The Role of He Ion-implantation on the Friction, Wear and Electrical Contact Resistance of Au

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Materials for Sliding Electrical contacts

- Electrical Contact Resistance
- Friction and Wear Performance

Gold

(+) Low Electrical Resistance
(+) Corrosion and Oxidation Resistance

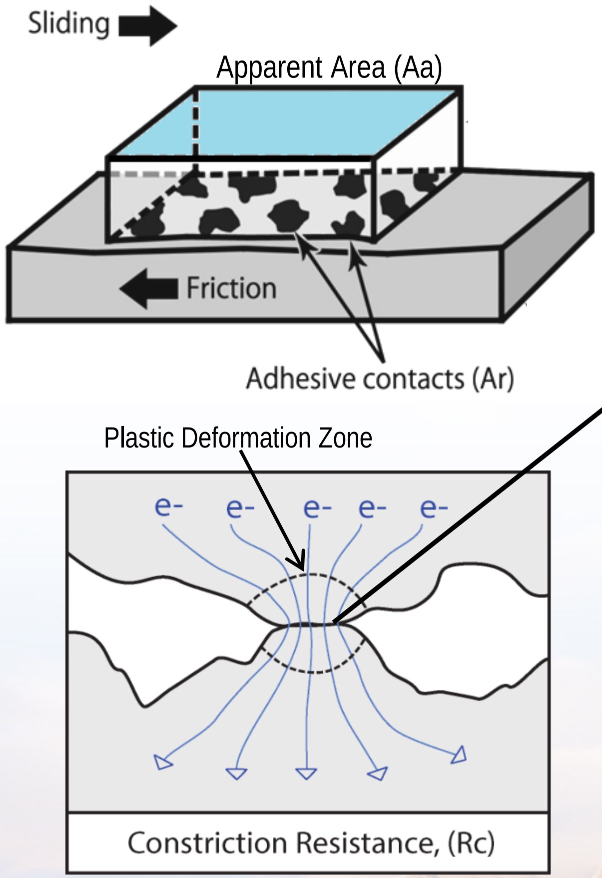
(-) Low Yield Strength

Mitigation

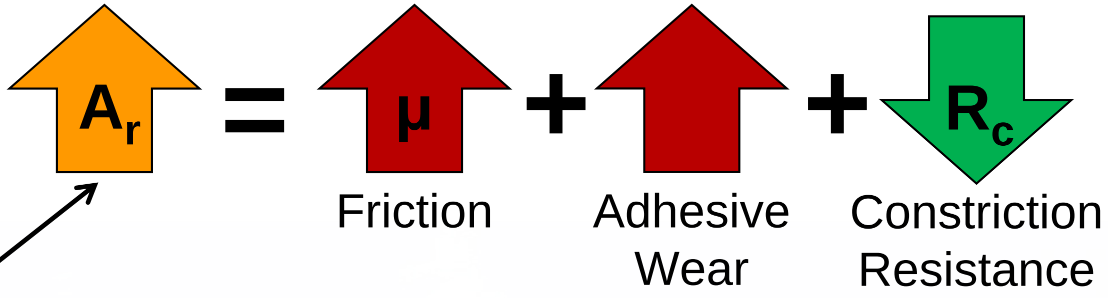
- Reduce Grain Size → Hall-Petch
- Minute Alloying → Solid solution Strengthening

Balancing Fiction & Electrical Contact Resistance is Fundamentally Challenging

Real Area of Contact (A_r) << Apparent Area of Contact (A_a)



A_r is a function of surface topography, applied load, and material properties (E, H, v)



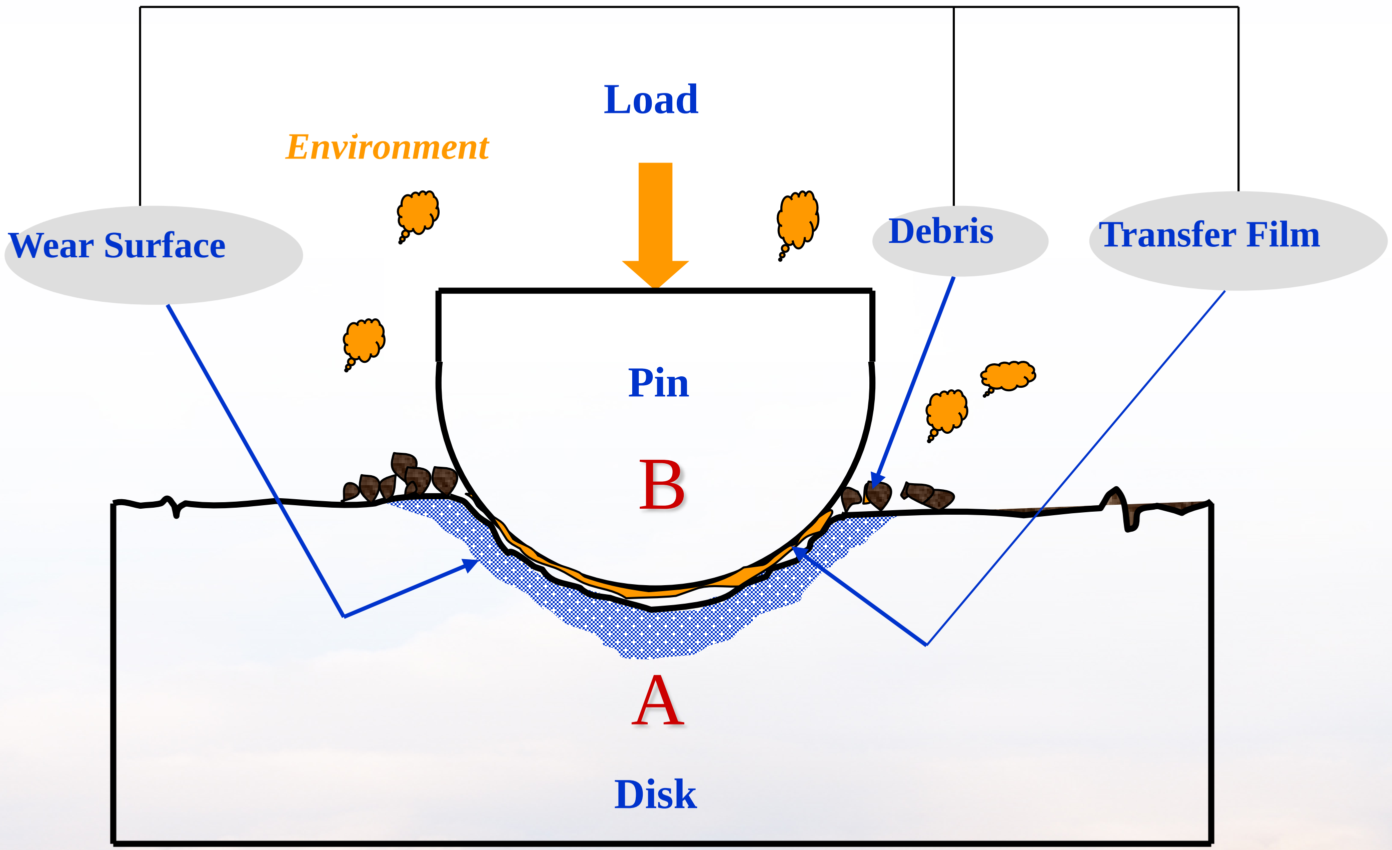
$$\mu \rightarrow f(\text{Adhesive Strength } (S_o), A_r)$$

- *Friction and Constriction Resistance are fundamentally opposing phenomena*
- *Arriving the desired balance between these is the challenge*

Archard, Journal of Applied Physics (1953) 24:981
R. Holm, Electrical Contacts Handbook (1958) Berlin: Springer-Verlag
Greenwood & Williamson, Proc. Royal Society (1966) A295:300
T.W. Scharf & S.V. Prasad, Journal of Material Science (2013) 48:511

Tribology (ECR) is a systems property

- Plastic deformation
- Diffusion (Diffusion Barriers)
- Tribochemistry and Environmental Reactions



T. W. Scharf and S. V. Prasad, J Mater. Sci. 48 (2013) 511–531

Hard Au

- Gold is typically hardened with minute alloying of Ni or Co (referred to as hard gold) to achieve the desired balance between friction, wear and ECR
- Current practice is to apply hard gold by electrodeposition, per ASTM B488 and MIL-DTL-45204

ASTM Type	Mass % Au excluding K, C and N
I	99.70
II	99.00
III	99.90

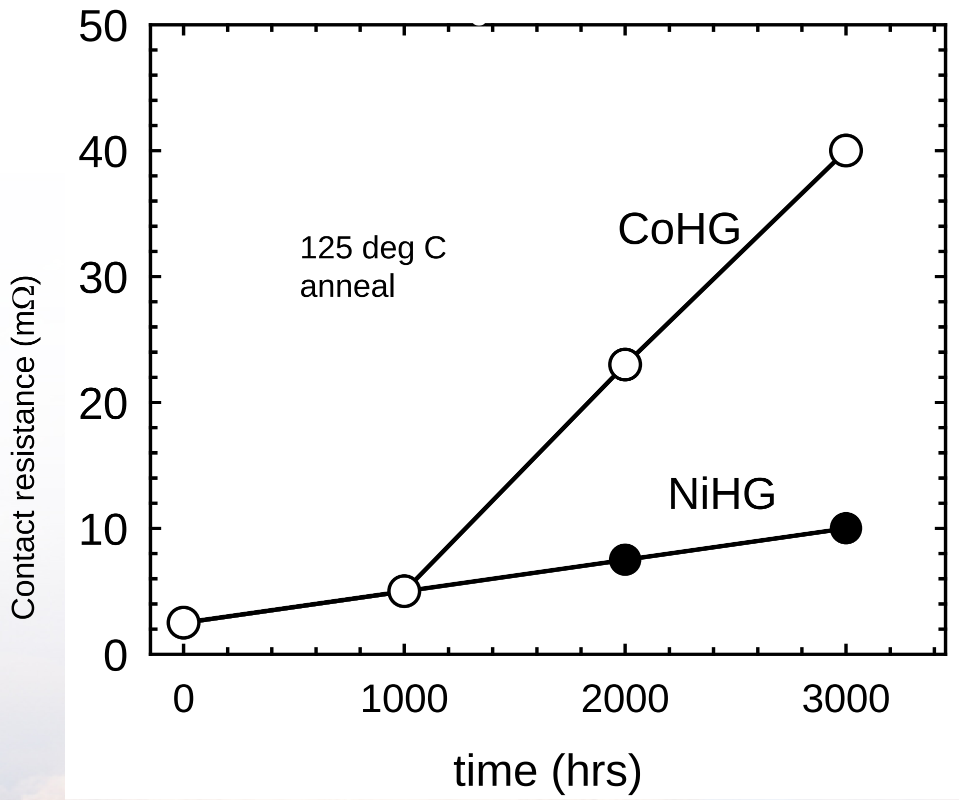
ASTM Code	Knoop Hardness
A	90 HK_{25} Maximum
B	91 - 129 HK_{25}
C	130 - 200 HK_{25}
D	> 200 HK_{25}

Nickel Underplating is used any time the substrate alloy contains Copper to prevent diffusion of Cu into Au coating.

Issues With Electroplated hard Au

Ni or Co used for hardening Au may diffuse to the surface over time

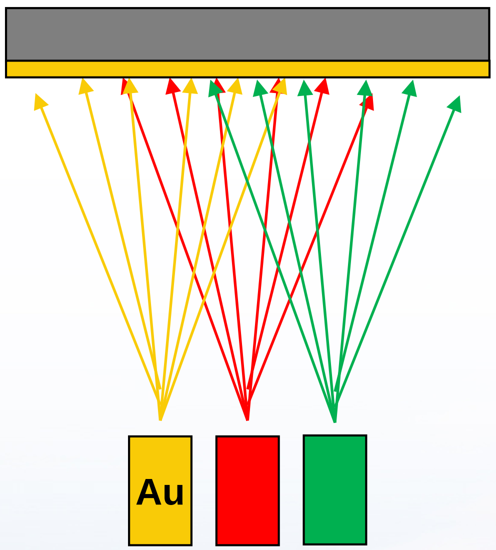
- Diffusion and segregation of hardeners and elements from “diffusion barriers” to the surface (ECR degradation)
- Limited electrochemistry (hardeners/diffusion barriers)
- Non-Technical issues…(OSHA and EPA regulations)



*Y. Okinaka and M. Hoshino, Gold Bulletin, **31**(1), 3 (1998).*

Physical Vapor Deposition

Nano-composite thin films of Au by E-Beam



Ion-Beam Implantation of pure Au films

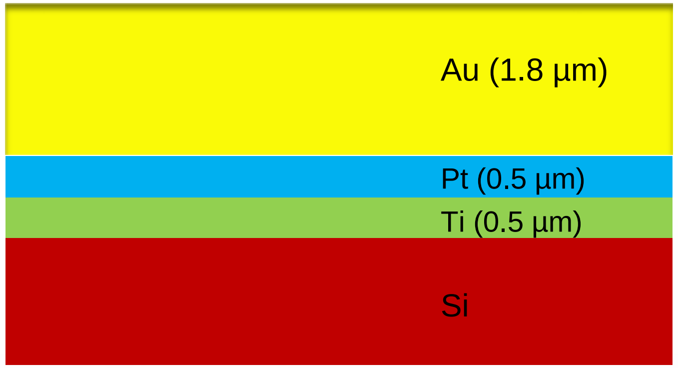
- **Film Synthesis**
  - Au films by e-beam evaporation
  - He Ion-Implantation
- **ECR-Tribology**
- **Wear Surface Analysis**
  - Scanning white light interferometry
  - Cross-sectional TEM (Subsurfaces)
    - FIB sample preparation

Why Helium?

- Inert gas with little chemical interaction
- Solubility limit is very low (≈ 1%) which leads to second phase bubble formation
- Observations of over pressurized He bubble formation in implanted metals is well documented and observed in Au

S.E. Donnelly; Radiation Effects (1985) 90:1-47
P.B. Johnson, R.W. Thomson, & D.J. Mazey; Letters to Nature (1990) 347:265-267

E-beam deposited Au and adhesion layers

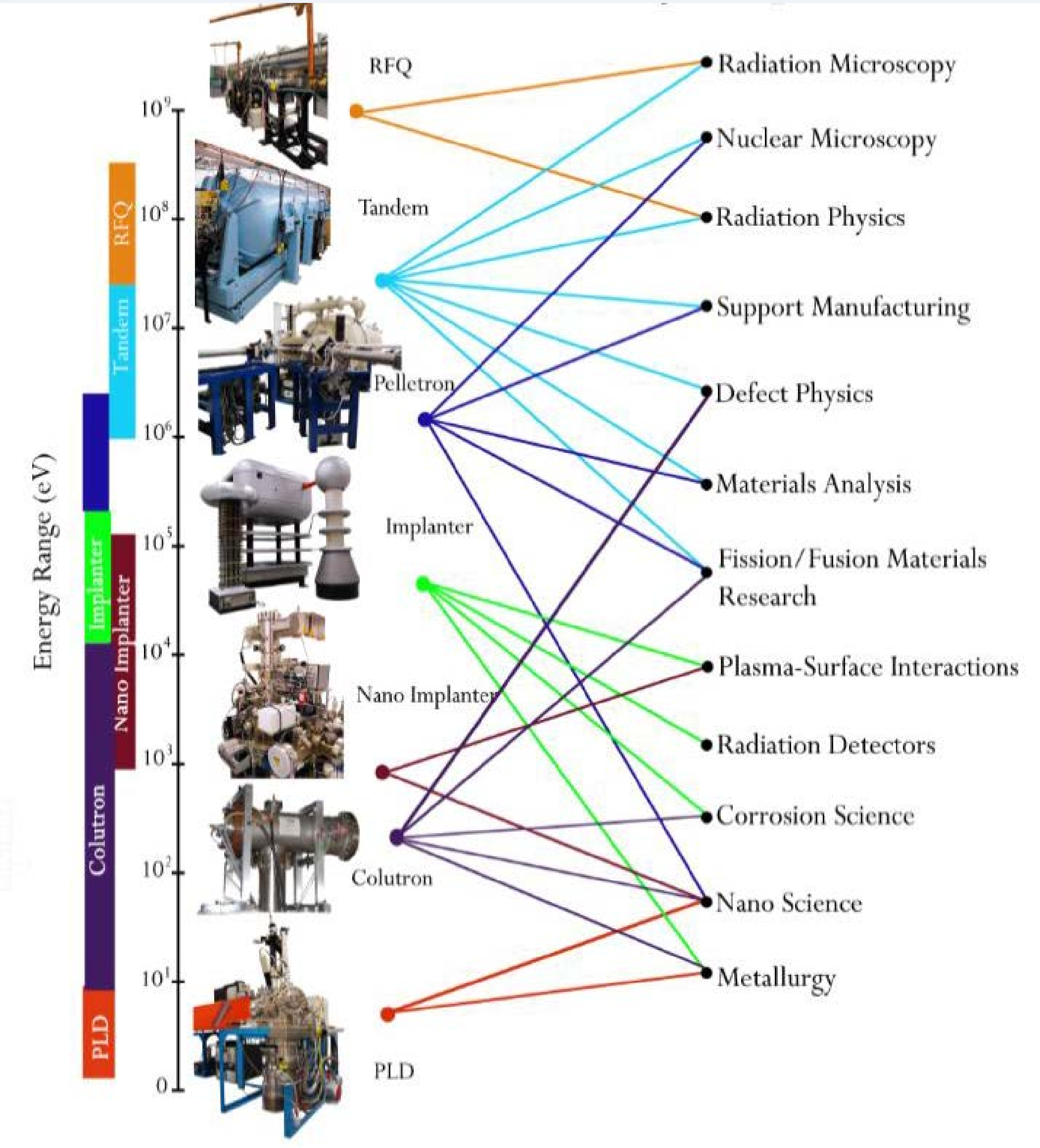


- He implantation in Ni achieved a significant increase in hardness, from 1.1 to 8.3 GPa

J.A. Knapp, D.M. Follstaedt, & S.M. Myers; Journal of Applied Physics (2008) 103:1

- Sandia ion beam capabilities allowed for the implantation energies required for full range of implantation into the E-beam thin Au layer.

Sandia Capabilities

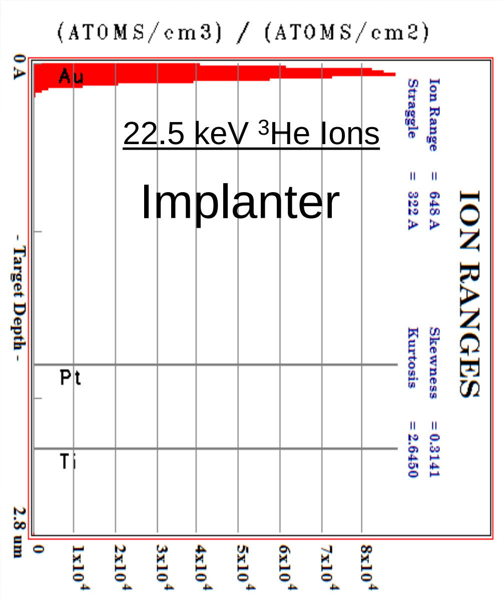


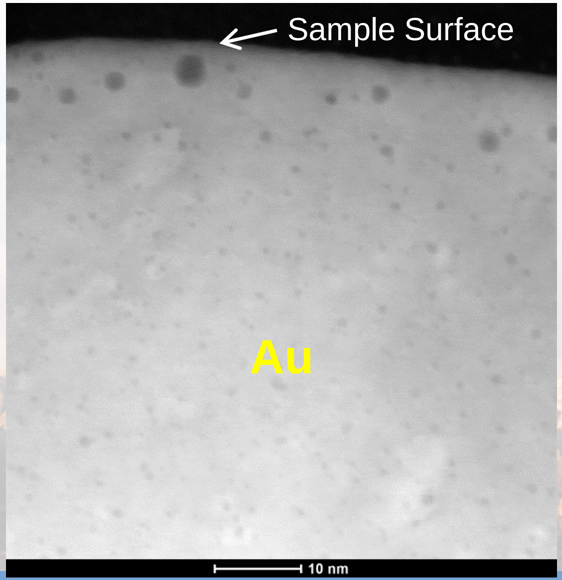
Pelletron and Implanter were used for He implantation of E-beam deposited pure Au

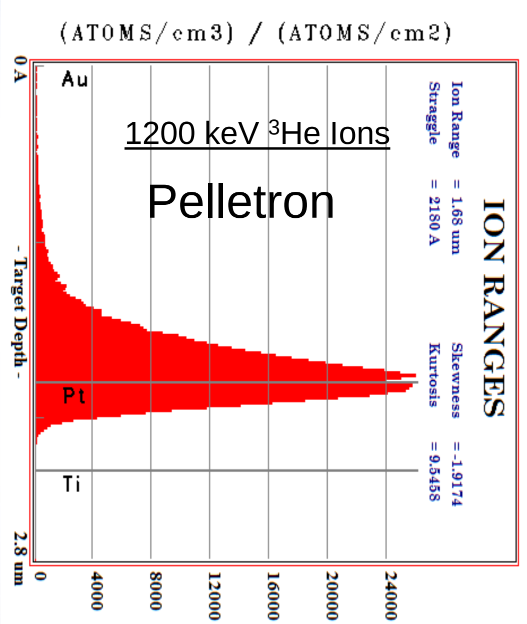
Modeling and STEM of He Implantation

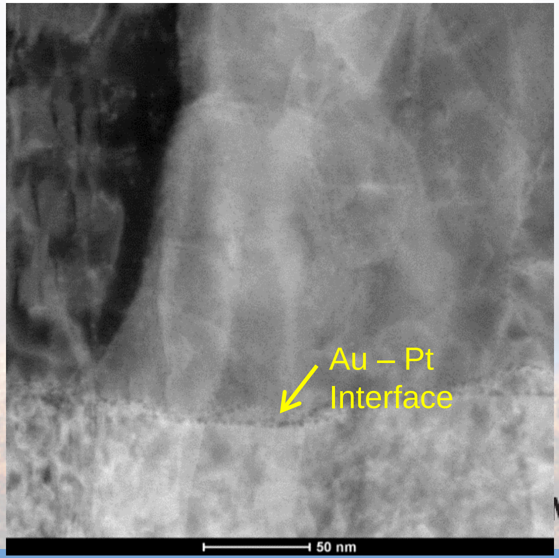
- **Simulations**: SRIM 2008 (The Stopping and Range of Ions in Matter, J.F. Ziegler, M.D. Ziegler and J.P. Biersack)
  - Monte-Carlo simulation of kinematic interaction based on empirical data fitted functions
  - Input variables of target material include density, AMU, and thickness.
  - Input variables of ions include AMU, energy, and angle of incidence.
  - Assumes isotropic material, thus no consideration for channeling effects
- AC-STEM used to observe the distribution of implanted bubbles

- Bubble locations are in good agreement with SRIM ion range predictions

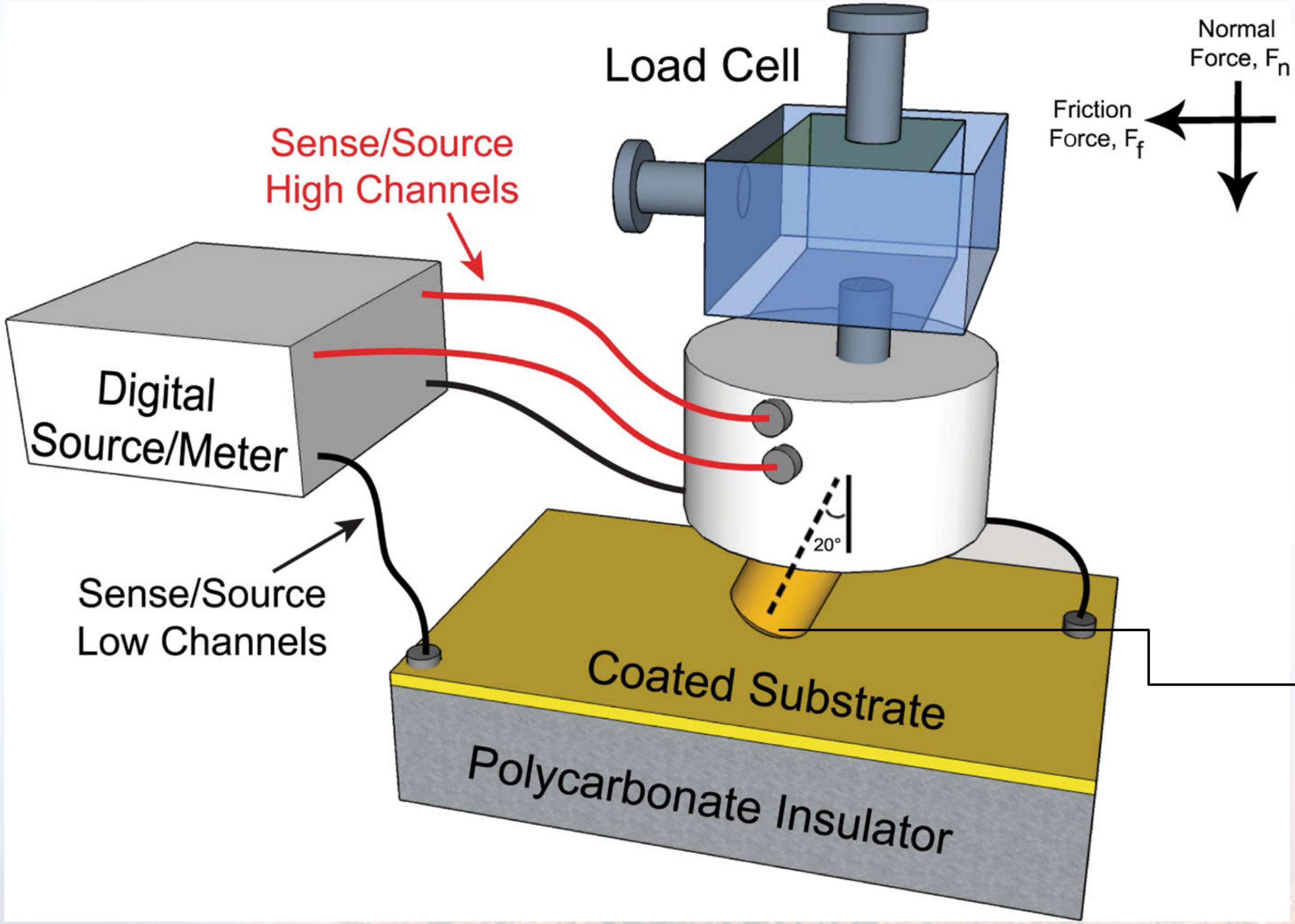


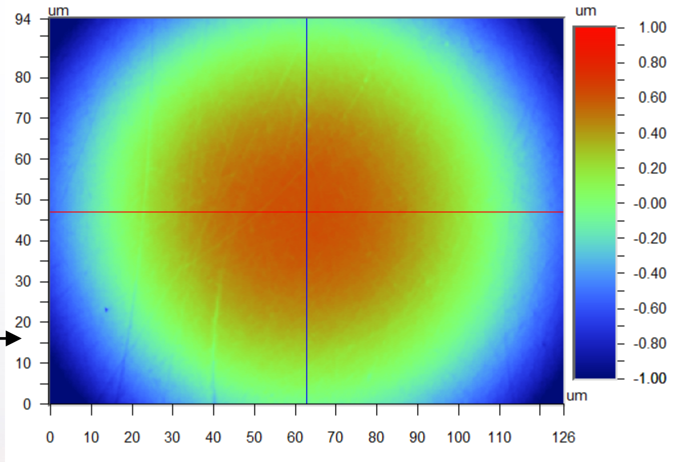






Electrical Contact Resistance (ECR) Measurements

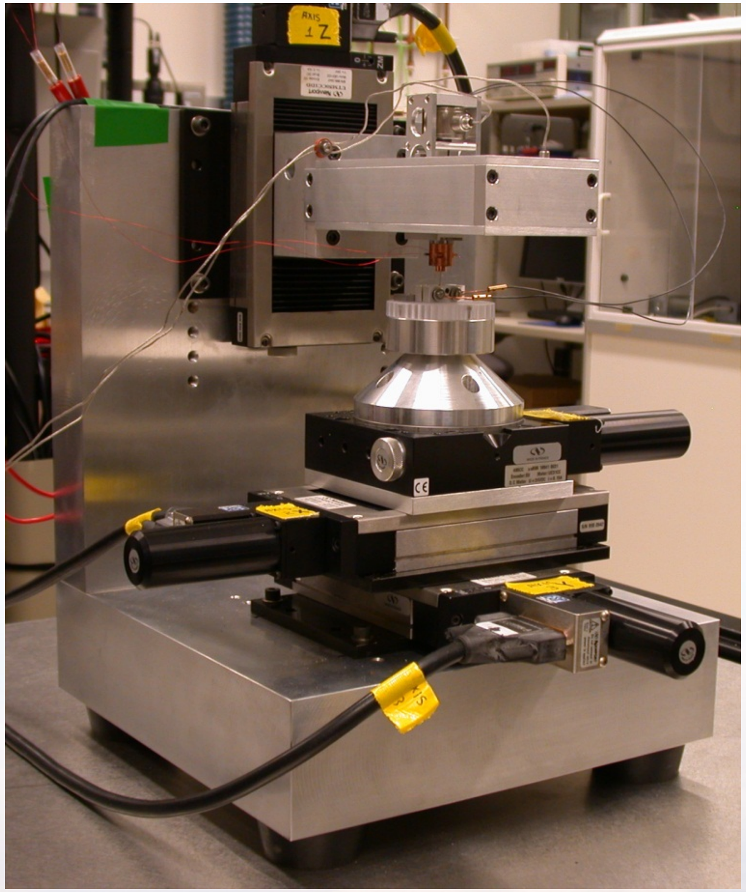




Hemi-spherically Tipped Pin

ECR-Tribometer

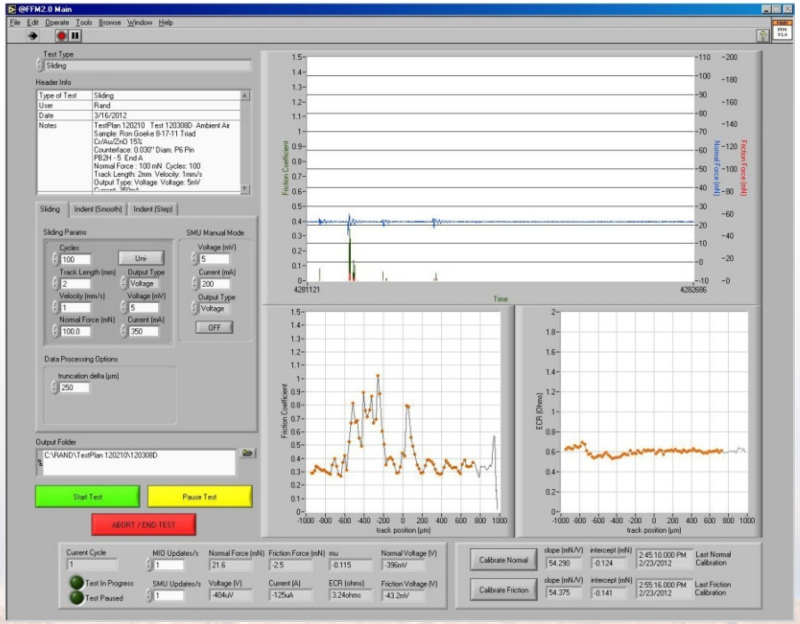
Simultaneous acquisition of friction force and contact resistance



Up to 2000 mA
1 mN to 1.5 N

Test Conditions

- o Neyoro G (Au-Cu), $\frac{1}{16}$ in. radius hemispherical tip rider
- o F_n = 100 mN (≈290 MPa contact stress)
- o 100 Cycles @ v = 1 mm/s
- o 1 – 2 mV bias to achieve approximately 100 mA
- o Lab air environment at room temperature



Data Acquisition

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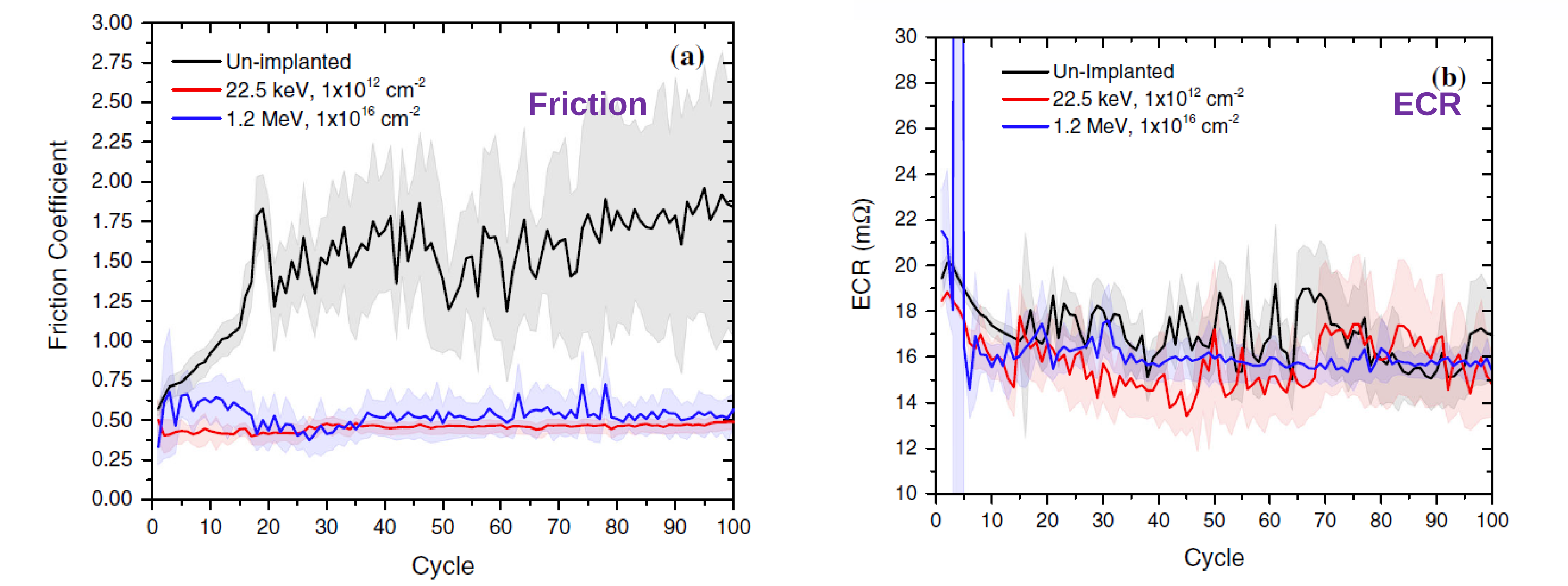
Significant Reduction in Friction



Shaded regions correspond to ±1r per cycle of data collected at 50 Hz

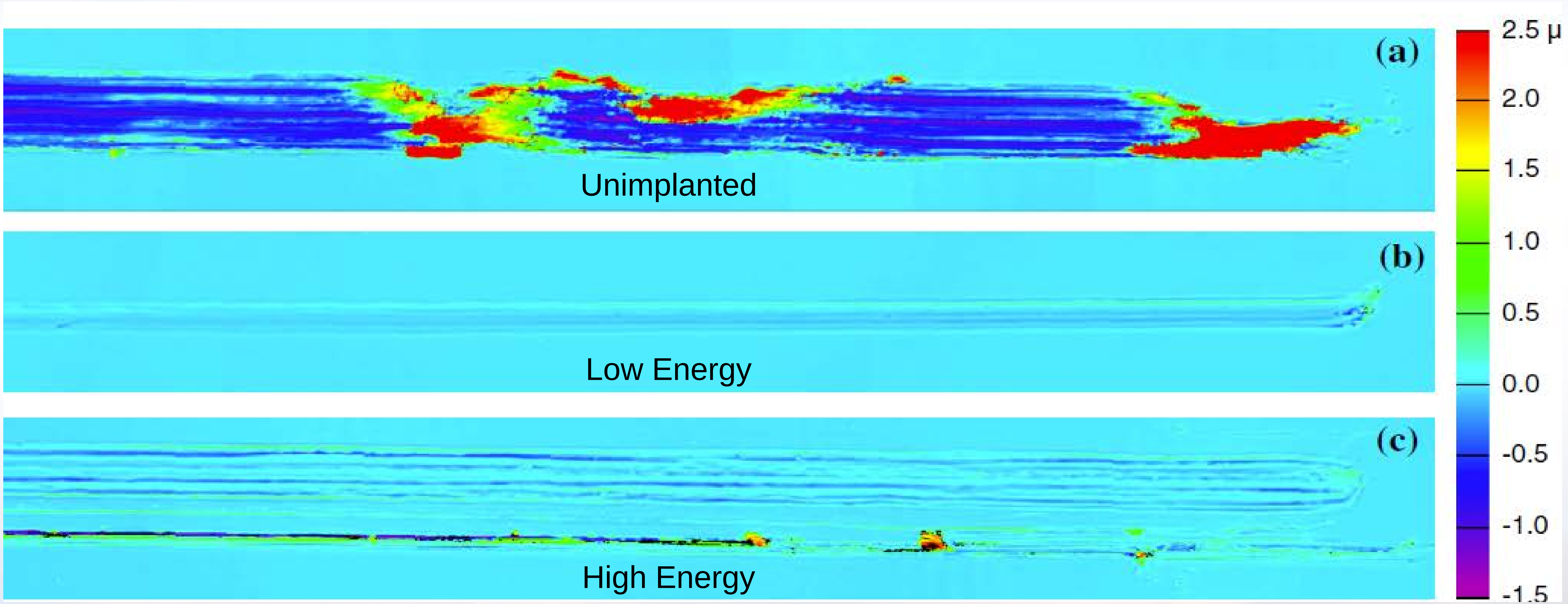
ECR and Wear Rates

He Ion Implant Conditions	Au Film Resistivity ($\mu\Omega$-cm)	Average Sliding ECR (mΩ)	Specific Wear Rate, k (mm^3-$(Nm)^{-1}$)	Transfer Film Volume (μm^3)
Un-implanted	2.62 ± 0.10	17.0 ± 1.5	4.3×10^{-3}	8239
E = 22.5 keV $\phi = 1\times10^{12}$ cm^{-2}	3.11 ± 0.05	15.8 ± 1.7	1.3×10^{-4}	-14
E = 1.2 MeV $\phi = 1\times10^{16}$ cm^{-2}	2.79 ± 0.42	16.1 ± 0.3	1.0×10^{-3}	263

Negative values of transfer film volume correspond to net volume loss of the pin.

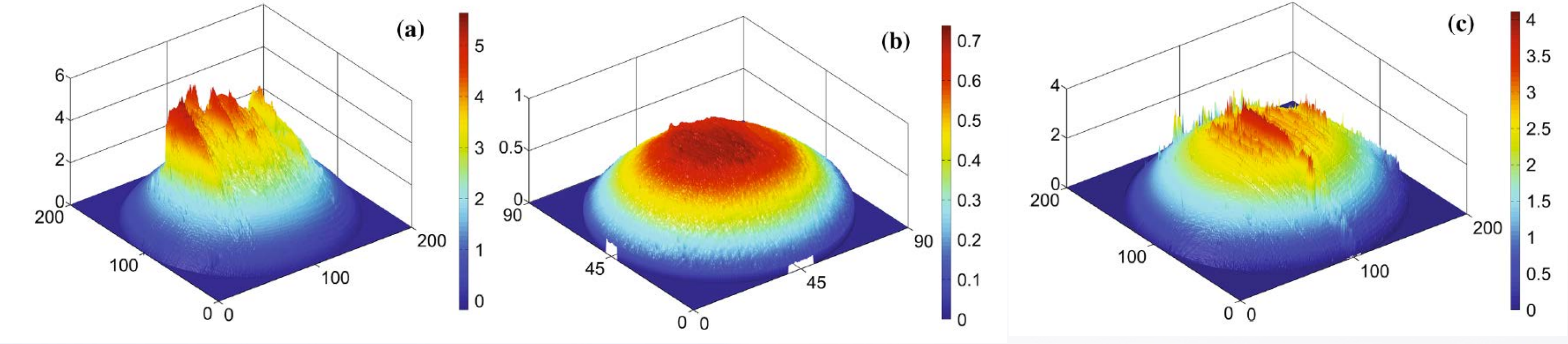
Measured values of Au film resistivity corrected for Ti and Pt conducting adhesion layers, average sliding ECR, specific wear rate of film, k, and transfer film volume onto Neyoro G alloy pin for un-implanted and He implanted films.

Topographical Maps of Wear Surfaces



Scanning white light interferometry spectral topographical maps of film surfaces after 100 sliding cycles at applied load of 100 mN. Black regions in c correspond to data loss

Topographical Maps of Transfer Films on Counterface Pins



Unimplanted

Low Energy

High Energy

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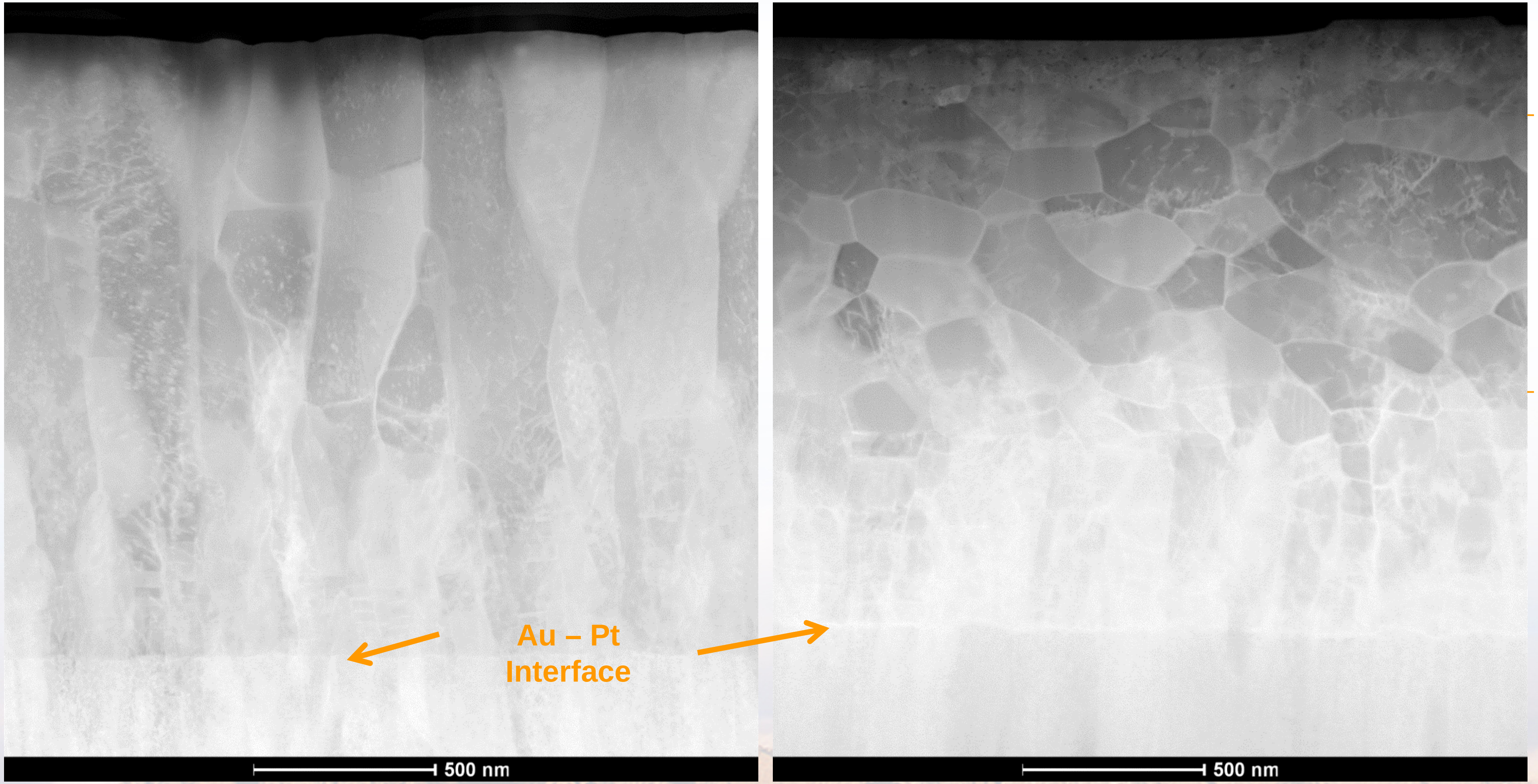
STEM Images of Subsurfaces

22.5 keV, 1 x 10^{12} cm^{-2}

Before Sliding ECR Test | After Sliding ECR Test

Columnar/(001) Texture



Wear Surface

Ultra-Nano

Breakdown of Texture

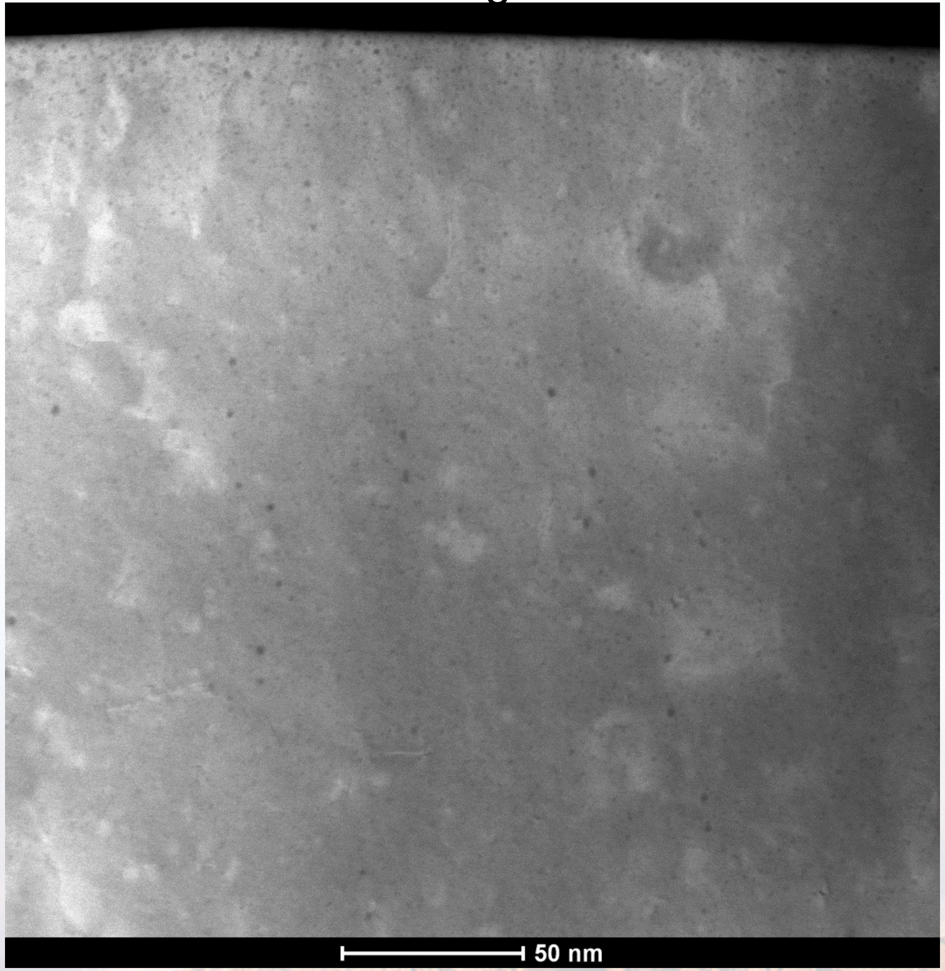
Textured

Recrystallization is observable after 100 cycles.

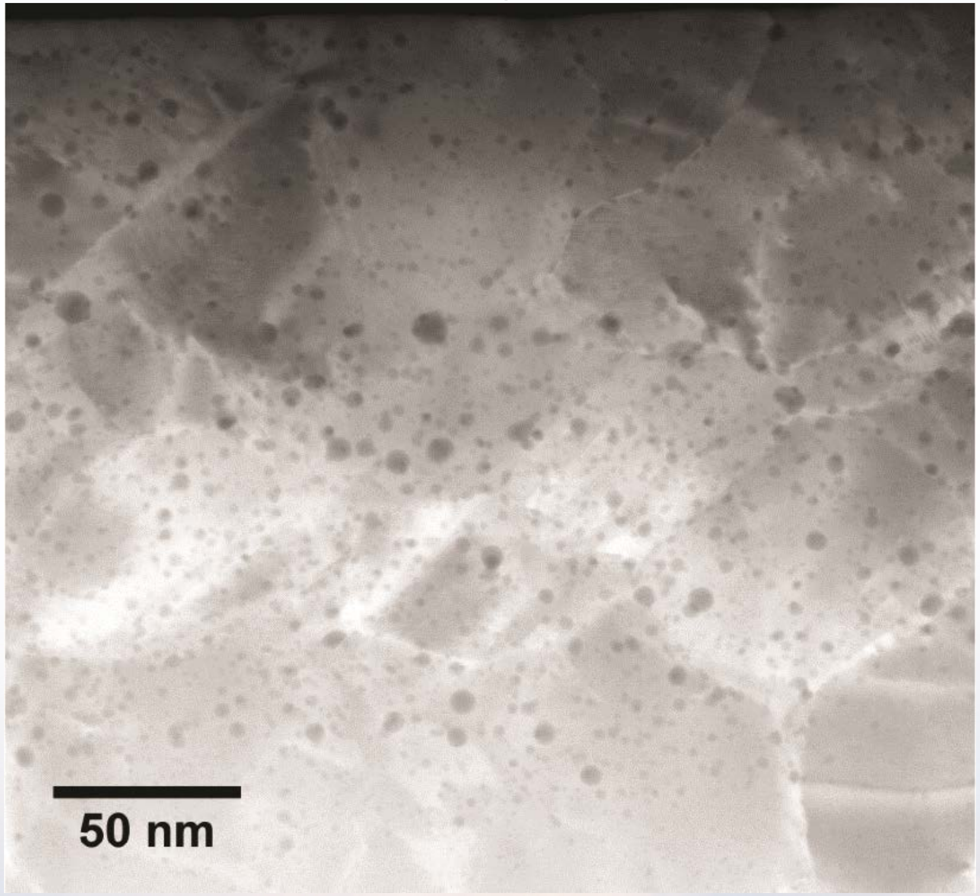
High Resolution HAADF STEM Images of Subsurfaces

22.5 keV, 1 x 10^{12} cm^{-2}

Before Sliding ECR Test



After Sliding ECR Test



Stable Ultrananocrystalline Grain Structure

An increase in both observable density and diameter of He bubbles, suggests wear induced He coalescence from interstitial and previously un-observable He

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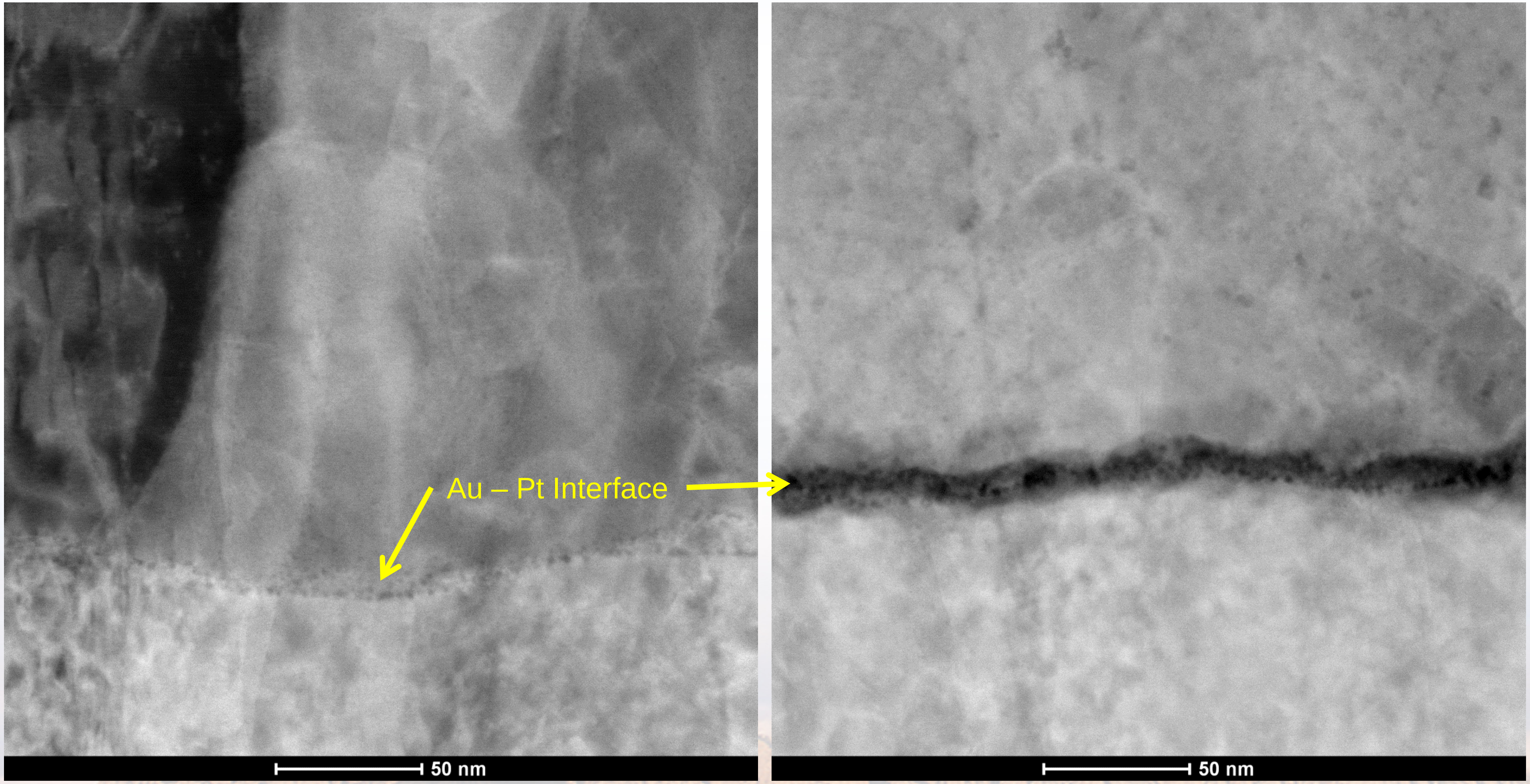
Coalescence of He at Interfaces During Sliding Contact

1200 keV, 1 x 10^{16} cm^{-2}

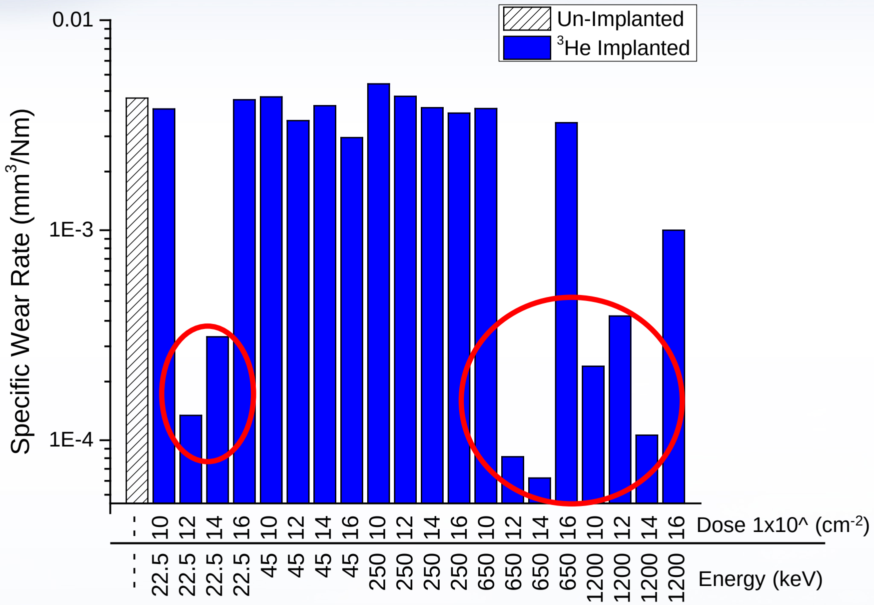
Before Sliding ECR Test

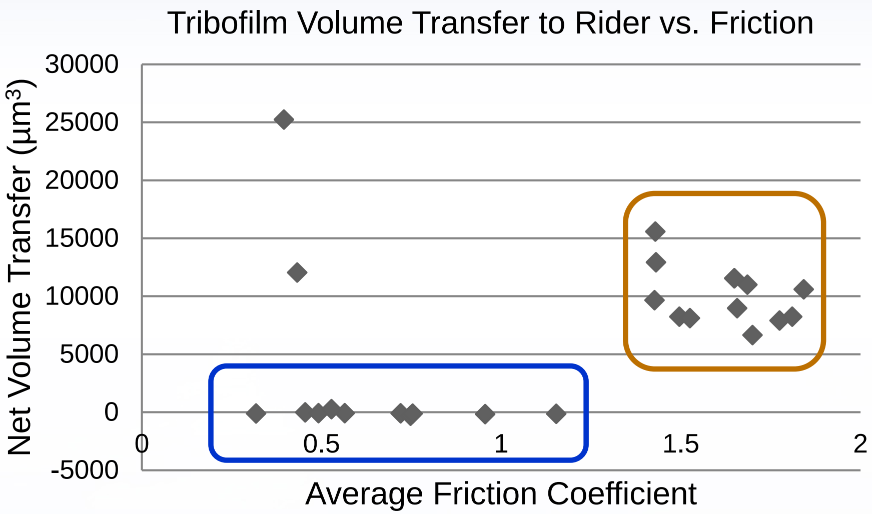
After Sliding ECR Test



Coalescence of He bubbles at the interface can be a reliability concern

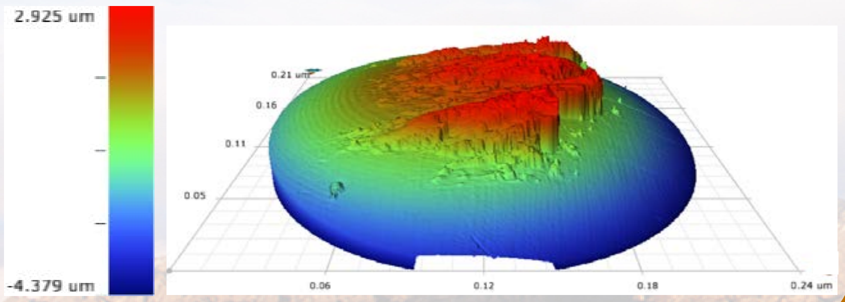
Summary of Data



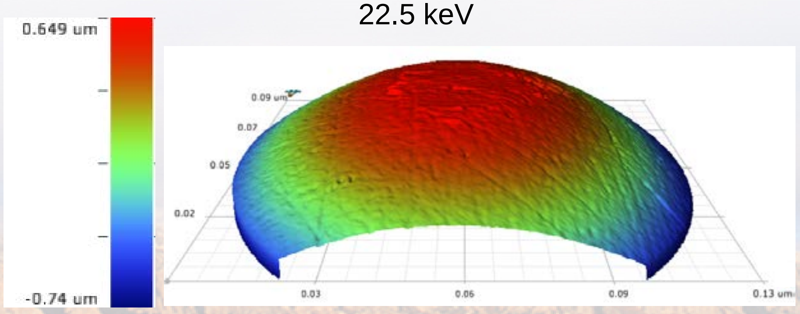


Scanning white light interferometer topographical construction of riders after 100 cycles

Rider after 100 cycles against Un-implanted Au



Rider after 100 Cycles against Au implanted to 1E12 cm^{-2} @ 22.5 keV



Concluding Remarks

- Significant reductions in friction and wear due to He-Implantation
  - A three fold decrease in COF and an order of magnitude in wear
- NO significant adverse effects on ECR
- Formation of stable nanocrystalline grain structures in the subsurface regions of wear surfaces

Acknowledgements

Ron Goeke (e-beam)
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Lisa Lowery (FIB Sample Prep)

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