

NANYANG TECHNOLOGICAL UNIVERSITY

SEMESTER 1 EXAMINATION 2018-2019

EE3013 – SEMICONDUCTOR DEVICES AND PROCESSING

November / December 2018

Time Allowed: 2 hours

INSTRUCTIONS

1. This paper contains 4 questions and comprises 9 pages.
2. Answer ALL questions.
3. All questions carry equal marks.
4. This is a closed book examination.
5. Unless specifically stated, all symbols have their usual meanings.
6. A List of Formulae is provided in Appendix A on pages 7 and 8. The Table of Physical Constants is provided in Appendix B on page 9.

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1. (a) The total junction capacitance of a GaAs p-n junction at $T = 300$ K is found to be 1.10 pF at a reversed bias voltage of 1 V. The doping concentration in one region is found to be $8 \times 10^{19} \text{ cm}^{-3}$, and the built-in potential is found to be $V_{bi} = 1.20$ V. Given the intrinsic carrier concentration (n_i) and relative permittivity (ϵ_r) of GaAs are $1.8 \times 10^6 \text{ cm}^{-3}$ and 13.1 , respectively, determine:

- (i) The doping concentration in the other region of the p-n junction.

$$V_{bi} = \frac{kT}{q} \ln \frac{N_A N_D}{n_i^2} \quad (3 \text{ Marks})$$

- (ii) The cross-sectional area of the p-n junction diode.

(3 Marks)

- (iii) What will happen to the junction capacitance value if the reverse-biased voltage is increased.

(3 Marks)

Note: Question No. 1 continues on page 2.

- (b) Figure 1 shows the high-frequency $C-V$ characteristic curve of a silicon MOS capacitor. The area of the device is $2 \times 10^{-3} \text{ cm}^2$. The metal-semiconductor work function difference $\phi_{ms} = -0.50 \text{ V}$, the relative permittivity of the oxide $\epsilon_r = 3.9$, and the semiconductor doping concentration is $2 \times 10^{16} \text{ cm}^{-3}$.

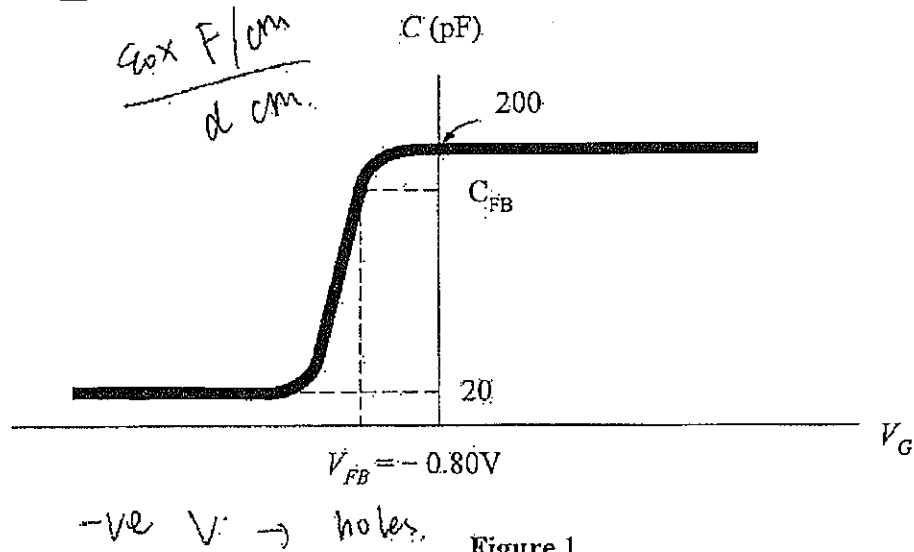


Figure 1

- (i) Is the semiconductor n- or p-type? (2 Marks)
- (ii) What is the oxide thickness? (3 Marks)
- (iii) What is the equivalent trapped oxide charge density (Q_o) where ($Q_o = Q_f + Q_m + Q_{ot}$)? (3 Marks)
- (c) (i) Explain why the base-emitter should be forward biased and the base-collector reversed biased for a p^+-n-p BJT under forward active mode. (4 Marks)
- $\begin{array}{c} p \rightarrow n \rightarrow p \\ \leftarrow \leftarrow \leftarrow \end{array}$
- (ii) State two ways to increase the cutoff frequency (f_T) of a BJT. (4 Marks)

2. (a) (i) A silicon dioxide layer was grown at 1050°C under wet oxidation on (100) silicon for 120 minutes. Assume that $A = 0.226 \mu\text{m}$ and $B = 0.287 \mu\text{m}^2/\text{hr}$. If the final thickness of the oxide is found to be $0.67 \mu\text{m}$, what is the thickness of the initial oxide?

(4 Marks)

- (ii) Name two applications of oxide in semiconductor devices. Explain if wet or dry oxidation is preferred in growing this oxide.

(4 Marks)

- (b) (i) A p-n junction is formed by diffusing pre-deposited boron atoms into the n-type silicon substrate at 1100°C for 1 hour. The dose for the pre-deposition is $2 \times 10^{13} \text{ atoms/cm}^2$. Assume that the diffusion is Gaussian, the doping concentration of the silicon substrate is $1.5 \times 10^{16} \text{ cm}^{-3}$, and $D_B = 9.2 \times 10^{-13} \text{ cm}^2/\text{s}$ at 1100°C , what is the junction depth?

(5 Marks)

- (ii) Name two advantages of thermal diffusion over implantation.

(4 Marks)

- (c) (i) A silicon wafer with a diameter of 20 cm is implanted with phosphorus ions at an implant energy of 150 keV to form a p-n junction. The implantation time is 10 seconds and the average current used is $5 \mu\text{A}$. Under these implant conditions, the values of the projected range (R_p) is $0.14 \mu\text{m}$ and the straggle range (ΔR_p) is $0.045 \mu\text{m}$. If the background concentration of the silicon wafer is found to be $1.6 \times 10^{14} \text{ cm}^{-3}$, what is the junction depth?

$$J + \frac{C}{s} \cdot \text{cm}^2$$

(5 Marks)

- (ii) Explain how a mass spectrometer in an ion-implantation system is used to select the desired ions for implant.

(3 Marks)

3. (a) Figure 2 shows the schematic of a lithography system used in many research labs to prototype new devices.

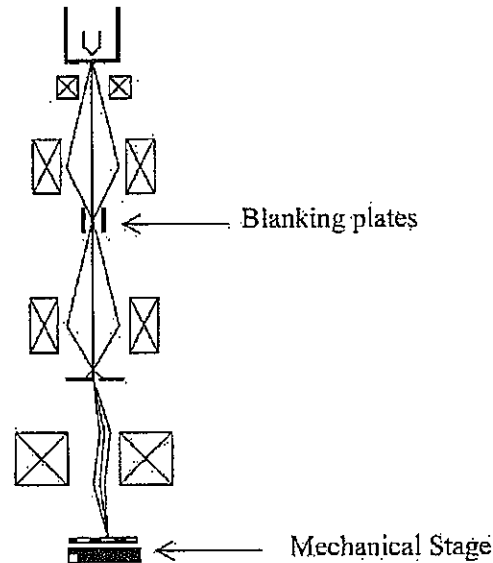


Figure 2

- (i) Name the lithography system. List the advantages and disadvantages of such a system as compared to optical lithography.

(5 Marks)

- (ii) State, giving reasons, the type of resist that is usually preferred for the above lithography system.

(3 Marks)

- (iii) An engineer deploys such a lithography system with step and repeat imaging features to print a submicron pattern. Given that the resists used have a k_1 value of 0.7, and that the minimum line-width is 8 nm, while the gap between the mask and the wafer is $10\text{ }\mu\text{m}$ determine the energy required for the system.

(4 Marks)

- (b) Define in a few sentences the differences between the following:

- (i) Hard and soft bake deployed in lithography processing steps.
- (ii) Mask and reticle used for lithography.
- (iii) X-ray and E-beam lithography.

(6 Marks)

Note: Question No. 3 continues on page 5.

(c) Figure 3 shows the objective lens of a projection lithography system.

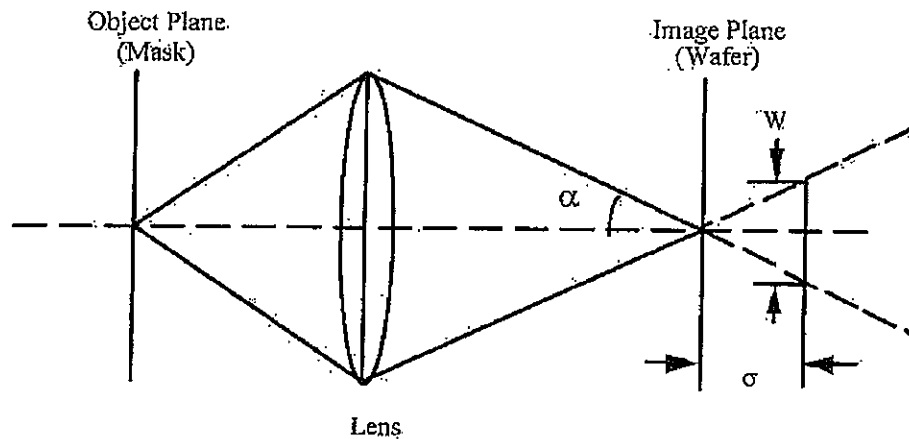


Figure 3

- (i) Assuming $\tan \alpha \sim \sin \alpha$, determine the Numerical Aperture (NA), given that the diameter of the objective lens and its focal length are 1.5 cm and 1 cm, respectively.
- (ii) Hence, determine the depth of focus of the system given that k_2 value is 0.85 and the wavelength of the optical source is 193 nm.

(7 Marks)

4. (a) In the plasma of a RIE system, consider an argon atom that is ionized during a collision in the plasma. Over a given mean free path, one of the particles will achieve a much higher speed. Explain, with a diagram, how that will affect the potential (voltage) of the plasma relative to that of either electrode.

(3 Marks)

- (b) What are the etch rate results and selectivity of a RIE system if the following parameters are changed?

- (i) RF frequency is decreased. hf
- (ii) RF power is decreased.
- (iii) DC bias is increased.
- (iv) Cathode size is decreased.

(4 Marks)

Note: Question No. 4 continues on page 6.

- C₁₀v₁ 57.
CF₄ 537.
- (c) The mixture of SF₆ and O₂ is commonly employed in the Si dry etching process. List the main volatile etch-product of this etching process and explain the roles played by the O₂ plasma. List two other types of commonly used gases for the Si dry etching process. Explain why an effective dry etching process for SiO₂ and Si₃N₄ cannot be developed using SF₆ and O₂ mixture.

(5 Marks)

- (d) Define the residence time of a gas molecule in a plasma system. Discuss what factors can affect the average residence time of the gas molecule of the plasma.

(3 Marks)

- (e) In a LPCVD process system, reaction gas is metered into a 100 liter reactor at a flow of 10 ml/sec. The resulting steady state pressure is 0.2 torr. Assume that 1 torr litre per second = 79 sccm.

- (i) Determine the pumping speed of the pump.
- (ii) Determine the residence time of a gas molecule in the reactor.
- (iii) If the flow is increased to 20 ml/sec, find the pressure and residence time.
- (iv) If a throttle valve is placed on the pump to cut the pumping speed to half, find the pressure and the residence time.

- (v) What possible modifications to the above system need to be made if a PECVD process is to be developed?

(10 Marks)

APPENDIX A

List of Selected Formulae**P-n junction**

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

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

Bipolar junction transistors

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

$$I_{CBO} = (1 + \beta_0) I_{CBO}; \quad p_n(x) = p_{n0} e^{qV_{EB}/kT} \left(1 - \frac{x}{W}\right); \quad \gamma = \frac{1}{1 + \frac{D_E}{D_p} \cdot \frac{N_B}{N_E} \cdot \frac{W}{L_E}};$$

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

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

MOS devices

$$\psi_s = 2\psi_B = \frac{2kT}{q} \ln\left(\frac{N_A}{n_i}\right); \quad W_m^2 = \frac{2\epsilon_s(2\psi_B)}{qN_A} = \frac{4\epsilon_s kT}{q^2 N_A} \ln\left(\frac{N_A}{n_i}\right); \quad V_T = \frac{qN_A W_m^2}{C_0} + 2\psi_B;$$

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

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

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

Thermal oxidation

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

Thermal diffusion

$$D = D_0 \exp\left(-\frac{E_a}{kT}\right)$$

Constant source diffusion:

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

Limited source diffusion:

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

Ion implantation

Before Annealing

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

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

After annealing

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

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}	eV/K
		1.38066×10^{-23}	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	1×10^{10}	cm ⁻³

END OF PAPER

Q1 (a) (i) $V_{bi} = \frac{kT}{q} \ln \frac{N_A N_D}{n_i^2} = 0.0259 \ln \frac{8 \times 10^{16} \times N}{(1.8 \times 10^6)^2} = 1.2V$
 $N = \frac{\exp(\frac{1.2}{0.0259}) \times (1.8 \times 10^6)^2}{8 \times 10^{16}} = 5.36 \times 10^{15} \text{ cm}^{-3}$

(ii) $W = \sqrt{\frac{2\epsilon_s}{q} (\frac{1}{N_A} + \frac{1}{N_D}) (V_{bi} - V)}$
 $= \sqrt{\frac{2 \times 8.85 \times 10^{-14} \times 1.8 \times 10^6}{1.6 \times 10^{-19}} \times (\frac{1}{8 \times 10^{16}} + \frac{1}{5.36 \times 10^{15}}) \times (1.2 + 1)}$
 $= 0.02953 \text{ cm}$

$C_{j0} = \frac{\epsilon_s}{W} = \frac{8.85 \times 10^{-14} \times 1.8 \times 10^6}{0.02953} = 5.3945 \times 10^{-6} \text{ F}$

$S = \frac{C_{j\text{total}}}{C_{j0}} = \frac{1.1 \times 10^{-12}}{5.3945 \times 10^{-6}} = 2.04 \times 10^{-7} \text{ cm}^2$

(iii) reverse bias voltage increase $\rightarrow (V_{bi} - V)$ increase.
 $\rightarrow W$ increase. $\rightarrow C_j$ decrease

Junction capacitance $(\frac{\epsilon_s}{W})$ will decrease.

(b) (i) the semiconductor is n-type.

(ii) $C_0 = 200 \times 10^{-12} = \frac{3.9 \times 8.85 \times 10^{-14}}{d} = \frac{\epsilon_{ox}}{d}$
 $d = \frac{3.9 \times 8.85 \times 10^{-14}}{200 \times 10^{-12}} = 1.726 \times 10^{-3} \text{ cm}$

(iii) $V_{FB} = \phi_{ms} - \frac{Q_f + Q_m + Q_{ot}}{C_0}$
 $-0.8 = -0.5 - \frac{Q_0}{200 \times 10^{-12}}$
 $Q_0 = 6 \times 10^{-11} \text{ C}$

(c) (i) base-emitter should be forward biased because in active mode, we want more holes to be injected from emitter to base.

base-collector should be reversed biased because we want to increase the energy barrier to prevent holes being injected back to base, and more holes can be drift to collector. the efficiency will be higher.

(ii) ① decrease doping concentration N_A or N_D .

② increase the reverse bias voltage for B-C junction. This two ways can both increase the depletion region. thus decrease the neutral ^{base} width w .

$$\text{Since } \tau_B = \frac{w^2}{2D_p} \quad \text{When } w \text{ decrease, } \tau_B \text{ decrease.}$$

$$f_T = \frac{1}{2\pi\tau_B} \quad \text{will increase.}$$

Q2 (a) (i)

$$t_{ox} + A t_{ox} = B(t + \tau)$$

$$0.67^2 + 0.226 \times 0.67 = 0.287(t + \tau)$$

$$\tau = 0.0917 \text{ hr.}$$

$$t_{oxi} = \frac{-0.226 + \sqrt{0.226^2 + 4 \times 0.287 \times 0.0917}}{2} = 0.0526 \text{ hr.}$$

(ii) ① gate oxide

dry oxidation because it requires thin, high quality layer.

② masking

wet oxidation. because it requires high rate. large area but not high quality needed.

$$2.(b) (i) N = \frac{Q}{\sqrt{\pi Dt}} \exp\left(-\frac{z^2}{4Dt}\right) = 1.5 \times 10^{16}$$

$$\frac{2 \times 10^{13}}{\sqrt{\pi \times 9.12 \times 10^{-13} \times 3600}} \exp\left(-\frac{z^2}{4 \times 9.12 \times 10^{-13} \times 3600}\right) = 1.5 \times 10^{16}$$

$$z = 1.845 \times 10^{-6} \text{ cm.}$$

(ii) ①. cheap.

②. No high energy ion damage.

$$(c) (i) N(x) = \frac{Q}{\sqrt{\pi} \Delta R_F} \exp\left[-\frac{(x-R_F)^2}{2 \Delta R_F^2}\right] = N_B$$

$$Q = \frac{It}{qA}$$

$$= \frac{5 \times 10^{-6} \times 10}{1.6 \times 10^{-19} \times \pi \times 10^3} = 9.95 \times 10^{11} \text{ atoms/cm}^2$$

$$\frac{9.95 \times 10^{11}}{\sqrt{\pi} \times 0.0445 \times 10^{-4}} \exp\left[-\frac{(x-0.14)^2}{2 \times 0.045^2}\right] = 1.6 \times 10^{14}$$

$$x = 0.3 \mu\text{m.}$$

$$(ii) F = qvB = \frac{mv^2}{r}$$



When the atom move to the output of mass spectrometer.

The r of the circle $r = \frac{mv}{qB}$ which is proportional to the mass. So we can select the desired atom with corresponding r .

Q3. (a) (i) E-beam lithography system.

Advantages.

- ① precise control of energy and dose
- ② small wavelength \rightarrow good resolution.
- ③ Beam focusing achieved.
- ④ able to register accurately over small areas.
- ⑤ low defect densities

Disadvantages.

- ① require ^{ultra} high vacuum system.
- ② sensitive to electronic and mechanical noise.
- ③ proximity effect.

(ii) use electron resist which is sensitive to e beam.

(iii) $W_{min} = \sqrt{K\lambda g}$
 $8 = \sqrt{0.7 \lambda \cdot 10000}$

$\lambda = 9.14 \text{ pm.}$

$\lambda = \frac{h}{\sqrt{2meV}}$ $V = \frac{\left(\frac{h}{\lambda}\right)^2}{2me}$

$= 18027.77 \text{ V.}$

$E = 18027.77 \text{ eV.}$ required.

(b) (i) soft bake improve the light absorbance for photoresist.

hard bake. hardens the resist for etching or

(ii) mask contain the full graphic pattern. used for single exposure.
while reticle contain part of the pattern. used for step and repeat process.

(iii) x-ray lithography system use x-ray for exposure.
e-beam system use electron beam for exposure.

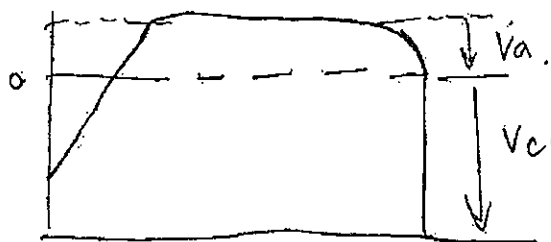
Q3 (c)

i) $NA = \sin \alpha \approx \tan \alpha = \frac{\frac{d}{2}}{f} = \frac{1.5}{2} = 0.75$

ii) $DOA = \frac{1.22 \lambda}{(NA)^2} = \frac{0.85 \times 10^{-3}}{0.75^2} = 291.64 \text{ nm}$

Q4 (a)

(not sure
even
during
exam)



higher speed \rightarrow higher energy \rightarrow higher voltage.

(b) (i) etch rate \downarrow . selectivity no change.

ii) etch rate \downarrow . selectivity no change.

iii) etch rate \uparrow . selectivity no change.

iv) \uparrow $(r_c) = V_a \left(\frac{A_a}{A_c} \right)$ increase energy
etch rate \uparrow . selectivity no change.

(c)

didn't
answer
well.

Q. react with SF_2 , SF_3 to form SOF and F .
reduce the recombination rate of the active F .
prevent SF_6 (unreactive)

(d). the time a gas molecule can stay in the chamber
before being pumped out.

$$tr = \frac{V}{S}$$

the chamber volume V and pumping
speed S can affect tr .

4(e) (i) $P = \frac{F \cdot 760}{S}$
 $S = \frac{10 \times 10^{-3} \times 760}{0.2}$
 $= 38 \text{ liter/s.}$

(ii) $tr = \frac{V}{S} = \frac{100}{38} = 2.63 \text{ s.}$

(iii) $P = \frac{20 \times 10^{-3} \times 760}{38} = 0.4 \text{ torr.}$

$tr = \frac{V}{S} = 2.63 \text{ s.}$

(iv) $S' = \frac{S}{2} = \frac{19}{1} \text{ liter/s.}$

$P = \frac{10 \times 10^{-3} \times 760}{19} = 0.4 \text{ torr.}$

$tr = \frac{V}{S} = 5.26 \text{ s.}$

(v) ① connect electrode with RF generator to generate plasma.

(7) ② wafer horizontally placed on the other electrode.

