Simon Fraser University

Mechatronic Systems Engineering

Midterm Exam for
ENSC 331/895: Introduction to MEMS

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27 June 2011

Time: 100 minutes

Name: Solutions

Student number:_______________

To verify identity, each candidate should be prepared to produce, upon request, his/her Simon Fraser University Library/IO card.

All writing must be submitted with this examination booklet (notes, drafts, calculations, etc.). This booklet must not be torn or mutilated in any way, and must not be taken from the examination room.

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- copying from the work of other candidates;
- purposely exposing written papers to the view of other candidates.

Question	Mark
1	/ 13
2	/ 14
3	/ 12
4	/ 11
5	/ 10
6	/ 15
Total:	/ 75

Deal-Groove model for oxidation rate of silicon:	$t_{ox}^2 + At_{ox} = B(t+\tau)$

Deal-Groove rate constants for oxidation of (100) silicon wafers

	A (μm)		*B (μm²/hr)*		*τ (hr)*	
Temperature (°C)	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**
900	0.423	1.136	0.004	0.172	2.79	0.169
1000	0.232	0.424	0.010	0.316	0.616	0.036
1100	0.139	0.182	0.024	0.530	0.174	0.010

Deal-Groove rate constants for oxidation of (111) silicon wafers

	A (μm)		*B (μm²/hr)*		*τ (hr)*	
Temperature (°C)	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**
900	0.252	0.676	0.004	0.172	1.72	0.102
1000	0.138	0.252	0.010	0.316	0.391	0.022
1100	0.083	0.109	0.024	0.530	0.114	0.006

Doping profiles and surface density of dopants (*x* is the depth into the wafer):

Diffusion with *constant concentration* of dopants at the surface	$C(x,t) = C_s \operatorname{erfc}\left(\frac{x}{2\sqrt{Dt}}\right)$	$Q = \frac{2\sqrt{Dt}}{\sqrt{\pi}} C_s$
Diffusion with *constant number* of dopants at the surface	$C(x,t) = \frac{Q}{\sqrt{\pi Dt}} \exp\left(-\frac{x^2}{4Dt}\right)$	Q
Doping with implantation	$C(x) = C_p \exp\left(-\frac{(x-R_P)^2}{2\Delta R_P^2}\right)$	$Q = \sqrt{2\pi}\, C_P \Delta R_P$

Mean free path of gas molecules	$\lambda = \frac{k_B T}{\sqrt{2}\sigma P}$

Thickness of spun photoresist	$T = K\frac{C\,\eta}{\sqrt{\omega}}$

Resolution in proximity and contact printing	$R = \frac{3}{2}\sqrt{\lambda\left(s + \frac{z}{2}\right)}$

Angle between <$h_1k_1l_1$> and <$h_2k_2l_2$> directions	$\cos\theta = \frac{h_1h_2 + k_1k_2 + l_1l_2}{\sqrt{(h_1^2+k_1^2+l_1^2)(h_2^2+k_2^2+l_2^2)}}$

Diffusion constant	$D = D_0 \exp\left(-\frac{E_a}{k_B T}\right)$

Boltzmann constant $k_B = 1.38 \times 10^{-23}\, J/K$	$1eV = 1.6 \times 10^{-19}\, J$
1 atmosphere = 760 Torr = 101 325 Pa	$1\mu m = 1000nm = 10^{-4}cm$

Question 1 (2+2+2+4+3 marks)

1-I. What is the main reason that silicon has become the most widely used semiconductor?

Existance of SiO_2

1-II. Using less than 20 words explain why microfabrication processes require a cleanroom.

Particles have the same dimensions as the devices

Many of the processes require extreme cleanness

1-III. Which microfabrication processing step is the most sensitive to particles in the environment?

Lithography

1-IV. Write four possible points that are usually found among the design rules for a given microfabrication process. Note that the question is NOT about specific numbers.
Do NOT write more than 4 points.

a) Minimum line widths

Etch hole spacing

b) Minimum gaps

c) Overlaps between layers

d) Enclosures

1-V. Assume that we want to form a 100nm layer of silicon nitride on the surface of a wafer. Explain why we do not attempt this by putting the silicon wafer in a furnace in presence of nitrogen as we do for thermal oxidation?

Si_3N_4 grows from the top surface of the film, SiO_2 grows from the bottom. It is hard for silicon atoms to pass through the Nitride layer.

Question 2 (4+3+7 marks)

2-I. A student needs to grow a 150nm thick layer of silicon dioxide on a (111) silicon wafer covered with a layer of native oxide. He calculates the required time for oxidation at 1000°C and loads the wafer into a furnace for *dry* oxidation. What is the thickness of the oxide film after two hours?

t_{ox} *(2 hr)*= 83 *nm*

$t_{ox}^2 + A\,t_{ox} \pm B\,(t+\tau)$

$A = 0.232$, $B = 0.010$, $\tau = 0.616$, $t = 2$

$\rightarrow \begin{cases} 0.083 \checkmark \\ -0.026 \end{cases}$

Time required to grow 150nm:

$0.15^2 + 0.232 \times 0.15 = 0.01\,(t + 0.616)$

$\rightarrow t = 5.114$ hrs.

2-II. After two hours, the lab technician turns on the steam flow into the furnace by mistake. The student takes out the wafer at exactly the time he had originally calculated. Aside from noticing the open steam valve, how may the student *immediately* realize that something has gone wrong during the process?

Different colour for the oxide layer

2-III. What is the final thickness of the oxide layer (±5%) at the surface of the wafer when the student measures it?

t_{ox} *(total)*= 822 *nm*

$A = 0.424$, $B = 0.316$, $\tau = 0.036$, $t = 5.114 - 2 = 3.114$ hrs

$t_{ox} = 83$ nm

Calculate τ'

$0.083^2 + 0.083 \times 0.424 = 0.316\,(\tau')$

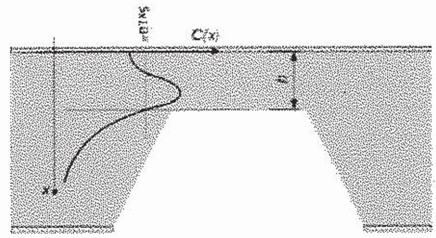
$\rightarrow \tau' = 0.133$ hrs

$t_{oxf}^2 + 0.424\, t_{oxf} = 0.316\,(3.114 + \tau')$

$$\rightarrow t_{oxf} = \begin{cases} 0.822 \checkmark \\ -1.02 \end{cases}$$

Question 3 (6+6 marks)

We would like to use the boron etch stop technique to create a membrane on a (100) silicon wafer. The etch stops if the boron concentration is higher than 5×10^{18} *atoms/cm³*. The process flow starts with doping the front side of the wafer using ion implantation with $Rp = 1\mu m$, $\Delta Rp = 0.43\mu m$, and $C_s = 1 \times 10^{19} atoms/cm^3$. Dopant concentration profile is displayed on the cross-section in the figure to the right (not to scale). A nitride layer is deposited on both sides of the wafer to serve as a hard mask during the etch (hatched areas).



3-I. The backside of the wafer is etched in KOH through an opening in the nitride layer until the etch stops at the depth where the boron concentration becomes higher than 5×10^{18} *atoms/cm³*.What is thickness of the silicon membrane (h)?

Membrane thickness (h): ___1.4___ μm

$$10^{19} e^{-\frac{(x-1)^2}{2 \times 0.34^2}} = 5 \times 10^{18}$$

$$\rightarrow \frac{(x-1)^2}{2 \times 0.34^2} = -\ln 0.5 \rightarrow (x-1)^2 = 0.16$$

$$\rightarrow x = 1 \pm 0.4 = \begin{cases} 1.4 \checkmark \\ 0.6 \end{cases}$$

3-II. For a separate set of wafers, the nitride layer is deposited only on the backside of the wafer but the rest of the process flow remains the same. What will be the silicon membrane thickness in this case?

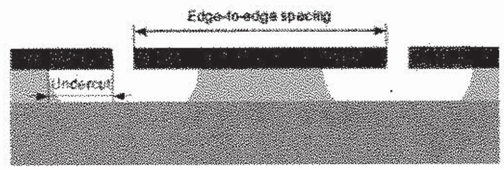
Membrane thickness: ___0.8___ μm

The top silicon will also be etched

$\rightarrow$ Membrane thickness $= 1.4 - 0.6 = 0.8 \mu m$

Question 4 (5+6 marks)

We want to develop the design rules for the release stage in a surface micromachining process. A dry isotropic etchant of the sacrificial layer (light gray area in the figure) is used for the release step. The maximum undercut after the release process is 10μm.



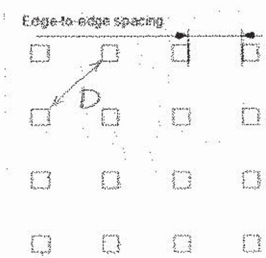
4-I. What are the maximum lateral dimensions of a structure that has to be fully released at the end of the process if we do not want to have etch holes on it?

Maximum lateral dimensions: 20 *μm*

10 μm from each side → $(L, W)_{max} = 2 \times 10\ \mu m = 20\ \mu m$

Allowing for a 10% slower etch → $(L, W)_{max} = 18\ \mu m$

4-II. Assume that the etch holes are created in a symmetric pattern on the structures that have to be released (see the figure). What is the recommended edge-to-edge spacing between the etch holes?



Allow for up to 10% variation in etch rates.

Etch hole spacing (edge-to-edge): 12.73 *μm*

Largest distance is diagonal

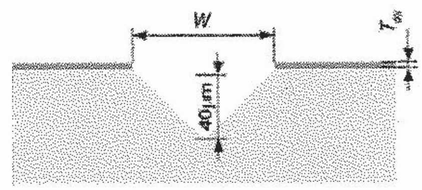
Allowing for the slower etch → $D = 18\ \mu m$

→ Max edge to edge spacing $= 18 \times \cos 45° = 12.73\ \mu m$

$20\ \mu m \longrightarrow 14.14\ \mu m$

Question 5 (4+6 marks)

We would like to etch 40μm deep groves on a (100) wafer (cross section shown to the right). The groves are etched in a KOH solution through a masking layer of thermally grown SiO_2. The relative etch rate of (100) to (111) planes is 100:1. The relative etch rate of (100) planes to SiO_2 is 120:1.



Use the equation on the 2nd page for angles between the planes.

5-I. What is the minimum required thickness of the SiO_2 layer (T_{ox} on the figure) so that it survives the process? Allow for a 10% variation in relative etch rates.

SiO_2 thickness (T_{ox}): 0.294 *μm*

40 μm of (100) silicon, 150 : 1 for Si : SiO_2 → 267 nm of SiO_2 will be etched

Allow for 10 % faster etch → $T_{ox} = 267\text{ nm}\,(1+10\%)$

$= 293.7\text{ nm}$

Angle : 54.7°

5-II. What is the required width of the mask opening (*W* on the figure) on the oxide layer?

Width of the opening (W): 56.6 *μm*

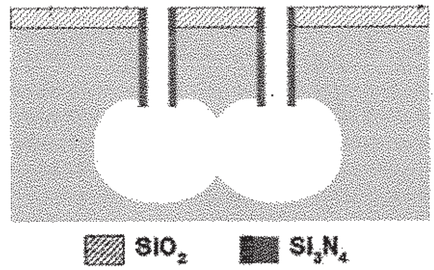
$$\left.\begin{array}{l} \dfrac{\text{Etch depth}}{W/2} = \tan\theta \\[2ex] \theta = \cos^{-1}\dfrac{1}{\sqrt{3}} = 54.7^\circ \end{array}\right\} \rightarrow W = \frac{2\times 40}{\tan 54.7} = 56.6\ \mu m$$

ignore the undercut

If not a bit narrower

Question 6 (15 marks)

Cross section of a microstructure is shown to the right. A silicon wafer is used as the substrate. Design the process flow using ONLY the following processes. You may use a given process more than once, if needed.



- Lithography
- Thermal oxidation
- Thermal evaporation
- Sputtering
- Piranha cleaning
- Nitride CVD
- Doping
- KOH etching
- XeF_2 etching
- HF etching
- Nitride RIE
- Silicon DRIE

Write down the processing steps for your fabrication flow in the order they need to be performed. Do NOT provide details on chemistry, etch rate, etc. Use as few steps as needed for a reliable process.

Number of masks: 1

Step 1: Piranha cleaning

Step 2: Thermal oxidation

Step 3: Lithography

Step 4: HF etching

Step 5: Silicon DRIE

Step 6: Nitride CVD

Step 7: Nitride RIE

Step 8: XeF_2 etching

Step 9: ______________________

Step 10: ______________________

Step 11: ______________________

Step 12: ______________________

Step 13: ______________________

Step 14: ______________________

Step 15: ______________________

You can use this space to answer the question or for your calculations