IC/MEMS Fabrication - Outline

- Fabrication overview
- Materials
- Wafer fabrication
- The Cycle:
  - Deposition
  - Lithography
  - Etching

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Fabrication

- IC Fabrication
  - Deposition
    - Spin Casting
    - PVD – physical vapor deposition
    - CVD – chemical vapor deposition
  - Lithography
  - Removal
    - Wet etching
    - Plasma etching
- Bulk Micromachining
- Surface Micromachining
  - MUMPS
- DRIE – deep reactive ion etch

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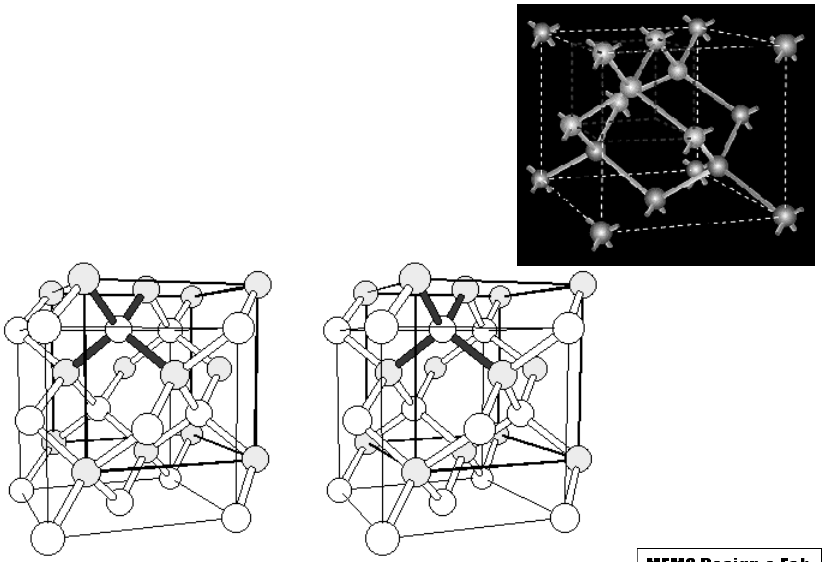
Materials

- Single crystal silicon – SCS
  - Anisotropic crystal
  - Semiconductor, great heat conductor
- Polycrystalline silicon – polysilicon
  - Mostly isotropic material
  - Semiconductor
- Silicon dioxide – SiO_2
  - Excellent thermal and electrical insulator
  - Thermal oxide, LTO, PSG: different names for different deposition conditions and methods
- Silicon nitride – Si_3N_4
  - Excellent electrical insulator
- Aluminum – Al
  - Metal – excellent thermal and electrical conductor

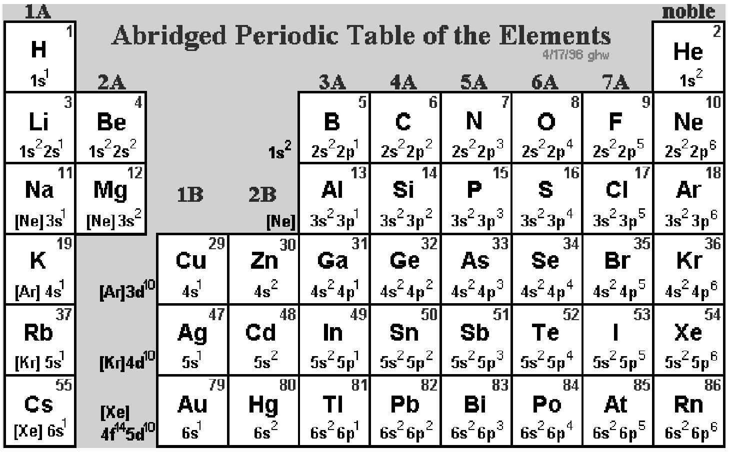
Silicon properties

- Semiconductor
  - Electrical conductivity varies over ~8 orders of magnitude depending on impurity concentration (from ppb to ~1%)
  - N-type and P-type dopants both give linear conduction, but from fundamentally different mechanisms
  - N-type touching P-type forms a diode
- Cubic crystal
  - Diamond lattice
  - Anisotropic mechanical properties

Diamond Lattice



Periodic Table



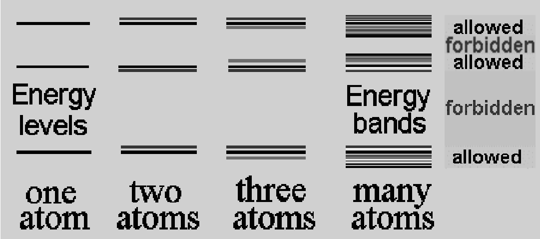
Abridged Periodic Table of the Elements

4/17/96 ghw

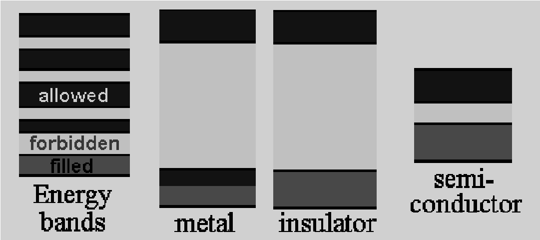
1A	2A		1B	2B	3A	4A	5A	6A	7A	noble
1 H $1s^1$										2 He $1s^2$
3 Li $1s^2 2s^1$	4 Be $1s^2 2s^2$			$1s^2$	5 B $2s^2 2p^1$	6 C $2s^2 2p^2$	7 N $2s^2 2p^3$	8 O $2s^2 2p^4$	9 F $2s^2 2p^5$	10 Ne $2s^2 2p^6$
11 Na $[Ne] 3s^1$	12 Mg $[Ne] 3s^2$			[Ne]	13 Al $3s^2 3p^1$	14 Si $3s^2 3p^2$	15 P $3s^2 3p^3$	16 S $3s^2 3p^4$	17 Cl $3s^2 3p^5$	18 Ar $3s^2 3p^6$
19 K $[Ar]\ 4s^1$		$[Ar]3d^{10}$	29 Cu $4s^1$	30 Zn $4s^2$	31 Ga $4s^2 4p^1$	32 Ge $4s^2 4p^2$	33 As $4s^2 4p^3$	34 Se $4s^2 4p^4$	35 Br $4s^2 4p^5$	36 Kr $4s^2 4p^6$
37 Rb $[Kr]\ 5s^1$		$[Kr]4d^{10}$	47 Ag $5s^1$	48 Cd $5s^2$	49 In $5s^2 5p^1$	50 Sn $5s^2 5p^2$	51 Sb $5s^2 5p^3$	52 Te $5s^2 5p^4$	53 I $5s^2 5p^5$	54 Xe $5s^2 5p^6$
55 Cs $[Xe]\ 6s^1$		[Xe] $4f^{14} 5d^{10}$	79 Au $6s^1$	80 Hg $6s^2$	81 Tl $6s^2 6p^1$	82 Pb $6s^2 6p^2$	83 Bi $6s^2 6p^3$	84 Po $6s^2 6p^4$	85 At $6s^2 6p^5$	86 Rn $6s^2 6p^6$

Band Structure of Electron Energies

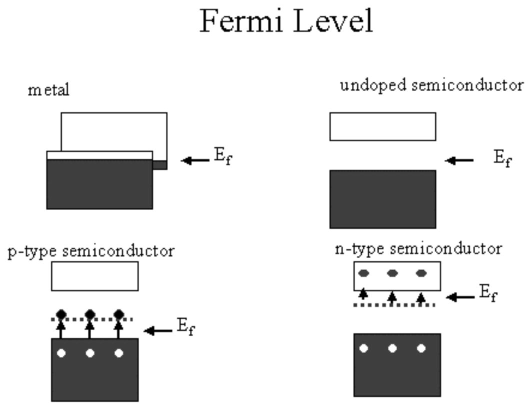
- http://www.physics.udel.edu/wwwusers/watson/scen103/99s/clas0416.html
- Bohr atom, Pauli exclusion principle
  - (not exactly right, but gives some intuition)



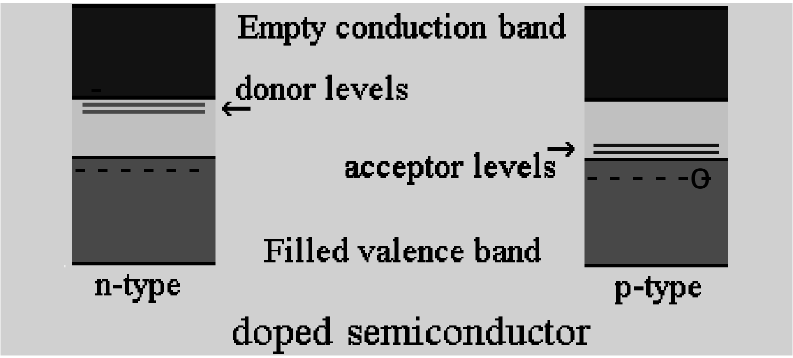
Band structure of Semiconductors



Conductors, insulators, semiconductors

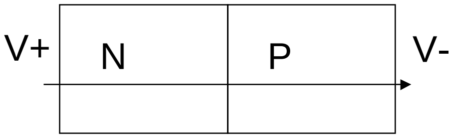


Doping semiconductors

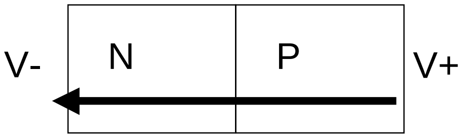


- Two different types of conduction
  - Electrons (negative, N-type)
  - Holes (positive, P-type)

Diodes



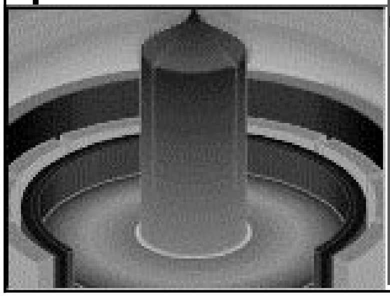
Tiny current
~pA

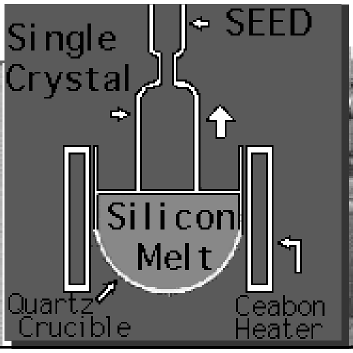


Current exponentially
dependent on voltage
pA to kA in ~1V

Silicon wafer fabrication

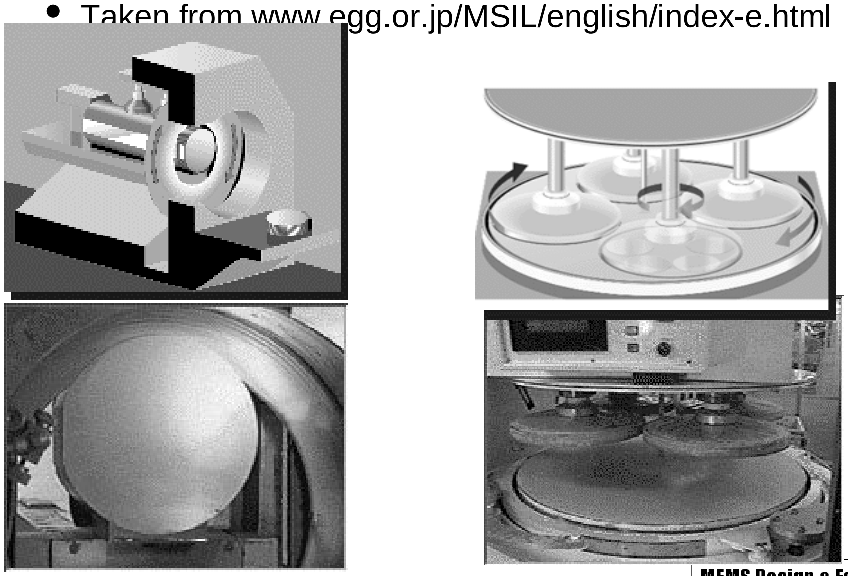
- Taken from www.egg.or.jp/MSIL/english/index-e.html





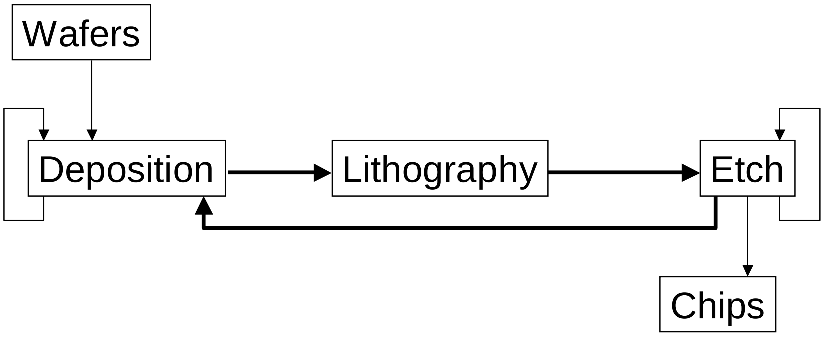
Silicon wafer fabrication – slicing and polishing

- Taken from www.egg.or.jp/MSIL/english/index-e.html



Process Flow

- Integrated Circuits and MEMS identical
- Process comlexity/yield related to # trips through central loop



Wafers

Deposition

Lithography

Etch

Chips

Deposition Issues - Compatibility

- Thermal compatibility
  - Thermal oxidation and LPCVD films are mutually compatible
  - Thermal oxidation and LPCVD are not compatible with polymers (melting/burning) and most metals (eutectic formation, diffusion, furnace contamination)
- Topographic compatibilitiy
  - Can not spin-cast over large step heights
  - Distributed-source deposition over deep trenches leaves keyholes

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Deposition Issues - Conformality

- A *conformal* coating covers all surfaces to a uniform depth
- A *planarizing* coating tends to reduce the vertical step height of the cross-section
- A *non-conformal* coating deposits more on top surfaces than bottom and/or side surfaces

Conformal Conformal Non-conformal

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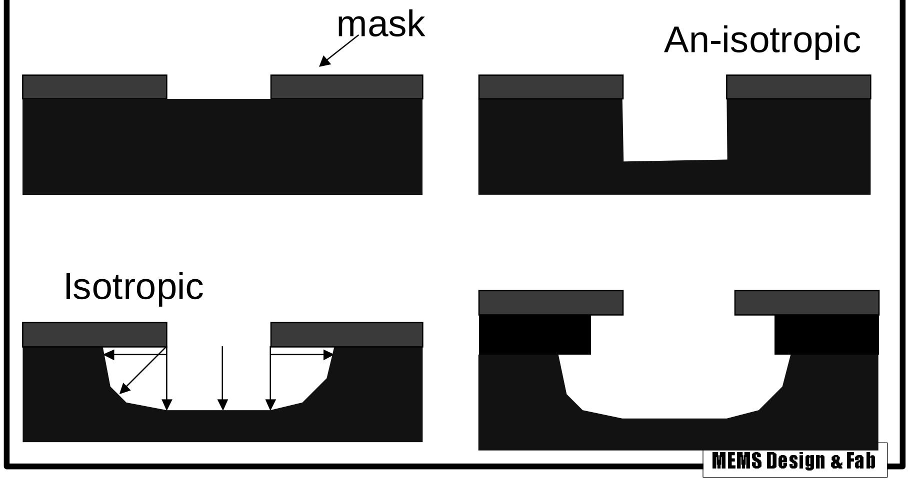
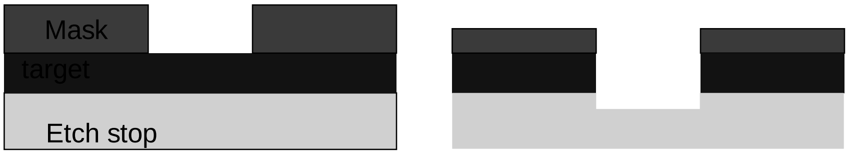
Etching Issues - Anisotropy

- Isotropic etchants etch at the same rate in every direction



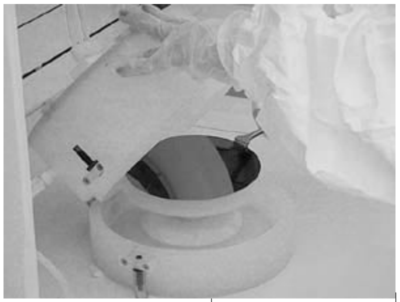
Etching Issues - Selectivity

- Selectivity is the ratio of the etch rate of the target material being etched to the etch rate of other materials
- Chemical etches are generally more selective than plasma etches
- Selectivity to masking material and to etch-stop is important



Spin Casting

- Viscous liquid is poured on center of wafer
- Wafer spins at 1000-5000 RPM for ~30s
- Baked on hotplates 80-500C for 10-1000s
- Application of etchants and solvents, rinsing
- Deposition of polymers, sol-gel precursors



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Physical Vapor Deposition - Evaporation

- Evaporated metals in a tungsten crucible
  - Aluminum, gold
- Evaporated metals and dielectrics by electron-beam
  - Refractory metals (e.g. tungsten)
  - Dielectrices (e.g. SiO2)

- Typically line-of-sight deposition
- Very high-vacuum required to prevent oxidation of e.g. aluminum

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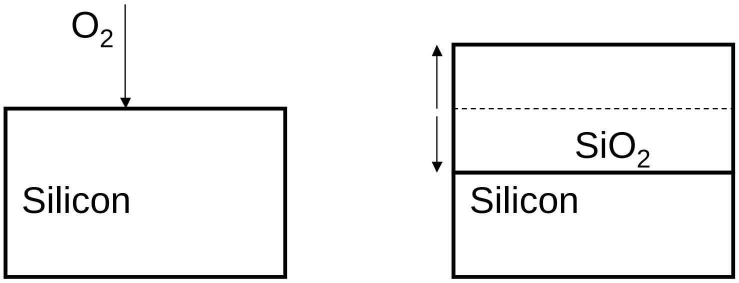
Physical Vapor Deposition - Sputtering

- Sputtered metals and dielectrics
  - Argon plasma sputters material (small #s of atoms) off target
  - Ejected material takes ballistic path to wafers
- Typically line-of-sight from a distributed source
- Requires high vacuum depending on material

Thermal Oxidation



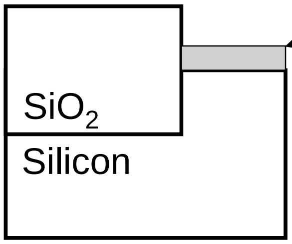
Silicon is consumed as the silicon dioxide is grown.

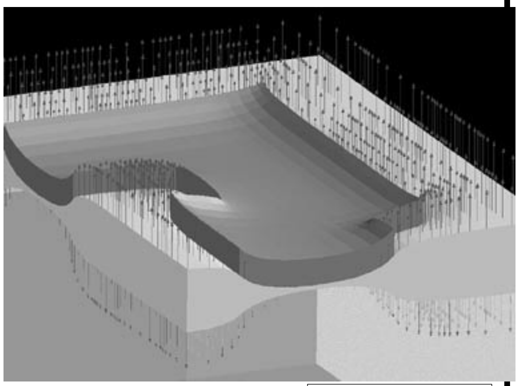
Growth occurs in oxygen and/or steam at 800-1200 C.

~2um films are maximum practical

Thermal Oxidation

- Oxidation can be masked with silicon nitride, which prevents O_2 diffusion

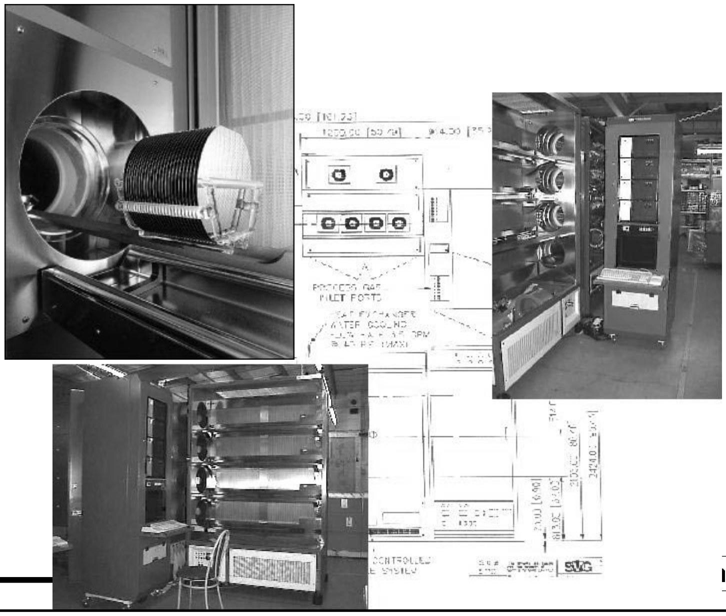




Chemical Vapor Deposition

- Gases dissociate on surfaces at high temperature
- Typically done at low pressure (LPCVD) rather than atmospheric (APCVD)
- LPCVD pressures around 300mT (0.05% atmosphere)
- Moderate Temperatures
  - 450 SiO_2
  - 580-650 polysilicon
  - 800 Si_xN_y
- Very dangerous gases
  - Silane: SiH4
  - Arsine, phosphine, diborane: AsH_3, PH_3, B_2H_6

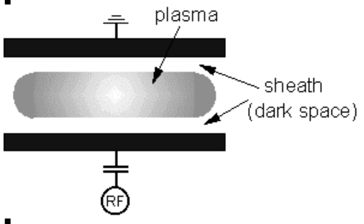
LPCVD Systems

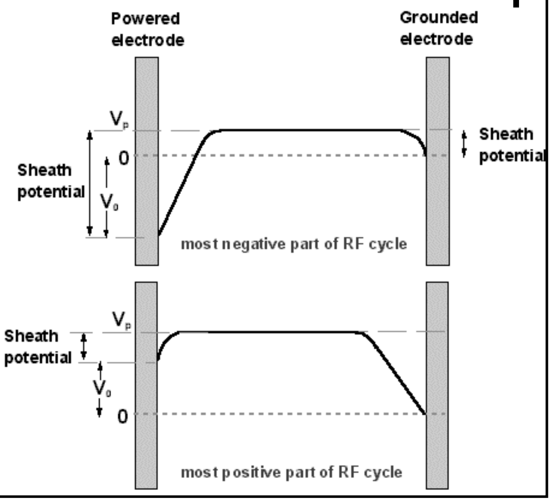


Wet etching

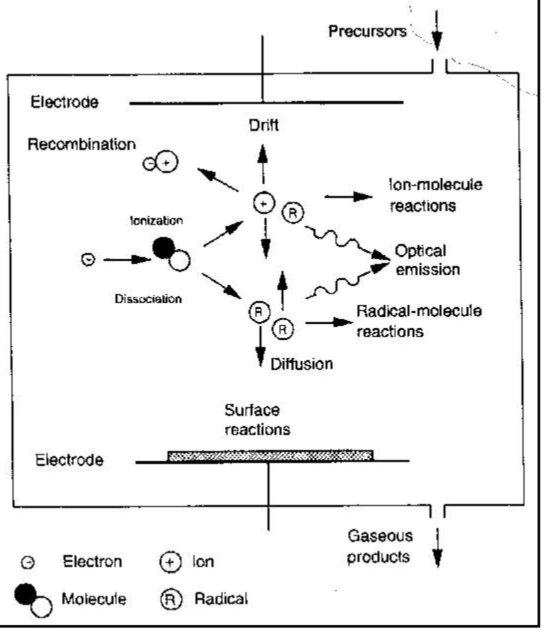
- Extremely selective
- Typically isotropic
- Not widely used

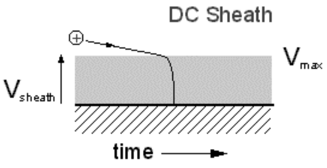
Plasma Etching



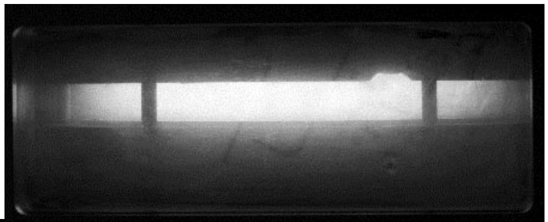


Plasma Etching



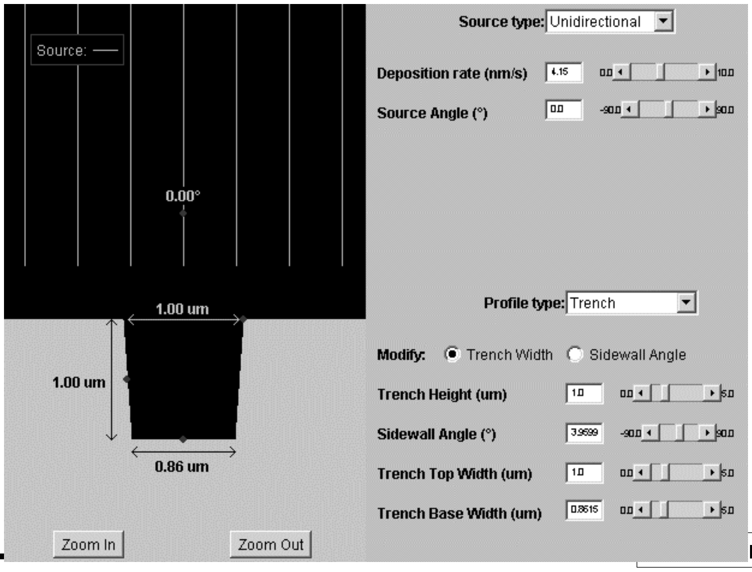


Plasma Etchers



ETCHING IN IC FABRICATION

LAVA/SAMPLE2D – www.eecs.berkeley.edu/~neureuth



Source type: Unidirectional

Deposition rate (nm/s) 4.15

Source Angle (°) 0.0

Profile type: Trench

Modify: ● Trench Width ○ Sidewall Angle

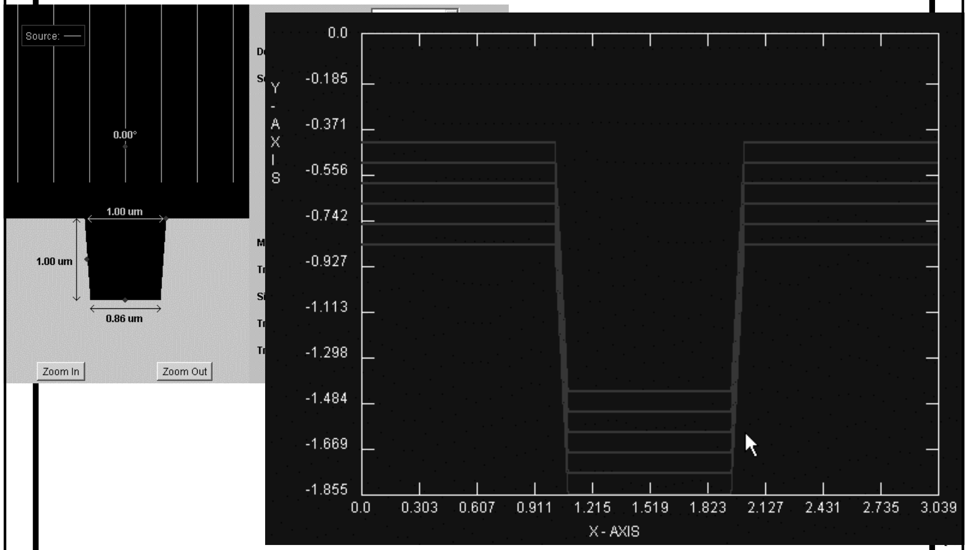
Trench Height (um) 1.0

Sidewall Angle (°) 3.9699

Trench Top Width (um) 1.0

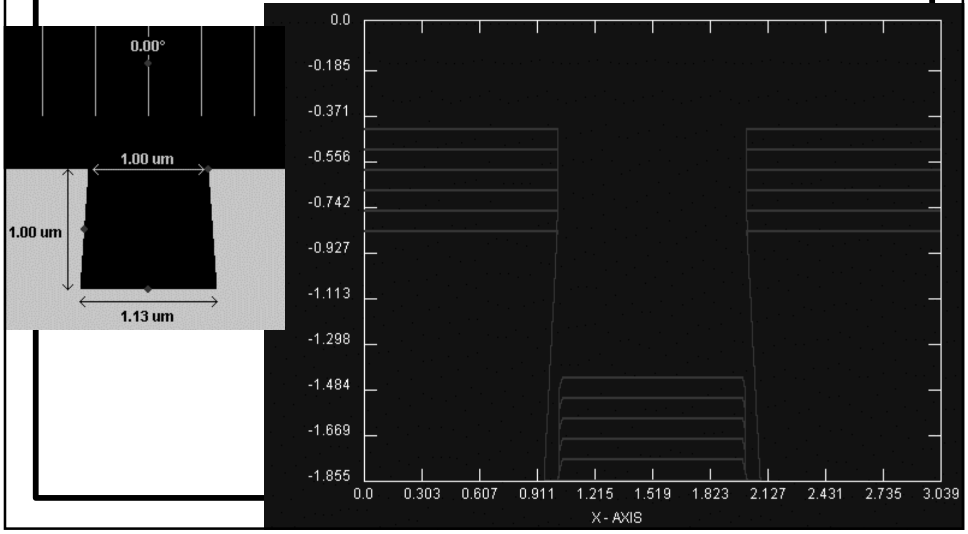
Trench Base Width (um) 0.8615

Line-of-sight deposition

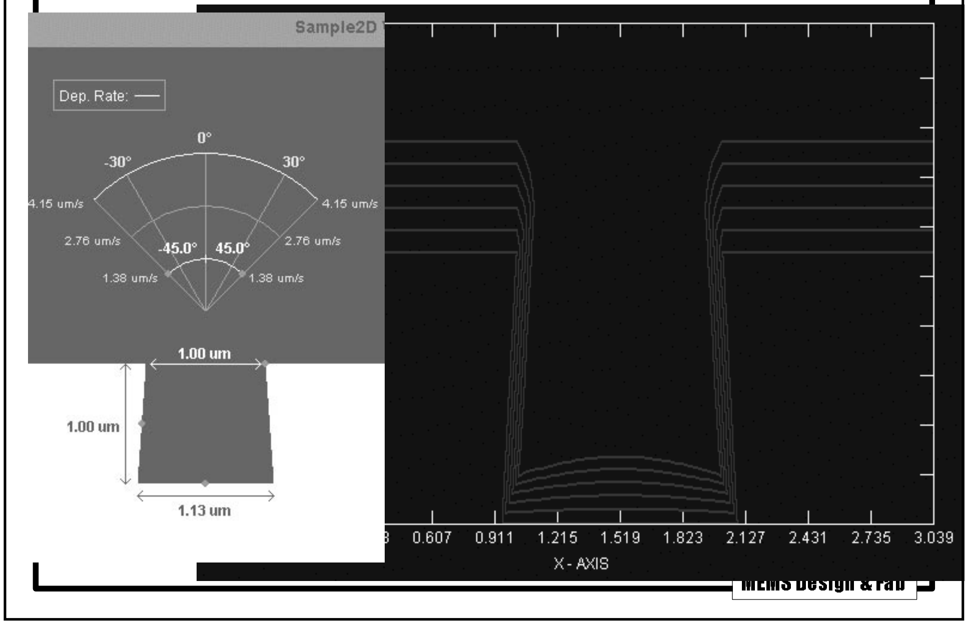


Step coverage problems

- Re-entrant sidewall angles cause discontinuity in metal lines

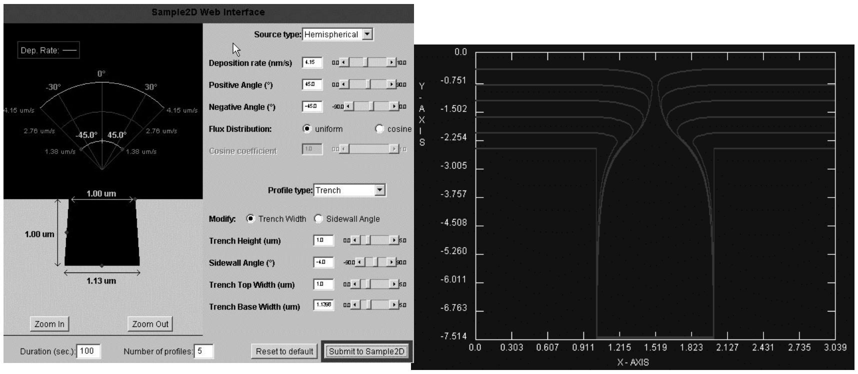


Hemispherical source improves step coverage



But isn't perfect - Keyhole effect

- Hemispherical/Isotropic deposition



Sample2D Web Interface

Source type: Hemispherical

Deposition rate (nm/s): 4.15

Positive Angle (°): 45.0

Negative Angle (°): -45.0

Flux Distribution: ● uniform ○ cosine

Cosine coefficient: 1.0

Profile type: Trench

Modify: ● Trench Width ○ Sidewall Angle

Trench Height (um): 1.0

Sidewall Angle (°): -4.0

Trench Top Width (um): 1.0

Trench Base Width (um): 1.1398

Duration (sec.): 100

Number of profiles: 5

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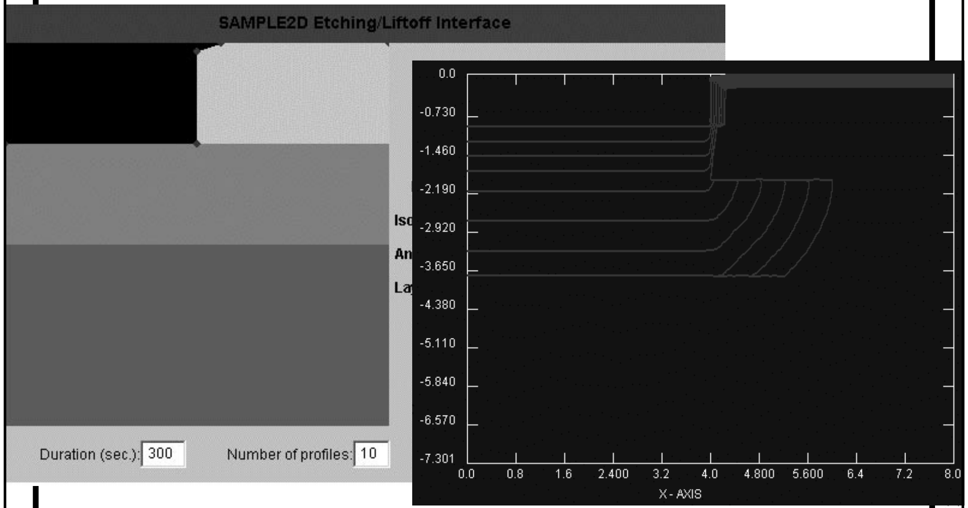
Etching simulation



SAMPLE2D Etching/Liftoff Interface

Duration (sec.): 300

Number of profiles: 10

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Summary

- Conformality of deposition is critical
- LPCVD and thermal oxidation temperatures limit the materials that can be used
- Selectivity of etchants is important
- Anisotropy of etchants is important