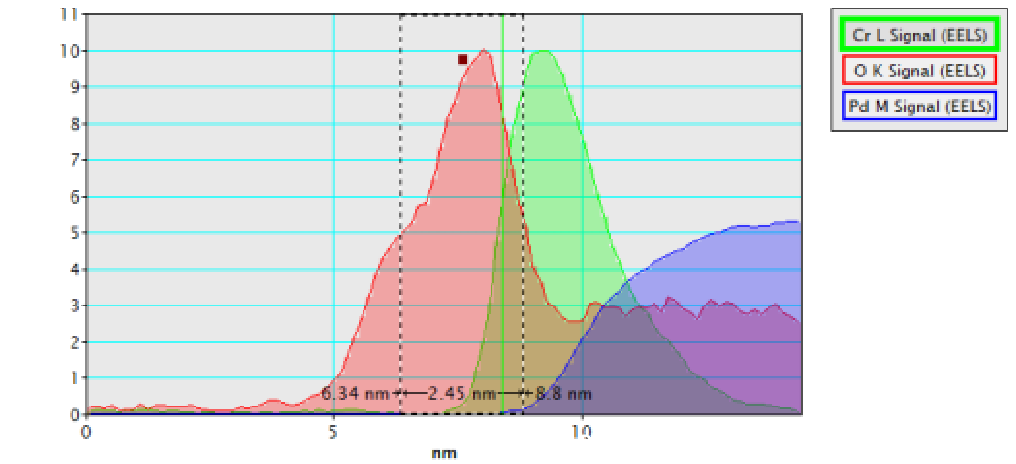


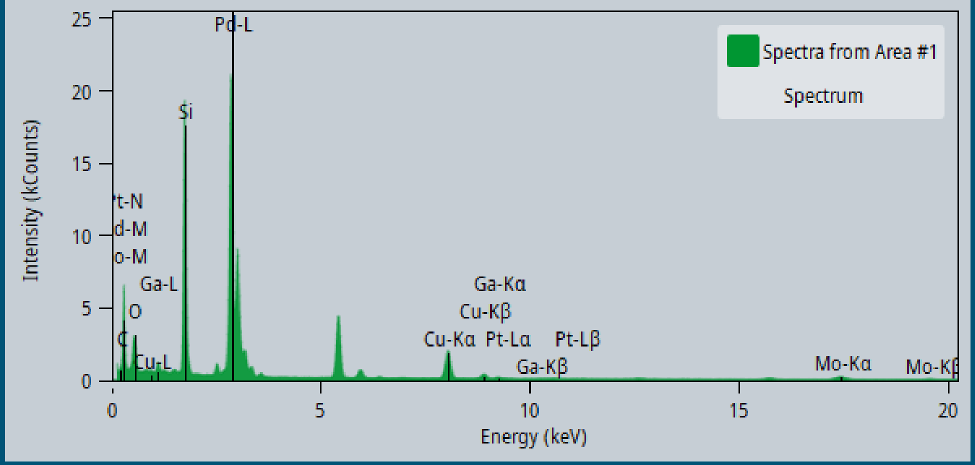


EDS measured 2.8 nm thick for Cr and 2.5 nm thick for oxide



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





EDS and EELS measurements by J. Sugar

Pd-MIS H-sensor operating principle

Metal – semiconductor junction forms a Schottky diode

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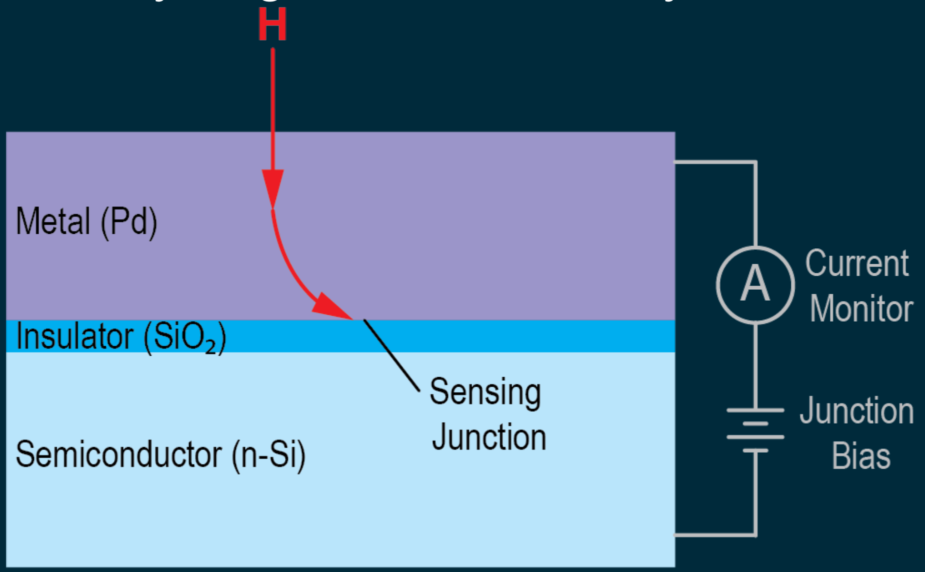

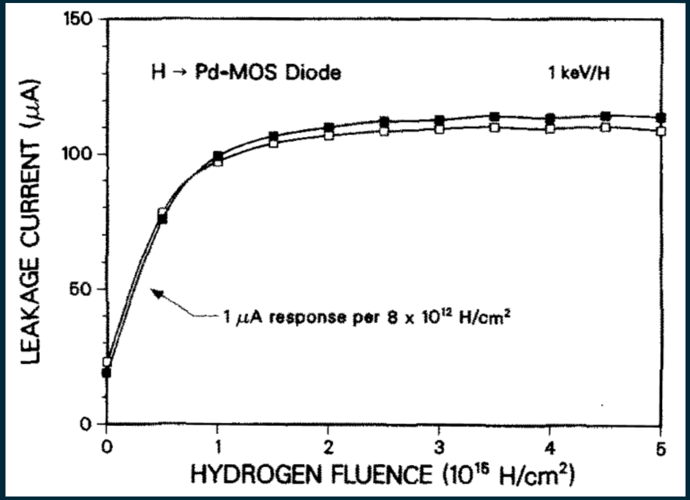

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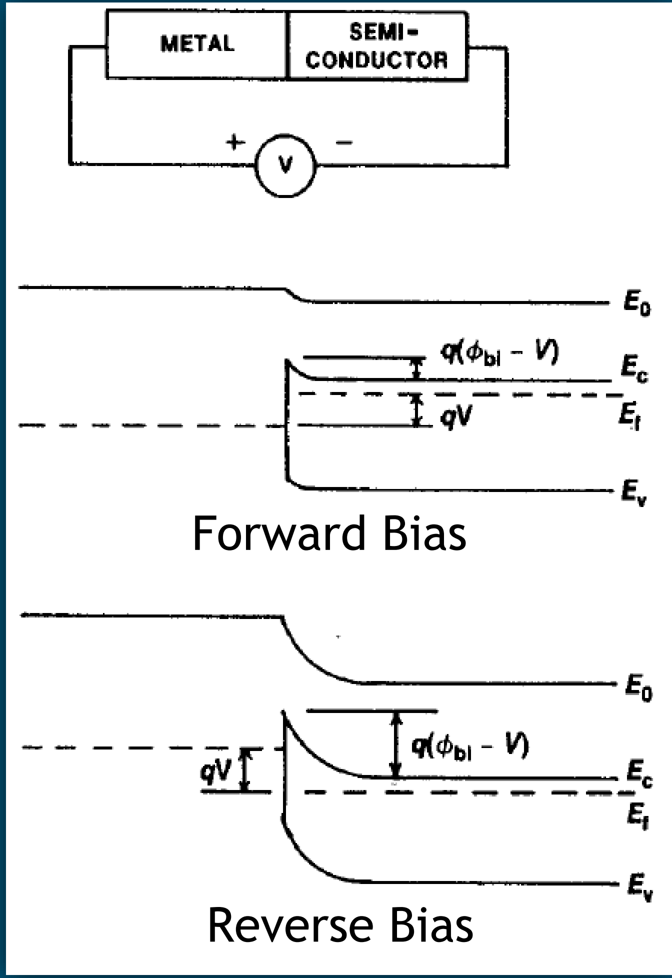

Metal-Semiconductor junction band diagrams shown in forward and reverse bias (oxide not shown for simplicity)