Materials for the hydrogen economy: (from smart windows) to hydrogen sensors

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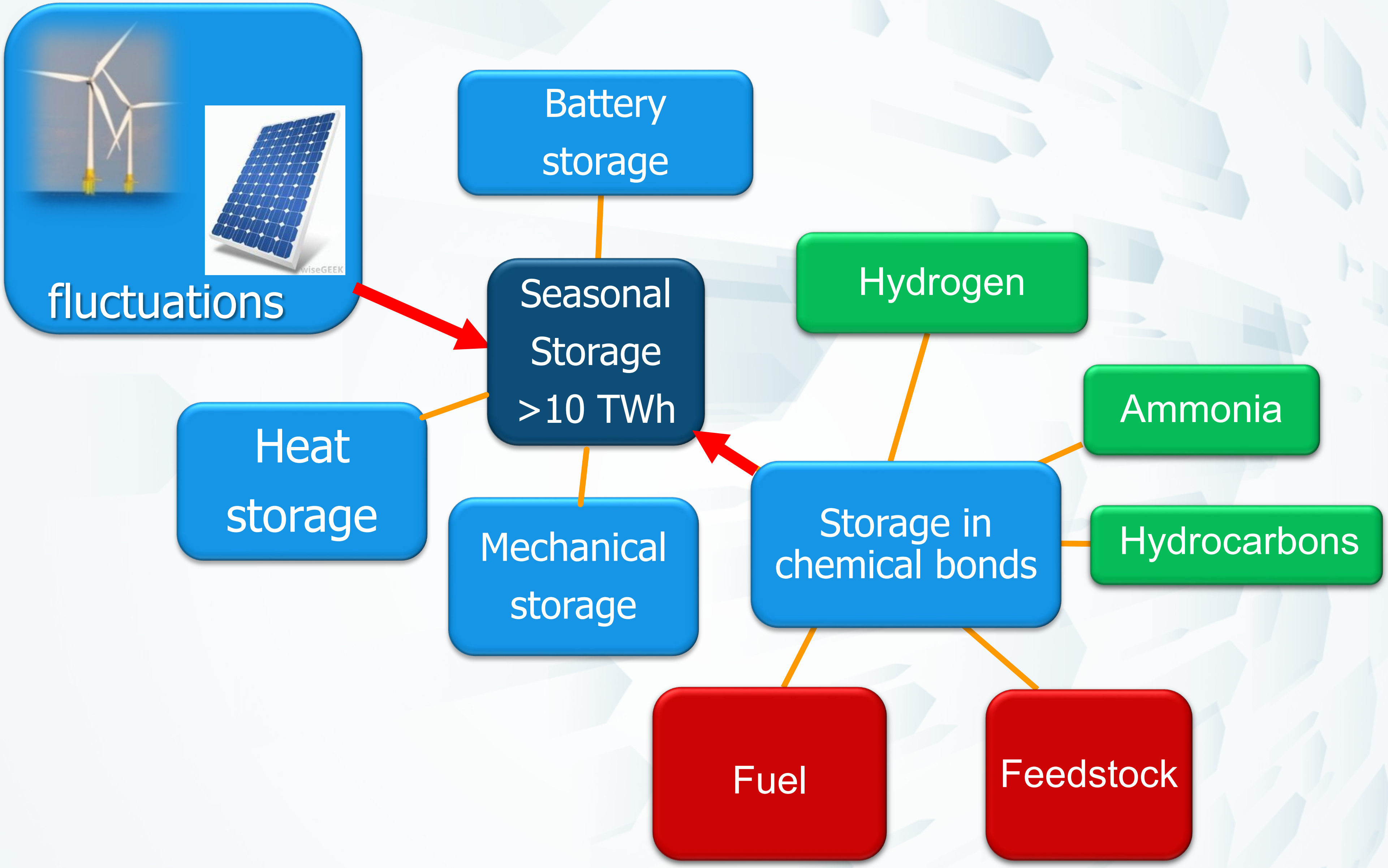
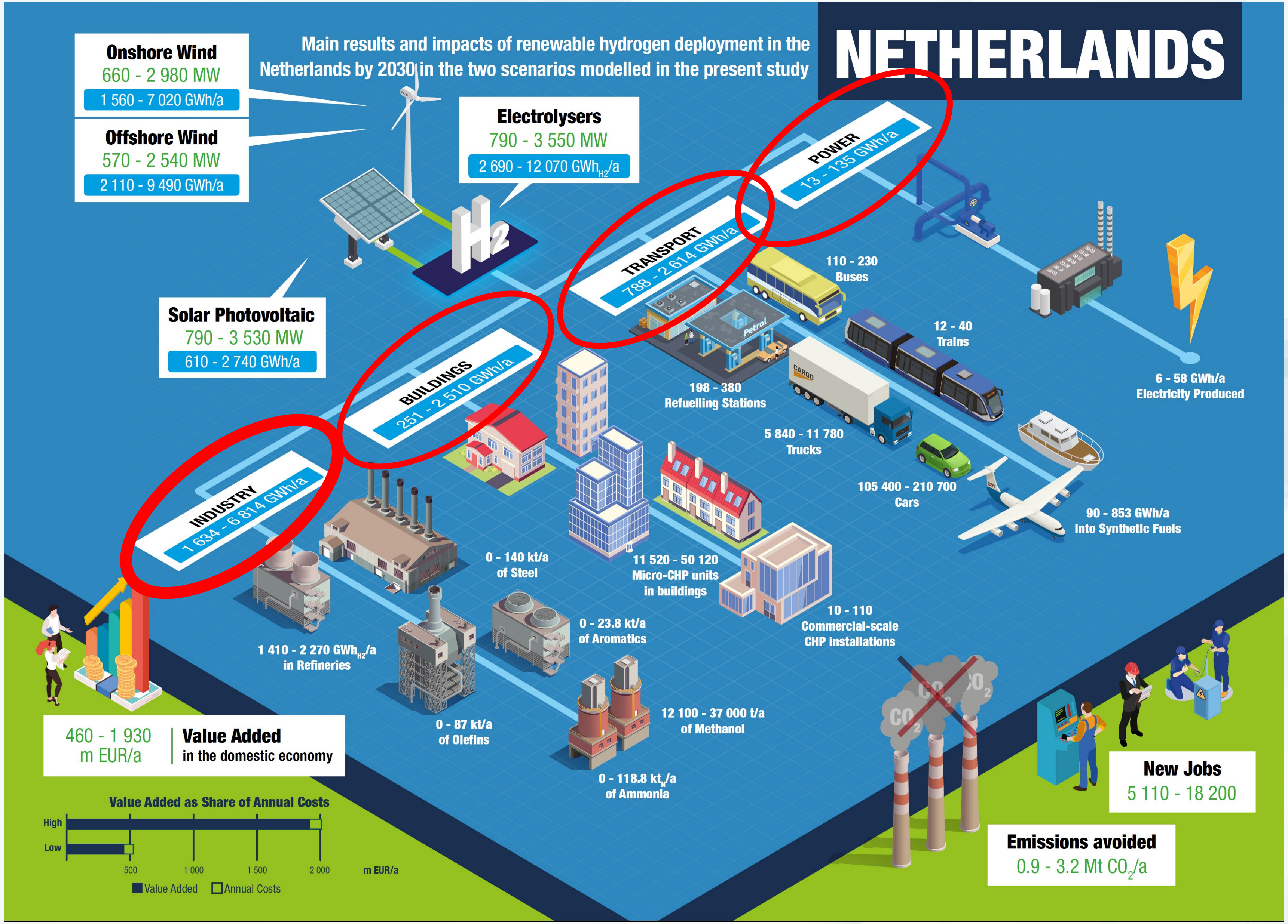
A sustainable energy system



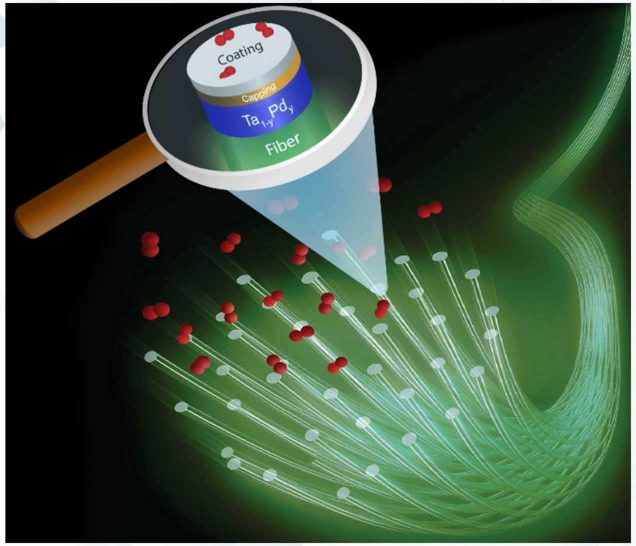
Hydrogen for industry, buildings, transport and power



Opportunities for **Hydrogen Energy Technologies** Considering the National Energy & Climate Plans (2020)

Why optical fiber hydrogen sensors?

- Readout can be separated from the sensing area.
- No electric currents near the sensing area
- No presence of oxygen required
- Relatively small
- Potentially a large sensing range



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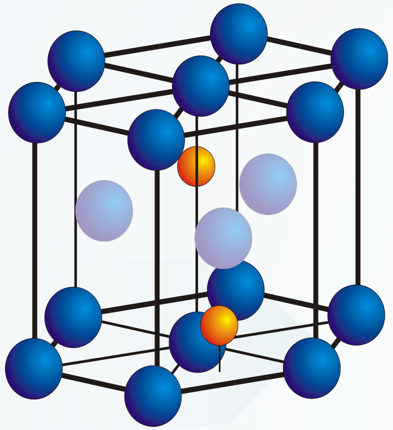
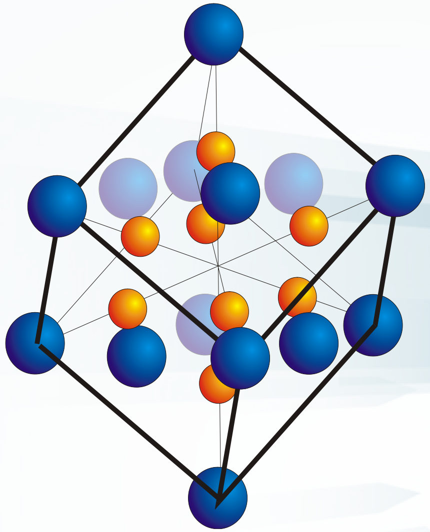
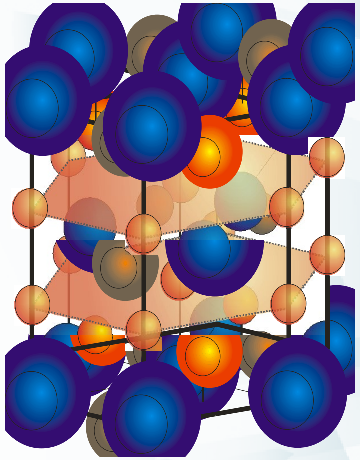
Our basis: Optical changes in RE-hydride thin films

hcp YH_0	fcc $YH_{1.9}$-$YH_{2.1}$	hcp/fcc $YH_{2.7}$-YH_3

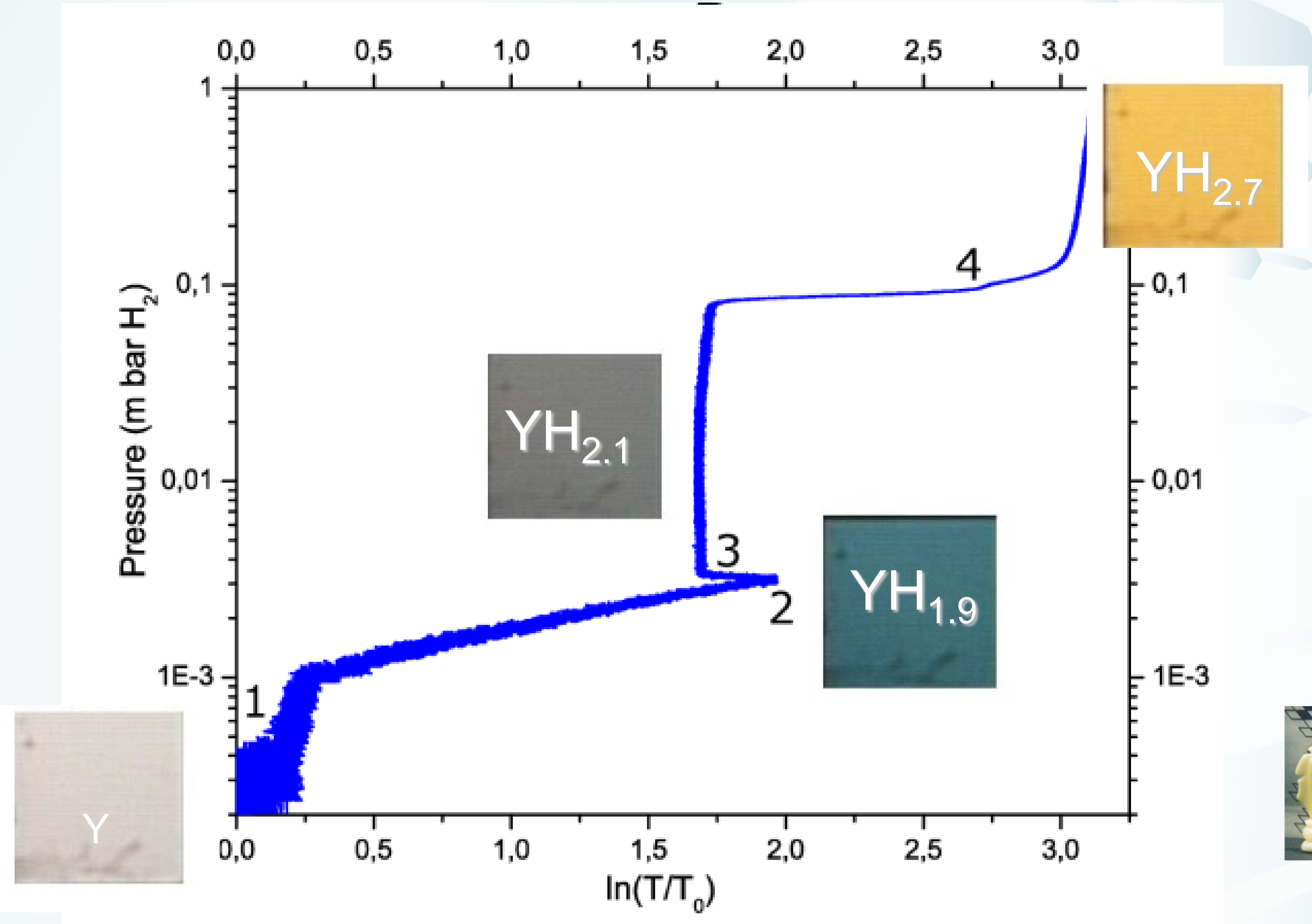


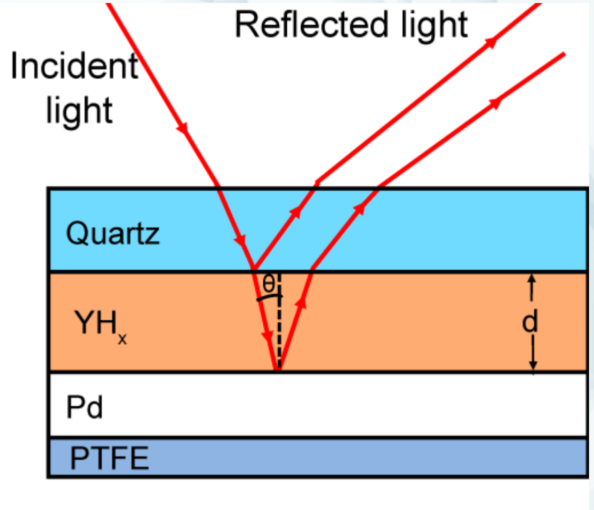




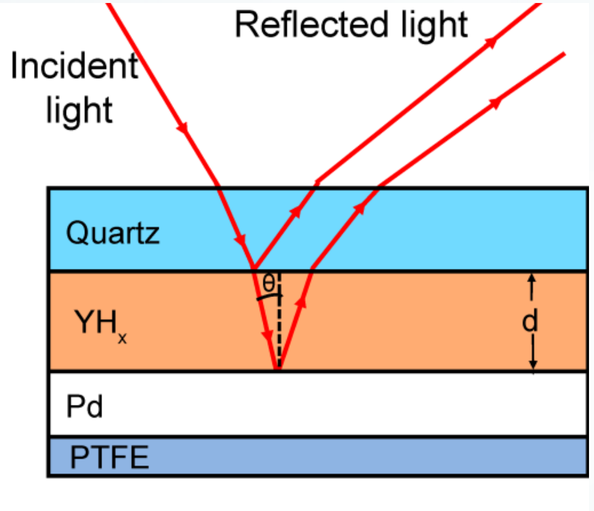
Huiberts et al., Nature 1996

Eye-readable hydrogen detector based on YH_x





Most simple approach:
Eye-readible hydrogen detector based on YH_x



$P_{H2} < 10^{-3}$ mbar

Desorbing from $P_{H2} > 10^{-1}$ mbar

$P_{H2} > 2.10^{-3}$ mbar

$P_{H2} > 10^{-1}$ mbar

Ngene et al., Advanced Functional Materials 24 (2014) 2374

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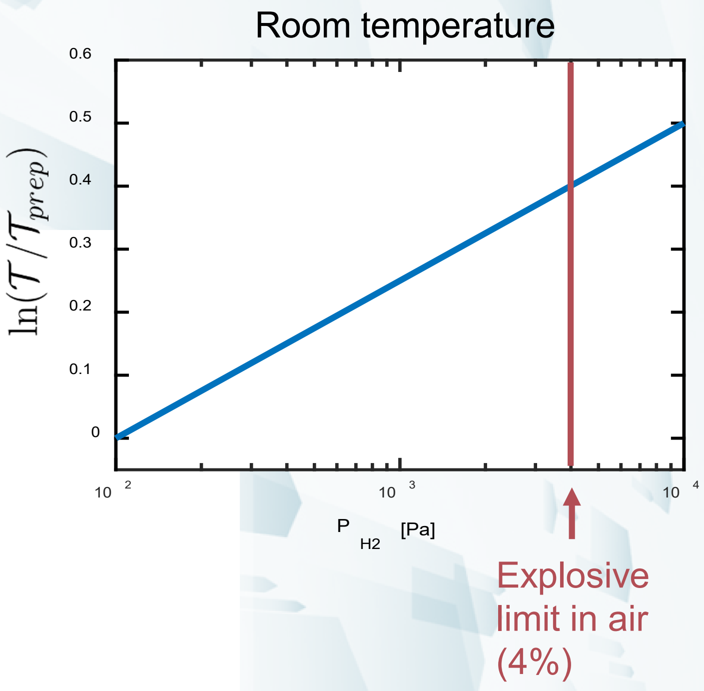
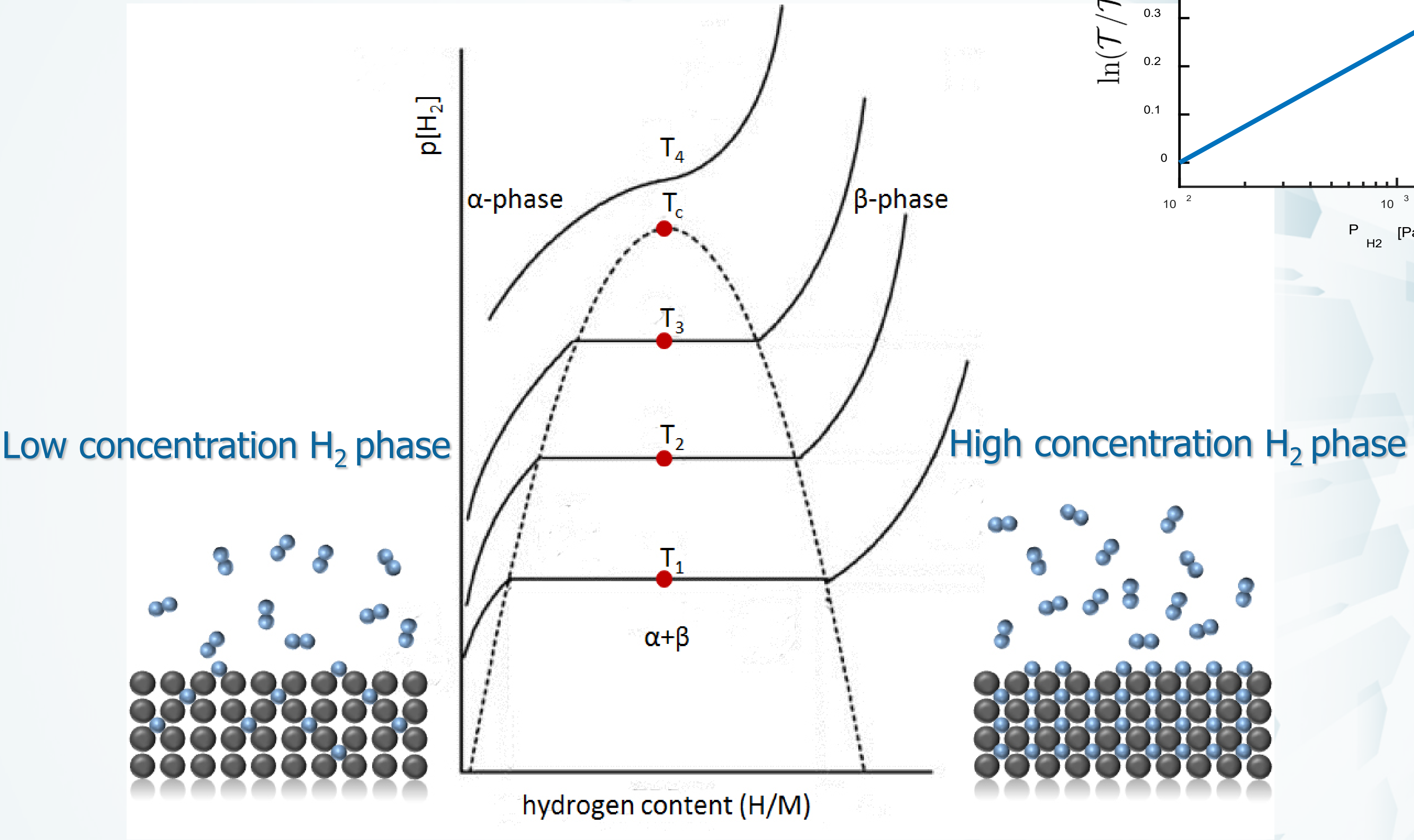
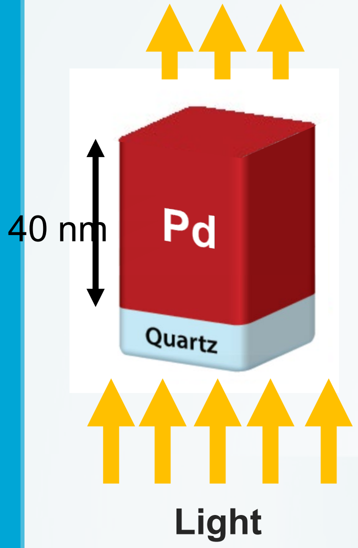
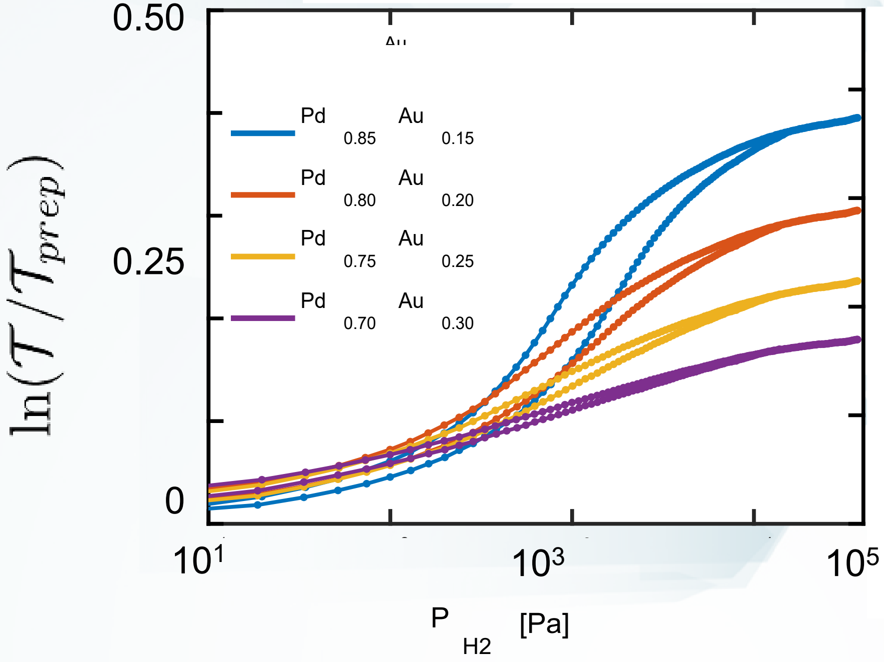
From hysteretic detector to sensor

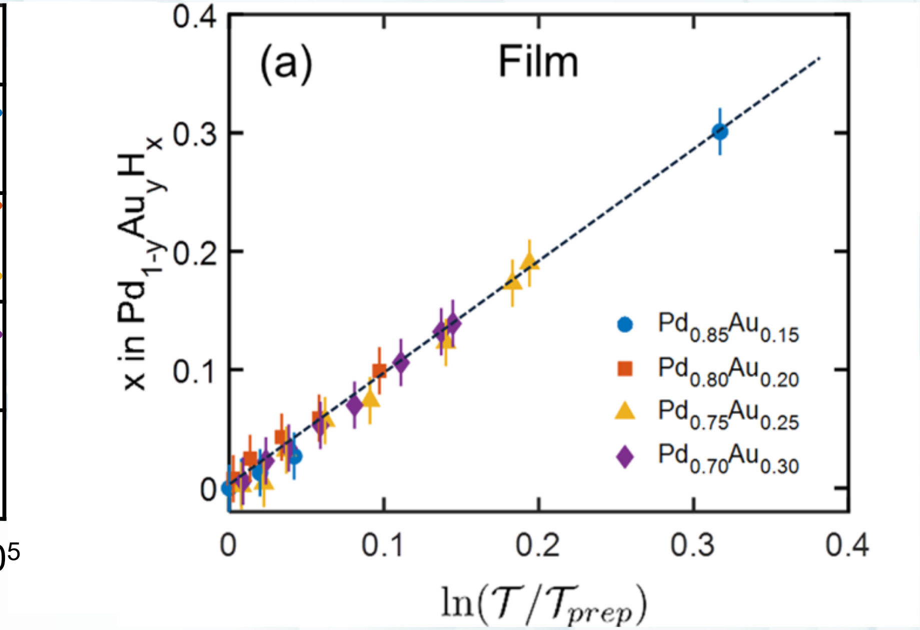




Hysteresis suppression in Pd-based sensor



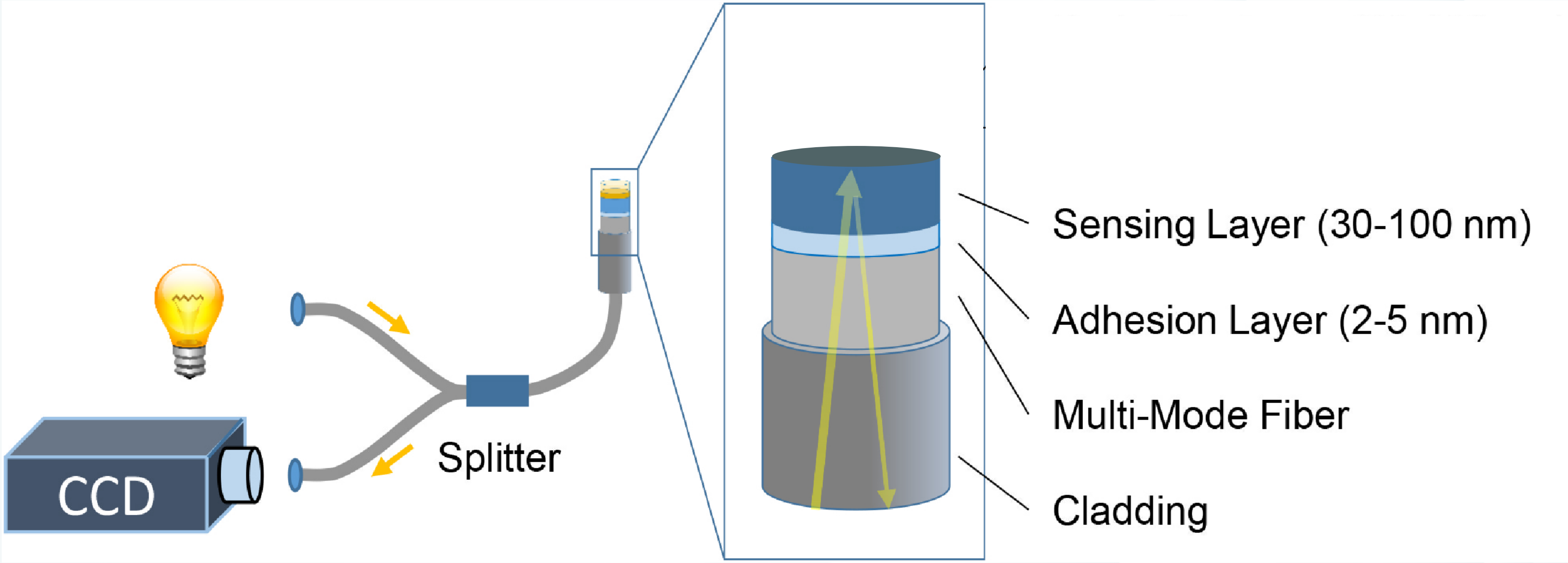




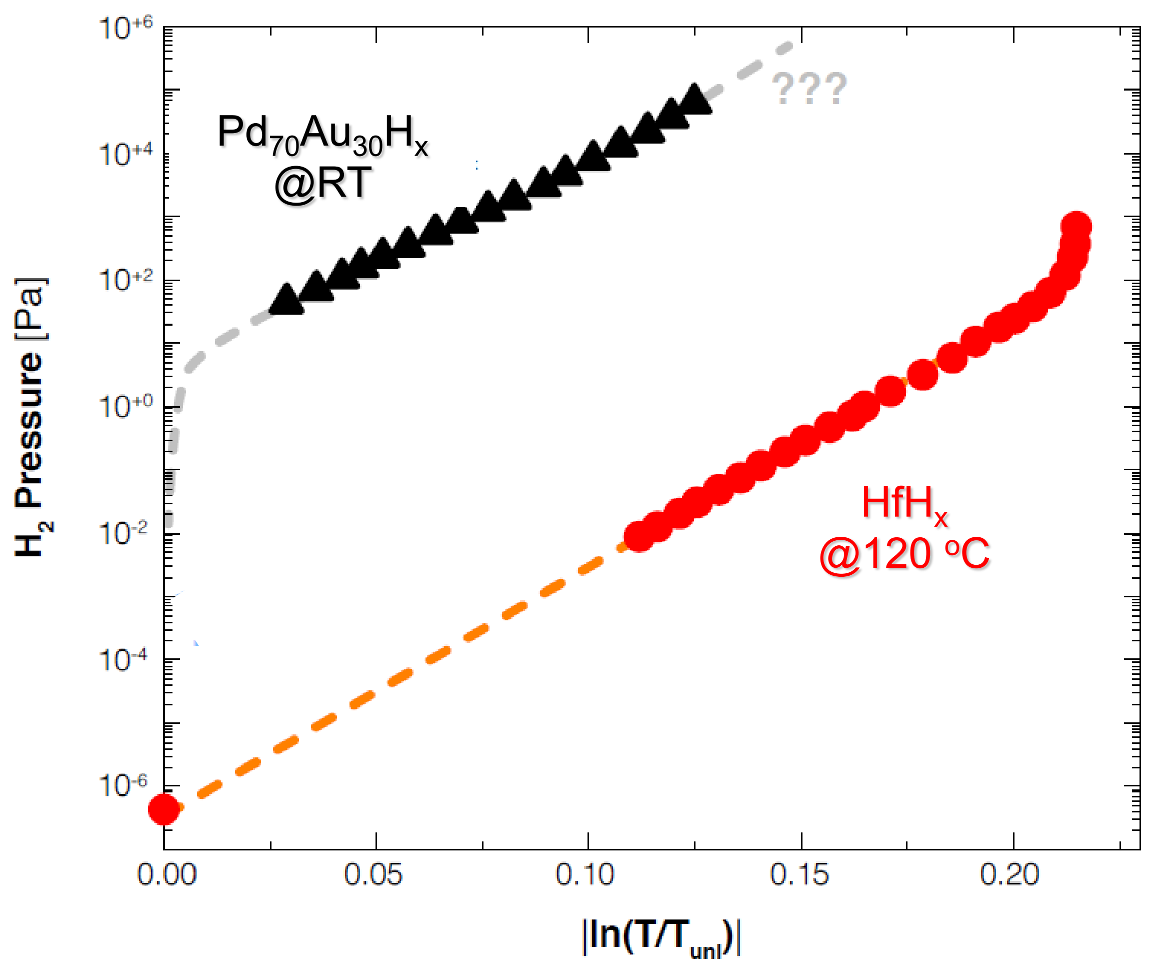
- Alloying reduces contrast and hysteresis
- H-content scales with optical contrast ($Ln(T/T_{prep})$)
- Alloying reduces number of available H-sites

ACS Appl. Mater. Interfaces 2019, 11, 15489−15497

Optical fiber hydrogen sensors, beyond Pd



Pressure range comparison



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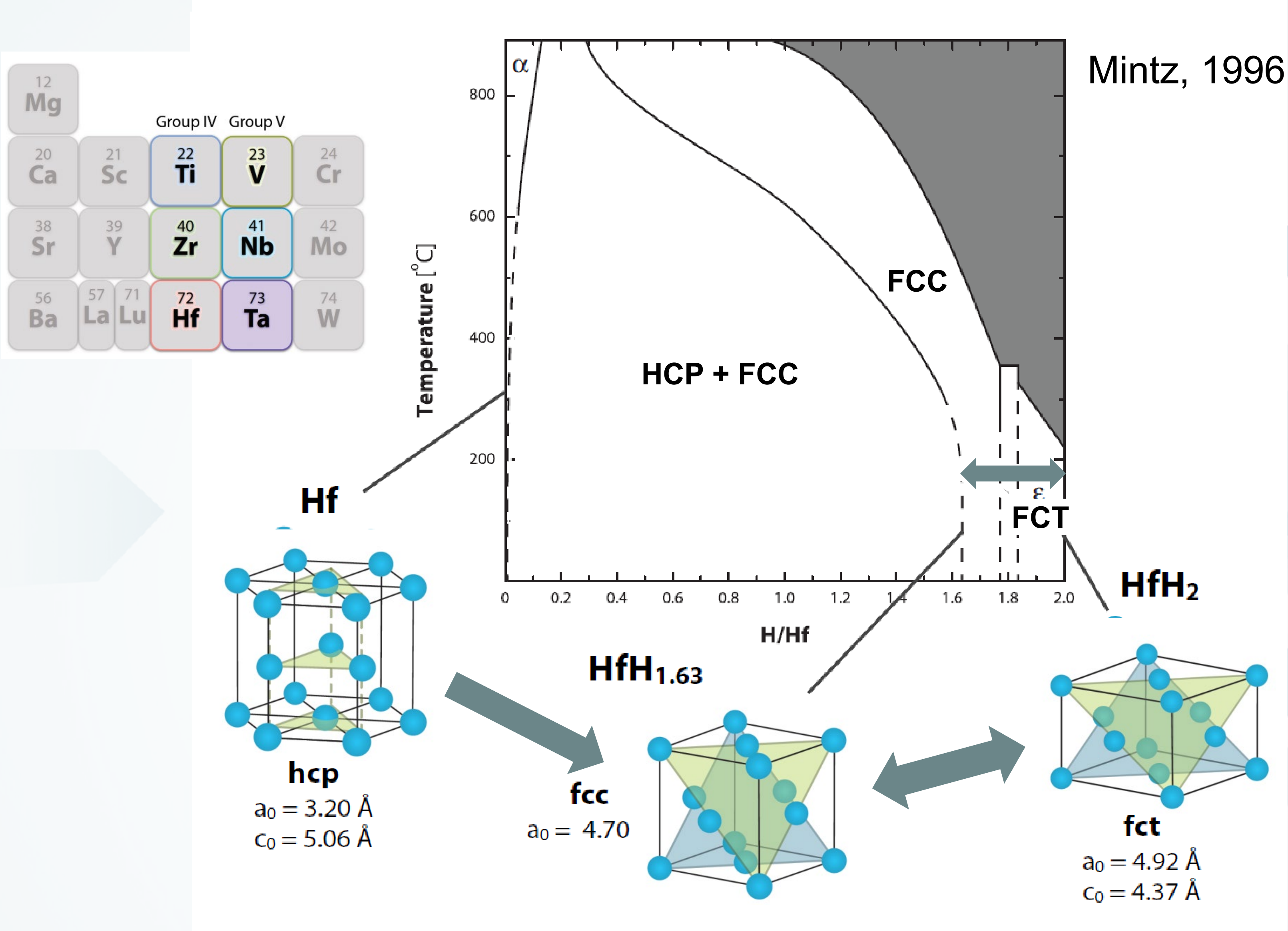
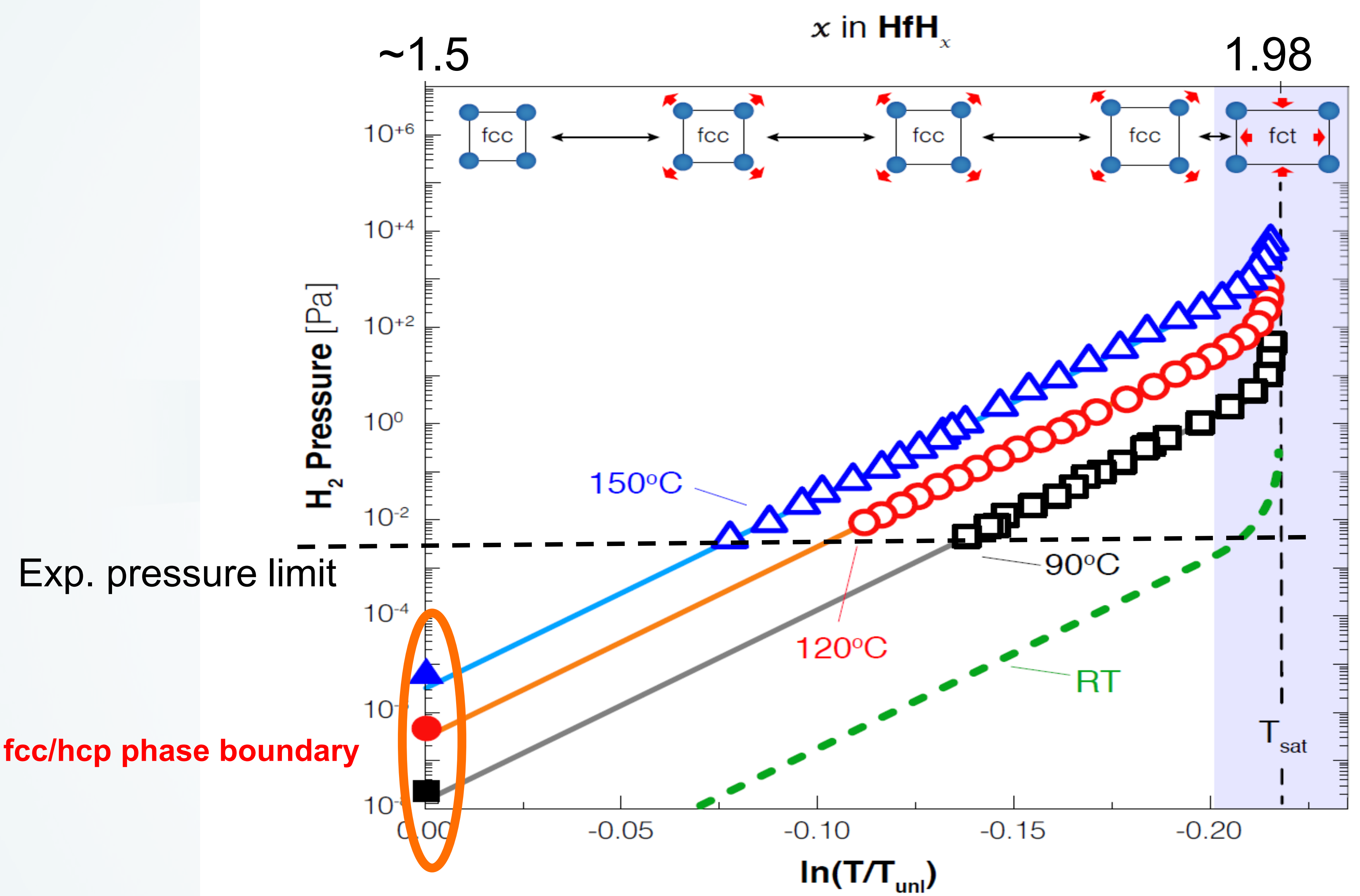
HfH_x thin films are free of hysteresis once they reach fcc

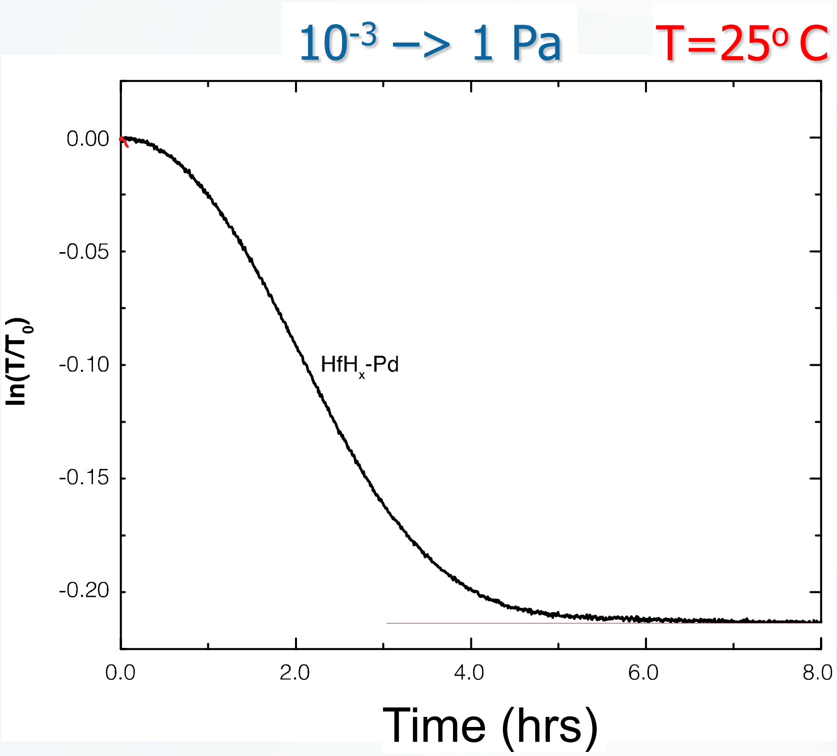


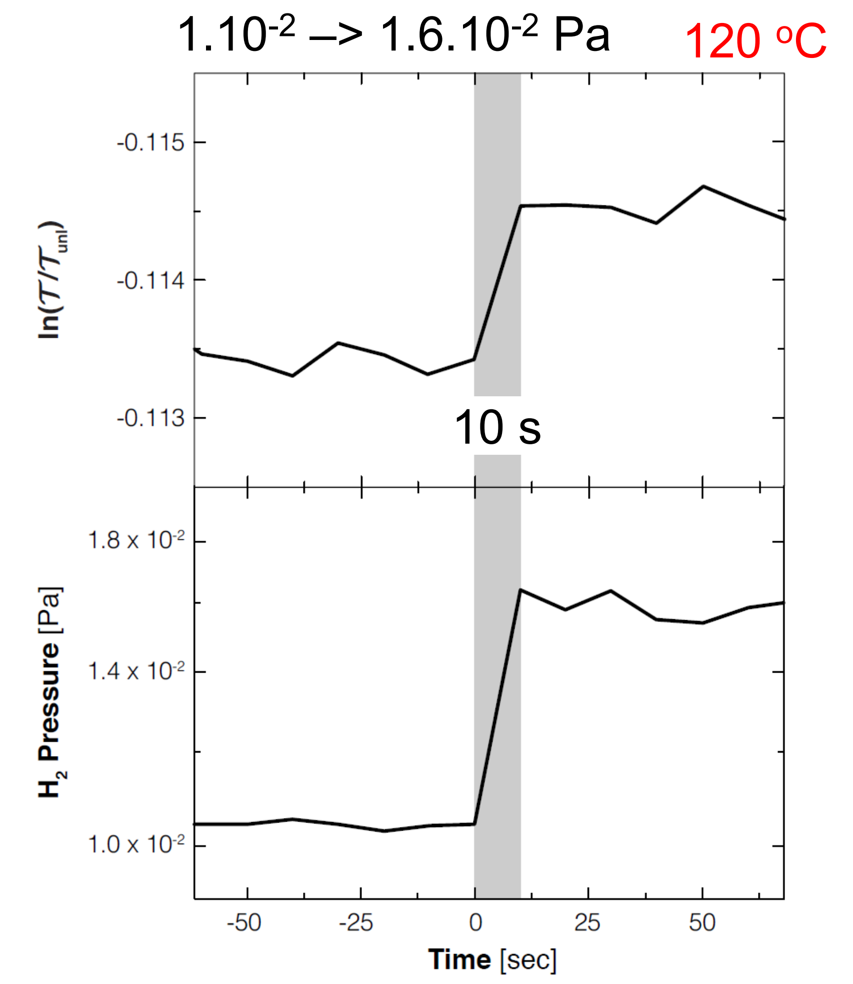
C. Boelsma, et al., *Hafnium,* Nature Comm. 8 (2017) 15718

Large range, linear temperature dependence



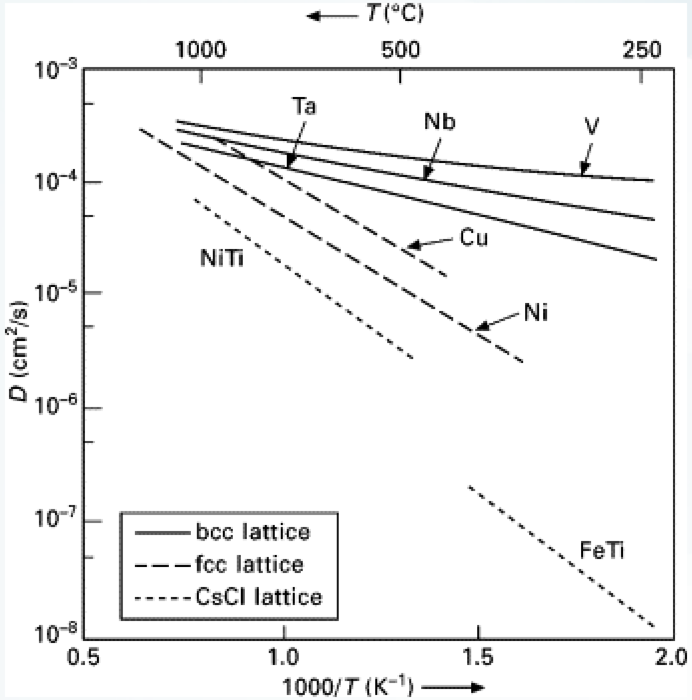
Optical response Pd-capped Hf

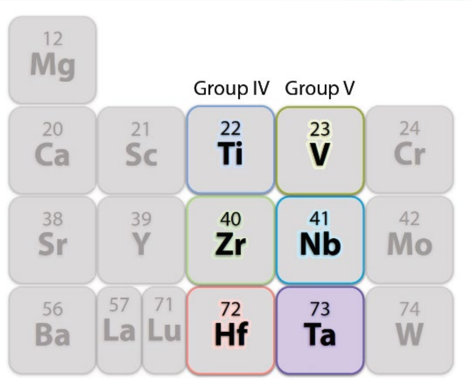


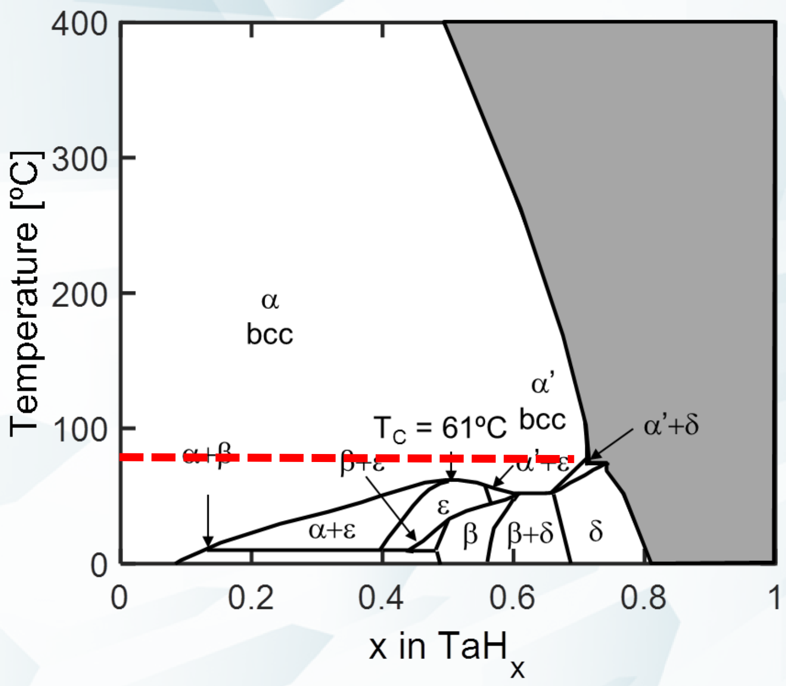


C. Boelsma, et al., *Hafnium,* Nature Comm. 8 (2017) 15718

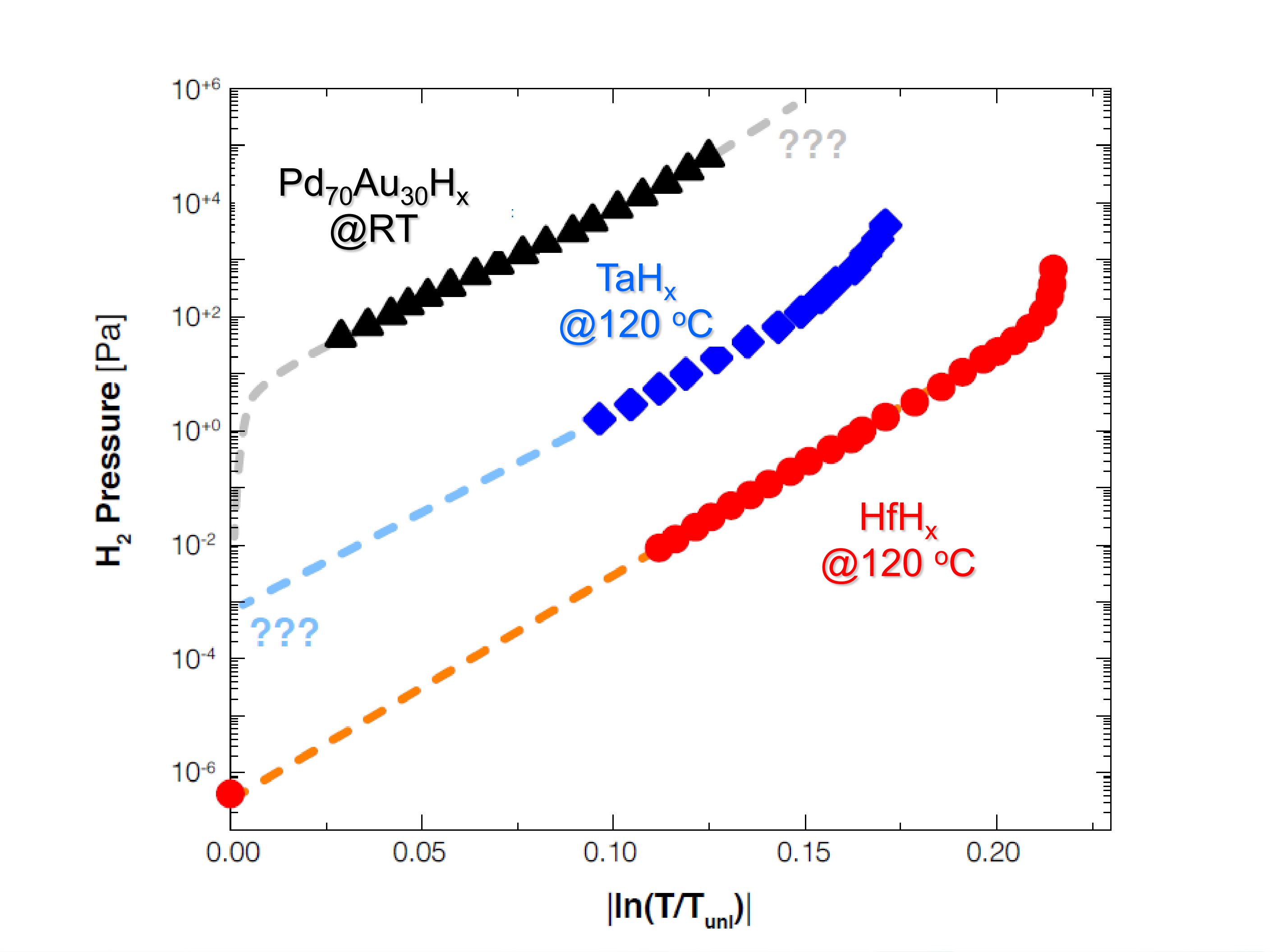
Tantalum: bcc lattice implies very fast diffusion







Pressure range comparison



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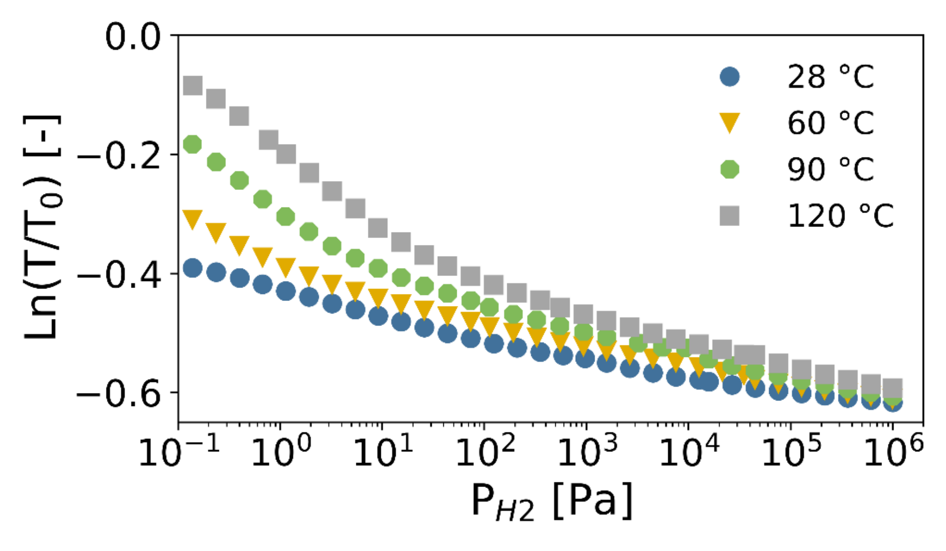
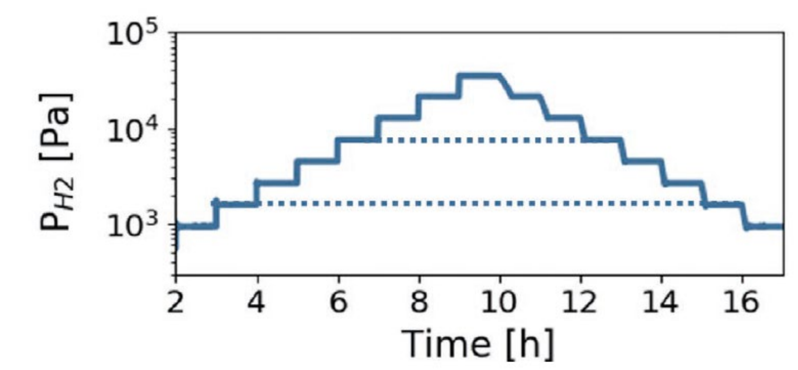
Ta: room temperature hydrogen sensing

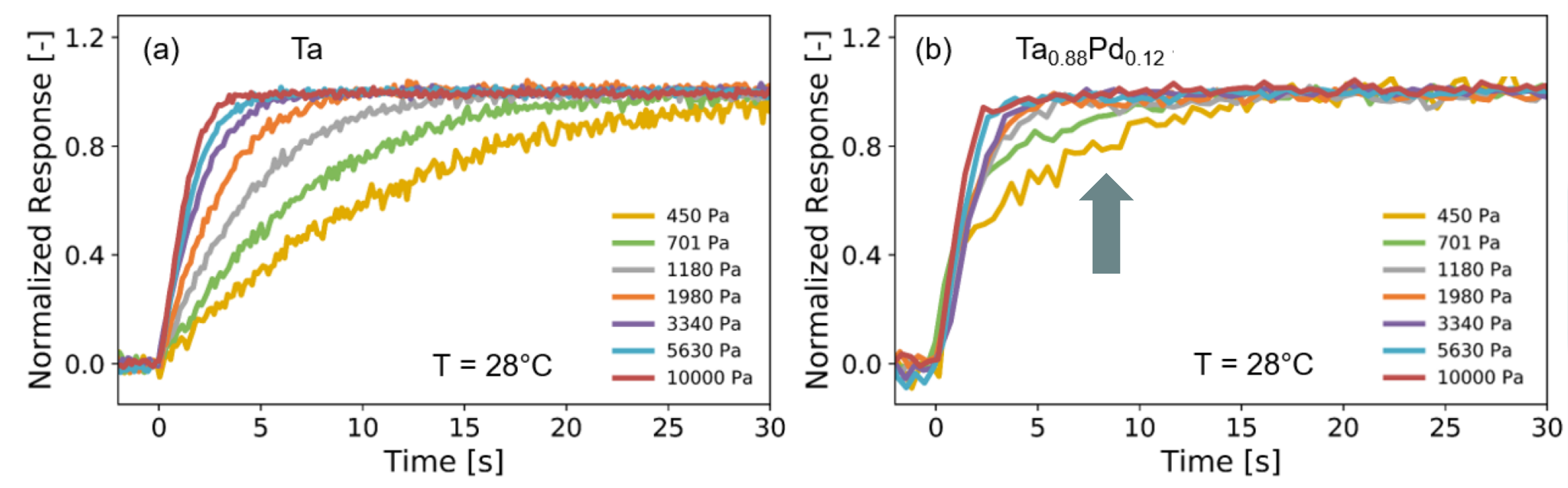
- Hydrogen sensing material covering 7 orders in pressure





- No hysteresis, even at room temperature

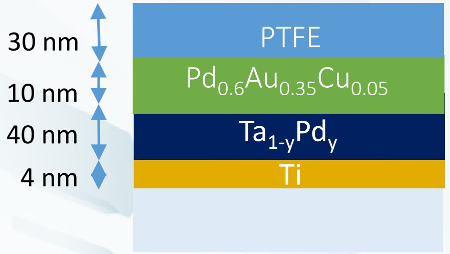
Sensing speed improves by alloying with Pd



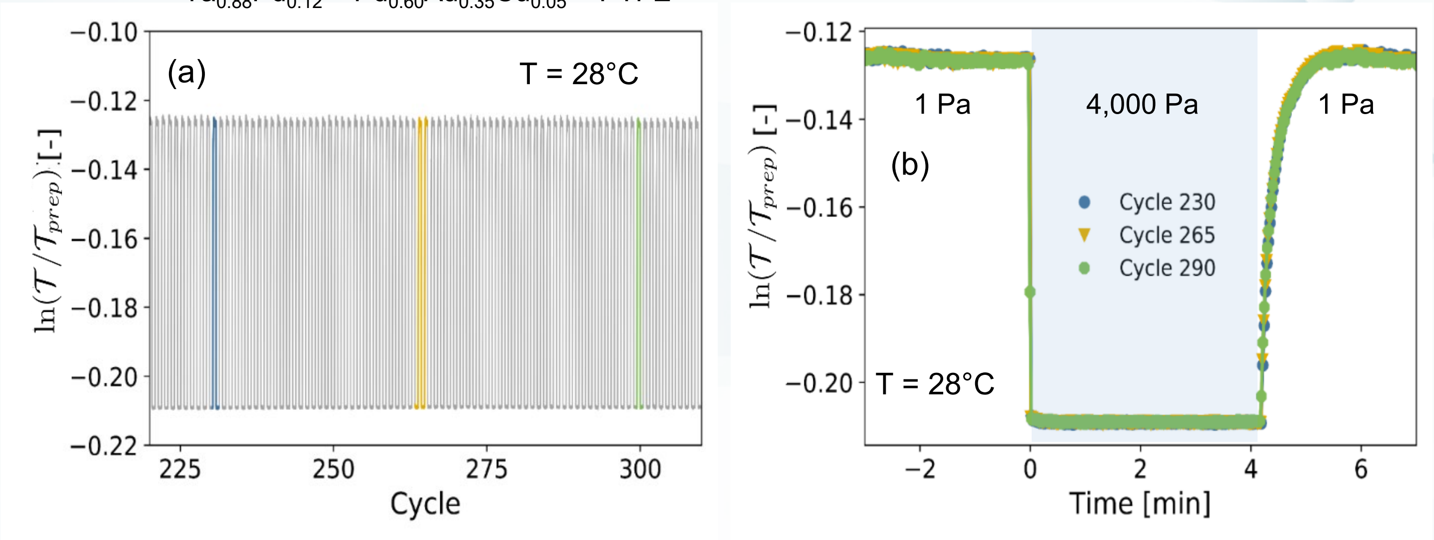
Optical response of a 40 nm film

LJ Bannenberg, H Schreuders, B Dam, Tantalum-Palladium: *hysteresis-free optical hydrogen sensor over 7 orders of magnitude in pressure with sub-second response*, Advanced Functional Materials 31 (2021) 2010483

Stability $Ta_{88}Pd_{12}$

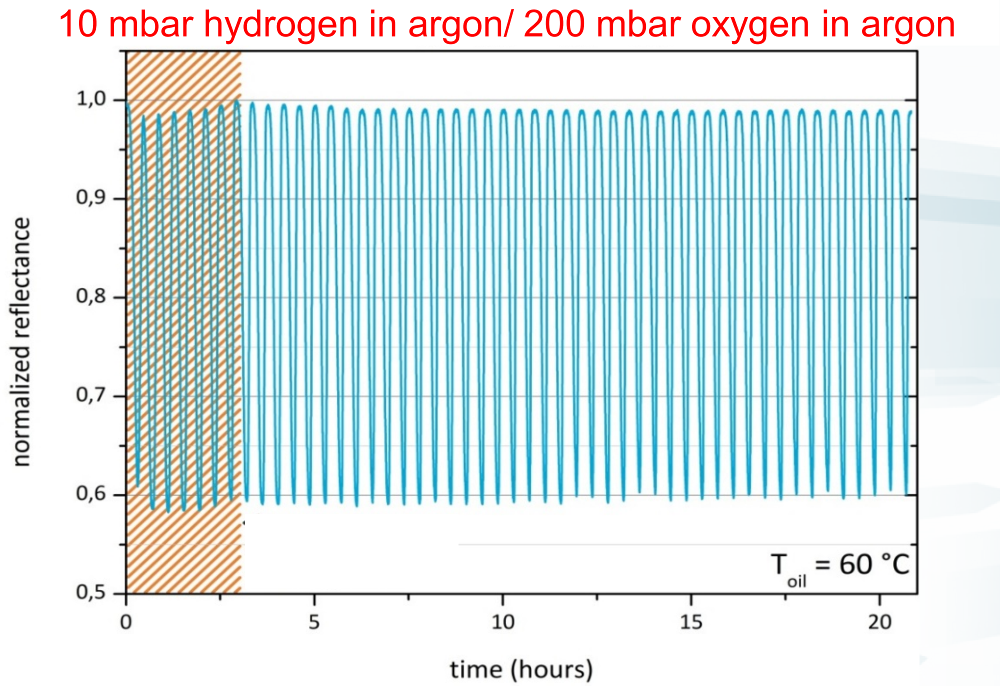


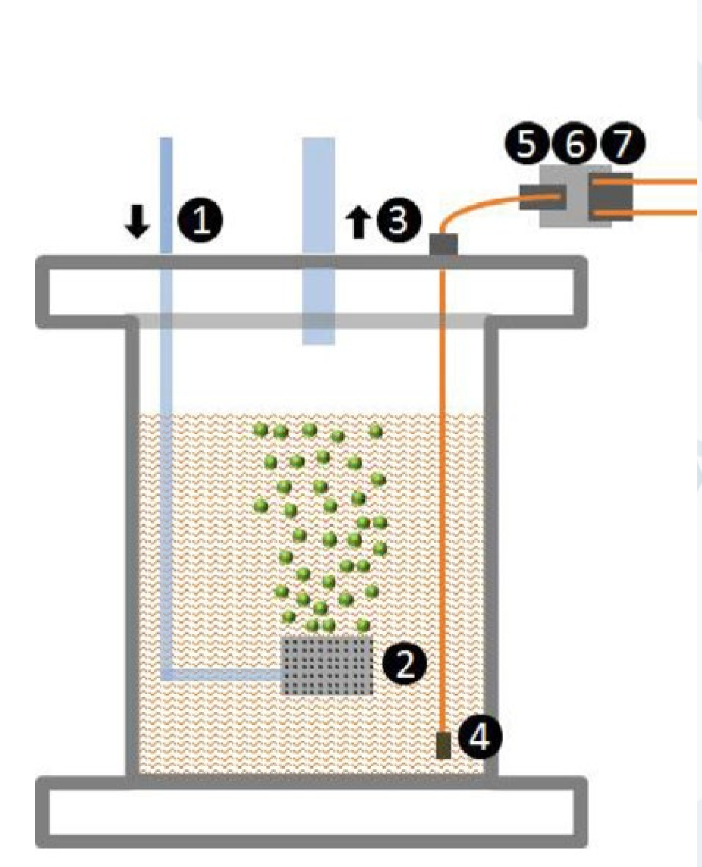
$Ta_{0.88}Pd_{0.12}$ – $Pd_{0.60}Au_{0.35}Cu_{0.05}$ + PTFE



Optical response is stable and reproducible for over at least 300 cycles.

Measuring hydrogen dissolved in oil using a Teflon coated Pd/MH-based sensor



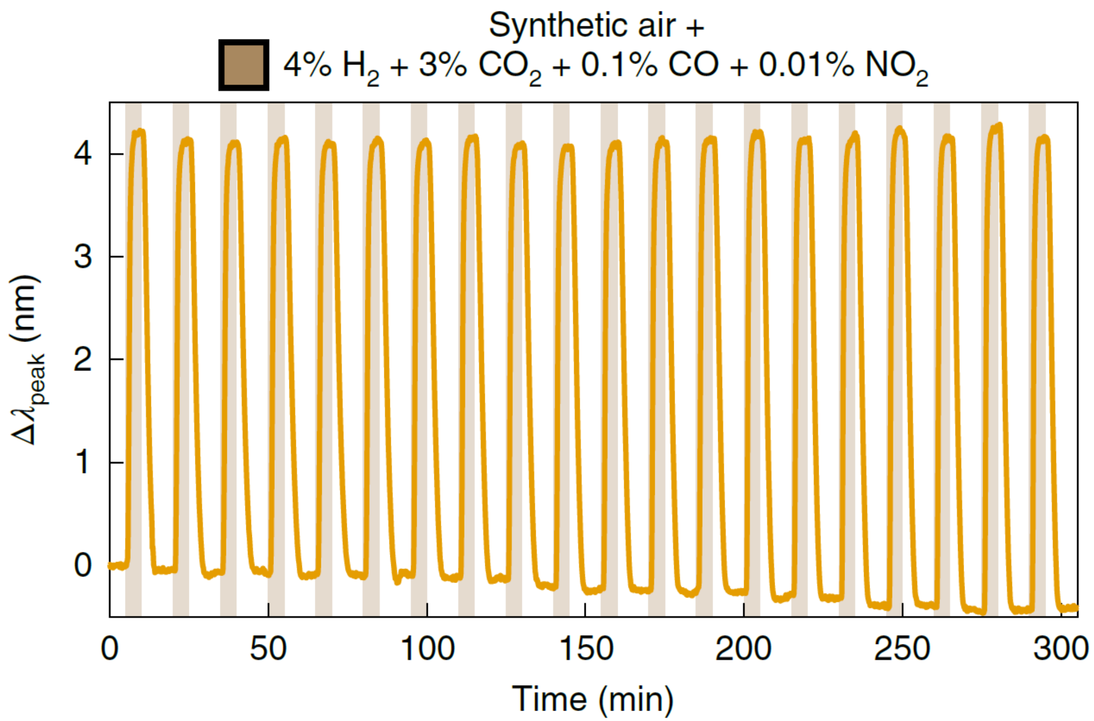


Henry's law: $pH_2 = k_H(T) \cdot C_{H2}$

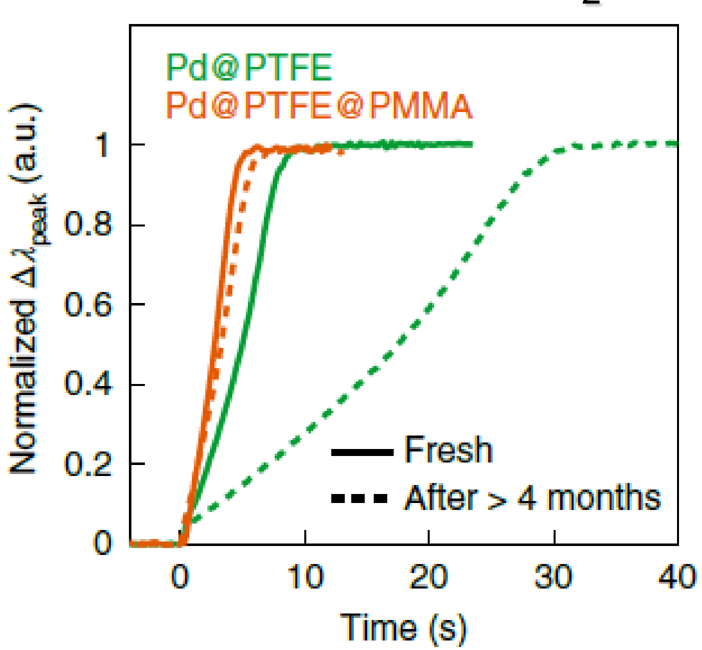
Mak et al.: Sensors and Actuators B190 (2014) 982

PTFE and PMMA protection layers needed to prevent Pd poisoning

- PTFE shortens the response times
- PMMA provides protection against deactivation of the sensor by e.g. CO and NO_2



0 to 40 mbar H_2



F. Nugroho, et al., Nature Materials 18 (2019), 489-495.

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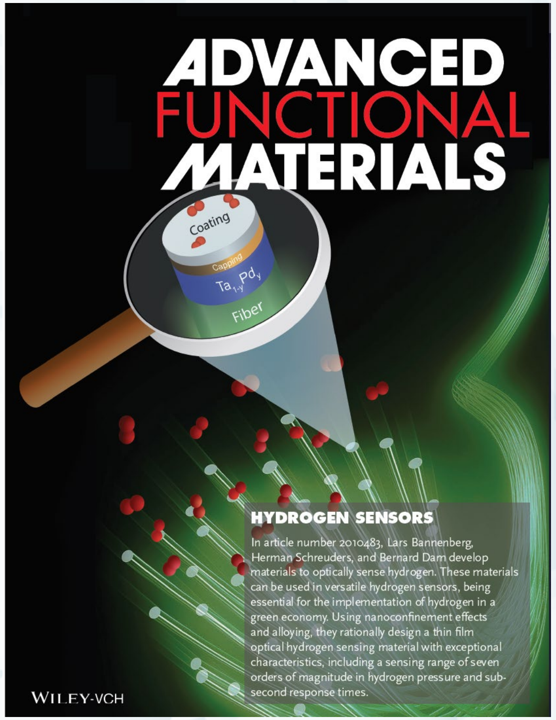
Conclusion

- Optical hydrogen sensors are an attractive way to reliably measure the hydrogen pressure.
- $Ta_{1-y}Pd_y$ is versatile hydrogen hysteresis-free sensing material that has a sensing range of at least 7 orders of magnitude in pressure
- $Ta_{1-y}Pd_y$ allows for sub-second response times at RT
- The Pd cap needs a protective coating to prevent poisoning in operando conditions



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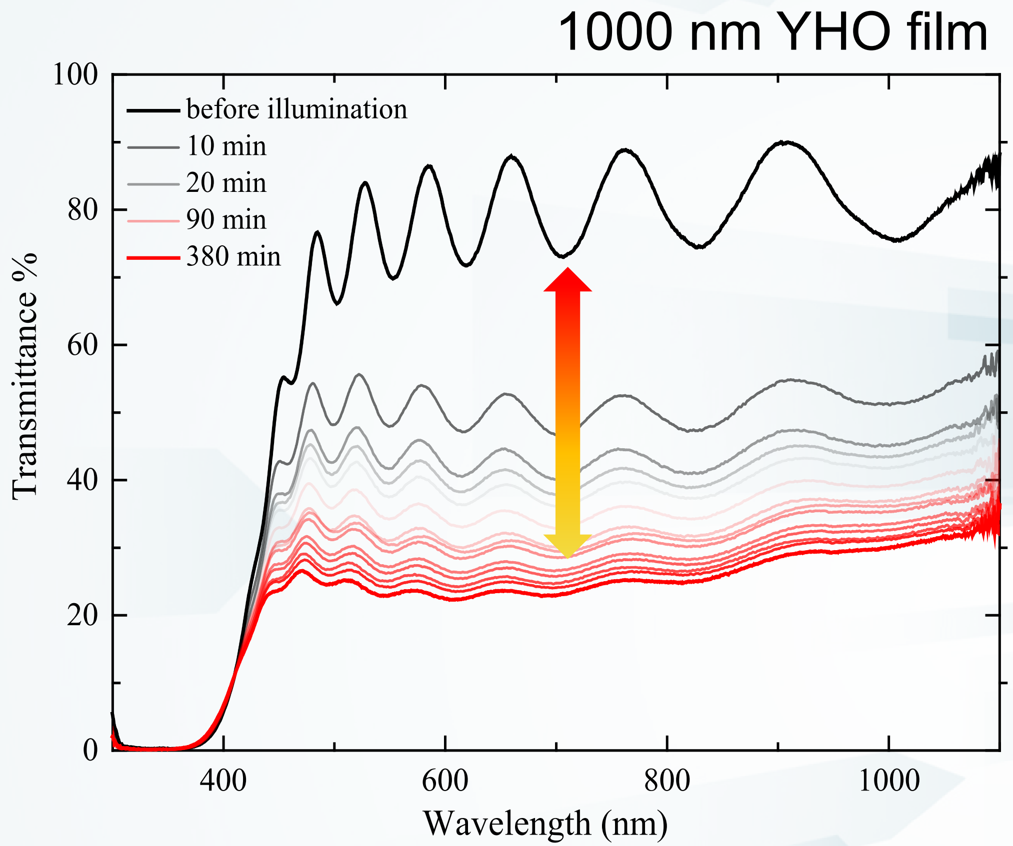
Reversible photo-darkening in REO_xH_{3-2x} thin films



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