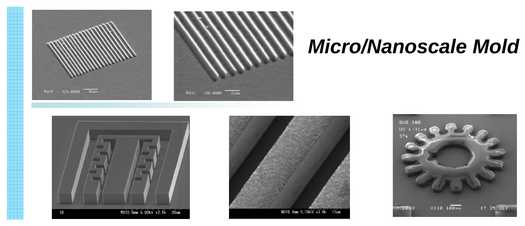
3-D Mold Fabrication by FIB for Polymer Replication: Experimentation and Optimization

Chung-Soo Kim and Jung-Bin Park

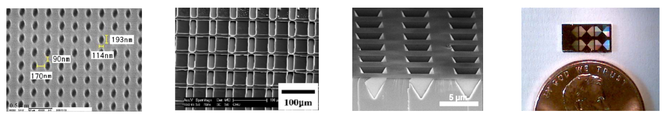
Sponsored by course of Design for Manufacturing in Seoul National University
Seoul National University of Technology for Focused Ion Beam System
Nano Fusion Technology Laboratory in SNU for Polymer Replication

Mold Fabrication

- Macro-Machining
- Micro-Transfer & Injection Molding
- Charged Particle Beam Lithography
- Imprint Lithography
- Femto-Second Laser
- Eximer Laser

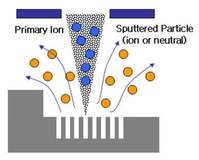


Micro/Nanoscale Mold

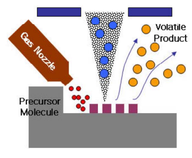


Focused Ion Beam

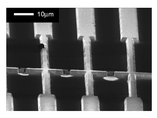
- Merits
  - High throughput, low penetration depth
- Hybrid process
  - Material destruction & Construction
- Various material
  - Destruction : All solid materials
  - Construction : C, W, Pt
- Scalable 3-D structure
  - Micro/Nanoscale 3-D construction
- Various application
  - MEMS/NEMS, SPM tip
  - Micro/Nanoscale medical device
  - Photonic device
  - Micro/Nanoscale mold



Destruction (Sputtering: Milling)

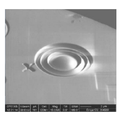


Construction (Deposition: FIB-CVD)

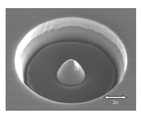


MEMS

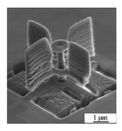
Fresnel Micro-Lens



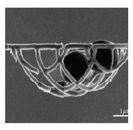
Tip



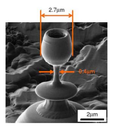
Manipulator



Nano-rotor



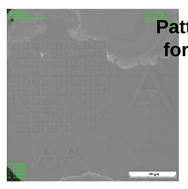
Nano-net



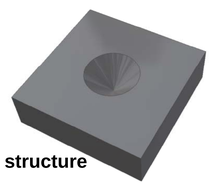
Wine glass

Material Selection

- Silicon substrate
  - Easy to get
  - Good surface roughness
  - Mesh Pattern for good positioning
    - 4 x 4 arrays in 1 substrate: 10 x 10 arrays in 1 array
- Conical structure
  - Variable 3-D structure
  - Dimension : Diameter (1.2 nm), Depth (0.6 nm)



Patterned silicon substrate for micro-mold fabrication

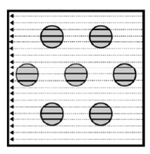


Desired Micro-mold structure

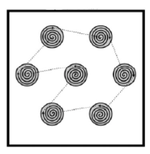
Nanofabrication Schematics

Scan Method

- Spiral Scan
  - A part of vector scan
  - Precious control (higher resolution than raster scan)
- 3-D Conical structure
  - Variable 3-D structure
  - Dimension : Diameter (1.2 micrometer), Depth (0.6 micrometer)



Raster scan



Spiral scan

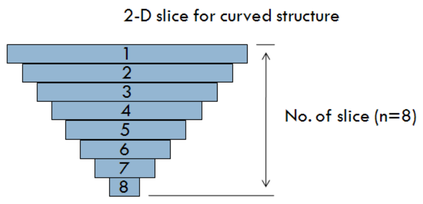
Parameter Selection

- Ion beam condition
  - 30 KeV Ga2+ ion beam
  - 91 pA of ion beam, 30 nm of spot diameter, and 13 A/cm2
  - 30 nm pixel size when 24 micrometer field of view (screen size)
- Processing condition (4 main factors)
  - Ion dose (ions/cm2): Quantity of ion
  - Dwell time (usec): Staying time of ion beam in 1 pixel
  - Beam overlap (%): How much the spot dia. overlaps
  - No. of slice:

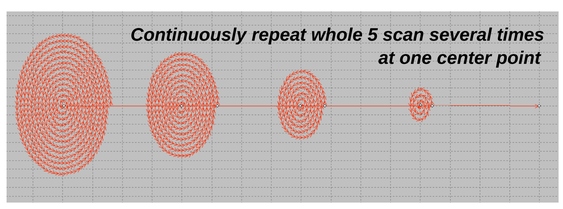
Comparisons btw Raster & Spiral Scan

	Raster scan	Spiral scan
1	Ion dose	Count Number
2	Dwell time	Dwell time
3	Beam overlap	Beam overlap
4	-	No. of slice

Fabrication Strategy



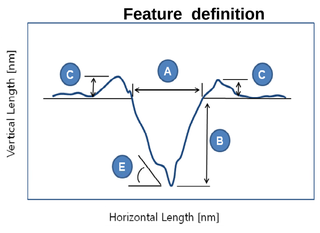
Continuous Slicing Method



Extended Continuous Slicing using Spiral Scan

Evaluation

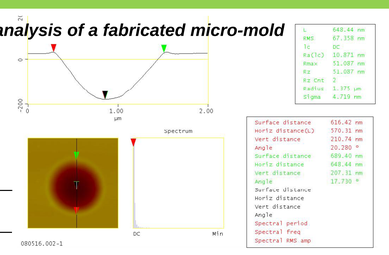
Feature definition

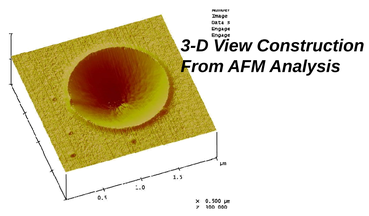


- Structural stability
  - A : Diameter [nm]
  - B : Depth [nm]
  - C : Height of the rim [nm]
  - E : Sidewall angle (°)
- Efficiency
  - Sputter yield [nm³/pC]
  - Cost

Experimental Design & Evaluation

2-D AFM analysis of a fabricated micro-mold





3-D View Construction From AFM Analysis

Levels of factors & Experimental condition

Level	Factor			
	Total count	Dwell time	Overlap	No. of slice
1	10000	0.5	0.5	5
2	20000	1	1	10
3	30000	2	1.5	15

$L_9(3^4)$ Orthogonal Array & Experimental Results

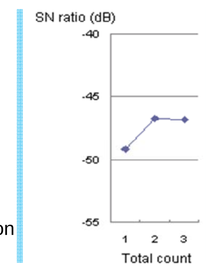
Orthogonal Array					*Structure dimension*								*Efficiency*			
No.	**Total Count**	**Dwell time**	**Beam overlap**	**No. of slice**	**Width (nm)**	***SN ratio***	**Height (nm)**	***SN ratio***	**Side wall angle**	***SN ratio***	**Height of rim (nm)**	***SN ratio***	**Sputter yield (nm³/pC)**	***SN ratio***	**Cost (200 EA, Won)**	***SN ratio***
1	1	1	1	1	1238.5	*-31.7*	459.5	*-43.0*	33.6	*-21.2*	10.8	*-20.7*	1432926	*123.1*	876973	*-118.9*
2	1	2	2	2	1199.5	*6.0*	205.7	*-51.9*	18.8	*-28.4*	6.1	*-15.7*	1654608	*124.4*	759477	*-117.6*
3	1	3	3	3	1215.0	*-23.5*	170.0	*-52.7*	15.7	*-29.3*	4.8	*-13.5*	1871086	*125.4*	671608	*-116.5*
4	2	1	2	3	1195.5	*-13.1*	735.1	*-42.6*	50.9	*-15.4*	16.7	*-24.5*	1468597	*123.3*	855671	*-118.6*
5	2	2	3	1	1223.0	*-27.2*	148.7	*-53.1*	13.6	*-29.9*	6.0	*-15.5*	2486783	*127.9*	505326	*-114.1*
6	2	3	1	2	1179.5	*-26.2*	768.6	*-44.5*	54.3	*-19.4*	30.3	*-29.6*	629341	*116.0*	1996748	*-126.0*
7	3	1	3	2	1125.0	*-37.5*	231.8	*-51.3*	21.8	*-27.3*	8.8	*-18.9*	1640149	*124.3*	766172	*-117.7*
8	3	2	1	3	1172.0	*-28.9*	769.7	*-44.6*	52.9	*-17.9*	27.2	*-28.7*	762776	*117.6*	1647451	*-124.3*
9	3	3	2	1	1183.5	*-24.3*	769.9	*-44.6*	53.3	*-18.4*	27.3	*-28.7*	861307	*118.7*	1458987	*-123.3*
	Ref. condition				**1200.0**		**600.0**		**45.0**		**0.0**		**lager**		**smaller**	

Optimum Experimental Condition

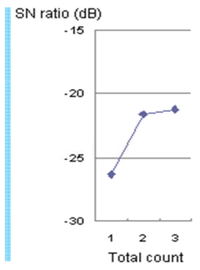
Evaluation value		Optimal condition			
		Total count	Dwell time	Overlap	No. of slice
Structural stability	Width	10000	1	1	10
	Height	20000	0.5	0.5	15
	Side wall angle	***30000***	***0.5***	***0.5***	***15***
Physical error	Height if the rim	10000	1	0.5	10
Efficiency	Sputter yield	10000	0.5	1.5	5
	Cost	10000	0.5	1.5	5

Discussion

- Structural stability
  - Different condition come out for with, height, and sidewall angle
  - Always good result in case of width
  - Btw Height & Sidewall
    - Dwell time & Overlap & No. of slice were the same
    - Total count : 30,000 (smaller SN ratio difference when height)
- Physical error
  - Base on Gaussian beam distribution, leads surface amorphization
  - Smaller when short irradiation time applied
- Efficiency
  - Sputter yield & Cost are the same
  - Short time when optimized by indicating the continuously-decreasing tendency of sputter yield as a function of time.

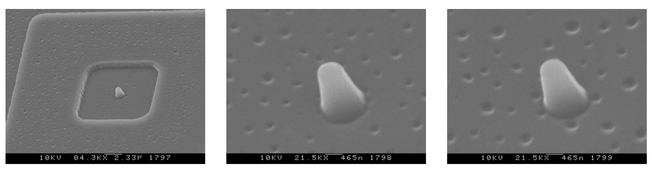


SN ratio of *Height*

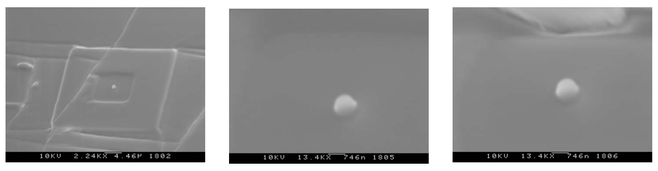


SN ratio of *sidewall angle*

Polymer Replication



PUA replication



PDMS replication

Conclusion

- Fabricate 3-D micro-mold
  - Continuous slicing method with spiral scan
  - Evaluation of Structural stability & Efficiency by using a specific evaluation form
- Optimization through Taguchi's experimental design
- Fabrication of mold by optimized condition
- Polymer replication by a silicon micro-mold

Chung-Soo Kim, 02-880-9073, reaves.kim@gmail.com
Jeong-Bin Park, 02-880-9073, jbpark82@snu.ac.kr