NANYANG TECHNOLOGICAL UNIVERSITY

SEMESTER 2 EXAMINATION 2013-2014

EE3013 – SEMICONDUCTOR DEVICES AND PROCESSING

April/May 2014 Time Allowed: 2 hours

INSTRUCTIONS

1. This paper contains 4 questions and comprises 7 pages.
2. Answer all 4 questions.
3. All questions carry equal marks.
4. This is a closed-book examination.
5. A **List of Selected Formulae** and a **Table of Physical Constants** are provided in **Appendices A** and **B** on pages 6 and 7, respectively.

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1. (a) Consider a Si *pnp* bipolar junction transistor (BJT) with impurity concentrations of 10^{19} cm^{-3}, 10^{17} cm^{-3} and 10^{16} cm^{-3} in the emitter, base and collector, respectively and operating at 300 K.

(i) How many possible operation modes does the BJT have and how are they defined?

(ii) Assume the BJT operates in the active mode. Sketch

- the one-dimensional schematic structure of the BJT with indication of depletion regions,
- the charge distribution across the emitter-base and base-collector junctions,
- the corresponding electrical field distribution across the two junctions and
- the energy band diagram.

(iii) State the expressions for the minority carrier concentration at the two boundaries of the neutral emitter region of the BJT operating under active mode.

(11 Marks)

Note: Question No. 1 continues on page 2

(b) Consider a real metal-SiO_2-Si (p-type) diode with an acceptor concentration of 5×10^{16} cm^{-3} biased at the onset of strong inversion. Assume that the work function difference is $\phi_{ms} = -0.7$ eV, the SiO_2 is 6 nm thick and has total charges of $Q_o/q = 10^{11}$cm^{-2}. Calculate the threshold voltage and the capacitance per unit area of the depletion layer.

(10 Marks)

(c) A n-channel metal-SiO_2-Si field effect transistor (MOSFET) can be treated as a combination of a metal-SiO_2-Si (p-type) diode and two p-n junctions. The source, p-region and drain will form an npn structure. If the SiO_2 layer in the MOSFET is removed, can the npn structure function as a bipolar junction transistor? Explain your answer.

(4 Marks)

2. (a) (i) Oxidation causes impurity redistribution in a Si wafer. What are the main factors which affect the impurity distribution and how do they affect the impurity redistribution in the Si wafer and oxide?

(ii) Describe limited source diffusion and constant source diffusion. Plot impurity distributions for the periods of t_1, t_2 and t_3 ($t_3>t_2>t_1$) for each of the two kinds of thermal diffusions.

(7 Marks)

(b) To form an n-p junction on a p-type Si wafer with a background concentration of 10^{14} cm^{-3}, a SiO_2 layer is first deposited as a mask and a window is then opened by removing the SiO_2 layer there for implantation of phosphorous. Assume that the phosphorous ion dose used is 10^{13} atoms/cm^2; the values of projected range and straggle are the same for phosphorous in Si and oxide, and the projected range and straggle are 0.12 μm and 0.045 μm, respectively.

(i) Find the peak concentration of the implanted profile and the junction depths from Si surface.

(ii) Estimate the required thickness of the mask SiO_2 if the maximum concentration of phosphorous at the interface of the SiO_2 and Si is at most 10% of the background concentration.

(11 Marks)

Note: Question No. 2 continues on page 3

(c) (i) Consider dry oxidation at fixed conditions. Describe how the oxidation rate varies with time and explain why.

(ii) The total thickness of oxide t_{ox} as a function of oxidation time t can be expressed as

$$t_{ox}^2 + At_{ox} = B(t+\tau)$$

where A, B and τ are constants. For oxidation with $t+\tau >> A^2/4B$ and $t > \tau$, show $t_{ox} \propto t^{1/2}$.

(7 Marks)

3. (a) One future possibility for lithography systems beyond conventional optical projection tools is an optical projection system using a 157-nm F_2 excimer laser. If its resolution is 0.2 μm, what is the expected numerical aperture of such a system? Assume $k = 0.75$.

(4 Marks)

(b) Actual projections for the above mentioned system suggest that it might be capable of resolving features beyond the 0.2 μm node technology. Suggest three approaches to actually achieving higher resolution with this system.

(6 Marks)

(c) An X-ray exposure system uses photons with energy of 1 keV. Due to some mistakes, or a dust particle, the separation between the mask and wafer is increased to 20 μm. Describe the effect of the increased gap on the image, and estimate the diffraction limited resolution that is achievable by this system. Assume $k = 1$.

(6 Marks)

(d) What type of photoresist requires shorter exposure time with higher throughput? What are the disadvantages of using such a resist?

(3 Marks)

(e) Explain orientation dependent etching of silicon. Give at least two applications of orientation dependent etching.

(6 Marks)

4. (a) What are the two commonly observed rate limiting mechanisms in chemical vapour deposition (CVD) systems? Under what conditions do they normally dominate the overall deposition rate?

(5 Marks)

(b) Sketch (with labels) a typical CVD system that deposits film in the regime that is limited by mass transport. Explain the preferred wafer stacking configuration deployed in such a system.

(5 Marks)

(c) Explain what is a reactive plasma and how it is generated in a DC glow discharge.

(5 Marks)

(d) What are the advantages and disadvantages of reactive ion etching (RIE) versus sputter etching? Cite an example of when one might want to use sputter etching rather than RIE.

(5 Marks)

(e) Figure 1 on page 5 shows the isoetch curve for silicon using the $HF:HNO_3$:diluent system. A hole must be wet etched through a silicon wafer that is 500 μm thick. The solution for the etch is a mixture of two parts of $HC_2H_3O_2$, two parts of HF and six parts of HNO_3. How long would the etch take?

(5 Marks)

Note: Question No. 4 continues on page 5

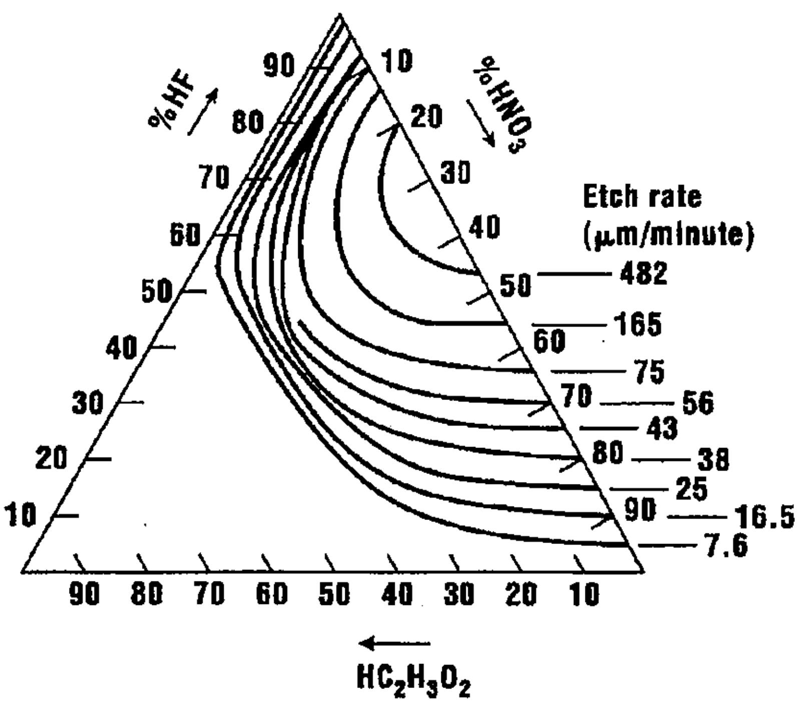
%HF
%HNO_3
Etch rate
(μm/minute)
482
165
75
56
43
38
25
16.5
7.6
90
80
70
60
50
40
30
20
10
$HC_2H_3O_2$

Figure 1

3

APPENDIX A

List of Selected Formulae

P-n junction:

$$V_{bi} = \frac{kT}{q}\ln\frac{N_A N_D}{n_i^2}; \quad N_A x_p = N_D x_n; \quad W = x_p + x_n; \quad C_j = \frac{\varepsilon_s}{W};$$

$$W = \sqrt{\frac{2\varepsilon_s}{q}[\frac{1}{N_A}+\frac{1}{N_D}](V_{bi}-V)}; \quad L_p = \sqrt{D_p \tau_p}.$$

Bipolar junction ransistor:

$$\gamma \equiv \frac{I_{Ep}}{I_E} = \frac{I_{Ep}}{I_{Ep}+I_{En}}; \quad \alpha_T \equiv \frac{I_{Cp}}{I_{Ep}}; \quad \alpha_0 = \gamma\alpha_T; \quad \beta_0 = \frac{\alpha_0}{1-\alpha_0}; \quad I_C = \alpha_0 I_E + I_{CBO};$$

$$I_{CEO} = (1+\beta_0)I_{CBO}; \quad p_n(x) = p_{no}e^{qV_{EB}/kT}(1-\frac{x}{W}); \quad \gamma = \frac{1}{1+\frac{D_E}{D_p}\cdot\frac{N_B}{N_E}\cdot\frac{W}{L_E}};$$

$$I_{Ep} = qA\frac{D_p p_{n0}}{W}e^{(qV_{EB}/kT)}; \quad I_{En} = qA\frac{D_E n_{E0}}{L_E}(e^{qV_{EB}/kT}-1); \quad I_{Cn} = qA\frac{D_C n_{C0}}{L_C};$$

$$p_{n0}\cdot N_B = n_{E0}\cdot N_E = n_{C0}\cdot N_C = n_i^2; \quad \tau_B = \frac{W^2}{2D_p}; \quad f_T = \frac{1}{2\pi\tau_B}.$$

MOS diode:

$$\psi_s = 2\psi_B = \frac{2kT}{q}\ln(\frac{N_A}{n_i}); \; W_m^2 = \frac{2\varepsilon_s(2\psi_B)}{qN_A} = \frac{4\varepsilon_s kT}{q^2 N_A}\ln(\frac{N_A}{n_i}); \; V_T = \frac{qN_A W_m}{C_o} + 2\psi_B;$$

$$\frac{C}{C_0} = \frac{1}{\sqrt{1+\frac{2\varepsilon_{ox}^2 V}{qN_A\varepsilon_s d^2}}}; \quad \frac{1}{C_{min}} = \frac{d}{\varepsilon_{ox}} + \frac{W_m}{\varepsilon_s}; \quad V_{FB} = \phi_{ms} - \frac{(Q_f + Q_m + Q_{ot})}{C_0}.$$

Enhancement mode NMOS

$$I_D = K_n[(V_{GS}-V_T)V_{DS} - \frac{V_{DS}^2}{2}] \text{ for } V_{DS} < V_{GS} - V_T; \quad V_T = \frac{qN_A W_m}{C_0} + 2\psi_B \text{ when } V_{FB} = 0;$$

$$I_D = \frac{K_n}{2}(V_{GS}-V_T)^2 \text{ for } V_{DS} \geq V_{GS} - V_T; \quad K_n = \mu_n C_{ox}\frac{W}{L}.$$

Thermal oxidation: $t_{ox}^2 + At_{ox} = B(t+\tau)$; $\tau = \frac{t_{oxi}^2}{B} + \frac{t_{oxi}}{B/A}$. $t_{ox} = \frac{-A+\sqrt{A^2+4B(t+\tau)}}{2}$

Constant source diffusion:

$$N(z,t) = N_s erfc(\frac{z}{2\sqrt{Dt}})$$

Limited source diffusion:

$$N(z,t) = \frac{Q}{\sqrt{\pi Dt}}\exp[-\frac{z^2}{4Dt}], \quad Q = \frac{2}{\sqrt{\pi}}N_s\sqrt{Dt}.$$

Ion implantation:

Before Annealing

$$N(x) = \frac{Q}{\sqrt{2\pi}\Delta R_p}\exp[-\frac{(x-R_p)^2}{2\Delta R_p^2}]$$

After annealing

$$N(x) = \frac{Q}{\sqrt{2\pi}(\Delta R_p^2 + 2Dt)^{1/2}}\exp[-\frac{(x-R_p)^2}{2(\Delta R_p^2 + 2Dt)}]$$

$$Q = \int_0^\infty N(x)\,dx = \sqrt{2\pi}N_p\Delta R_p$$

APPENDIX B

Table of Physical Constants

Physical Constant	Symbol	Value	Units
Electronic charge	q	1.6×10^{-19}	C
Boltzmann's constant	k	8.62×10^{-5} 1.38066×10^{-23}	eV/K J/K
Planck's constant	h	6.626×10^{-34}	J·s
Permittivity of free space	ε_0	8.85×10^{-14}	F/cm
Dielectric constant of Si	ε_{Si}	11.7	-
Dielectric constant of SiO_2	ε_{ox}	3.9	-
Electron Mass	m	9.11×10^{-31}	kg
Speed of Light	c	3×10^{8}	m/s
Bandgap of Si at 300 K	E_g	1.12	eV
Intrinsic carrier concentration in Si at 300 K	n_i	9.65×10^{9}	cm^{-3}

END OF PAPER

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1(a) P N P
10^{19} 10^{17} 10^{16}

(i) 4 modes
depending on the voltage polarities on the E-B junction and B-C junction.

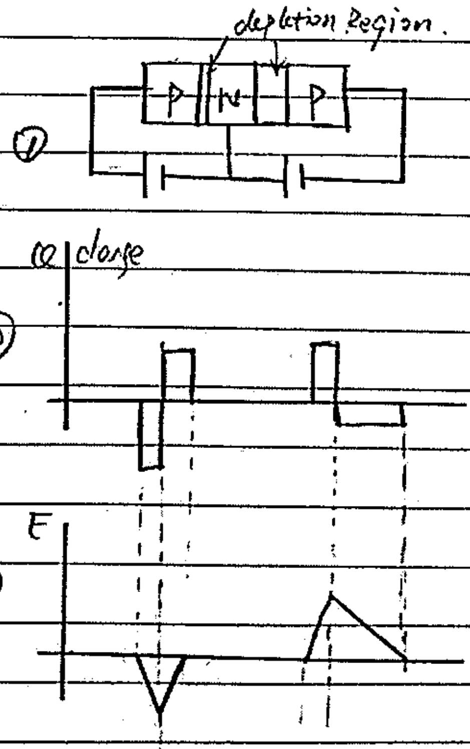
① Active mode: E-B junction is forward-biased.
B-C junction is reversed-biased.

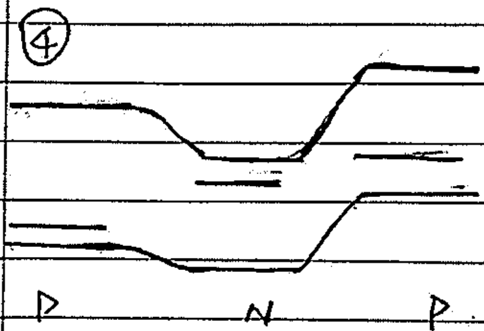
② Saturation Mode: Both E.B & BC Junction are forward-biased

③ Cutoff mode: Both EB & BC Junction are ~~inverted~~ inversed-biased.

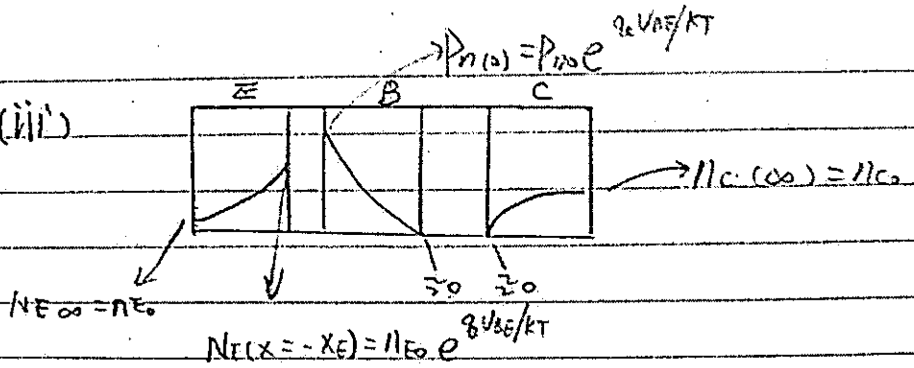
④ Inverted Mode: the EB juntion is reversed-biased and the CB juntion is forward-biased.

1(a) (ii) BJT active mode.

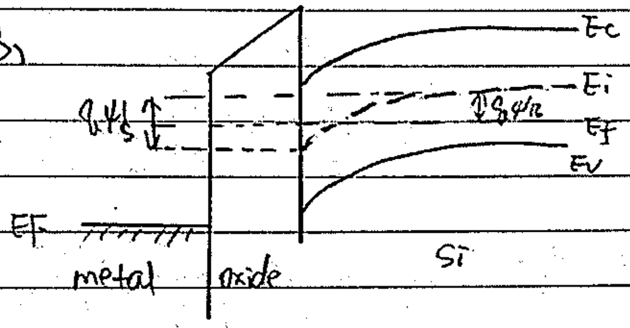




1(a) (iii)



1(b)



$\phi_{ms} = -0.7\, eV$ $\quad Q_0/q_e = 10^{11}\ cm^{-2}$ $\quad SiO_2 : 6nm = 6\times10^{-7} cm$

notice : $V_T = \dfrac{q_e N_A W_m}{C_o} + 2\psi_B + \phi_{ms} - \dfrac{Q_f + Q_m + Q_{ot}}{C_o}$

$C_o = \dfrac{\epsilon_{ox}}{d} = 5.75\times10^{-7} F$

$W_m = \sqrt{\dfrac{4\epsilon_s kT}{q_e \cdot q_e N_A} \ln\left(\dfrac{N_A}{n_i}\right)}$ $\qquad$ note: $\dfrac{kT}{q_e} \approx 0.0259$

$= \left(\dfrac{4\times11.7\times8.85\times10^{-14}\times0.0259\times\ln\left(\frac{5\times10^{16}}{9.65\times10^{9}}\right)}{1.6\times10^{-19}\times5\times10^{16}}\right)^{\frac{1}{2}}$

$\approx 1.44\times10^{-5}$ cm

$\dfrac{q_e N_A W_m}{C_o} = \dfrac{1.6\times10^{-19}\times5\times10^{16}\times1.44\times10^{-5}}{5.75\times10^{-7}}$

≈ 0.2 V.

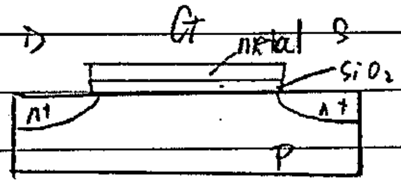
1

(b) $\psi_s = 2\psi_B = \frac{2kT}{q} \ln\left(\frac{N_A}{n_i}\right) = 2 \times 0.0259 \ln\left(\frac{5\times 10^{16}}{9.65\times 10^{9}}\right) \doteq 0.8V$

$\frac{Q_o}{C_o} \doteq 0.0278\ V$

$V_T = 0.2 + 0.8 - 0.7 - 0.0278 = 0.2722\ V$

1(c)



If the SiO_2 is removed, the P type silicon is directly connected with the metal (conductor). Thus, at strong inversion, the electron from P side will absorbed by metal. The current will not flow between source and drain

2(a) (i) The doping concentration will redistribute between semiconductor and oxide depending on Both segregation coefficient m, and diffusion coefficient D.

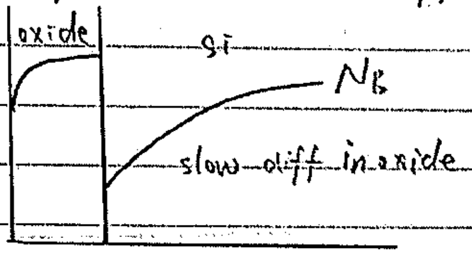
$m = \frac{\text{Equilibrium concentration of impurity in Si}}{\text{Equilibrium concentration of impurity in oxide}}$

$D = \frac{\mu kT}{q}$ (μ: electron or hole mobility)

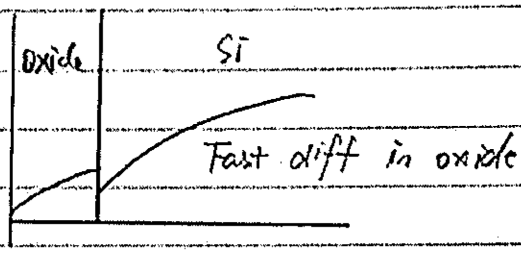
2. (a) (i)

case 1 $m<1$

If oxide takes up impurity, such as Boron, the impurity in Si will be less than that in oxide thus, $m<1$
The impurity redistribution in the oxide and Si will then depend on the diffusity of the impurity.



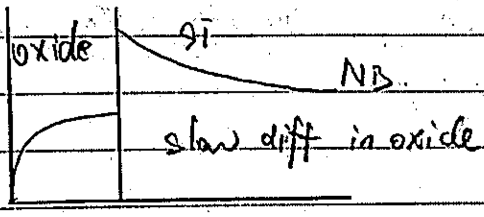
(Boron)



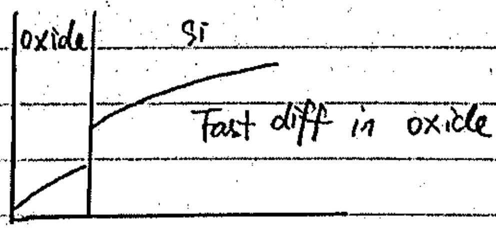
(Boron with hydrogen environment)

case 2 $m>1$

If the oxide rejects the impurity, the impurity in Si will be more than in oxide $m>1$

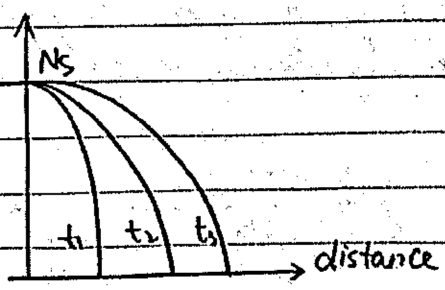


(Phosphorous)

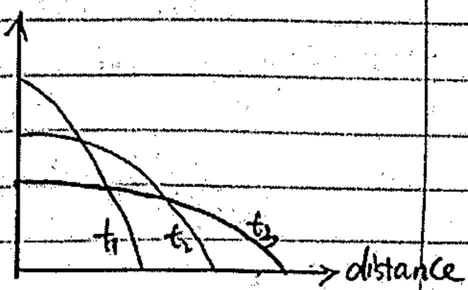


(Gallium)

(a)
2 (ii)



(Constant Source diffusion)



(limited source diffusion)

Constant Source Diffusion : the impurity concentration at the surface of the solid remains constant.
limited Source Diffusion : Total amount of impurity amounts at surface is fixed.

2 (b) (i) $N_B = 10^{14}\ cm^{-3}$

$Q = 10^{13}$

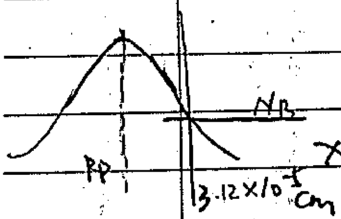
$R_p = 0.12 um = 0.12 \times 10^{-4}\ cm$

$\Delta R_p = 0.045 um = 0.045 \times 10^{-4}\ cm$

Peak concentration $N(x) = \dfrac{Q}{\sqrt{2\pi}\,\Delta R_p} = \dfrac{10^{13}}{\sqrt{2\pi} \times 0.045 \times 10^{-4}} \doteq 8.865 \times 10^{17}\ cm^{-3}$

Juntion Depth $N_B = N(x) = 10^{14} = \dfrac{Q}{\sqrt{2\pi}\,\Delta R_p} \cdot \exp\left[-\dfrac{(x-R_p)^2}{2\Delta R_p^2}\right]$

$1.12798 \times 10^{-4} = \exp\left[-\dfrac{(x-R_p)^2}{2\Delta R_p^2}\right]$

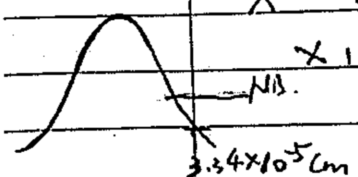


$x_1 \doteq 3.12 \times 10^{-5}\ cm$ $\quad x_2 \doteq -7.18 \times 10^{-6}\ cm$ //

2 (b) (ii) $0.1 \times N_B = \dfrac{Q}{\sqrt{2\pi}\,\Delta R_p} \exp\left[-\dfrac{(x-R_p)^2}{2\Delta R_p^2}\right]$

$10^{13} = 8.865 \times 10^{17} \exp\left[-\dfrac{(x-R_p)^2}{2\Delta R_p^2}\right]$

$x^2 - 0.24 \times 10^{-4} x - 3.18 \times 10^{-10} = 0$



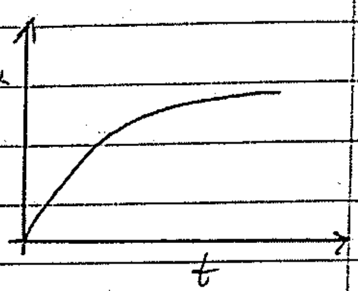
$x_1 = 3.34 \times 10^{-5}\ cm$ $\quad x_2 = -9.4 \times 10^{-6}\ cm$ //

$t_{ox} = 3.34 \times 10^{-5}\ cm$ //

2(C) (i) Dry oxidation the oxidation rate decrease with time.

For short time $t_{ox} = \frac{B}{A}(t+\tau)$

$$\frac{d\,t_{ox}}{dt} = \frac{B}{A} + \frac{B}{A}\tau'$$



For long time $t_{ox} = \sqrt{Bt}$

$$\frac{d\,t_{ox}}{dt} = \frac{\frac{1}{2}\sqrt{B}}{\sqrt{t}}$$

(rate is the gradient)

note: when oxide is formed at the surface, the oxygen is difficult to penetrate through the SiO_2 thus the oxidation rate decrease.

2(C) (ii) $t_{ox}^2 + A t_{ox} = B(t+\tau)$

$$\Rightarrow \quad t_{ox} = \frac{-A + \sqrt{A^2 + 4B(t+\tau)}}{2}$$

$\because$ $t+\tau >> A^2/4B$, $B>0$

$\therefore$ $(t+\tau)\cdot 4B >> A^2$

$t > \tau$

$\therefore$ $t_{ox} = \frac{-A + 2\sqrt{Bt}}{2}$

$\therefore$ $t_{ox} \propto t^{\frac{1}{2}}$

3(a) $\lambda = 157\,nm = 157 \times 10^{-3}\,um$

$W_{min} = \frac{k\lambda}{NA}$ $NA = \frac{k\lambda}{W_{min}} = \frac{0.75 \times 157 \times 10^{-3}}{0.2} \approx 0.589$

3(b) ① Immersion lithography $\Rightarrow$ ~~decrease~~ Increase the NA

② Optical Proximity Correction $\Rightarrow$ decrease the K

③ off - Axis Illumination $\Rightarrow$ decrease the K

3(c) $W_{min} = \sqrt{k\lambda g}$ (increase the gap will decrease the Resolution W_{min} increases)

$E = hf = \frac{hc}{\lambda} \Rightarrow \lambda = \frac{hc}{E} = \frac{3 \times 10^{8} \times 6.626 \times 10^{-34}}{1000 \times 1.6 \times 10^{-19}} \approx 1.24 \times 10^{-9}\,m$

$W_{min} = \sqrt{k\lambda g} = \sqrt{1.24 \times 10^{-9} \times 20 \times 10^{-6}} \approx 1.58 \times 10^{-7}\,m$

3(d) negative resist.

Disadvantages: swelling take place during development
lower step coverage.

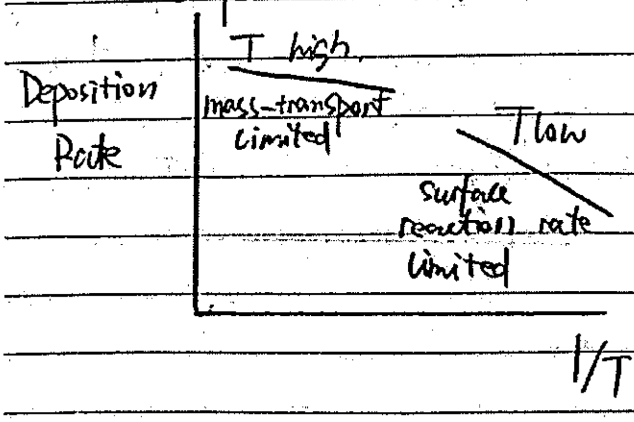
3(e) The etching rate is depend on the orientation of silicon.

Si etching rate Si <111> < Si <110> < Si <100>

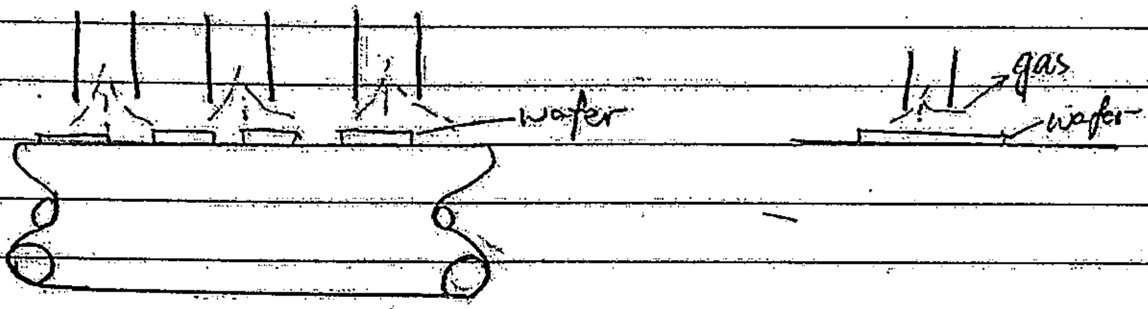
Application : ① chemical machining of semiconductor materials
② V sharp and vertical groove cutting
③ Wafer defect investigation (crystal defects)

4 (a) ① mass - transport - limited : Occurs at high temperature
Deposition rate is not determined by the surface reaction rate. but the reactive species diffuse & absorb on the surface.

② Surface - reaction - rate limited
Occurs at low temperature.
Deposition Rate is mainly determined by the chemical rate on the substrate.
Deposition Rate sensitive to temperature.



4 (b) APCVD



The wafer is horizontally arranged.

4(c) Plasma: An ionized gas with about equal amounts of positive ions and negatively charged particles.

When DC voltage appiled, the relased electrons accelerate towards the +ve electrode, leave the positive ion.

4(d) Advantage: more selectivity than sputtering etching
higher Etching rate with lower damage

Disadvantage: Etching process ~~is~~ control is complicated
less directionallity

4(e) $HC_2H_3O_2 : HF : HNO_3$
$2 : 2 : 6$

$t = 500\ \mu m$
etching rate $\approx 31.5\ \mu m/min$
$T = \frac{500\ \mu m}{31.5\ \mu m/min} \approx 15.9$ mins

All the Best!

2

35 T