

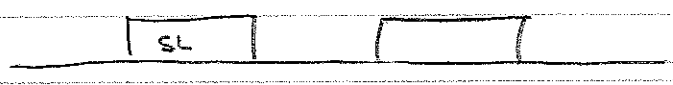
# Exam #1 Solutions

Mean = 51.7  
 $\sigma = 23.2$

1. To achieve sub-lithographic features (10nm vs 50nm), use sidewall spacer approach.

Step 1: Deposit sacrificial layer on Si wafer

Step 2: Pattern SL using photolithography



Step 3: Conformal deposition (CVD)

of 10nm (plus a little more to account for lateral etch) of  $\text{SiO}_2$

Step 4: Anisotropic etch oxide

leaving just oxide spacers



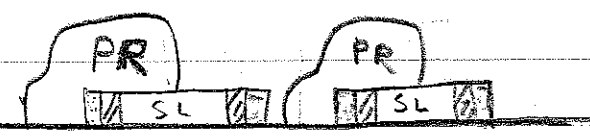
Step 5: Conformal (CVD) deposition of 10nm of  $\text{Si}_3\text{N}_4$

Step 6: Anisotropic nitride etch

leaving double spacers.

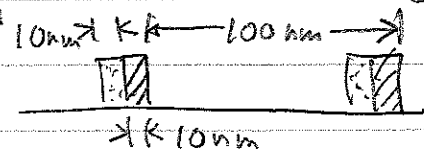


Step 7: Photo lithography to protect half of spacer pairs



Step 8. Etch  $\text{Si}_3\text{N}_4$  and  $\text{SiO}_2$

Step 9: Strip Photoresist and etch sacrificial layer



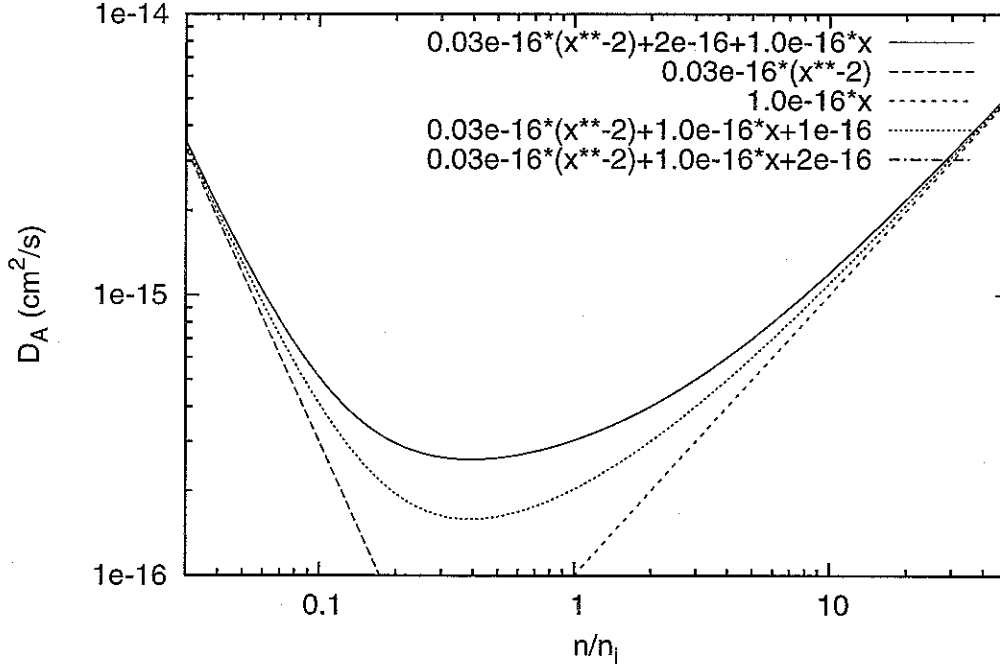
Minimum spacing is 100nm since photolith half-pitch is 50nm

One might think of using polysilicon for sacrificial layer, but need to remove w/o etching substrate (could use timed etch). Another option might be W (Tungsten), needs to withstand light during  $\text{SiO}_2$ ,  $\text{Si}_3\text{N}_4$  depositions

2. Considering diffusion via charged point defects near equilibrium,

$$D_A^* = D_A^0 + D_A^- \left(\frac{n}{n_i}\right) + D_A^- \left(\frac{n}{n_i}\right)^2 + D_A^+ \left(\frac{n}{n_i}\right)^{-1} + D_A^{++} \left(\frac{n}{n_i}\right)^{-2}$$

For  $(n/n_i) \gg 1$ ,  $D_A \propto (n/n_i)$  (based on peak slope approaching 1). Assuming this term dominates for  $(n/n_i) = 50$  gives coefficient of  $1.0 \times 10^{16} \text{cm}^2/\text{sec}$ . For  $(n/n_i) \ll 1$ ,  $D_A \propto (n/n_i)^{-2}$ . Based on value at  $(n/n_i) = 0.03$ , coefficient is  $3 \times 10^{-18} \text{cm}^2/\text{sec}$ . For  $(n/n_i) \sim 1$ , need additional term. Try constant. Once value of  $D_A^0 = 2 \times 10^{-16}$  is added as required to fit  $(n/n_i) > 1$ , it can be seen that  $(n/n_i)^{-1}$  term is negligible.



Diffusivity of low concentrations of "A" versus  $(n/n_i)$  for constant background dopings under near-equilibrium conditions.

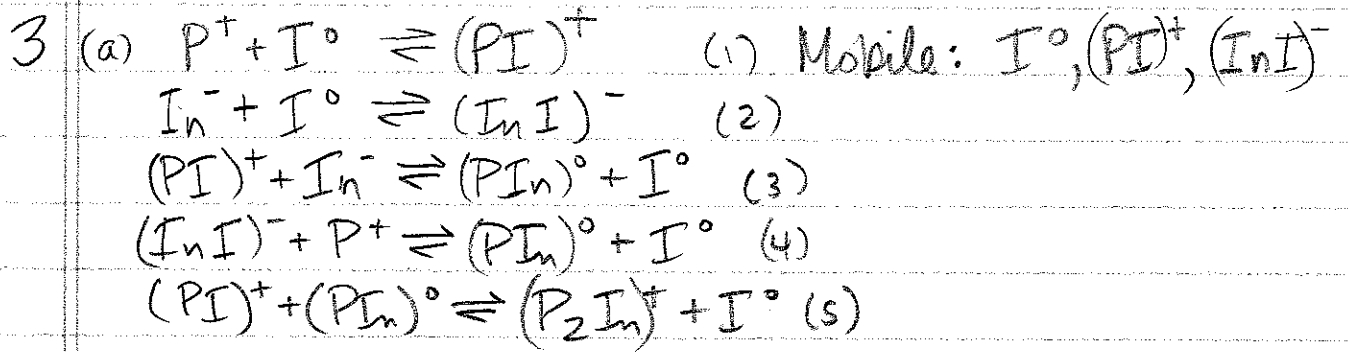
Considering diffusion as function of point defect injection in intrinsic material:

$$D_{Ai} = D_{Ai}^* \left[ f_I \left(\frac{C_I}{C_I^*}\right) + (1 - f_I) \left(\frac{C_V}{C_V^*}\right) \right] = D_{Ai}^* \left[ f_I \left(\frac{C_I}{C_I^*}\right) + (1 - f_I) \left(\frac{C_I}{C_I^*}\right)^{-1} \right]$$

For,  $C_I = C_I^*$ ,  $D_{Ai} = D_{Ai}^* = 3.03 \times 10^{-16} \text{cm}^2/\text{sec}$  which is value from first plot with  $n = n_i$ . Adjusting  $f_I$  to match plot at  $C_I/C_I^* = 20$  gives  $f_I = 0.2$ . The data only gives  $f_I$  for  $n = n_i$ , so there are multiple options. Assuming that all charge terms have same fractional I contribution:

$$D_A = \left[ 2 + \left(\frac{n}{n_i}\right) + 0.03 \left(\frac{n}{n_i}\right)^{-2} \right] \left[ 0.2 \left(\frac{C_I}{C_I^*}\right) + 0.8 \left(\frac{C_I}{C_I^*}\right)^{-1} \right] 10^{-16} \text{cm}^2/\text{sec}$$

In identifying what the impurity might be, we can look first at Fermi level dependence. We note that 'A' diffuses via both positively (++) and negatively (-) charged defects. This suggests that it might be a group IV material rather than a dopant. The impurity diffuses primarily with vacancies. Larger impurities can be expected to diffuse more with V and less with I, while Si self-diffusion has an  $f_I$  near 0.5. Thus, the evidence suggests that 'A' may be a group IV element heavier than Si. The most likely option would seem to be Ge, since it still has a substantial (0.2) interstitial component to diffusion, although Sn is another option.



(A)  $\frac{\partial C_{P^+}}{\partial t} = -R_1 - R_4$  \*  $J_{(PI)^+} = -d_{(PI)^+} \left[ \nabla C_{(PI)^+} + C_{(PI)^+} \nabla \ln \left( \frac{n}{n_0} \right) \right]$

(B)  $\frac{\partial C_{In^-}}{\partial t} = -R_2 - R_3$  \*  $J_{(InI)^-} = -d_{(InI)^-} \left[ \nabla C_{(InI)^-} - C_{(InI)^-} \nabla \ln \left( \frac{n}{n_0} \right) \right]$

(C)  $\frac{\partial C_{(PI)^+}}{\partial t} = -\nabla \cdot J_{(PI)^+} + R_1 - R_3 - R_5$

(D)  $\frac{\partial C_{(InI)^-}}{\partial t} = -\nabla \cdot J_{(InI)^-} + R_2 - R_4$

(E)  $\frac{\partial C_{(PIIn)^0}}{\partial t} = R_3 + R_4 - R_5$  \*  $J_{I^0} = -d_{I^0} \nabla C_{I^0}$

(F)  $\frac{\partial C_{(P_2In)^+}}{\partial t} = R_5$

(G)  $\frac{\partial C_{I^0}}{\partial t} = -\nabla \cdot J_{I^0} - R_1 - R_2 + R_3 + R_4 + R_5$

$R_1 = k_1^f \left[ C_{P^+} + C_{I^0} - \frac{C_{(PI)^+}}{K_1} \right]$

$R_2 = k_2^f \left[ C_{In^-} + C_{I^0} - \frac{C_{(InI)^-}}{K_2} \right]$

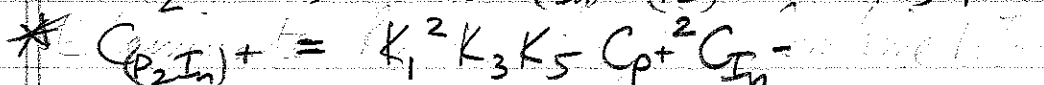
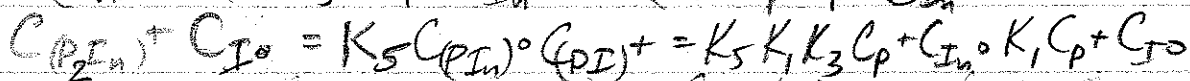
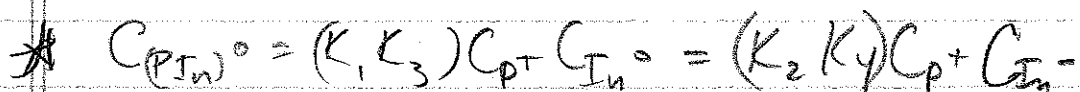
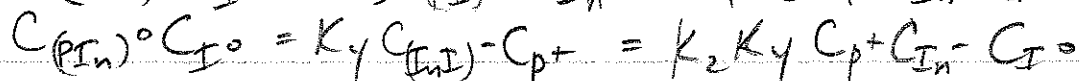
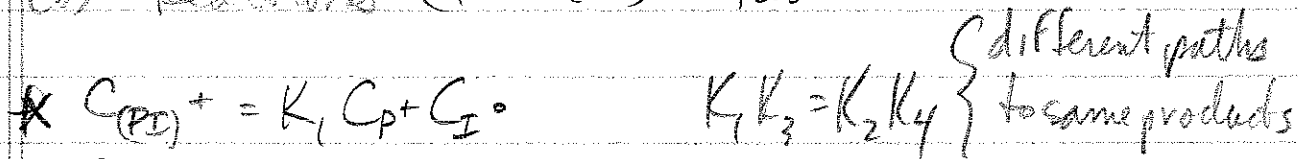
$R_3 = k_3^f \left[ C_{(PI)^+} + C_{In^-} - \frac{C_{(PIIn)^0}}{K_3} \right]$

$R_4 = k_4^f \left[ C_{(InI)^-} + C_{P^+} - \frac{C_{(PIIn)^0}}{K_4} \right]$

$R_5 = k_5^f \left[ C_{(PI)^+} + C_{(PIIn)^0} - \frac{C_{(P_2In)^+}}{K_5} \right]$

$K_1 K_3 = K_2 K_4$   
 since they represent  
 different paths  
 for same products  
 $1+3 = 2+4$

(b) Reactions (1) - (4) "fast"



Eliminate  $R_1 - R_5$ , equations for total P, total In, total I<sub>0</sub>

$$(A) + (C) + (E) + 2(F) : \frac{\partial}{\partial t} (C_P + C_{(PI)^+} + C_{(PI)^0} + 2C_{(P_2In)^+}) = -\nabla \cdot J_{(PI)^+}$$

$$(B) + (D) + (E) + 2(F) : \frac{\partial}{\partial t} (C_{In^-} + C_{(In)^-} + C_{(PI)^0} + 2C_{(P_2In)^+}) = -\nabla \cdot J_{(In)^-}$$

$$(C) + (D) + (G) : \frac{\partial}{\partial t} (C_{(PI)^+} + C_{(In)^-} + C_{I^0}) = -\nabla \cdot [J_{I^0} + J_{(PI)^+} + J_{(In)^-}]$$

In terms of  $P^+$ ,  $In^-$ ,  $I^0$ ; substitute for



using above equations in (a) and (b) [starred]

$$\text{with } \frac{n}{n_i} = \eta + \sqrt{\eta^2 + 1} \quad \text{where } \eta = \frac{N_d^+ - N_a^-}{2n_i}$$

$$(c) \frac{\partial}{\partial t} C_p^{\text{total}} = -\nabla \cdot \underset{\text{neglect}}{J_{(PE)^+}}$$

$$C_p^{\text{total}} = C_p^+ + \cancel{C_{(PE)^+}} + C_{(PE)^0} + 2C_{(P_2I_n)^+}$$

$$\approx C_p^+ + K_1 K_3 C_p^+ C_{I_n^-} + 2K_1^2 K_3 K_5 C_p^{+2} C_{I_n^-}$$

$$C_{I_n}^{\text{total}} \approx C_{I_n^-} + K_1 K_3 C_p^+ C_{I_n^-} + K_1^2 K_3 K_5 C_p^{+2} C_{I_n^-}$$

Limiting cases:

i)  $C_{I_n^-}$  small enough that  $C_{(PE)^0}, C_{(P_2I_n)^+} \ll C_p^+$

$$J_{P^+} = d_{(PE)^+} \left[ \nabla C_{(PE)^+} + C_{(PE)^+} \nabla \ln\left(\frac{n}{n_i}\right) \right], \quad C_{(PE)^+} = K_1 C_p^+ C_{I^0}^*$$

$$= \left[ d_{(PE)^+} K_1 C_{I^0}^* \right] \left[ \nabla C_p^+ + C_p^+ \nabla \ln\left(\frac{n}{n_i}\right) \right]$$

Ignoring drift term:  $D_p^{\text{total}} \approx d_{(PE)^+} K_1 C_{I^0}^*$

w/ drift term:  $D_p^{\text{total}} \approx h d_{(PE)^+} K_1 C_{I^0}^*$

ii)  $I_n$  concentration very large, but  $P$  concentration low, so very few  $(P_2I_n)^+$ :  $C_p^{\text{total}} \approx C_{(PE)^0} = K_1 K_3 C_p^+ C_{I_n^-}$

$$C_{I_n}^{\text{total}} \approx C_{I_n^-} + C_{(PE)^0} \approx C_{I_n^-} + C_p^{\text{total}}$$

$$C_p^+ \approx \frac{C_p^{\text{total}}}{K_1 K_3 C_{I_n^-}} \approx \frac{C_p^{\text{total}}}{K_1 K_3 (C_{I_n}^{\text{total}} - C_p^{\text{total}})}$$

Neglecting drift term (depends on  $I_n$  concentration gradient):

$$D_p^{\text{total}} \nabla C_p^{\text{total}} = d_{(PE)^+} K_1 C_{I^0}^* \nabla \left[ \frac{C_p^{\text{total}}}{K_1 K_3 (C_{I_n}^{\text{total}} - C_p^{\text{total}})} \right]$$

$$= \frac{d_{(PD)} + K_1 C_{T0}^*}{K_1 K_3} \left[ \frac{(C_{In}^{total} - C_p^{total}) \nabla C_p^{total} - C_p^{total} \nabla (C_{In}^{total} - C_p^{total})}{(C_{In}^{total} - C_p^{total})^2} \right]$$

$$= \frac{d_{(PD)} + C_{T0}^*}{K_3} \left[ \frac{\nabla C_p^{total}}{(C_{In}^{total} - C_p^{total})} + \frac{C_p^{total} \nabla C_p^{total}}{(C_{In}^{total} - C_p^{total})^2} - \frac{C_p^{total} \nabla C_{In}^{total}}{(C_{In}^{total} - C_p^{total})^2} \right]$$

$$D_p^{total} = \frac{d_{(PD)} + C_{T0}^*}{K_3 (C_{In}^{total} - C_p^{total})} \left[ 1 + \frac{C_p^{total}}{(C_{In}^{total} - C_p^{total})} \right]$$

drift term  
due to  
gradient in  
 $In$  concentration

iii) Very large  $P$  concentration, moderately large  $In$  concentration

$$C_{In}^{total} \approx K_1 K_3 K_5 C_p^2 C_{In}^- \approx C_{(P_2 In)}^+$$

$$C_p^{total} \approx C_p^+ - 2C_{(P_2 In)}^+ = C_p^+ - 2C_{In}^{total}$$

$$D_p^{total} = h d_{(PD)} K_1 C_{T0}^* \text{ as in (i)}$$

Other limiting cases also possible to consider

$$(d) n-p = C_p^+ - C_{In}^- + C_{(P_2 In)}^+ = C_p^+ - C_{In}^- + K_1^2 K_3 K_5 C_p^2 C_{In}^-$$

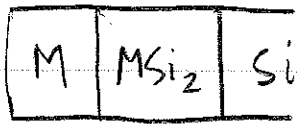
$$= C_p^+ + (K_1^2 K_3 K_5 C_p^2 - 1) C_{In}^-$$

Actually increases with  $C_{In}^-$  if  $C_p^+ > (K_1^2 K_3 K_5)^{-1/2}$

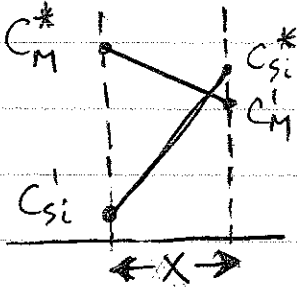
$$n-p = C_p^+ (1 + K_1^2 K_3 K_5 C_p^+ C_{In}^-) - C_{In}^-$$

Increases as  $C_p^+$  for large  $C_p^+$

4



(a) Silicon fluxes in steady-state



$$\frac{D_{Si}(C_{Si}^* - C_{Si}^I)}{x} = k_{Si} C_{Si}^I$$

$$\Rightarrow C_{Si}^I = \frac{D_{Si} C_{Si}^*}{D_{Si} + k_{Si} x}$$

Metal fluxes  
in steady-state:

$$\frac{D_M(C_M^* - C_M^I)}{x} = k_M C_M^I \Rightarrow C_M^I = \frac{D_M C_M^*}{D_M + k_M x}$$

$$\begin{aligned} \frac{dx}{dt} &= \frac{1}{N_{MSi_2}} \left[ k_M C_M^I + \frac{1}{2} k_{Si} C_{Si}^I \right] \\ &= \frac{1}{N_{MSi_2}} \left[ \frac{k_M D_M C_M^*}{D_M + k_M x} + \frac{k_{Si} D_{Si} C_{Si}^*}{2(D_{Si} + k_{Si} x)} \right] \end{aligned}$$

(b) The film growth rate can not be reduced to simple linear-parabolic model unless  $D_M/k_M = D_{Si}/k_{Si}$ 

$$\text{For very thin } (x \rightarrow 0) \quad \frac{dx}{dt} \approx \frac{1}{N_{MSi_2}} \left[ k_M C_M^* + \frac{1}{2} k_{Si} C_{Si}^* \right]$$

$$\text{For very thick } (x \gg \frac{D_M}{k_M}, \frac{D_{Si}}{k_{Si}})$$

$$\begin{aligned} \frac{dx}{dt} &\approx \frac{1}{N_{MSi_2}} \left[ \frac{D_M C_M^*}{x} + \frac{D_{Si} C_{Si}^*}{2x} \right] \\ &= \frac{1}{N_{MSi_2} x} \left[ D_M C_M^* + \frac{1}{2} D_{Si} C_{Si}^* \right] \end{aligned}$$