Quantized (Patterned) Magnetic Disks and Ultrafast Laser-assisted Nanofabrication

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Outline

Introduction

- Limit of traditional thin film media
- Quantized magnetic disks – concept and advantage
- Patterned magnetic nanostructure – effects of size and shape

Large area nickel QMDs of 18 Gbits/in^2 (190 nm period)

- Interference lithography for NIL mold fabrication
- Process steps
- Results – SEM, AFM & MFM images, and hysteresis
- Discussion – switching and interaction
- Writing

Fabrication of 100 and 50 nm period grating for much higher (15×) density

Laser-assisted rapid nanofabrication:

LADI of metals, planarization of metals and silicon, high-aspect ratio via hole filling, nano-transfer printing, nano-tip formation, and wafer bonding.

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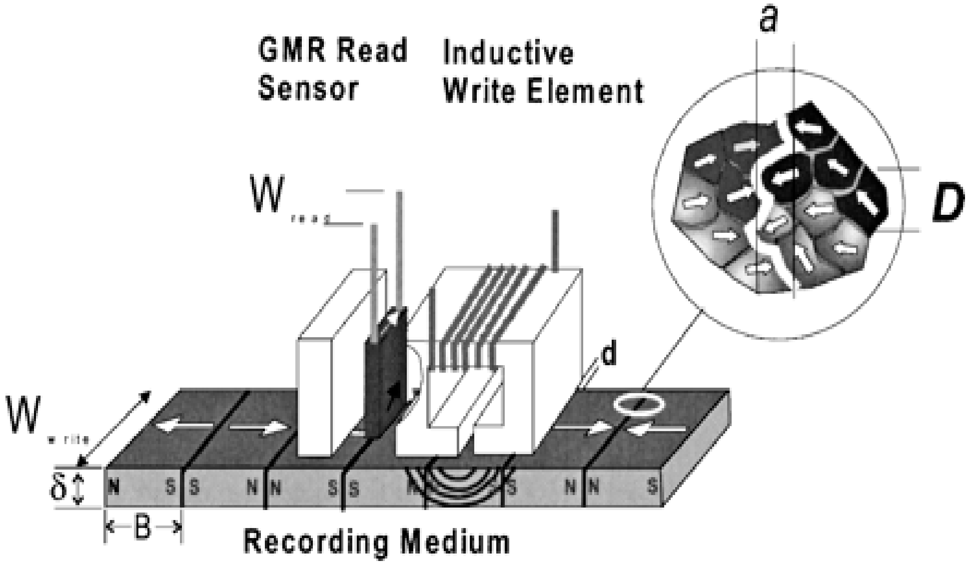
Super-paramagnetic Limit of Traditional Thin Film Media

SNR ∝ number of grains in one bit, so need ~100 grains per bit.

Fine grain can be switched by thermal energy (super-paramagnetic)

Data life time $= 10^{-10} e^{KuV/K_BT}$ (sec), so need D≥6 nm

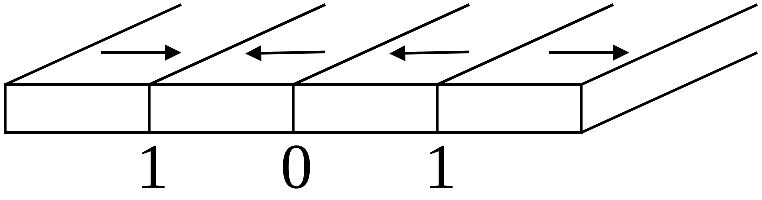
Conclusion: thin film media can not support, say, 200 Gbits/in^2.

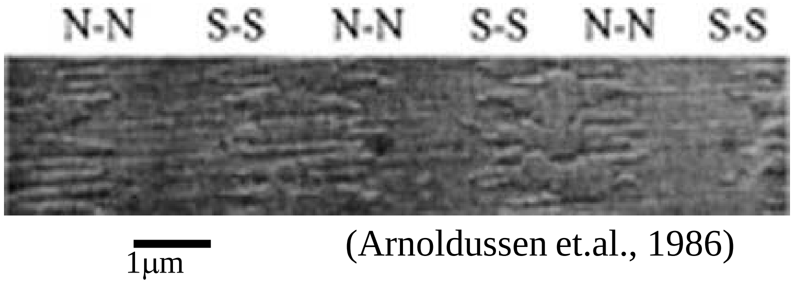


(Weller, *Annu. Rev. Mater. Sci.* 30: 611-644 2000)

Saw-tooth Transition in Traditional Thin Film Media

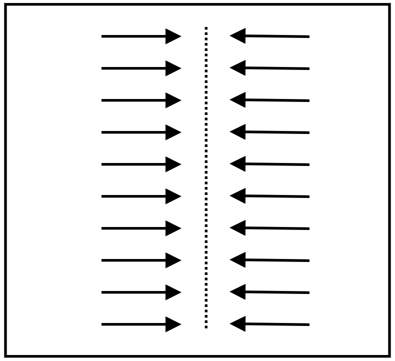
(leads to transition noise and jitter)

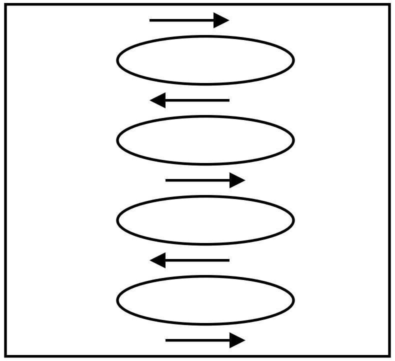


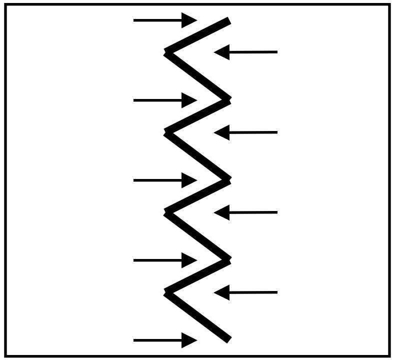


(Arnoldussen et.al., 1986)

Formation of zigzag transition:





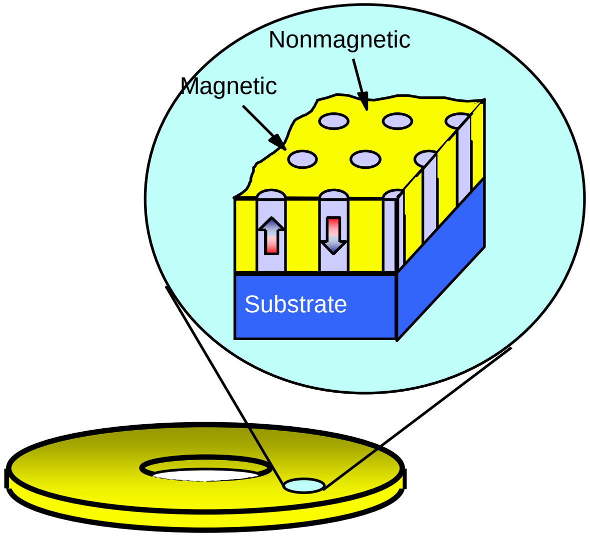


low exchange energy
high magnetostatic energy

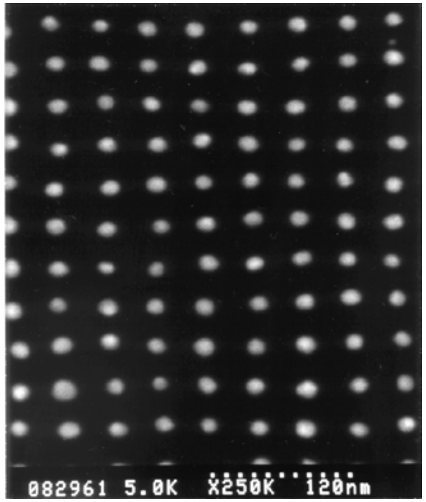
low magnetostatic energy
high exchange energy

Tradeoff:
low total energy

Quantized Magnetic Disks (QMDs)



Schematic of QMD



SEM image of a 400 Gdots/in^2 density by nanoimprint lithography and liftoff. Dot size 10nm, period 40nm.

Advantage over conventional thin film disk:

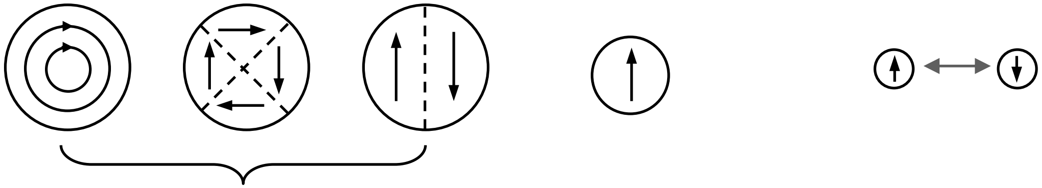
- Overcome superparamagnetic limit thus capable of ultra-high density recording
- Smooth transition hence low media noise
- All-or-nothing writing process, thus can tolerate large head-field gradient
- Robust and precise tracking through patterning

Disadvantage: Cost associated with large area nano-patterning

However, NIL is promising for patterning QMD with low cost and high throughput

Effects of Patterning on Magnetic Properties

Size effect:

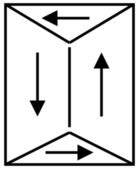


Vertex or multi-domain

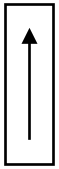
Single-domain

Super-paramagnetic

Shape effect:



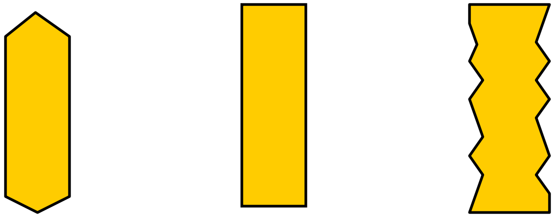
Closure-domain



Single-domain.

Shape anisotropy switching field $H_{sw}=(N_x-N_z)M_s$

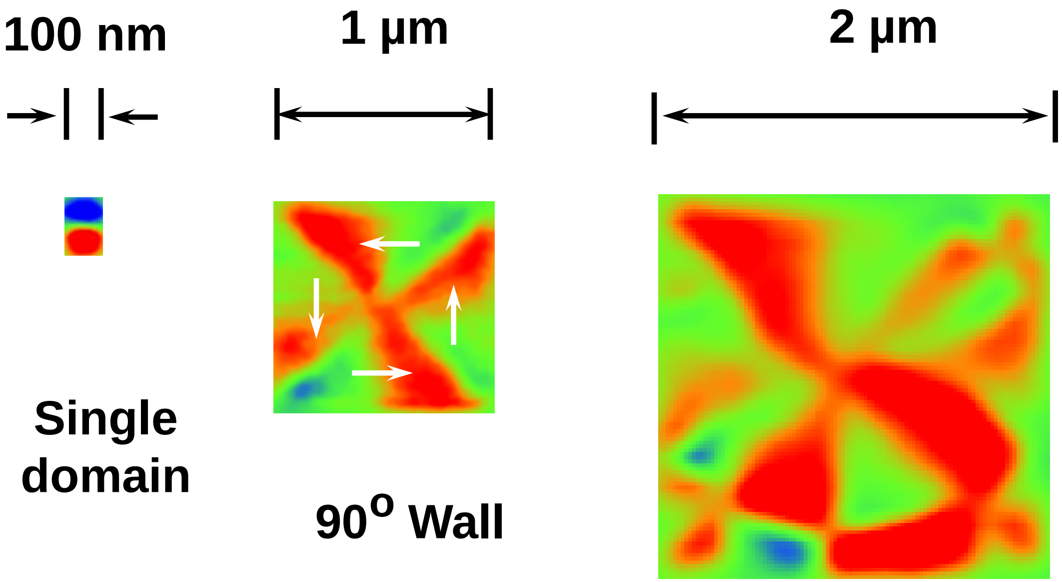
Edge effect:



Switching field $H_{sw}>>H_{sw0}$ H_{sw0} $H_{sw}<H_{sw0}$

Effects of Patterning on Magnetic Properties (Experiment)

- Control domain structure by patterning (e.g., at nanoscale, single domain forms spontaneously)
- Control switching field by patterning (e.g., due to shape anisotropy, patterning can increase the switching field by a factor of 60)

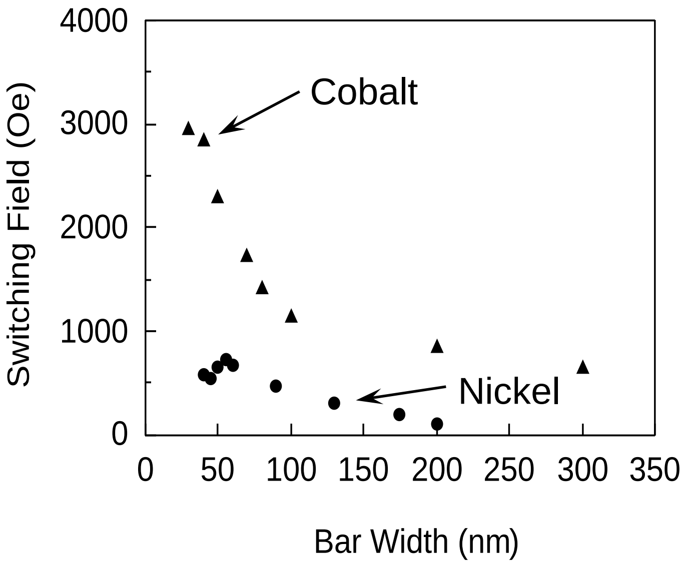


Single domain

90° Wall

Chaos

MFM image, 35 nm thick cobalt square (size effect)



Rectangular Co and Ni bars (both shape and size effect)

Chou SY, *Proceedings of the IEEE*, 85(4), 652(1997)

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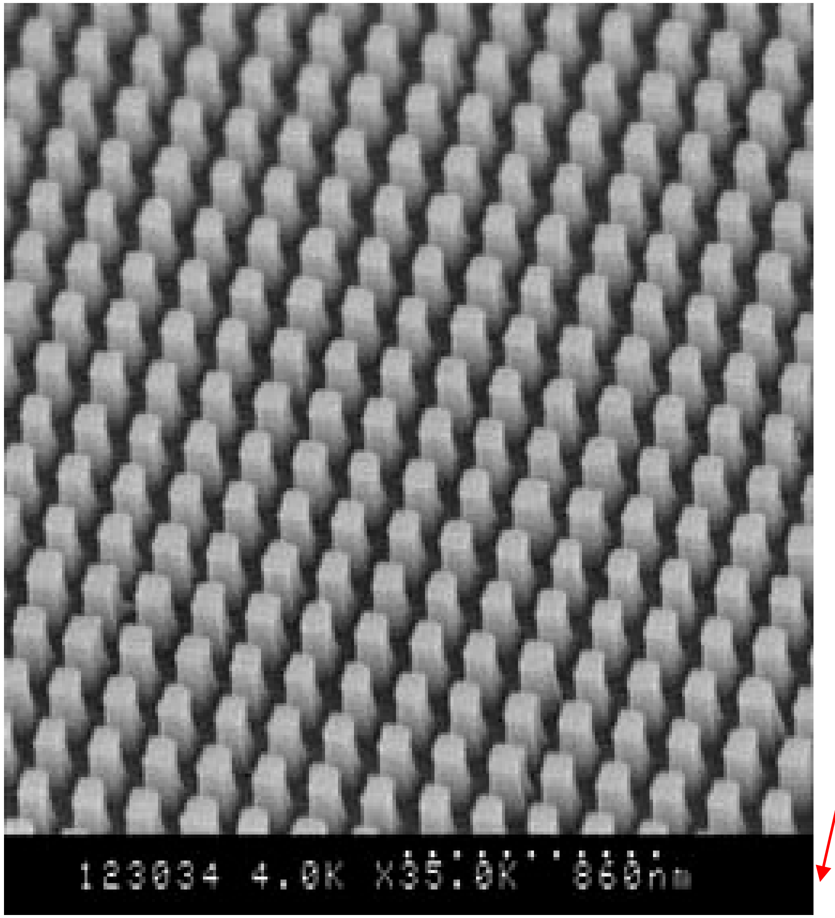
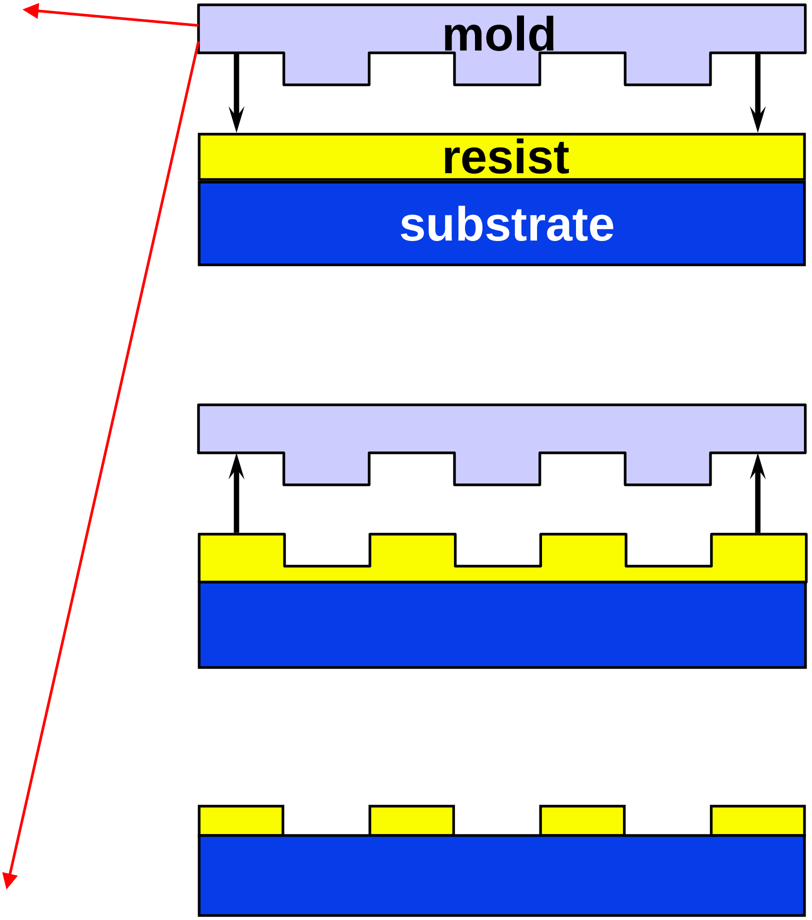
190nm Period Pillar Mold Fabricated by Interference Lithography and Double NILs



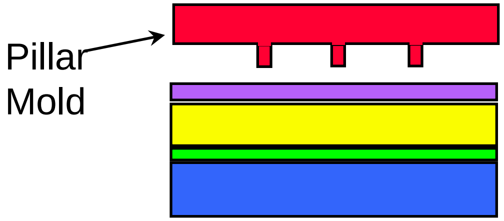


Nanoimprint lithography (NIL)

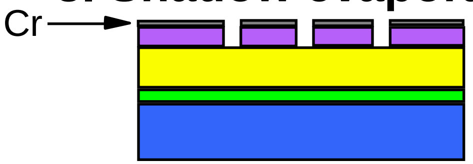
Quantized Magnetic Disk Fabrication

1. Initial Substrate and Films

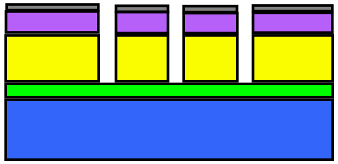
2. Nanoimprint Lithography



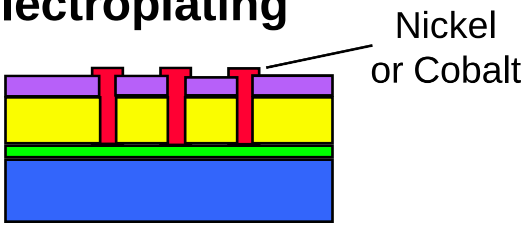
3. Shadow evaporate Chrome



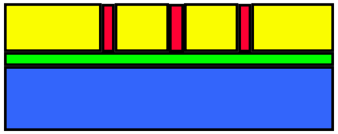
4. Reactive Ion Etching



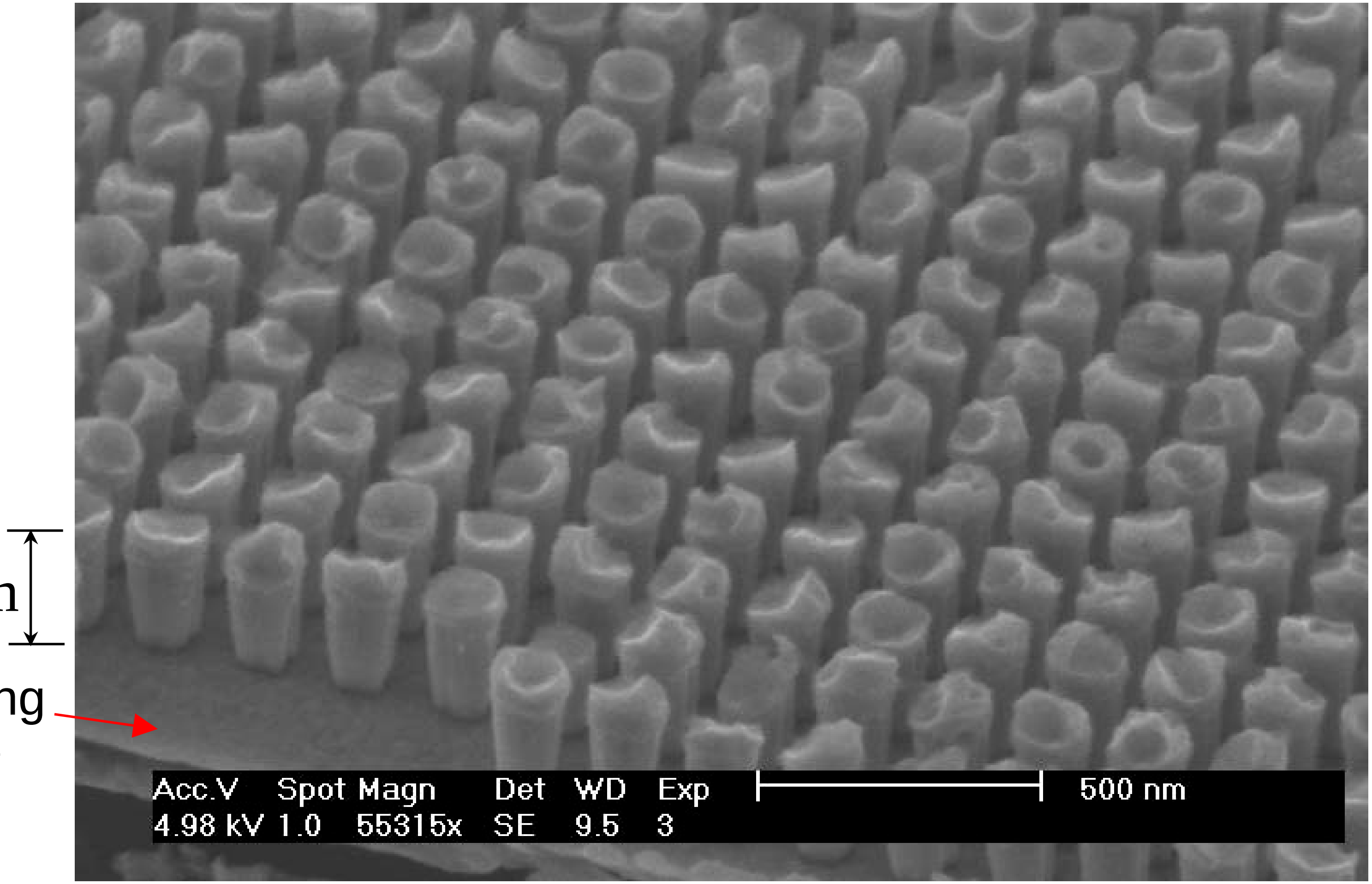
5. Electroplating



6. Chemical Mechanical Polishing



Electrodeposited 190nm Period Ni Pillar Array (no polishing and stripped SiO_2)

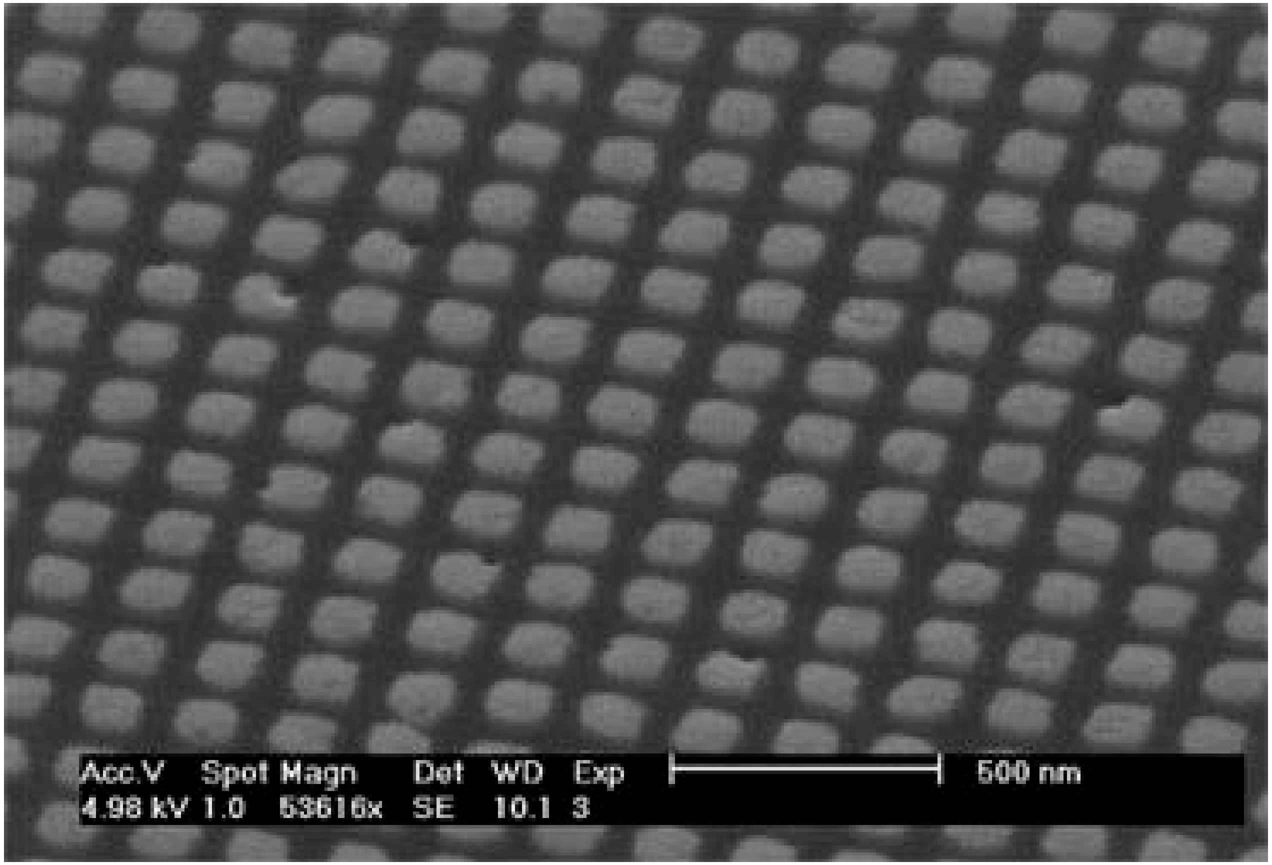


370nm

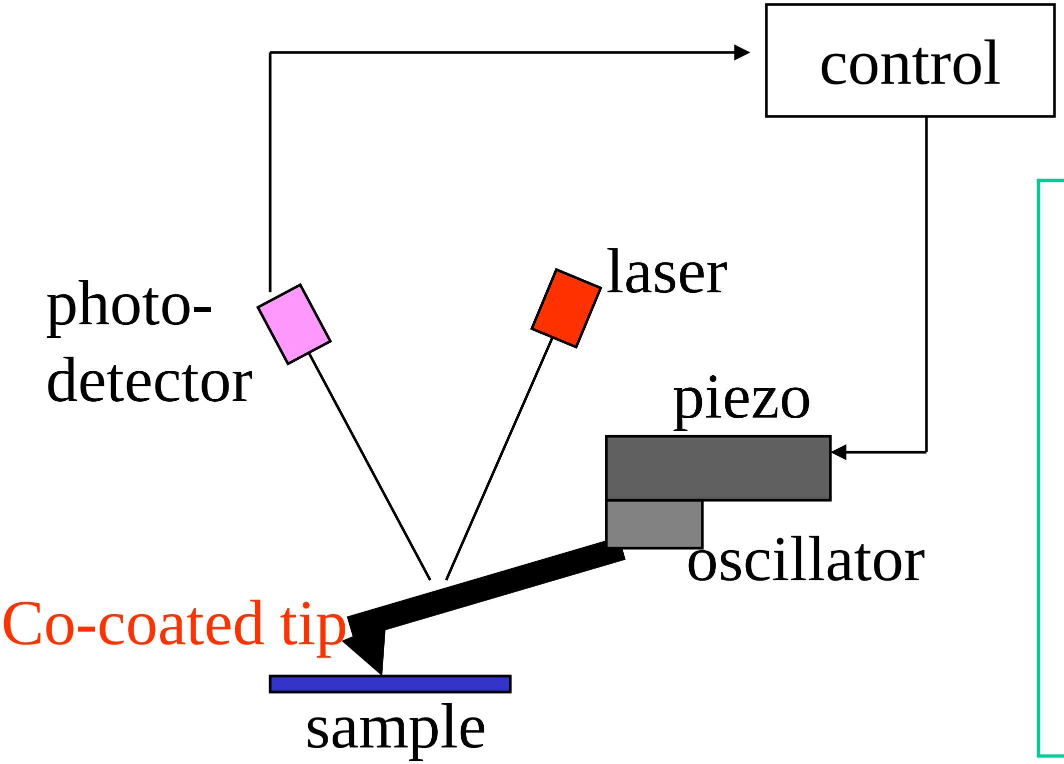
Plating base

Large Area Ni Pillar Array Embedded in SiO$_2$ after Chemical Mechanical Polishing

(QMD1, pillar height 240nm, diameter 110nm)



Magnetic Force Microscopy (MFM)

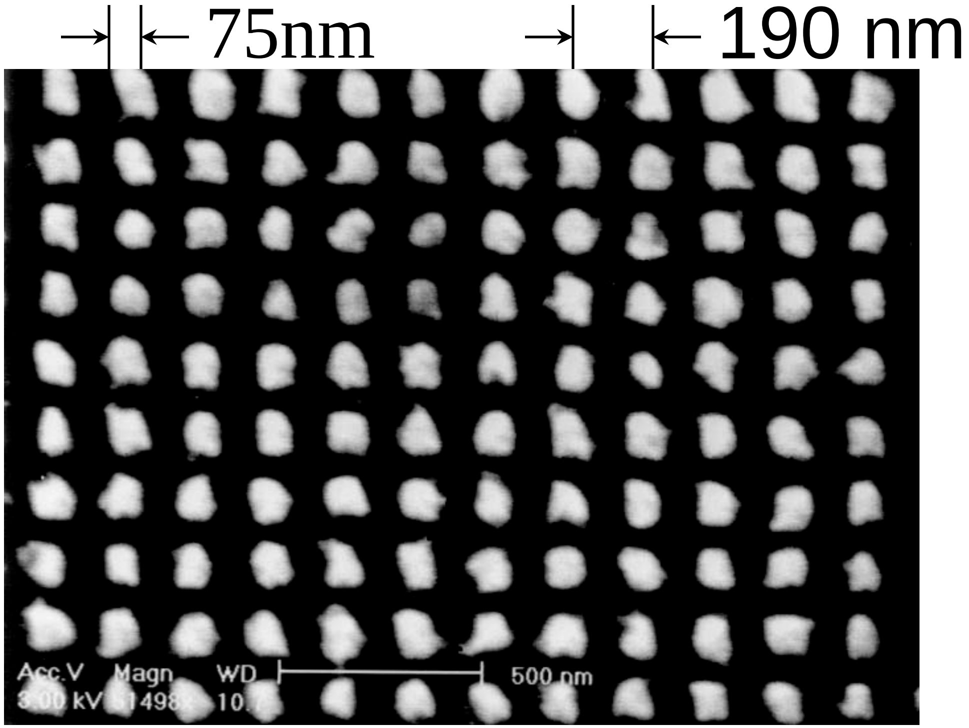


Phase shift

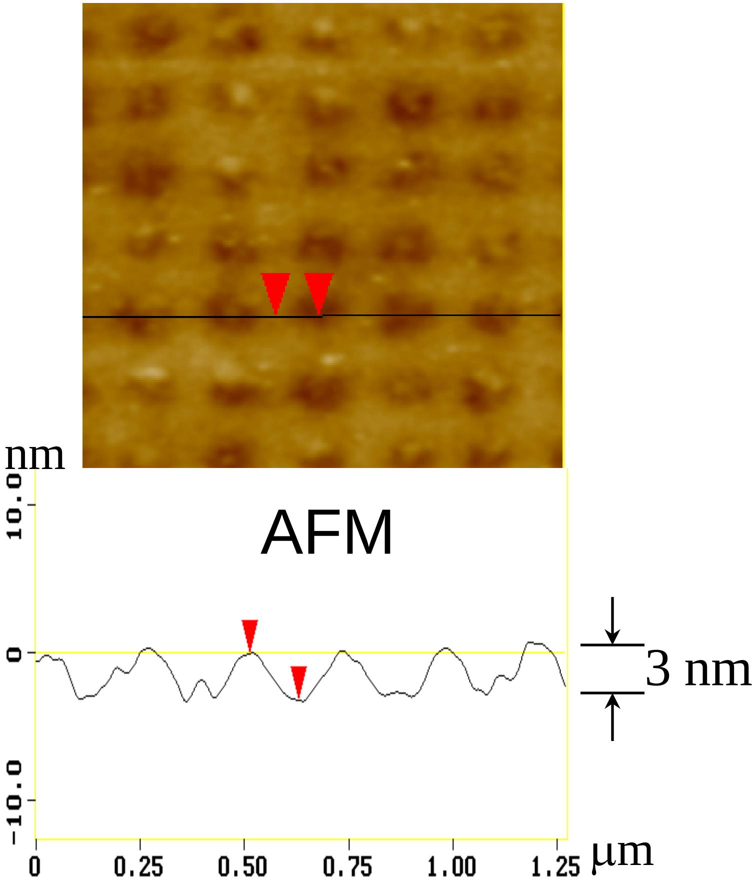
$$\Delta\Phi = \frac{Q}{K}(m \cdot \nabla^2 H)$$

Q: quality factor
K: spring constant
m: tip magnetic moment
H: magnetic field from sample

Large Area Ni QMD with Pillar diameter 75 nm and Height 400 nm (QMD2)



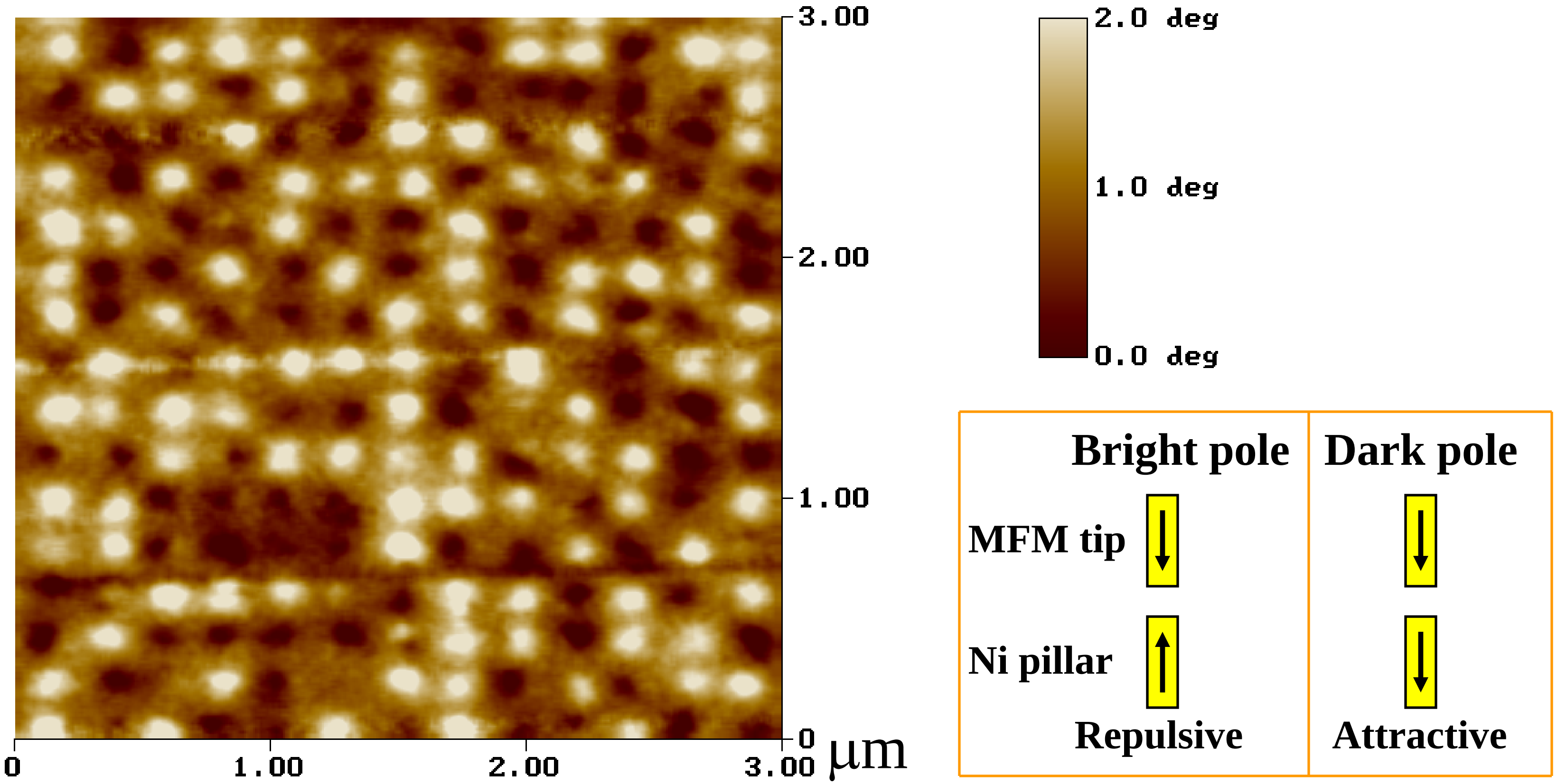
SEM



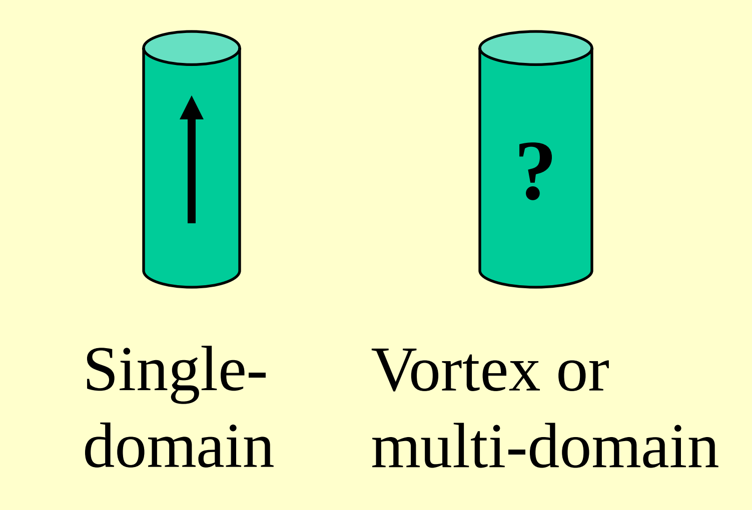
AFM

MFM Image of 18 Gbits/in^2 Large Area QMD in Demagnetization State

(QMD2, pillar diameter 75 nm, height 400 nm)



Discussion: Single Domain Formation



Single-domain

Vortex or multi-domain

Magnetostatic energy ~ L^3

Domain wall energy ~ L^2

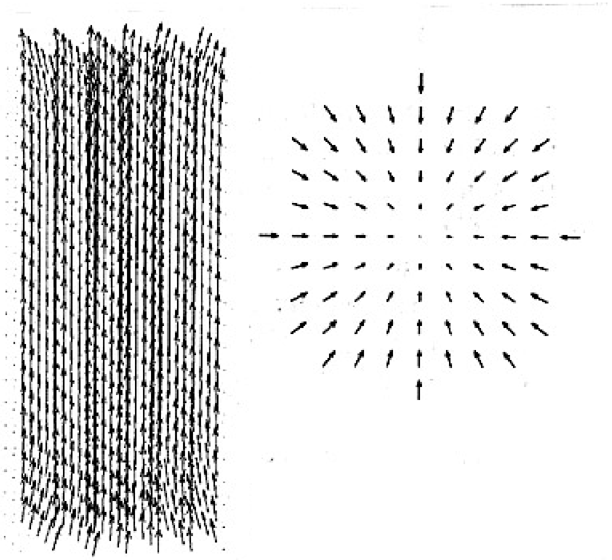
Thus, sufficient small particle favors single domain

Aharoni's analytical theory:

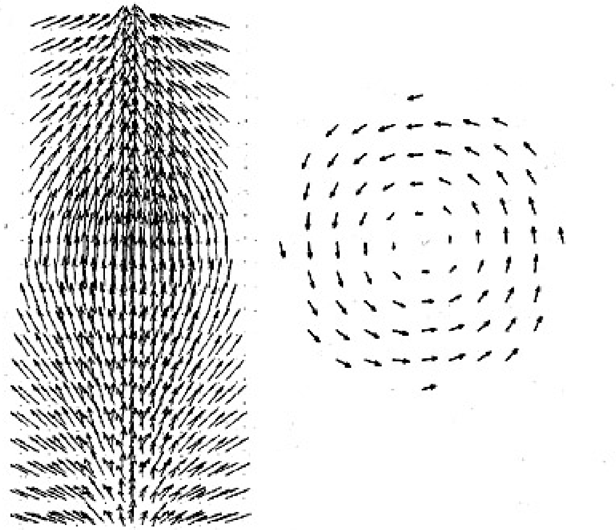
If cylinder radius $R < R_{c0} = \frac{q}{M_s}\sqrt{\frac{C}{N_z}}$, (C is exchange constant, and both N_z and q depends on cylinder aspect-ratio only) then single domain is the lowest energy state.

Thus QMD2 (R=37.5nm, aspect ratio=5.3) that satisfied this criterion formed single domain while QMD1 (55nm, 2.2) didn't.

Micromagnetic Simulation of Magnetization Distributions in Nickel Cylinders



D < 3.5 λ_{ex}, flower state
(high moment, large MFM signal)



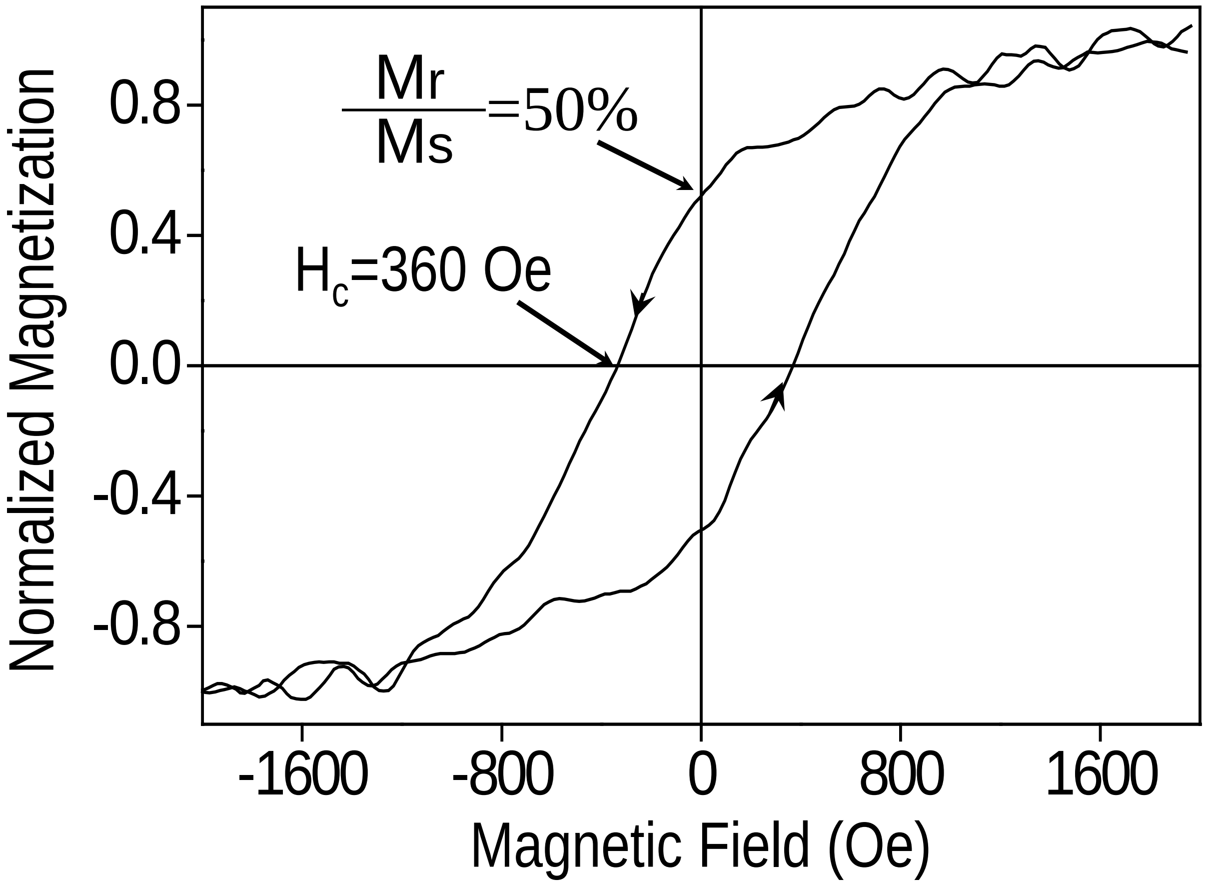
D > 3.5 λ_{ex}, vortex state
(low moment, weak MFM signal)

Here λ_{ex} is exchange length, which is about 25 nm for Ni.
QMD1 D=110nm, vortex; QMD2 D=75nm, flower (quasi-single domain).

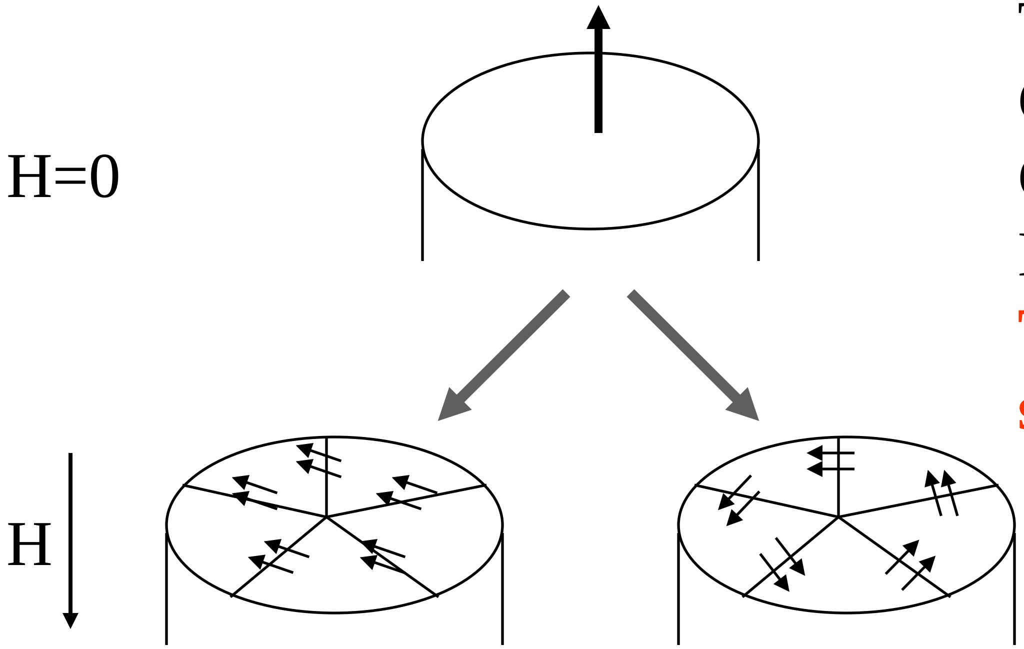
Ross *et al.*, *Physical Review B*, 65 144417-1 (2002)

Hysteresis Loop of Ni QMD with Switching Field of 360 Oe and Large Magnetostatic Interaction

(Hc=85 Oe for flat film)



Switching of a Single Domain Ni Pillar



Theoretical switching field
Curling: 406Oe
Coherent: 2540Oe
Experiment: 360 Oe
Thus curling is the switching mechanism

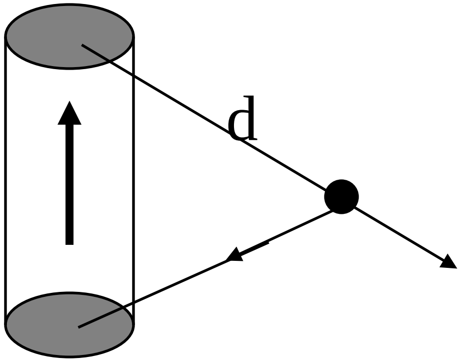
Coherent rotation:
high magnetostatic energy
zero exchange energy

Curling rotation:
low magnetostatic energy
high exchange energy

Estimation of Magnetostatic Interaction (Theory)

(maximum demagnetizing field exerted on each pillar)

Rough estimation:



$$H_{\text{int}} = 2\theta\frac{P}{d^2}\cos$$

$$(P = Ms \cdot \pi R^2)$$

Total H_{demag}=Σ H_{int}=405 Oe

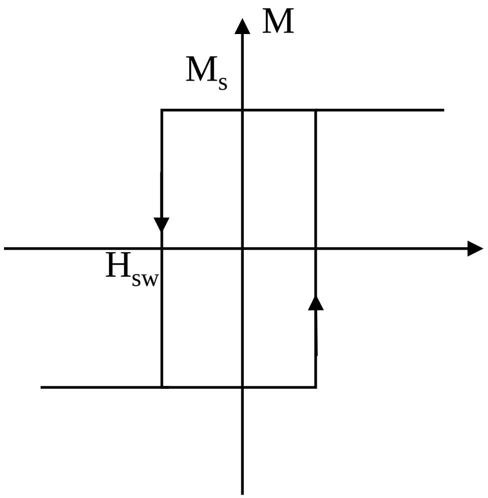
More accurate calculation:

$$H_{\text{int}} = -2M_s\left[\cot^{-1} f(x,y) + \cot^{-1} f(-x,y) + \cot^{-1} f(x,-y) + \cot^{-1} f(-x,-y)\right]$$

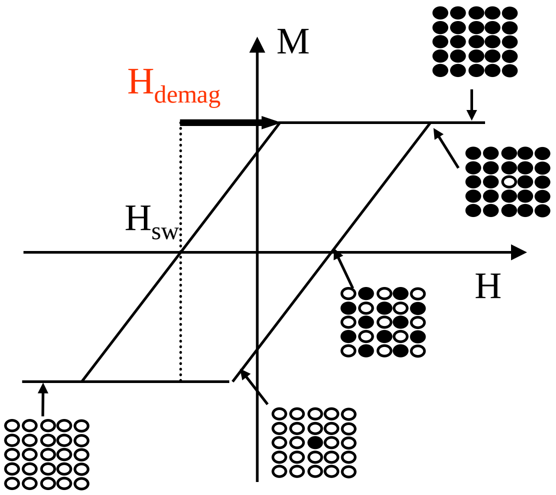
$$f(x,y) = \frac{\left[(R-x)^2 + (R-y)^2 + c^2\right]^{1/2} c}{(a-x)(a-y)}$$

Total H_{demag}=Σ H_{int}=522 Oe

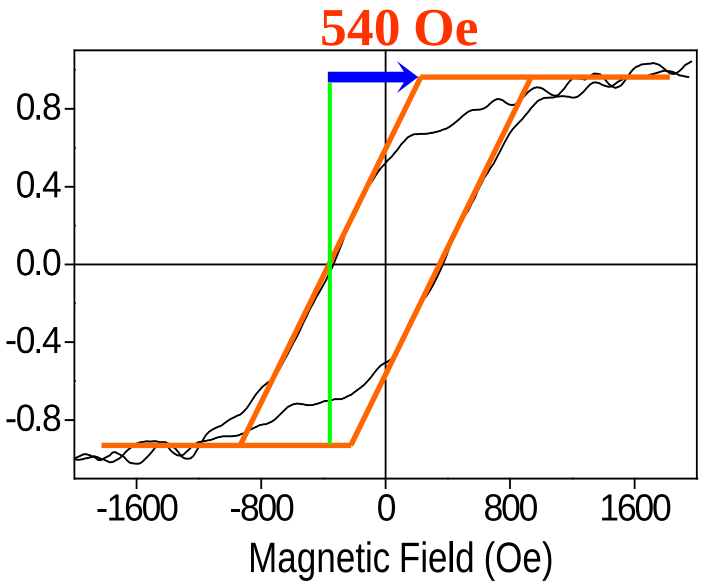
Estimation of Magnetostatic Interaction (experiment)



Without interaction



With interaction



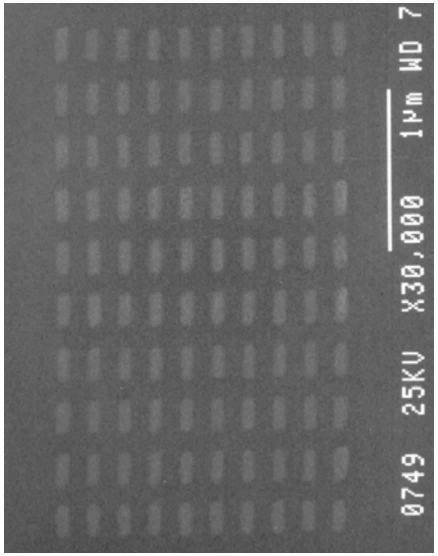
H$_{demag}$ is larger than switching field (360 Oe)
To overcome this interaction:

- reduce pillar size, but this will reduce read-back signal
- increase switching field by utilizing crystalline anisotropy

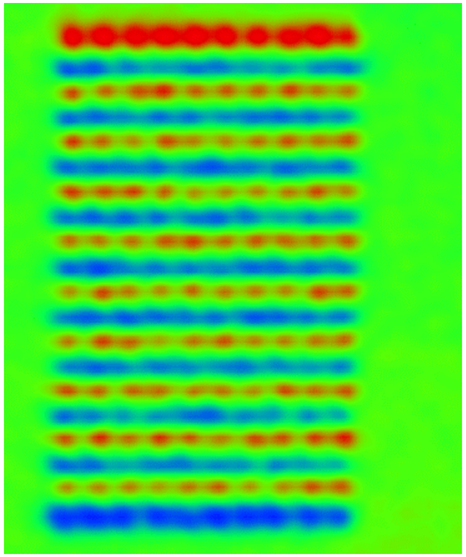
QMD Writing by MFM tip

(10 Gbit/in^2 Longitudinal QMD)

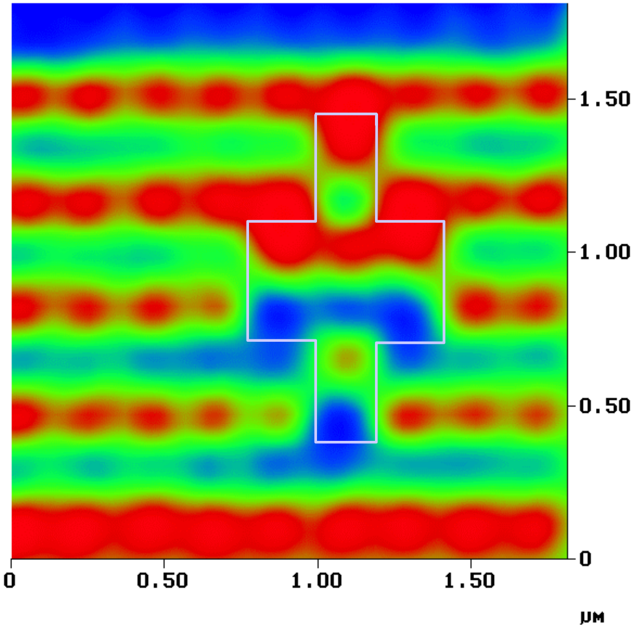
(Size: 60 nm × 200 nm, Spacing: 130 nm)



SEM image



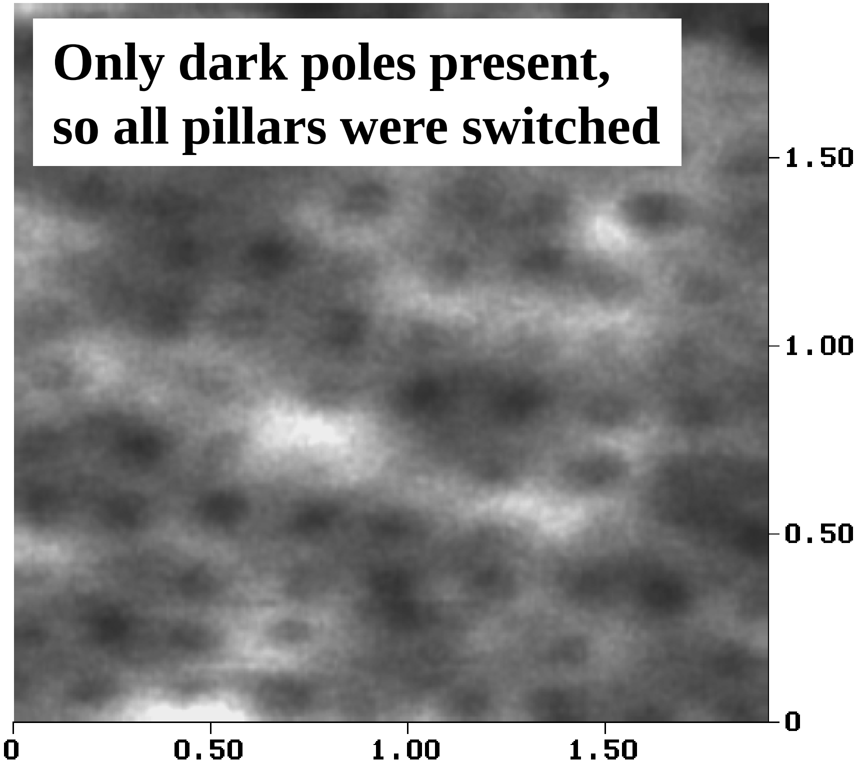
MFM image



Pattern written by MFM tip

Kong, *Jpn. J. Appl. Phys. 1*, 37 (11): 5973-5975(1998)

MFM Image of Ni QMD scanned with a High Moment MFM Tip


Only dark poles present, so all pillars were switched

MFM tip could be used to write perpendicular Ni QMD

Summary for QMD

- 18 Gbits/in^2 Ni QMDs were fabricated by nanoimprint lithography and electroplating.
- Single domain is achieved for Ni pillars with height 400nm and diameter 75nm. The average switching field is 360 Oe.
- Curling rotation is the magnetization reversal mode.
- Magnetostatic coupling between neighboring pillars is significant.

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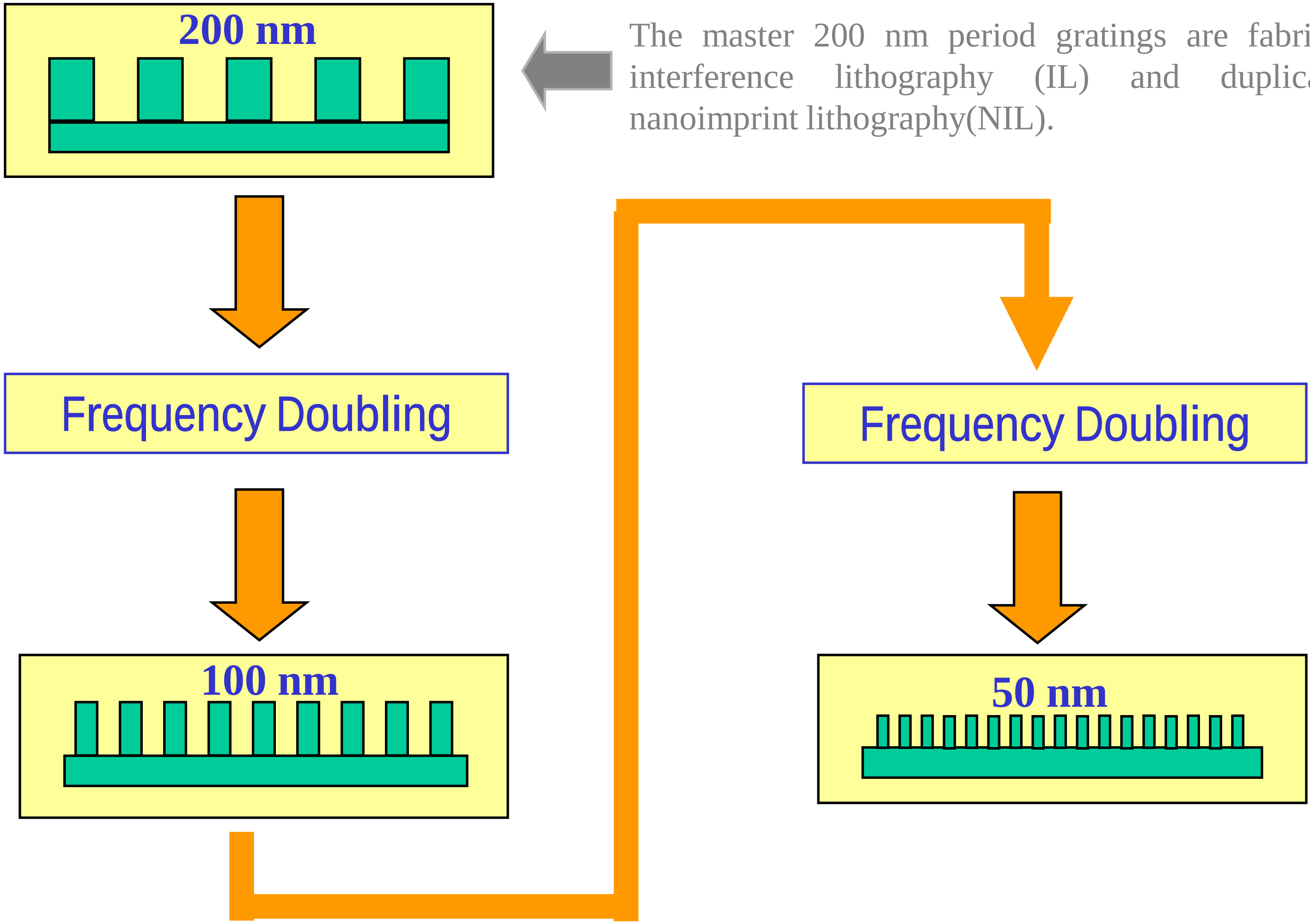
Motivation

- Fabrication of large area sub-200nm period grating is a challenge to conventional approaches such as interference lithography.

- Many applications require sub-200nm period grating
  - — sub-wavelength optical devices
  - — genomics, DNA stretching, sorting…
  - — quantum dot devices
  - — ultrahigh density patterned magnetic disks

Fabrication Process Flow

The master 200 nm period gratings are fabricated by interference lithography (IL) and duplicated by nanoimprint lithography(NIL).



200 nm

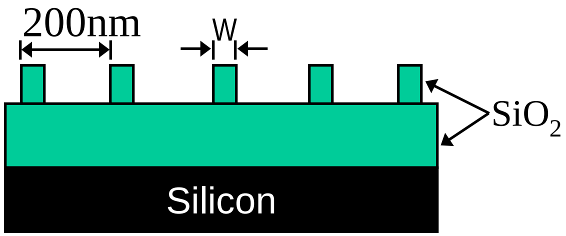
Frequency Doubling

100 nm

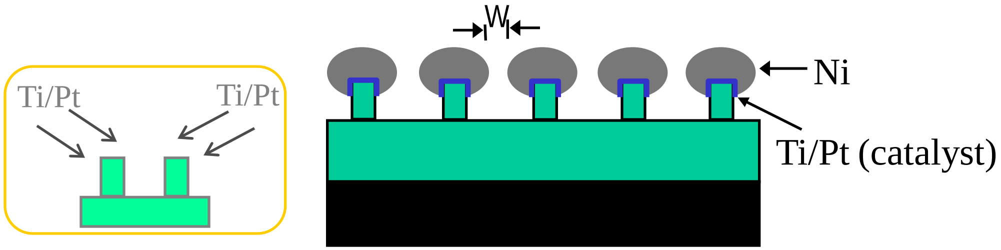
Frequency Doubling

50 nm

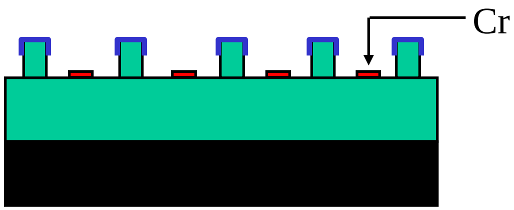
A Novel Frequency Doubling Process



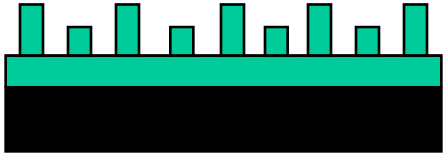
1. NIL duplicate 200 nm period grating with narrow line



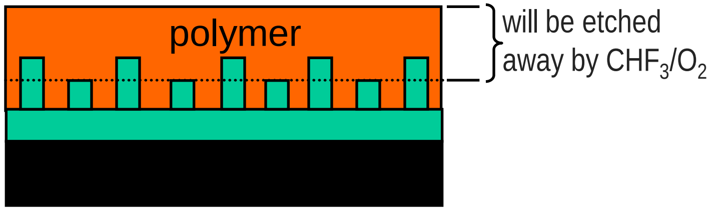
2. Angle-evaporate Ti/Pt and electroless Ni plating



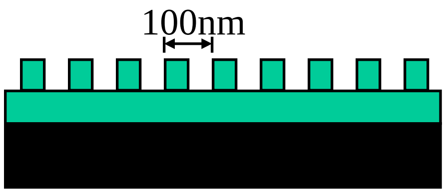
3. Deposite Cr and its liftoff by Ni in nitric acid



4. RIE SiO_2 and wet-etch remove metals

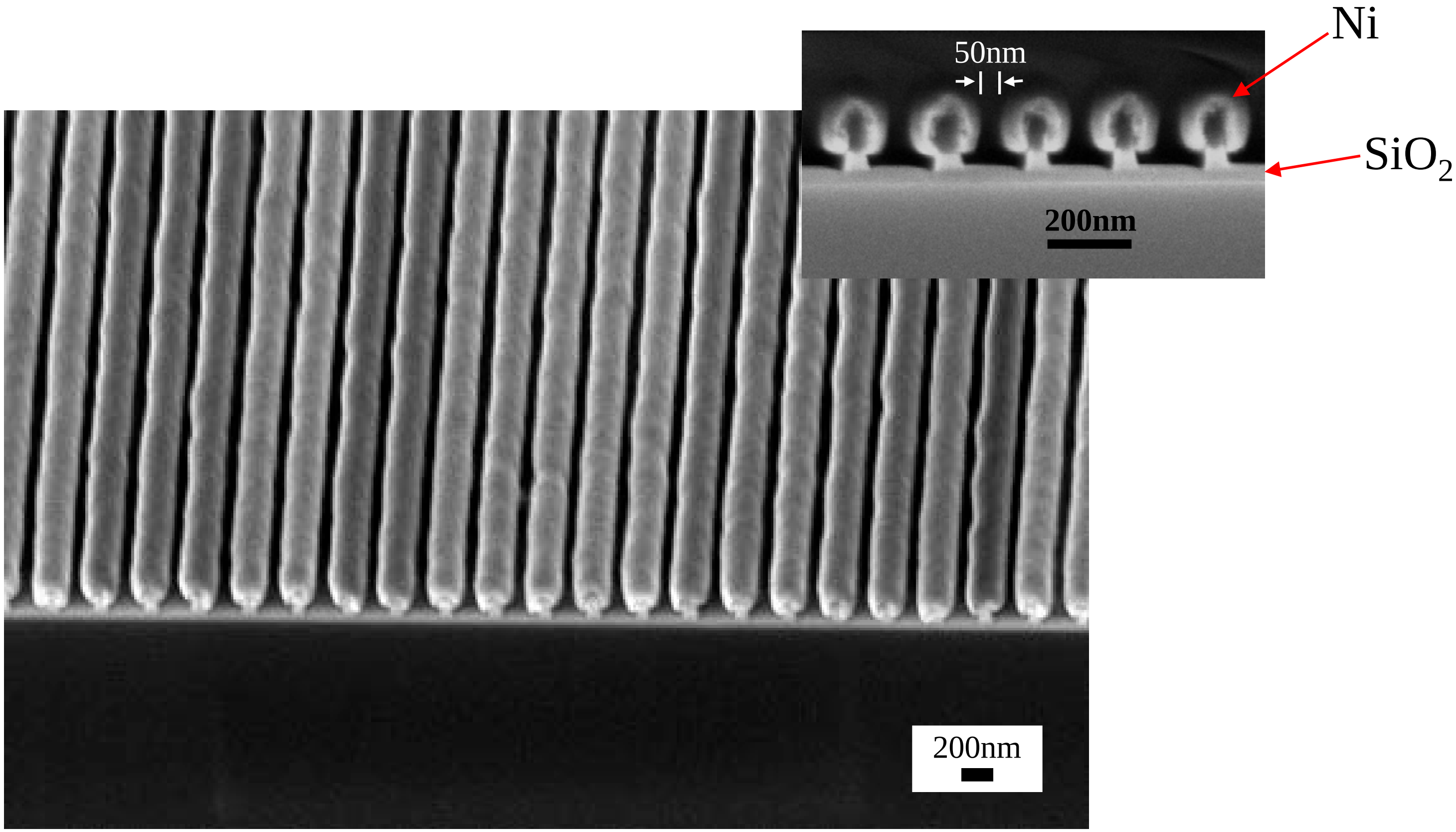


5. Spin-on polymer with same etch rate as SiO_2

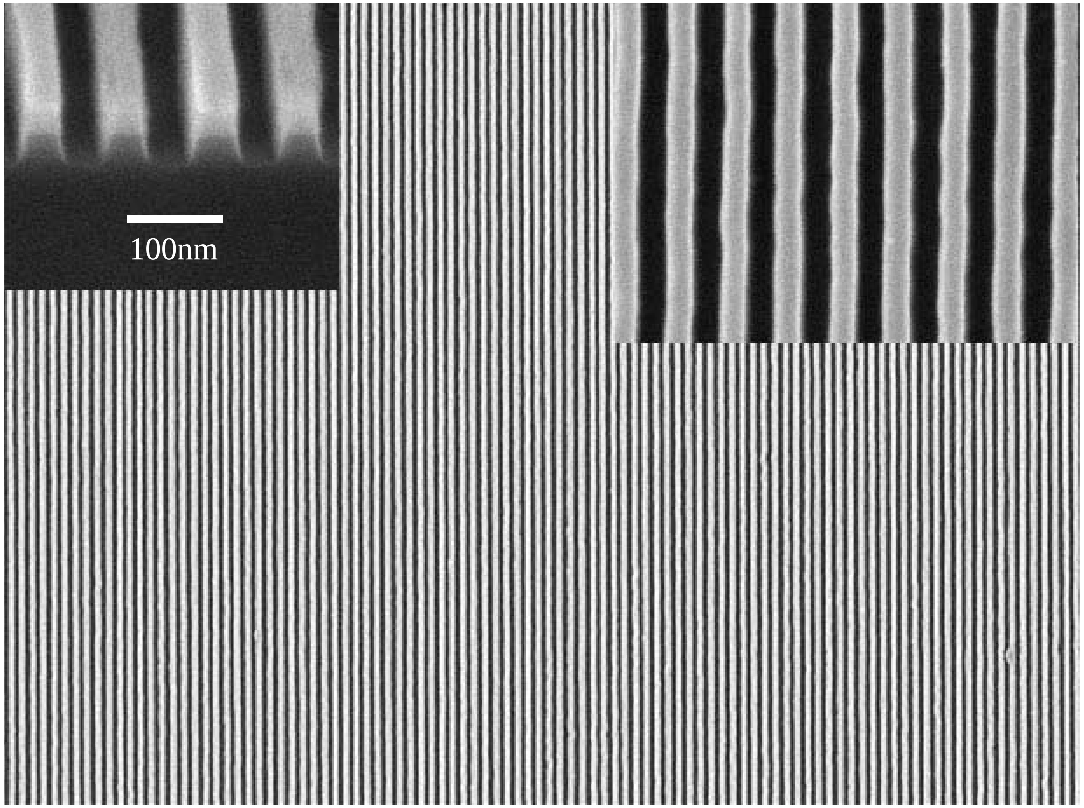


6. Planarization by polymer etch-back

Electroless Ni Plating onto 200 nm Period SiO_2 Grating



Large Area 100 nm Period Grating in SiO_2 by Spatial Frequency Doubling



Uniformity of Electroless Ni Plating across a 10cm Wafer

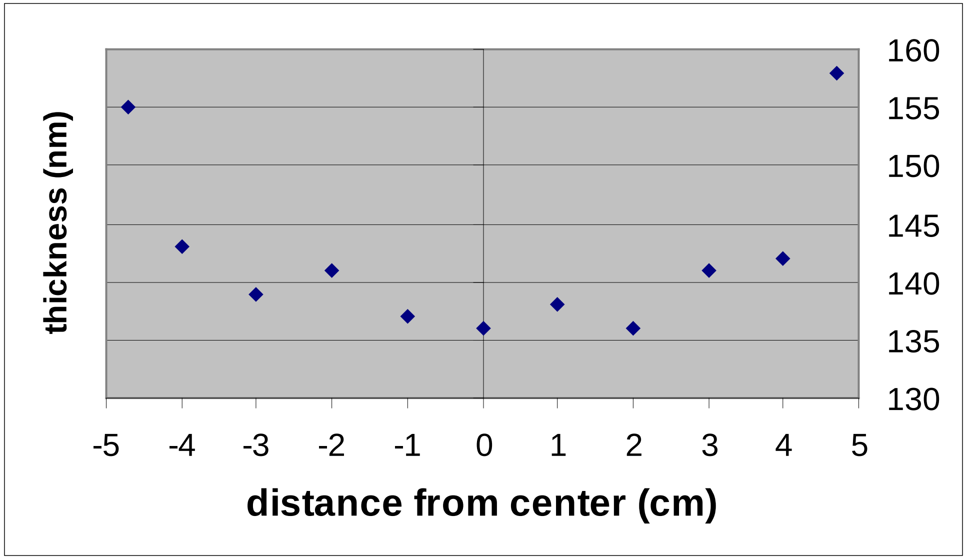
Achieved **<5% thickness variation** except near the wafer edge

Key pointes of electroless Plating:

- Also referred as chemical plating, no current source needed.
- Metal is plated out of solution by chemical reduction of metal ions.
- Substrate must be coated with catalyst, such as Pt, Pd, Ni…
- Intrinsically much more uniform than electroplating.

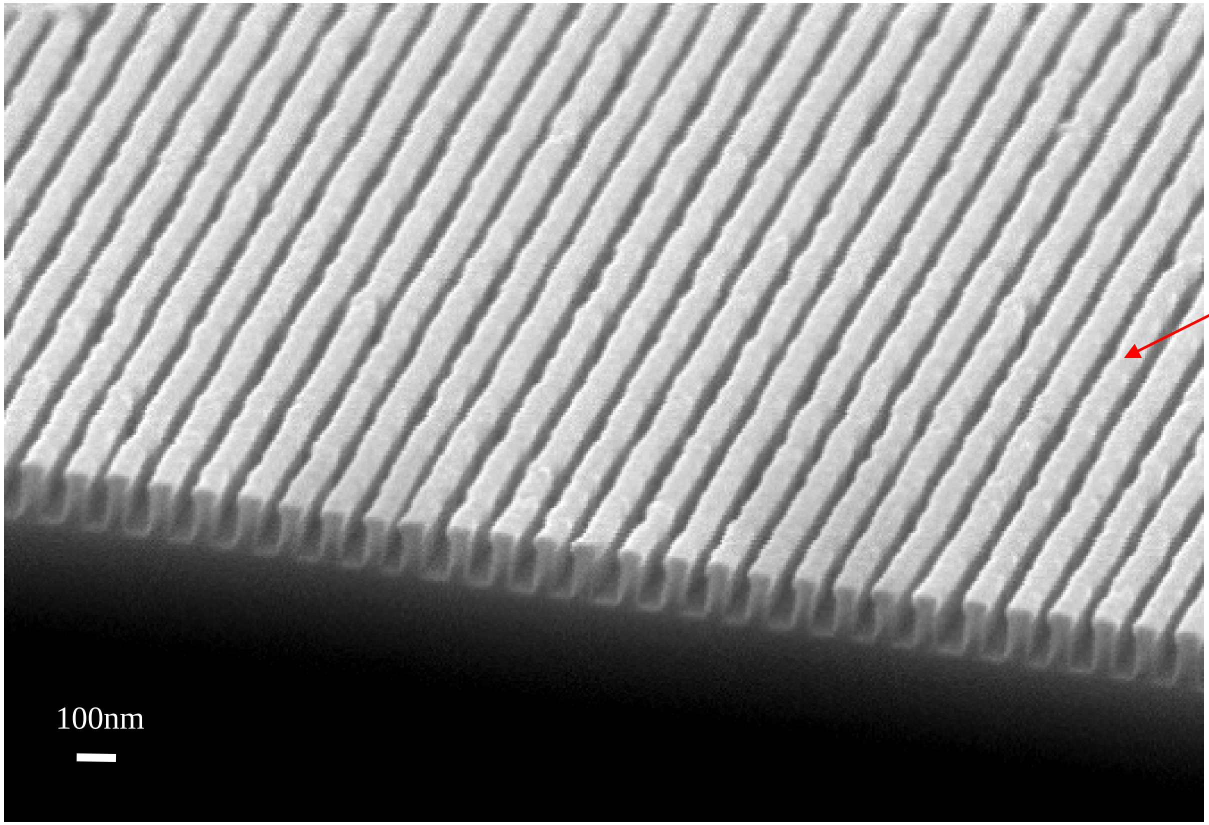
Deposition rate can be limited by:

- Chemical reaction rate (very uniform).
- Mass diffusion rate (wafer edge deposits faster).
- Or both.



(thickness is measured by AFM)

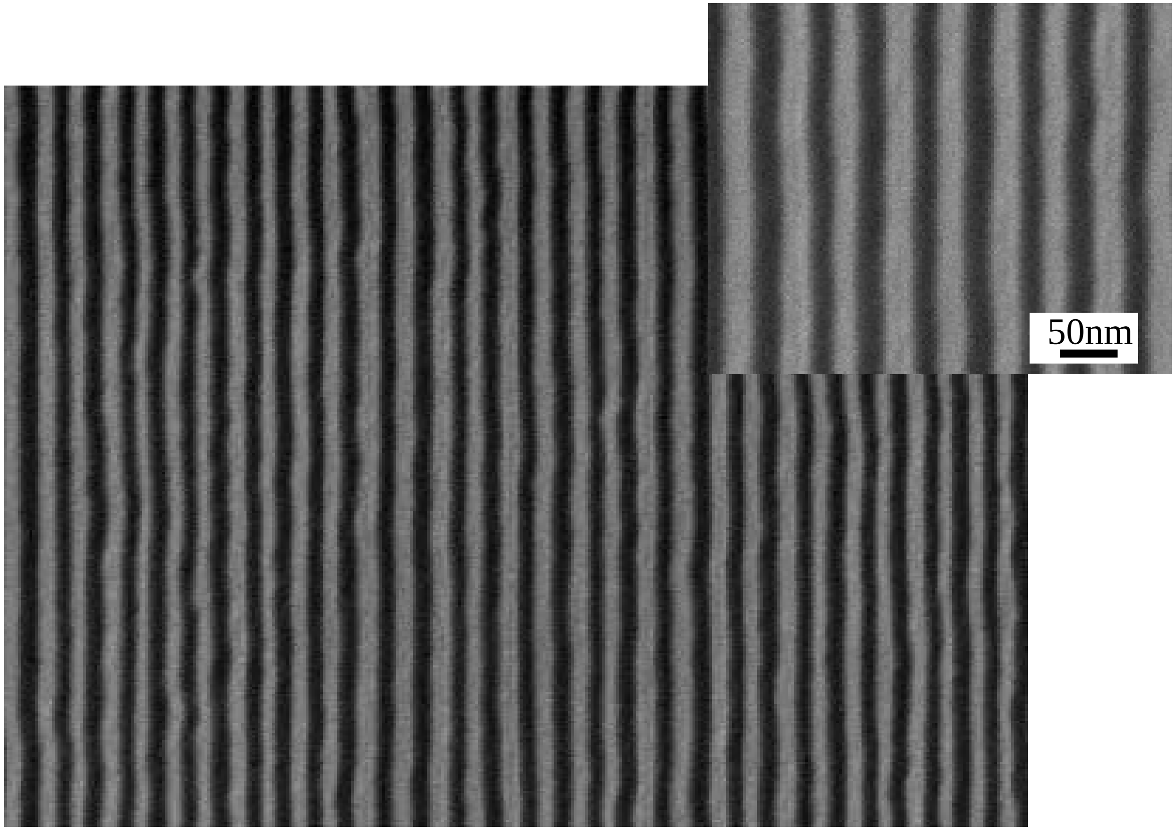
Resist Grating Imprinted by 100 nm Period SiO_2 Grating Mold



NIL resist

(residual resist on trench bottom has been removed by O_2 RIE)

Large Area 50 nm Period Grating in SiO_2 by Frequency Doubling from a 100 nm Period Grating

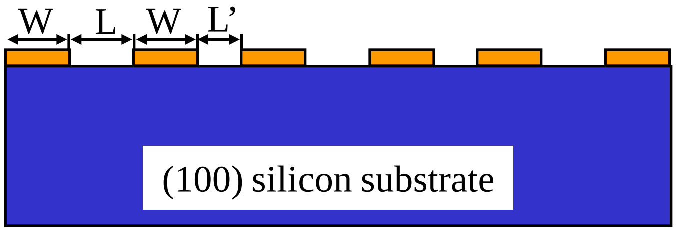


Factors Leading to Line/trench-width Variation and Non-Periodicity

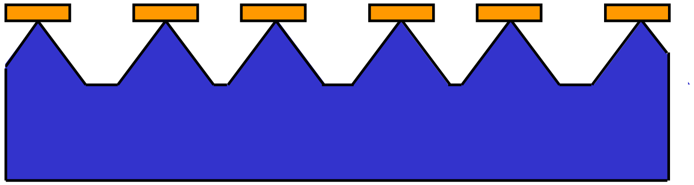
- Master grating line roughness and duty-cycle variation
- SEM line-width measurement error
- Plating thickness non-uniformity and film roughness
- Tapered RIE profile when etching narrow trench

Goal: <5nm non-periodicity for 100nm period grating,
<3nm non-periodicity for 50nm period grating.

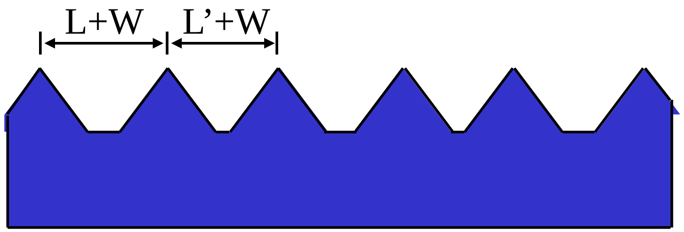
Process to Improve Periodicity of Frequency-Doubled Gratings with Equal Line-width but Unequal Trench-width (i.e. L≠L')



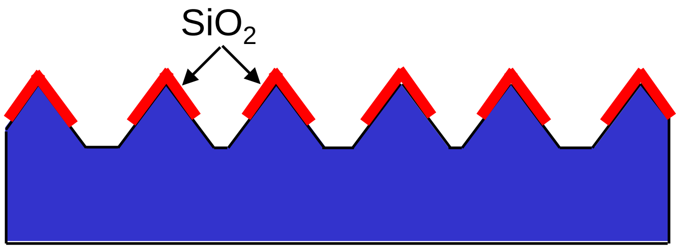
1. Si_3N_4 grating on (100) silicon wafer with grating along <110> crystal direction.



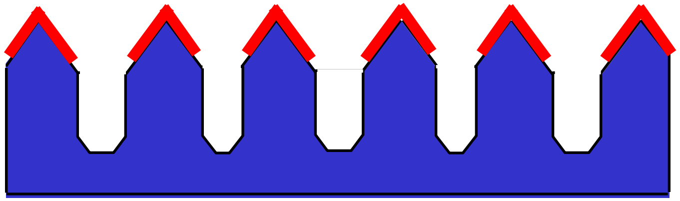
2. Anisotropic Si etch by KOH



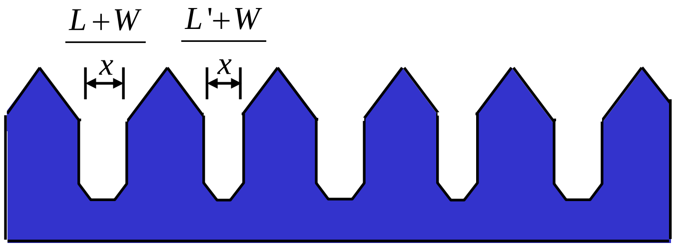
3. Etch Si_3N_4 (if it remained on Si after previous step).



4. Angle evaporate very thin SiO_2.



5. Chlorine RIE Si with oxide as mask.



6. Strip oxide in BOE.

e.g. trench-width difference $\Delta L \Rightarrow \Delta L_0/3$ for 35° angle evaporation

Summary for Grating

- Demonstrated a new low-cost spatial frequency doubling method that involves only NIL, electroless plating, metal liftoff, and RIE.

- Fabricated large area 50 nm period grating by doubling twice from a 200 nm period grating. This process could be scalable for even smaller period gratings.

- Combined with NIL, this method would find a number of applications in the field of magnetic recording media and random access memory, and optical, biological and electrical devices.

Outline

Introduction

- Limit of traditional thin film media
- Quantized magnetic disks – concept and advantage
- Patterned magnetic nanostructure – effects of size and shape

Large area nickel QMDs of 18 Gbits/in^2 (190 nm period)

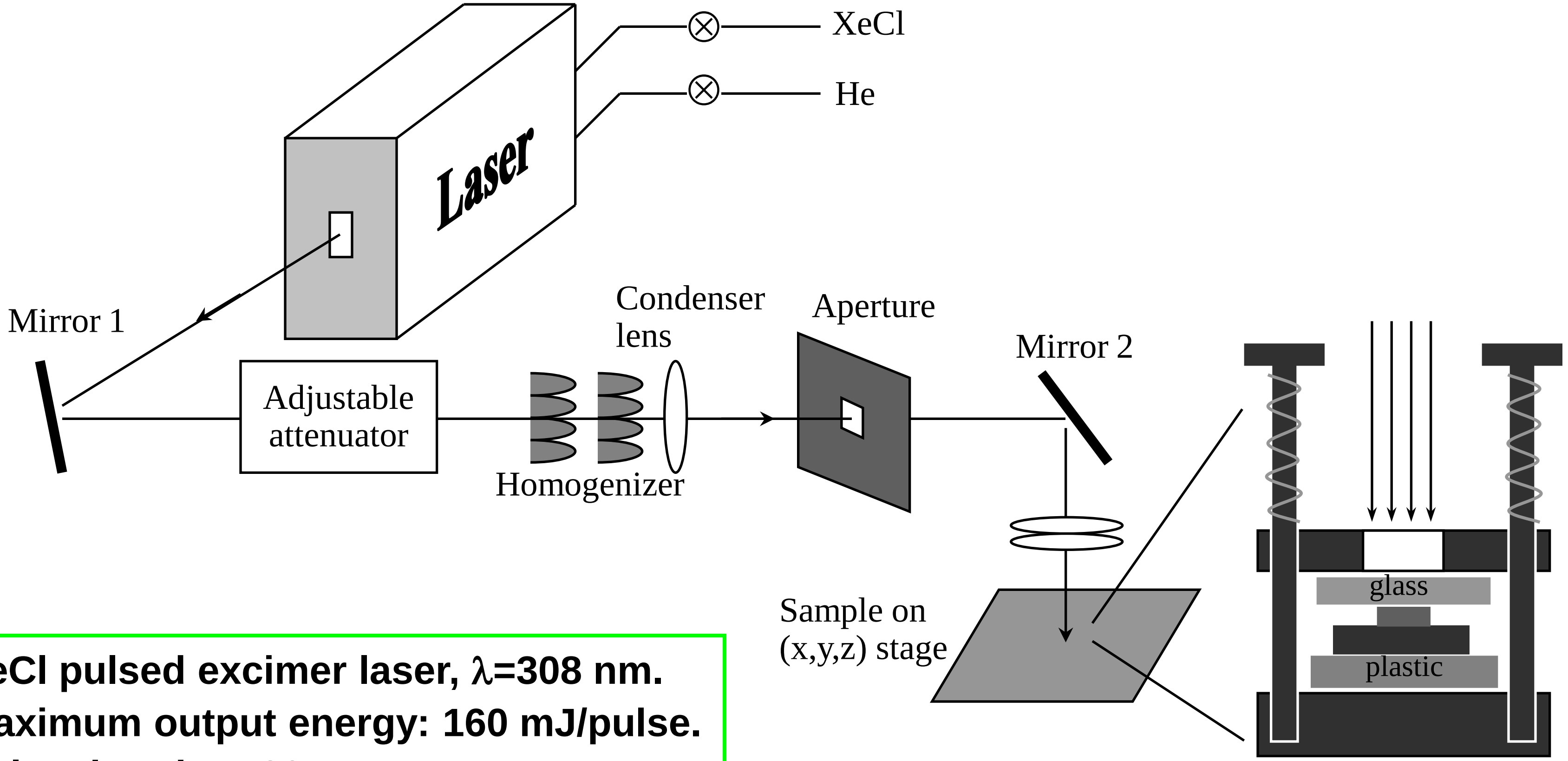
- Interference lithography for NIL mold fabrication
- Process steps
- Results – SEM, AFM & MFM images, and hysteresis
- Discussion – switching and interaction
- Writing

Fabrication of 100 and 50 nm period grating for much higher (15×) density

Laser-assisted rapid nanofabrication:

LADI of metals, planarization of metals and silicon, high-aspect ratio via hole filling, nano-transfer printing, nano-tip formation, and wafer bonding.

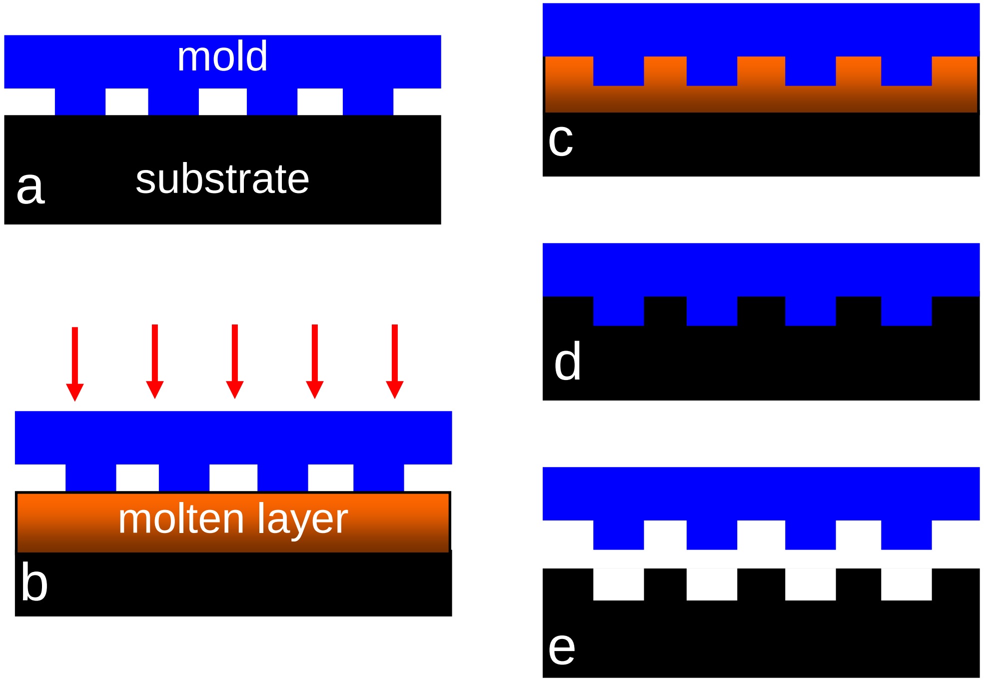
Experiment Setup



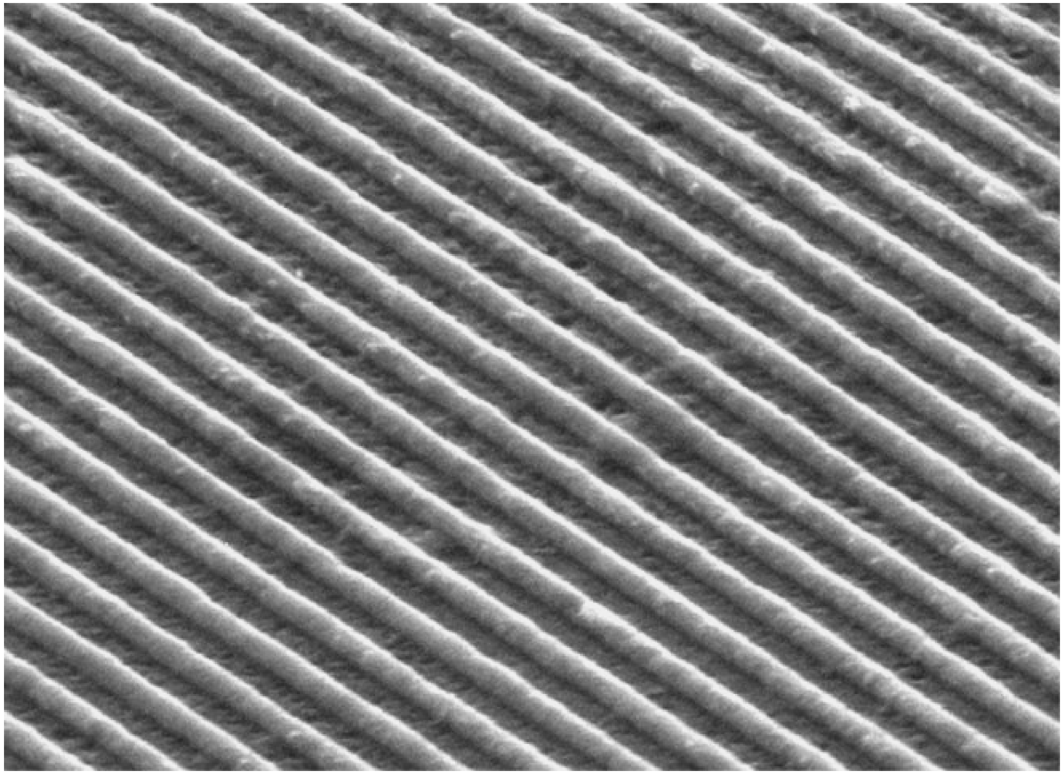
- XeCl pulsed excimer laser, λ=308 nm.
- Maximum output energy: 160 mJ/pulse.
- Pulse duration: 20 ns.

Laser-assisted Direct Imprint (LADI)

- **One-step patterning process**
  Replaces the steps of resist patterning, pattern transfer by etching, and resist removal all into one single step**.**
- **This step takes only order 100 ns!**
- **Minimal heating of the substrate**
  Mold and substrate can have different thermal expansion.
- **Metal can be readily patterned.**
- **Application: IC interconnect, flexible/durable NIL metal mold**

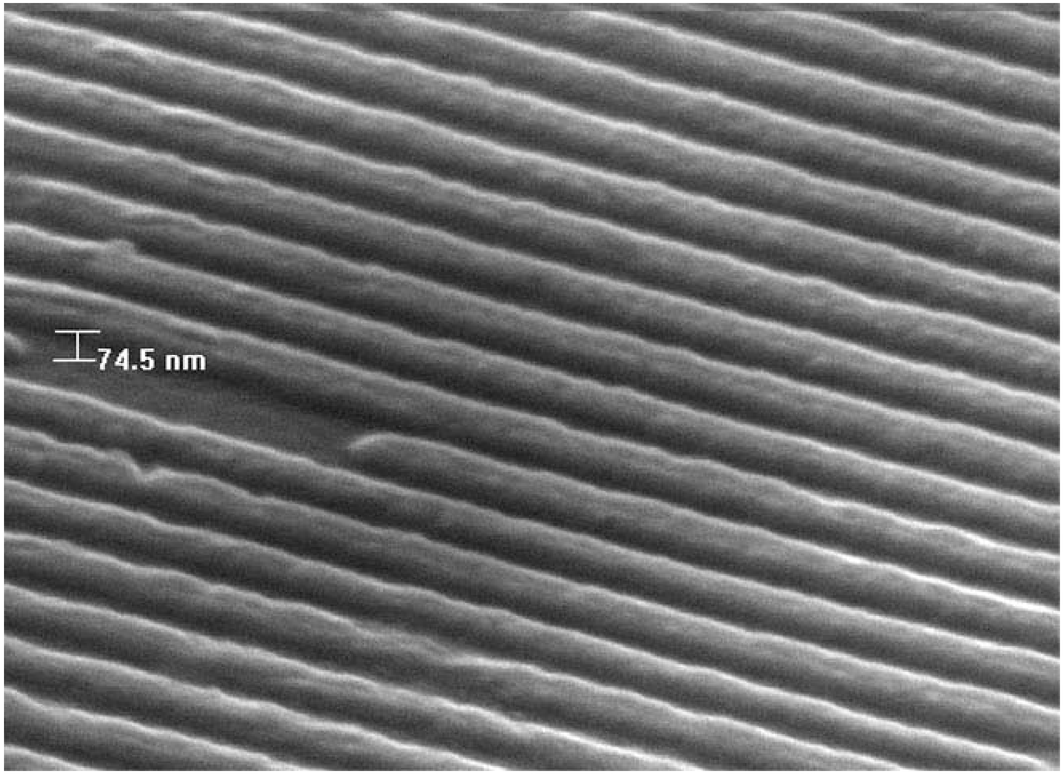


200 nm Period Grating Pattern by LADI: Cu



Pattern height: 100 nm. Laser fluence: 0.24 J/cm^2.
Line was rounded due to surface tension and volume shrinkage upon solidification.

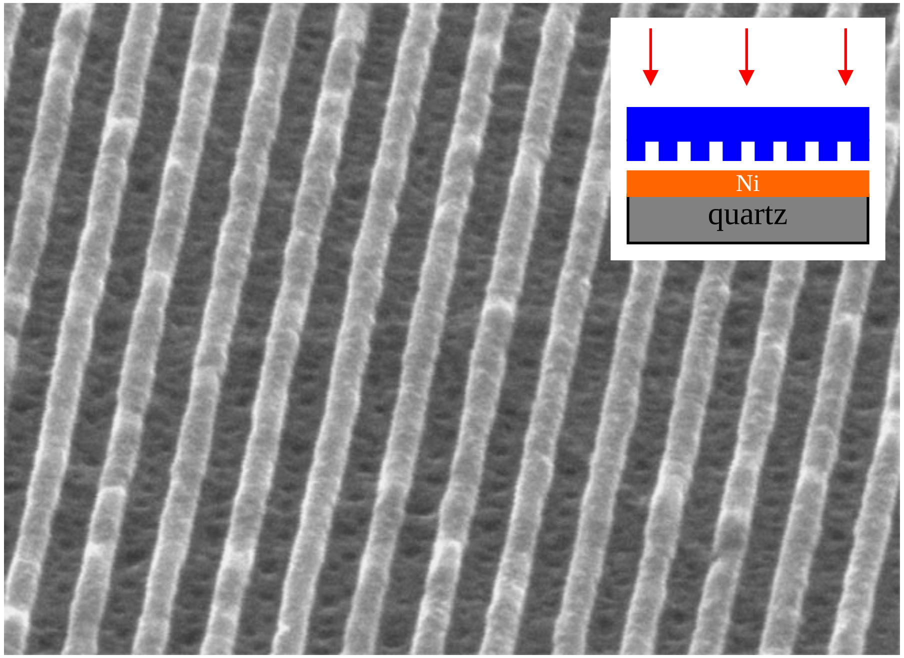
200 nm Period Grating Pattern by LADI: Al



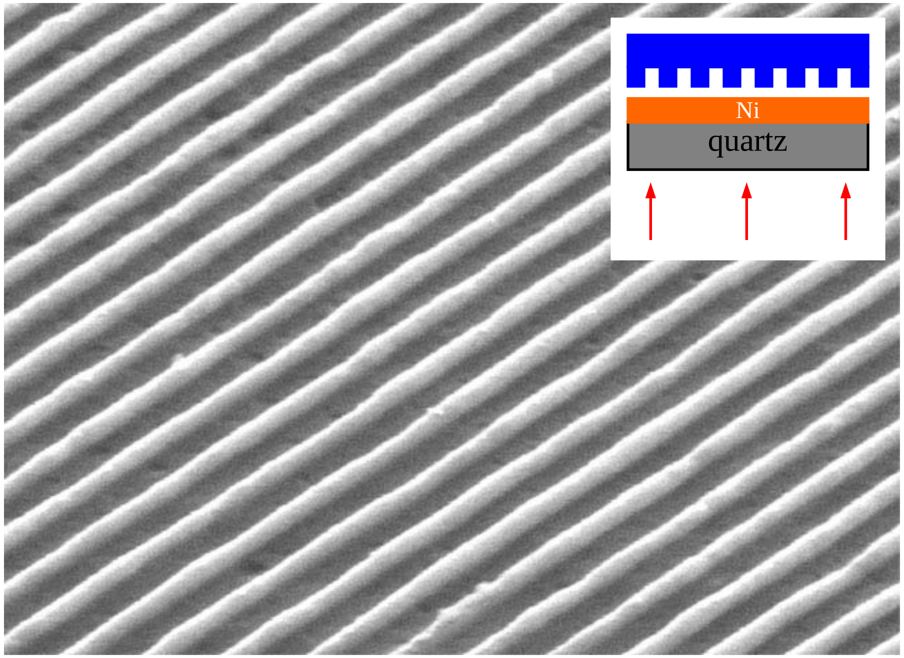
- Laser fluence: 0.22 J/cm^2.
- The lines are less smooth due to the hard skin of Al oxide.
- But the trench bottom is smooth: quartz mold not melted while melting Al.

200 nm Period Grating Pattern by LADI: Ni

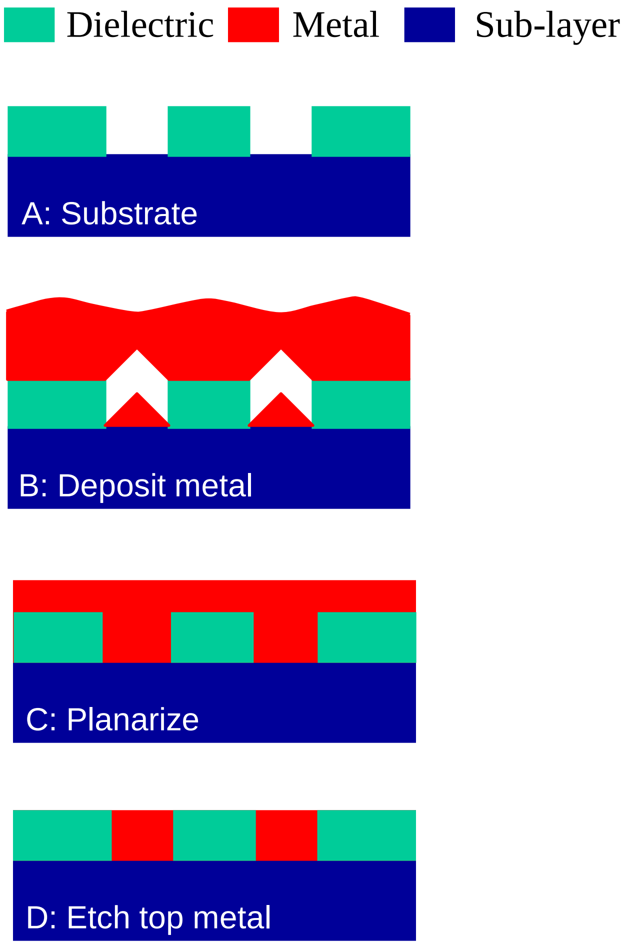
Front side illumination, 0.41 J/cm^2



Back side illumination, 0.60 J/cm^2



Laser-assisted Planarization



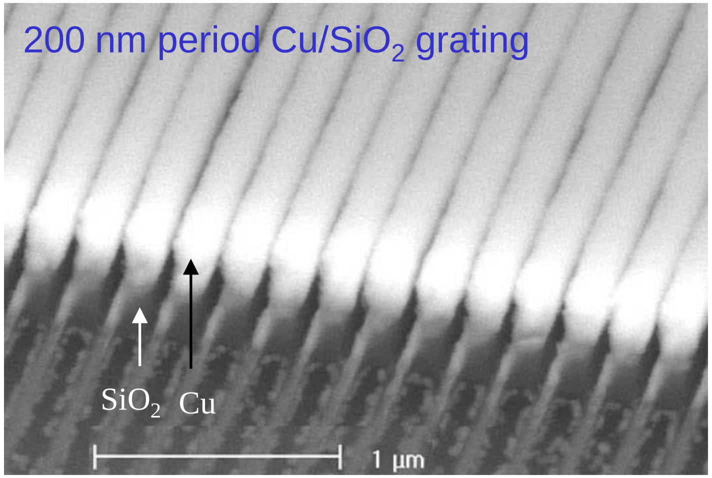
- **Flatten/smoothen surface momentarily.**

- **Fill underneath voids at the same time.**
  Unlike CMP, it can solve the problem
  of poor film step-coverage.

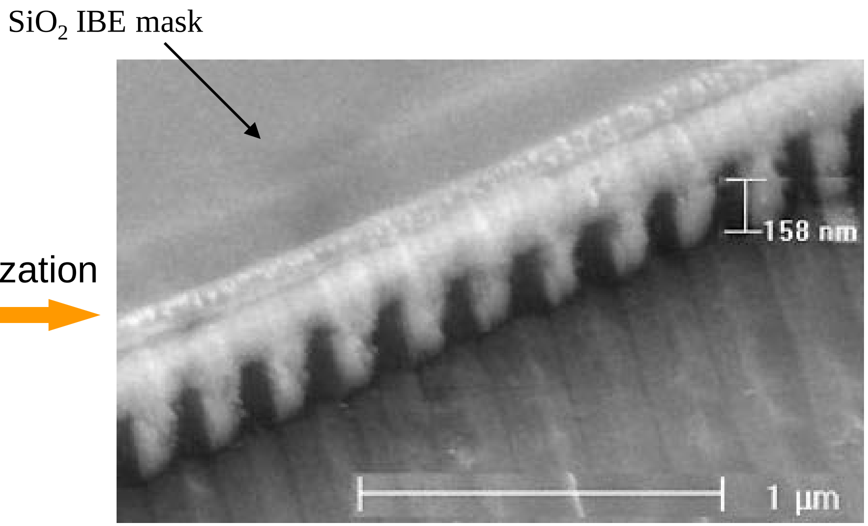
- **Both semiconductor and metal can be readily patterned.**

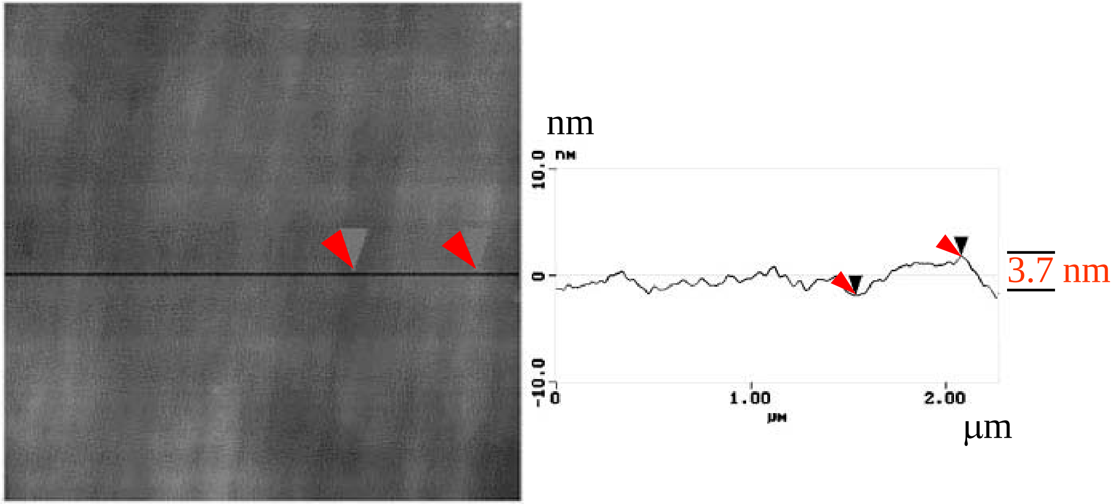
- **Application: IC interconnect.**

Laser-assisted Planarization of 200 nm-Period Cu Grating



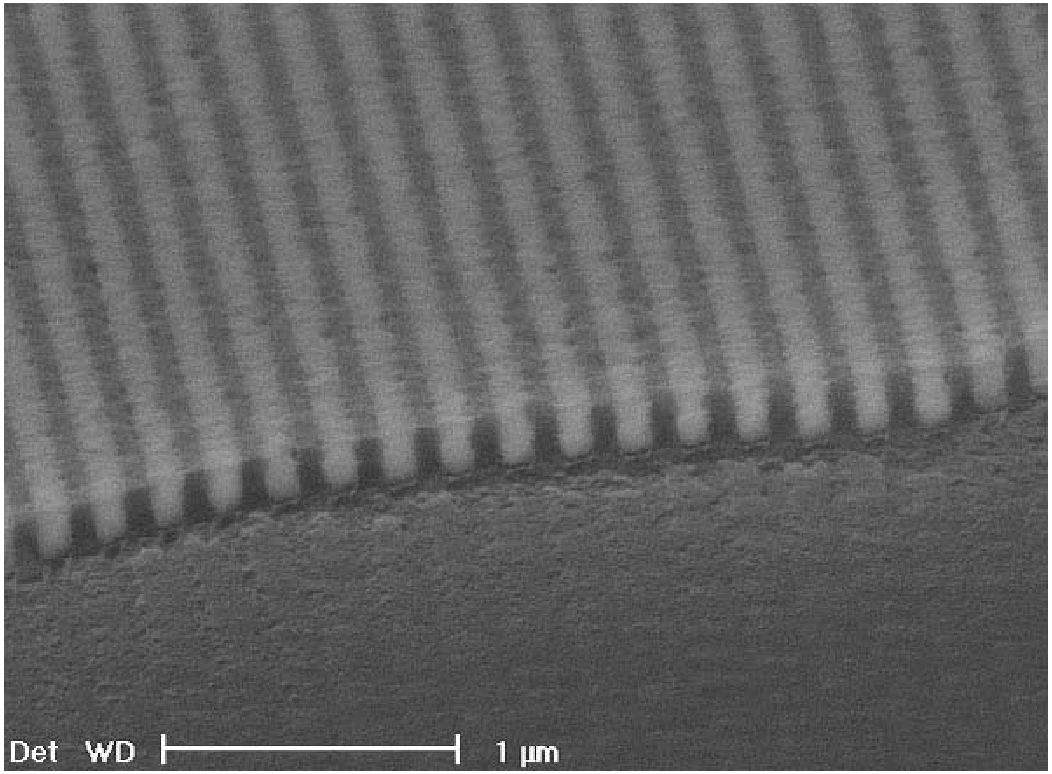
Planarization





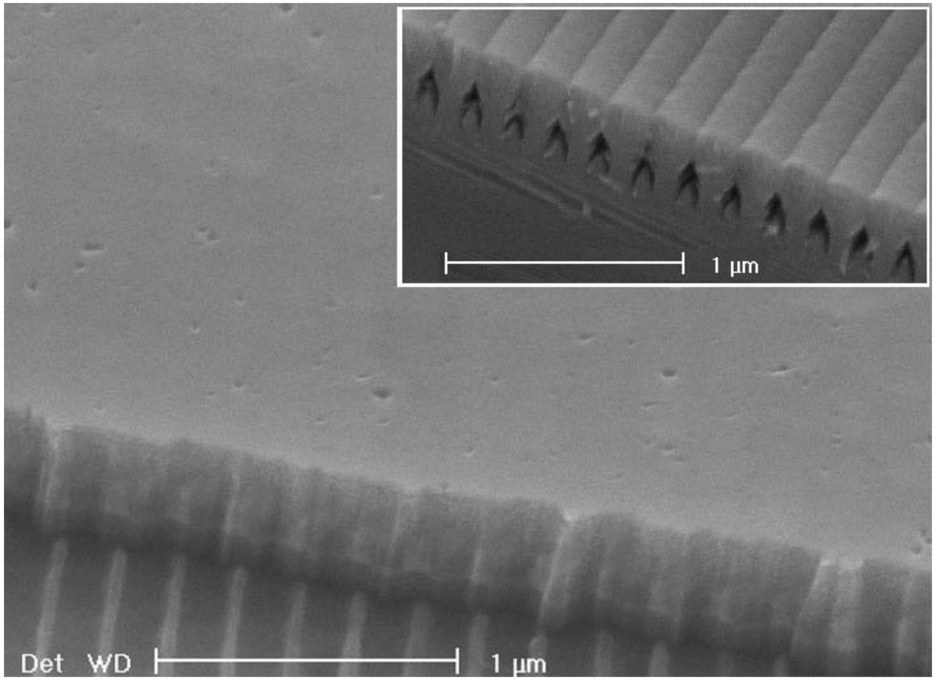
AFM: 3.7 nm surface fluctuation

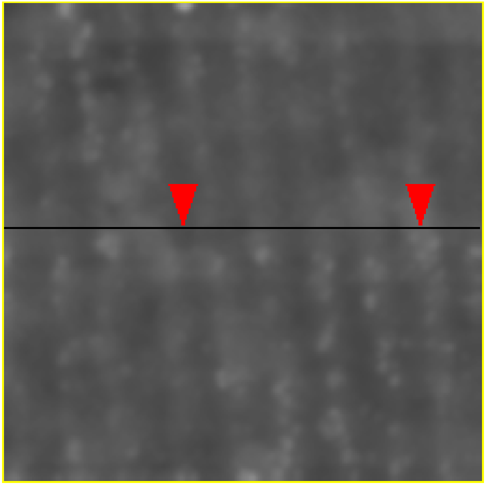
100 nm-Wide Cu Wires Embedded in SiO_2 by Etching Cu on Top

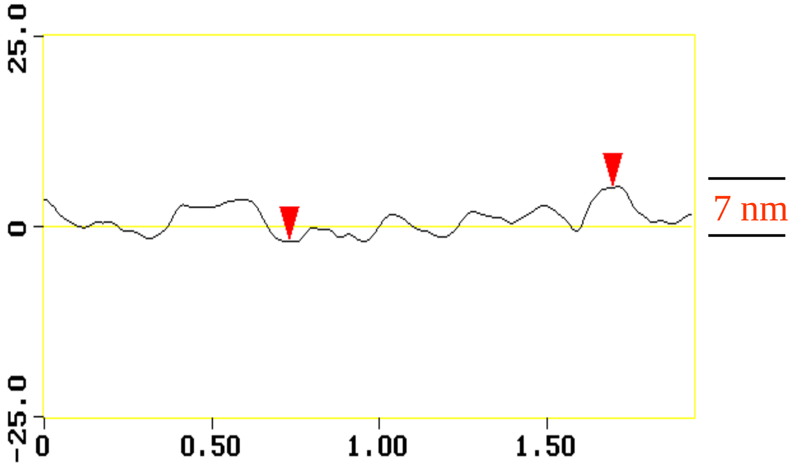


Voids underneath were all filled with Cu

Laser-assisted Planarization of 200 nm-Period Si Grating



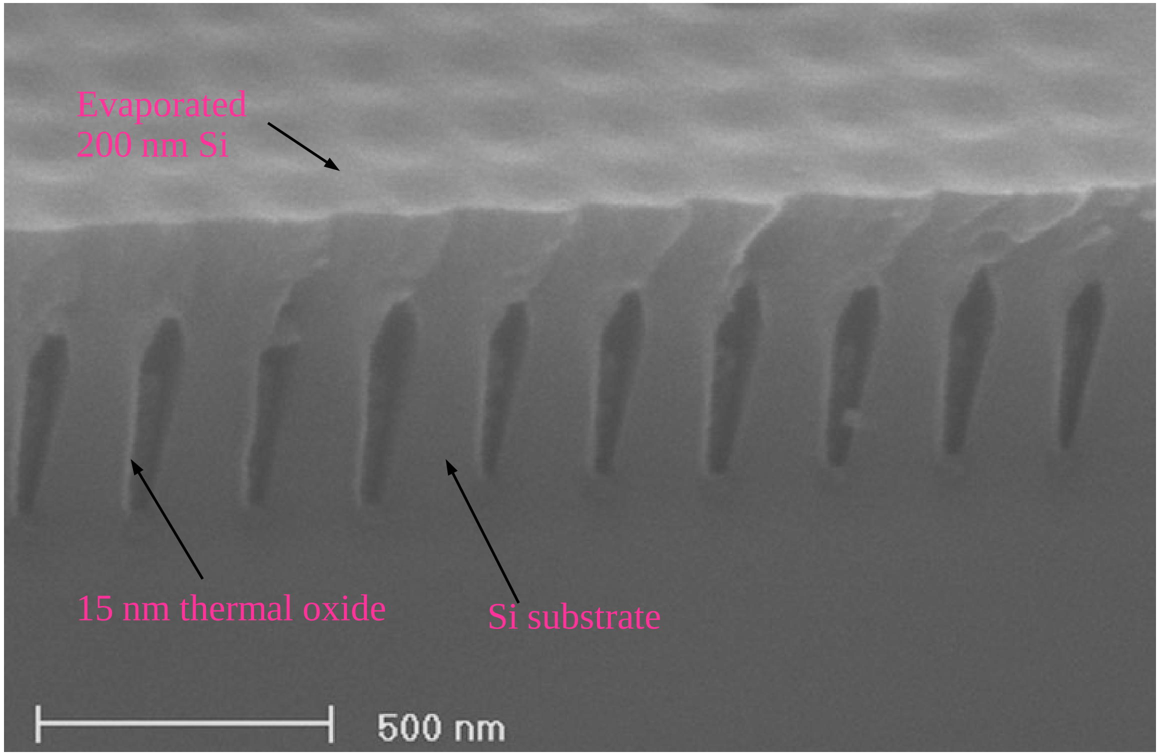




Surface fluctuation: 7 nm.
Not as smooth due to Si oxidization.

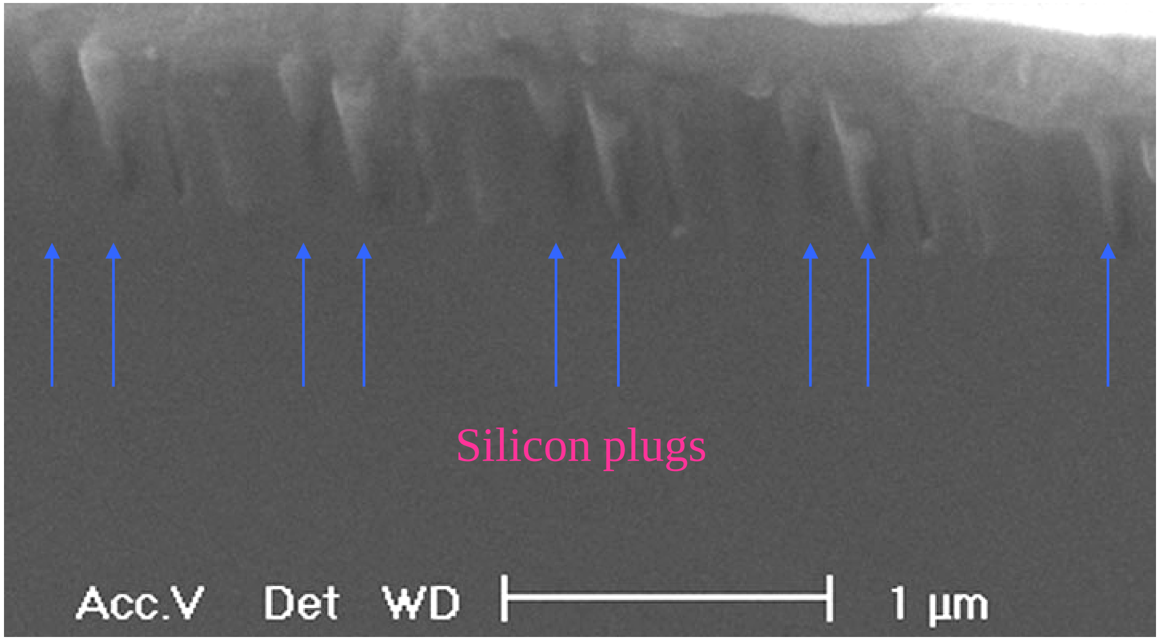
Laser-assisted Via-hole Filling: *Before*

With sufficient pressure and melting time, it can fill vias which are too small/deep for Tungsten CVD process.



Hole: 100 nm by 500 nm, aspect ratio 5:1.

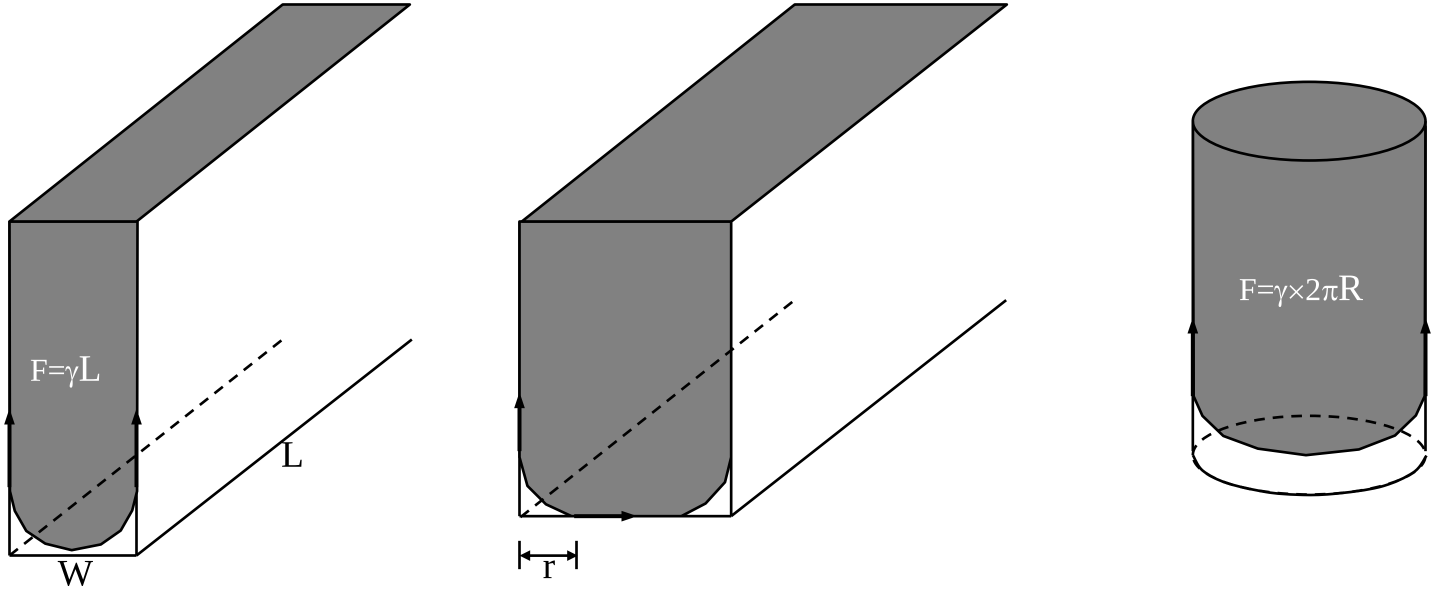
Laser-assisted Via-hole Filling: *After*



Most holes are filled with Si plugs.

Longer pulse duration τ will increase heat penetration depth, thus deeper melting and deeper hole filling. ($L \propto \tau^{0.5}$)

Discussion: how much pressure needed



$$P = \frac{2\gamma L}{WL} = \frac{2\gamma}{W}$$

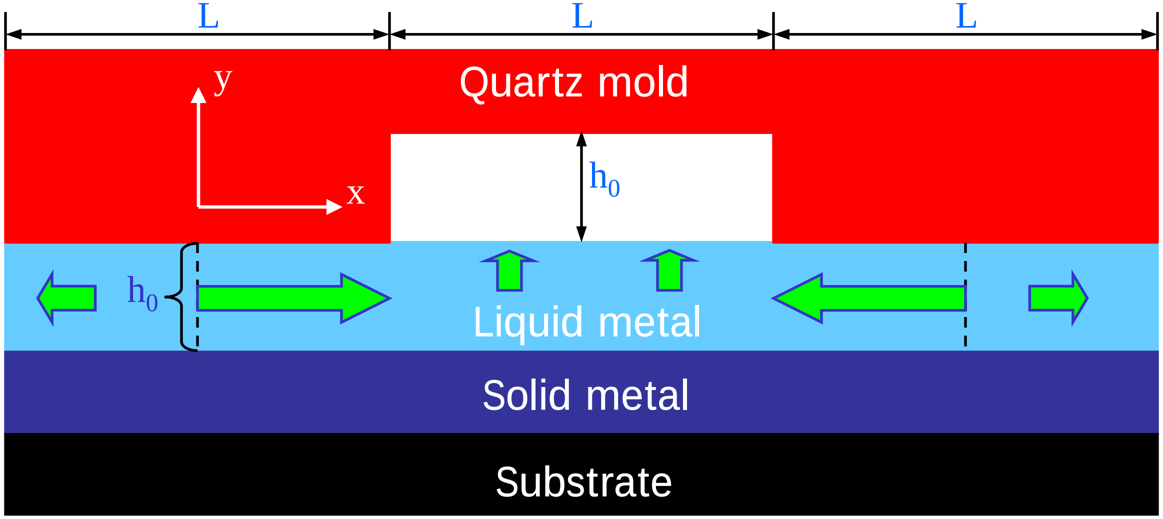
$$P = \frac{2\gamma L \cos 45^o}{\sqrt{2}rL} = \frac{\gamma}{r}$$

$$P = \frac{\gamma \times 2\pi R}{\pi R^2} = \frac{2\gamma}{R}$$

- **Pressure ∝ surface tension / dimension.**
- **Order 10^2 atm is needed for 100 nm feature size.**
- **Considerably smaller pressure is possible by pre-coating a wetting lining layer.**

Discussion: how big feature can be patterned

(how far the liquid can flow before it freezes)



$$L = \frac{2h_0}{3}\sqrt{\frac{p\tau}{\mu}}$$

Inertial force is ignored.

p: pressure.

τ: melting time.

μ: viscosity.

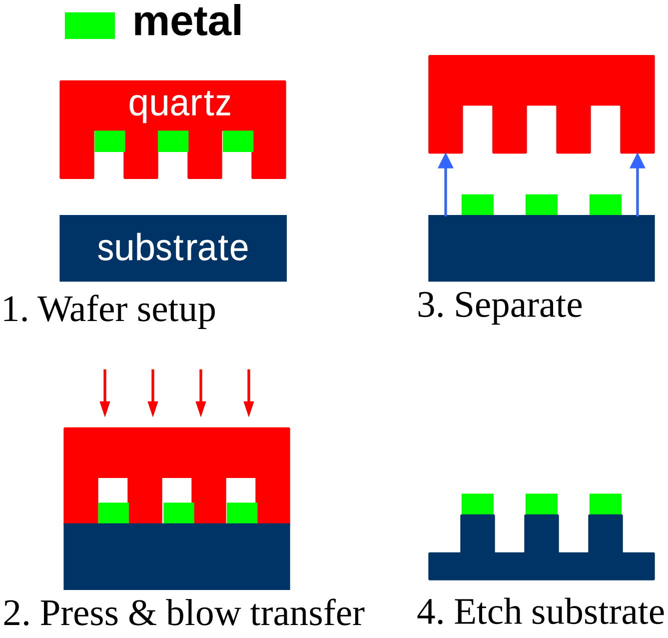
Material	L	**Assume:** P=400 atm τ=100 ns h_0=200 nm
Cu	4.9 μm	
Ni	4.2 μm	
Si	12.0 μm	

Experiment: 17 μm Si has been patterned, but failed for several tens of μm.

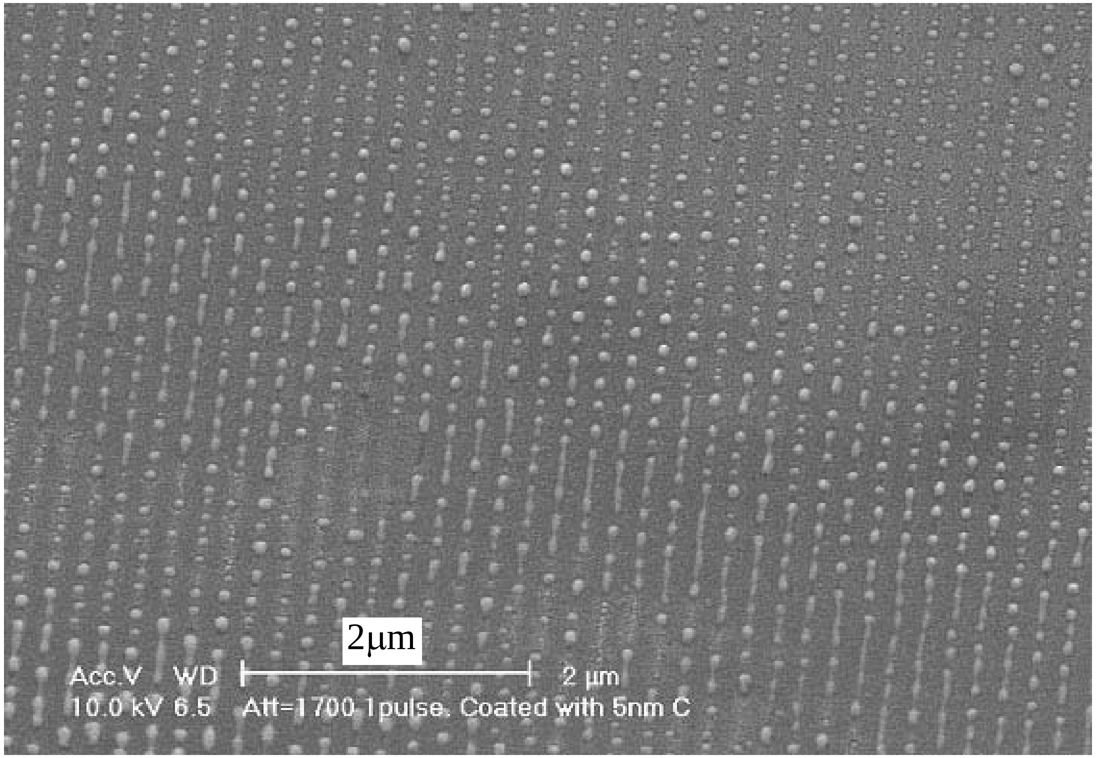
Impact: pattern density averaged over area ~L^2 should be uniform.

Laser-induced Nanotransfer Printing (LI-nTP)

- **Dry process.**
  No solvent or liquid chemicals, suitable for organic semiconductors.
- **Ultra-fast.**
- **Simpler setup than most other 'soft lithographies'.**
- **Can transfer metals, semiconductors, and light-absorbing polymers.**
- **Need less pressure than e.g. 'cold welding'.**
- **Transferred material may adhere poorly to the substrate, then used as etching mask only.**
- **Surface tension may cause droplet formation.**



200 nm-Period Cu Grating Transferred to Quartz Substrate by LI-nTP in Air



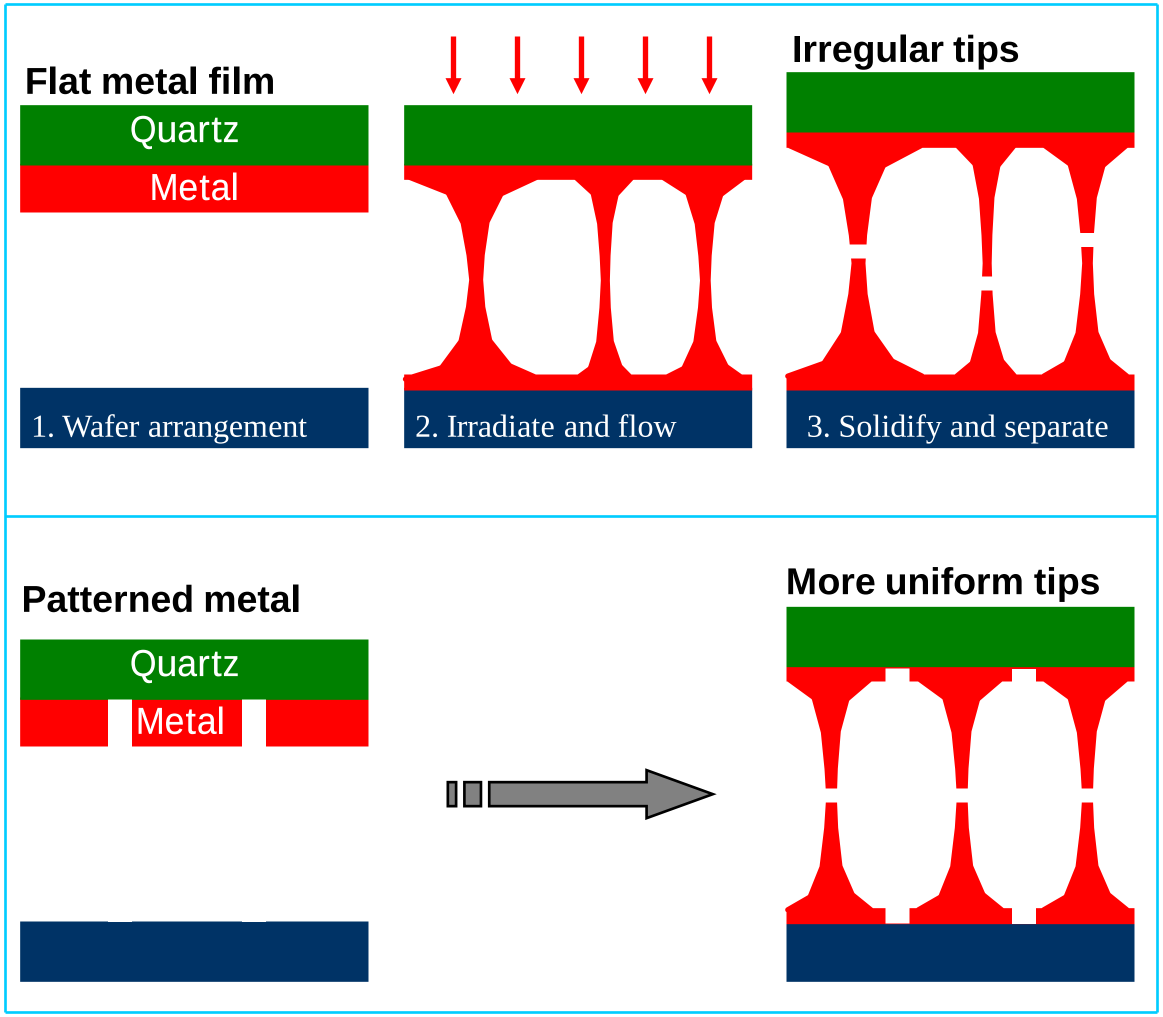
Laser fluence 1.9 J/cm^2.

Peak intensity 96 MW/cm^2.

Possible route to eliminate droplet formation: solid phase transfer

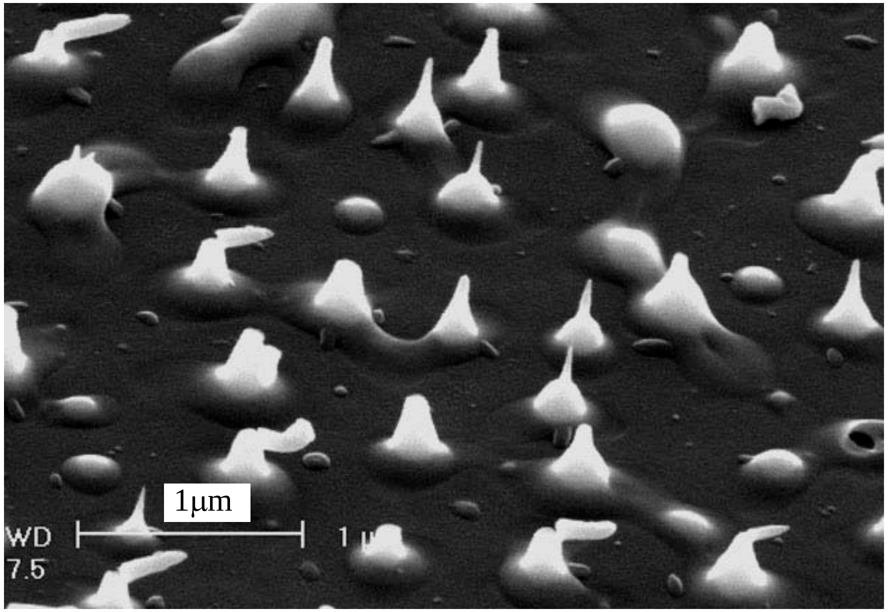
Laser-induced Nano-tip Formation

- Liquid metal is propelled to the substrate by boiling pressure at the quartz/metal interface.
- Liquid bridge is broken by surface tension before separation.
- Sharp tips with high aspect ratio could be achieved by optimizing the process.
- Application: AFM/MFM tips, field-emission flat panel display.

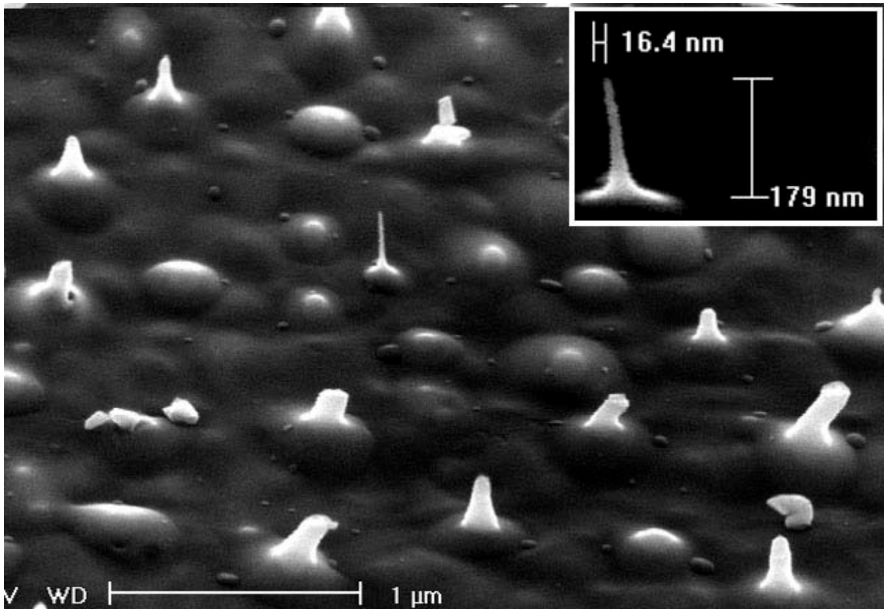


Cr nano-tips

Cr tips formed on Si/SiO_2 substrate.



Cr tips formed on quartz wafer that was originally coated with 20 nm Cr.

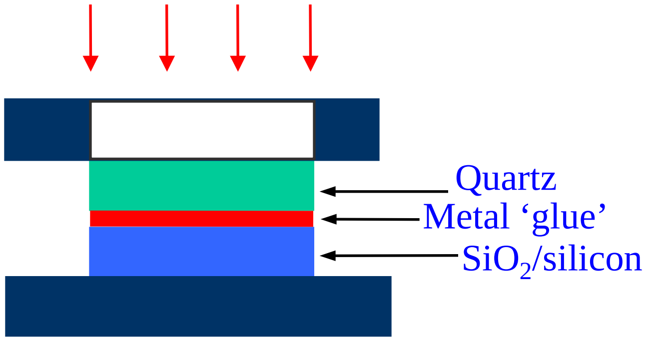


The finest tip has an apex diameter 10 nm and aspect-ratio 1:18.

0.45 J/cm^2, 1 pulse

Laser-assisted Wafer Bonding

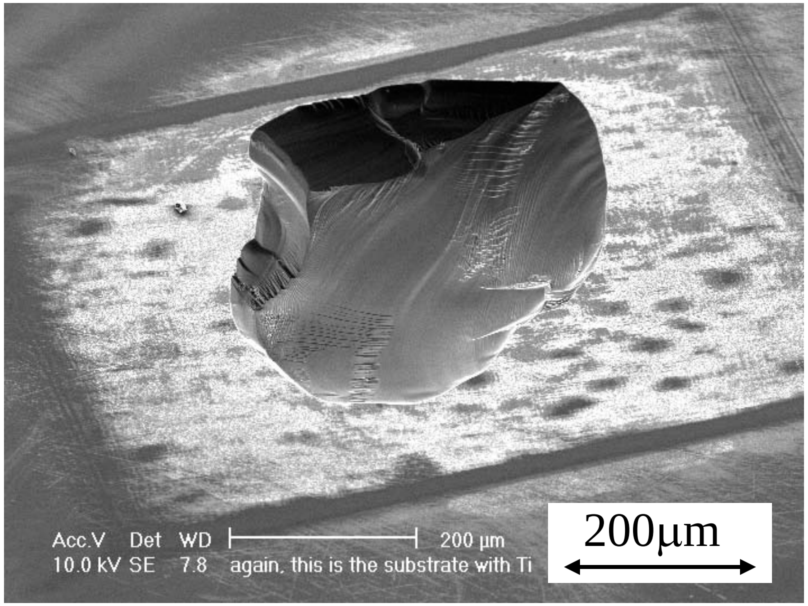
- **Fast, nanosecond.**
- **Bonding is strong.**
- **Negligible bulk wafer heating.**
  Two wafers can have different thermal expansion.
- **No need of ultra-cleanness and atomic smooth surface.** Many other bonding methods do.
- **Bonded wafers can stand at elevated temperature.**
- **Capable of selective bonding, leave fragile active device untouched.**
- **At least one wafer need to be transparent.**
- **Need higher pressure.**
- **Throughput limited by laser beam size.**



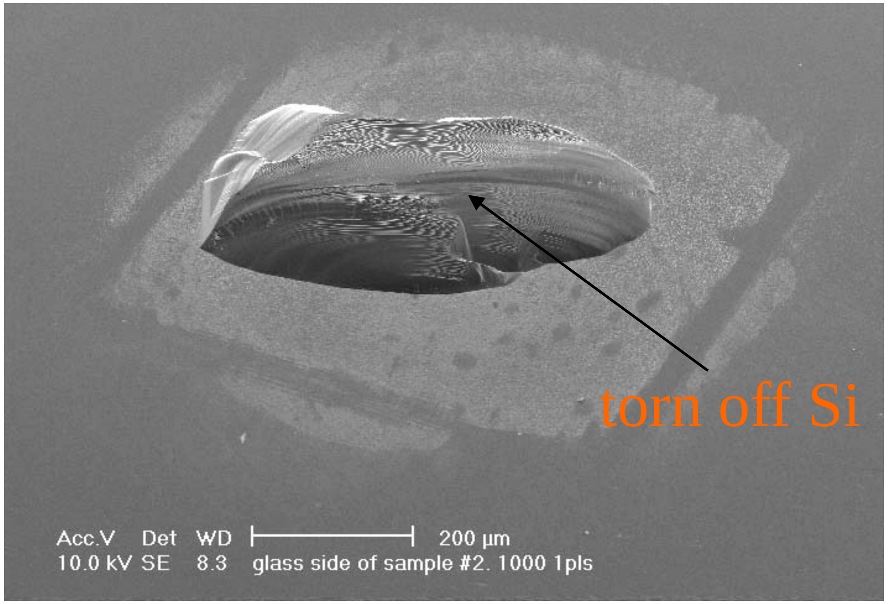
- Metals that oxidize easily can be used as glue, such as Cr, Ti, Mo, Ta…
- When the metal is melted by a laser under pressure, the un-oxidized atoms below the oxidized surface layer could rise to the surface and bond to the oxygen atoms on the bonding partner.

Laser Assisted Wafer Bonding by 20 nm Ti

SiO_2/Si substrate



Quartz bonding partner

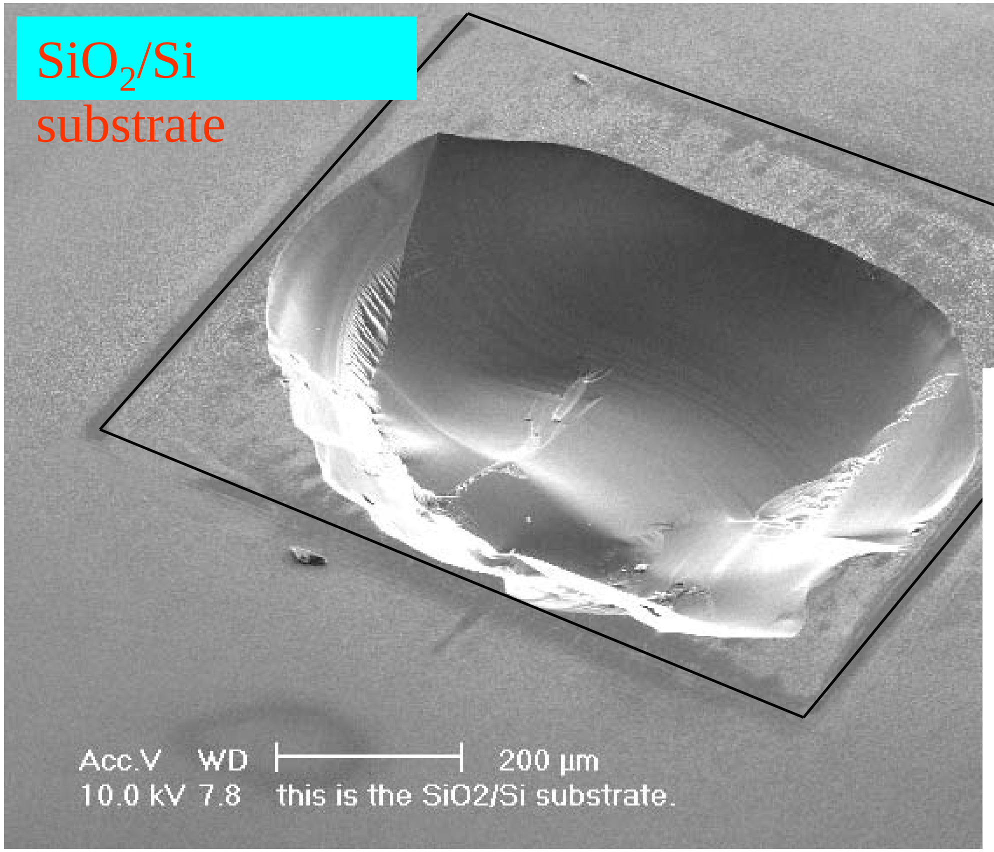


torn off Si

- The “glue” metal can be originally evaporated on both wafers.
- Outside the big torn-off area was also bonded. Many micro-torn-off patches, indicating smaller bonding force.

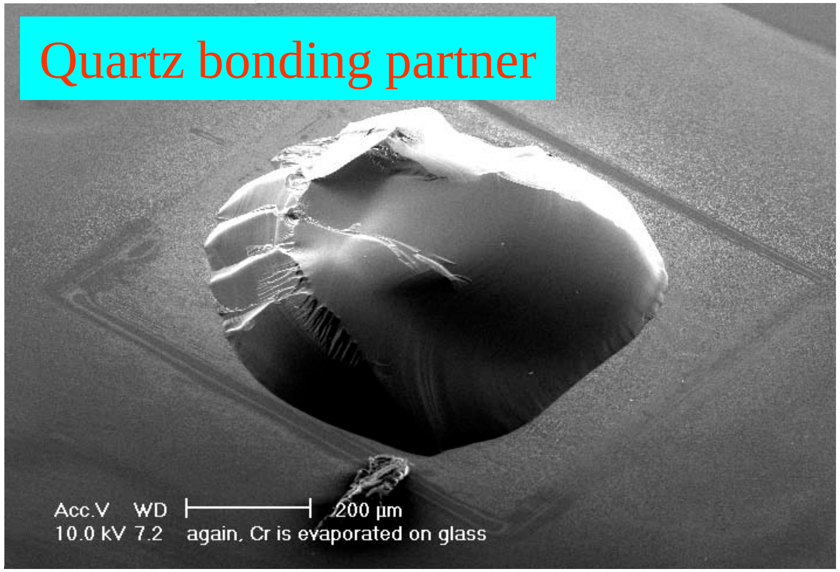
0.38 J/cm^2, 1 pulse

Laser Assisted Wafer Bonding by 20 nm Cr Originally Evaporated on the Quartz Substrate



SiO_2/Si substrate

Area directly under 0.8 mm mold square



Quartz bonding partner

0.45 J/cm^2, 1 pulse

Summary for Laser-assisted Nanofabrication

- Fabricated 200 nm-period Cu, Ni and Al gratings over 1 mm^2 area using LADI process (takes ~100 ns).
- Planarized and smoothed Cu and Si surfaces by laser melting under pressure, which also squeezed the molten film to completely fill the voids underneath.
- Filled 100 nm-wide and 500 nm-deep via-holes with Si plugs using a similar process.
- Deposited sub-100 nm wide Cu lines onto a substrate using laser-induced nanotransfer printing.
- Formed Cr tips with apex diameter as small as 10 nm and aspect ratio up to 18:1 by boiling and vapor-propelling the molten Cr from its support toward a receiving substrate, and solidifying before the end of the mass transfer.
- Bonded quartz and silicon wafers using a pulsed laser to melt or boil a metal ‘glue’.

Acknowledgement

- Professor Stephen Y. Chou for guidance through the past six years.
- Haixiong Ge and Lei Chen for developing NIL resist and mold treatment.
- Zhaoning Yu and Wei Wu for interference lithography and grating mold fabrication.
- Xiaoyun Sun and Wei Wu for assistance in QMD template fabrication.
- Chris Keimel for showing me laser-assisted nanofabrication.