

# MICROELECTRONIC TECHNOLOGIES

## EXAMS NOTES

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*...Scooby-doo?...*



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# Chapter 1

## Exams notes

### 1.1 CZ-growth

#### 1.1.1 Doping concentration in the ingot

CZ growth of silicon gives different doping concentrations for the wafers depending on the distance from the top of the ingot.

The parameters that we need to have the doping concentration at a certain value  $x$  are the segregation coefficient  $k$  and the initial dose of doping  $C_0$

$$C = C_0 k (1 - f)^{k-1} \quad (1.1)$$

where  $f$  is the % of the ingot where we are.

### Dimostrazione

Define

- $V_0, I_0, C_0$  volume, concentration and number of impurities in the initial fused silicon
- $V_l, I_l, C_l$  same of before but in the melted silicon after a certain time  $t$
- $V_s, I_s, C_s$  same of before but in the solid cristal

When a little volume of silicon solidifies the concentration of impurities in the melt varies as

$$dI_l = -kC_l dV_s = -kC_l = \frac{I_l}{V_0 - V_s} dV_s \quad (1.2)$$

so we can write

$$\int_{I_0}^{I_l} \frac{dI_l}{I_l} = \int_0^{V_s} -k \frac{dV_s}{V_0 - V_s} \quad (1.3)$$

doing the integration and getting rid of the log units we arrive at

$$I_l = I_0 \left(1 - \frac{V_s}{V_0}\right)^k \quad (1.4)$$

by using the following relation

$$C_s = -\frac{\partial I_l}{\partial V_s} \quad (1.5)$$

we get the result

$$C_s = C_0 k (1 - f)^{k-1} \quad (1.6)$$

Form the concentration we can derive the resistivity of the wafer as

$$\rho = \frac{1}{q\mu C} \quad (1.7)$$

#### 1.1.2 Maximum pulling rate

$$v_p^{max} = \frac{1}{LN} \sqrt{\frac{2\sigma\epsilon k_m T_m^5}{3r}} \propto \sqrt{\frac{1}{r}} \quad (1.8)$$

### 1.2 Deal-Grove model

Using the correct tables parameters we can derive the coefficients  $B$  and  $B/A$  for wet or dry oxidation throught theyr Ahrrenius form

$$B = C_1 \cdot \exp\left(-\frac{E_1}{kT}\right) \quad B/A = C_2 \cdot \exp\left(-\frac{E_2}{kT}\right) \quad (1.9)$$

or in an alternative way with theyr expressions

$$B = \frac{2DHP_G}{N} \quad B/A = \frac{HP_G}{N \left(\frac{1}{k_s} + \frac{1}{h}\right)} \quad (1.10)$$

remember that

- B is related to the transport through the present oxide so it isn't dependent on cristal orientation.
- B/A is related to the interaction with the surface it's activation energy it's  $\simeq 2eV$  that is the energy to break one Si-Si bond and it's strongly dependent on cristal orientation in fact

$$\left(\frac{B}{A}\right)_{\langle 111 \rangle} = 1.68 \left(\frac{B}{A}\right)_{\langle 100 \rangle} \quad (1.11)$$

Notice that none of the mentioned parameters depends on pressure.

The model gives us the following expression

$$\frac{x^2}{B} + \frac{x}{B/A} = t + \tau \quad (1.12)$$

The boundary between the 2 regimes ,parabolic and linear, is given by the following thickness

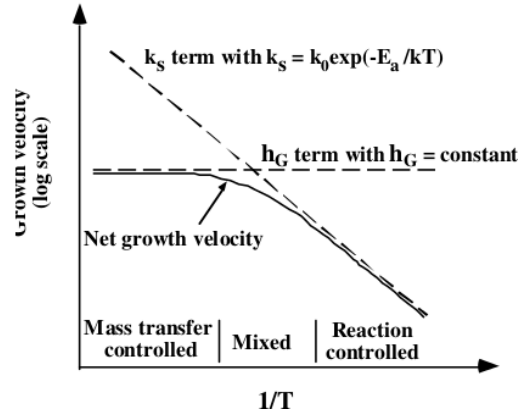
$$x_b = \frac{B}{2B/A} \quad (1.13)$$

Beware that 46% of the  $SiO_2$  grows inside the silicon and the other 56% over it.

In the first 20nm of  $SiO_2$  the model is underestimating the real value of the thickness (exponential term).

## 1.3 CVD

### 1.3.1 Regimes



The velocity of deposition of a material in APCVD is determined by the slowest of two proces that operates in parallel; the transport of byproducts through the stagnant layer and the "reaction" with the surface.

The velocity can be mathematically described as

$$v = \frac{k_s h_g}{k_s + h_g} \frac{C_T}{N} Y \quad (1.14)$$

where  $k_s$  is the chemical surface reaction rate (has an Arrhenius form so strongly dependent on temperature) and  $h_g$  the mass transport coefficient (independent form temperature). We can distinguish in two case

- $k_s \ll h_g$  we are in surface reaction controlled regime; the geometry of the reaction does not matter so much this is the best case
- $h_g \ll k_s$  mass transport controlled regime; the geometry of the reactor is fundamental to control the stagnant layer

### 1.3.2 APCVD rate

#### Dimostrazione

Only two fluxes are present in the CVD deposition

- $F_1$  flux of material near the surface.  
It can be modelled as

$$F_1 = h_g(C_g - C_s) \quad (1.15)$$

where  $C_g$  is the concentration of species to be deposited in the bulk of the reactor,  $C_s$  the concentration near the surface and  $h_g$  is the mass transport coefficient.

- $F_2$  reaction and deposition flux at the surface.  
It can be modelled as

$$F_2 = k_s C_s \quad (1.16)$$

with  $k_s$  reaction rate at the surface.

In stationary condition this two have to be equal from this I can extract  $C_s$  and then remembering that  $P_g/P_t = C_g/C_t$  we arrive at the following formula

$$v = \frac{F}{N} = \frac{k_s h_g}{k_s + h_g} \frac{P_g}{P_t} C_t \quad (1.17)$$

### 1.3.3 LPCVD

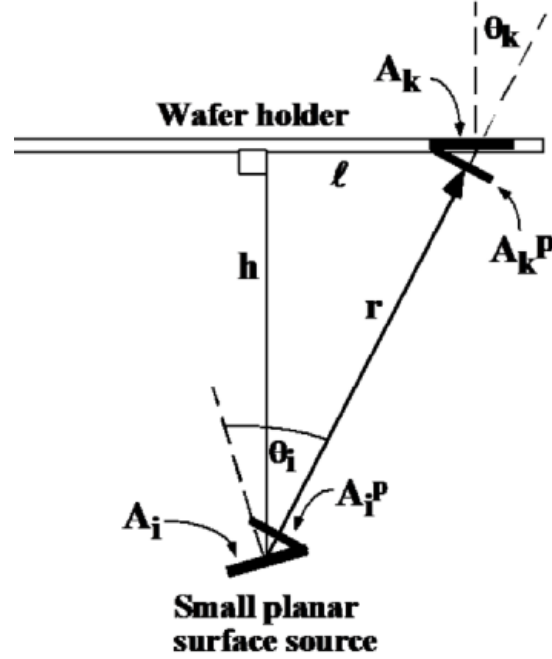
Form APCVD we can increase the value of  $h_g$  since we hope to stay in surface reaction controlled regime decreasing the value of the pressure since

$$h_g = \frac{D_g}{\sigma_g} \quad (1.18)$$

where  $D_g$  is the diffusivity of the gas and  $\sigma_g$  the stagnant layer thickness and  $D_g \simeq 1/P$ . This means to do a LPCVD.

## 1.4 PVD

### 1.4.1 Evaporation from small source



The evaporation rate from a small surface is defined as

$$v = \frac{R_{evap}}{\pi N r^2} \cos(\theta_i) \cos(\theta_k) \quad (1.19)$$

where  $R_{evap}$  is the evaporation rate and  $N$  is the density of the material that we are depositing.

## 1.5 Etch rate

### 1.5.1 Linear model

The supposition at the base of this model is that chemical and physical etch act in an independent manner.

The total etch rate will be given by

$$E = \frac{1}{N} (F_i k_i + k_f F_c S_c) \quad (1.20)$$

with  $F_c$  flux of chemical species,  $S_c$  sticking coefficient,  $k_c$  reaction rate constant,  $k_i$  sputtering efficiency and  $F_i$  flux of ionic species.



## Anisotropy

The anisotropy value can be found considering that horizontal etch is done only by the chemical species

$$E_{horizontal} = \frac{1}{N} F_c S_c k_f \quad (1.21)$$

so the anisotropy constant is

$$A = \frac{E}{E_{horizontal}} = \frac{(F_i k_i + k_f F_c S_c)}{F_c S_c k_f} \quad (1.22)$$

### 1.5.2 Ion enhanced

Two process cooperating the ion etch and the byproducts deposition. We can assume the number of deposited byproducts as

$$D = S_c(1 - \theta)F_c \quad (1.23)$$

With  $F_c$  flux of chemical species,  $S_c$  sticking coefficient and  $(1-\theta)$  number of available sites. The number of byproducts removed as

$$R = K_i \theta F_i \quad (1.24)$$

with  $K_i$  sputtering efficiency,  $F_i$  flux of ionic species and  $\theta$  number of occupied states. In stationary conditions  $D=R$  so we can extract  $\theta$  as

$$\theta = \frac{1}{1 + \frac{K_i F_i}{S_c F_c}} \quad (1.25)$$

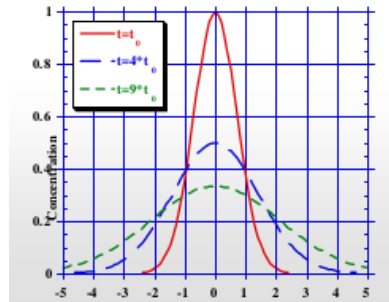
so substituting this into the R expression we get the etch rate as

$$E = \frac{1}{N} \left( \frac{1}{K_i F_i} + \frac{1}{S_c F_c} \right) \quad (1.26)$$

with N density of the material to be etched.

## 1.6 Dopants diffusion analytic solutions

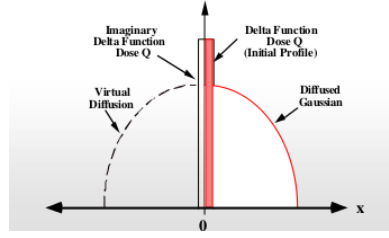
### 1.6.1 Delta function in doped region



$$C(x, t) = \frac{Q}{2\sqrt{\pi Dt}} \exp\left(-\frac{x^2}{4Dt}\right) \quad (1.27)$$

### 1.6.2 Delta function near a surface

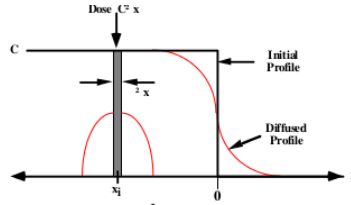
Is like a "mirrored" case of the delta function in a doped region



$$C(x, t) = \frac{Q}{\sqrt{\pi Dt}} \exp\left(-\frac{x^2}{4Dt}\right) \quad (1.28)$$

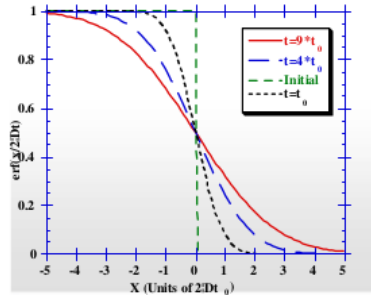
### 1.6.3 From an infinite source of dopant in silicon

Sum of gaussian problems or sum of delta functions



$$C(x, t) = \frac{Q}{2} \operatorname{erfcf}\left(\frac{x}{2\sqrt{Dt}}\right) \quad (1.29)$$

### 1.6.4 From an infinite source of dopant at surface



Symmetry considerations leads to

$$C(x, t) = Q \cdot \operatorname{erfcf}\left(\frac{x}{2\sqrt{Dt}}\right) \quad (1.30)$$

the dose Q is

$$Q = 2C_s \sqrt{\frac{Dt}{\pi}} \quad (1.31)$$

## 1.7 Ion implant

### 1.7.1 Stopping mechanism

Two main mechanisms are in action in ion stopping

- $S_n(E)$  Two body collision with other atoms.  
Can be modelled as a Coulomb scattering with a correcting factor for the atom shielding.  
It becomes relevant only at the end of the process.
- $S_e(E)$  Dragged by electrons (electronic stopping power).  
Polarization fields created by stationary charge atoms creates a viscous space where the ion has to travel. Momentum is exchanged with orbital electrons.  
The energy can be modelled as a motion into a viscous medium

$$S_e(E) = k\sqrt{E} \quad (1.32)$$

The dispersion relation with energy is

$$\frac{dE}{dx} = -N(S_n(E) + S_e(E)) \quad (1.33)$$

That integrated gives us the projected range as

$$R_p = \int_0^{R_p} dx = \int_0^{E_{implant}} \frac{dE}{N(S_n(E) + S_e(E))} \quad (1.34)$$

### 1.7.2 Range and +1 model

Given an implant of an element with a dose  $Q$  and an energy  $E$  we can find from tables the values of

- $R_p$  the projected range of our implant that is the maximum of our gaussian distribution that we expect
- $\Delta R_p$  the standard deviation of our gaussian distribution

So we will have a distribution like

$$C(x) = C_p \exp\left(-\frac{(x - R_p)^2}{2\Delta R_p^2}\right) \quad (1.35)$$

where  $C_p$  is the concentration at the peak of our distribution.

The total dose implanted will be  $Q = \sqrt{2\pi\Delta R_p^2} C_p$  and so  $C_p = \frac{Q}{\sqrt{2\pi\Delta R_p^2}}$  doing so we can write

$$C(x) = \frac{Q}{\sqrt{2\pi\Delta R_p^2}} \exp\left(-\frac{(x - R_p)^2}{2\Delta R_p^2}\right) \quad (1.36)$$

If we want to know the dose that is present after a certain depth  $x$

$$Q_{imp} = \int_x^{+\infty} C_p \exp\left(-\frac{(x - R_p)^2}{2\Delta R_p^2}\right) dx \quad (1.37)$$

That becomes

$$Q_{imp} = \frac{Q}{2} \operatorname{erfc} \left( \frac{x - R_p}{\sqrt{2} \Delta R_p} \right) \quad (1.38)$$

The function  $\operatorname{erfc}$  has the following proprieties

- $\operatorname{erfc}(x) = 1 - \operatorname{erf}(x)$  if  $x > 0$
- $\operatorname{erfc}(x) = 1 + \operatorname{erf}(x)$  if  $x < 0$

If we want to estimate the amount of interstitial caused by an implant using the +1 model we can say that the concentration of interstitial is equal to the dose  $Q$  implanted in silicon. If the silicon is fully amorphised and then re-crystallized there are no interstitial due to ion implantation since in an amorph crystal do not exists interstitials or defects.

### 1.7.3 With dopant diffusion

After an implant (with a certain dose  $Q$  and having also  $R_p$  and  $\Delta R_p$ ) there will always be a thermal annealing process for a certain time  $t$  at a temperature  $T$ .

The profile of the doping will be a gaussian with the standard deviation modified by the diffusion due to thermal treatment so like

$$C(x) = \frac{Q_i}{\sqrt{2\pi(\Delta R_p^2 + 2Dt)}} \exp \left( -\frac{(x - R_p)^2}{2(\Delta R_p^2 + 2Dt)} \right) \quad (1.39)$$

From this we can know the concentration of dopants for all  $x$ .

Beware to correctly set  $Q$  depending on the symmetry of the system.

### 1.7.4 Diffusion length of dopants and supersaturation of I

Diffusion length is defined as the sigma of the gaussian considering an annealing process in an inert ambient and not the ion implantation so

$$l_d = \sqrt{D^* t} \quad (1.40)$$

where  $D^*$  is the equilibrium diffusivity in an inert ambient and it has an Arrhenius form so depends a lot on temperature.

In case we are in an oxidizing/nitride ambient we have an enhanced diffusivity that can be written as

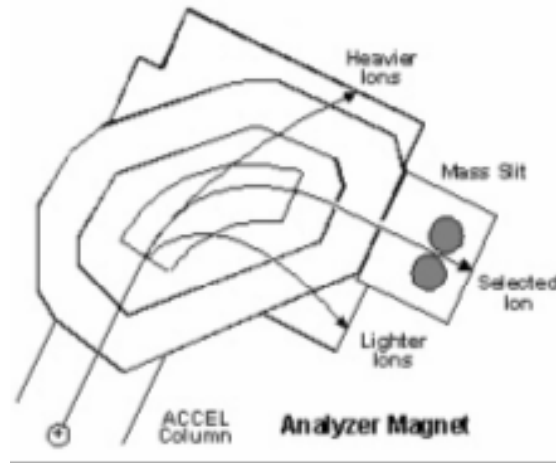
$$D_{eff} = D^* \left( \frac{C_I}{C_I^*} f_i + \frac{C_V}{C_V^*} f_v \right) \quad (1.41)$$

where we used

- $f_{i/v}$  interstitial/vacancy type mechanism fraction (typically one is 1 one is 0)
- $C_{V/I}^*$  vacancy/interstitial equilibrium concentration
- $C_{V/I}$  vacancy/interstitial concentration

From this expression we can derive the supersaturation of I or V that is the term  $\frac{C_I}{C_I^*}$

### 1.7.5 Analyser; tune for B



Electrons enters in the chamber with potential  $V$  where there is a perpendicular magnetic field  $B$ . This will make electrons curve with a  $R$ .

We can relate the ions mass and the magnetic field considering two equations:

- Motion equation of ions

$$\frac{mv^2}{R} = q|\vec{v} \times \vec{B}| = qvB \quad (1.42)$$

- Conservation of energy

$$\frac{1}{2}mv^2 = qV \quad (1.43)$$

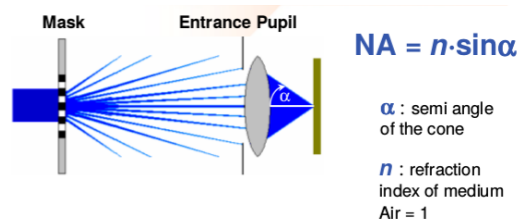
By extracting  $v^2$  by one of the two and substituting we get the following expression

$$\sqrt{\frac{m}{q}} = \frac{RB}{\sqrt{2V}} \quad (1.44)$$

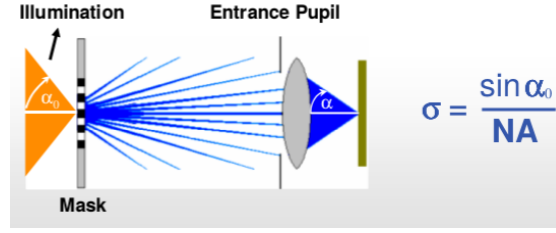
## 1.8 Lito

### 1.8.1 Resolution limit

Defining some parameters of our lito tool as:



NA determines the maximum number of diffraction orders that can be captured by projection lens and thus the quality of the reconstructed image.



It defines the illumination of the mask, depends from source extension. For  $\sigma = 0$  we have coherent illumination  $\sigma = 1$  incoherent illumination.

For a coherent illumination that means a light perpendicular to the mask we have that the minimum resolution is

$$R = \frac{1}{2} \frac{\lambda}{NA} \quad (1.45)$$

For a partially coherent illumination that means a light tilted by an angle  $\theta$  the resolution is

$$R = \frac{1}{2} \frac{\lambda}{(1 + \sigma)NA} \quad (1.46)$$

### Double patterning

With double patterning the R calculated before can be reduce further to R/2.

### 1.8.2 Contrast value

Given a certain profile of aerial image the contrast value is

$$C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \quad (1.47)$$

With equal values of contrast it's better to choose the one with higher  $I_{max}$

## 1.9 Back end

### 1.9.1 Technology scaling; propagation delay

Propagation delay of a metal wire can be modelled as

$$\tau \simeq 0.89 \cdot \varepsilon_{oxide} \varepsilon_0 \rho \frac{A}{F_{min}^2} \quad (1.48)$$

### 1.9.2 Electromigration

The critical lenght of the cluster can be expressed as

$$L_{crit} = \frac{2\sigma_{crit}\Omega}{Z^*q\rho J} \quad (1.49)$$

Where  $\Omega$  is the volume of the atom of metal and  $\sigma_{crit}$  the value of the maximum stress.

## Chapter 2

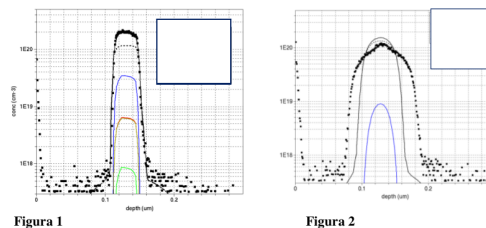
# Theory questions

18/02/11

Descrivere, con l'aiuto di disegni se necessario, due tecniche per realizzare **floating gate auto-allineate** nell'ambito del flusso di processo di una memoria flash.

21/10/09

Una opportuna crescita epitassiale di silicio, con possibilità di doping in-situ, è stata utilizzata per ottenere il profilo di drogaggio in As mostrato in figura1 (si consideri solo il grafico in dots neri).



Il wafer e' stato poi sottoposto ad un trattamento termico (700 C, 1h ca). Il profilo di As in silicio osservato e' riportato nella figura2 (dots neri) e confrontato con le previsioni teoriche di diffusione (curva nera) basate su un semplice modello "alla Fick". **Il modello "alla Fick" sottostima** decisamente la diffusione dell'arsenico. Provare a spiegare qualitativamente il fenomeno, basandosi sui seguenti "indizi" -La solubilità solida dell'As alla temperatura della crescita epitassiale e' inferiore a  $2 \times 10^{20} \text{ cm}^{-3}$ . -L'arsenico inattivo in silicio tende a formare cluster As/vacanza

21/10/09

Descrivere una tecnica di **"end point detection"** per attacchi in plasma. Discutere brevemente di come effetti di **"micro-loading"** possano avere impatto sull'efficacia della rivelazione dell' "end point" descritta.

19/7/10

Descrivere, con l'aiuto di disegni, il flusso di processo per realizzare un livello di **metallizzazione in rame**, usando, in luogo della litografia "tradizionale", tecniche di **"double patterning"**.

19/7/10

### Channeling effects

10/6/10

Descrivere brevemente, e con l'aiuto di disegni, il flusso di processo per realizzare **due livelli di metal ( e relative “vias”) in rame**.

25/09/15

Sia dato un **capacitore MOS** realizzato su un substrato di silicio di tipo p. Tracciare la caratteristica CV ideale del capacitore in questione, descrivendone brevemente l'andamento.

1Illustrare come la presenza di trappole all'interfaccia ossido/silicio può modificare la caratteristica CV.

25/09/15

Descrivere, con l'aiuto di disegni se necessario, almeno due tecniche di **“dimezzamento del pitch”**, per pattern regolari di linee e spazi. Si illustrino brevemente pro e contro per ciascuna tecnica illustrata.

03/7/2009

**TED**