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

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Macroscale 3D printing is fast becoming mainstream

Additive Manufacturing (3D printing) has enabled rapid prototyping and manufacture of components with highly complex shapes

Plastic keychain pendant

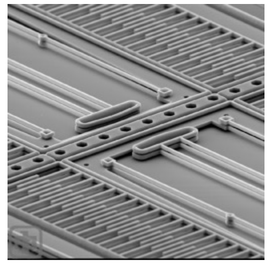
Jet engine components

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

Images: Penn AddLab, GE

Can we additively manufacture at the nanoscale? 3

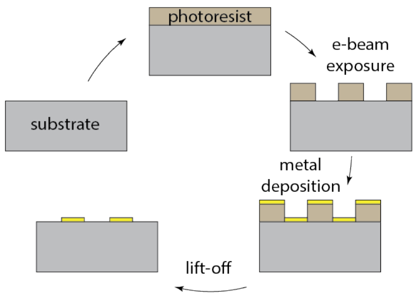
Microgears



Comb drive

Micro and nano electromechanical devices (MEMS/NEMS) require fabrication of parts with complex shapes at small scales

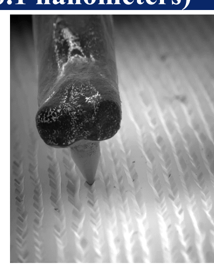
courtesy: Sandia National Labs



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

Most nanolithography techniques involve multi-step processes

Atomic force microscopes (AFM) can image surfaces at small scales (above 0.1 nanometers) 4



In a phonograph

Grooves on a vinyl record vibrate the stylus as it travels along them.

These vibrations are picked up to produce sound and/or music

https://youtu.be/GuCdsyCWmt8
courtesy: Applied Science/Ben Krasnow

AFM’s can measure topography and apply forces across a range of contact sizes (1 nm to 1 µm)

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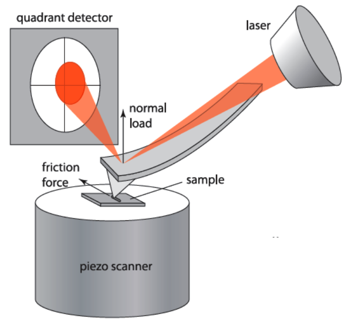

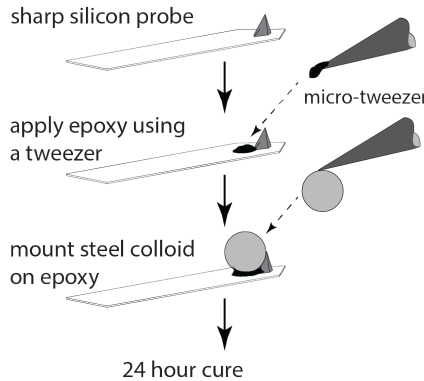

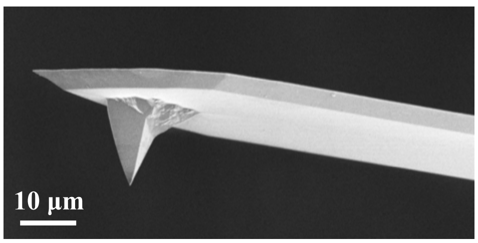

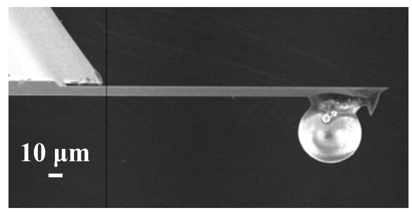

Additive nanopatterning with AFM is currently limited

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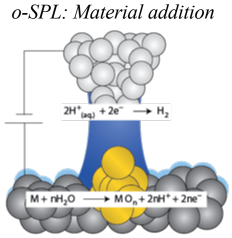
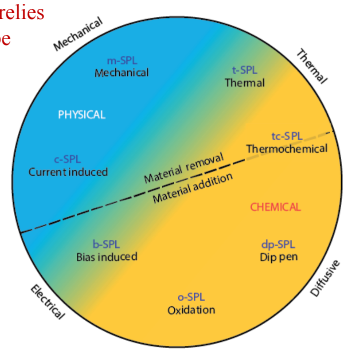
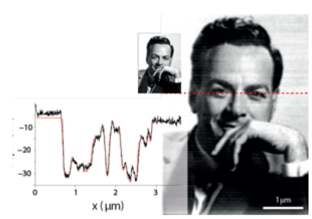
Scanning Probe Lithography (SPL)
is a direct-write technique and relies on conventional Scanning Probe Microscopes

o-SPL: Material addition





t-SPL: Material removal



Scanning Probe Lithography, using AFM’s is generally used for substractive nanopatterning

SPL methods for additive nanopatterning are severely limited in capabilities

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

The AFM can be operated in a liquid bath

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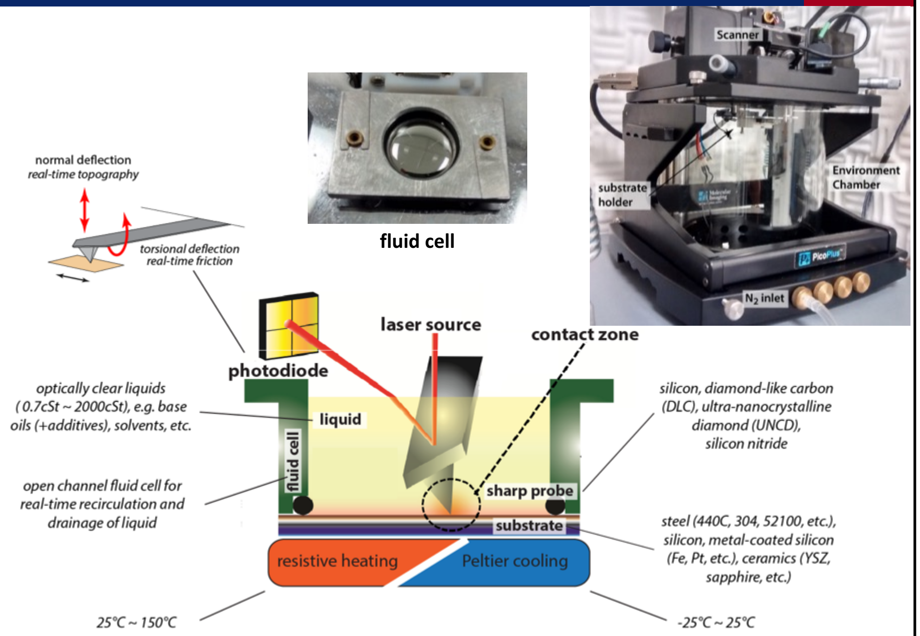

Nano-Tribological Printing uses AFM probes for patterning

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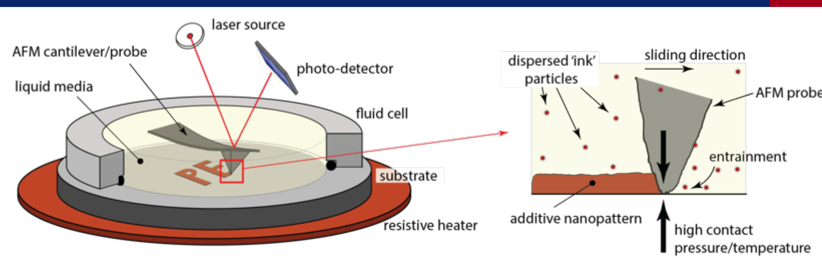
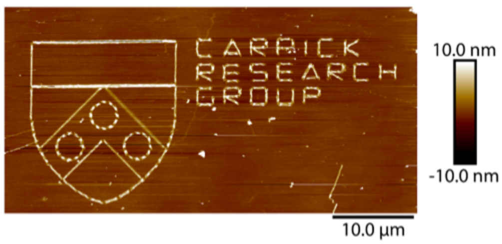
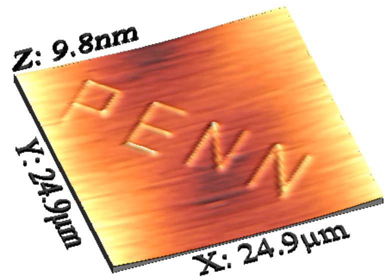


In Nano-Tribological Printing, patterning occurs due to *in-situ* confinement and stress-induced coagulation of ink material

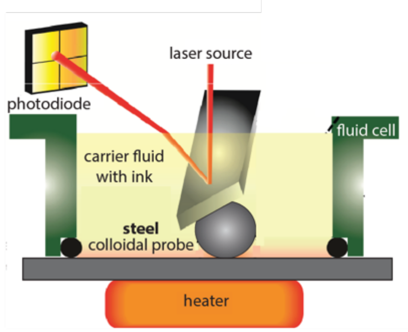
Programmed motion can be used to customize patterns

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

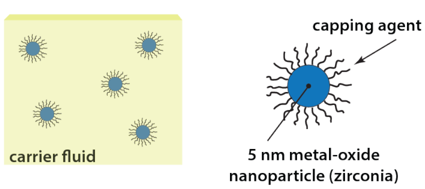




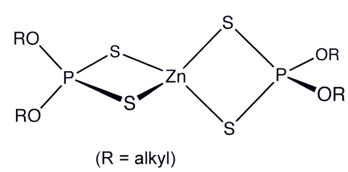
NTP ink can be in the form of dispersed nanoparticles



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



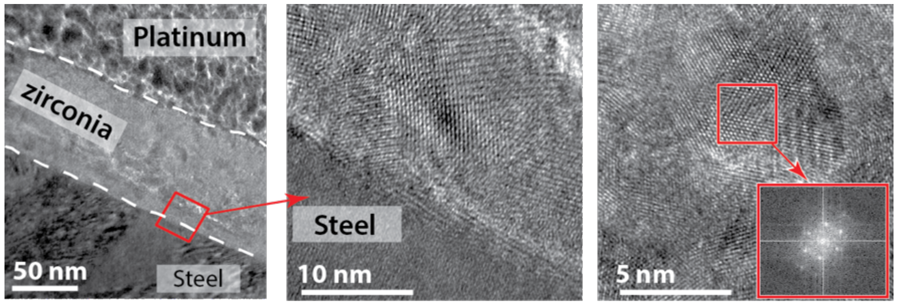
Nanoparticles as patterning ink



Zinc Dialkyldithiophosphates (ZDDP) at high temperature

Molecular species as patterning ink

Nanoparticle patterns are dense and robust



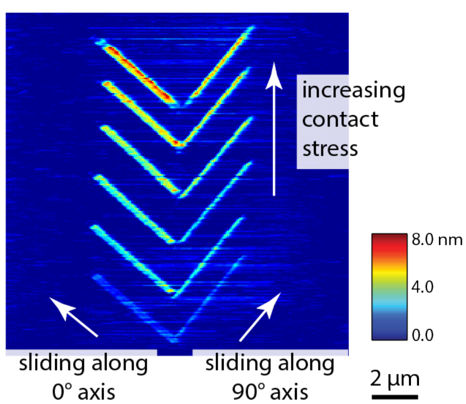
Tribological stress results in strong bonding between nanocrystals and a dense microstructure

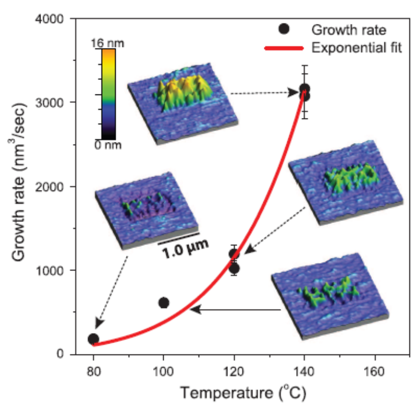
Samples	Young's Modulus E (GPa)	Hardness H (GPa)
Nanoscale pattern	**151.7 ± 5**	**7.3 ±0.7**
Bulk zirconia (1)	**215-266**	**9.2**

Although they have some porosity, zirconia nanopatterns have extremely good mechanical properties

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

Patterning through mechanochemical reactions





Pattern width changes with scan angle due to probe asymmetry

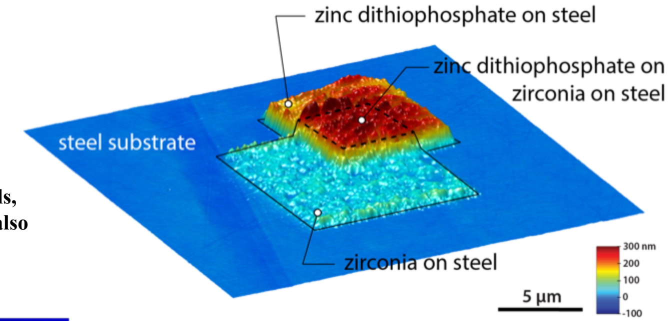
Pattern thickness varies with contact pressure

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

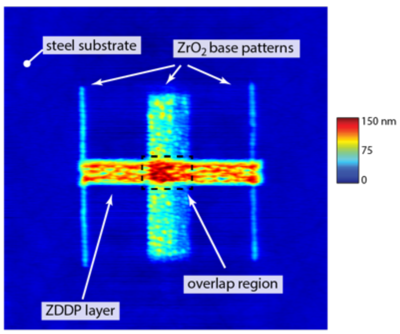
ZDDP growth rate increases exponentially with temperature

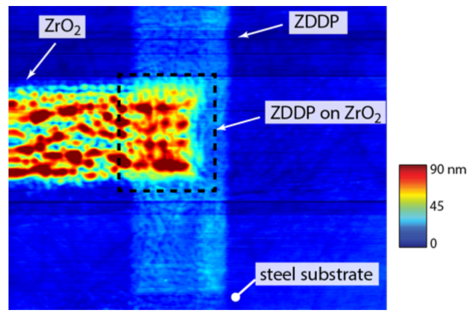
[1] N.N. Gosvami *et al.*, Science (2015)

Patterning of multi-material heterostructures



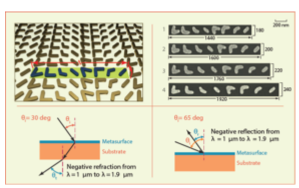
Using multiple ink materials, layered nanostructures can also be generated



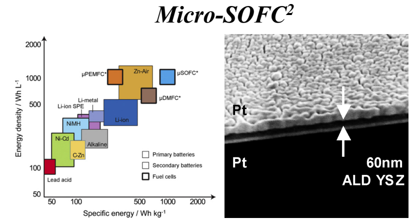


Applications of Nanotribological Printing

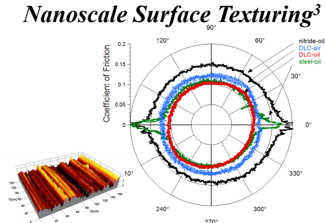
Photonics[1]



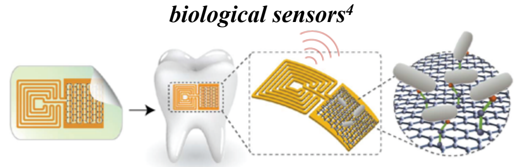
Micro-SOFC[2]



Nanoscale Surface Texturing[3]



Printing of circuits for chemical and biological sensors[4]



Components and coatings for NEMS/MEMS devices

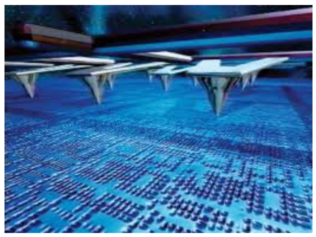
Next Generation Transistors and Electrical Switches

Nanoscale thermal barrier coatings

[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)

Key Limitations

- Single-probe patterning is intrinsically slow and low-throughput
  - Parallelization (e.g. IBM Millipede) of AFM probes can dramatically increase patterning rates



courtesy: IBM

courtesy: SwissLitho

- Material thickness is *generally* limited by available contact stresses
- The top and sides surfaces are somewhat rough; smallest dimension so far ~100 nm
- Since NTP requires applied stress at the contact, freely suspended structures (e.g. suspension bridge spans) cannot be fabricated without using etchable resists.

Closing Remarks

- Nano-Tribological Printing is a new, versatile method for printing complex nanopatterns 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 patterns 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