Simon Fraser University

Mechatronic Systems Engineering

Midterm Exam for
ENSC 331: Introduction to MEMS

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Time: 90 minutes

Name: SOLUTIONS

Student number: ________________

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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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Question	**Mark**
1	/ 20
2	/ 20
3	/ 20
4	/ 20
Total:	/ 80

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	$C(x) = C_p \exp\left(-\frac{(x-R_P)^2}{2\Delta R_P^2}\right)$	$Q = \sqrt{2\pi}\, C_P \Delta R_P$

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

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

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

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

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

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	$1\mu m = 1000nm = 10^{-4}cm$

The complimentary error function

λ	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
erfc(λ)	9.44E-1	8.88E-1	8.32E-1	7.77E-1	7.24E-1	6.71E-1	6.21E-1	5.72E-1	5.25E-1	4.80E-1
λ	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
erfc(λ)	4.37E-1	3.96E-1	3.58E-1	3.22E-1	2.89E-1	2.58E-1	2.29E-1	2.03E-1	1.79E-1	1.57E-1
λ	1.05	1.10	1.15	1.20	1.25	1.30	1.35	1.40	1.45	1.50
erfc(λ)	1.38E-1	1.20E-1	1.04E-1	8.97E-2	7.71E-2	6.60E-2	5.62E-2	4.77E-2	4.03E-2	3.39E-2
λ	1.55	1.60	1.65	1.70	1.75	1.80	1.85	1.90	1.95	2.00
erfc(λ)	2.84E-2	2.37E-2	1.96E-2	1.62E-2	1.33E-2	1.09E-2	8.89E-3	7.21E-3	5.82E-3	4.68E-3
λ	2.05	2.10	2.15	2.20	2.25	2.30	2.35	2.40	2.45	2.50
erfc(λ)	3.74E-3	2.98E-3	2.36E-3	1.86E-3	1.46E-3	1.14E-3	8.89E-4	6.89E-4	5.31E-4	4.07E-4
λ	2.50	2.55	2.60	2.65	2.70	2.75	2.80	2.85	2.90	2.95
erfc(λ)	4.07E-4	3.11E-4	2.36E-4	1.78E-4	1.34E-4	1.01E-4	7.50E-5	5.57E-5	4.11E-5	3.02E-5

Question 1 (6+2+4+2+6 marks)

1-I. Name three applications of silicon dioxide in MEMS fabrication and application?

a) chemical protection

b) Sacrificial layer

c) Electrical isolation

1-II. E-beam lithography can be used to create features on the order of few nm. Explain why it has not replaced UV lithography in microelectronics industry?

slow speed

1-III. List two reasons for why a high temperature annealing of the wafer is performed after ion implantation?

a) Drive-in the dopants

b) Heal the crystal

1-IV. What is the major advantage of lift-off over the typical "deposition + etch" process for deposition of a metal layer on a substrate? Mention one reason only.

No metal etching /etchant is needed

1-V. List three main applications of plasma in microfabrication and the reason for its use in each of those applications.

a) Etching (RIE): Activation of chemicals

b) Sputtering: Ion bombardment of the target

c) Deposition (PECVD): Lowering the reaction temperature.

Question 2 (10+10 marks)

We have an n-doped silicon wafer with a background concentration of $2 \times 10^{16}\ dopants/cm^3$. It is required to have a junction depth of $3\mu m$ at a Boron diffusion temperature of $1075°C$. What is the required time under the following circumstances? For boron, $E_a = 3.46eV$ and $D_0 = 0.76\ cm^2/s$.

2.I. The wafer is doped using constant surface concentration method with $10^{18}\ dopants/cm^3$.

Time = 25.4 *Hours*

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

$$2\times10^{16} = 10^{18}\, erfc\left(\frac{3\times10^{-4}}{2\sqrt{Dt}}\right) \Rightarrow erfc^{-1}\left(\frac{2\times10^{16}}{10^{18}}\right) = 1.65$$

$$\rightarrow \sqrt{Dt} = 9.09\times10^{-5} \longrightarrow Dt = 8.26\times10^{-9}\ cm^2$$

$$D = 0.76\, e^{\frac{-3.46\times1.6\times10^{-19}}{1.38\times10^{-23}(273+1075)}} = 9.04\times10^{-14}\ \frac{cm^2}{s}$$

$$t = \frac{8.26\times10^{-9}}{9.04\times10^{-14}} = 91371\ sec = 25.4\ hrs$$

2.II. The final doping profile is Gaussian with a surface concentration of $10^{18}\ dopants/cm^3$.

Time = 17.7 *Hours*

$$C(x) = \frac{Q}{\sqrt{\pi Dt}}\, e^{\frac{-x^2}{4Dt}}$$

$$\left.\begin{array}{l} C(0) = \dfrac{Q}{\sqrt{\pi Dt}} = 10^{18} \\ C(x = 3\times10^{-4}) = \dfrac{Q}{\sqrt{\pi Dt}}\, e^{\frac{-(3\times10^{-4})^2}{4Dt}} \end{array}\right\} e^{\frac{-9\times10^{-8}}{4Dt}} = \frac{2\times10^{16}}{10^{18}}$$

$$\rightarrow Dt = 5.75\times10^{-9}\ cm^2,\quad D = 9.04\times10^{-14}\ \frac{cm^2}{s}$$

$$t = 63606\ sec = 17.67\ hrs$$

Question 3 (5+8+7 marks)

We want to grow a layer of oxide on a bare <100> silicon wafer with only native oxide on it. Determine the oxide thickness under each of the following scenarios.

3-I. Wet oxidation at 1100°C for 2 hours.

t_{ox}: 94.5 nm

$$A = 0.182,\ B = 0.530,\ \tau = 0.010$$

$$t_{ox}^2 + 0.182\, t_{ox} = 0.530(2 + 0.01)$$

$$\rightarrow t_{ox} = \begin{cases} 0.945\ \mu m \ \checkmark \\ -1.127\ \mu m \end{cases}$$

3-II. Wet oxidation for 2 hours followed by dry oxidation for 22 hours, both at 1000°C.

t_{ox}: 755 nm

$$\begin{cases} A = 0.424 \\ B = 0.316 \\ \tau = 0.036 \end{cases}$$

$$t_{ox}^2 + A_w t_{ox} = B_w(t + \tau_w)$$

$$\rightarrow t_{ox} = \begin{cases} 0.618\ \mu m \ \checkmark \\ -1.041\ \mu m \end{cases}$$

$$(0.618)^2 + 0.232(0.618) = 0.010(\tau' + 0.616)$$

$$\rightarrow \tau' = 51.91\ hrs$$

$$t_{ox}^2 + 0.232\, t_{ox} = 0.010(22 + 0.616 + 51.91)$$

$$\rightarrow t_{ox} = \begin{cases} 0.755\ \mu m \ \checkmark \\ -0.987\ \mu m \end{cases}$$

3-III. Dry oxidation for 22 hours followed by wet oxidation for 2 hours, both at 1000°C.

t_{ox}: 776 nm

$$t_{ox}^2 + A t_{ox} = B(t+\tau) \qquad \begin{cases} A = 0.232 \\ B = 0.010 \\ \tau = 0.616 \end{cases}$$

$$\rightarrow t_{ox} = \begin{cases} 0.374\ \mu m \ \checkmark \\ -0.606\ \mu m \end{cases}$$

$$(0.374)^2 + 0.424(0.374) = 0.316(0.036+\tau')$$

$$\boxed{A = 0.424,\ B = 0.316\ \ \tau = 0.036}$$

$$\rightarrow \tau' = 0.908\ \text{hrs}$$

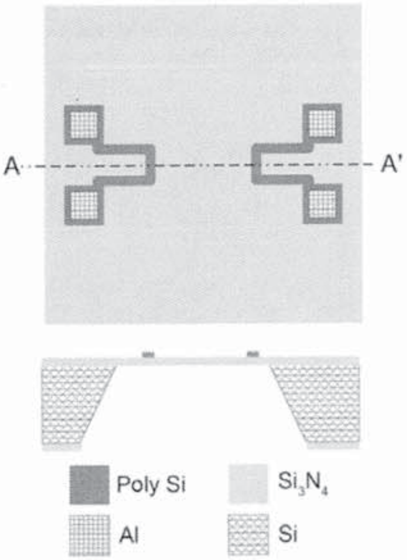
$$t_{ox}^2 + 0.424\, t_{ox} = 0.316(0.908 + 0.036 + 2)$$

$$t_{ox} = \begin{cases} 0.776\ \mu m \ \checkmark \\ -1.20\ \mu m \end{cases}$$

Question 4 (20 marks)

Top view and cross section of a microstructure consisting of a released nitride membrane with poly silicon piezoresistors is shown to the right. Design the process flow using ONLY the following processes. Specify the orientation of the wafer that you need (i.e., <100> or <111>). If needed, use a process more than once.

- Front side lithography
- Back side lithography
- Photoresist stripping
- Thermal oxidation
- Thermal evaporation
- Sputtering
- Nitride CVD
- Nitride RIE
- Wet etching of Al
- Doping
- KOH etching
- XeF_2 etching
- HF etching
- CVD of poly silicon
- Silicon DRIE
- Silicon RIE
- Front side protection
- Back side protection



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. The lithography steps include all the required steps to transfer the pattern to the photoresist on the substrate (i.e., spinning, exposure, and development).

Number of masks: ____________ *Orientation of substrate*: _______

Step 1: Nitride CVD

Step 2: CVD of Poly Si

Step 3: Front side litho (Mask 1)

Step 4: Silicon RIE

Step 5: photoresist stripping

Step 6: sputtering of Al

Step 7: Front side litho (Mask 2)

Step 8: wet etching of AL

Step 9: photo resist stripping

Step 10: Front side protection

Step 11: Back side litho (Mask 3)

Step 12: Nitride RIE

Step 13: photoresist stripping

Step 14: KoH etching

Step 15: Removal of protective layer (release)

Step 16: ____________________

Step 17: ____________________

Step 18: ____________________

You can use this space to answer any question with proper reference or for your calculations.