Lecture 11:

Si / Poly-Si etch
- Reactive Ion Etching -

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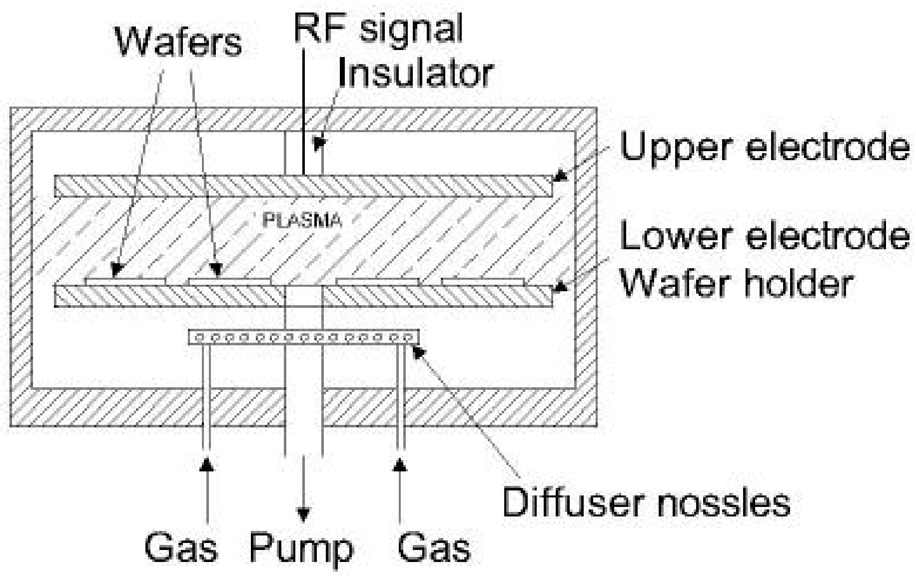
RIE Principles (1)

- Reactive Ion Etching
- Process in which chemical etching is accompanied by ionic bombardment
- Combination of physical and chemical etching
- Anisotropic etching



Typical parallel-plate reactive ion etching system

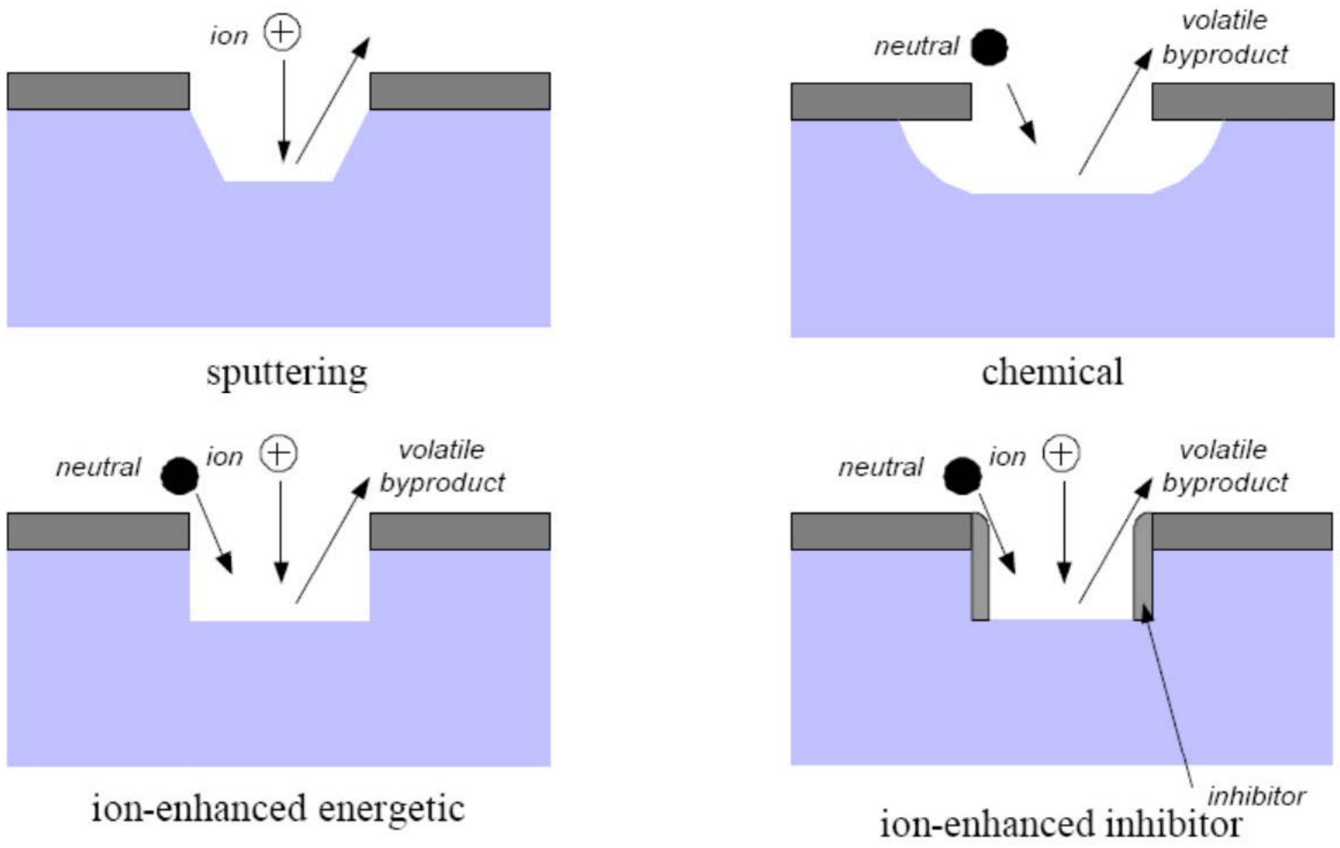
RIE Principles (2)

	Plasma Etching		Reactive Etching		Physical Etching	
	Barrel Reactor	Planar Reactor	Ion	Ion Beam	Sputtering	Ion Beam Milling
Substrate Location	Surrounded by plasma	On grounded electrode in Plasma	On powered electrode in plasma	In beam, remote from plasma	On powered electrode in plasma	In beam, remote from plasma
Pressure (torr)	10^{-1} ~ 1	10^{-1} ~ 1	10^{-2} ~ 10^{-1}	10^{-4} ~ 10^{-3}	10^{-5} ~ 10^{-3}	10^{-4}
Ion energy(eV)	0	1 ~ 100	100 ~ 1000	100 ~ 1000	100 ~ 1000	100 ~ 1000
Active Species	Atoms. Radicals	Atoms, radicals, reactive ions	Radicals, reactive ions	Reactive ions	Ar^+ ions	Ar^+ ions
Products	Volatile	Volatile	Volatile	Volatile	Nonvolatile	Nonvolatile
Mechanism	Chemical	Chemical/ Chemical-Physical	Chemical/ Physical	Chemical/ Physical	Physical	Physical
Etch Profile	Isotropic	Isotropic/ Anisotropic	Isotropic/ Anisotropic	Anisotropic	Anisotropic	Anisotropic
Selectivity	30 : 1 – 10 : 1	10 : 1 – 5 : 1	30 : 1 – 5 : 1	10 : 1 – 3 : 1	1 : 1	1 : 1
Resist Compatibility	Excellent	Excellent	Good	Good	Poor	Poor
Device Damage	Little	Little	Some possible	Some possible	Very possible	Very possible
Etch Rate (um/min)	0.1 ~ 0.5	0.1 ~ 0.5	0.05 ~ 0.1	0.05 ~ 0.1	0.02 ~ 0.05	0.02 ~ 0.05
Resolution (um/min)	3	2	1 ~ 2	1 ~ 2	0.5 ~ 1	0.5 ~ 1

Ref: J. D. Lee, “Silicon Integrated Circuit microfabrication technology,” 2nd edition

RIE Principles (3)

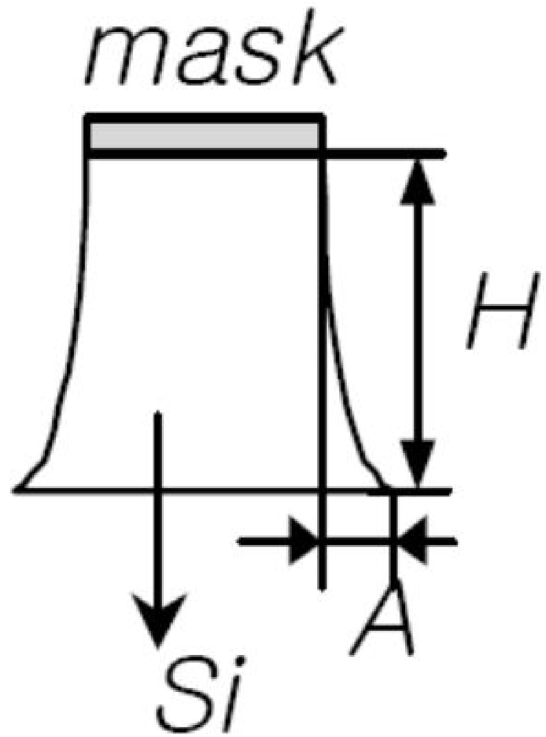
- Mechanism of RIE (Reactive Ion Etching)



- Gas type, Chamber pressure, Ion generation influences

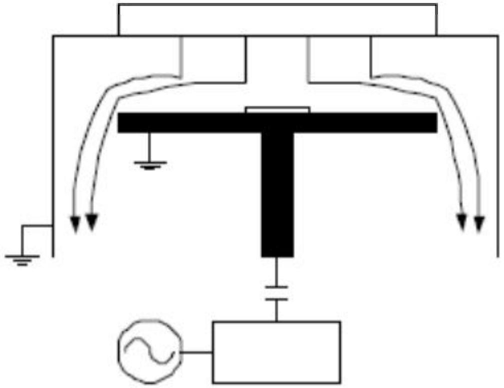
RIE Principles (4)

- Etch performance valuation
  - Etch rate
  - Anisotropy (define as 1-A/H)
  - Selectivity to mask material
  - Micro-loading effect (RIE lag)
  - Macro-loading effect
    (dark field or bright field)
  - Etch uniformity
  - Surface quality

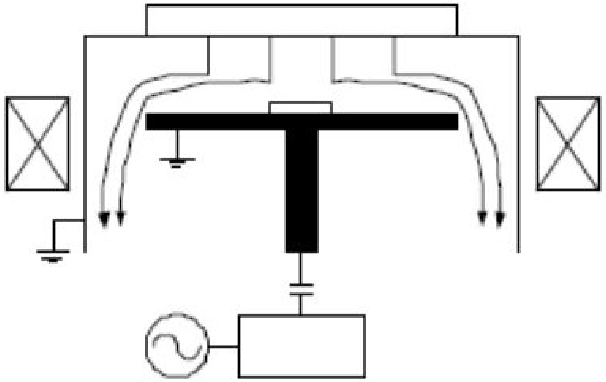


RIE Principles (5)

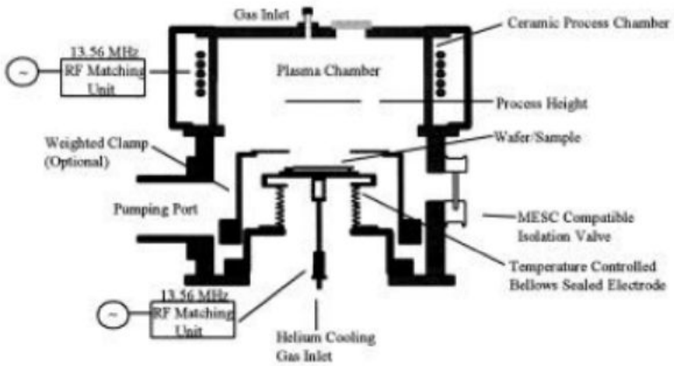
- Several RIE system



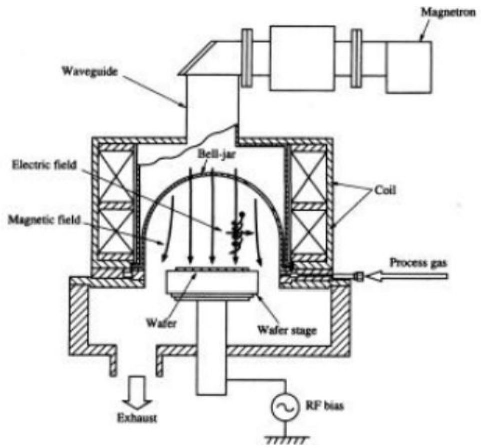
CCP: capacitively coupled plasma



MERIE: magnetically enhanced RIE



ICP: inductively coupled plasma



μERIE: microwave electron cyclotron resonance

Mask Materials for RIE

- Etch mask
  - PR (Photo Resist), Hard mask (SiO_2, Al) is used
  - Selectivity

    = etch rate of etching material / etch rate of mask
  - Usually, standard PR (for CMOS) is not adequate for O_2 plasma etch → hard mask required

  - Selectivity of silicon:AZ1512
    - Cl based etch (physical etch): <2
    - F based etch (chemical etch): < 10

      (if O_2 gas is inserted the chamber the selectivity would be lower than 10)

Reaction in RIE Process (1)

- Reactants
  - Cl-based
    - Sputtering or ion-enhanced etch mechanism
    - High anisotropy
    - Low selectivity
    - Cl_2, BCl_3
  - F-based
    - Chemical etch mechanism
    - High selectivity
    - High etch rate
    - Isotropic etching
    - SF_6

Reaction in RIE Process (2)

- An example of RIE mechanisms (Cl based)

Ion and electron formation

$e + Cl/Cl_2 \rightarrow Cl^+/Cl_2^+ + 2e$

Etchant formation

$e + Cl_2 \rightarrow 2Cl + e$

Adsorption of etchant on the substrate

$Cl/Cl_2 \rightarrow Si_{surf}\text{-}nCl$

Reaction on surface

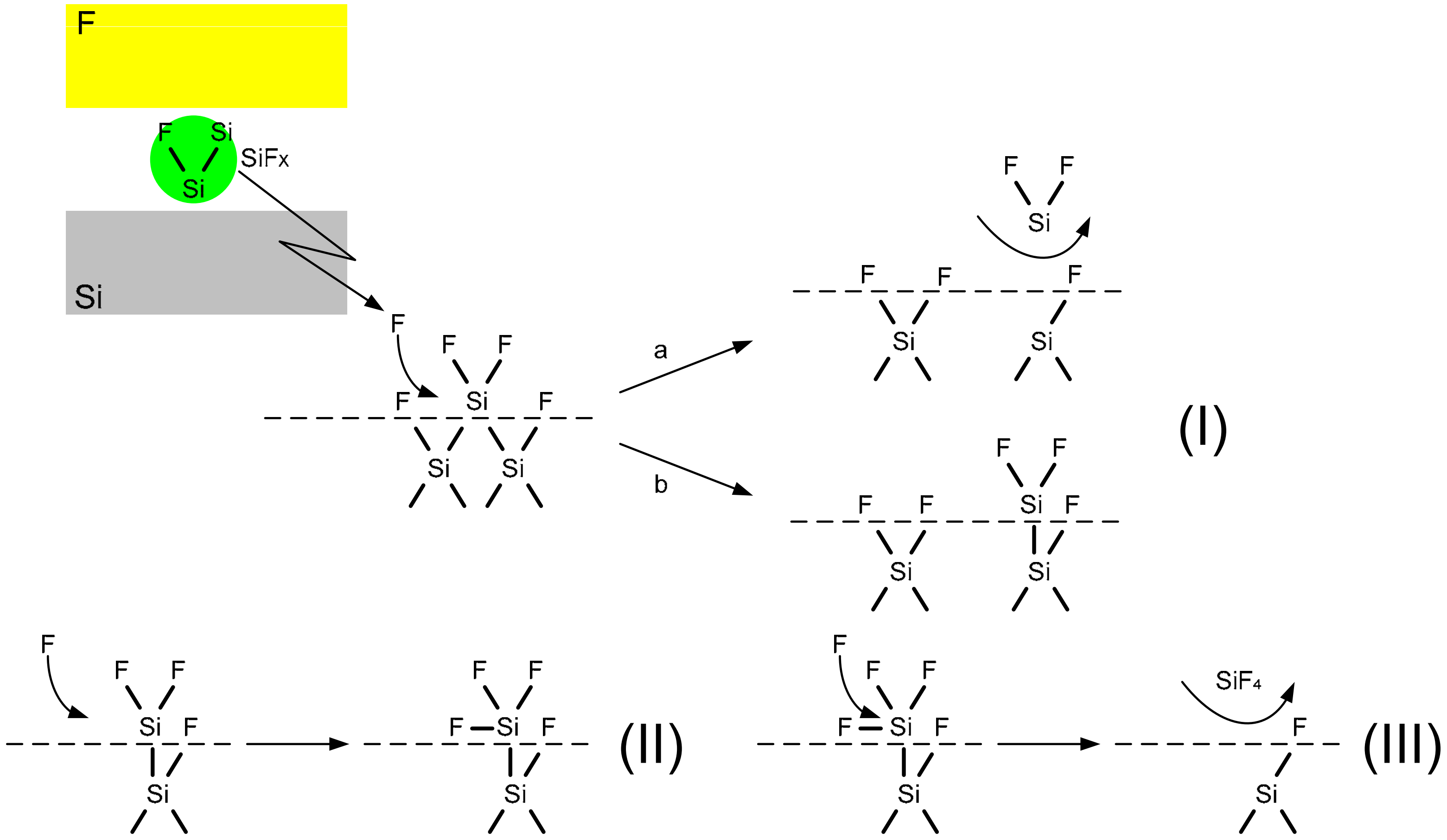
$Si_{surf}\text{-}nCl \xrightarrow{(ions)} SiCl_{x(ads)}$

Product desorption

$SiCl_{x(ads)} \xrightarrow{(ions)} SiCl_{x(gas)}$

Reaction in RIE Process (3)

- An example of RIE mechanisms (F based Si etch)



CCP: BCl_3 Recipe and Example (1)

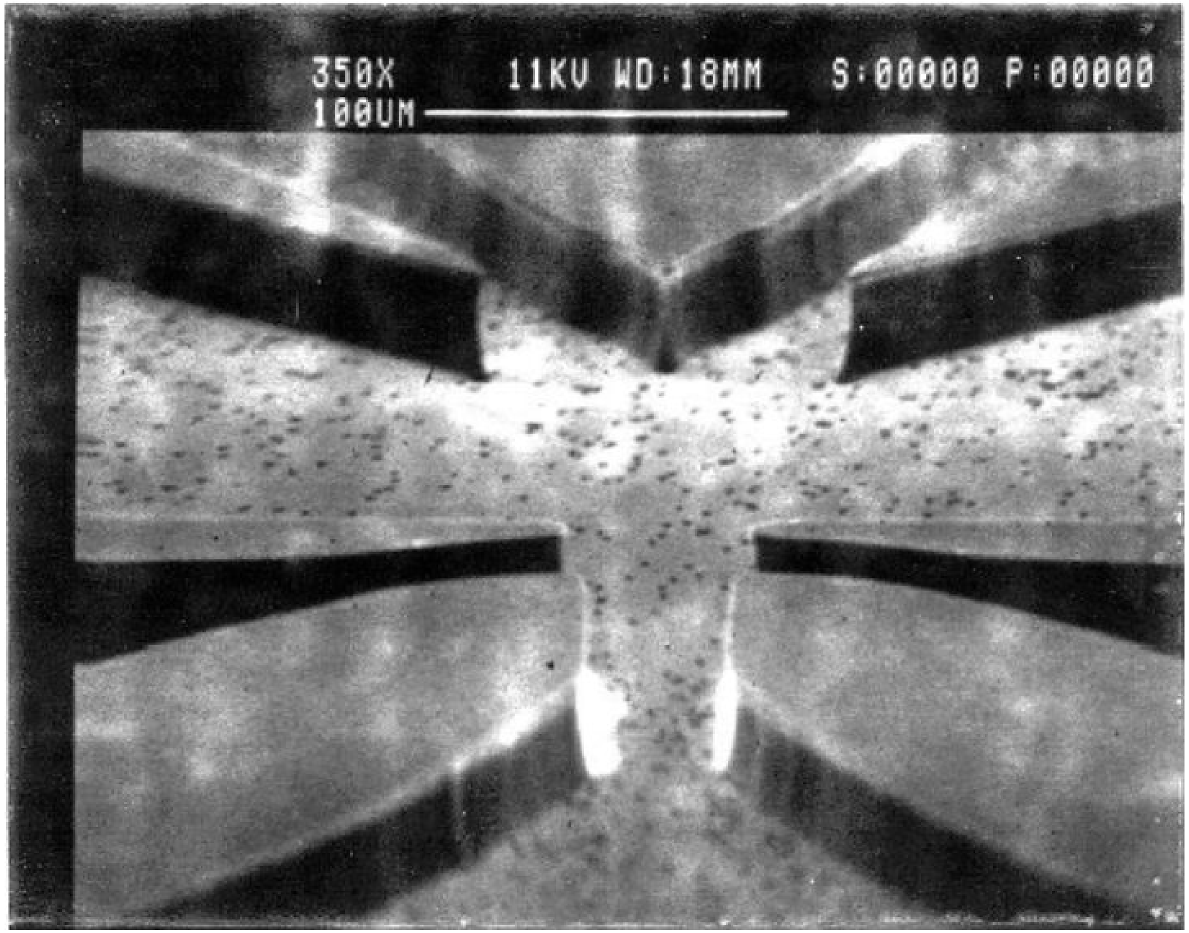
- System: Drytek DRIE-284
- Process parameter

		Step 1	Step 2	Step 3
Power		200 W	300 W	475 W
Pressure		20 mTorr	20 mTorr	40 mTorr
Time		1 min	1 min	10 min
Gas	Cl_2	0 sccm	2 sccm	50 sccm
	BCl_3	14 sccm	14 sccm	5 sccm
	N_2	7 sccm	7 sccm	0 sccm

- Etch rate: 850 nm/min
- Selectivity: 8.5:1 for oxide hard mask

CCP: BCl_3 Recipe and Example (2)

- Fabrication example (proportional amplifier)



CCP: SF_6 Recipe and Example (1)

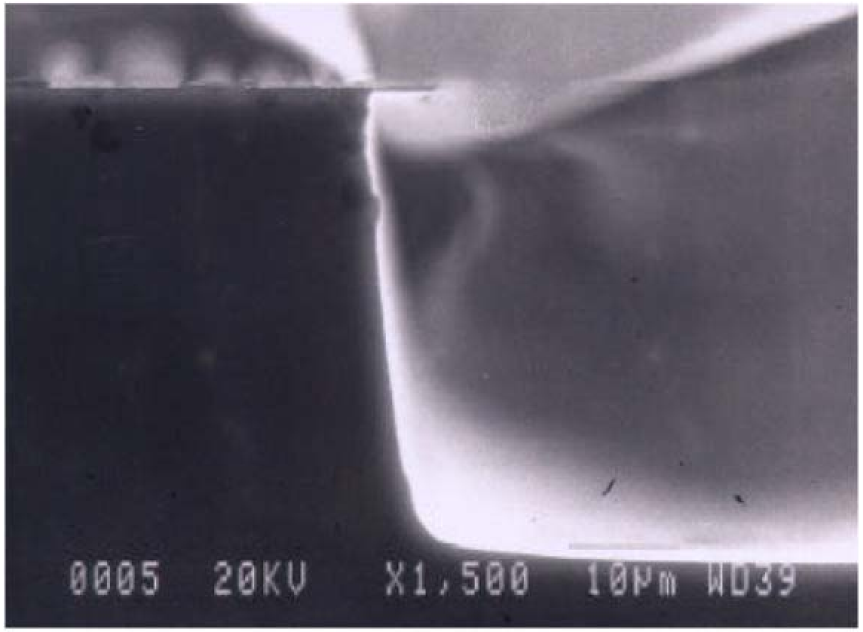
- System: Drytek DRIE-284
- Process parameter

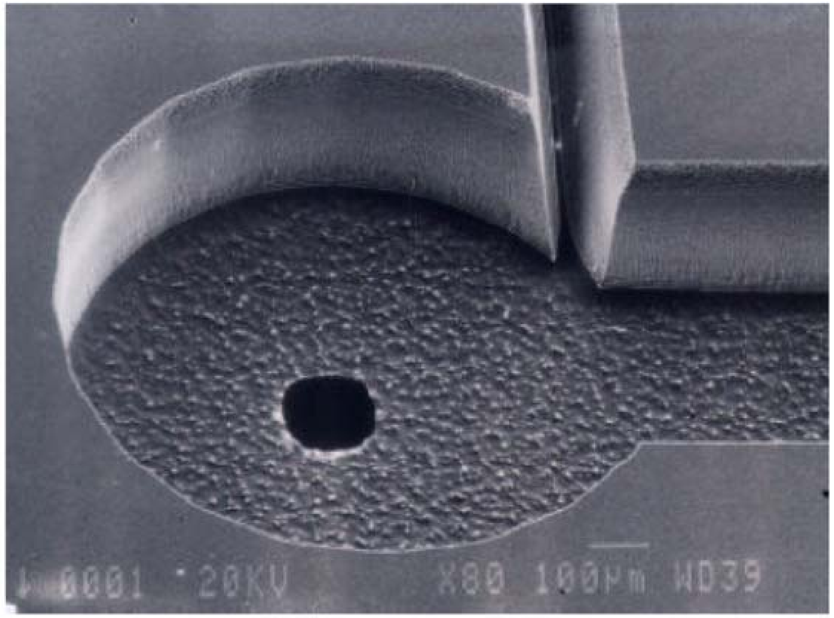
Power	150 W
Pressure	150 mTorr
SF_6	30 sccm
O_2	10 sccm

- Etch rate: 4.2 um/min
- Selectivity: 14.2:1 for oxide hard mask

CCP: SF_6 Recipe and Example (2)

- Fabrication example (vortex amplifier)





CCP: Poly-Si Etch Test (1)

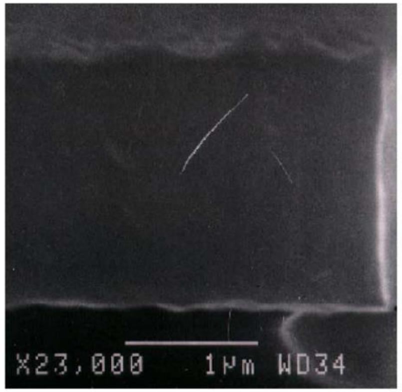
- System: Drytek DRIE-284

- Process parameter

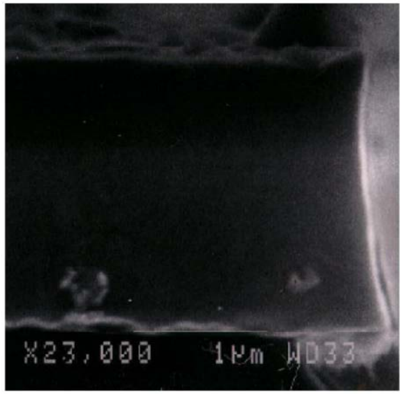
Power	300 W
Pressure	75~250 mTorr
Cl_2	58 sccm
He_2	100 sccm

CCP: Poly-Si Etch Test (2)

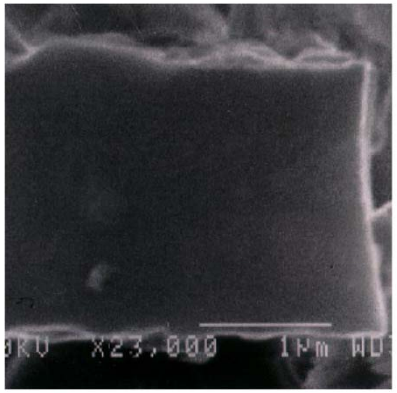
- Test results



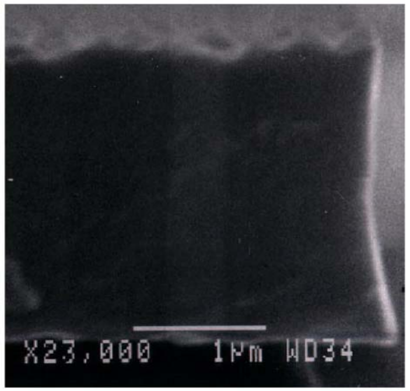
100 mTorr



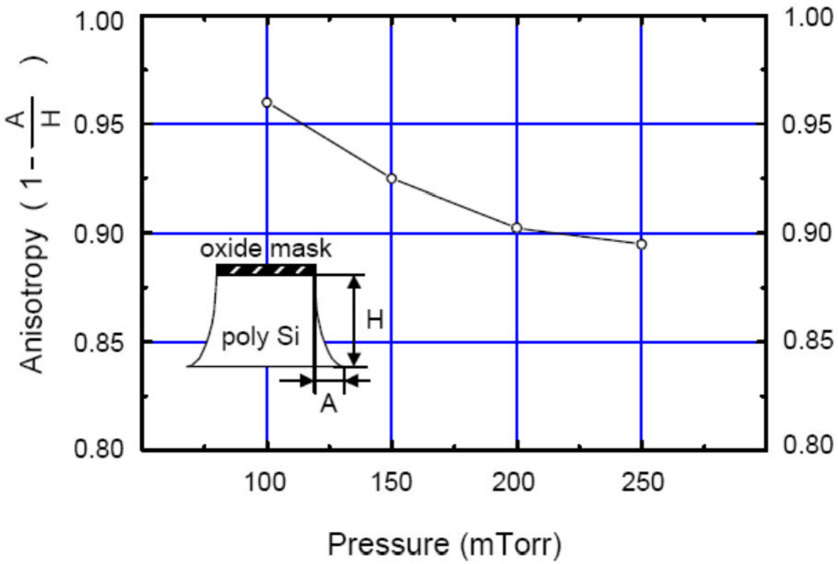
150 mTorr



200 mTorr



250 mTorr

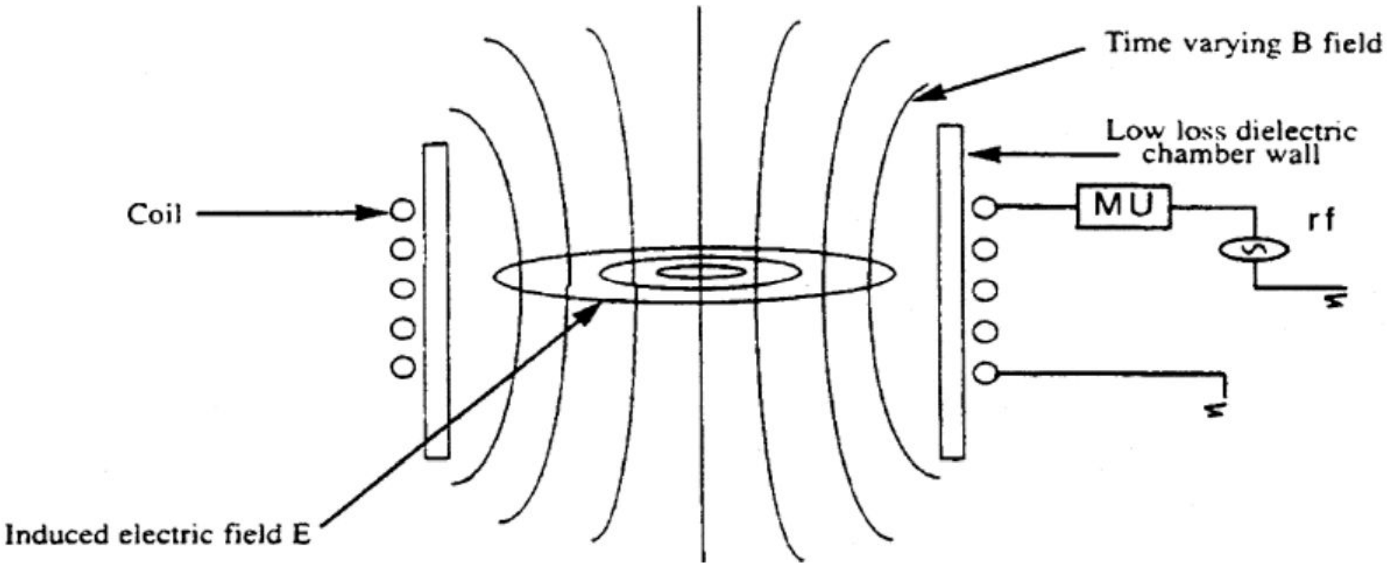


Etch anisotropy as a function of pressure

Ref: S. Lee, et. al., *IOP JMM*, vol. 8, pp. 330-337, 1998.

ICP Etch System

- Inductive Coupled Plasma etch
- Low pressure: less than 30 mTorr
  → improving ion directionality
- High ion density: more than 10^{11} cm^{-3}

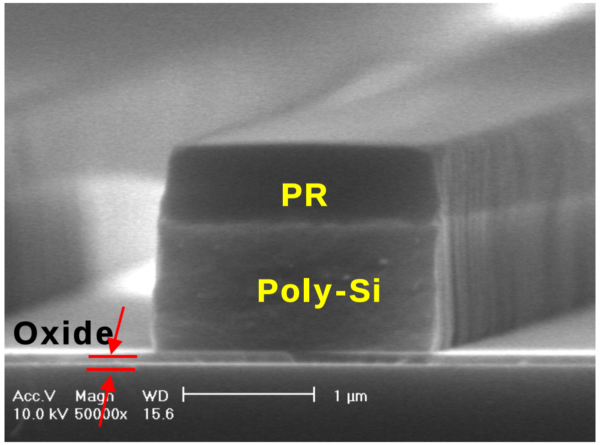


ICP: Poly-Si Etch Recipe of ISRC (1)

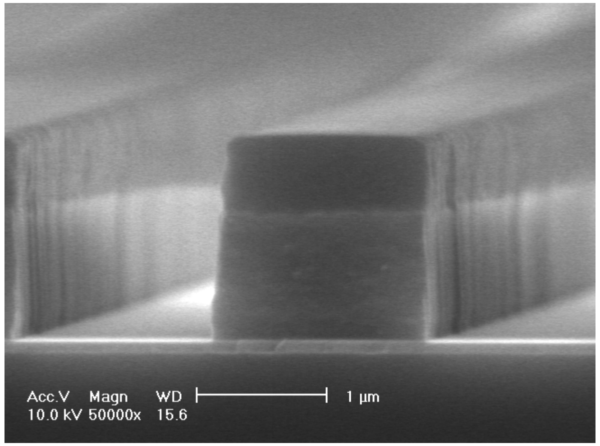
- System: STS ICP poly Etcher
- Process parameter

		Step 1 (native oxide etch)	Step 2 (poly-Si etch)
Power	Coil	600 W	900 W
	Platen	100 W	50 W
Pressure		2 mTorr	2 mTorr
Time		15 sec	60 sec
Temperature		20 ^{O}C	20 ^{O}C
Gas	Cl_2	20 sccm	0 sccm
	HBr	0 sccm	20 sccm
	O_2	0 sccm	1 sccm

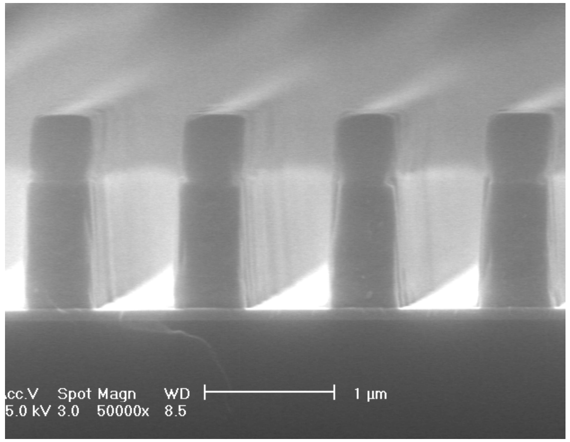
ICP: Poly-Si Etch Recipe of ISRC (2)



Line width: 2 um



Line width: 1.5 um



Line width: 0.55 um

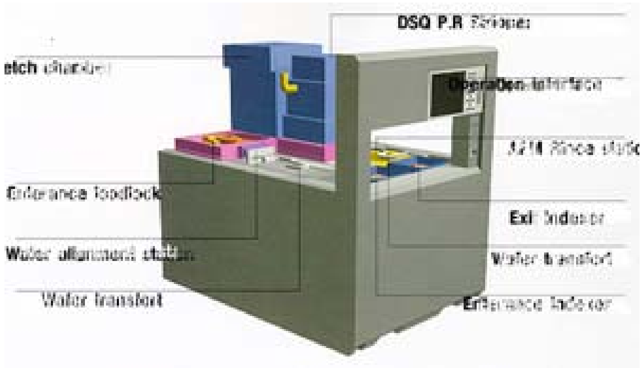
- Etch rate of poly-Si: 0.3 um/min
- Selectivity to PR: 3:1
- Selectivity to oxide: 100:1
- Etch profile: 88 $^{\circ}$ to 90 $^{\circ}$

ICP RIE System in ISRC (1)

- STS ICP poly Etcher (in CMOS area)
- Plasma source type: ICP (inductively coupled plasma)
- Main feed gas :HBr, Cl_2, Ar, SF_6, O_2, He_4
- Main power: 13.56 MHz – 1000 W
- Bias power: 13.56 MHz - 30/300 W

ICP RIE System in ISRC (2)

- TCP-9600 (in CMOS area)
- LAM Research, USA
- Features
  - Plasma source type: TCP (transformer coupled plasma)
  - Main feed gas: Cl_2, O2, SF_6, He
  - Main power: 13.56 MHz
  - Bias power: 13.56 MHz



- Stand Process Parameter
  - Main feed gas: Cl_2 (100 sccm), O_2 (10 sccm)
  - Main power: 13.56 MHz, 300 W
  - Bias power: 13.56 MHz, 40 W
  - Operating pressure: 5 mTorr

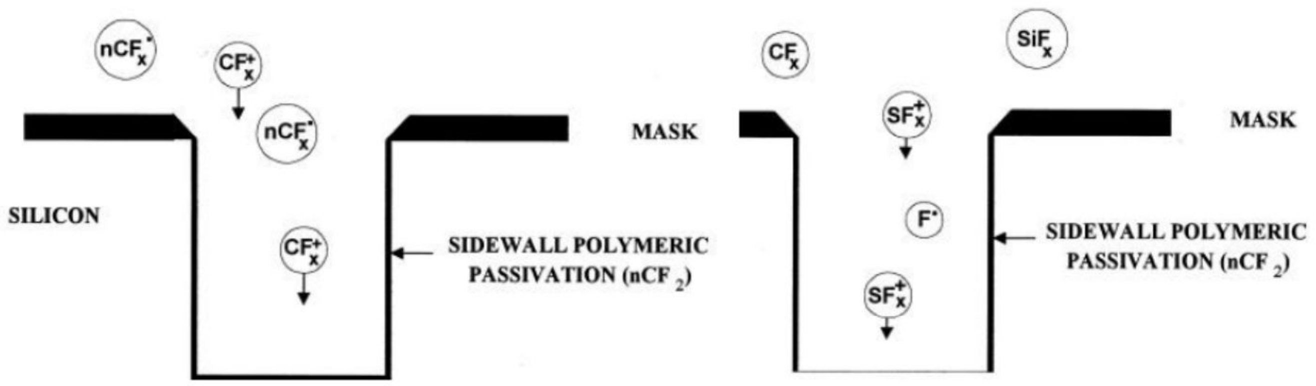
Various Gas for Poly-Si Etching

Gas	Reactor Type	Pressure (torr)	Etch Rate (μm/min)	Etch Selectivity	Comments
CCl_4/Argon	Planar	.4	.02(Undoped)	Poly Si : SiO_2 15:1	-
SiF_4(50%)/ Argon(50%)	Planar	.2	.4(Undoped)	Poly Si : SiO_2 25:1	-
CF_4/O_2	Barrel	.2	.05 ~ .1(Undoped)	Poly Si : Si_3N_4 : SiO_2 25 : 2.5: 1	-
CF_4/O_2(4%)	Planar	.4	.057(Phos doped)	Poly Si : SiO_2 10:1	-
C_2ClF_3	Planar	.225	.05(Phos doped)	Poly Si : SiO_2 3.5 :1	-
CF_4(92%)/O_2(8%)	Planar	.35	.115(Phos doped) .105(Phos doped)	Poly Si : SiO_2 10:1 Poly Si : SiO_2 9:1	Isotropic
C_2F_4(50%)/ CF_3Cl(50%)	Planar	.4	.159(Phos doped) .098(Undoped)	Poly Si : SiO_2 8:1 Poly Si : SiO_2 5:1	Isotropic
C_2F_4(81%)/ CF_3Cl(19%)	Planar	.4	.082(Phos doped) .070(Undoped)	Poly Si : SiO_2 5:1 Poly Si : SiO_2 4:1	Anisotropic
C_2F_4(92%)/ Cl_2(8%)	Planar	.35	.057(Phos doped) .050(Undoped)	Poly Si : SiO_2 6:1 Poly Si : SiO_2 5:1	Anisotropic
CF_3Cl	Planar	.35	.08(Phos doped) .03(Undoped)	Poly Si : SiO_2 13:1 Poly Si : SiO_2 6:1	Intermediate between Isotropic and Anisotropic

Ref: J. D. Lee, "Silicon Integrated Circuit microfabrication technology," 2nd edition

Deep Reactive Ion Etching (1)

- Uses high density plasma to alternatively etch silicon and deposit etch resistant polymer on sidewall
  - Unconstrained geometry 90^{O} side walls
  - High aspect ratio 1:30
  - Easily masked (PR, SiO_2)
- Bosch process: sidewall passivation → etch → sidewall passivation → etch …



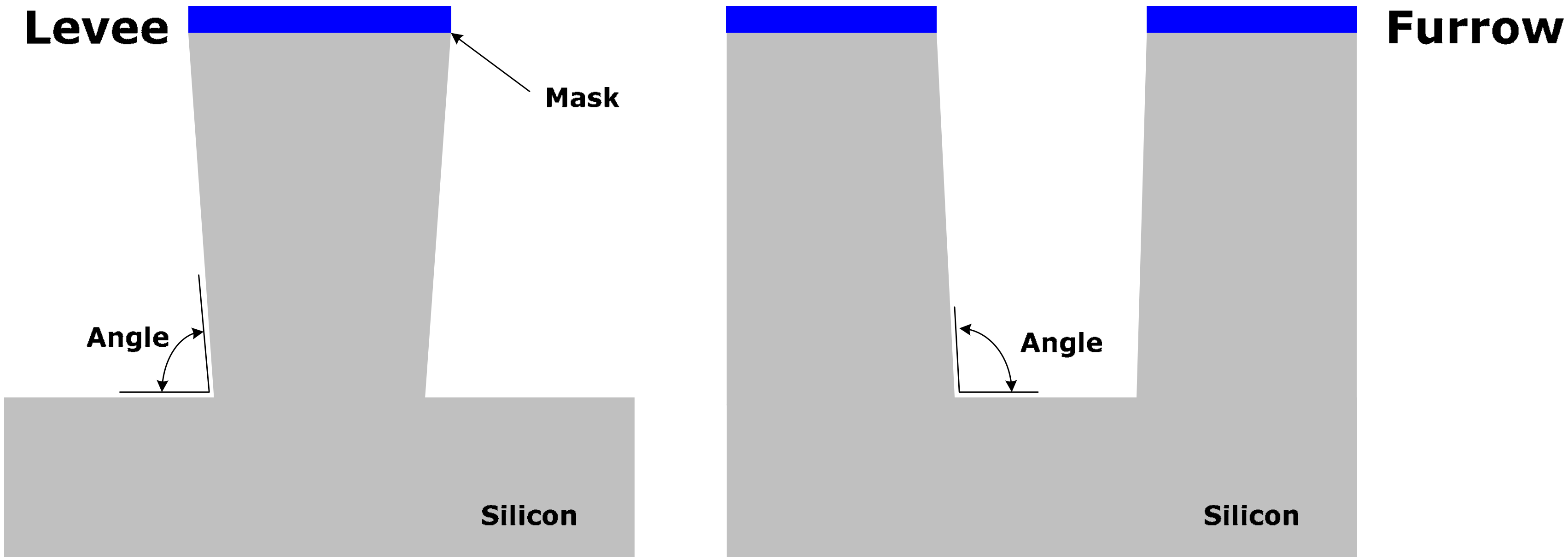
ASE process deposition step   ASE process etch step

Deep Reactive Ion Etching (2)

- Characteristics of the Deep RIE process
  - SF_6 flow: 30 ~ 150 sccm
  - C_4F_8 flow: 20 ~ 100 sccm
  - Etch cycle: 5 ~ 15 sec
  - Deposition cycle: 5 ~ 12 sec
  - Pressure: 0.25 ~ 10 Pa
  - Temperature: 20 ~ 80 ^{O}C
  - Etch rate: 1.5 ~ 4 um/min
  - Selectivity to resist mask: more than 75:1
  - Selectivity to oxide mask: more than 150:1
  - Sidewall angle: $90^{O} \pm 2$
  - Etch depth capability: up to 500 um

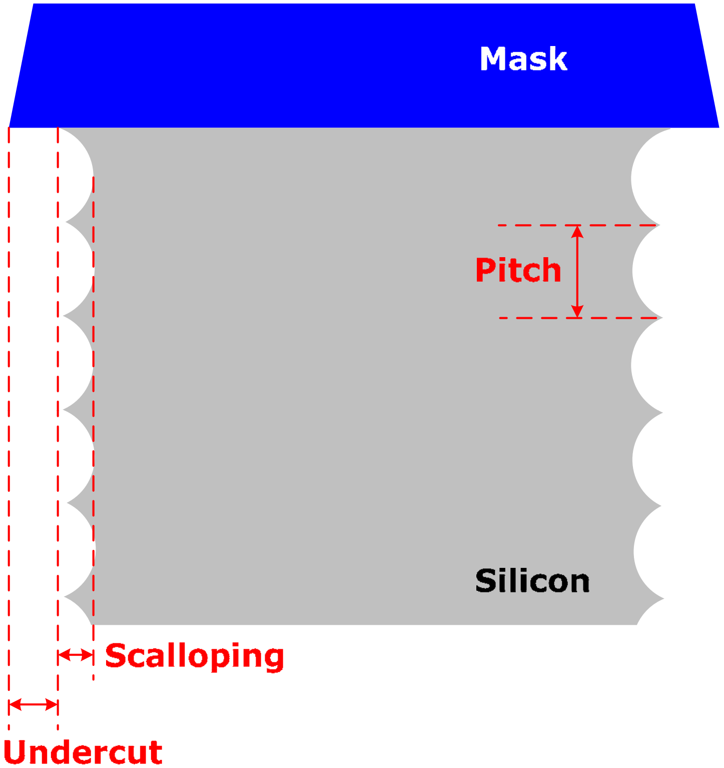
Deep Reactive Ion Etching (3)

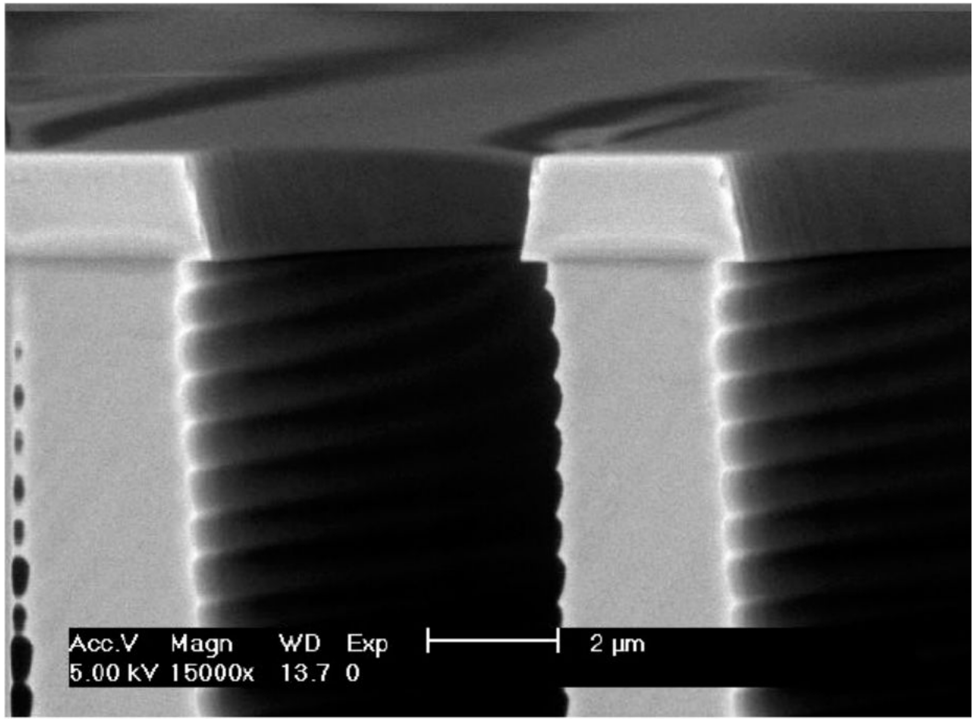
- Fence (levee) structure and trench (furrow) structure have different etch side wall profile



Deep Reactive Ion Etching (4)

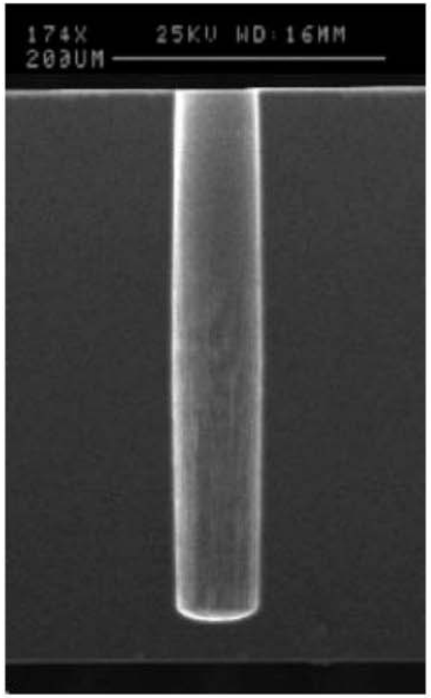
- Characteristics of Bosch process
  - Scalloping
  - Under cut



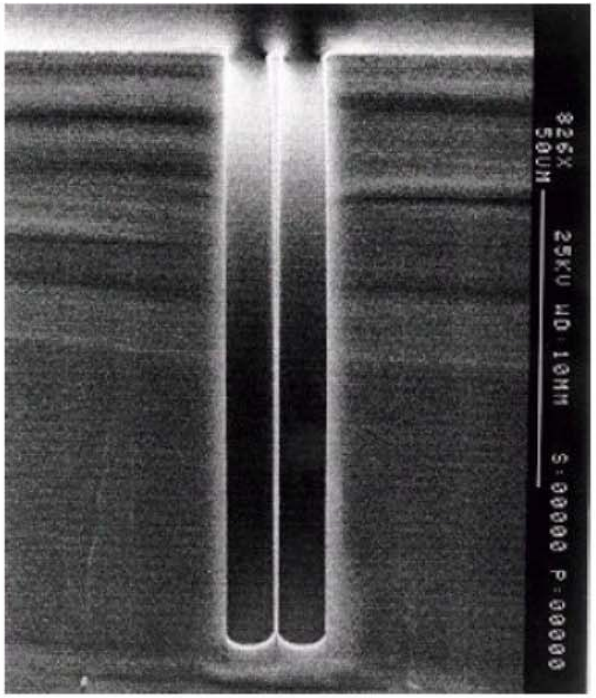


Deep RIE Example (1)

- Fabrication example (deep trench)



350㎛-depth

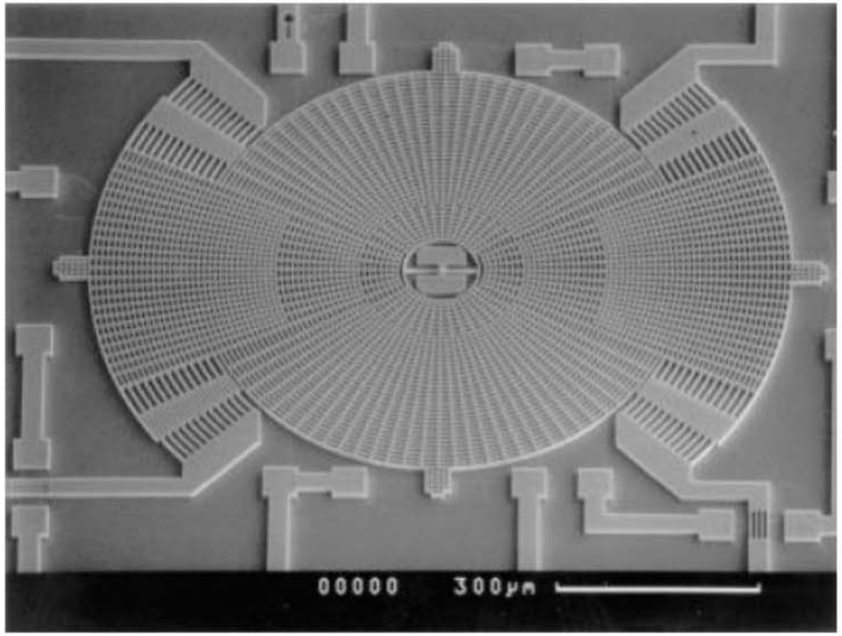


100㎛-depth

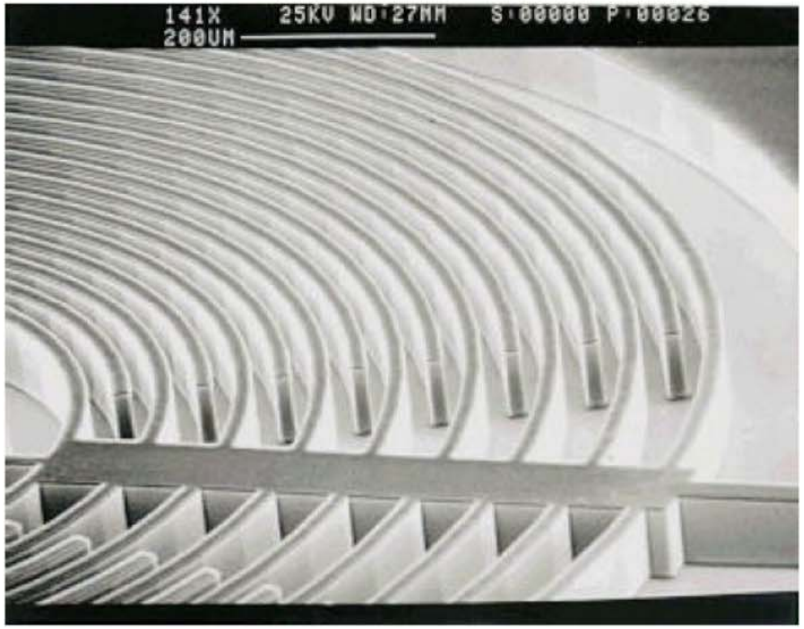
80㎛-depth, 4.5㎛ space width, 2㎛ line width

Deep RIE Example (2)

- Fabrication example (IMU device)



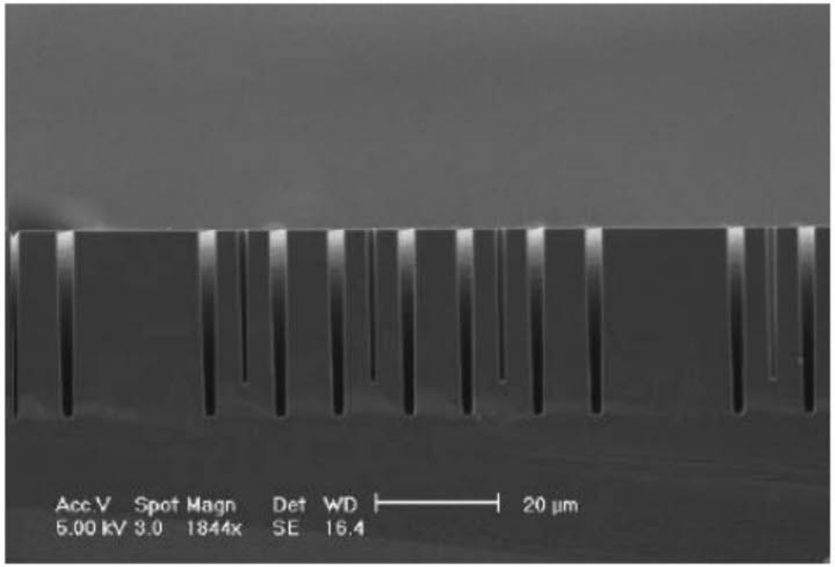
Gyroscope

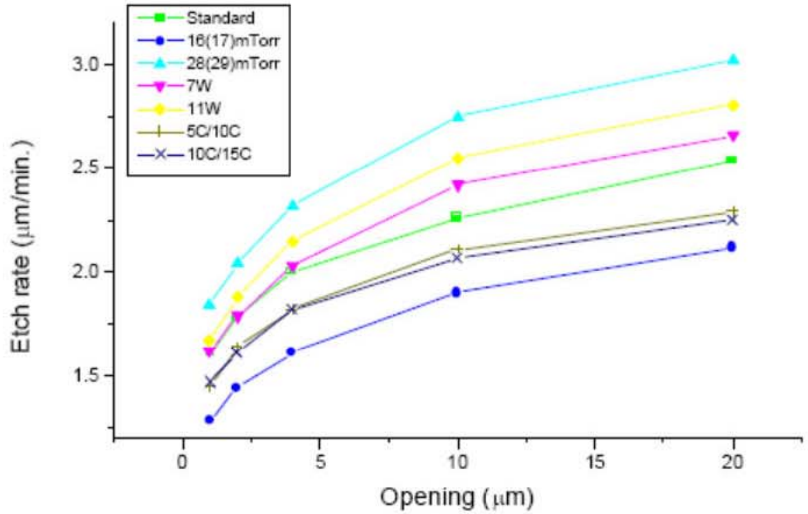


Accelerometer (170㎛-depth)

RIE Lag in Deep RIE Process

- RIE lag (microloading effect)
  - Etch rate differs from the area of opening

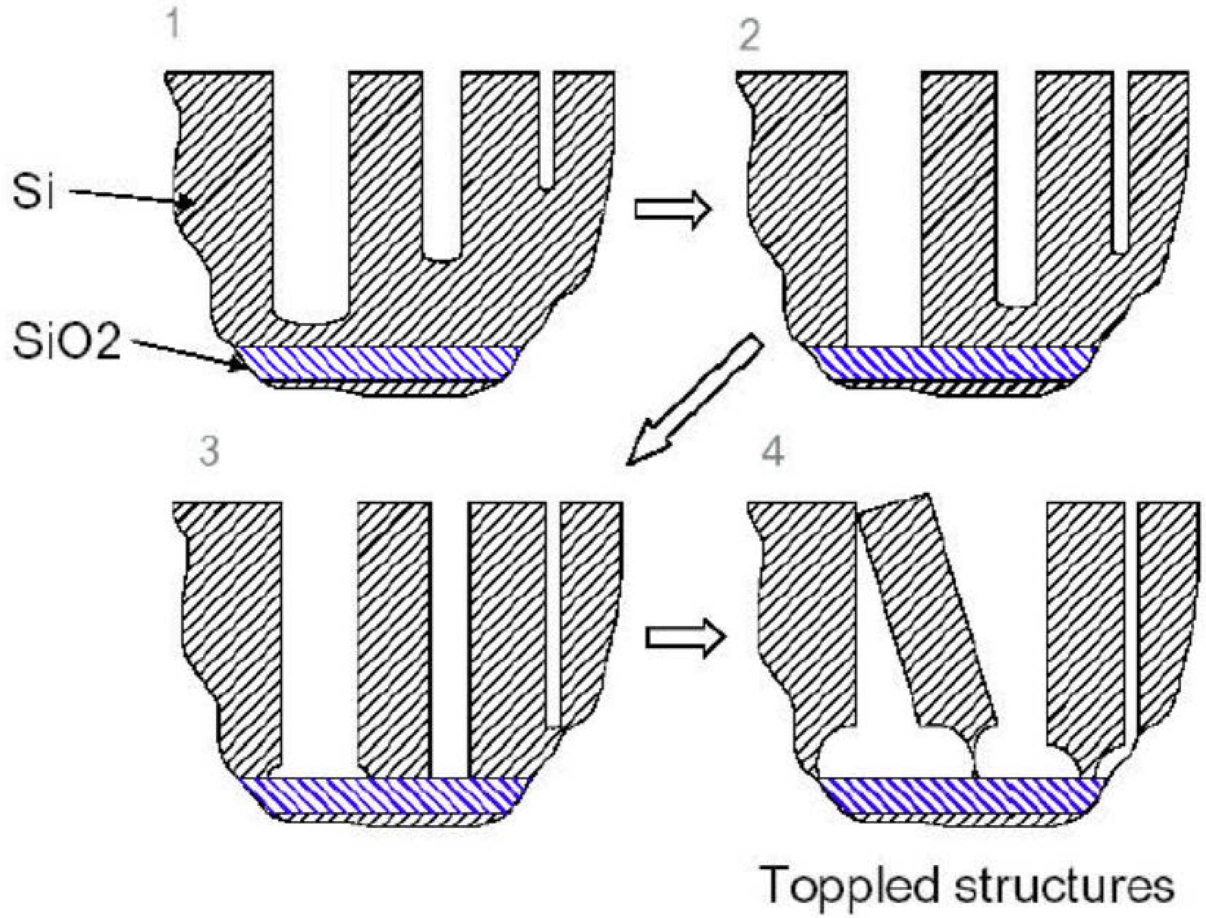




Plasma-Therm, SLR-7701-10R-B data

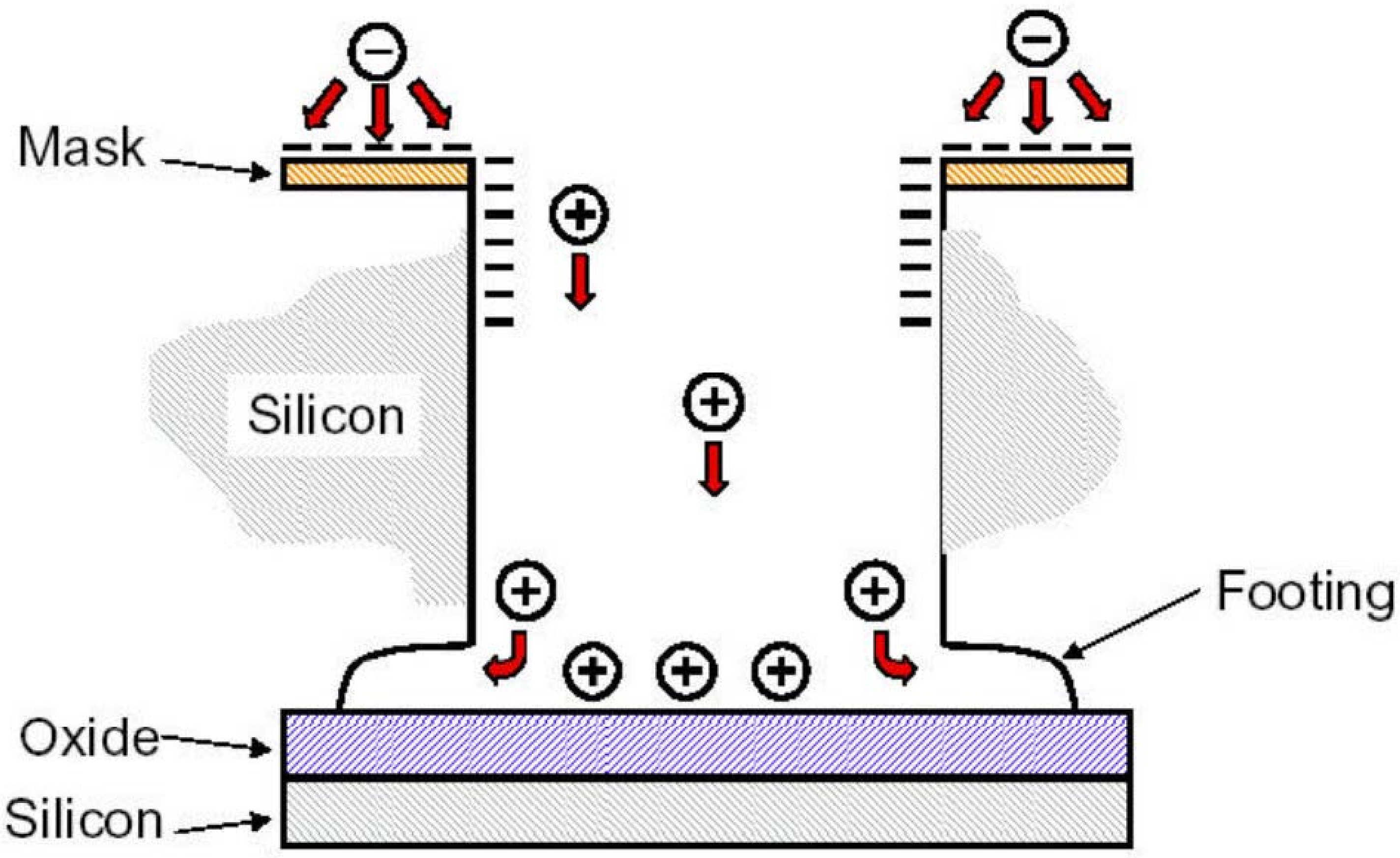
Footing in Deep RIE Process (1)

- Footing



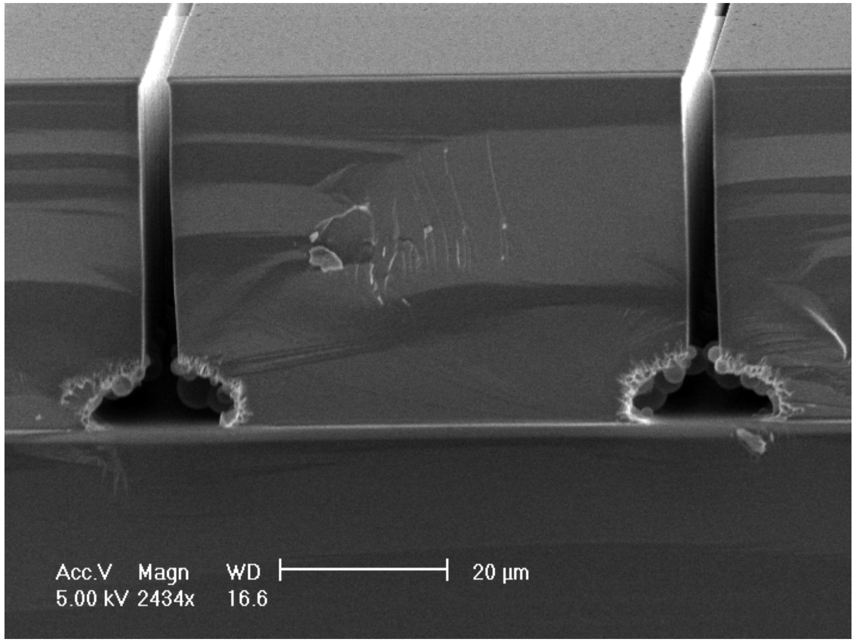
Footing in Deep RIE Process (2)

- Footing formation

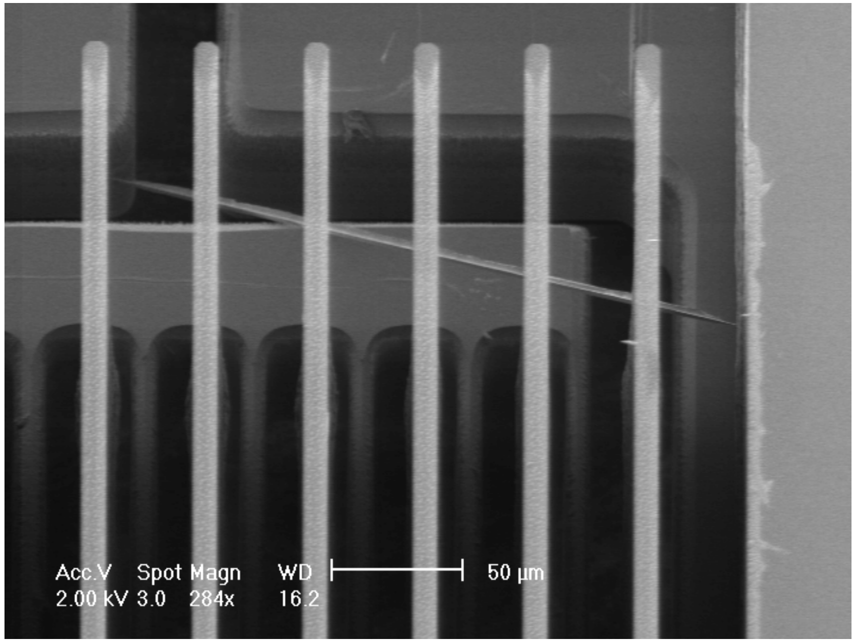


Footing in Deep RIE Process (3)

- Footing SEM pictures



Notching



Fragments

Deep RIE System in ISRC (1)

- ICP deep silicon RIE (in MEMS area)
- Plasma-Therm, SLR-7701-10R-B
- Plasma source type: ICP (inductively coupled plasma)
- High aspect ratio up to 20~30
- Feature
  - 2 kW, ICP source and 500W bias power
  - gas line: C_4F_8, SF_6, Ar, O_2, NF_3, C_2F_6)

		Deposition	Etch A	Etch B
Time (sec)		5	3	5
Gas (sccm)	C_4F_8	70	0.5	0.5
	SF_6	0.5	50	100
	Ar	30	30	30
Power (W)	RF1 (bias)	1	9	9
	RF2 (source)	825	825	825
Pressure (mTorr)		22	23	23

Deep RIE System in ISRC (2)

- Etch rate: 2.35 um/min

- Under cut at the top of 4 um line & space: 0.41 um
- RIE lag (2 um/4 um): 24 % etch rate difference

- Selectivity to resist mask: 75:1
- Selectivity to oxide mask: 199:1

- Sidewall profile (levee): 88.5 ^{o}
- Sidewall profile (furrow): 90 ^{o}

- Etch depth capability: up to 500 um

Reference

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9. J. D. Lee, “Silicon Integrated Circuit microfabrication technology,” 2nd edition