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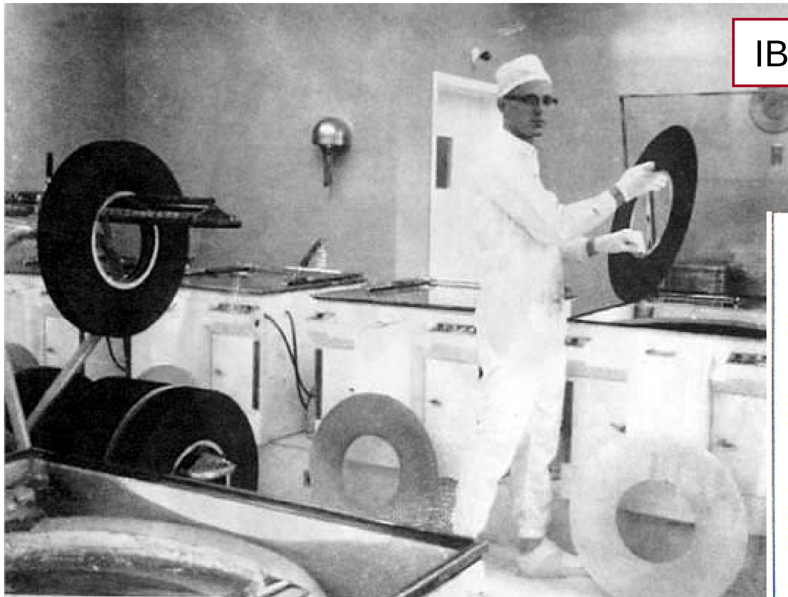
Nanofabrication for Patterned Magnetic Media

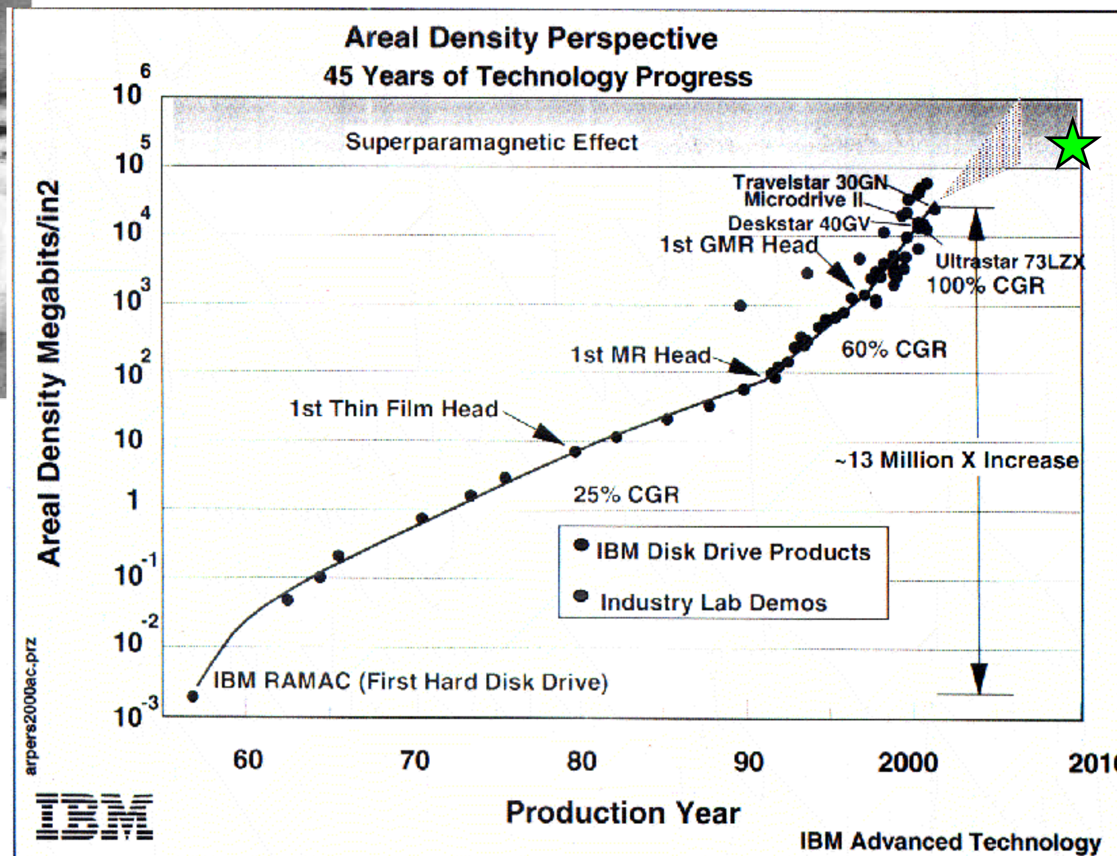
Dan Kercher

San Jose Research Center

Hitachi Global Storage Technologies



IBM Disk Fabrication 1956



- **Areal storage density has been the driving factor for the hard drive industry**
- **Since 1956 desity storage has increased 150 million times**
- **Hitachi purchased the IBM HDD business in 2003**
  - Hitachi Global Storage Technologies

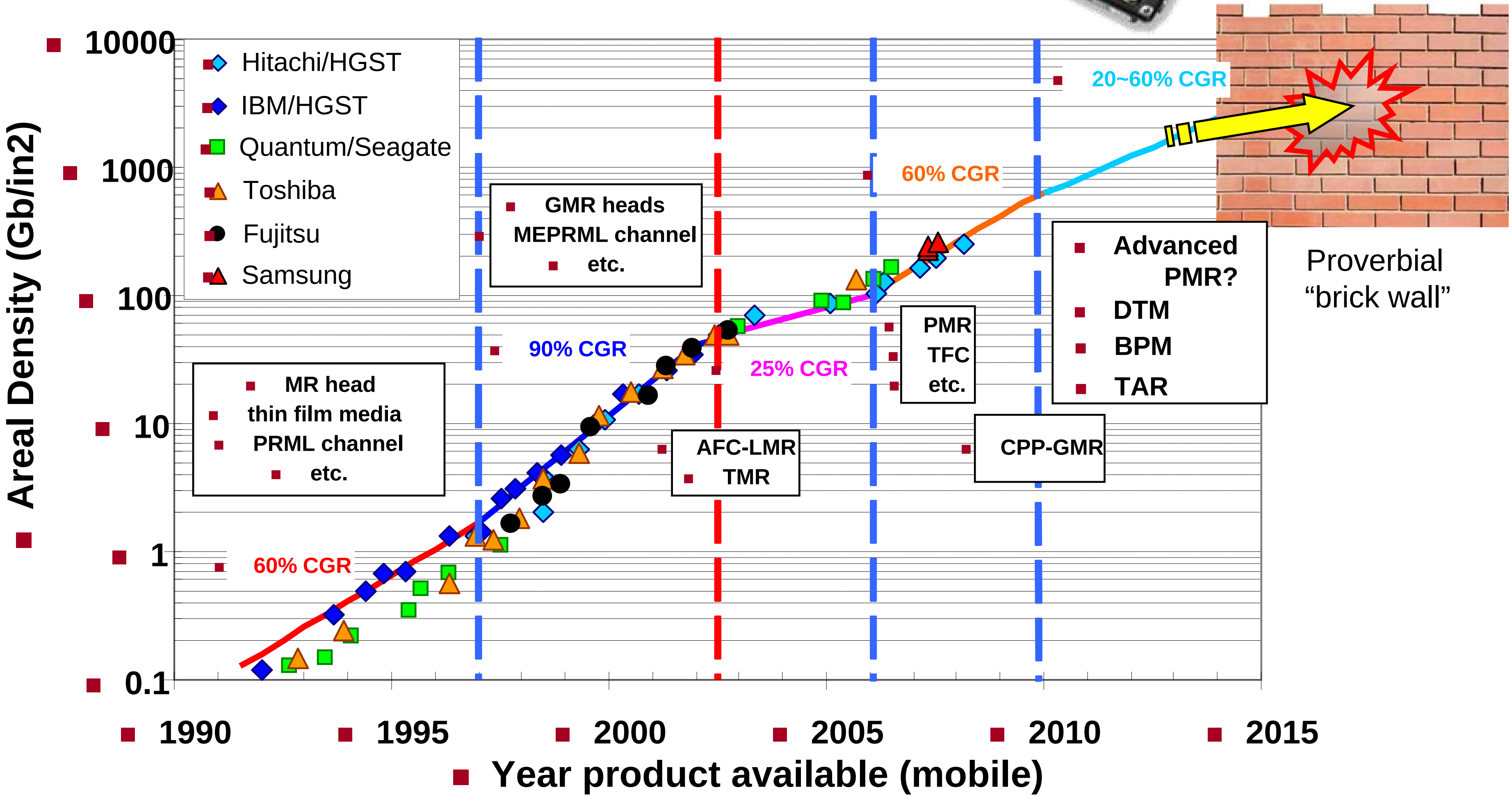
Hard Drives Yesterday and Today

- In 1956, the IBM 350 could store 5MB of data
  - Enough room for about two MP3 files
- HGST's latest 7mm thick Z-series drive holds 320GB

The Areal Density Trend

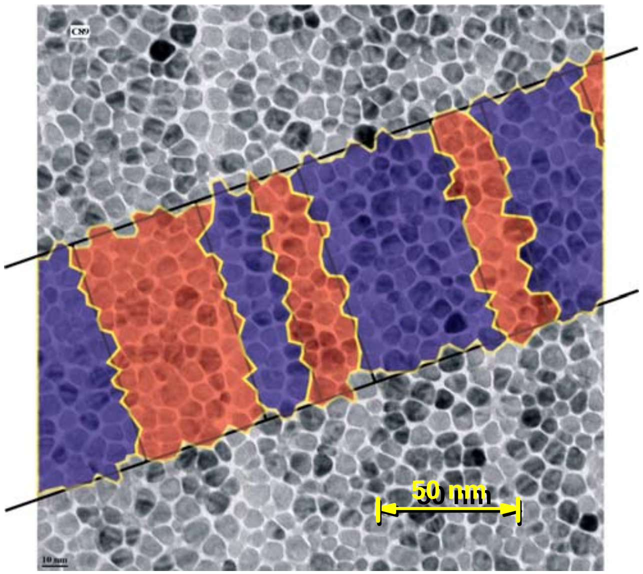
After 50 years of continuous progress…

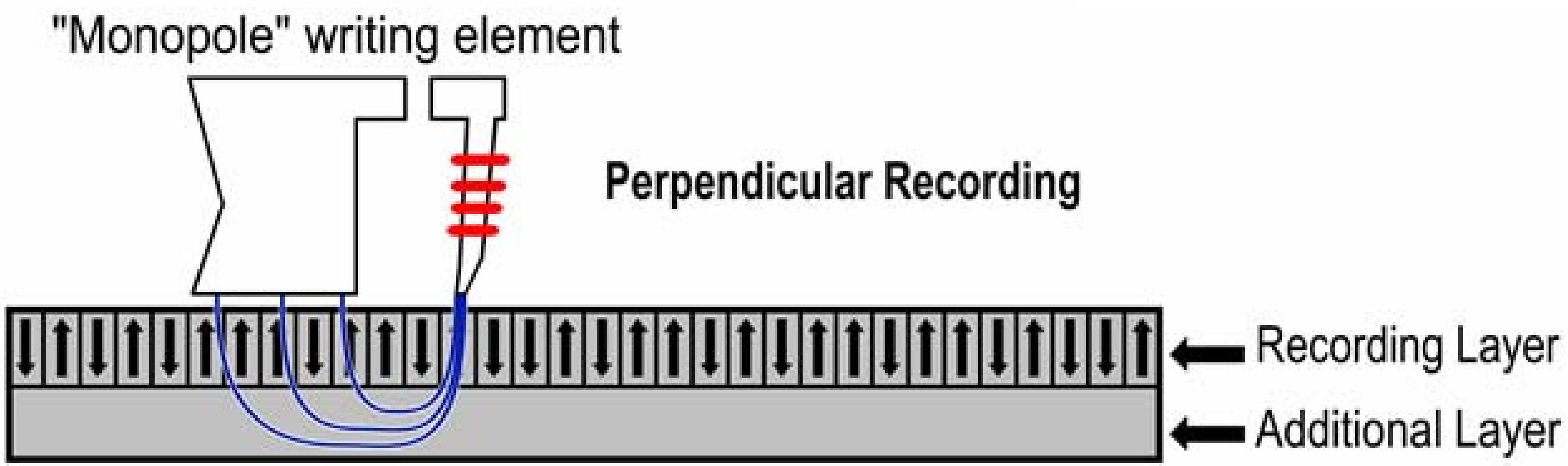
…will we hit the brick wall?



Perpendicular Media for Data Storage

- **Magnetic data storage relies on a thin film of granular magnetic media**
- **A read/write head flies above the spinning hard disk**
- **A small coil and pole tip generate a strong field to magnetize the media up or down**
- **A GMR sensor is used to read back the magnetic signal**





Problems with Granular Magnetic Media

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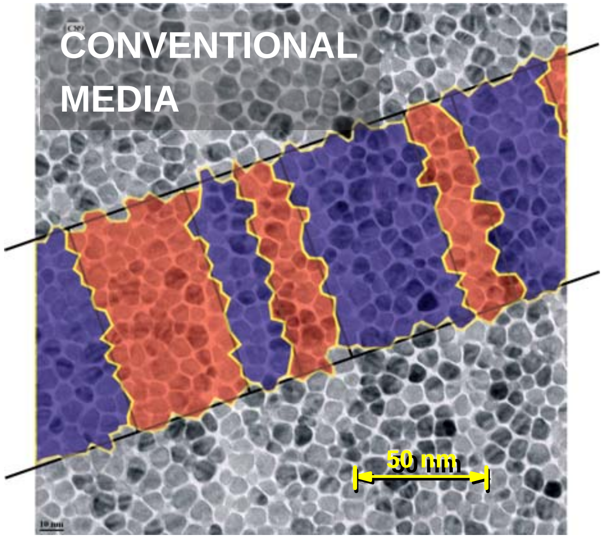
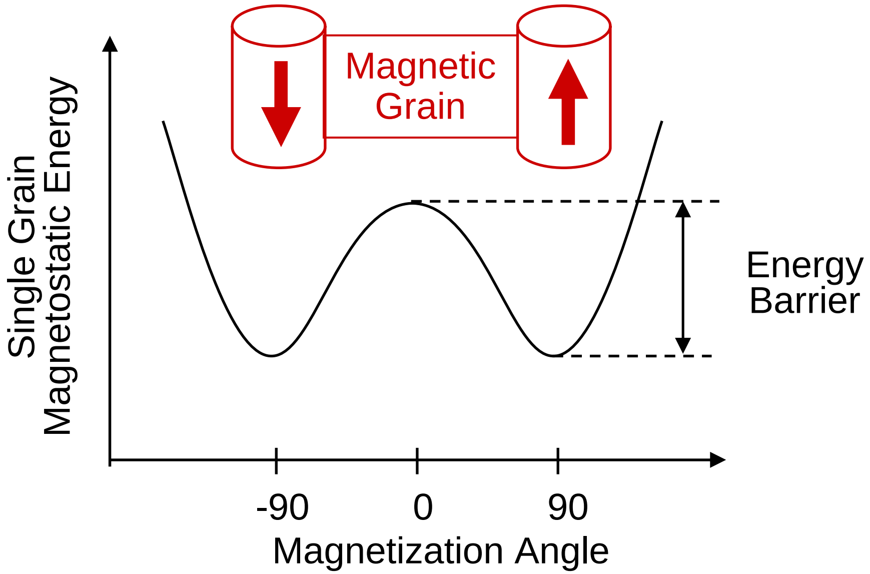




Magnetic Stability: $\frac{\text{energy barrier}}{\text{thermal energy}} \propto \frac{\text{anisotropy x volume}}{k_B \text{ x temperature}} = \frac{K_u V}{k_B T} > 70$

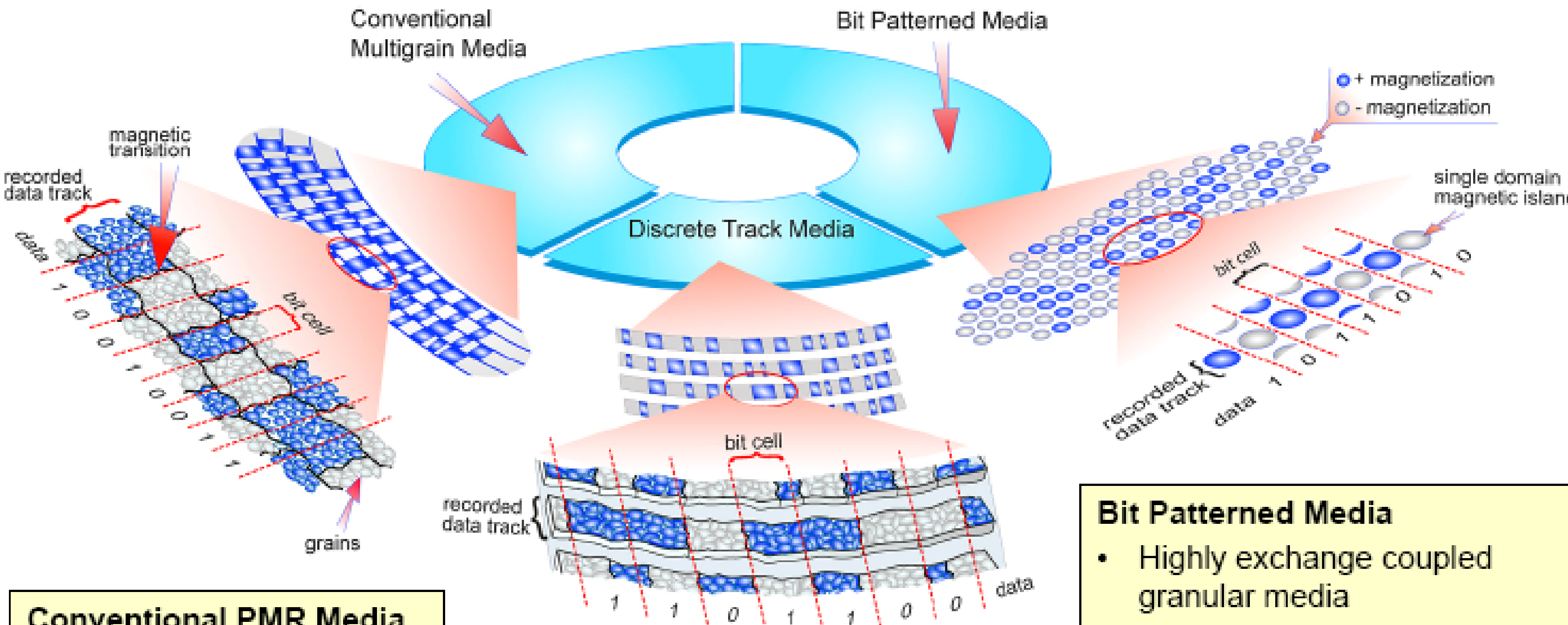
GRANULAR MEDIA PROBLEMS:

- To increase density, need smaller grains
- Smaller grains are thermally unstable
- To avoid thermal instability, increase grain anisotropy Ku
- This increases the medium coercivity and makes the medium more difficult to write

SOLUTIONS:

- Work with higher anisotropy:
  - Capped and exchange spring media
  - Thermally assisted recording (TAR)
- **Work with larger 'grains': patterned media**

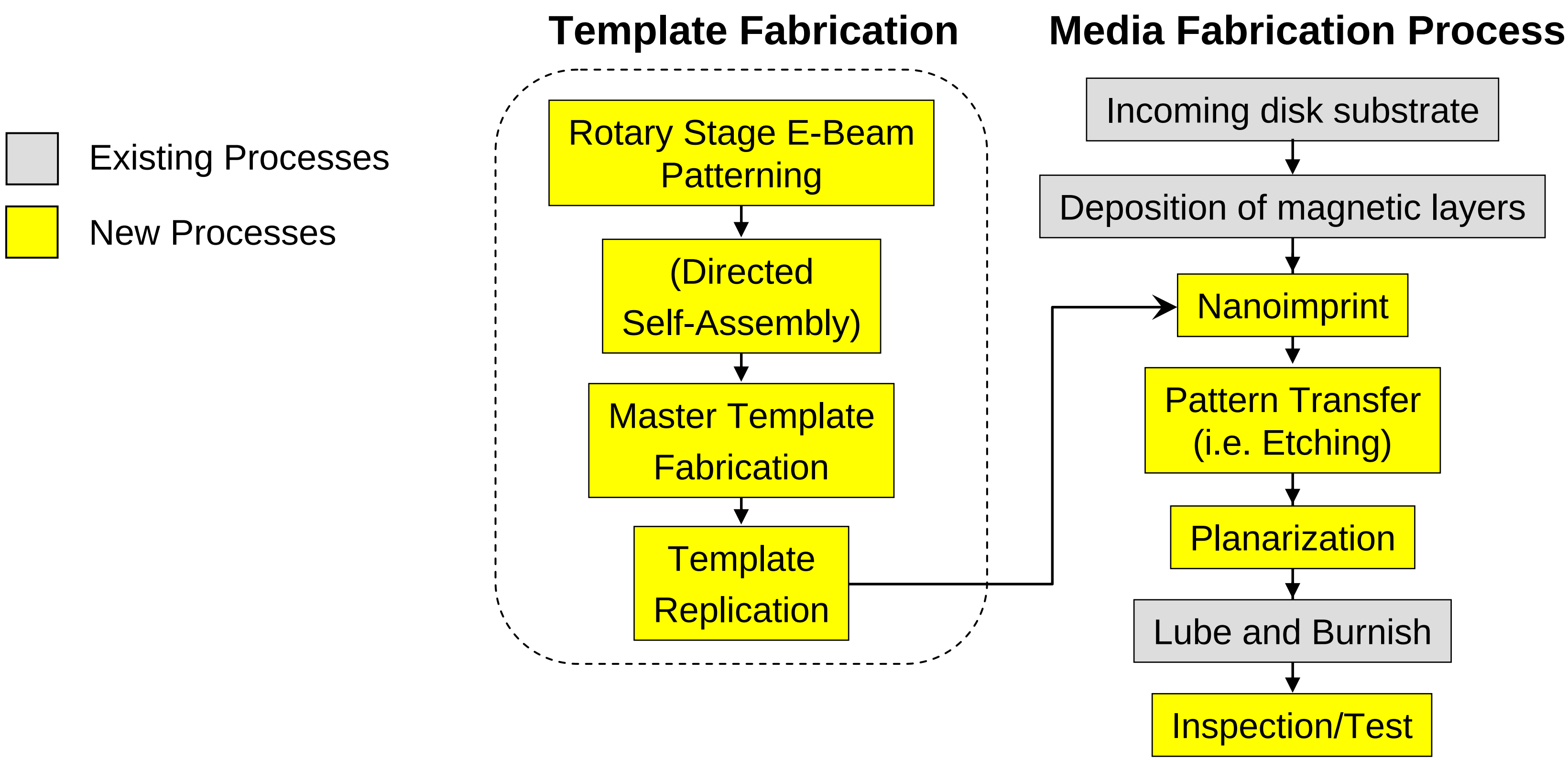
Patterned Media



Conventional PMR Media
- Continuous granular recording layer
- Multiple grains per bit
- Boundaries between bits determined by grains
- Thermal stability unit is 1 grain (~ 6 nm diam.)

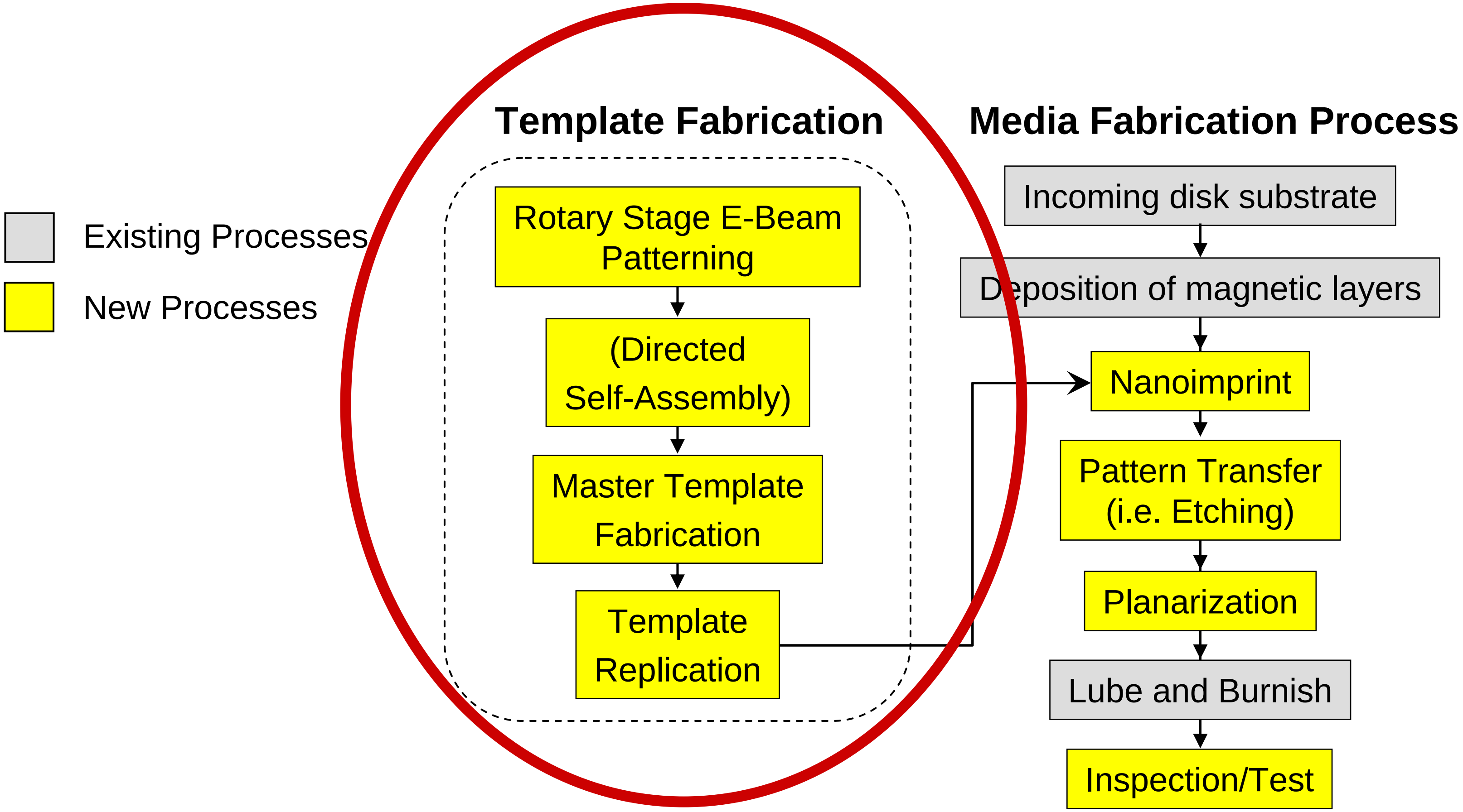
Discrete Track Media
- Conventional PMR media, with patterned tracks
- Multiple grains per bit
- Eliminates track edge noise and reduces adjacent track interference
- Thermal stability unit is still 1 grain (~ 6 nm diam.)

Bit Patterned Media
- Highly exchange coupled granular media
- Multiple grains per island, but each island is a single domain particle
- Bit locations determined by lithography
- Therm. stab. unit is 1 island (~15 nm diam.)



- The HGST patterned media fabrication plan inserts steps into traditional PMR disk process flow

Template Fabrication



Needed: A Different Roadmap

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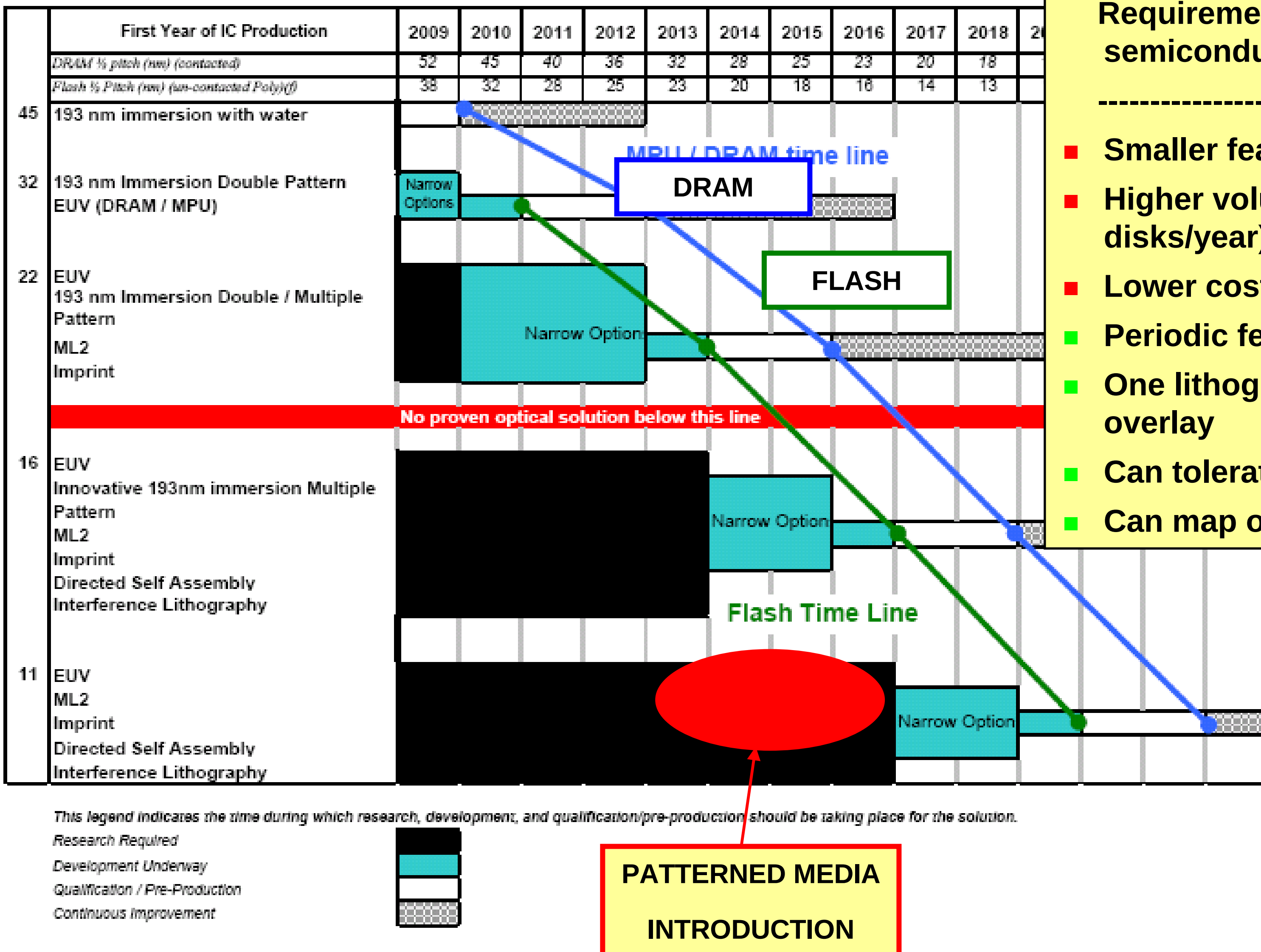


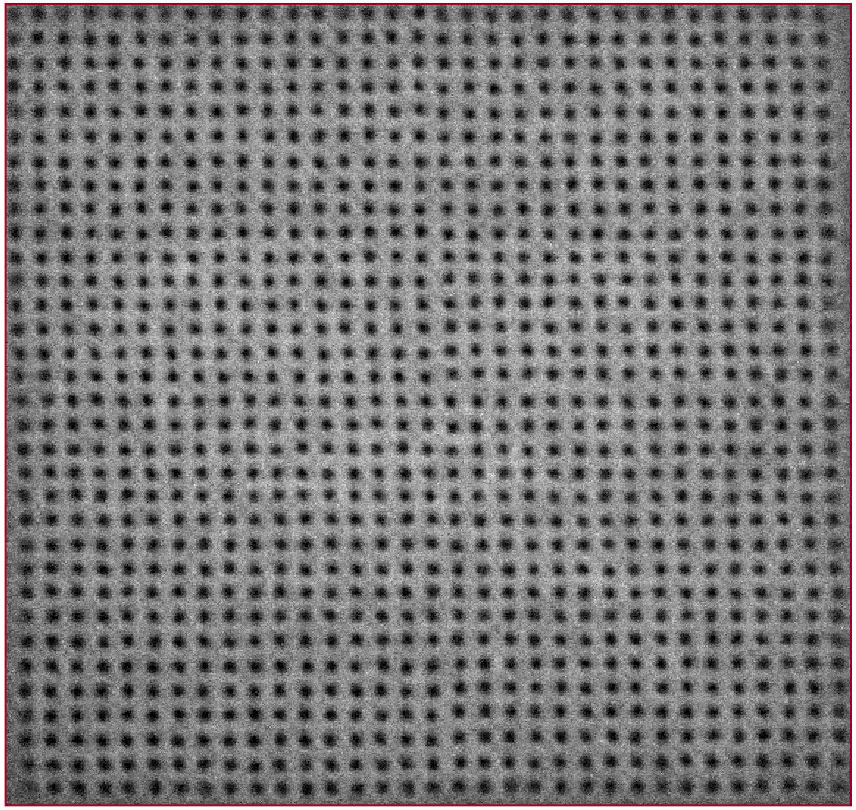
2009 ITRS Lithography Roadmap

Requirements compared to semiconductor fab:

- Smaller features sooner
- Higher volume (1 billion disks/year)
- Lower cost target (< $5/disk)
- Periodic features
- One lithography level; no overlay
- Can tolerate 1E-4 defect rate
- Can map out large defects

E-beam Lithography for Full Disk Templates

- To fabricate patterned media disks, a master pattern is first generated by e-beam lithography on fused silica substrates
- The small feature size (10–50 nm), precision tolerance requirements of 1nm 1sigma, and pattern extent require extreme measures including:
  - **Rotary-stage e-beam architecture**
  - **Cold ultrasonic development**
  - **Multiple exposures of features**
  - **Blanker-less writing**
- With e-beam write currents around 10nA and ZEP resist, writing the full 65mm disk surface can take a few days
- Ensuring low patterning defect counts with long e-beam write times over large areas is challenging

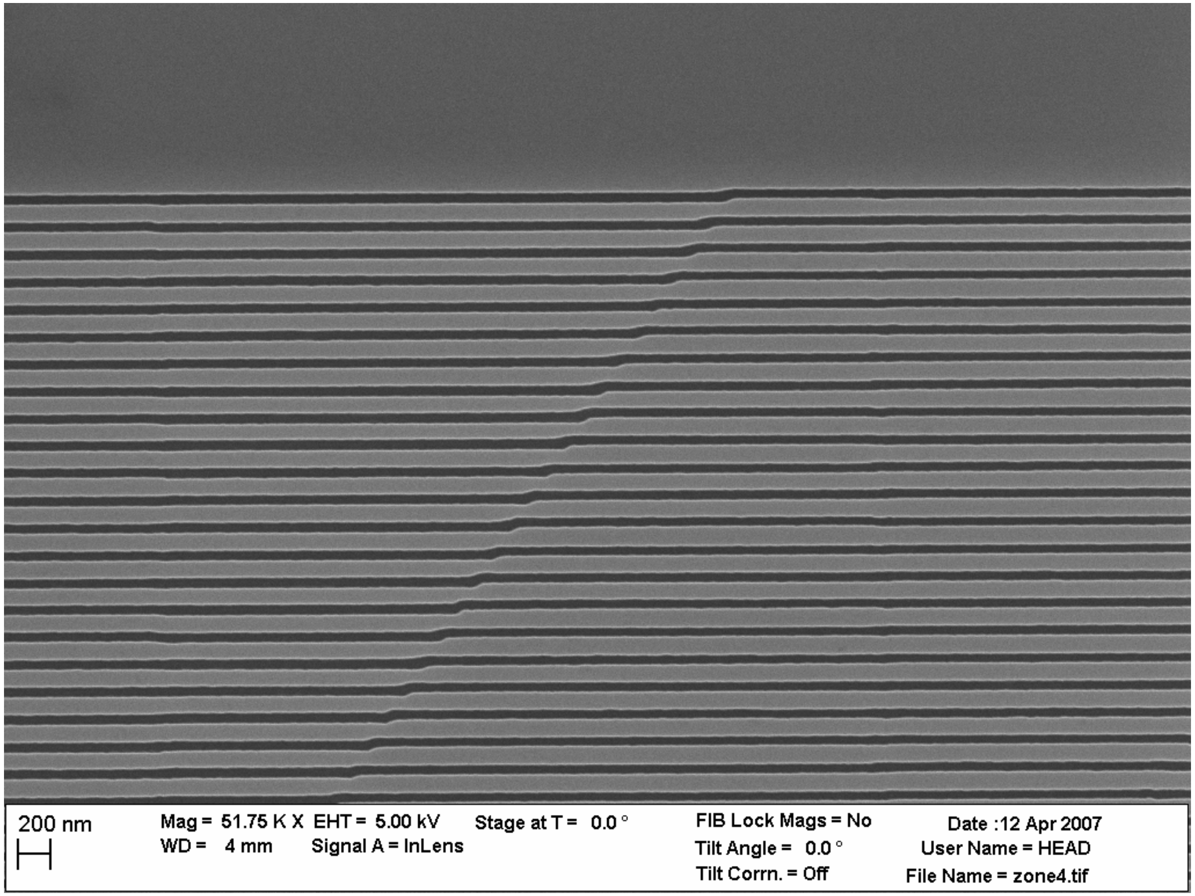


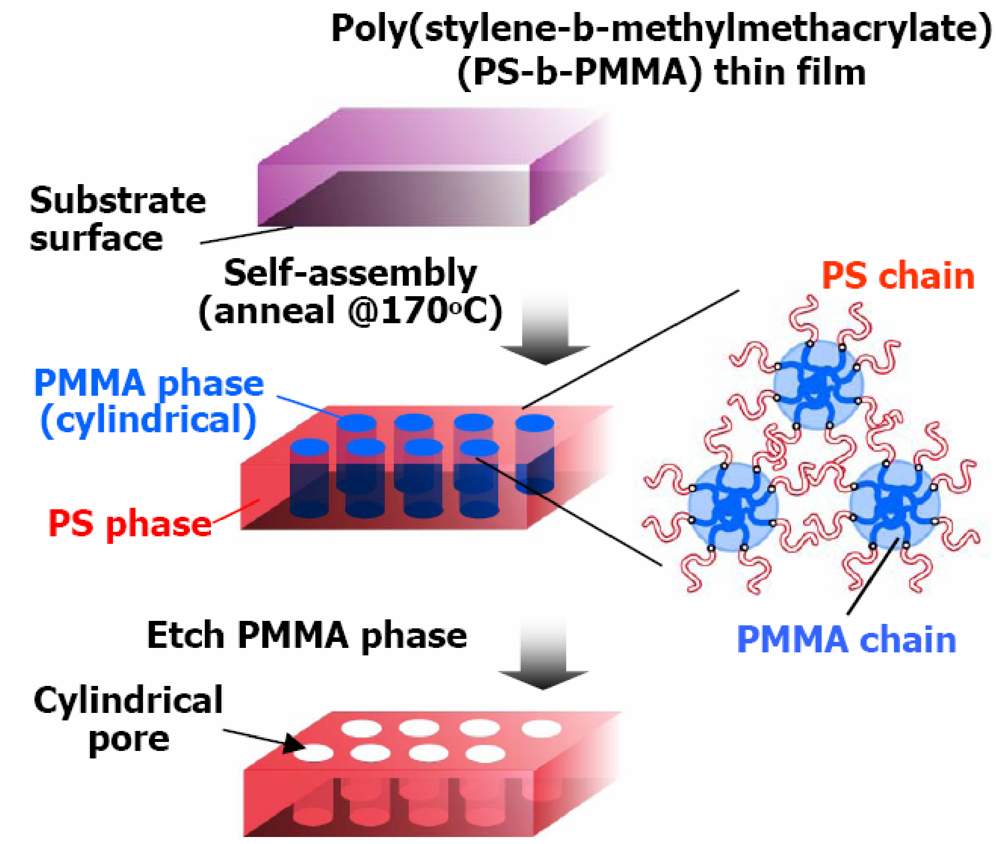
720 Gbit/in² (30 nm period):
Holes etched in Si master mold, E. Dobisz, HGST

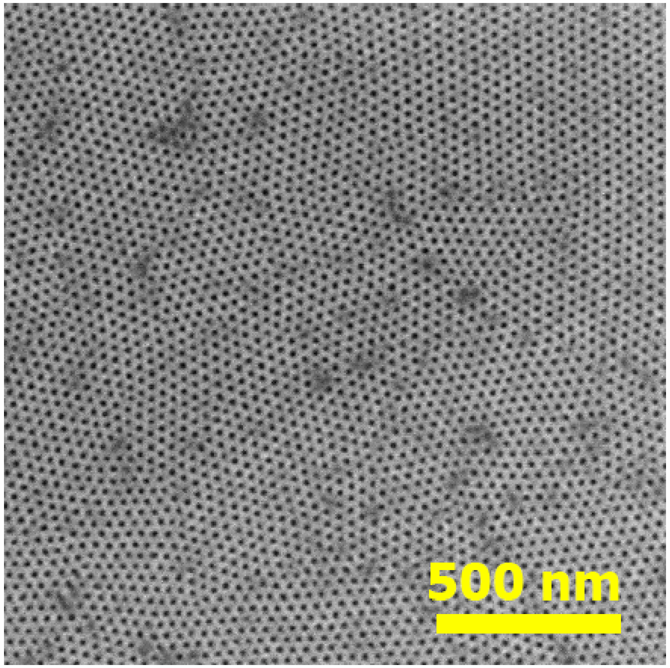
Problems with XY e-beam Stage

- **Field stitching errors can be seen when trying to write circular tracks with an XY positioning stage**
- **Typical field stitching errors are ~20nm**
- **BPM imprinting templates require extremely small features sizes (10-50nm) and strict position accuracy, ~1nm 1sigma**
- **Field stitching errors can not be compensated for with servo sectors**
- **To meet these demands, HGST is currently using an Elionix, 100keV, rotary stage e-beam tool**

Field Stitch Defects on a Direct E-beam Write DTR Disk







H. Yoshida – Hitachi Research Lab

- As deposited PS-b-PMMA microphase separates into short range ordered HCP
- Chemically pre-patterning the substrate with e-beam lithography allows for long range ordering

Directed Assembly for Pattern Rectification and Density Multiplication

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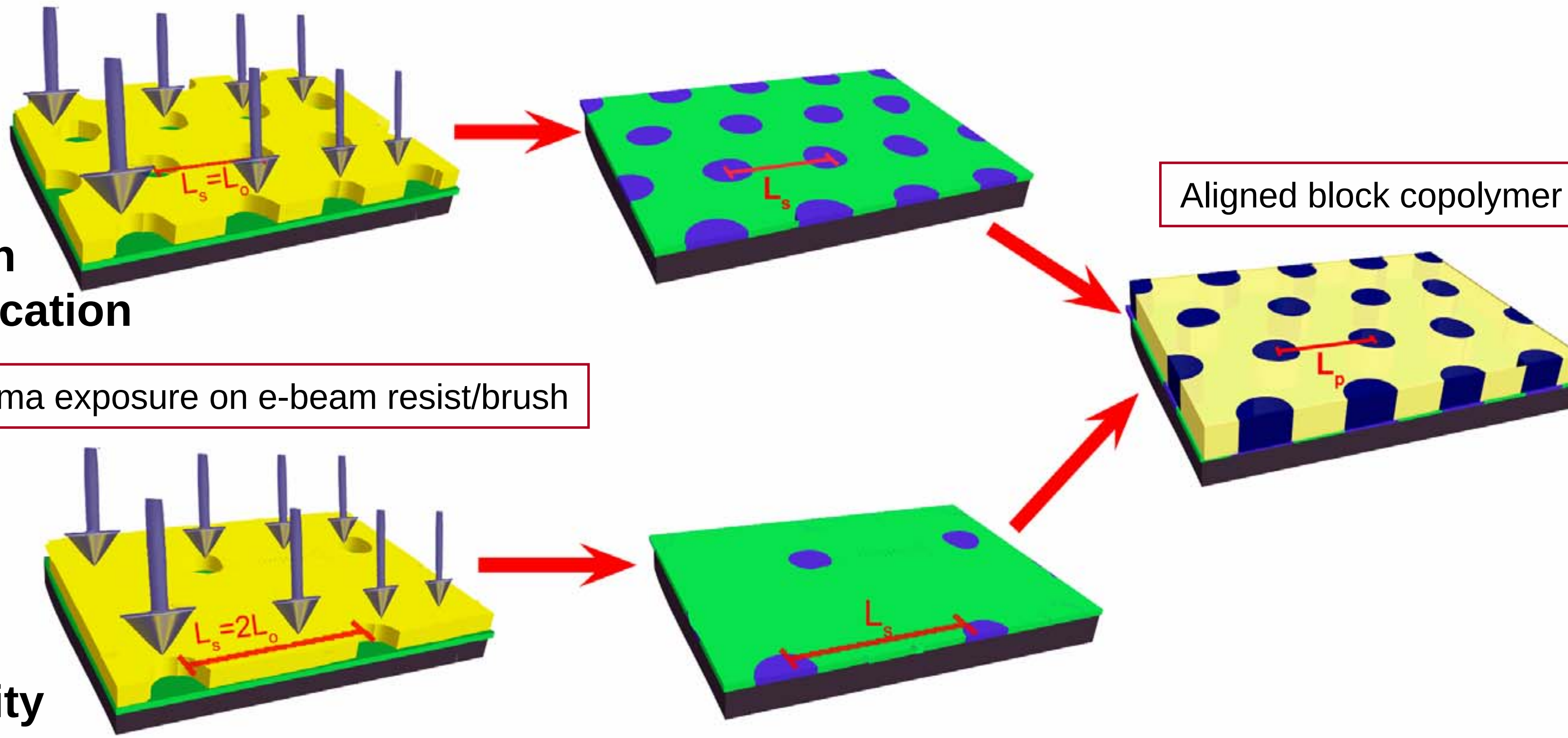


Pattern Rectification

O2 plasma exposure on e-beam resist/brush

Density Multiplication

Aligned block copolymer

Definitions:

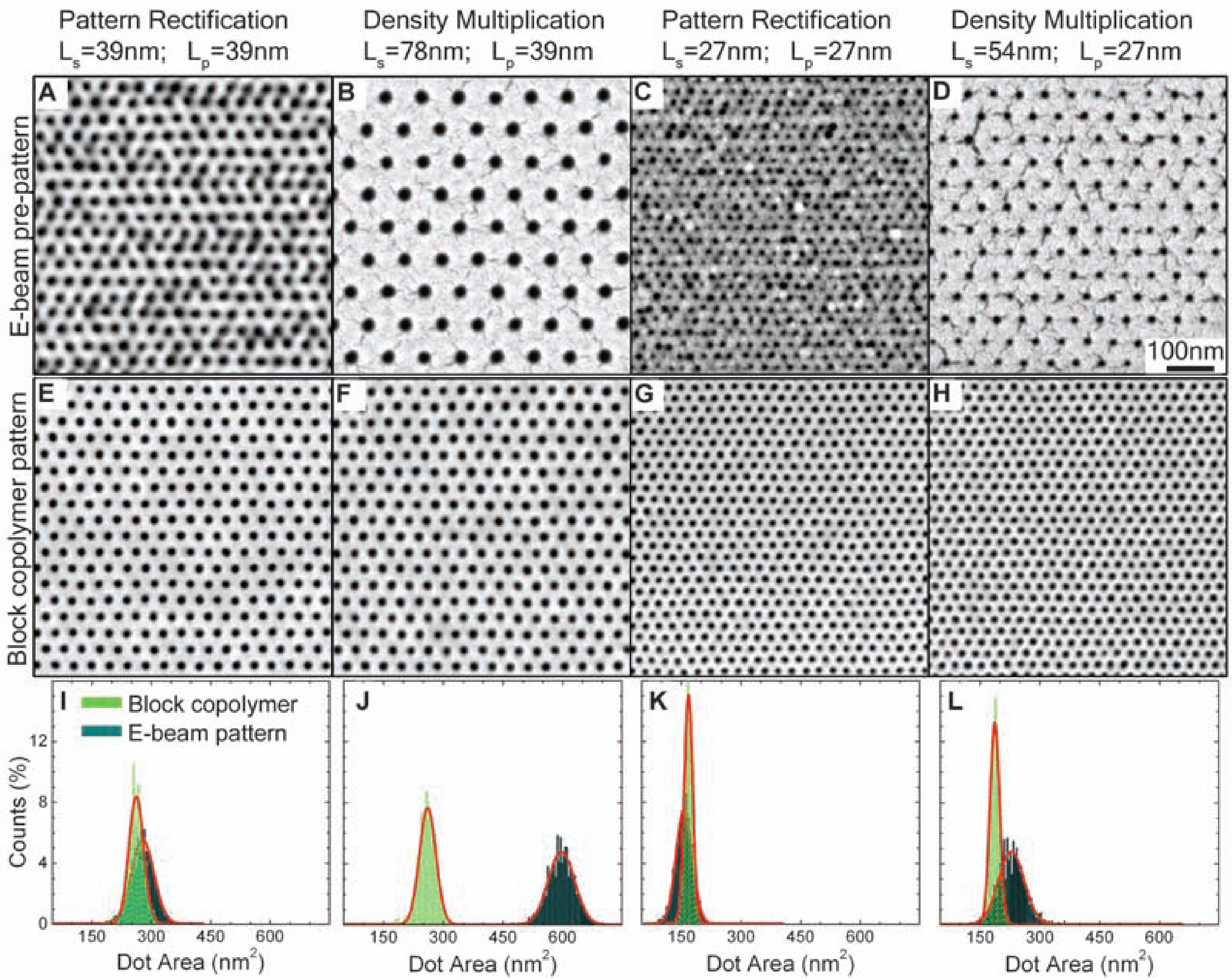
L_s = E-beam pattern pitch

L_o = Block copolymer natural pitch

L_p = Block copolymer pitch on top of chemical pattern

R. Ruiz, H. Kang, F. A. Detcheverry, E. Dobisz, D. S. Kercher, T. R. Albrecht, J. J. de Pablo, P. F. Nealey, **Science 2008**

Pattern Density Multiplication from Directed Self Assembly



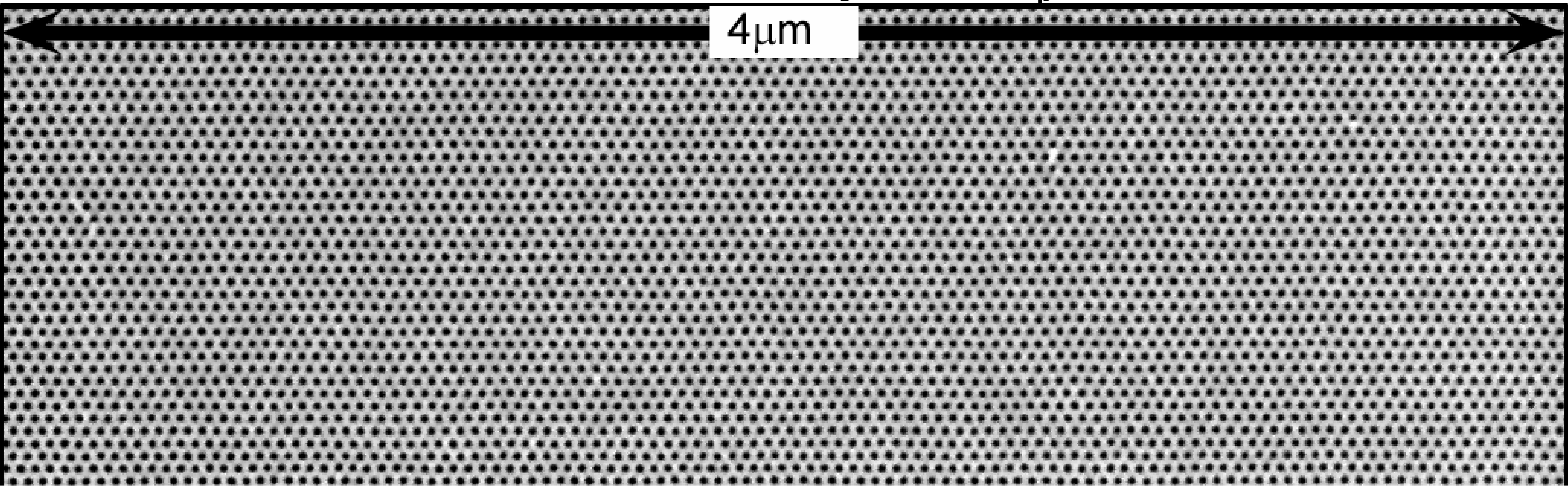
R. Ruiz, E. Dobisz, D. Kercher – HGST

H. Kang, P. Nealy – Univ. Wisconsin

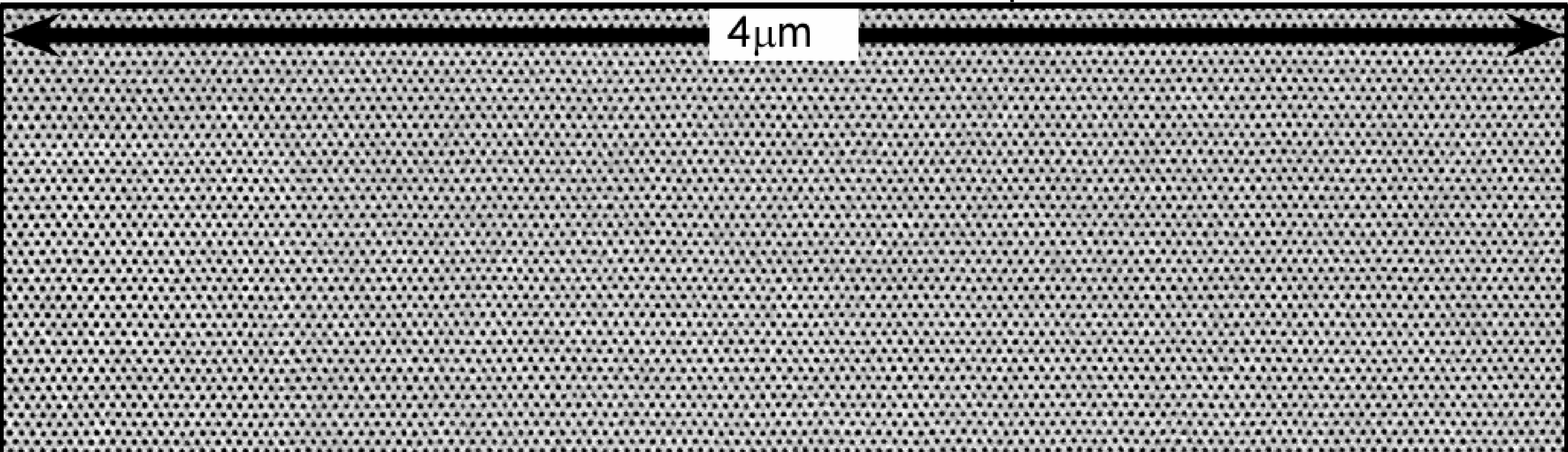
Dot Size Distribution

Long-range order

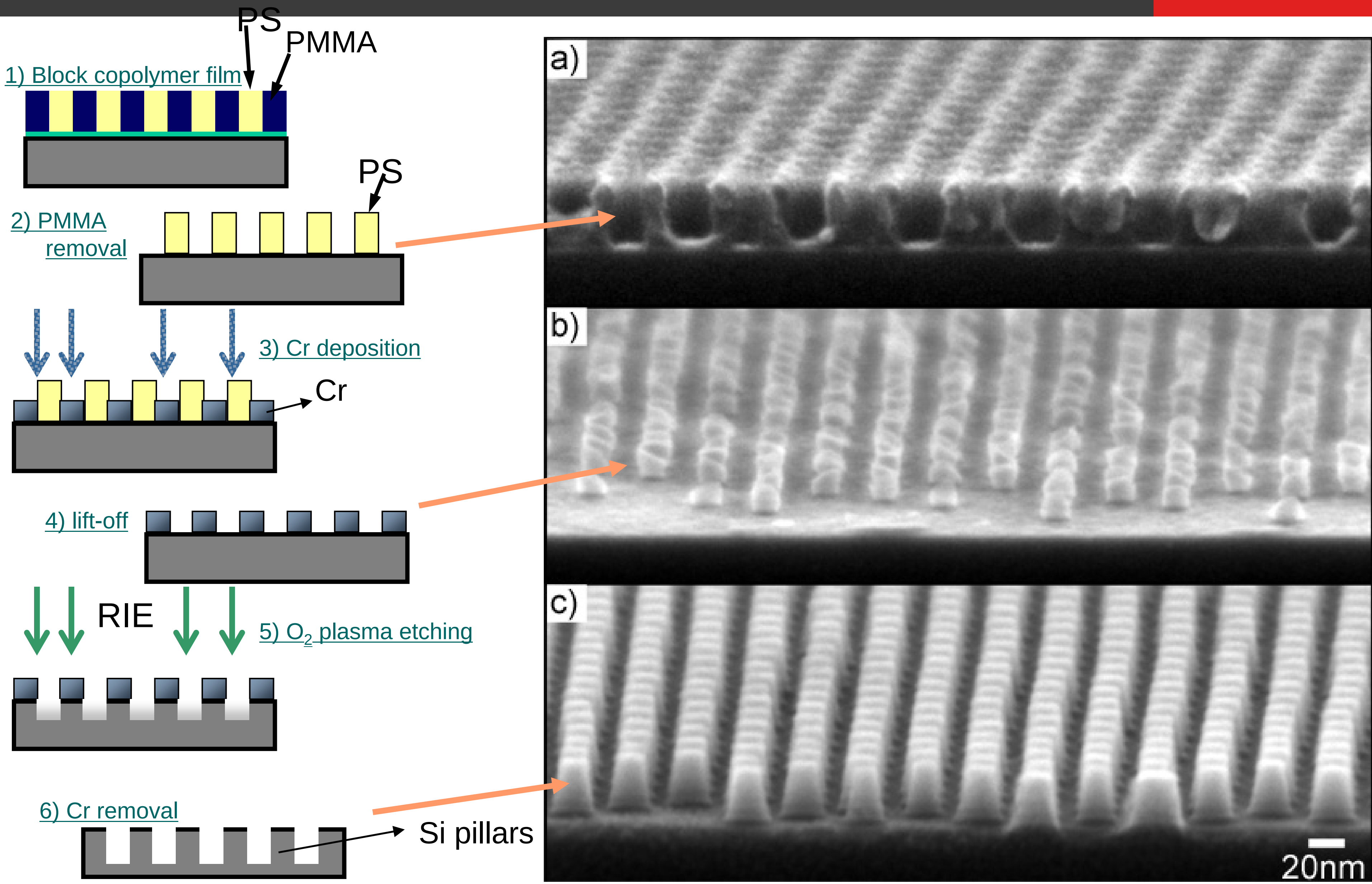
Density multiplication. 490Gb/in^2 L_s=78nm; L_p=39nm



Density multiplication. 1Tb/in^2 L_s=54nm; L_p=27nm

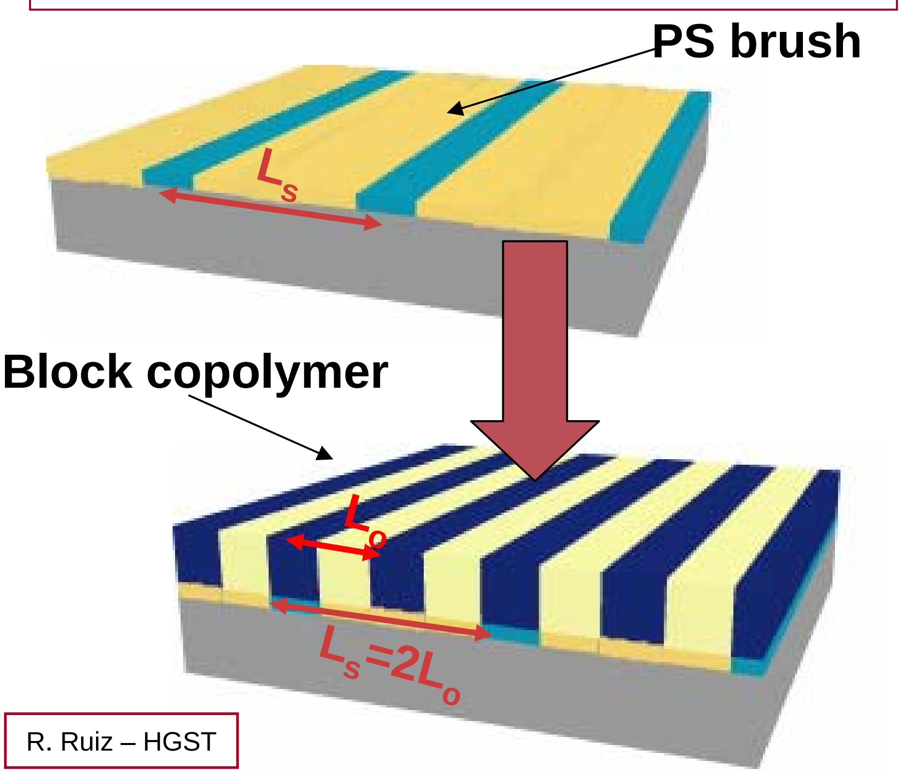


Pattern Transfer



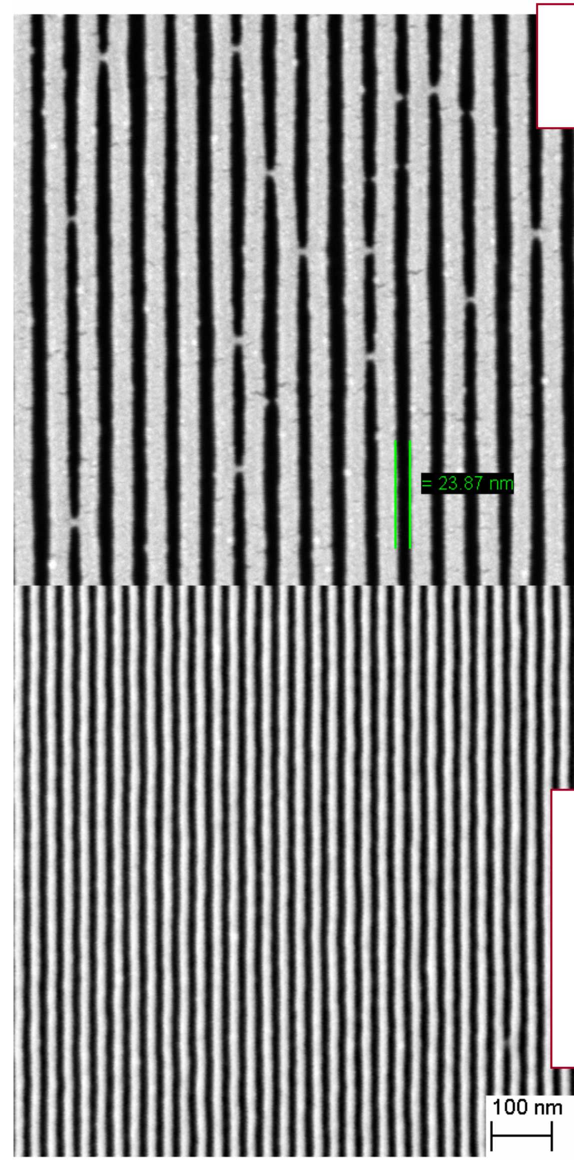
Pattern Density Multiplication for Line/Space Patterns

- Line and space pattern density multiplication, suitable for DTM, has been demonstrated
- 27nm pitch lines from a 54nm pitch e-beam pattern



R. Ruiz – HGST

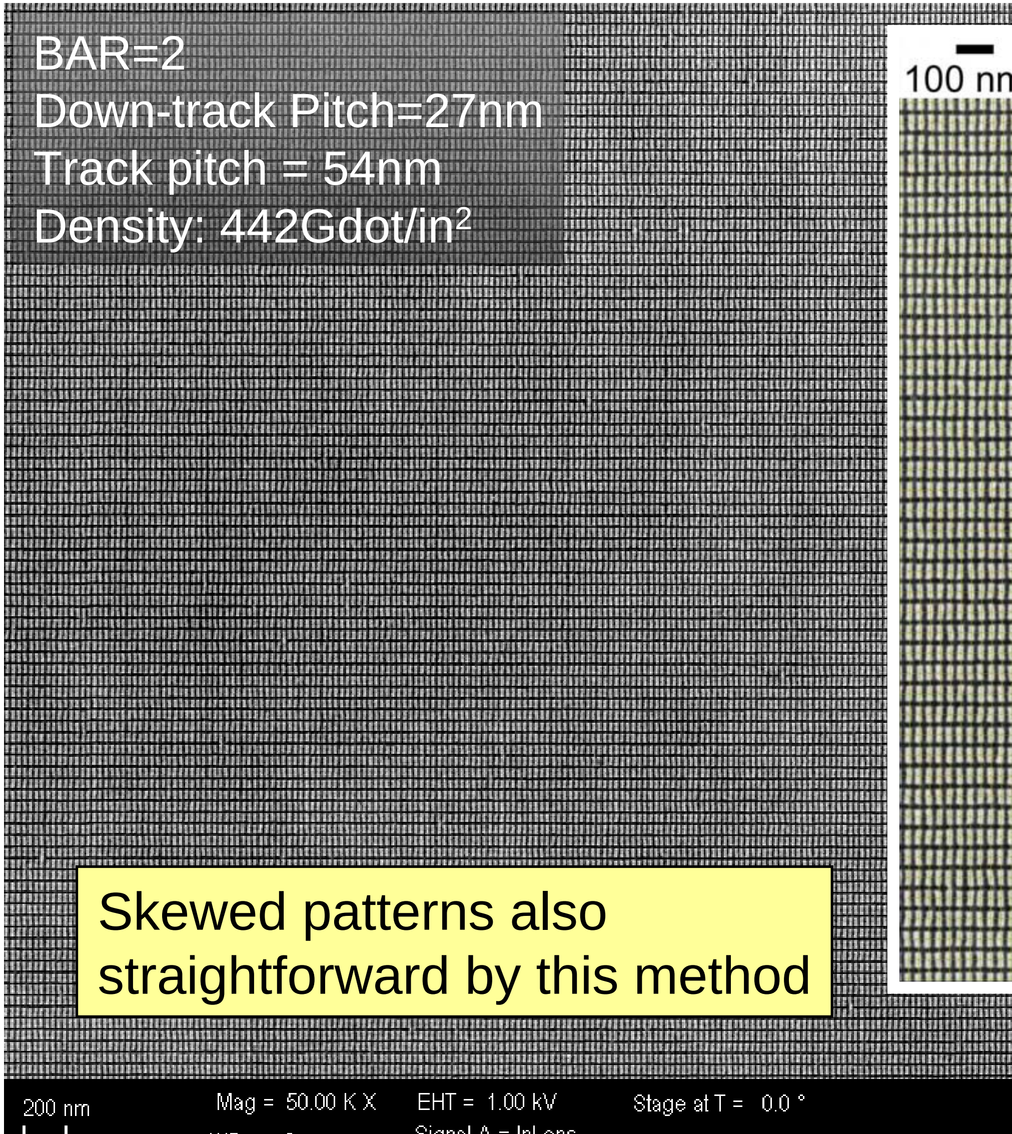
PMMA resist on PS brush



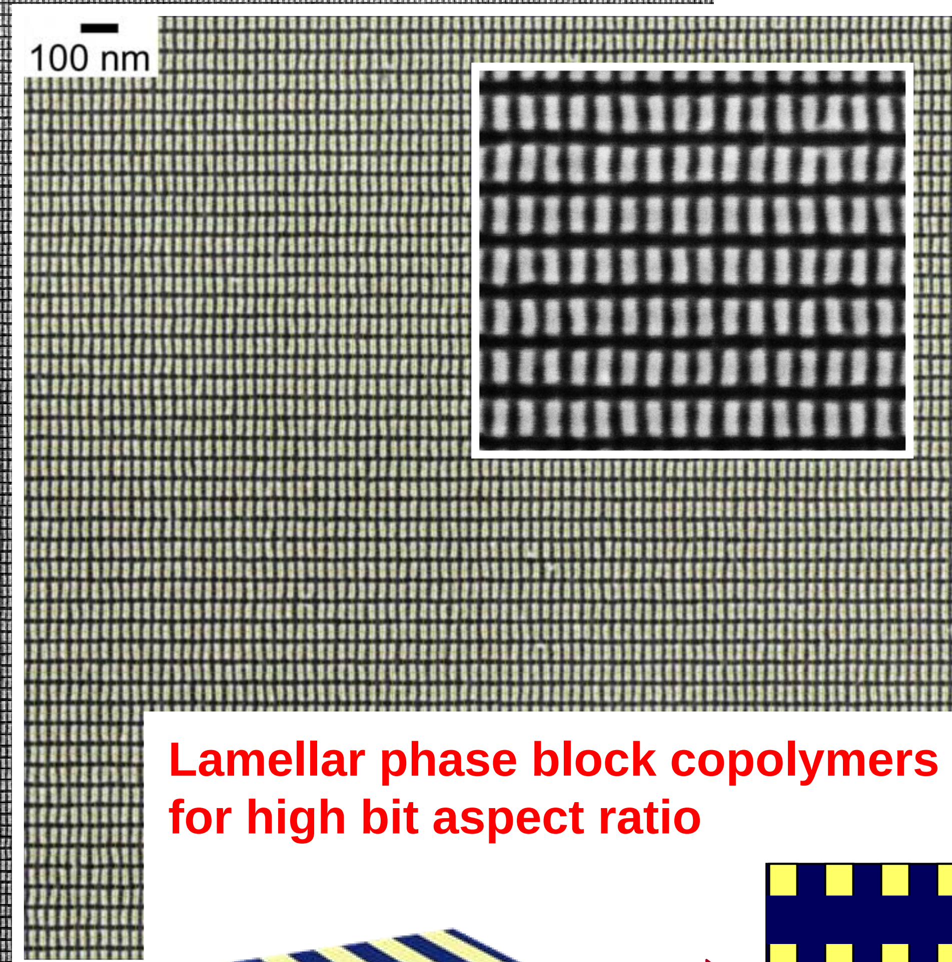
L_s=54nm
L_o=27nm

Lamellar block copolymer on pre-patterned substrate

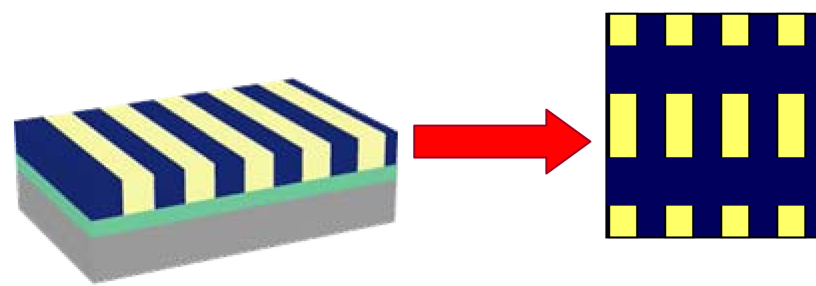
High BAR: Density multiplication of lamellae



U.S. patent application US20090308837A1, published 12/17/09

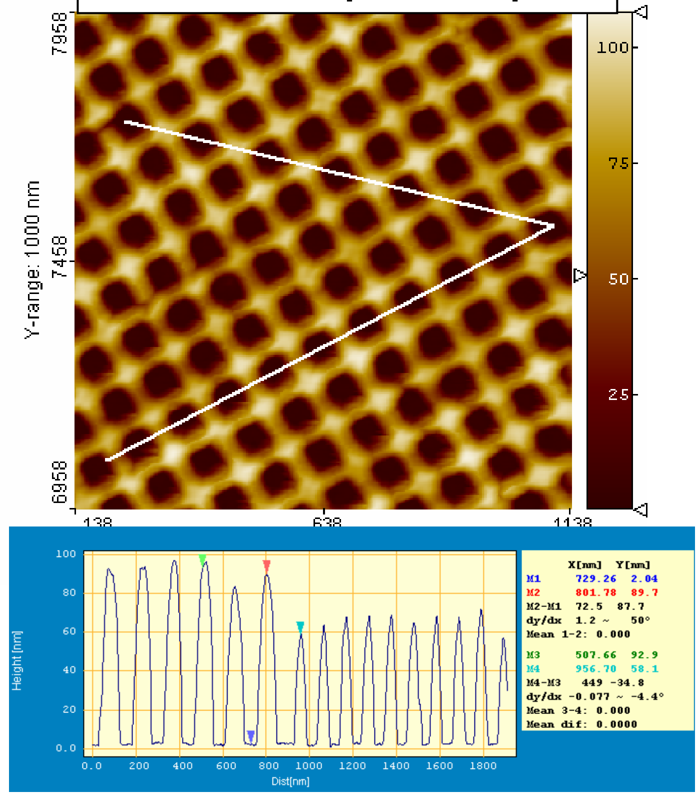


Lamellar phase block copolymers for high bit aspect ratio

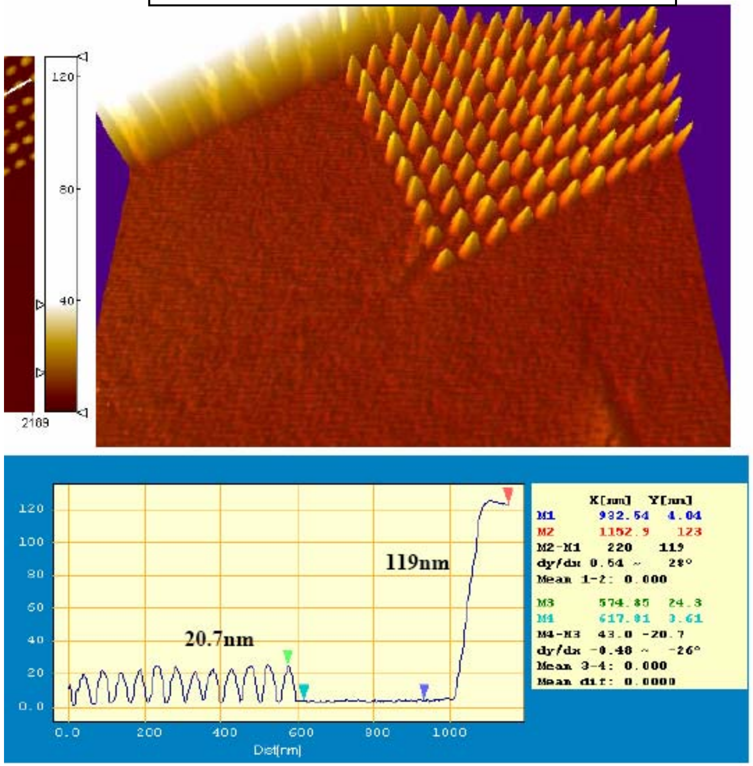


- **When dry etching nano-imprint templates our initial process resulted in large etch rate differences depending on feature size**
- **This is caused by various problems including RIE lag and ion scattering**

Resist from a pillar template



Resist from a hole template

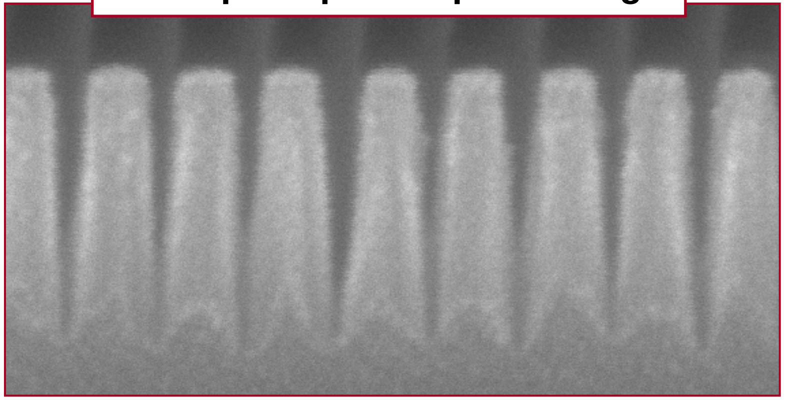


35nm pitch patterns in nano-imprint resist

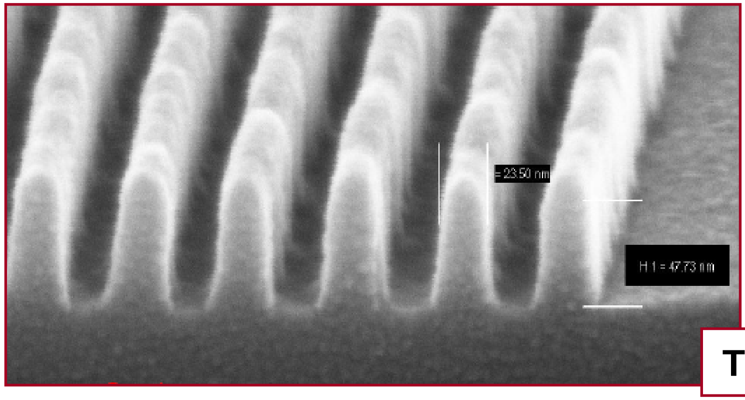
Ideal Imprint Template Fabrication

- **Even though very high aspect ratio structures can be achieved, they are not useful for the nano-imprint process**
  - 2:1 aspect ratio or lower is ideal
- **With a properly selected SiO2 etch recipe, vertical sidewall and flat etched trench bottoms can be achieved at 14nm half pitch**

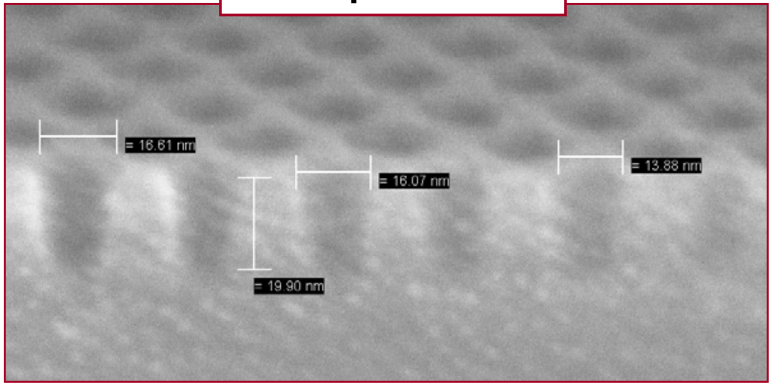
35nm pitch pillars: poor design



48nm pitch lines, Cr hard mask remaining

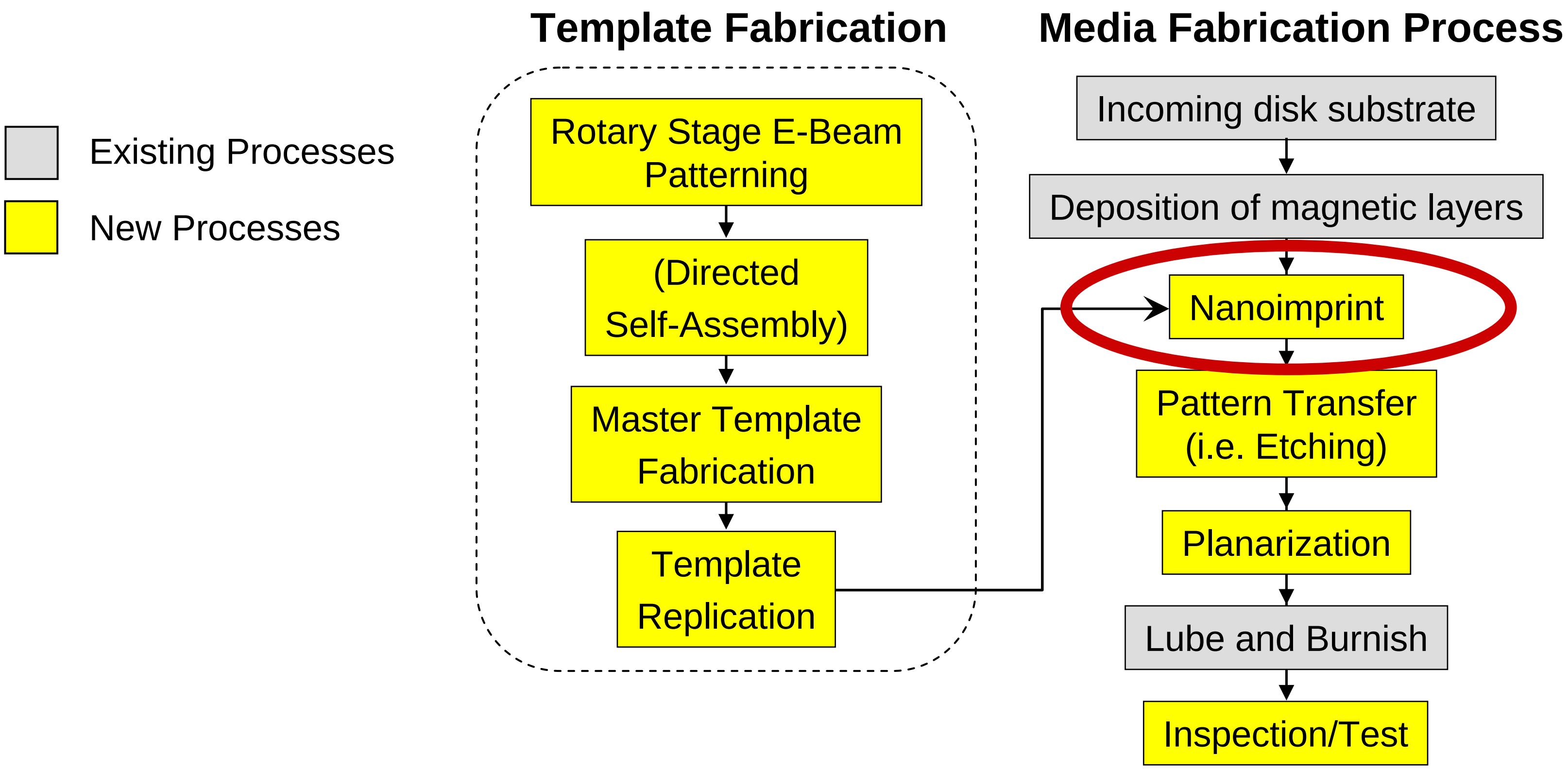


27nm pitch holes



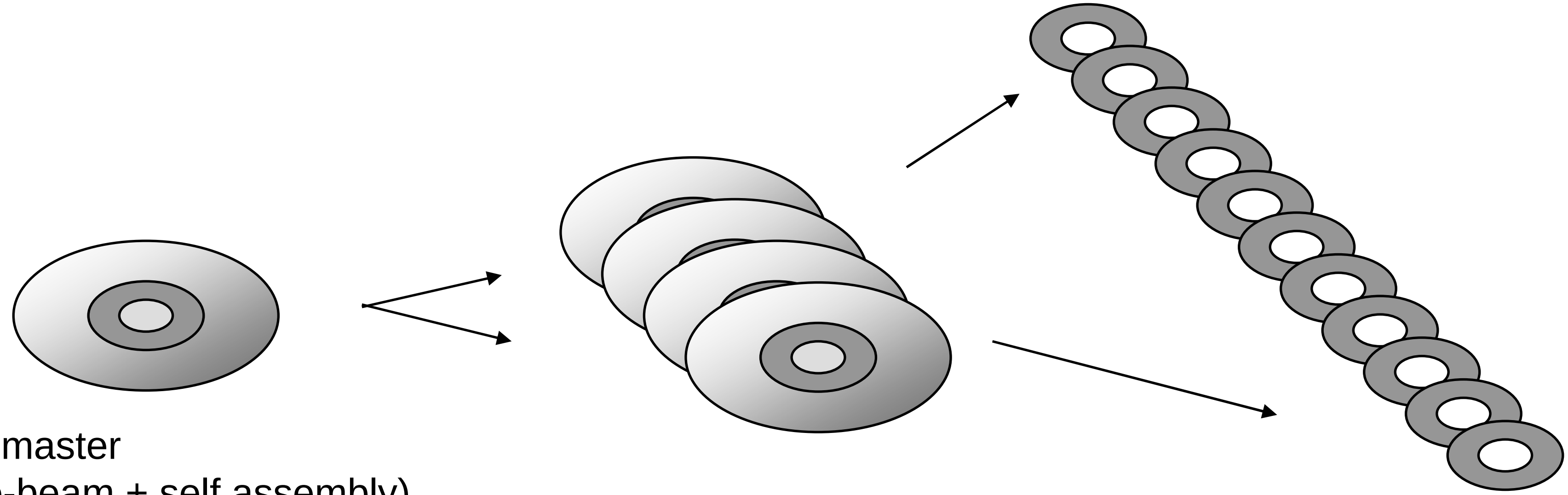
T. Hirano, K C Patel

Nano-imprint



Replication of patterns via Nanoimprinting

- **E-beam master will be expensive (many days to write on master pattern)**
- **Two generation nanoimprinting process envisioned for low-cost replication**



1 master
(e-beam + self assembly)

10,000 replica

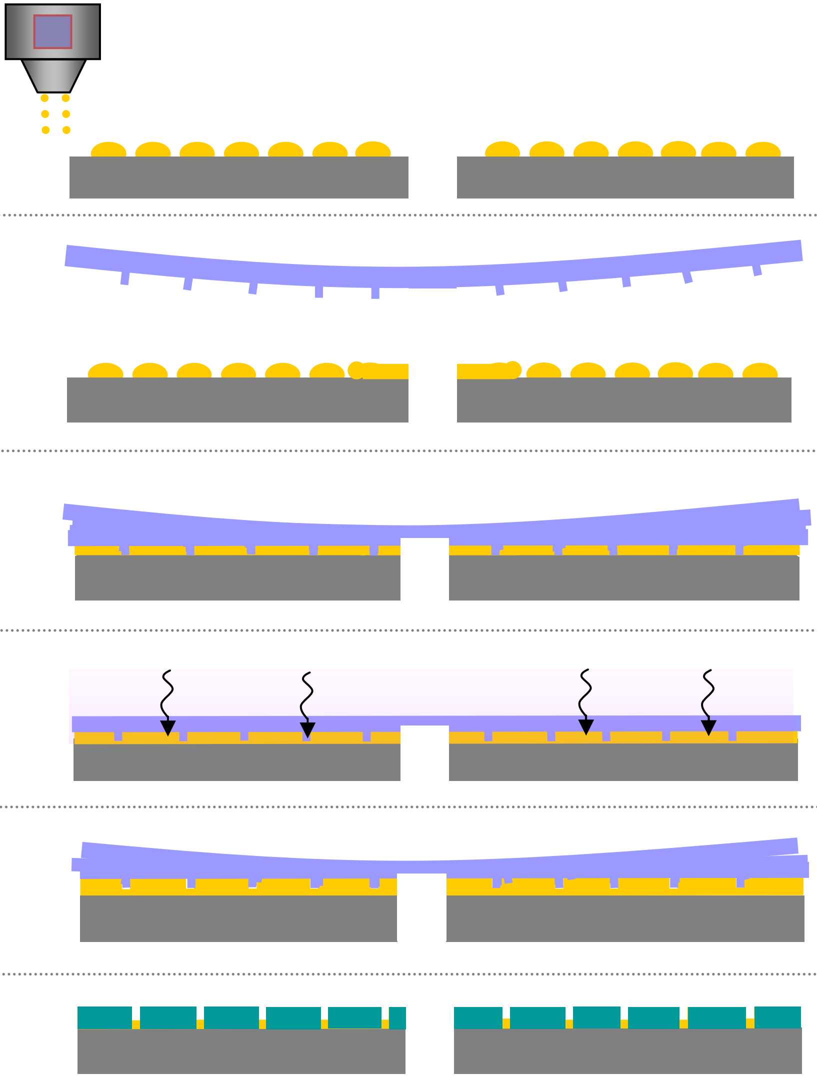
nanoimprint molds

100,000,000 imprinted

disk substrates

UV-cure nanoimprinting with ink-jet resist dispense

Graphic: MII



- Resist dispensing (ink jet)

- Thin template is bowed so initial contact in the center of the disk

- Capillary forces pull template into conformal contact with the disk

- Expose with UV light to cure the imprint resist

- Separate template from disk

- Etch

Spreading of Ink-jet Printed Resist

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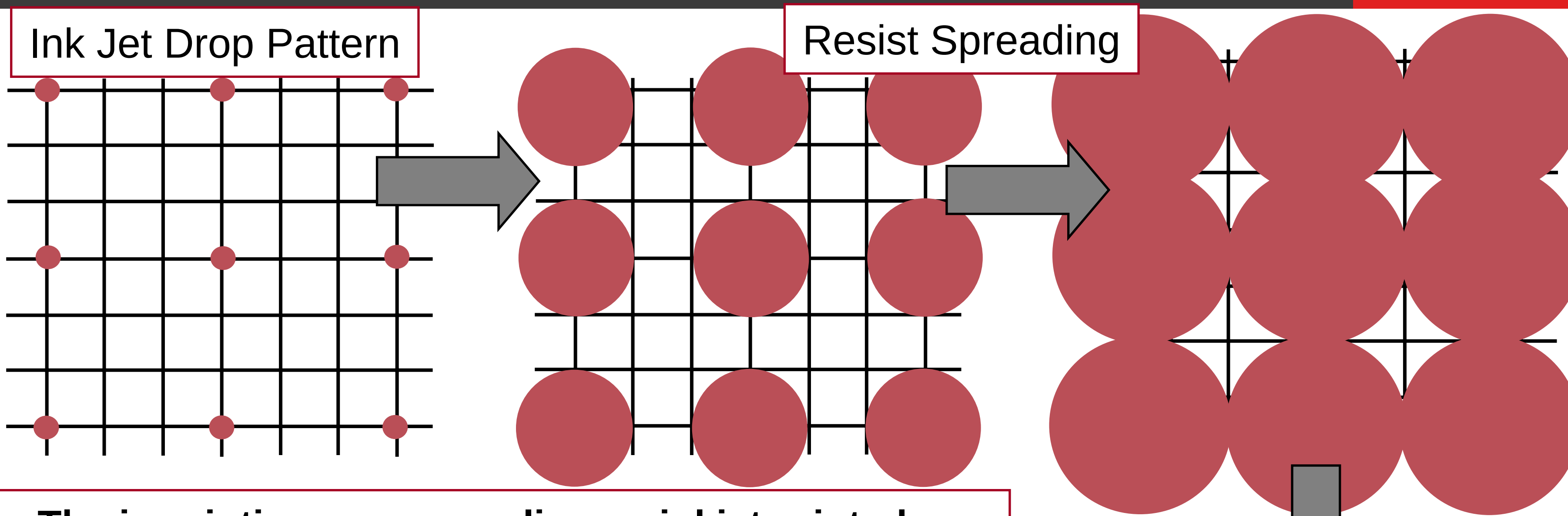
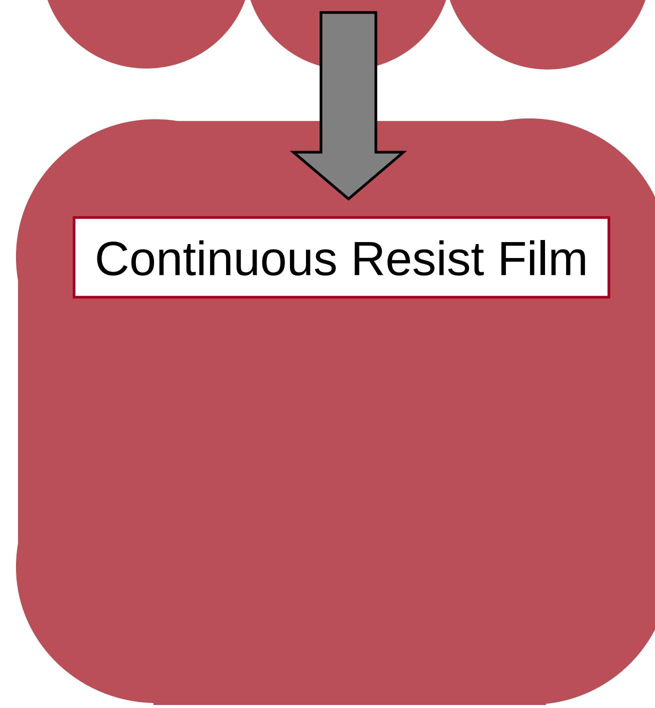


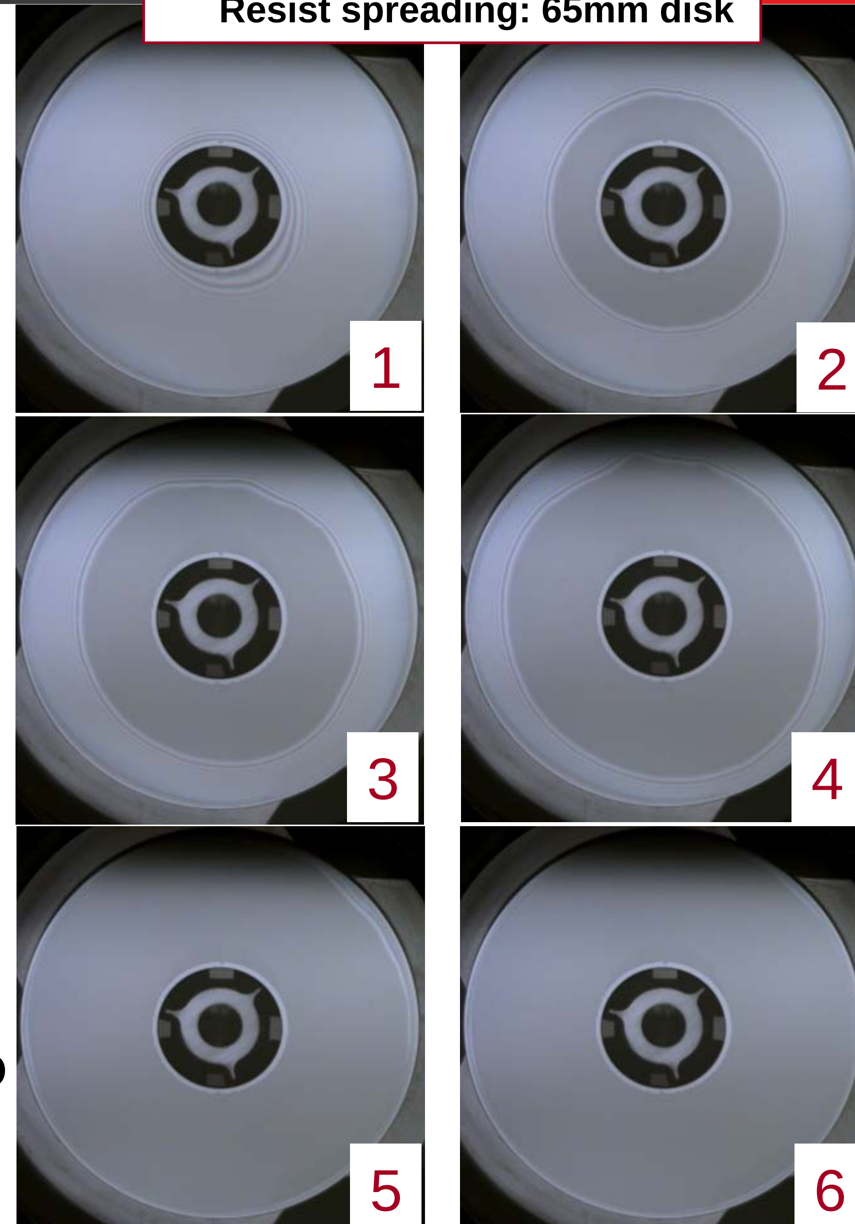
- **The imprinting process relies on inkjet printed resist drops**
- **The closer the droplets are in spacing, the higher the volume of imprint resist**
- **Surface tension is the driving force for resist spreading**
- **Too little resist volume results in unfilled areas**
- **Too much resist volume results in a thick residual layer**



Nanoimprinting on Disks

- **65mm disk imprinting: one step process with no overlay requirements**
- **Hard imprint templates are preferred (fused silica)**
  - Long lifetime
  - No feature deformation during imprinting
  - Easily cleaned if contaminated
- **Template is coated with a release agent**
- **Disks are coated with an adhesion promoter**
- **Resist dispensed with ink-jet printer**
- **Fast spreading is important for high throughput**
- **Proper design is required to ensure that excess resist does not build up at the OD and ID of the disk**

Resist spreading: 65mm disk



Formation of a Uniform Resist Film

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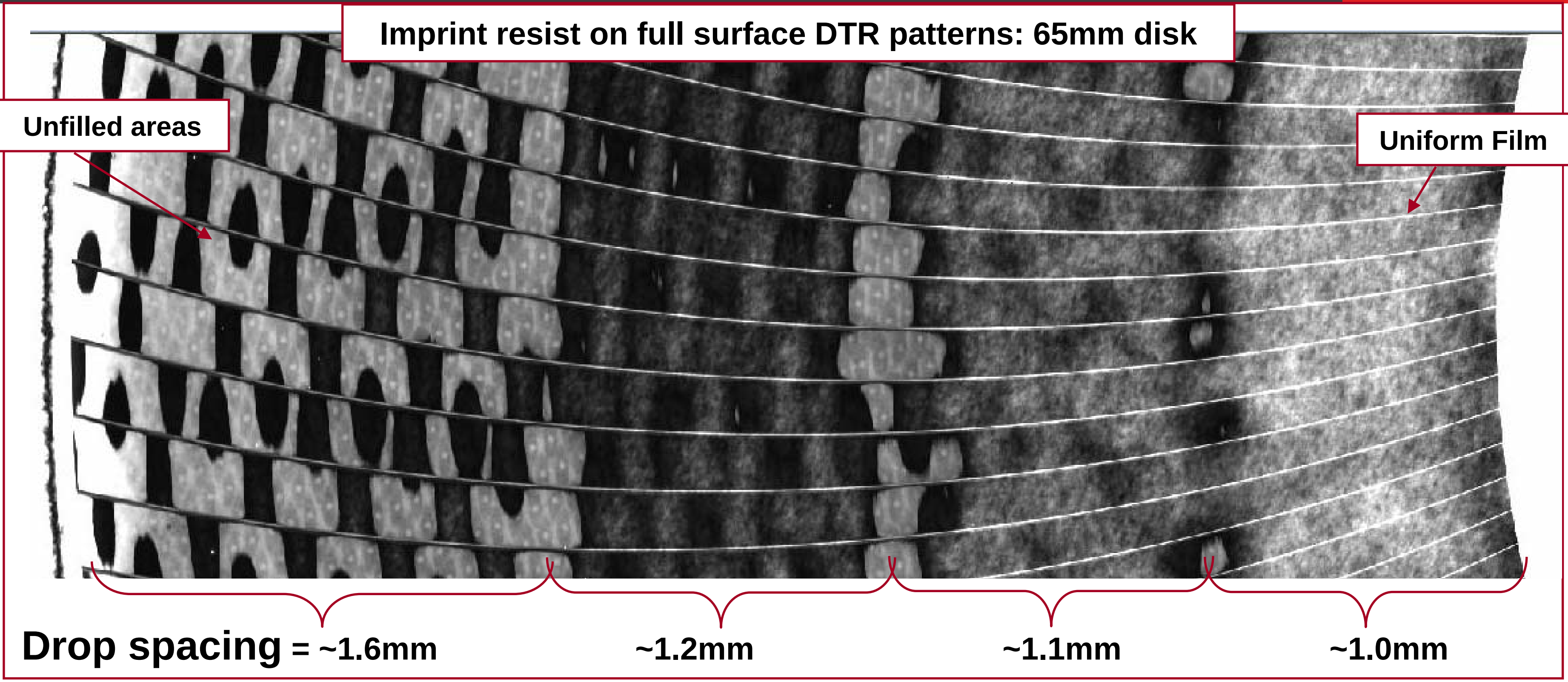

- Candela images show the spreading of imprint resist with a DTR template for various ink-jet dispense droplet spacing
- For this particular DTR imprint template, resist drops spaced too far apart (>1.2mm spacing) will not form a continuous resist film
- Resist drops at 1.1mm spacing show some variation in thickness

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NIL Requirements

- High disk throughput ~800dph
  - Parallel processing of disks may be required to keep pace with sputtering equipment
- Double side imprinting
- Fast spreading of the imprint resist
- Thin resist residual layer thickness [RLT]
- Excellent resist filling in small features with no unfilled areas
  - Low viscosity polymer
- Low particle defects on disks
  - Very clean incoming substrates
  - Good adhesion and release properties
- Clean imprint templates

Molecular Imprints, Imprio 1100, first generation single side disk imprinter, ~20dph, installed in 2007

HGST Disk Imprinting Equipment

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MII Imprio 2200 NIL Tool

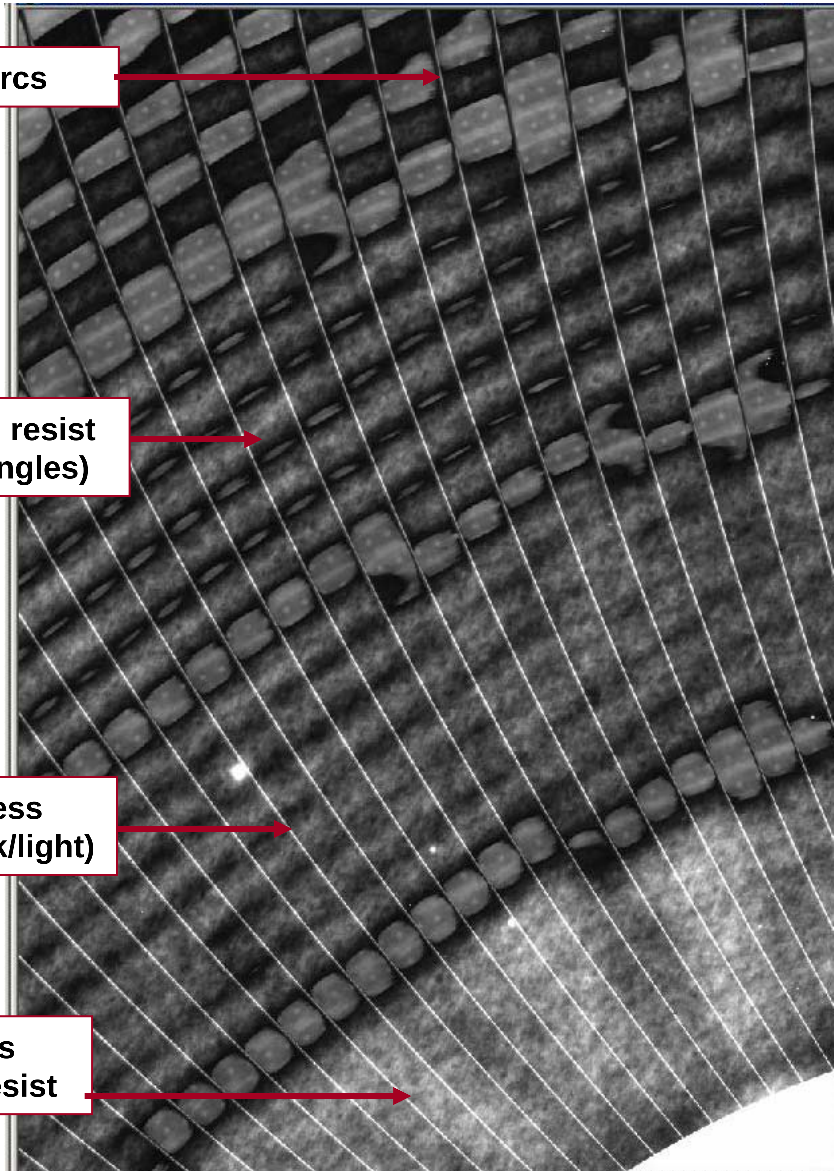
180dph double side disk imprinting system, installed at YB in 2009

NuTera™ HD7000

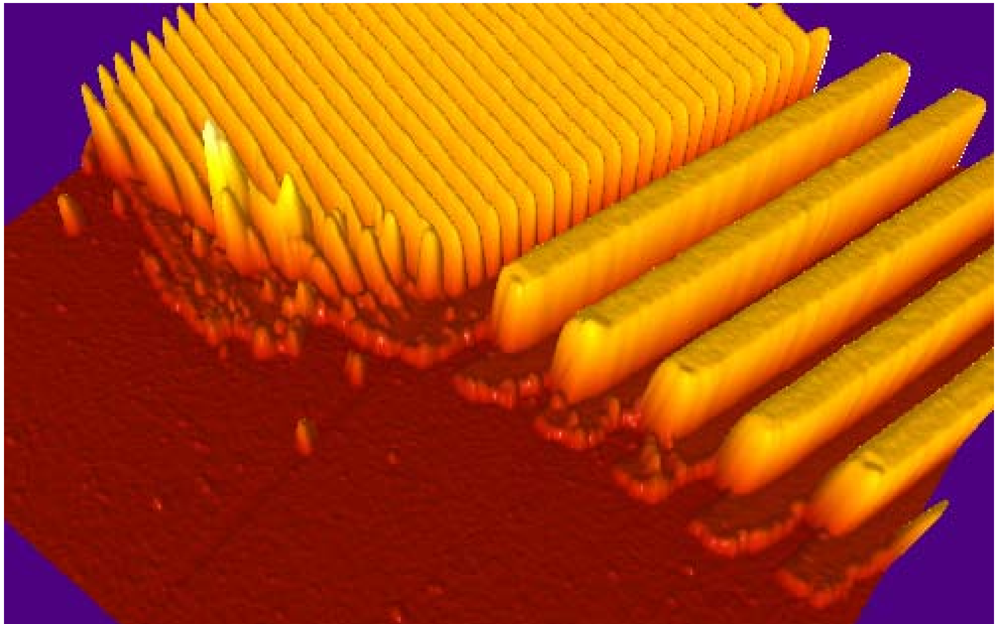
300dph double side disk imprinting system, installed at Cottle Rd in 2010

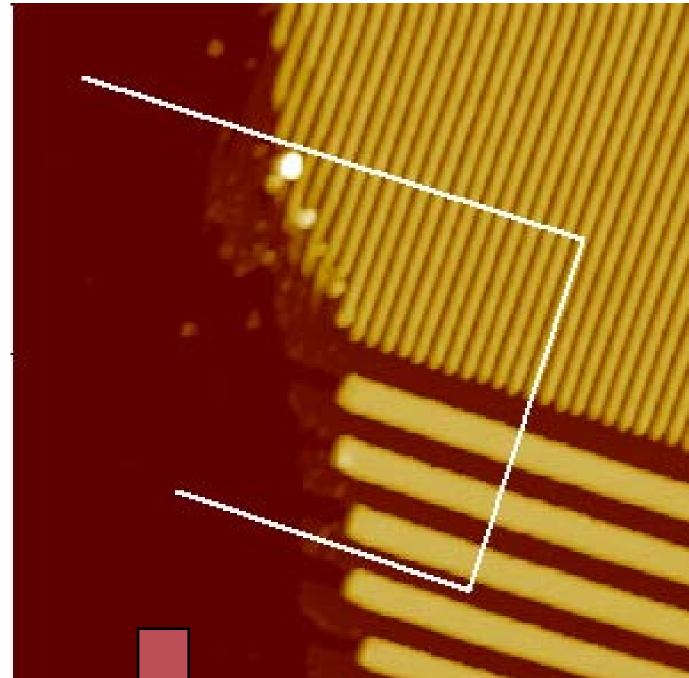
Resist Spreading in Template Features

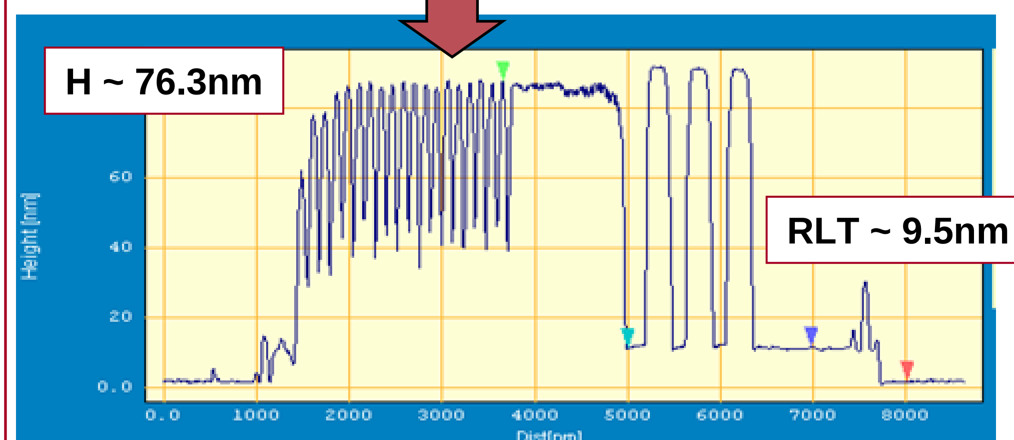
- **In a DTR nano-imprint template, the majority of patterns are circumferential grooves (data tracks)**
- **This Candela image shows the resist flow for various ink jet drop patterns**
- **After spreading, the unfilled areas are thin rectangles oriented along the tracks**
- **The resist prefers to flow along the template track grooves**
- **Understanding resist flow is important when creating an ink jet drop pattern for a template**



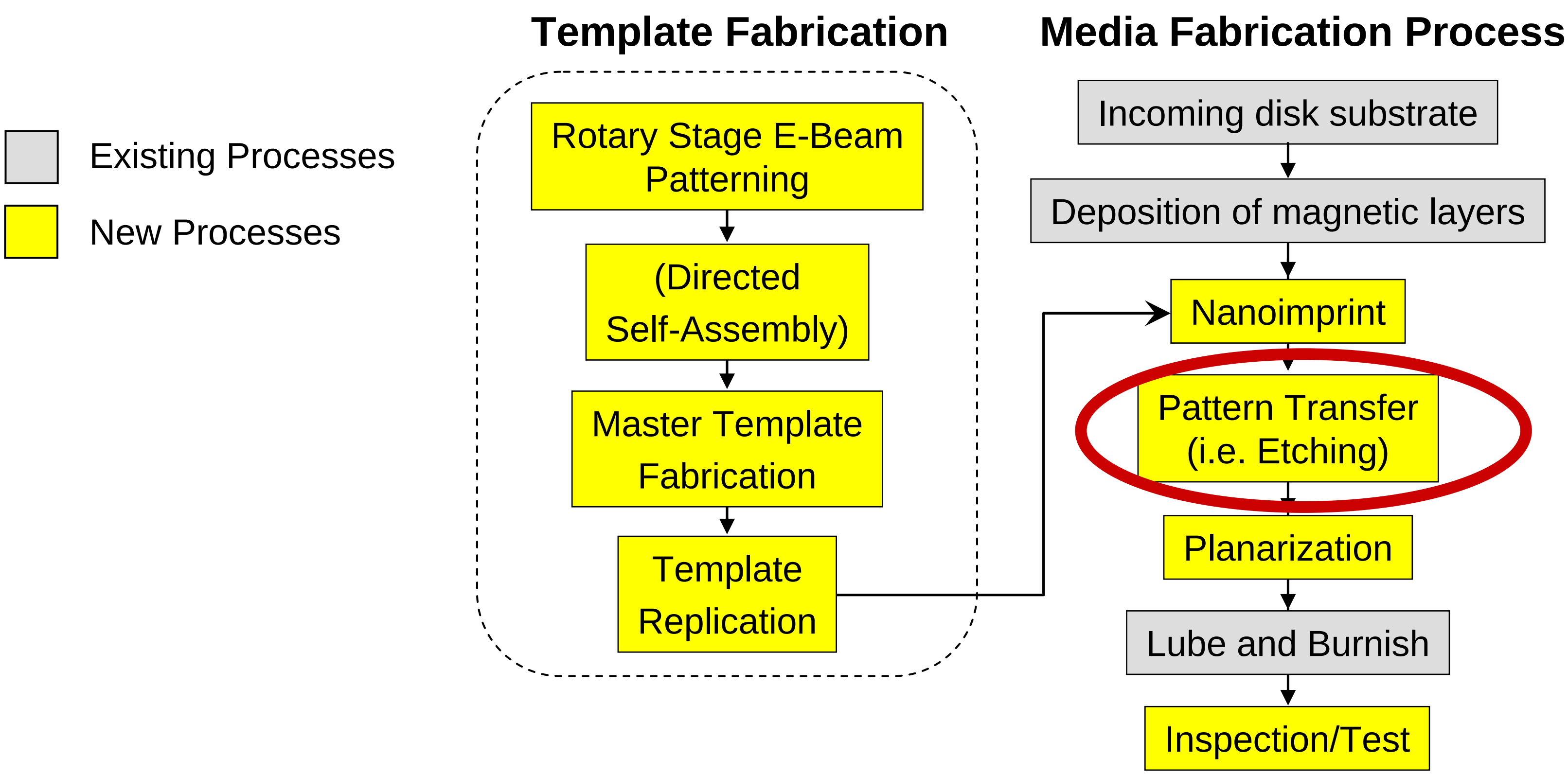
Residual Layer Thickness



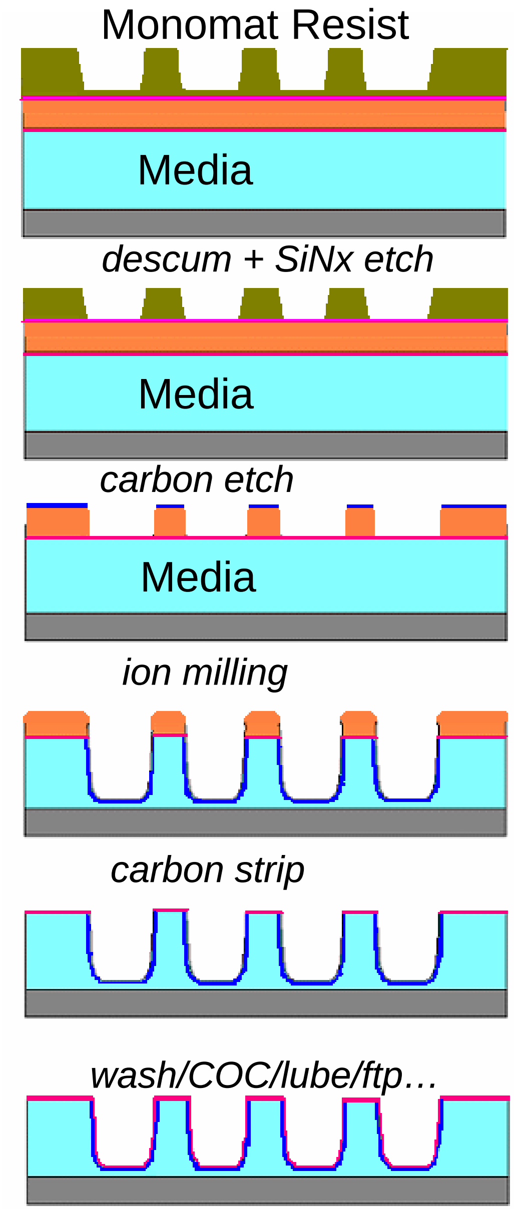




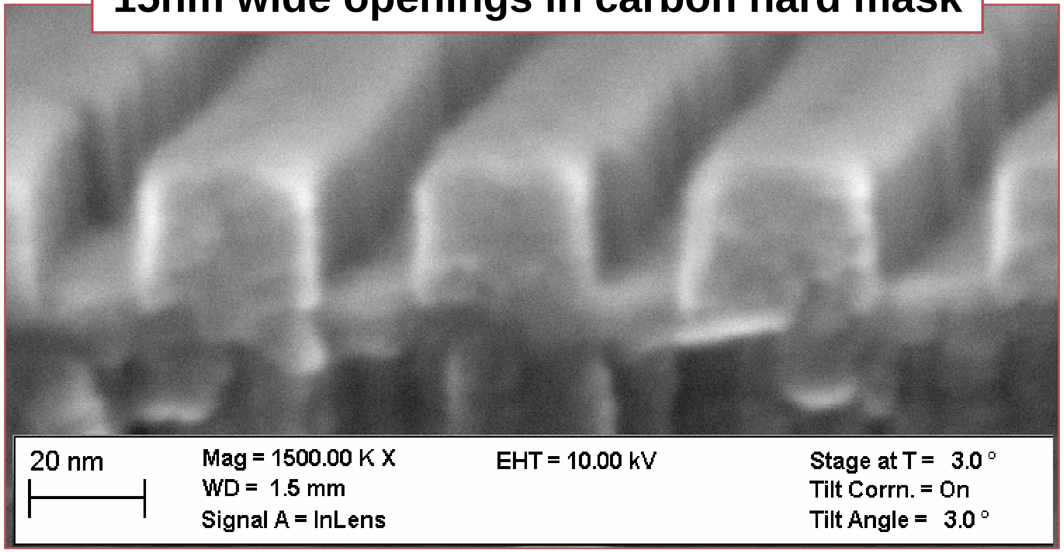
- **A thin residual layer thickness is required for pattern transfer purposes**
- **AFM measurement along a scratch on the imprinted resist can measure the RLT**
- **With the appropriate ink jet dispense pattern, RLT can be kept below 10nm**


Template Fabrication
Media Fabrication Process
Existing Processes
New Processes
Rotary Stage E-Beam Patterning
(Directed Self-Assembly)
Master Template Fabrication
Template Replication
Incoming disk substrate
Deposition of magnetic layers
Nanoimprint
Pattern Transfer (i.e. Etching)
Planarization
Lube and Burnish
Inspection/Test

Media Etch Process Flow



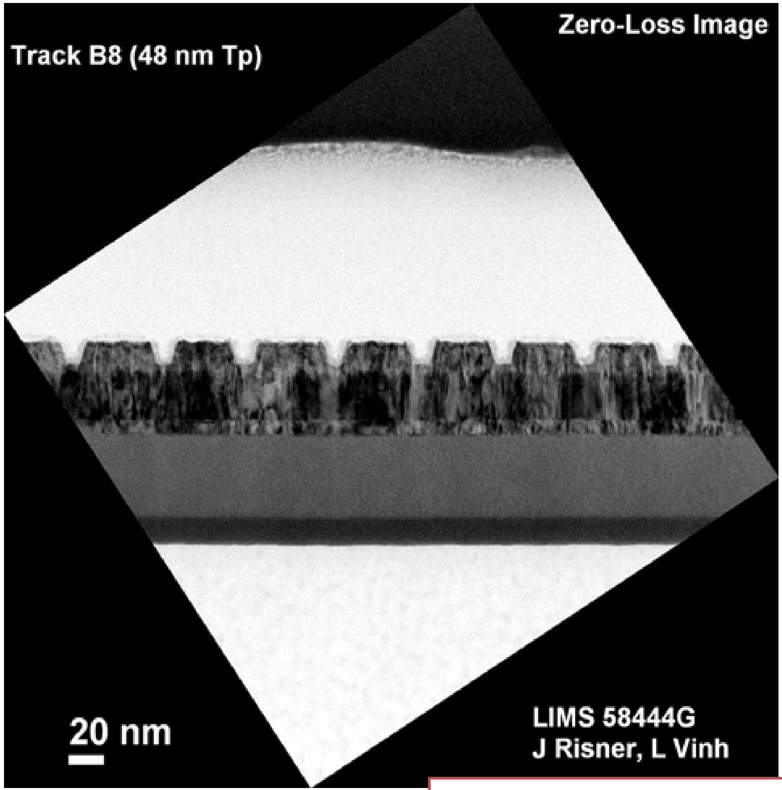
15nm wide openings in carbon hard mask

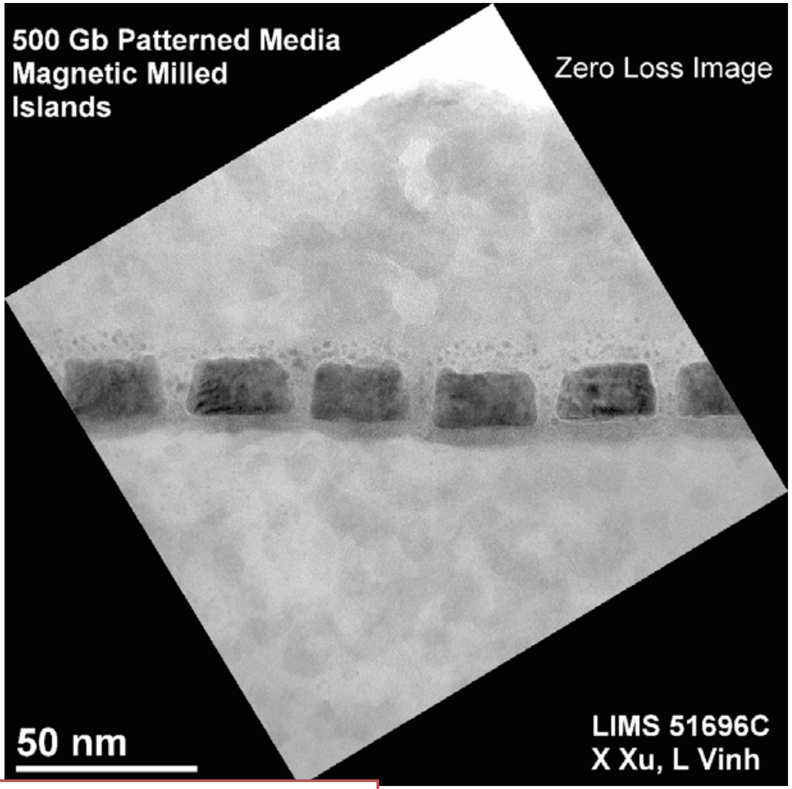


- **The media etch process flow transfers the imprinted pattern into a carbon hard mask**
- **A CO2 plasma etch for Carbon hard masks can produce very vertical wall angles**
- **Carbon is the best material choice as an ion milling hard mask due to its low sputter yield**
- **After the media etch and hard mask strip, a final carbon overcoat is deposited to stop corrosion**

Etching of Magnetic media

- **Magnetic materials can not be etched with a reactive process**
- **Ar ion beam etching, or sputter etching, is used to transfer the image into magnetic films**
- **Both tracks and dot patterns can be etched**





TEM images of etch magnetic films

High Resolution Media Etching

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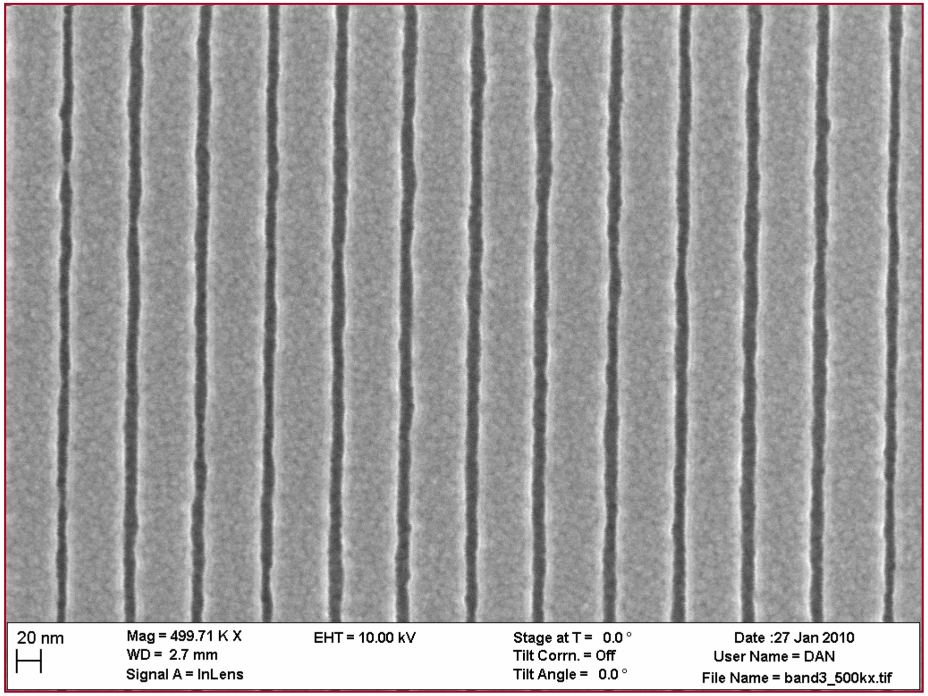
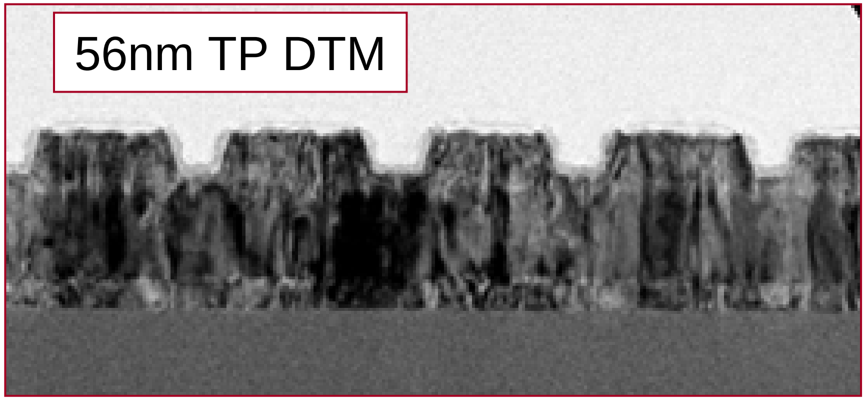
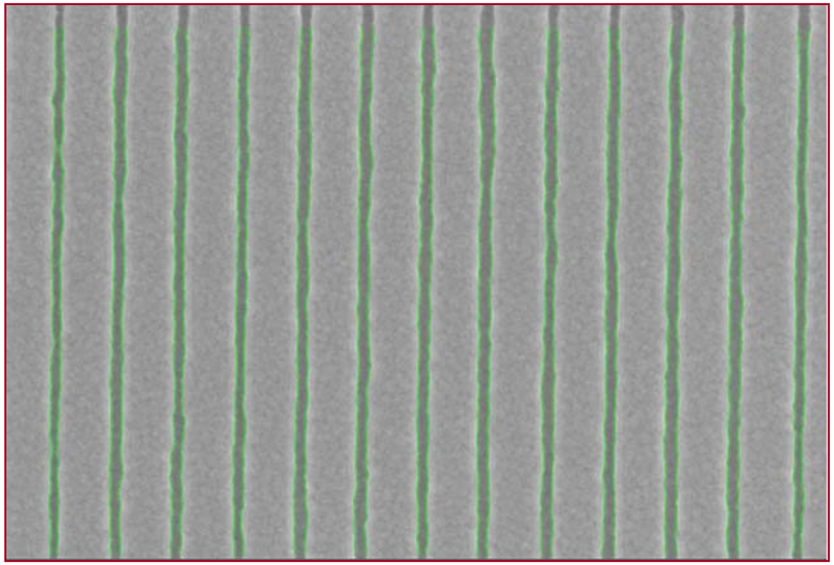




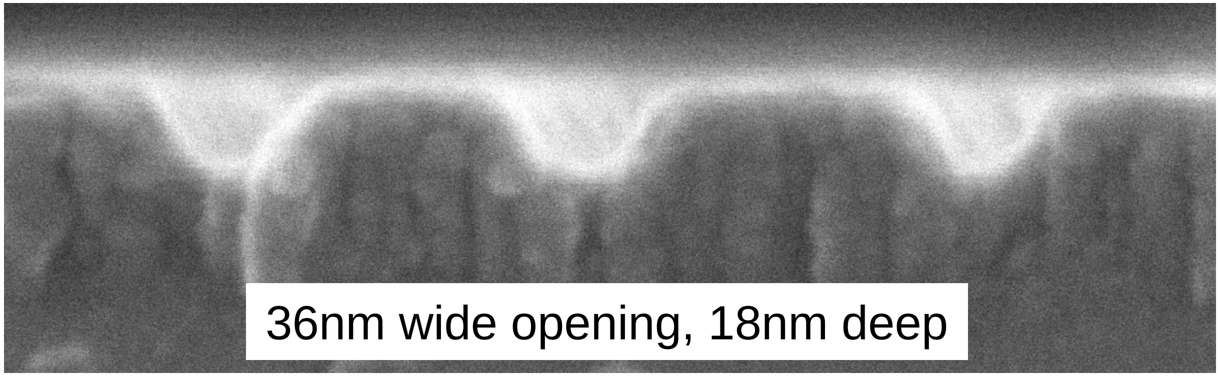


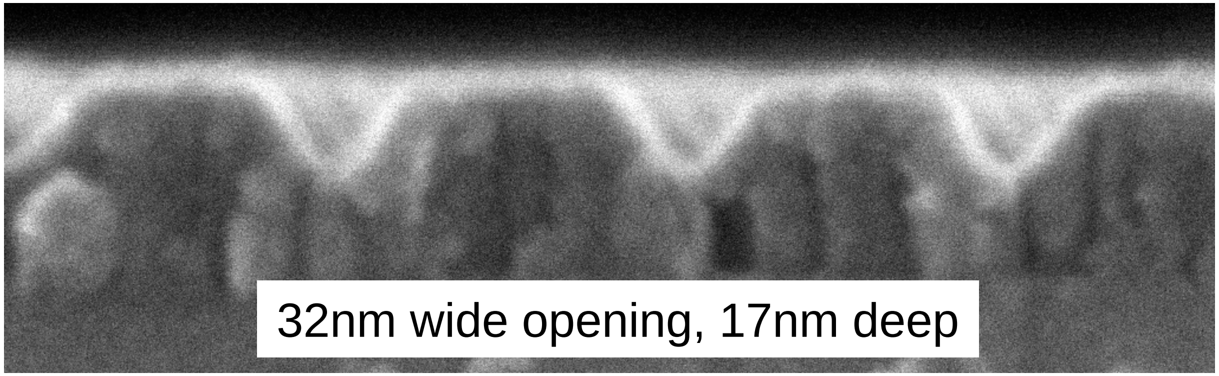
LER: 2.3 nm 3σ LWR: 3.5 nm 3σ

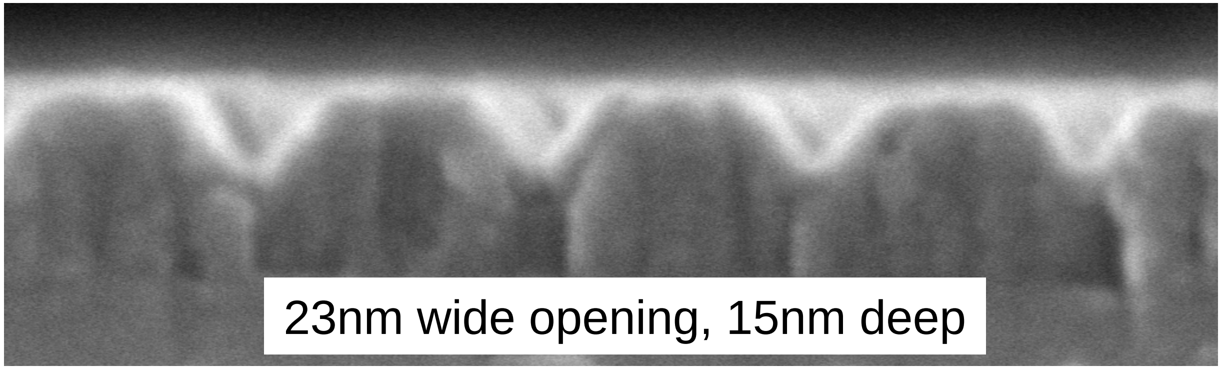
- **Pattern transfer from nano-imprinted resist can result in very well defined magnetic patterns**
- **LER less than 1nm at 1 sigma**

Limitations for Patterned Media Etching?

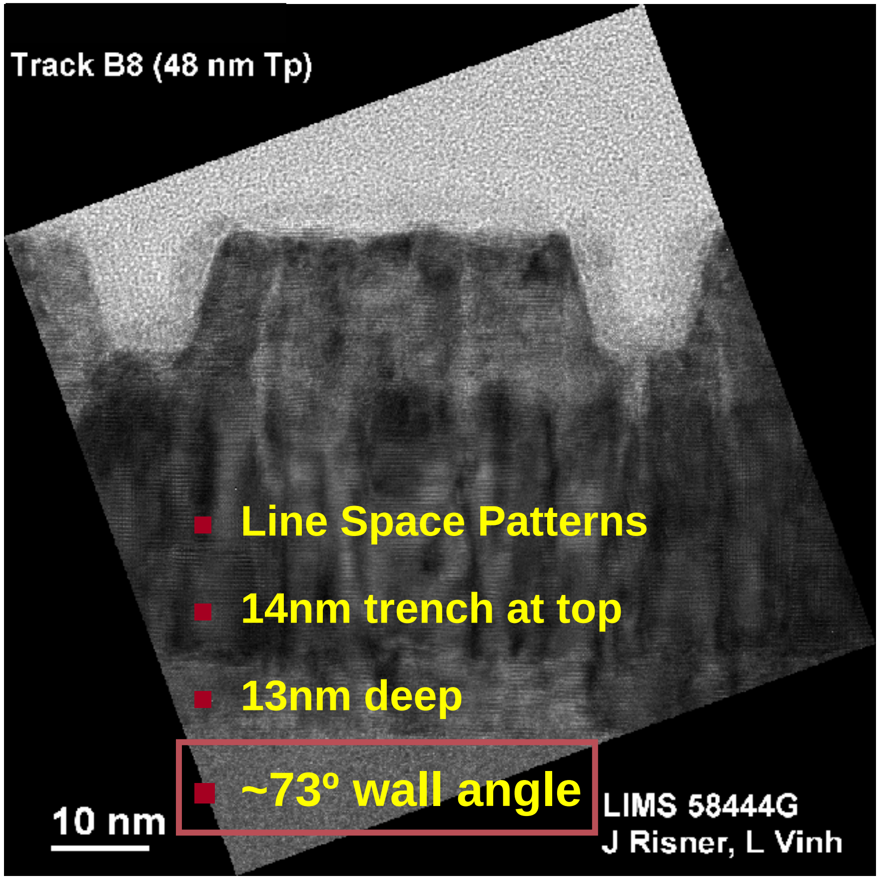
- Experiments have shown some limitations of our process when ion beam etching narrow features
- The etch front appears to pinch off for smaller features
- SEM images show 36, 32, and 23nm grooves all etched on the same disk

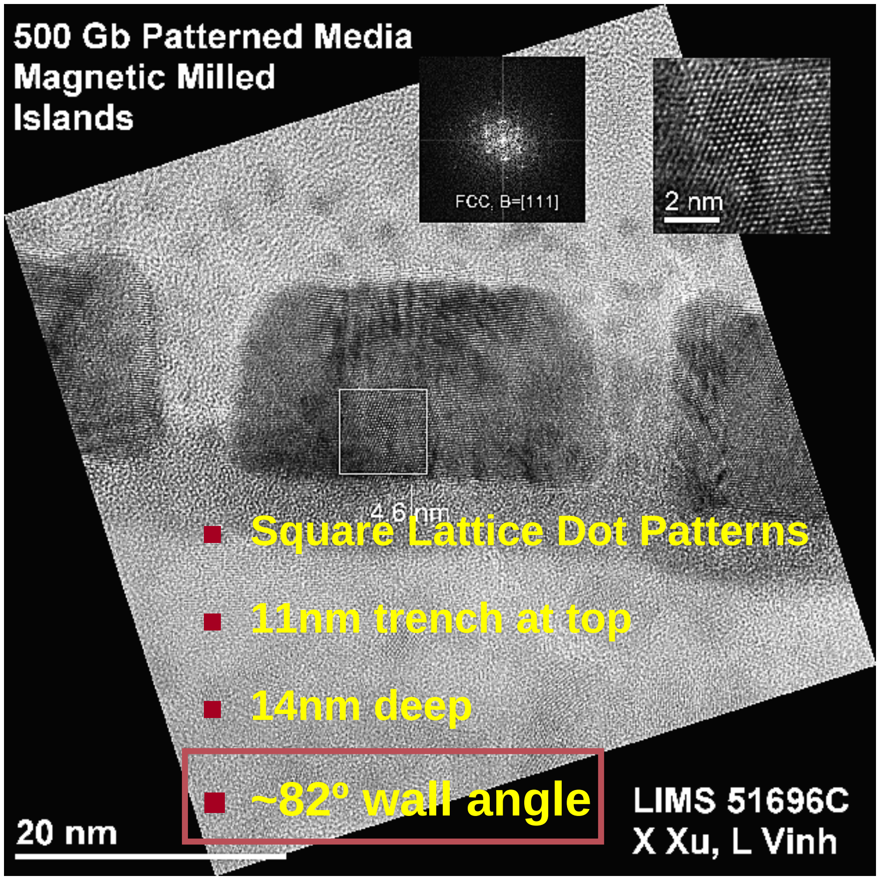






Sidewall Angle Comparison Between Lines and Dots

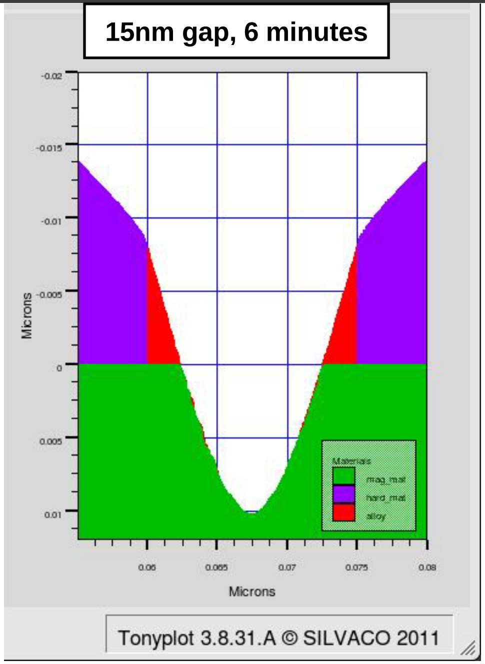


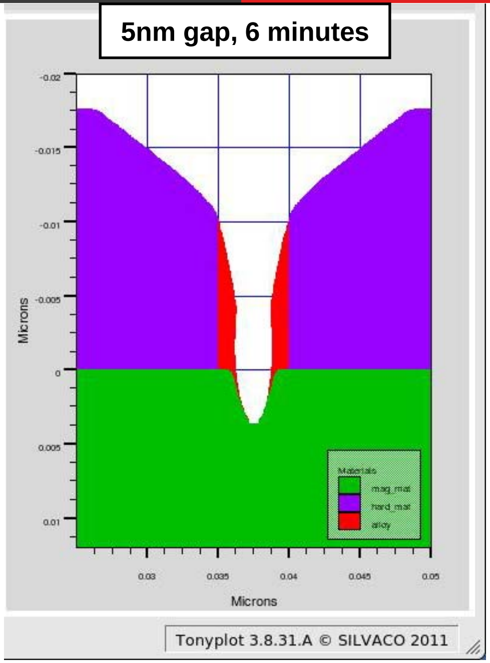


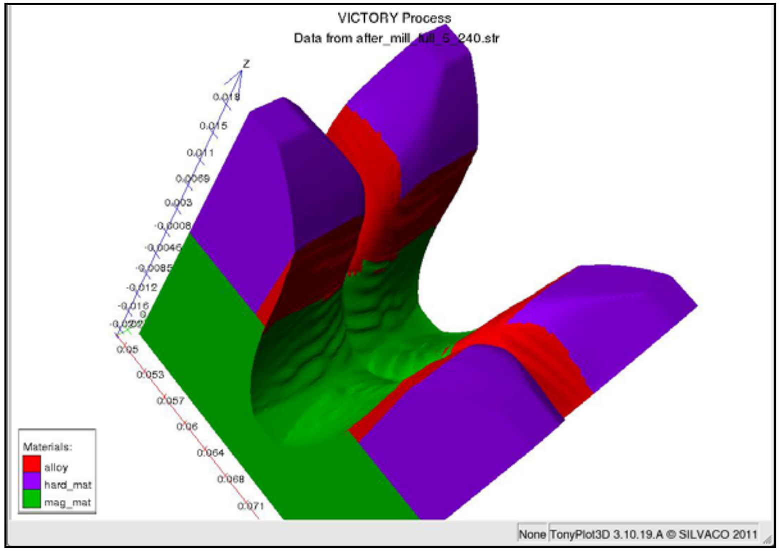
- **Line/Space patterns, with less solid angle for etch material to escape, have shallower sidewall angles**

Ion Beam Etch Test Simulation

- **A patterned media type Monte Carlo simulation was run using the Silvaco Victory Etch package**
- **The simulation shows the etching of magnetic bits with a carbon hard mask**
- **Two different bit spacings were investigated in the same simulation run**
- **When considering beam tilt, rotation, beam divergence, and mask erosion, there is significant pinch-off for small dimensional features**

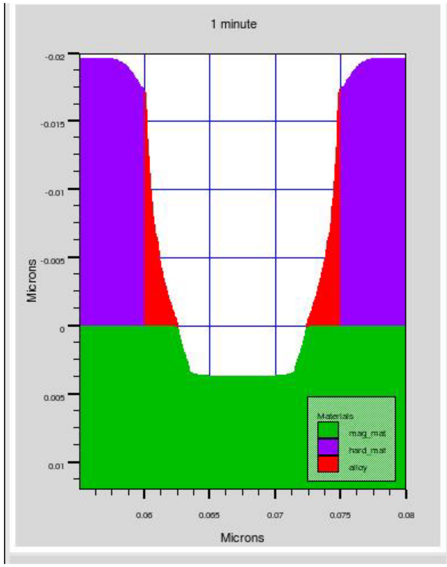




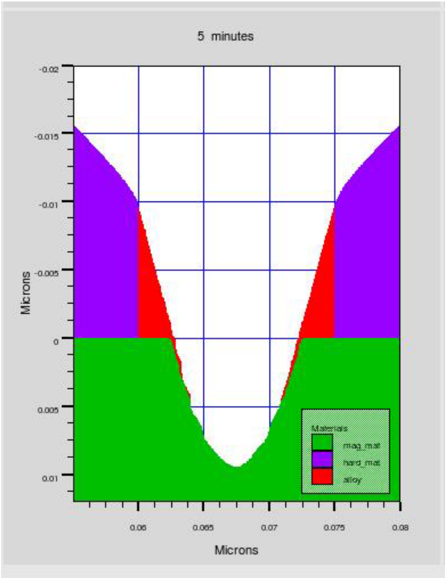


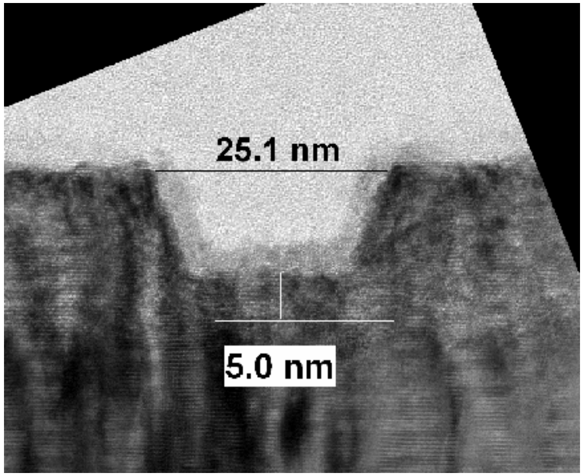
Comparison With Real World Observations: Pinch-off

- **As the etch time increases, the rate decreases and the flat etch bottom is lost**

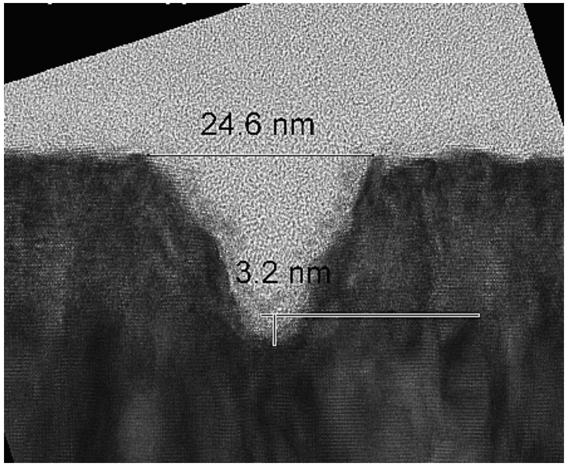


Simulation: 15nm groove
t = 1min → 5min





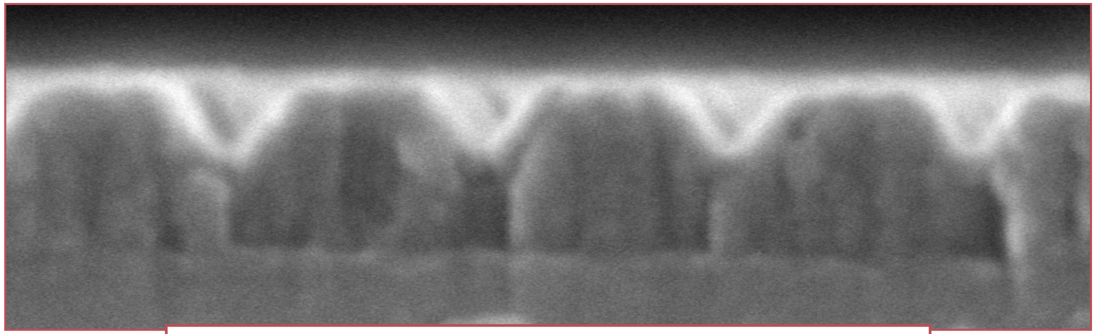
DTR Tracks: 25nm groove
t = 2min → 5min



Comparison With Real World Observations: Etch Depth

- **Narrow etched grooves show shallow etch depth: all images at t = 5min mill**

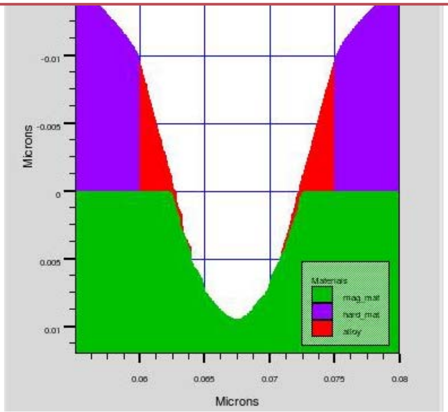
36nm wide opening, 18nm deep



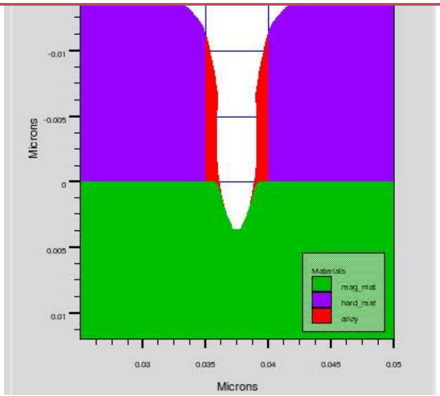
23nm wide opening, 15nm deep

Media etch performance can be improved with sturdier and thinner hard masks

15nm wide opening, 9nm deep



5nm wide opening, 4nm deep



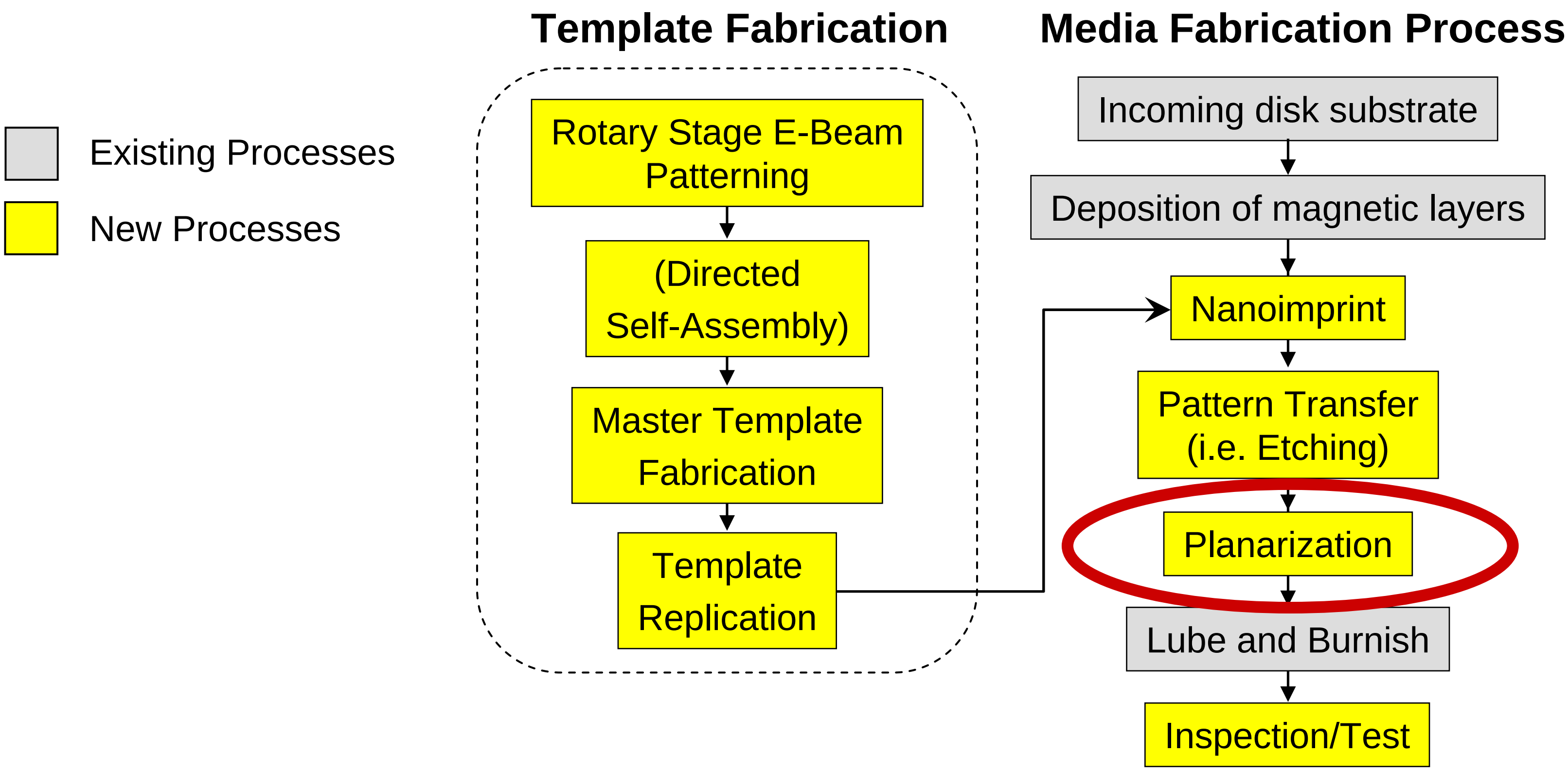
High Volume Disk Etching

- **HGST investigated potential high volume patterned media etch equipment from Veeco, Cannon-Anelva, and Intevac**
- **Lifecycle problems and grid replacement costs were problems for ion beam etch systems**
- **In 2010 HGST purchased an Intevac disk etch tool that utilizes CCP and ICP stations for reactive ion and sputter etch processes, as well as disk planarization**
- **High disk throughput, ~500 dph can be achieved with a proper process flow**

INTEVAC

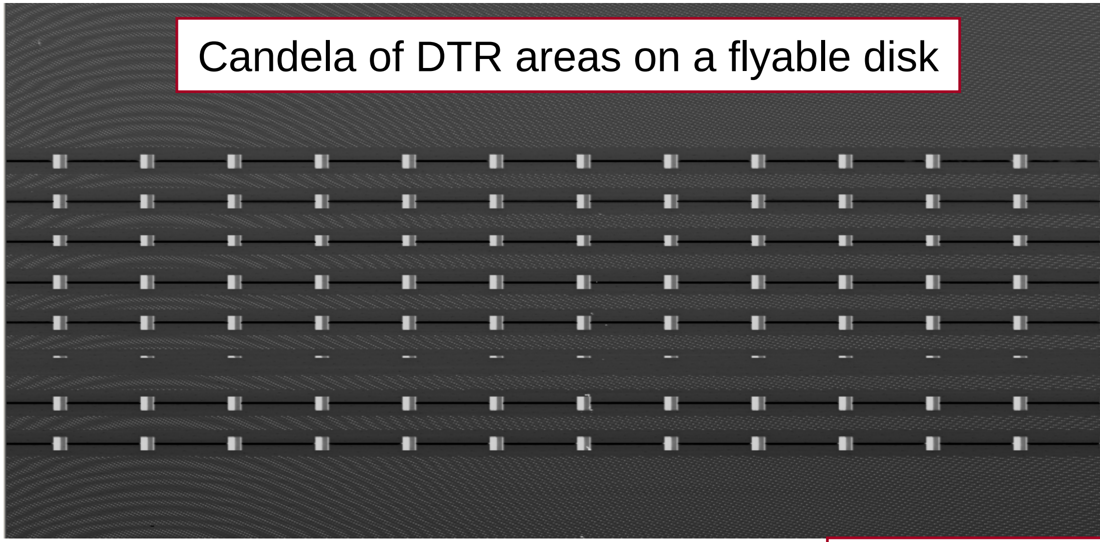
Lean 200 Disk Platform

Disk Planarization



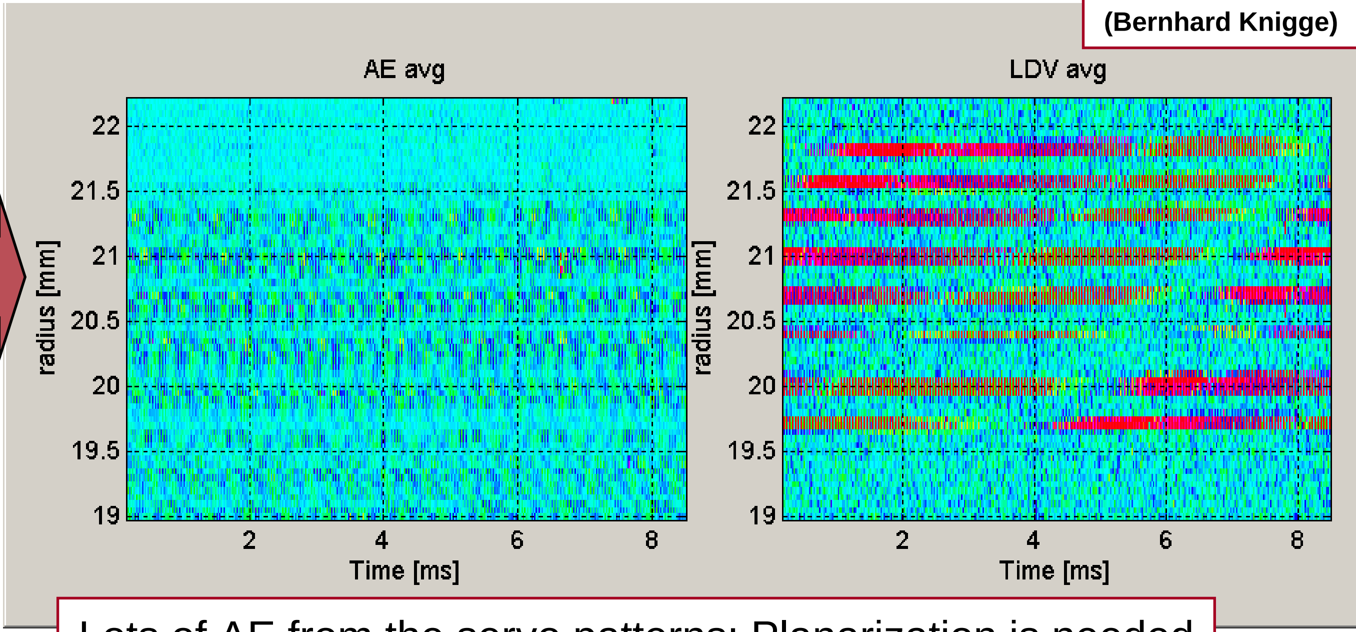
Flyable Imprinted Disks

- The imprint pattern transfer process can produce clean and flyable disks
- Finished disks can be tested on the drag tester, spin stand, and in prototype drives
- Variations in pattern density result in fly height modulation



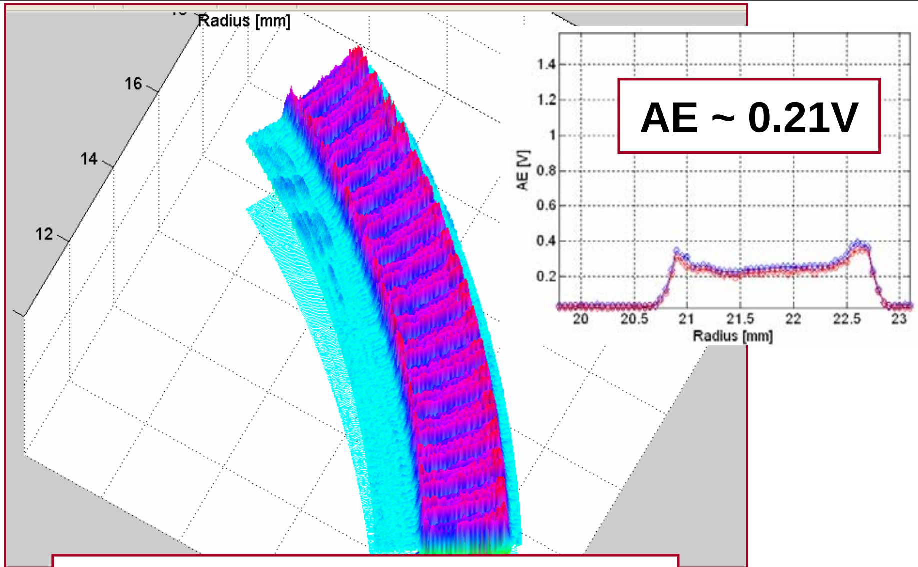
(Bernhard Knigge)

- AE and LDV maps on an imprinted disk
- Fly height ~3.0nm

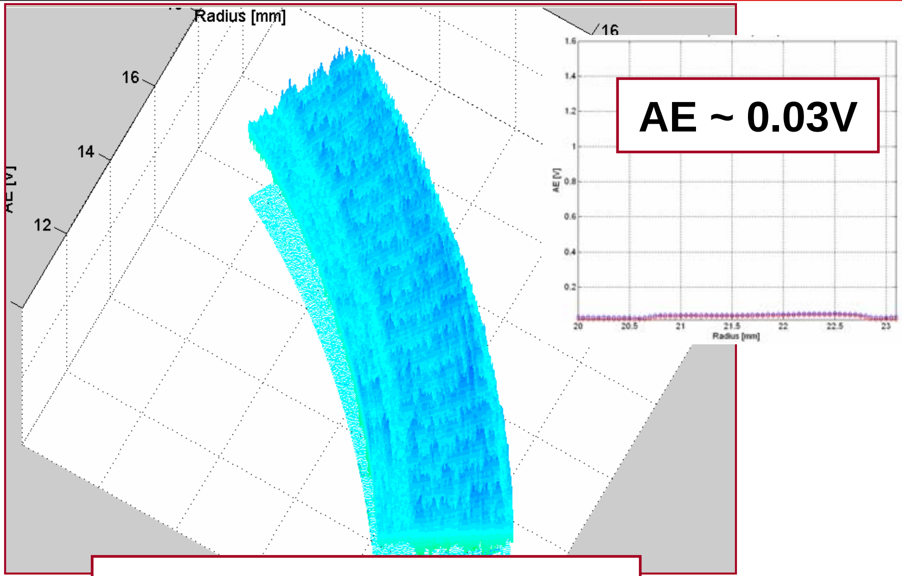


Lots of AE from the servo patterns: Planarization is needed

Improved Flyability with Planarization



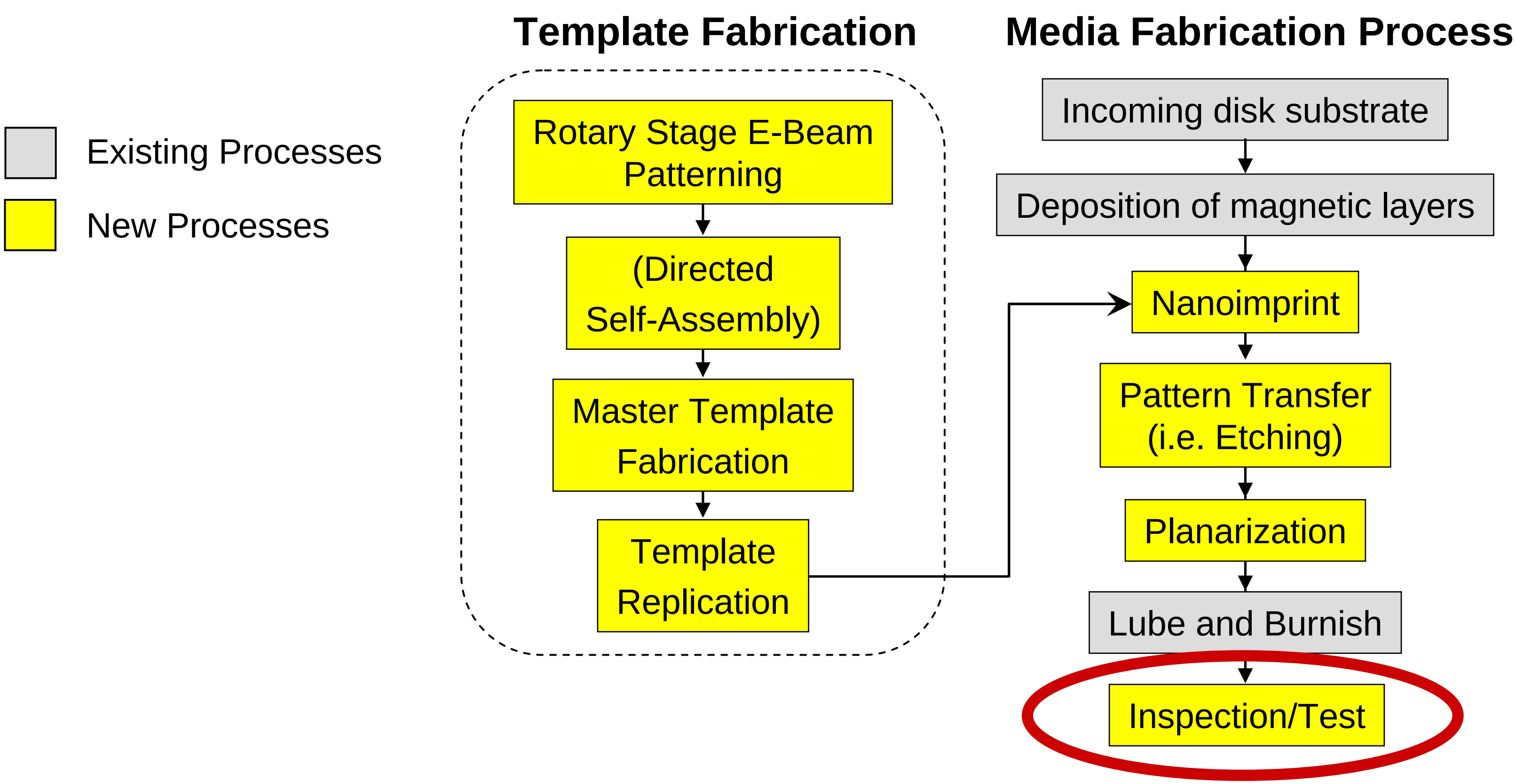
DTM Media Un-planarized



DTM Media Planarized

- **Imprint planarization has been used to fill 20nm deep DTM grooves**
- **Acoustic emission data is shown from a read/write head flying at 3nm height on a 2mm wide DTM area**
  - **Large acoustic emission is due to unplanarized servo patterns (left image)**
  - **DTM patterns with a 5nm recess have a much lower acoustic emission (right image)**
- **The process is clean enough that read-write heads can fly and perform testing**

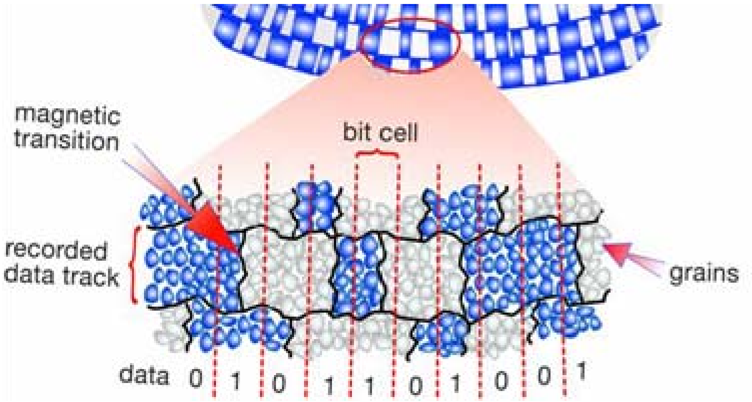
Inspection/Test

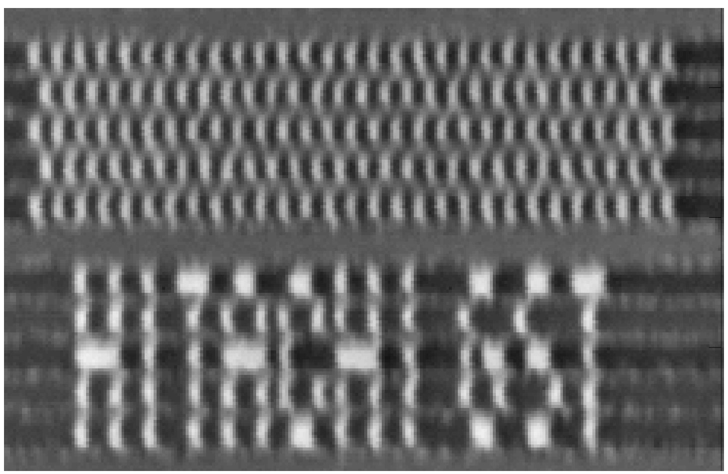


Conventional Recording vs. Bit Patterned Recording

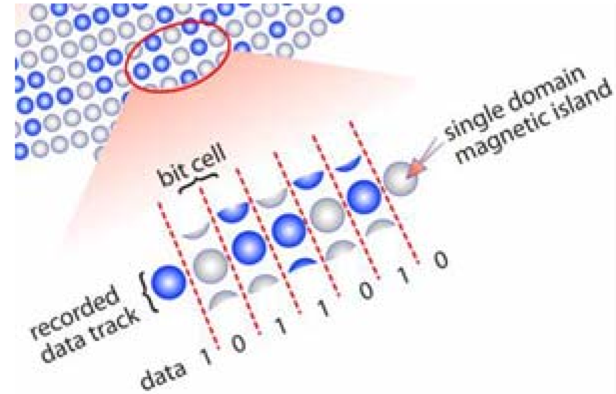
HITACHI
Inspire the Next

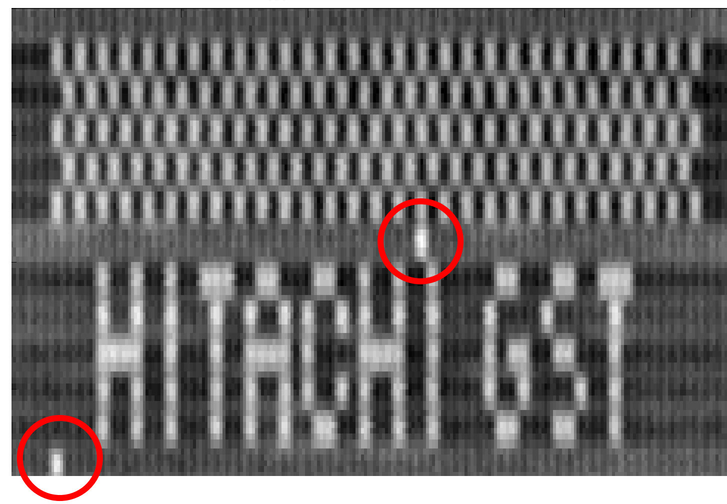
Conventional granular media





Bit patterned media





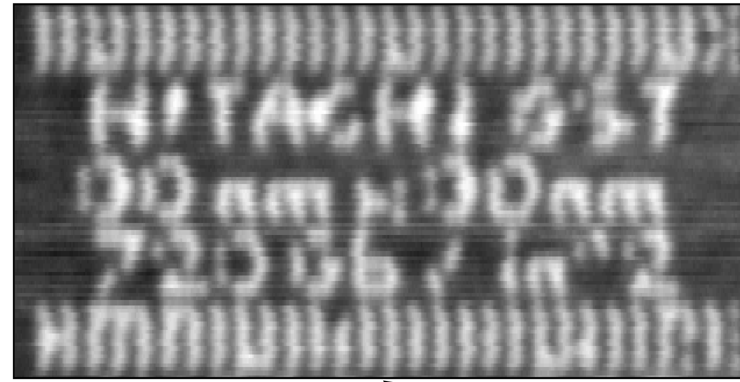
- Bit shape: defined by head field profile (curved) vs. patterned island shape
- Noise: grain statistics vs. patterning roughness, write errors, and tolerances
- Thermal stability and bit errors: grain reversal vs. island reversal

BPM Areal Density Progress at HGST

HITACHI Inspire the Next

Drag tester results: M. Grobis

720 Gb/in²



100 Gb/in²

200 Gb/in²

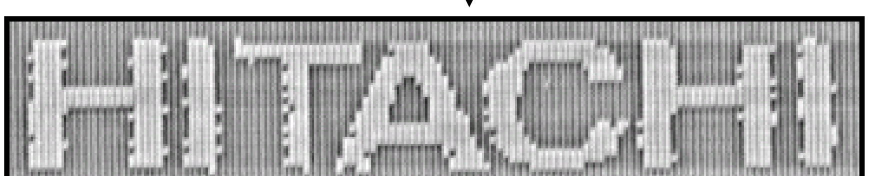
300 Gb/in²

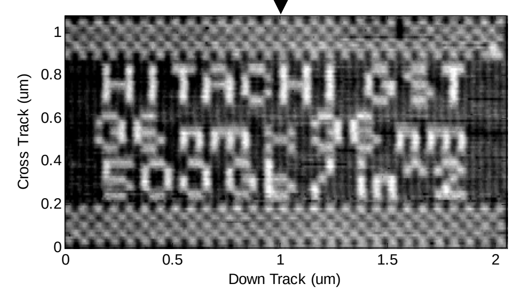
500 Gb/in²

720 Gb/in²

2007 | **2008** | **2009** | **2010** | **2011**

~ 10 Gb/in² (multiple islands/bit)

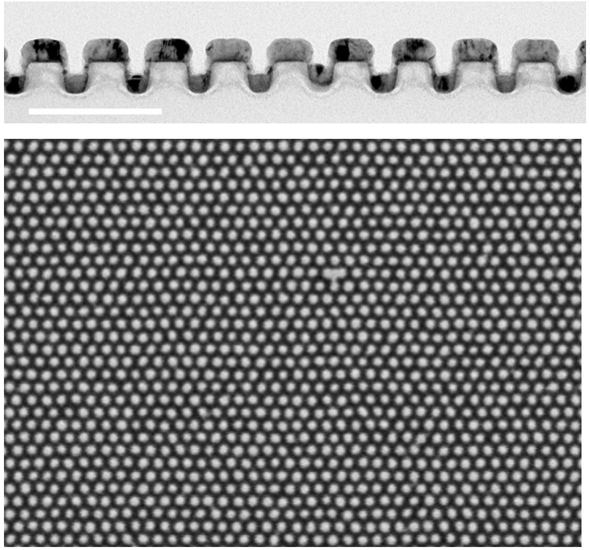




500 Gb/in²

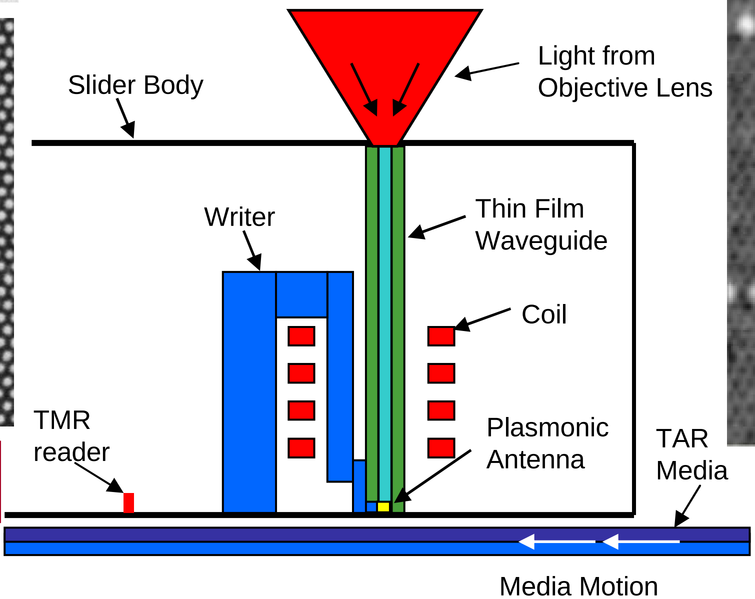
BPM + Thermal Assist Head: 1 Tb/in^2

Co/Pd Media on Pre-Patterned Substrate

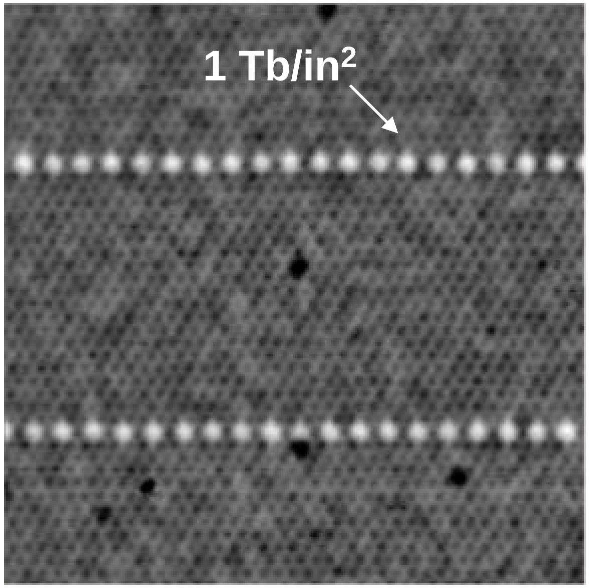


1Tb/in^2 = 27nm pitch

Schematic of a TAR Head



MFM Image of Tracks



- Combination of TAR and BPM (BP-TAR) is capable of extremely small track pitch
  - 24nm track pitch with similar notch width in near field optical aperture
  - Near-field focusing on islands
  - Restricted lateral heat flow
- Five times lower threshold laser power compared to continuous media using same head

B. Stipe et al., Nature Photonics 2010

Summary

- Patterned Media is a potential solution for extending the areal density growth of magnetic data recording beyond the limits of conventional media
- The small size and tolerances required, down to 1 σ = ~1 nm , suggest that master pattern generation will be done with a rotary stage e-beam tool plus lithographically assisted self assembly
- Nano-imprint template fabrication relies on high quality dry etch recipes
- Pattern transfer of nano-imprinted disks can create flyable disks
- To be competitive patterned media must achieve both high areal density and low cost manufacturing
- Patterned media combined with thermal assisted recording shows promising benefits to maintain the needed growth in bit areal density