Nanometer Scale Patterning and Processing

Spring 2016

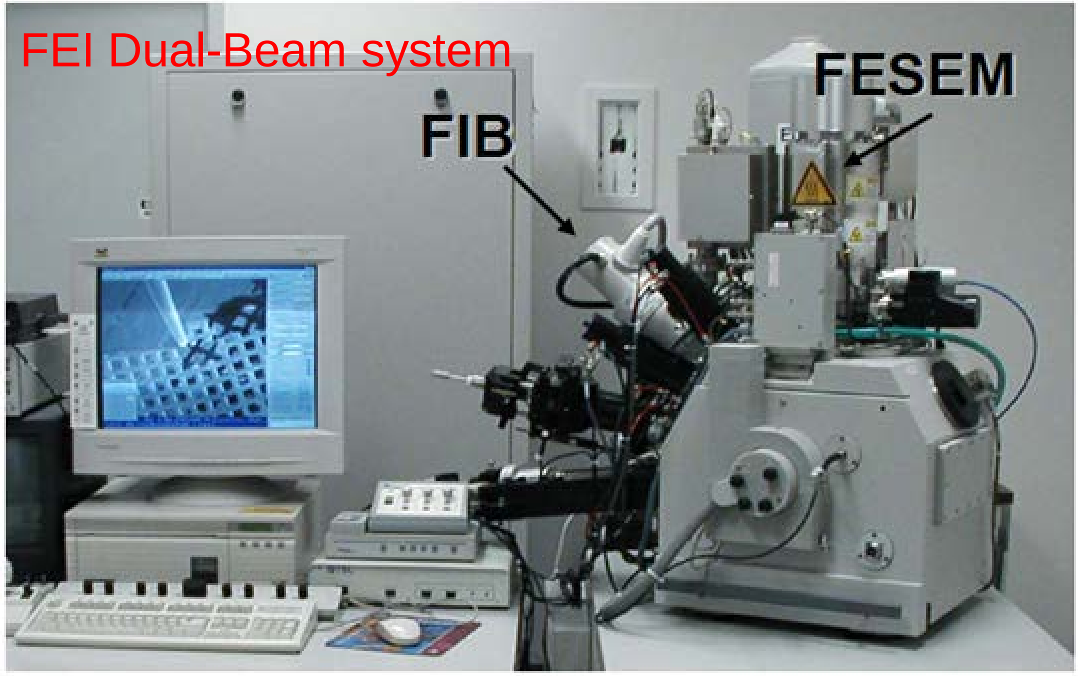
Lecture 28

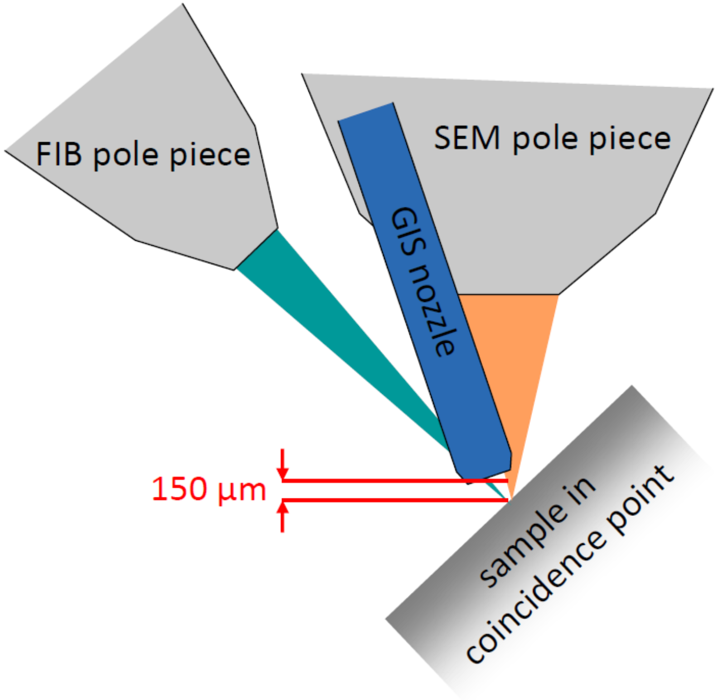
Focused Ion Beam Induced Deposition

Focused ion beam (FIB)

1. Focused ion beam induced deposition.
2. Focused electron beam induced deposition.
3. Deposition rate (electron and gas flux-limited regimes)
4. Deposit composition (carbon/metal)

DualBeam FIB/SEM plus GIS





GIS: Gas Injection Systems

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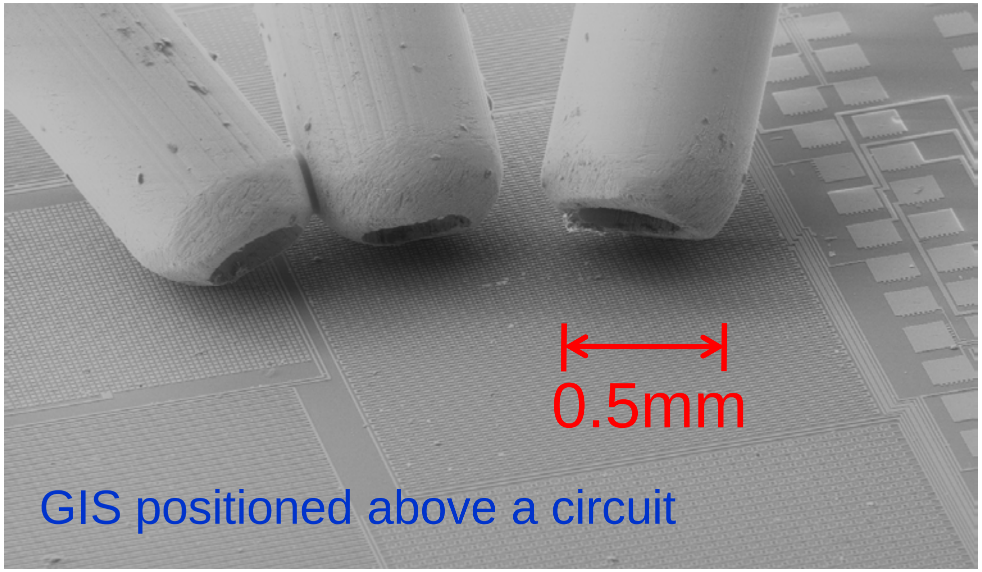
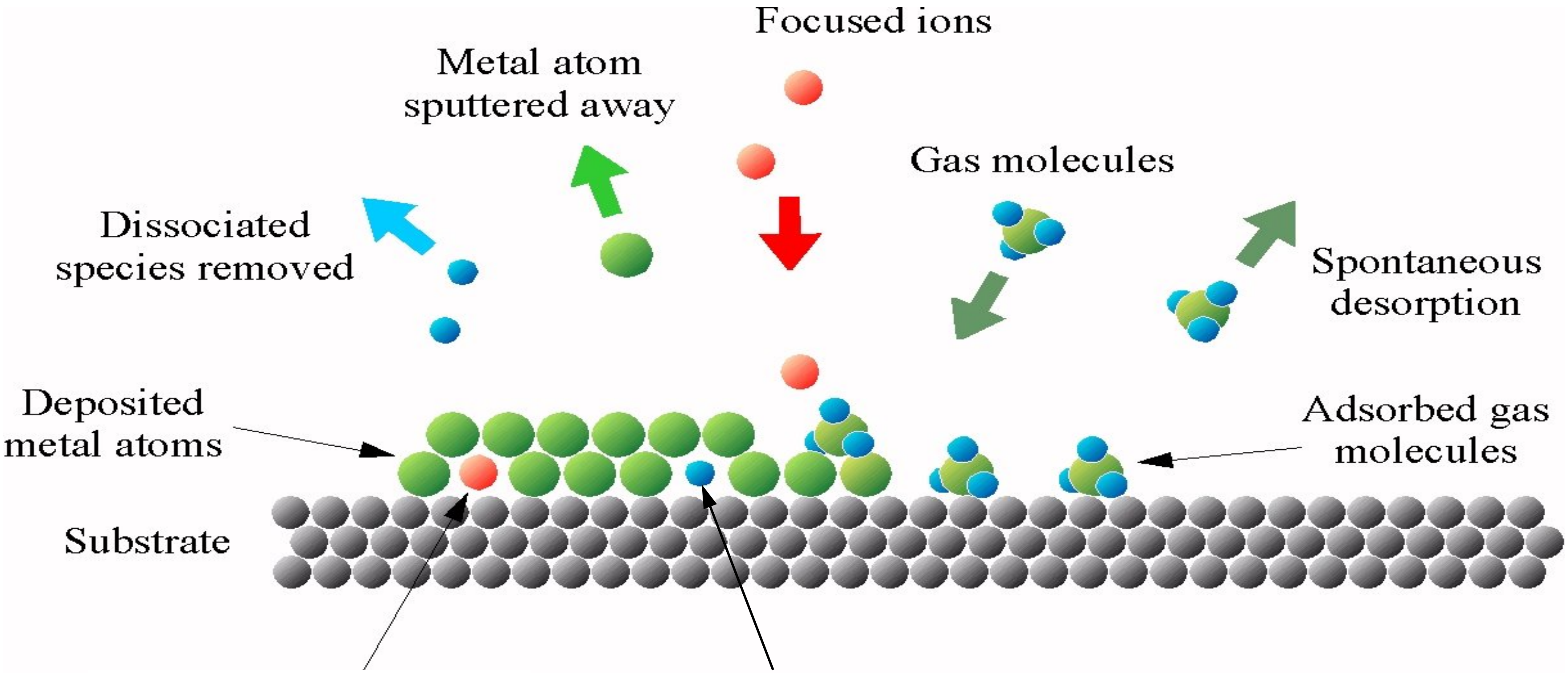


GIS positioned above a circuit

- Gases are delivered to the sample surface via a needle in close proximity to the surface (~50-150μm).
- Gas pressure is of order 10^{-5} mbar.
- Interaction of ion beam with gas causes either enhanced removal of sample material, or deposition of one of the elements within the gases.
- A metal-organic gas is used to deposit metals via ion/electron beam assisted chemical vapor deposition.
- An insulator can also be deposited, e.g. SiO_2 from tetraethyl orthosilicate (TEOS).
- Reactive gases are used to etch samples via reactive ion etching.

FIB assisted (chemical vapor) deposition process



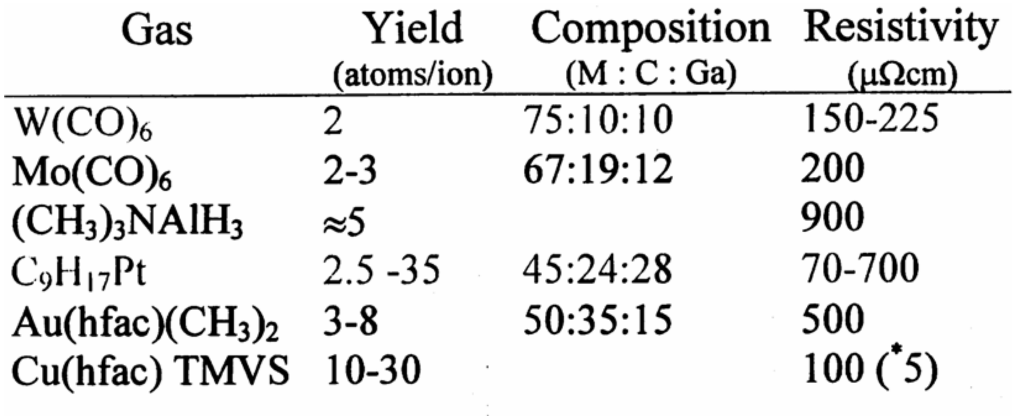
Primary ions remaining as impurities

Dissociated elements remaining as impurities

1. Adsorption of gas molecules on substrate
2. Dissociation/decomposition of gas molecules by the ion beam
3. Deposition of the material atoms and removal of the organic ligands

“Studies of structures elaborated by focused ion beam induced deposition”, Prestigiacomo, MEE 2004.

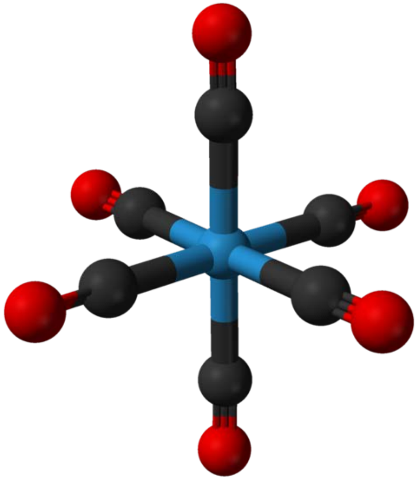
Gases used for metal, oxide and C deposition



Gas	Yield (atoms/ion)	Composition (M : C : Ga)	Resistivity (μΩcm)
$W(CO)_6$	2	75:10:10	150-225
$Mo(CO)_6$	2-3	67:19:12	200
$(CH_3)_3NAlH_3$	≈5		900
$C_9H_{17}Pt$	2.5 -35	45:24:28	70-700
$Au(hfac)(CH_3)_2$	3-8	50:35:15	500
Cu(hfac) TMVS	10-30		100 (*5)

hfac – hexafluoro acetyl
acetanoate
TMVS – trimethyl vinyl silane

$W(CO)_6$



More deposition materials:

- Al: Trimethylamine alane (TMAA), 1Torr vapor pressure at 25°C
- SiO_2: O_2 and tetramethoxysilane (TMOS) $Si(OCH3)_4$
- C: phenanthrene

Ion beam assisted deposition

Properties:

- Resistivity much higher than bulk value (10-5000×)
- Carbon contamination
- Gallium contamination
- Chemistry not well understood

Collision cascade model – Au deposition

- In principle, decomposition of precursor gas may take place either in the gas phase or on the surface; but actually deposition rate insensitive to gas pressure, so gas phase decomposition is unimportant.
- Deposition go beyond beam spot size with yield higher than would be by only direct ion-molecule collision.
- Yield better correlated with energy loss to the nuclei than with energy loss to the electrons.
- Therefore, collision cascade has to play an important role in the decomposition.
- In the case of gold, sputtering (of excited surface atoms) will occurs for E>3.8eV.
- For energy E>0.95eV (dissociation energy of the absorbate), deposition will occur.

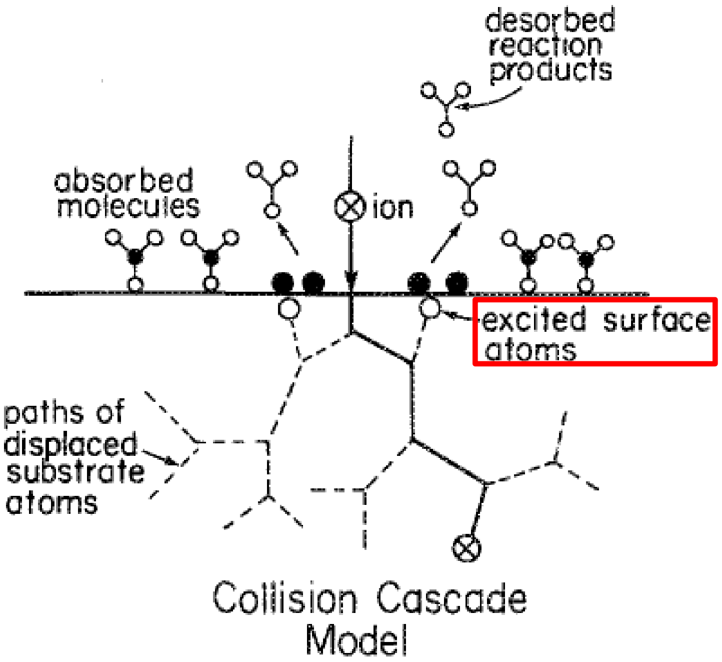


FIG. 4. Schematic of the collision cascade process of surface adsorbate decomposition.

“Mechanism of ion beam induced deposition of gold”, Melngailis, JVST B, 1994.

FIB deposition: role of SE and primary ion

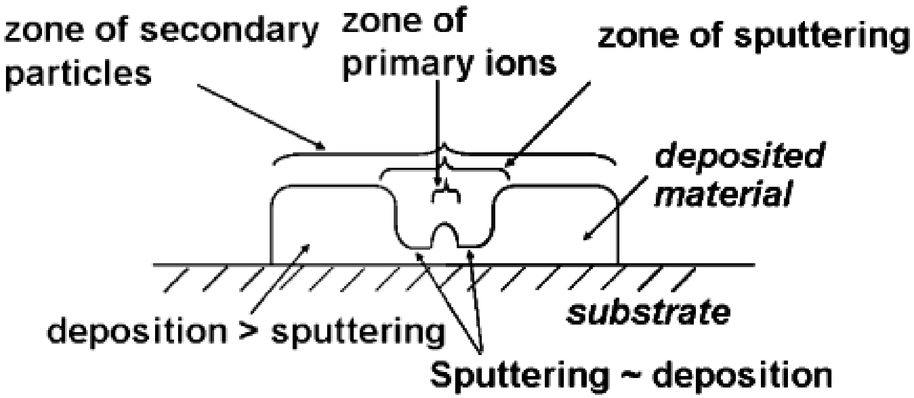


Fig. 5. Sketch of reaction zones of different mechanisms involved in IBID.

- Though the yield for primary ion induced deposition is low, its contribution is not negligible due to high ion flux (central tip).
- SE is most important, causing deposition well beyond beam size.
- Next to the beam, both sputtering and deposition (induced by secondary/ sputtered atoms) are important.
- At longer dwell time (1ms), gas is depleted at the beam center and net sputtering occurs, leading to a central nano-hole.

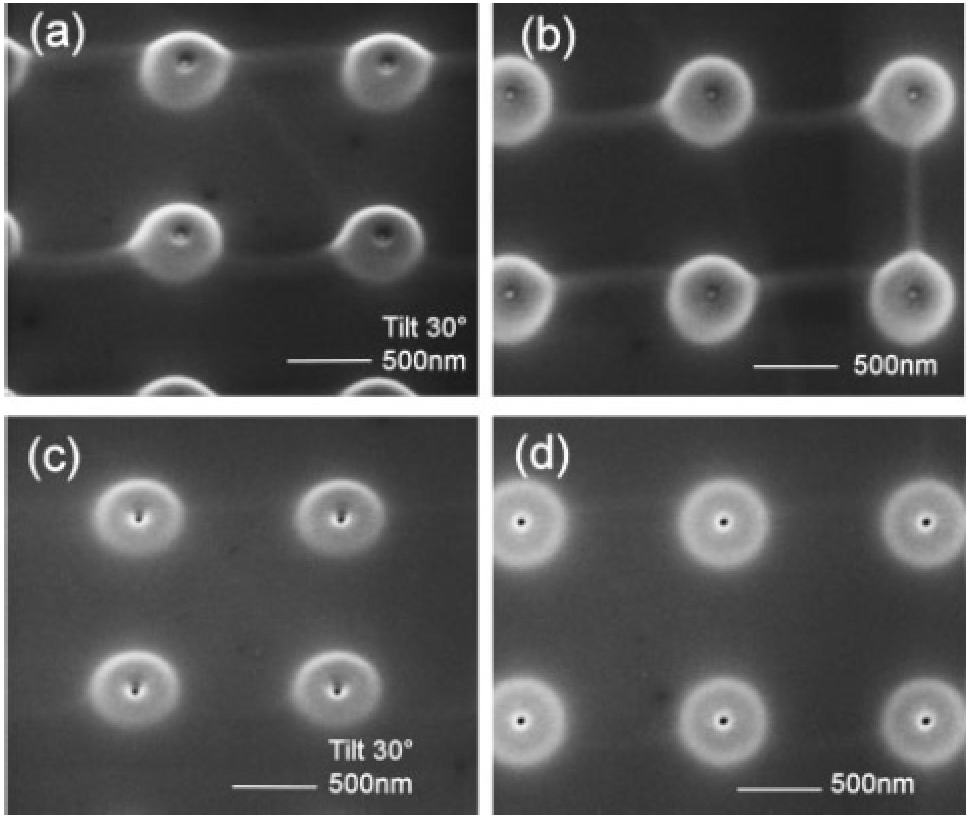


Fig. 4. SEM images of doughnut-like structures grown at spot mode with 15pA ion beam current (a,b) with a central tip (dwell time 0.1ms, exposure time 20s per spot); (c,d) with a central nanohole (dwell time 1ms, exposure time 20s).

30keV Ga^+ FIB using $(CH_3)_3Pt(CpCH_3)$, beam size 13nm

"The Complex Mechanisms of Ion-Beam-Induced Deposition", Chen, JJAP, 2008

Effect of ion species and energy on yield and purity

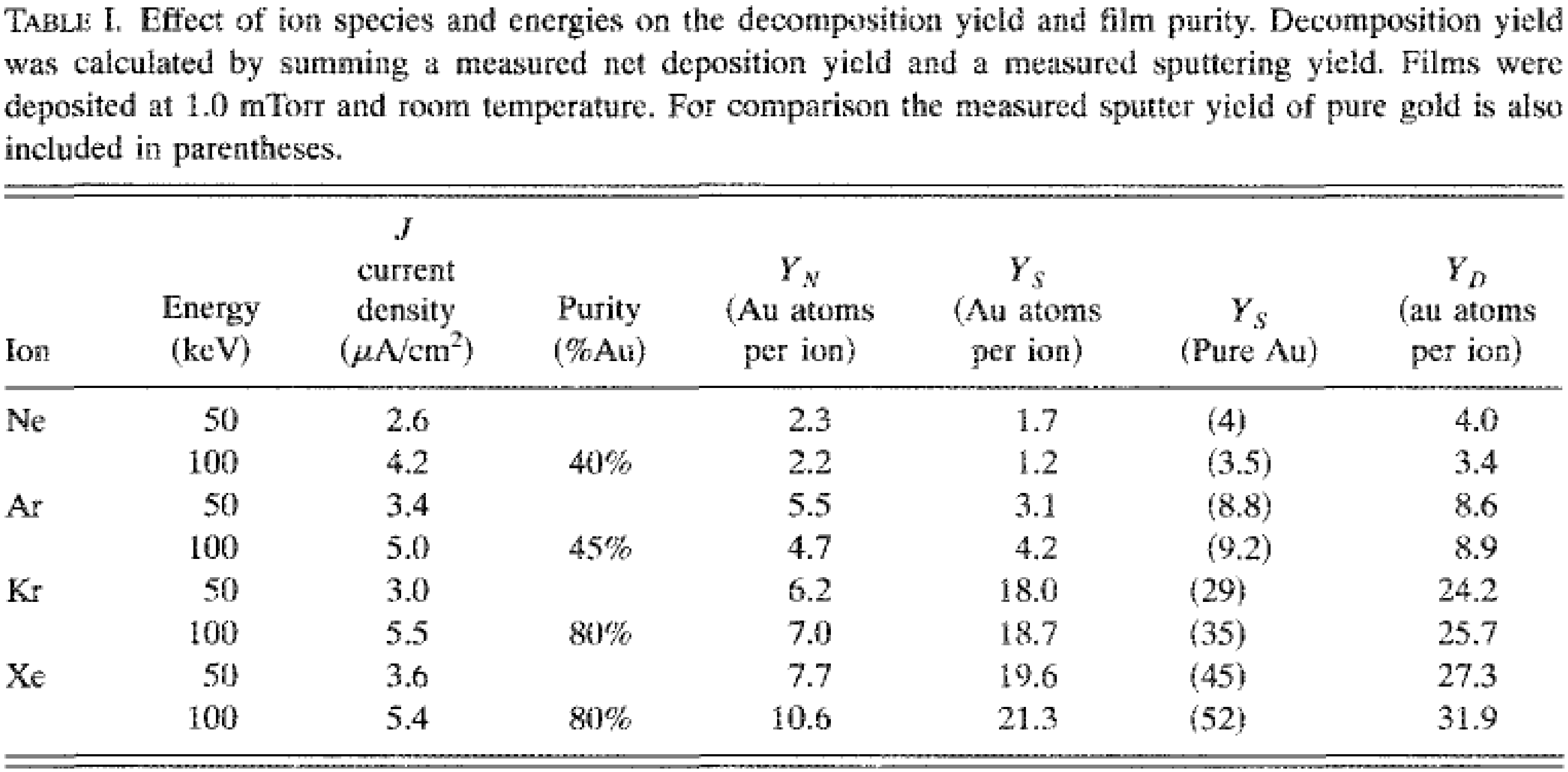


TABLE I. Effect of ion species and energies on the decomposition yield and film purity. Decomposition yield was calculated by summing a measured net deposition yield and a measured sputtering yield. Films were deposited at 1.0 mTorr and room temperature. For comparison the measured sputter yield of pure gold is also included in parentheses.

Ion	Energy (keV)	J current density (μA/cm^2)	Purity (%Au)	Y_N (Au atoms per ion)	Y_S (Au atoms per ion)	Y_S (Pure Au)	Y_D (au atoms per ion)
Ne	50	2.6		2.3	1.7	(4)	4.0
	100	4.2	40%	2.2	1.2	(3.5)	3.4
Ar	50	3.4		5.5	3.1	(8.8)	8.6
	100	5.0	45%	4.7	4.2	(9.2)	8.9
Kr	50	3.0		6.2	18.0	(29)	24.2
	100	5.5	80%	7.0	18.7	(35)	25.7
Xe	50	3.6		7.7	19.6	(45)	27.3
	100	5.4	80%	10.6	21.3	(52)	31.9

$$Y_N=Y_D-Y_S$$

Y_N=net deposition, Y_D=deposition, Y_S=sputtering

Heavier ion, higher yield.

Lighter ion, lower purity, would be worse for e-beam induced deposition.

MeIngailis, “Mechanism of ion beam induced deposition of gold”, JVST B, 1994.

Effect of ion incident angle

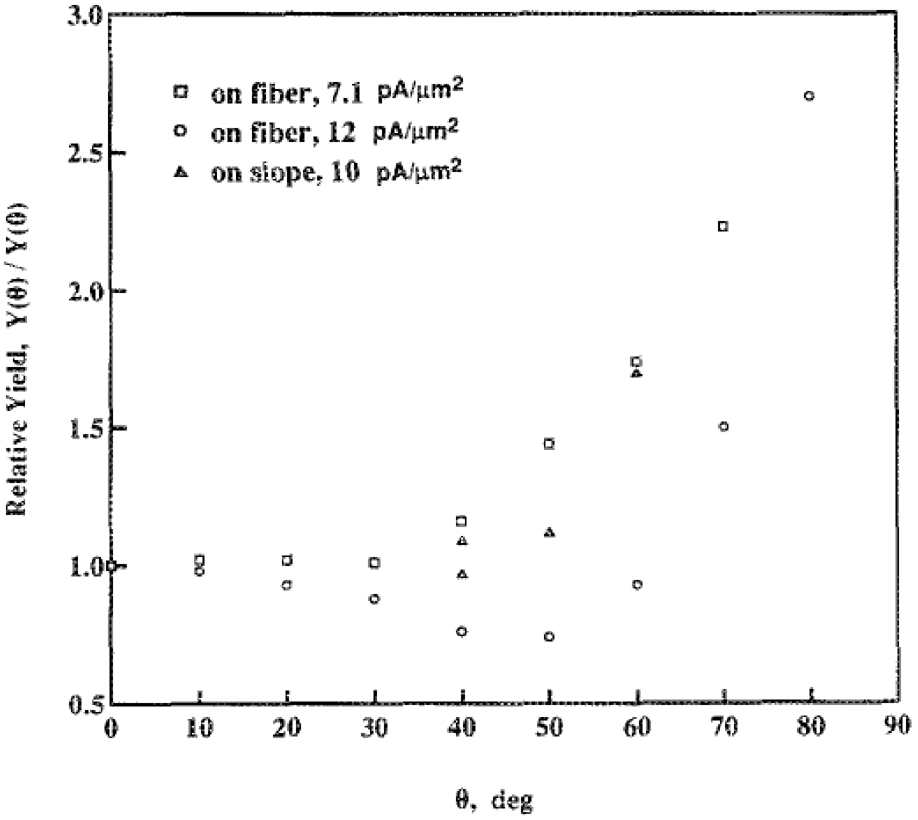


FIG. 6. The relative deposition yield vs angle of incidence for deposition from $W(CO)_6$. The current density values quoted are the average ion current density that would be incident on a sample normal to the ion beam. Total beam current was 280 pA. The data for $\theta > 45°$ can only be taken as the upper limit because of the rippling effect.

According to collision cascade model, deposition yield should be closely related to sputter yield, as atoms come out of the surface (sputtered away) or excited at the surface (not sputtered away) would induce decomposition.

It was found that deposition yield does increase with angle of incidence, but not as fast as milling/sputtering yield.

“Focused ion beam induced deposition and ion milling as a function of angle of ion incidence”, JVST B, 1992.

Deposition parameters

Dwell time: residence time at one point, desire one monolayer deposition per dwell time. About 0.4μs for C; 0.2μs for Pt.

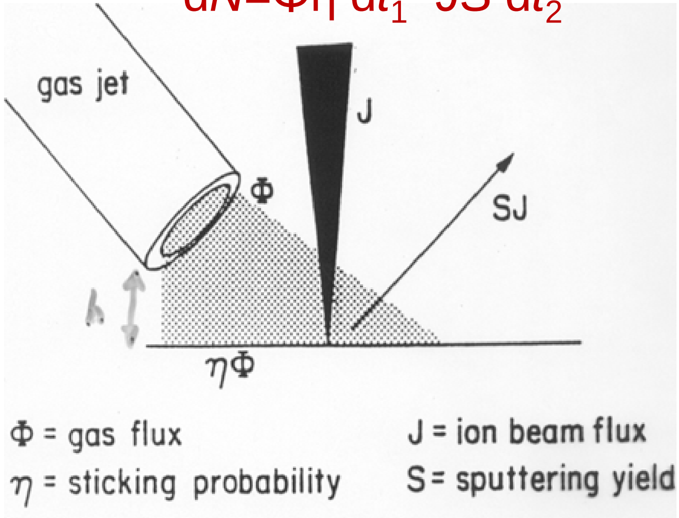
Refresh time: time between successive dwells at same point

Overlap: amount two consecutive points overlap to obtain uniform deposition. typical 25% (positive overlap) to -100% (negative overlap)

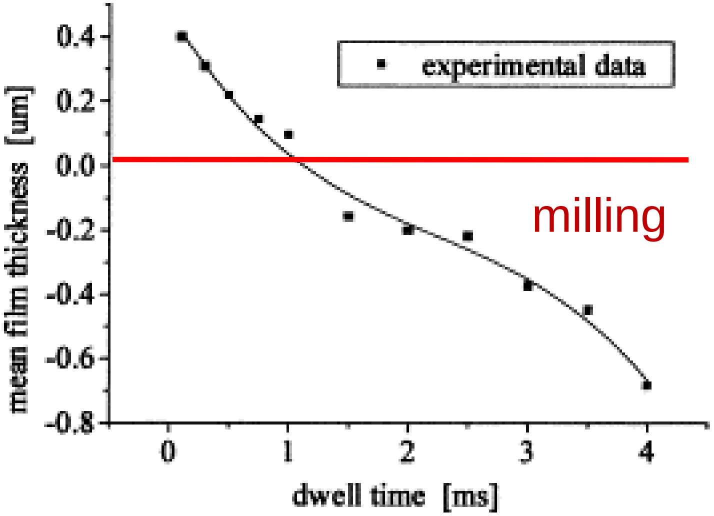
Ion current: area × 5pA/μm^2

Competition between deposition and sputtering

$dN=\Phi\eta\, dt_1 - JS\, dt_2$



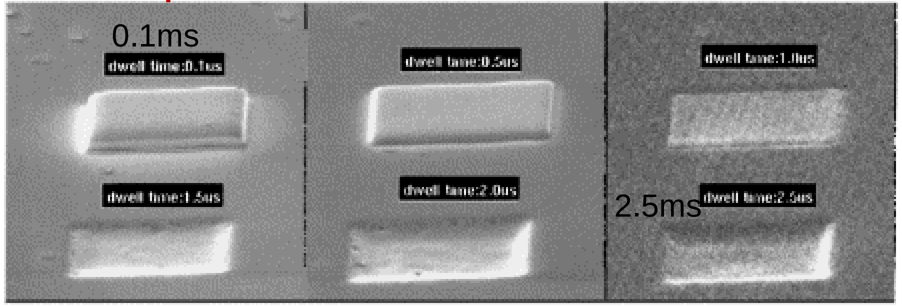
deposition



milling

Fig. 4. Dwell time vs mean film thickness under ion dose 3nC/μm^2, spot size 25nm, and current 207pA.

Net deposition



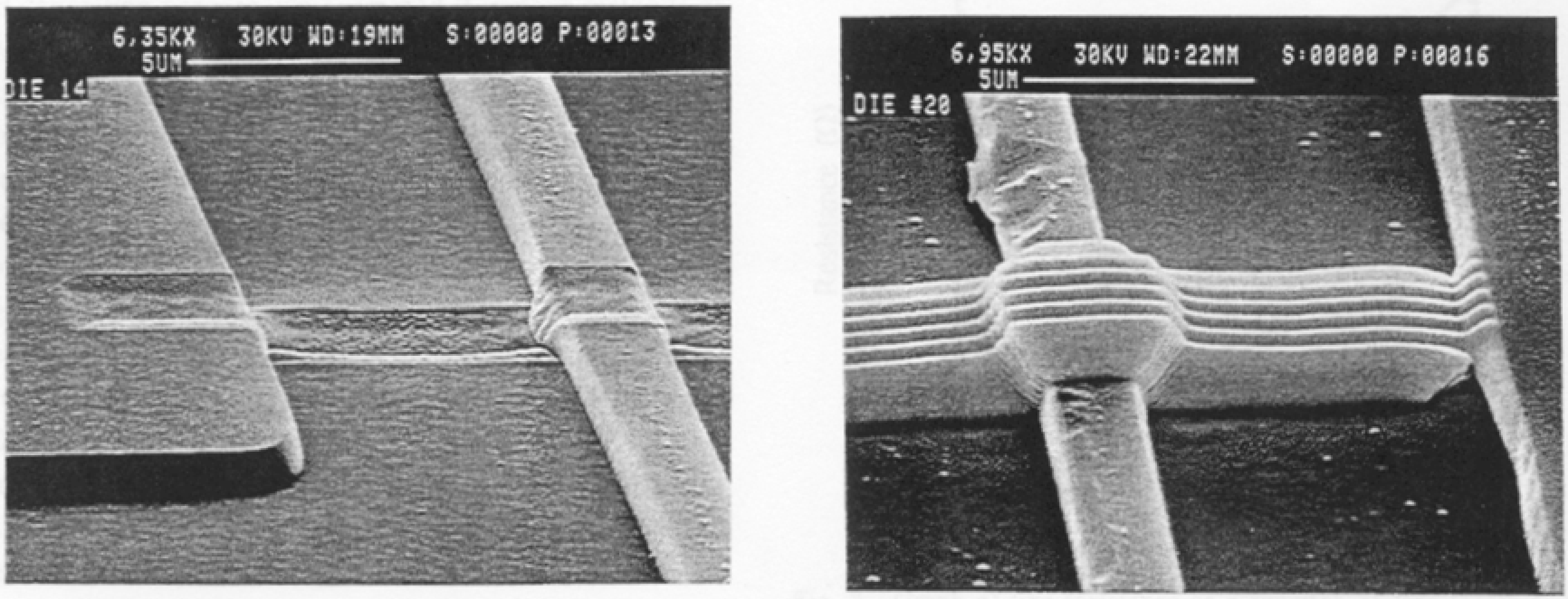
Net milling

Fig. 3. Deposited tungsten by FIB with different dwell times from 0.1 to 2.5 ms, and the same ion dose 6nC/μm^2, refresh time 1000μs, *X* and *Y* step size 71nm and 68nm, beam spot size 25 nm

Fu, "Characterization of focused ion beam induced deposition process and parameters calibration", Sensors and Actuators A, 2001.

Competition between deposition and sputtering

W: deposition vs. sputtering

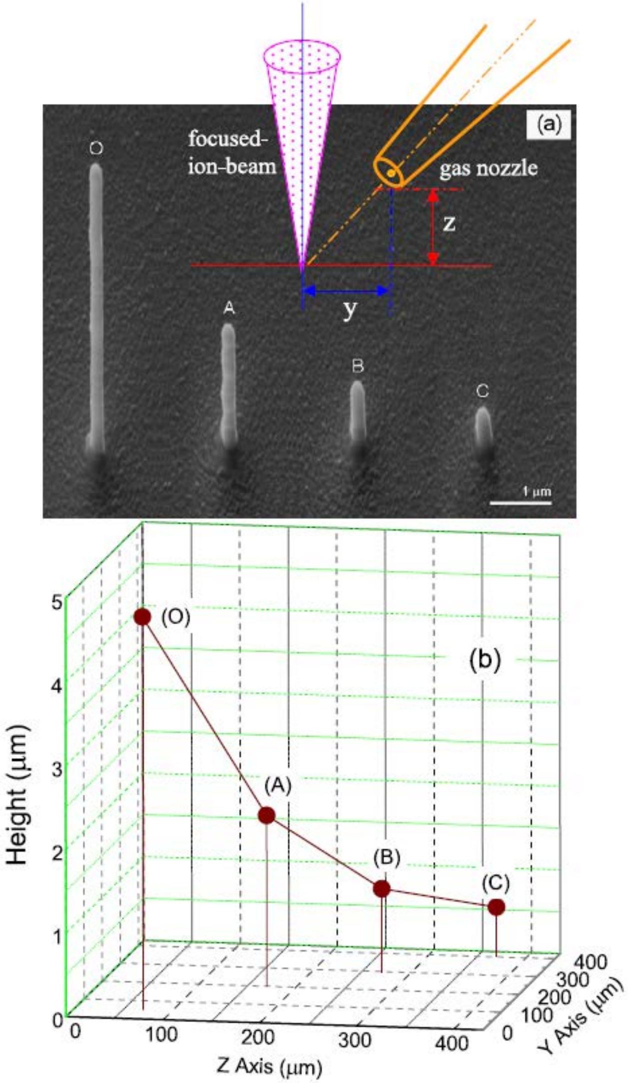


W deposited with 15µs dwell and 0.16µm step size, sputtering exceeds deposition.

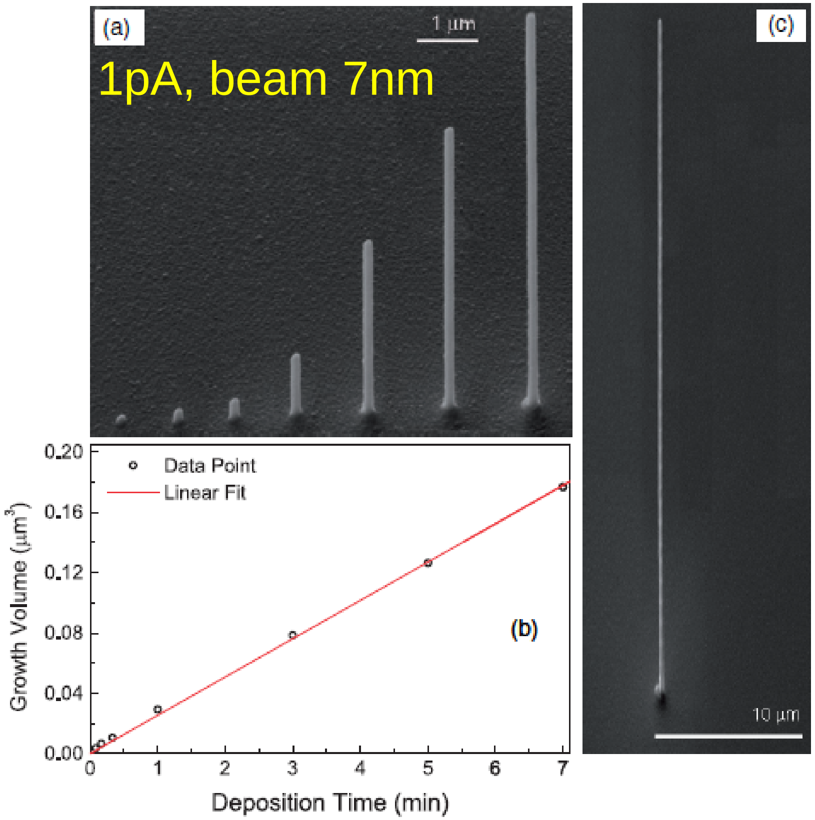
W deposited with 0.3µs dwell and 0.6µm step size

J. Mohr and R. Oviedo, 19th ISTFA Proceedings, Nov. 1993, p.391

Deposition limited by gas diffusion and absorption



Effect of the gas precursor nozzle position on nano-rod growth. Limited by diffusion.



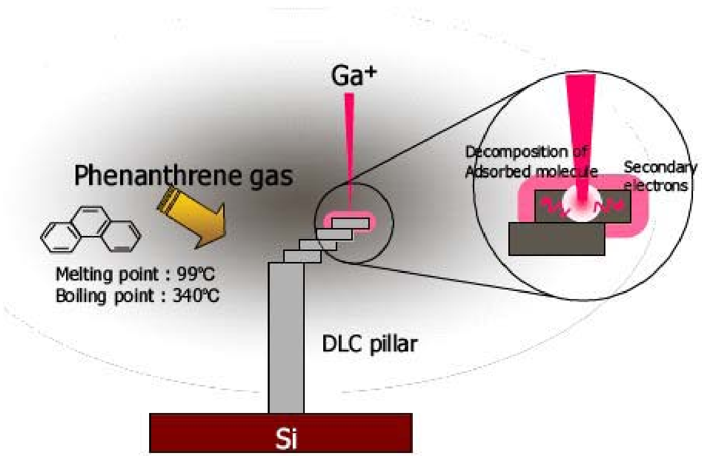
1pA, beam 7nm

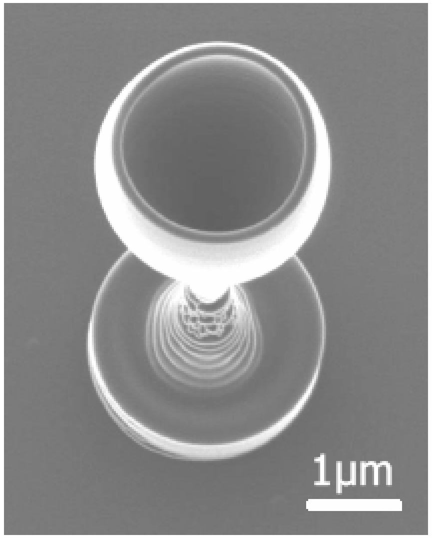
Figure 3. Nanorods deposited under optimized conditions with target cross-sectional size of 40 × 40 nm^2: (a) SEM images of rods deposited for 5, 10, 20, 60, 180, 300 and 420 s (from left to right); (b) growth volume as a function of deposition time; (c) a very tall nanorod with a height up to 45 μm. SEM images were taken with a viewing angle of 54°.

NOT limited by gas diffusion under optimal conditions.

Li and Warburton, Nanotechnology, 2007

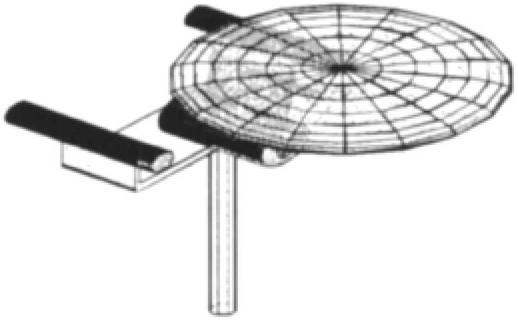
3D structure by FIB deposition



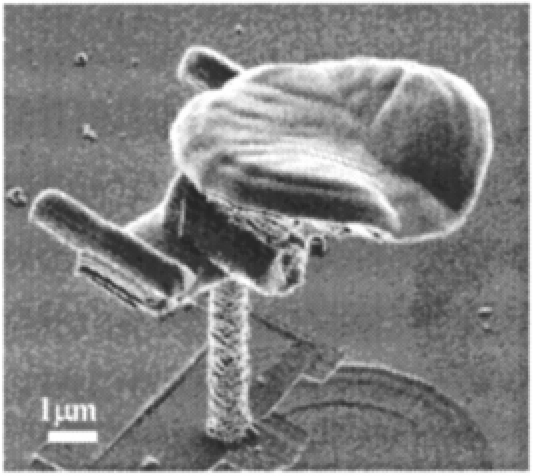


Diamond-Like Carbon Wineglass

Fujii et al, MRS Symp. Proc. 0983-LL08-08 (2007)



(a) 3-D CAD model



(b) SIM image (tilt 45deg)

Hoshino et al, *J. Vac. Sci. Technol. B*, **21** 2732 (2003)

(order of pixels matters)