Nano-Tribological Printing: A novel additive manufacturing method for nanostructures

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Additive Manufacturing at the Macroscale

Additive Manufacturing (AM) has enabled rapid prototyping and manufacture of components with highly complex shapes

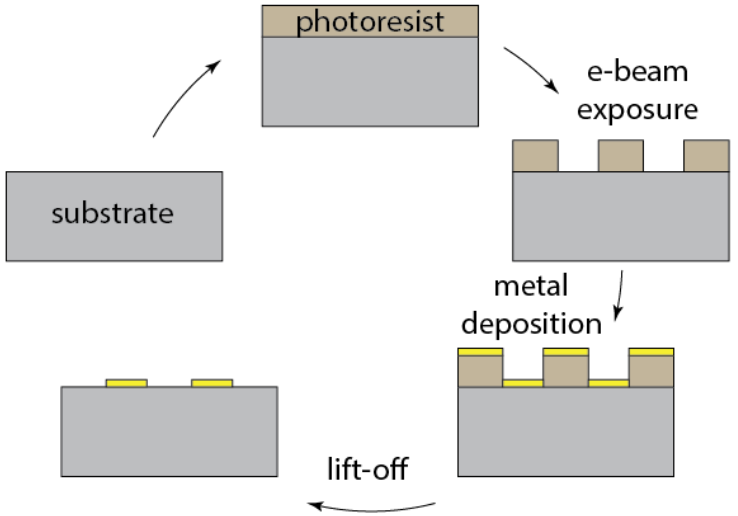
Though initially restricted to soft polymers, more recent AM techniques are capable of manufacturing metallic and ceramic components

Images: Penn AddLab, GE

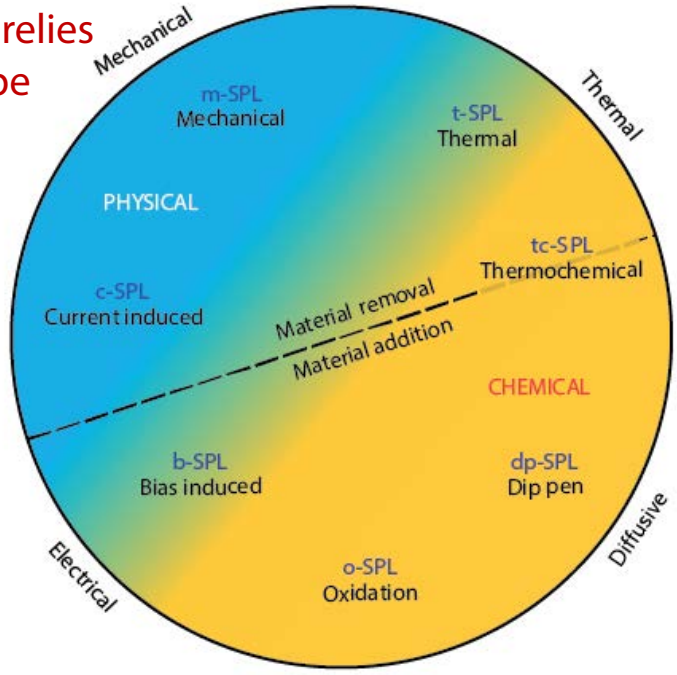
State of the Art in Nanoscale Lithography

Traditional nanoscale patterning techniques include electron-beam lithography, nano-imprint lithography and molecular assembly

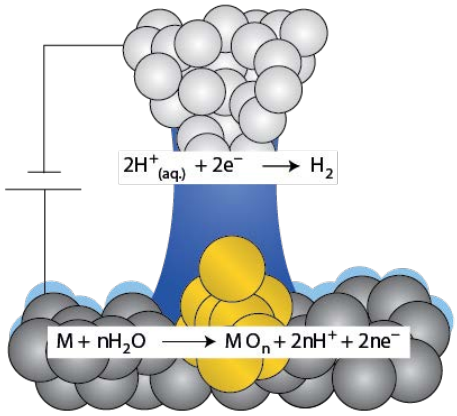
Most nanolithography techniques involve multi-step processes



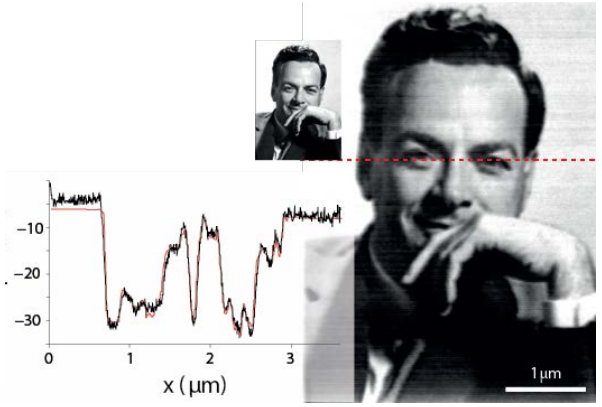
Scanning Probe Lithography (SPL) is a direct-write technique and relies on conventional Scanning Probe Microscopes



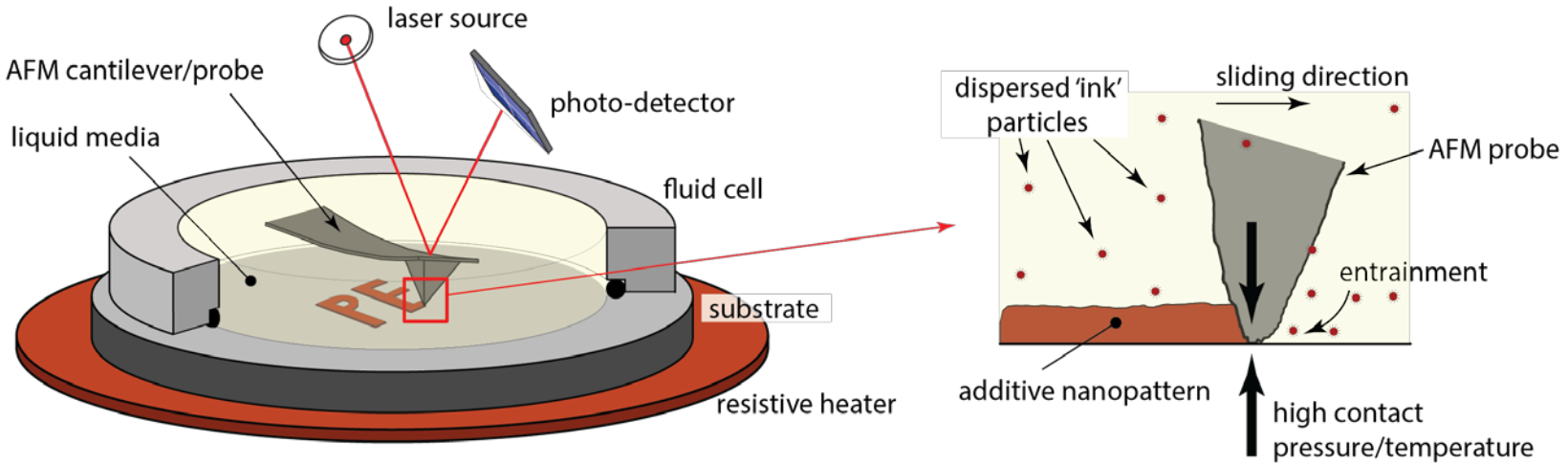
o-SPL: Material addition



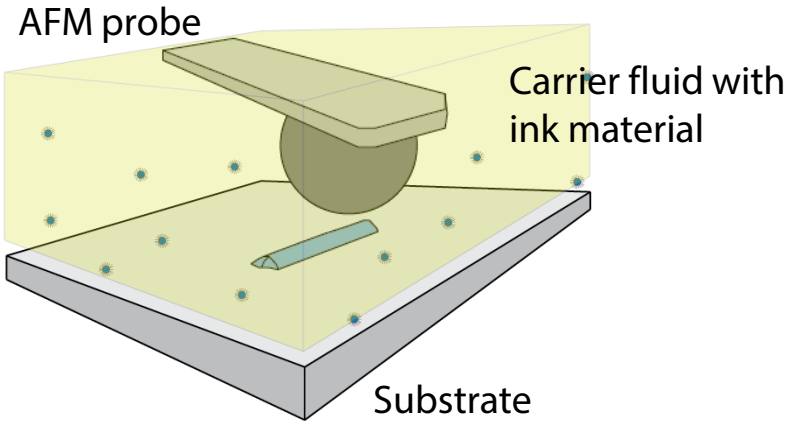
t-SPL: Material removal



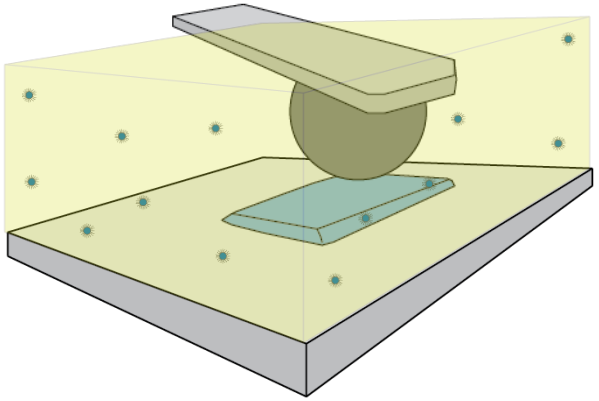
R. Garcia *et al.*, Nat. Nanotech. (2014)



In Nano-Tribological Printing, patterning occurs due to *in-situ* confinement and stress-induced coagulation of ink material

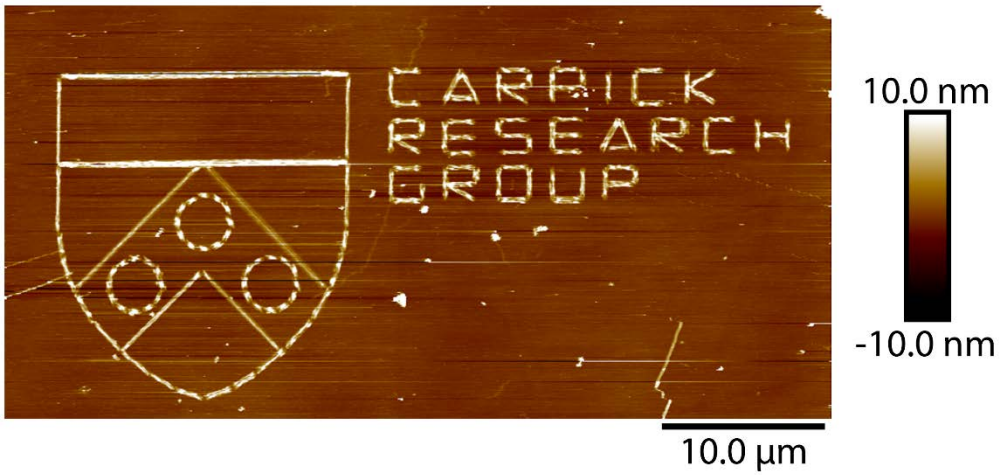


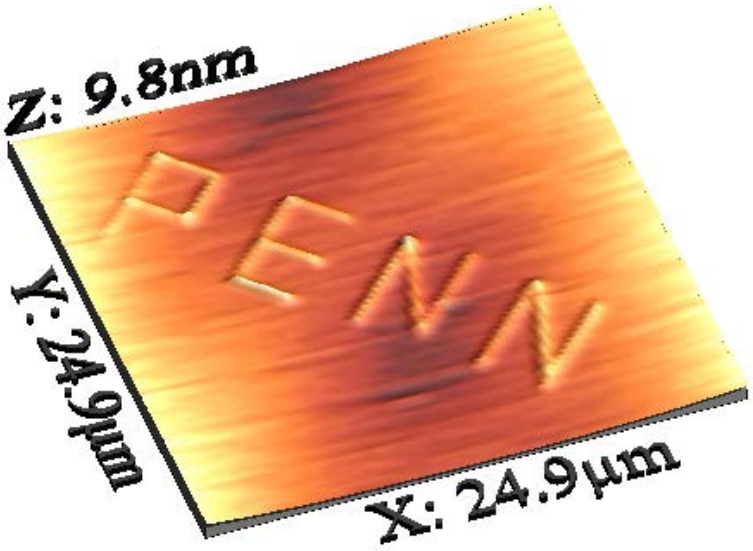
Tribological stresses induce patterning



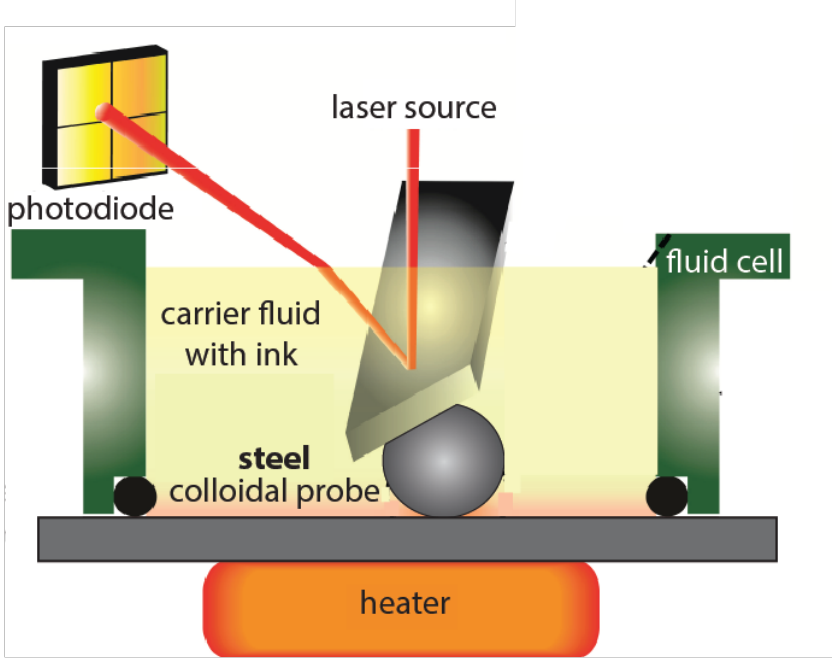
Variations in tip motion can be used for writing complex patterns

Programmed AFM-tip motion can be used for creating complex patterns





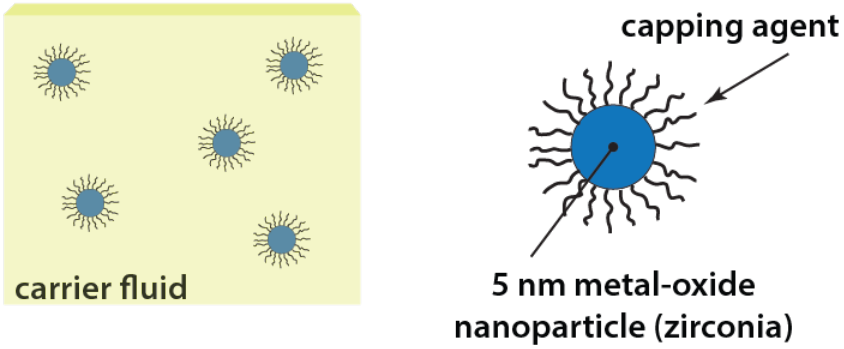
SPM-Based Printing With Various Ink-Materials



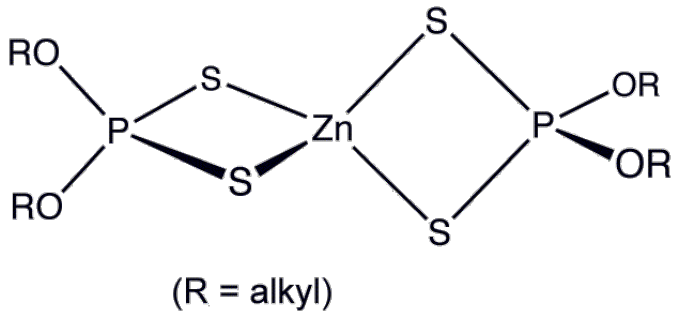
Fluid-cell Atomic Force Microscopy

Nanoparticle patterning performed with steel colloids on different substrates (steel results reported here) in an AFM fluid cell.

Nanoparticle patterns were created at room temperature



Zirconia printing at room temperature

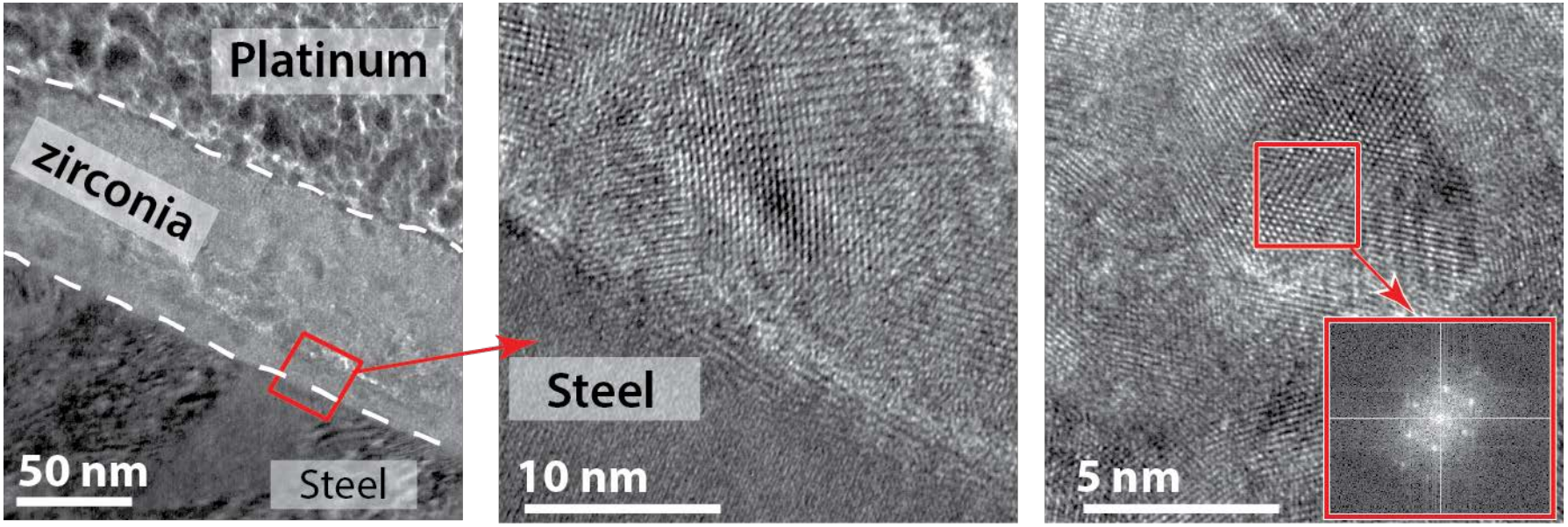


Zinc Dialkyldithiophosphates (ZDDP) at high temperature

Nanoparticles as patterning ink

Molecular species as patterning ink

Patterns are Dense and Mechanically Robust



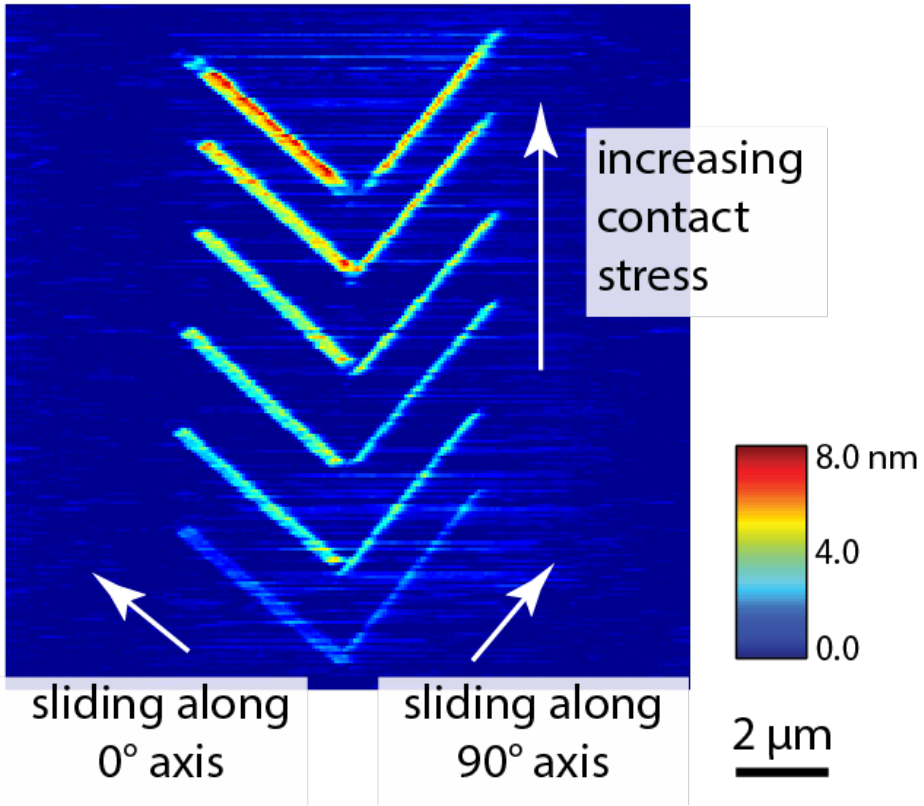
Tribological stress results in strong bonding between nanocrystals and a highly dense microstructure

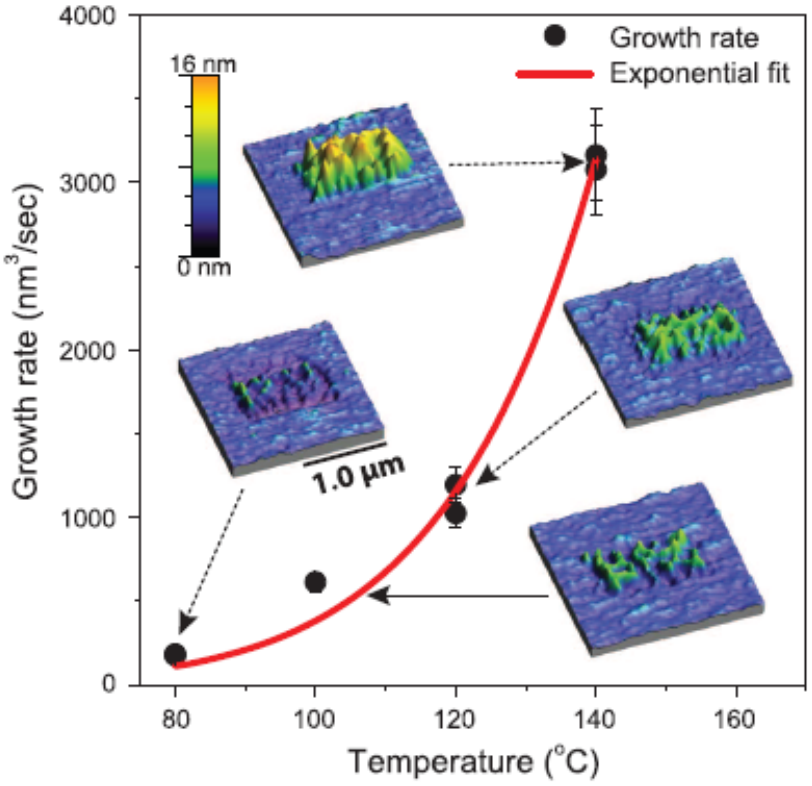
Samples	E (GPa)	H (GPa)
Bulk zirconia [1]	**215-266**	**9.2**
Nanoscale pattern	**151.7 ± 5**	**7.3 ±0.7**

Measured mechanical properties of zirconia patterns approach values reported for bulk zirconia

[1] J.F. Shackelford et al., Ceramic and Glass Materials: Structure, Properties and Processing, 2008

Chemical patterning with ZDDP





Pattern width changes with scan angle due to probe asymmetry

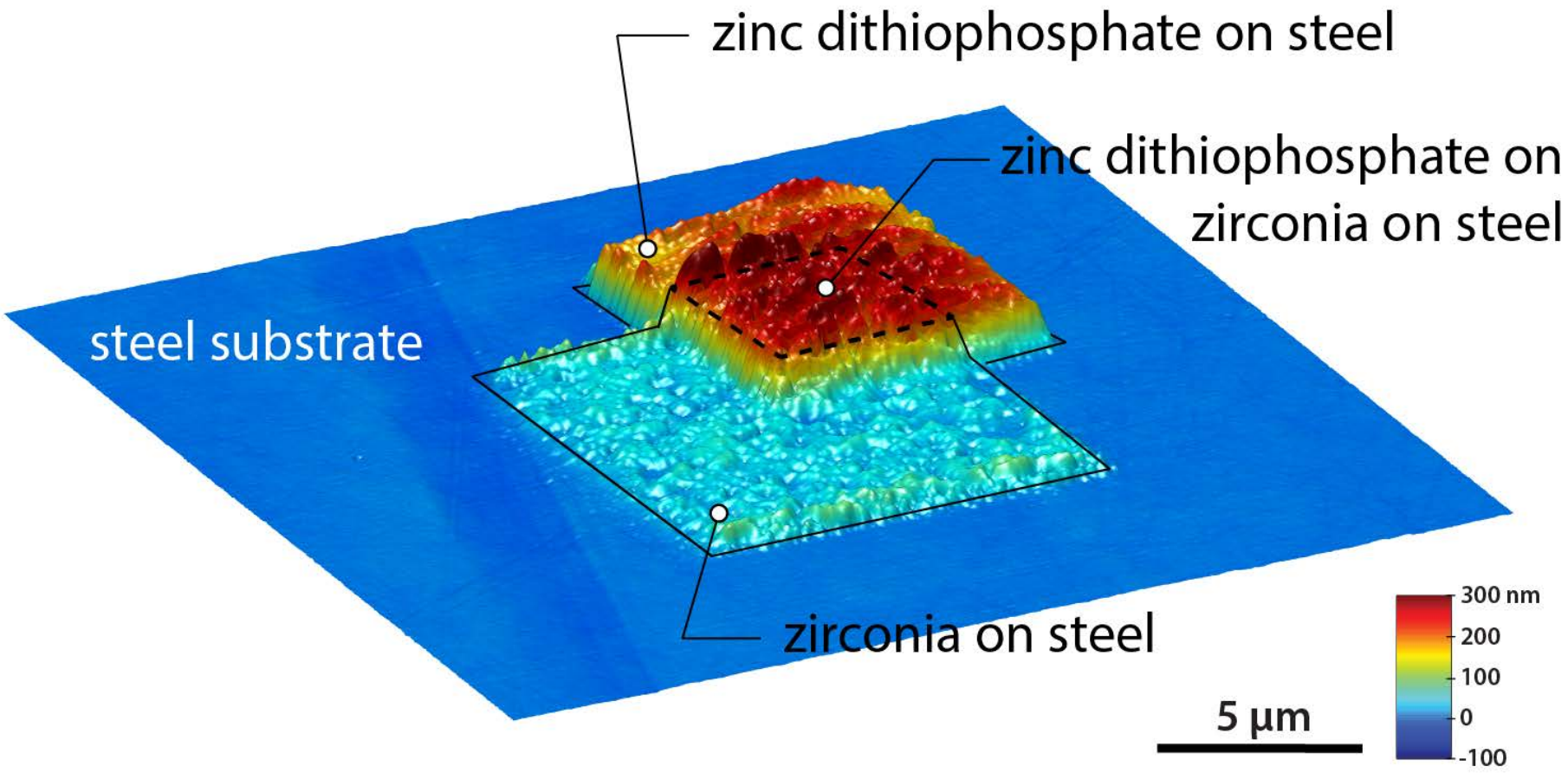
Pattern thickness varies with contact pressure

Patterning rate and pattern thickness can also be accelerated with temperature[1]

ZDDP growth rate increases exponentially with temperature

[1] N.N. Gosvami *et al.*, Science (2015)

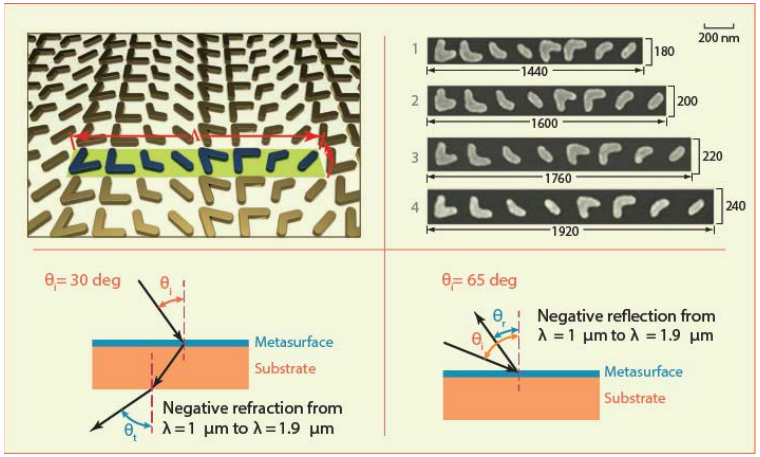
Layered Heterostructures with NTP



Using multiple ink materials, layered nanostructures can also be generated

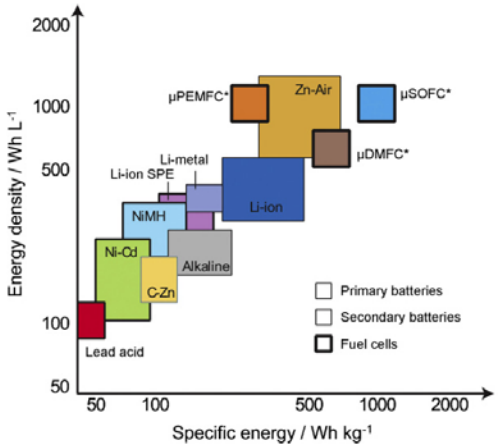
Applications of Nanotribological Printing

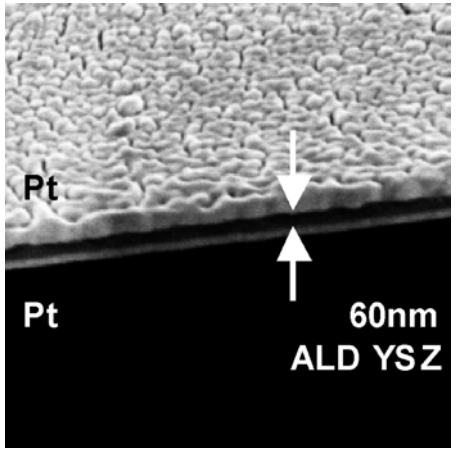
Photonics[1]



Nano-antenna array metasurfaces

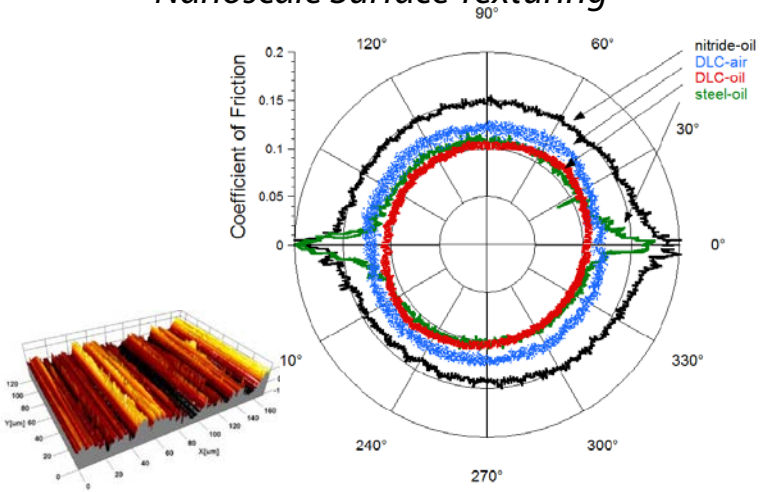
Micro-SOFC[2]



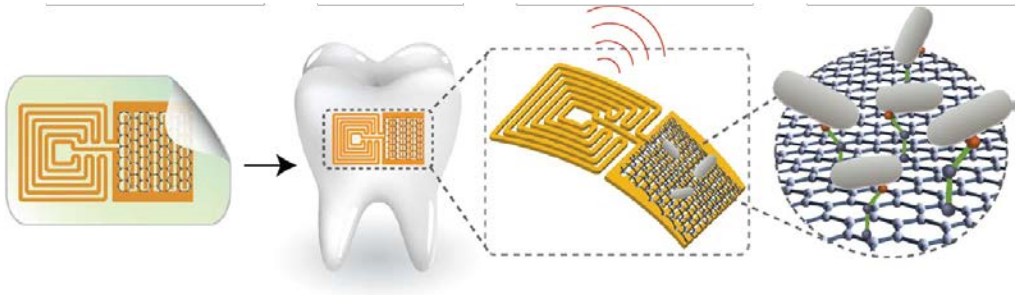


Electrolytic YSZ layers in micro-SOFC

Nanoscale Surface Texturing[3]



Nano circuit printing and biological sensors[4]



[1] A.V. Kildishev *et al.*, Science (2013)

[2] J.H. Shim *et al.*, Chem. Mater. (2007)

[3] R. Erck *et al.*, Proc. ASME/STLE IJTC (2012)

[4] M.S. Mannoor *et al.*, Nat. Comm. (2012)

Closing Remarks

- Nano-Tribological Printing is a versatile method for printing complex patterns with varying pattern height and shape
- It provides a novel additive printing technique capable of creating robust patterns without the need for chemical or thermal stimulus
- In-situ imaging during patterning provides real-time assessment of pattern quality
- Printed patters show highly dense microstructure and mechanical properties nearly similar to corresponding bulk material values
- Nano-Tribological Printing can be scaled up with SPM arrays (e.g. IBM millipede)

Acknowledgements

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- Prof. I-Wei Chen (Penn) for useful discussions
- Members of the Carpick Research Group for discussions and feedback