ENGINEERING TRIPOS PART IIB

Friday 9 May 2008 2.30 to 4

Module 4M6

MATERIALS AND PROCESSING FOR MICROSYSTEMS (MEMS)

*Answer not more than **three** questions.*

All questions carry the same number of marks.

*The **approximate** percentage of marks allocated to each part of a question is indicated in the right margin.*

Attachments: 4M6 Data Book (13 pages).

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS
Engineering Data Book
CUED approved calculator allowed

You may not start to read the questions printed on the subsequent pages of this question paper until instructed that you may do so by the Invigilator

1 (a) What factors affect the selection of particular materials in the design of a MEMS device? [25%]

(b) Fig. 1 shows a microcantilever beam of thickness h, width b and length l that is to be used for detecting a particular single strand of DNA. The beam is to be oscillated by mounting the system on a piezoelectric stack. The top side of the microcantilever will be coated in the complementary single strand of DNA, so that a change in the resonant frequency of the microcantilever will occur upon attachment of the single strand of DNA to be detected. The oscillation of the microcantilever is detected by reflecting a laser beam off the top surface of the microcantilever onto a photodetector.

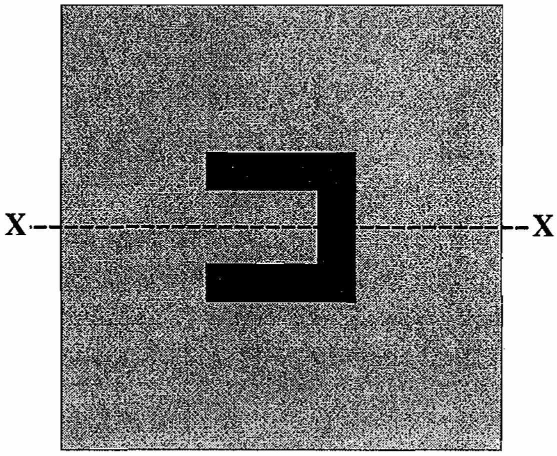
(i) What is the figure of merit for the selection of the microcantilever beam material if the resonant frequency is to be maximised for a given beam size? [15%]

(ii) Hence, suggest a suitable material for the fabrication of the microcantilever beam. Justify your answer. [15%]

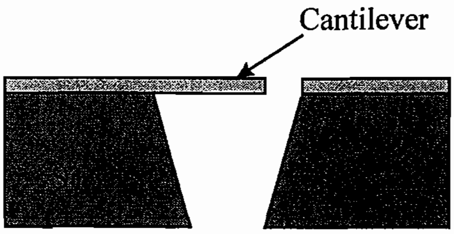
(iii) Construct a process flow for the fabrication of your microcantilever beam from a bare silicon wafer. Justify your choice of processes. [45%]

NOTE: The spring constant k for a beam of thickness h, width b and length l is given by

$$k = \frac{Ebh^3}{12l^3} .$$



Plan view



Cross section X-X

Fig. 1

2 (a) Describe how *rf magnetron sputtering* can be used for the deposition of metallic thin films as well as metal oxides and metal nitrides. Illustrate your answer by including a schematic diagram of an rf magnetron sputtering system. [40%]

(b) Define the term *sputtering yield* in reference to rf magnetron sputtering. [5%]

(c) Sketch graphs showing how the sputtering yield varies as a function of each of the following factors:

angle of incidence of the sputtering ions;

energy of the sputtering ions.

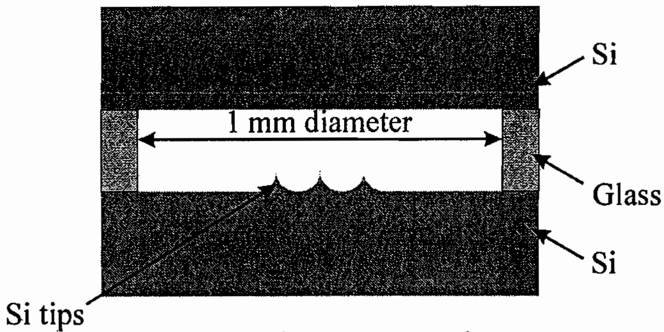
Why is argon gas most commonly used for sputtering metals? [25%]

(d) What type of intrinsic stress would you normally find in sputtered films? Justify your answer. Why could a high intrinsic stress be a problem for the production of MEMS devices? [20%]

(e) A lift-off technique is to be used for patterning a 200 nm thick layer of aluminium on the surface of a silicon wafer. Explain why it would be preferable to use evaporation for the deposition of the aluminium layer rather than sputtering. [10%]

3 (a) Describe the process by which two silicon wafers may be joined together by *direct (fusion) bonding*. Why is wafer bonding important for the fabrication of MEMS devices? Give an example of a real MEMS device whose fabrication includes wafer bonding to illustrate your answer. [40%]

(b) Fig. 2 shows a simple field emission device consisting of a layer of glass 500 μm thick sandwiched between two highly n-type silicon wafers. The glass contains a hole of 1 mm diameter on one side of which is a bare silicon surface and on the other is a bare silicon surface that has, at its centre, a small array of sharp silicon tips that are 3 μm high and ~6 μm in diameter at their base. This cavity is filled with a vacuum such that, when a high voltage is applied between the two silicon wafers of the appropriate polarity, an electron field emission current flows from the silicon tips to the top silicon wafer. Describe a process flow for the fabrication of this device, assuming that the glass has been supplied to you with the 1 mm hole already drilled into it. [60%]



Cross section (not to scale)

Fig. 2

4 (a) With the aid of diagrams, describe the following photolithographic printing techniques. In each case you should explain what limits the critical dimension and suggest general situations under which it is appropriate to use each technique:

proximity printing;
contact printing;
projection printing. [45%]

(b) (i) Explain the procedure for defining patterns by *microcontact printing*. What advantages does this technique have over photolithography other than lower cost? [15%]

(ii) Describe the process flow for producing a PDMS stamp to be used in microcontact printing. [20%]

(iii) Under what circumstances is reducing processing cost particularly important for economically viable MEMS device manufacture? Illustrate your answer by giving an example of a type of MEMS device that you think would be particularly suited to microcontact printing. [20%]

END OF PAPER

Materials & Processes for Microsystems

Data Book
2005 Edition

http://www2.eng.cam.ac.uk/~ajf/4M6/

CONTENTS

SECTION 1: MATERIAL PROPERTIES

1.1 CRYSTALLINE SILICON (C-SI)

Property	Value
Atomic weight	28.1
Atomic density	5×10^{28} m^{-3}
Band gap at 300 K	1.12 eV
Chemical resistance	High (resistant to most acids and some bases)
Density	2400 kg m^{-3}
Dielectric constant	11.8
Dielectric strength	3×10^{8} V m^{-1}
Electron mobility	0.150 m^2 V^{-1} s^{-1}
Fracture strength	6 GPa
Hole mobility	0.040 m^2 V^{-1} s^{-1}
Intrinsic carrier concentration	1.45×10^{16} m^{-3}
Intrinsic resistivity	2.3×10^{3} Ω m
Knoop hardness	850 kg mm^{-2}
Lattice constant	0.543 nm
Linear coefficient of thermal expansion at 300 K	2.6×10^{-6} K^{-1}
Melting point	1688 K
Minority carrier lifetime	2.5×10^{-3} s
Poisson ratio	0.22
Relative permittivity	11.8
Specific heat at 300 K	713 J kg^{-1} K^{-1}
Thermal conductivity at 300 K	156 W m^{-1} K^{-1}
Tempertaure coefficient of the Young Modulus at 300 K	90×10^{-6} K^{-1}
Thermal diffusivity	0.9×10^{-4} m^2 s^{-2}
Yield strength	7 Gpa
Young modulus	190 GPa

1.2 Hydrogenated Amorphous Silicon (a-Si:H)

Property	Value
Activation energy of conduction at 300 K	0.7 – 0.8 eV
Chemical resistance	Fairly high (resistant to most acids and some bases)
Compressive Stress	-1 – 0.5 GPa
Dark conductivity	10^{-9} – 10^{-8} Ω^{-1} m^{-1}
Defect density	10^{22} m^{-3}
Electron mobility	10^{-4} m^{2} V^{-1} s^{-1}
Hole mobility	2×10^{-6} m^{2} V^{-1} s^{-1}
Hydrogen content	5 – 15 at. %
Optical (Tauc) gap	1.75 – 1.85 eV
Photoconductivity	10^{-3} – 10^{-3} Ω^{-1} m^{-1}
Photosensitivity	10^{6}
Poisson ratio	0.25
Refractive index	3.5 – 3.8
Urbach energy	50 – 60 meV
Young modulus	130 – 160 GPa

1.3 Polycrystalline Diamond

Property	Value
Breakdown strength	10^{9} V m^{-1}
Density	3500 kg m^{-3}
Dielectric constant	5.5
Electron mobility	0.22 m^{2} V^{-1} s^{-1}
Energy gap	5.5 eV
Hole mobility	0.16 m^{2} V^{-1} s^{-1}
Knoop hardness	10^{10} kg m^{-2}
Melting point	4000° C
Thermal conductivity	2000 W m^{-1} K^{-1}
Thermal expansion coefficient	8×10^{-8} K^{-1}
Yield strength	53 GPa
Young modulus	1035 GPa

1.4 POLYCRYSTALLINE SILICON (POLY-SI)

Property	Value
Density	2320 kg m^{-3}
Dielectric constant	4.2
Electron mobility	$(3 - 60)\times10^{-3}$ m^2 V^{-1} s^{-1}
Fracture strength	0.8 – 2.84 GPa
Poisson ratio	0.23
Refractive index	4.1
Residual stress	Compressive
Thermal conductivity	30 – 70 W m^{-1} K^{-1}
Thermal expansion coefficient	2.8×10^{-6} K^{-1}
Young modulus	160 GPa

1.5 SILICON DIOXIDE (A-SIO)

Property	Value
Band gap at 300 K	9 eV
Density	2200 kg m^{-3}
Dielectric constant	3.9
Dielectric strength	10^9 V m^{-1}
Etch rate in buffered HF	100 nm min^{-1}
Melting point	~1600° C
Poisson ratio	0.20
Resistivity	$10^{12} - 10^{14}$ Ω m
Refractive index	1.46
Residual Stress	~350 MPa (Compressive)
Thermal conductivity	1.4 W m^{-1} K^{-1}
Thermal expansion coefficient	0.35×10^{-6} K^{-1} (Thermal) 2.3×10^{-6} K^{-1} (PECVD)
Young modulus	70 GPa

1.6 SILICON NITRIDE (A-SIN)

Property	Value
Band gap at 300 K	5.3 eV
Density	3440 kg m^{-3}
Dielectric constant	7.5
Dielectric strength	10^9 V m^{-1}
Etch rate in concentrated HF	20 nm min^{-1}
Etch rate in buffered HF	1 nm min^{-1}
Hydrogen content	4 – 8 at. % (LPCVD) 20 – 25 at. % (PECVD)
Melting point	3440° C
Poisson ratio	0.27
Resistivity	10^{12} - 10^{14} Ω m
Refractive index	2.01
Thermal conductivity	19 W m^{-1} K^{-1}
Thermal expansion coefficient	1.6×10^{-6} K^{-1}
Yield strength	6.9 Gpa
Young modulus	380 GPa

SECTION 2: COMMON FORMULAE &DATA

2.1 DOPING

For the case of an infinitely deep medium where C→0 as x→∞ and there is a constant concentration of impurities at the surface as a function of time, C_s, then the solution to the diffusion equation is

$$C(x,t) = C_s \operatorname{erfc}\left(\frac{x}{2\sqrt{Dt}}\right) \qquad (2.8)$$

For ion implantation, dopants are implanted with a Gaussian distribution,

$$N_i(x) = \frac{Q_i}{\Delta R_p \sqrt{2\pi}} \exp\left[\frac{-1}{2}\left(\frac{x - R_p}{\Delta R_p}\right)^2\right] \qquad (2.9)$$

2.2 THERMAL CRYSTALLISATION

For a material undergoing thermal crystallisation, the nucleation rate of crystallites is given by

$$N \propto \frac{1}{T} \exp\left[\frac{-\left(E_d + \Delta G_n^{*}\right)}{kT}\right] \qquad (3.5)$$

Once nucleated, crystals grow with a velocity given by

$$v \propto \exp\left[\frac{-\left(2E_d - \Delta G'\right)}{2kT}\right] \qquad (3.6)$$

2.3 THERMAL EVAPORATION

For a material undergoing thermal evaporation, the flux of atoms evaporating per second, F, is given by

$$F = N_0 \exp\left(\frac{-\Phi_e}{kT}\right) \qquad (5.1)$$

where $N0$ is a slowly varying function of temperature and Φe is the activation energy required to evaporate one molecule which is related to the enthalpy of formation of the evaporant, H, by

$$\Phi_e = \frac{H}{N_A} \qquad (5.2)$$

The deposition rate at a distance d from the source is

$$R \sim \frac{\cos\beta \cos\theta}{d^2} \qquad (5.3)$$

2.4 SPUTTERING

The Sigmund expression for sputter yield is

$$S \propto \frac{eE}{Ua\{M_t/M_i\}} \qquad (5.4)$$

where U is the heat of sublimation of the target material, a is a near linear function of (M_i/M_t), M_i is the ion mass, M_t is the target atom mass, E is the ion energy and e is the momentum transfer function which for elastic collisions is given by

$$e = \frac{4M_iM_t}{(M_i + M_t)^2} \qquad (5.5)$$

2.5 ELECTROPLATING

From the Faraday Law of electrolysis, the mass of metal deposited per unit area per unit time, M, is given by

$$M = \frac{JA}{zF} \qquad (5.11)$$

where, assuming 100% current efficiency, J is the current density ***due to metal ions***, A and z are the atomic weight and valency of the metal respectively and F is the Faraday constant, which is 96500 C.

2.6 ELASTIC MODULI

For an anisotropic ***cubic*** material, we may still calculate the Young modulus in an arbitrary crystallographic direction from the compliance coefficients,

$$E = \frac{1}{S_{11} - (2S_{11} - 2S_{12} - S_{44})(l_1^2 l_2^2 + l_2^2 l_3^2 + l_1^2 l_3^2)} \qquad (6.8)$$

Additionally, we may gain an estimate of the Young modulus for a polycrystalline cubic material from the complaince coefficients by averaging equation (6.8) over all directions

$$\overline{E} \approx \frac{1}{0.6S_{11} + 0.4S_{12} + 0.25S_{44}} \qquad (6.9)$$

The Poisson ratio for any normal plane in an anisotropic cubic material is

$$\nu = -E\left[S_{12} + \left(S_{11} - S_{12} - \frac{S_{44}}{2}\right)(l_1^2 m_1^2 + l_2^2 m_2^2 + l_3^2 m_3^2)\right] \qquad (6.11)$$

The Shear modulus is dependent on the Young modulus and Poisson ratio

$$G = \frac{E}{2(1+\nu)} \qquad (6.22)$$

The Bulk modulus is given by

$$K = \frac{E}{3(1-2\nu)} \qquad (6.27)$$

2.7 PIEZOELECTRICITY

For piezoelectric materials,

$$D = d\sigma + \varepsilon_0 \varepsilon_r\big|_\sigma E \qquad (6.33a)$$

$$D = e\varepsilon + \varepsilon_0 \varepsilon_r\big|_\varepsilon E \qquad (6.33b)$$

and the electromechanical coupling coefficient is given by

$$k = \sqrt{\frac{de}{\varepsilon_0 \varepsilon_r\big|_\sigma}} \qquad (6.35)$$

2.8 PIEZORESISTIVITY

For piezoresistive materials, the Ohm Law becomes

$$\mathbf{E} = [\boldsymbol{\rho}_e + \boldsymbol{\Pi} \cdot \boldsymbol{\sigma}] \cdot \mathbf{J} \qquad (6.38)$$

For a cubic material, such as silicon, once again the situation is simplified. The resistivity term becomes a simple scalar. We use the same numbering system for the stress tensor, so that

$$[x, y, z, yz, zx, xy] \Leftrightarrow [1,2,3,4,5,6] \qquad (6.39)$$

The field-current relationships, given the symmetry of the cubic system, become

$$\frac{E_x}{\rho_e} = [1 + \pi_{11}\sigma_x + \pi_{12}(\sigma_y + \sigma_z)]J_x + \pi_{44}(\tau_{xy}J_y + \tau_{xz}J_z)$$

$$\frac{E_y}{\rho_e} = [1 + \pi_{11}\sigma_y + \pi_{12}(\sigma_x + \sigma_z)]J_y + \pi_{44}(\tau_{xy}J_x + \tau_{yz}J_z) \qquad (6.40)$$

$$\frac{E_z}{\rho_e} = [1 + \pi_{11}\sigma_z + \pi_{12}(\sigma_x + \sigma_y)]J_z + \pi_{44}(\tau_{xz}J_z + \tau_{yz}J_y)$$

Where the three independent coefficients from the fourth rank piezoresistive tensor are

$$\rho_e\pi_{11} = \Pi_{1111}$$

$$\rho_e\pi_{12} = \Pi_{1122} \qquad (6.41)$$

$$\rho_e\pi_{44} = \Pi_{2323}$$

Change in resistance due to the piezoresistivity effect is given by

$$\frac{\Delta R}{R} = \pi_l\sigma_l + \pi_t\sigma_t \qquad (6.42)$$

Where σ_l and σ_t are the longitudinal and transverse stress and π_l and π_t may be determined from the piezoelectric coefficients using the transformation

$$\pi_l = \pi_{11} - 2(\pi_{11} - \pi_{12} - \pi_{44})(l_1^2 l_2^2 + l_1^2 l_3^2 + l_2^2 l_3^2) \qquad (6.43a)$$

$$\pi_t = \pi_{12} + (\pi_{11} - \pi_{12} - \pi_{44})(l_1^2 t_1^2 + l_2^2 t_2^2 + l_3^2 t_3^2) \qquad (6.43b)$$

2.9 MICROSCOPY

For a simple optical system comprising an objective and condenser, it can be shown that the resolving power is given by

$$\delta = \frac{C\lambda}{\eta \sin \alpha} \qquad (8.2)$$

In an electron microscope, the electron wavelength is given by the de Broglie equation,

$$\lambda = h/p \qquad (8.3)$$

2.10 THE STONEY EQUATION

The Stoney equation states that

$$\sigma = \frac{E}{6(1-\nu)} \frac{t_s^2}{t} \left(\frac{1}{R_c} - \frac{1}{R_0} \right) \qquad (8.7)$$

2.11 X-RAY DIFFRACTION

The Bragg equation for diffraction states that constructive interference will only occur when

$$n\lambda = 2d \sin \theta \quad (8.8)$$

For a given set of planes (h k l) in a cubic unit cell with side lengths a, b and c, the plane separation in equation 8.8 will be given by

$$\frac{1}{d^2} = \frac{h^2}{a^2} + \frac{k^2}{b^2} + \frac{l^2}{c^2} \qquad (8.9)$$

The structure factor, $Fhkl$, the modulus of which gives the amplitude of the wave diffracted by a particular set of planes, and is given by

$$|F_{hkl}| = \sum_{1}^{N} f_n \exp[2\pi j(hu_n + kv_n + lw_n)] \quad (8.10)$$

Table 4.1 Diffraction peaks observed and not present in some common bravais lattices.

Bravais lattice	Diffraction present	Diffraction absent
Simple	All	None
Base centred	h and k not mixed	h and k mixed
Body centred	$(h + k + l)$ even	$(h + k + l)$ odd
Face centred	h, k and l not mixed	h, k and l mixed

2.12 UV-VISIBLE SPECTROMETRY

The absorption coefficient, α, of a material may be determined as a function of photon energy,

$$\%T = (100 - \%R)\exp(-\alpha t)$$

$$\alpha = \frac{-1}{t} \ln\left(\frac{\%T}{100 - \%R} \right) \qquad (8.13)$$

2.13 FOURIER TRANSFORM INFRARED SPECTROMETRY

The size of the absorption peaks provide a rough guide to elemental composition (±1 at. %),

$$C = -K_A \int \frac{\ln(\%T/100)}{kt} \partial k \qquad (8.14)$$

Wavenumber (cm^{-1})	Bond	Vibrational mode type
460	Si—O_2	Rock
630	Si—H	Bend
630	Si—H_2	Rock
630	Si—H_3	Rock
630	Si—H_3	Wag
805	Si—O_2	Bend
820	Si—H_2	Twist
840	Si—N	Stretch
860	Si—H_3	Bend
880	Si—H_2	Bend
905	Si—H_3	Bend
920	Si—O	Stretch
1080	Si—O_2	Stretch
1150	N—H	Bend
2000	Si—H	Stretch
2090	Si—H_2	Stretch
2140	Si—H_3	Stretch
3350	N—H	Stretch

2.14 PHOTOLITHOGRAPHY

The empirical expression for photoresist thickness is

$$t = \frac{KC^{\beta}\eta^{\gamma}}{R^{\alpha}} \qquad (9.2)$$

where C is the polymer concentration in g per 100 ml, *h* is the intrinsic viscosity, *R* is the number of rotations per minute, *K* is a calibration constant and α, β and γ are resist-dependent constants.

For positive resists, contrast is given by

$$\gamma = \frac{1}{\left(\log D_P - \log D_P^0\right)} = \left[\log \frac{D_P}{D_P^0}\right]^{-1} \qquad (9.3)$$

whilst for negative resists

$$\gamma = \frac{1}{\left(\log D_g^0 - \log D_g^i\right)} = \left[\log \frac{D_g^0}{D_g^i}\right]^{-1} \qquad (9.4)$$

The resolution for shadow printing using a conventional resist of thickness z and with a print gap between the mask and the resist surface of s is given by

$$R = \frac{3}{2}\sqrt{\lambda\left(s + \frac{z}{2}\right)} \qquad (9.5)$$

whilst for a projection printing system,

$$R = \frac{k_1\lambda}{N} \qquad (9.6)$$

where

$$N = n\sin\theta_{\max} = \frac{D}{2F} \qquad (9.7)$$

2.15 ETCHING

Etch Rates for Micromachining and IC Processing (Å/min) v. 4.4 29 July 1996
U.C. Berkeley Microfabrication Laboratory / Berkeley Sensor & Actuator Center / Kirt R. Williams
The top etch rate was measured by the author with fresh solutions, clean chambers, etc.
The center and bottom values are the low and high etch rates observed by the author and others in the UCB Microlab using fresh and used solutions, clean and "dirty" chambers, etc.

ETCHANT EQUIPMENT CONDITIONS	TARGET MATERIAL	MATERIAL SC Si <100>	Poly n+	Poly undop	Wet Ox	Dry Ox	LTO undop	PSG unanl	PSG annld	Stoic Nitrid	Low-σ Nitrid	Al/ 2% Si	Sput Tung	Sput Ti	Sput Ti/W	OCG 820PR	Olin HuntPR
Concentrated HF (49%) Wet Sink Room Temperature	Silicon oxides	-	0	-	23k 18k 23k	F	>14k	F	36k	140	52 30 52	42 0 42	<50	F	-	P 0	P 0
10:1 HF Wet Sink Room Temperature	Silicon oxides	-	7	0	230	230	340	15k	4700	11	3	2500 2500 12k	0	11k	<70	0	0
25:1 HF Wet Sink Room Temperature	Silicon oxides	-	0	0	97	95	150	W	1500	6	1	W	0	-	-	0	0
5:1 BHF Wet Sink Room Temperature	Silicon oxides	-	9	2	1000 900 1080	1000	1200	6800	4400 3500 4400	9	4 3 4	1400	<20 0.25 20	F	1000	0	0
Phosphoric Acid (85%) Heated Bath with Reflux 160°C	Silicon nitrides	-	7	-	0.7	0.8	<1	37	24 9 24	28 28 42	19 19 42	9800	-	-	-	550	390
Silicon Etchant (126 HNO_3 : 60 H_2O : 5 NH_4F) Wet Sink Room Temperature	Silicon	1500	3100 1200 6000	1000	87	W	110	4000	1700	2	3	4000	130	3000	-	0	0
KOH (1 KOH : 2 H_2O by weight) Heated Stirred Bath 80°C	<100> Silicon	14k	>10k	F	77 41 77	-	94	W	380	0	0	F	0	-	-	F	F
Aluminum Etchant Type A (16 H_3PO_4 : 1 HNO_3 : 1 HAc : 2 H_2O) Heated Bath 50°C	Aluminum	-	<10	<9	0	0	0	-	<10	0	2	6600 2600 6600	-	0	-	0	0
Titanium Etchant (20 H_2O : 1 H_2O_2 : 1 HF) Wet Sink Room Temperature	Titanium	-	12	-	120	W	W	W	2100	8	4	W	0 0 <10	8800	-	0	0
H_2O_2 (30%) Wet Sink Room Temperature	Tungsten	-	0	0	0	0	0	0	0	0	0	<20	190 190 1000	0	60 60 150	<2	0
Piranha (~50 H_2SO_4 : 1 H_2O_2) Heated Bath 120°C	Cleaning off metals and organics	-	0	0	0	0	0	-	0	0	0	1800	-	2400	-	F	F
Acetone Wet Sink Room Temperature	Photoresist	-	0	0	0	0	0	-	0	0	0	0	-	0	-	>44k	>39k
CF_4+CHF_3+He (90:30:120 sccm) Lam 590 Plasma 450W, 2.8T, gap=0.38cm, 13.56MHz	Silicon oxides	W	1900 1400 1900	2100 1500 2100	4700 2400 4800	W	4500	7300 3000 7300	6200 2500 7200	1800	1900	-	W	W	W	2200	3000
CF_4+CHF_3+He (90:30:120 sccm) Lam 590 Plasma 850W, 2.8T, gap=0.38cm, 13.56MHz	Silicon oxides	W	2200 2200 2700	1700 1700 2100	6000 2500 7600	W	6400 6000 6400	7400 5500 7400	6700 5000 6700	4200 4000 6800	3800	-	W	W	W	2600 2600 6700	2900 2900 7200
SF_6+He (13:21 sccm) Technics PE II-A Plasma 100W, 250mT, gap=2.6cm, 50kHz sq. wave	Silicon nitrides	300 300 1000	730 730 800	670 670 760	310	350	370	610	480 230 480	820	620 550 800	-	W	W	W	690 690 830	630
CF_4+CHF_3+He (10:5:10 sccm) Technics PE II-A Plasma 200W, 250mT, gap=2.6cm, 50kHz sq. wave	Silicon nitrides	1100	1900	W	730	710	730	W	900	1300	1100	-	W	W	W	690	600
SF_6+He (175:50 sccm) Lam 480 Plasma 150W, 375mT, gap=1.35cm, 13.56MHz	Thin silicon nitrides	W	6400	7000 2000 7000	300 220 400	W	280	530	540	1300 830 2300	870	-	W	W	W	1500 1300 1500	1400
SF_6+He (175:50 sccm) Lam 480 Plasma 250W, 375mT, gap=1.35cm, 13.56MHz	Thick silicon nitrides	W	8400	9200	800	W	770	1500	1200	2800 2100 4200	2100	-	W	W	W	3400 3100 3400	3100
SF_6 (25 sccm) Tegal Inline Plasma 701 125W, 200mT, 40°C	Thin silicon nitrides	W	1700	2800	1100 1100 1600	W	1100	1400	1400	2800 2800 2800	2300	-	W	W	W	3400 2900 3400	3100
CF_4+CHF_3+He (45:15:60 sccm) Tegal Inline Plasma 701 100W, 300mT, 13.56MHz	Si-rich silicon nitrides	W	350	360	320	W	320	530	450	760	600	-	W	W	W	400	360
Cl_2+He (180:400 sccm) Lam Rainbow 4420 Plasma 275W, 425mT, 40°C, gap=0.80cm, 13.56MHz	Silicon	W 5000 5000	5700 3400 6300	3200 3200 3700	8 8 380	-	60	230	140	560	530	W	W	-	-	3000 2400 3000	2700
HBr+Cl_2 (70:70 sccm) Lam Rainbow 4420 Plasma 200W, 300mT, 40°C, gap=0.80cm, 13.56MHz	Silicon	W	450 450 740	460	4 4 10	-	0	0	0	870	26	W	W	-	-	350 350 500	300
Cl_2+BCl_3+$CHCl_3$+N_2 (30:50:20:50 sccm) Lam 690 RIE 250W, 250mT, 60°C, 13.56MHz	Aluminum	W	4500	W	680	670	750	W	740	930	860	6000 1900 6400	W	-	-	6300 3700 6300	6300 3300 6100
SF_6 (80 sccm) Tegal Inline Plasma 701 200W, 150mT, 40°C, 13.56MHz	Tungsten	W	5800	5400	1200 2000 2000	W	1200	1800	1500	2600	2300 1900 2300	-	2800 2800 4000	W	W	2400 2400 4000	2400
O_2 (51 sccm) Technics PE II-A Plasma 50W, 300mT, gap=2.6cm, 50kHz sq. wave	Descumming photoresist	-	0	0	0	0	0	0	0	0	0	0	0	0	-	350	300
O_2 (51 sccm) Technics PE II-A Plasma 400W, 300mT, gap=2.6cm, 50kHz sq. wave	Ashing Photoresist	-	0	0	0	0	0	0	0	0	0	0	0	0	-	3400	3600
HF Vapor 1 cm over plastic dish Room temperature and pressure	Silicon oxides	-	0	0	660	W	780	2100	1500	10	19	A	0	A	-	P 0	P 0
XeF_2 Simple custom vacuum chamber Room temperature, 2.6 Torr	Silicon	4600 2900 100k	1900 1100 2500	1800 1100 2300	0	-	0	0	0	120 120 180	2 0 2	0	800 440 1000	290 50 380	-	0	0

Notation: - =test not performed; W=not performed, but known to *Work* (≥ 100 Å/min); F=not performed, but known to be *Fast* (≥ 10 kÅ/min);
P=some of film *Peeled* during etch or when rinsed; A=film was visibly *Attacked* and roughened.
Rates measured are rounded to two significant figures.
Etch areas are all of a 4-inch wafer for the transparent films and half of the wafer for single-crystal silicon and the metals.
Etch rates will vary with temperature and prior use of solution or plasma chamber, area of exposure of film, other materials present (e.g., photoresist), film impurities and microstructure, etc. *Some variation should be expected.*