

MICROELECTRONIC TECHONOGIES

EXAMS NOTES

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

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If you want to find the source code of this pdf or more material of other topics please visit my
github account
<https://github.com/matteobaldo>

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.

Dimostration

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

$$C_s = C_0 k \left(1 - \frac{V_s}{V_0}\right)^{k-1} \quad (1.6)$$

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

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

1.2 Deal-Grove model

Using the correct tables parameters we can derive the coefficents 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

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

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

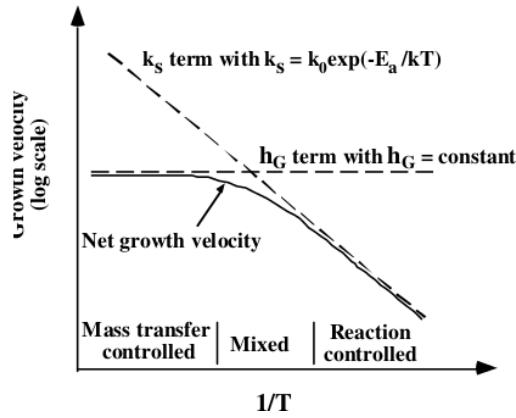
$$x_b = \frac{B}{2B/A} \quad (1.13)$$

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 thikness (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 Ahrrenius form so strongly dependent on temperature) and h_g the mass transport coefficient (independent from 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

Dimostration

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 transpor 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

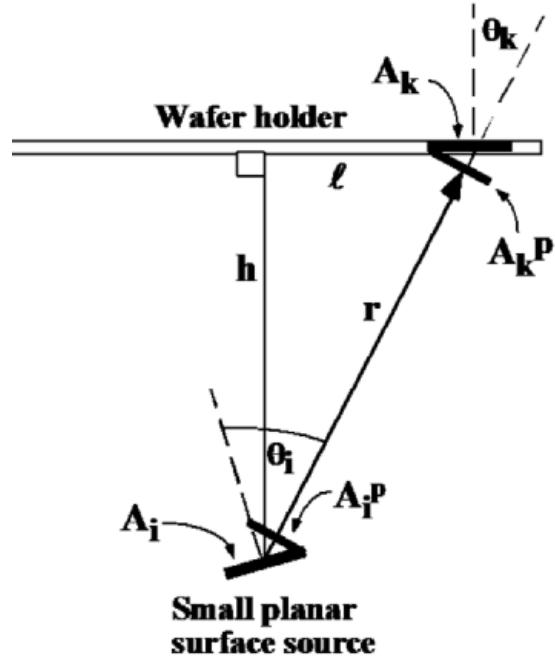
Form APCVD we can increase the value of h_g since we hope to stay in surface reaction controlled regime decreasing the value of the pressure since

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

where D_g is the diffusivity of the gas and σ_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 enanced

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 avabile sites. The number of byproducts removed as

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

with K_i sputtering efficency, F_i flux of ionic species and θ number of occupied states.

In stationary conditions $D=R$ so we can extract θ as

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

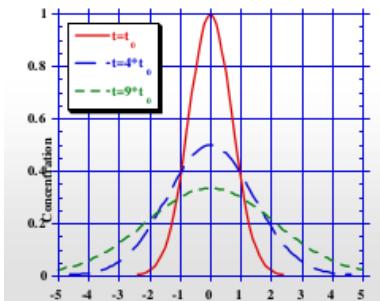
so substituting this into the R expression we get the etch rate as

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

with N density of the material to be etched.

1.6 Dopants diffusion analytic solutions

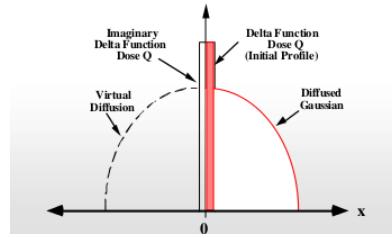
1.6.1 Delta function in doped region



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

1.6.2 Delta function near a surface

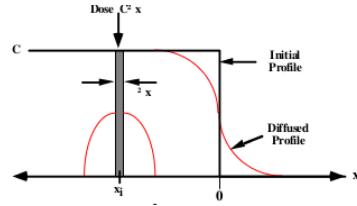
Is like a "mirrored" case of the delta function in a doped region



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

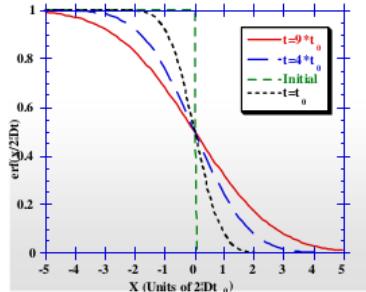
1.6.3 From an infinite source of dopant in silicon

Sum of gaussian problems or sum of delta functions



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

1.6.4 From an infinite source of dopant at surface



Symmetry considerations leads to

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

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 mechanism 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 have 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
- ΔR_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 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 than re-crystallized there are no interstitial due to ion impantation since in an amorph cristal 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 ΔR_p) there will always be a therma 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 threatment 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 Ahrrenius form so depends a lot on temperature.

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

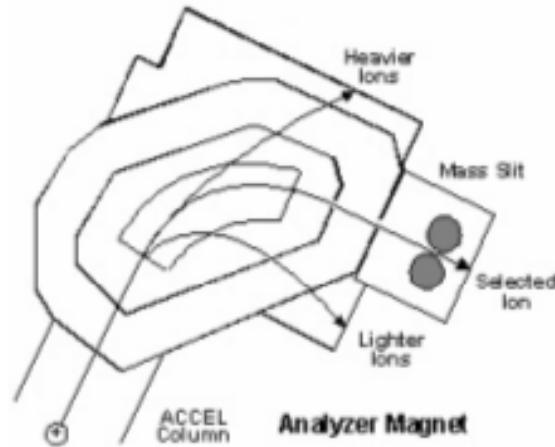
$$D_{eff} = D^* \left(\frac{C_I}{C_I^*} f_i + \frac{C_V}{C_V^*} f_v \right) \quad (1.41)$$

where we used

- $f_{i/v}$ interstitial/vacancy type mechanism fraction (tipically 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 enter 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

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

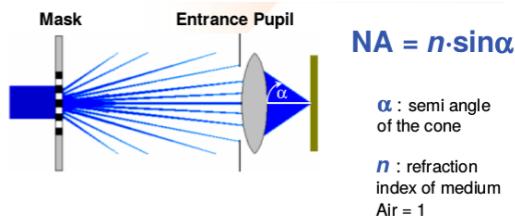
By extracting v^2 by one of the two and substitutin we get the following expression

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

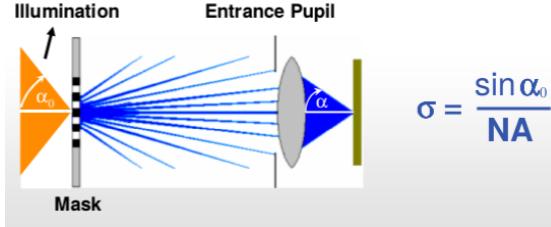
1.8 Lito

1.8.1 Resoution 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 θ 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 Ω is the volume of the atom of metal and σ_{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 droggaggio in As mostrato in figura1 (si consideri solo il grafico in dots neri).

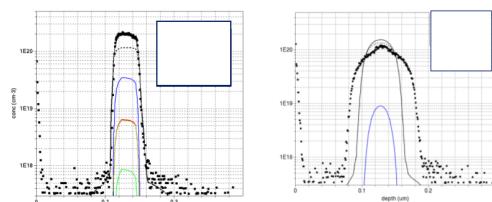


Figura 1

Figura 2

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** decimamente 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 $2\text{E}20 \text{ cm}^{-3}$. -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 condensatore in questione, descrivendone brevemente l'andamento.

Illustrare 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

Chapter 3

Hand-Notes

In this chapter there are some scheme I wrote by hand.
There are a lot of errors of grammar and spelling forgive me and pass on.

SILICON INGOT

- First transition from non crystalline material to diamond cubic lattice structure: Germanium now in crystal structures. Defects in non crystalline material acts as G-R centers degrading performances.
- Orientation or crystal changes properties in silicon at some where with half incomplete bonds
- Si: Diamond cubic lattice structure: two nested FCC units offset by $\frac{3}{4}$ in all directions, atom covalently bonded to 4 NN
- Bulk properties generally isotropic as no differences in dopant diffusion for (111) (100) crystal. (\approx)

- DEFECTS

↳ POINT DEFECTS

Anything other than Si on lattice is point defect (Frenkel pair F+V)

Native point defect: missing Si vacancy V extra atom I interstitial concentration increasing with T. Concentration tendency to be equal no thermodynamic reason

↳ LINE DEFECTS, DISLOCATIONS

Line: edge dislocation, loop dislocation. Extra plane terminates in a dislocation. Usually present at start catalyzed due to high T steps fabrication, or stress in thin film deposition (stress also due to RTA or RTO). Form during cooling process as agglomeration of V or I. Can move due to shear stress along $\{111\}$ planes (Burton vector).

↳ 2D DEFECTS

Stacking faults form along $\{111\}$ planes insertion of normal or extra plane extrinsic if extra plane intrinsic if no plane. Surface stacking faults when reaches the surface

↳ VOLUME DEFECTS

Aggregation or point defects (precipitates of dopants impurities) as due to too high doping concentrations

Production of Silicon: quartzite (sand, SiO₂) \sim MGS \sim EGGS

From ingot to wafer as: Ingot shaped till a uniform diameter, flats cuts (resistance in cutting wafer), saw into individual wafers, mechanical wiping (wafer wipers), round edges, chemical etching of surfaces + chemical mechanical etch of surface, CMP

- CZOCITRALSKI CRYSTAL GROWTH

↳ MAXIMUM PULL RATE $V_{\text{max}} = \frac{1}{LN} \sqrt{\frac{20 \epsilon k_m T^5}{3\Gamma}}$

L = latent heat of fusion
 N = density of Si
 Γ = Stephan-Zeemann constant
 ϵ = viscosity of silicon
 k_m = thermal conductivity at melting T_m

↳ DOPING INCORPORATED

All impurities segregate between liquid and solid phases. $K_0 = \frac{C_s}{C_L}$ equilibrium segregation coefficient. This means impurities have different solubility in solid and liquid phase. Generally $K < 1$ that means doping increase ~~decrease~~ at end of ingot

Additional heat of dV freezes means

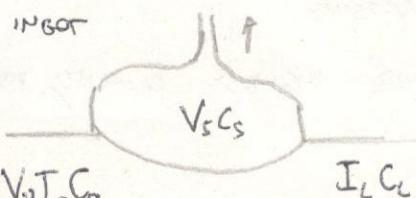
$$dI = -K_0 C_L dV = -K_0 \frac{I_L}{V_0 - V_s} dV$$

$$C_s = C_0 K (1-f)^{k-1}$$

$$\int_0^{V_s} \frac{dI_0}{I_0} = -K_0 \int_0^{V_s} \frac{dV}{V_0 - V_s}$$

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

$$K_0 C_s = -\frac{dI_L}{dV_s}$$



ING DIDN'T CONSIDER A LOT OF NON IDEALITIES (BUT IT'S A GOOD MODEL) USING INHOMOGENEITIES IN IMPURITY CONCENTRATION OR CONDUCTION CONSTANTS IN MOLT.

ELECTRICAL MEASUREMENT

THIS TECHNIQUE NOT GOOD SCANNING RESOLUTION WE ASSUME PARAMETERS UNIFORM.

→ HOT POINT PROBE

TWO PROBES ONE 25-100°C HOTTER HAVING OHMIC CONTACT WITH WAFER A VOLTMETER WILL MEASURE THE POTENTIAL WHOSE POLARITY DETERMINES THE TYPE OF MATERIAL P-n. HOT PROBES & THERMAL ENTHALPY ARE HIGHER THAN COLD PROBES SO WILL GO THROUGH GOLD ONE DUE TO T GRADIENT; @ MOVING TO COLD LEADS + FIXED SITE ON HOT ONE DETERMINING THE AV. SAME WITH P TYPES BUT WITH REVERSED POLARITY. VOLTMMETER IS USED TO AVOID CURRENT FLOW AND TO ACHIEVE PICKUP OF E IN IMPEDANCE CIRCUIT $I_n = q \mu n P_n \frac{dV}{dx}$ Pn THERMOELECTRIC POWER POSITION FOR h NEGATING FOR E. VOLTAGE UNKNOWN AS SETBACK VOLTAGE.

→ 4 POINT PROBES

4 POINT PROBES TO AVOID CURRENT SPREADING AND CONTACT RESISTANCE PROBLEMS, EXTERNAL PROBES INJECT CURRENT INTERNAL HIGH IMPEDANCE VOLTMETER TO NOT USE CURRENT FLUX INSIDE ROOM THIS $\rho = 2 \pi s \frac{V}{I}$ S DISTANCE BETWEEN PROBES (WAFER DIAMETER AND THICKNESS $\gg s$)

→ Hall Effect

STRONG MEASUREMENT METHODS SINCE WE CAN DETERMINE TYPE, RESISTIVITY AND CARRIER MOBILITY

- DEFECTS MEASUREMENT WITH A GATE PROCESS (STRESS TEST) AND THEN ELECTRONIC MICROSCOPY

→ EMISSION MICROSCOPY

RESOLUTION OF OPTICAL SYSTEM GIVEN BY FIRST ORDER TO $R_s = \frac{\lambda}{NA}$ NA NUMERICAL APERTURE THAT IN EMISSION MICROSCOPY 0.01 AND $\lambda = 2$.

→ SEM SCANNING EMISSION MICROSCOPY

BEAM OF 10-20kV FOCUSED WITH ELECTROSTATIC - MAGNETIC LENS, FROM RESTED IN XY PLANE BY SOME BLOCKS WILL BACKSCATTER FROM THE SAMPLE OTHER EXCITES MATERIAL THAT WILL PRODUCE X-RAYS. SEM COLLECT X-RAYS AND E AND DYSPLAMS THE INTENSITY OF THE SIGNAL ON A SCREEN. RESOLUTION $R_s \approx 5 \text{ nm}$ AND LARGEST DIAFORIS OF FOCUS

→ TEM TRANSMISSION ELECTRON MICROSCOPY

OPERATES BY PASSING ELECTRONS COMPACTLY THROUGH THE SAMPLE, HIGHER ENERGY 100-300kV AND SAMPLE HAVE TO BE THINNER THAN 1μm. IMAGE COMES FROM TRANSMITTED ELECTRONS AFTER THEY PASS THROUGH THE SAMPLE AND IMAGED ON A PHOTOGRAPHIC PLATE. RESOLUTION OF 0.2nm IN AXIAL OR STOKE DIMENSIONS

→ IMAGING FROM SLIDES

→ I AND V CAN BE CHANGED

→ IF A DISLOCATION IF WE CAN IDENTIFY A BOUND VECTOR

→ ORIGIN DEFECTS INCORPORATED IN MOLT BUT WITH ANNEALING PROCESS POSSIBLY TO LET THEM MOVE IN THE BULK AWAY FROM SURFACES IN THIS WAY PROCESSING

→ EPITAXY GROWTH OF SILICON AT GND TO HAVE HIGHEST QUALITY.

SILICON OXIDATION

- INTEGRITY BETWEEN Si AND SiO_2 VARY FROM MECHANICAL OR ELECTRICAL DEFECTS AND IT'S STATUS OVER TIME, ONE OR THE BEST INTEGRITY WE CAN OBTAIN
- BURN AT RT Si EXPOSED TO OXYGEN AMBIENT FORM A THIN NATIVE OXIDE OR $0.5\text{-}1\text{nm}$ UNTIL AFTER A FEW HOURS STOPS AT $1\text{-}2\text{nm}$
- THERMAL OXIDES IN THE RANGE OF $10\text{-}30\text{nm}$ ARE USED UNDER Si_3N_4 LAYERS AS SOURCE NGLIEF OR PAD OXIDES DURING LOCOS PROCESSES. THICKER OXIDES USED AS MASKS.
- INTEGRITY Si-SiO₂ BETTER IF SiO_2 GROWTH NOT DEPOSITED
- OXIDATION PROCESS OCCURS AT Si-SiO₂ INTERFACE, NEW INTERFACE CONSTANTLY FORMING AND MOVING DOWNWARDS INTO SILICON SUBSTRATE (DEMONTATION WITH 2 ISOTOPES OF OXYGEN AND THEN MASS ANALYSIS).
- PROCESS INVOLVES A VOLVING EXPANSION BECAUSE OF ROOM NEEDED FOR OXYGEN. GROWTH IS 46% IN SILICON AND 56% OUTWARD. THIS CAUSES "BOSS" PEAK IN LOCOS PROCESSES.
- NO CRYSTALLINE FORMS OF SiO_2 WHOSE LATTICE SITES MATCHES Si SUBSTRATE SO SiO_2 IS AMORPHOUS. BURN IF AMORPHOUS HAS A SHORT RANGE ONGE SiO_2 TENDENCY BASIC FORMS OF SiO_2 . TETRAEDRAL BOND FORMATION BY SHARING OXYGEN ATOMS (BRIDGING OXYGEN ATOMS NOT SHARED NON-BRIDGING OXYGEN ATOMS)
- SiO_2 GROWTH ON SILICON IS IN COMPRESSIVE STRESS AND IN ADDITION THERMAL EXPANSION COEFFICIENT ADD COMPRESSIVE STRESS TOO. THICKNESS OF CUBICATIC MUST BE ENOUGH TO SUSTAIN THIS STRESS. CURVATURE OF A WAFER AS A MEASUREMENT METHOD FOR OXIDE THICKNESS.
- FIRST ORDER THE INTERFACE IS PEAKET DIRECT TRANSITION IN OXIDE OF $10^9\text{-}10^{11}\text{cm}^{-2}$ COMPARED TO A Si SURFACE DENSITY OF 10^{15}cm^{-2} . MOST DEFECTS RELATED TO INCOMPATIBILITY OXIDIZED Si ATOMS OR Si ATOMS WITH DUNDLING BONDS
- DEFECTS IN SiO_2

↳ Q_f FIXED OXIDE CHARGE FOUND EXPERIMENTALLY A SHEET OR POSITIVE CHARGE IN OXIDE VARY CLOSE TO INTERFACE ($\approx 2\text{nm}$) AND IT'S LIKELY ASSOCIATED WITH THE TRANSITION FROM Si-SiO₂. DO NOT CHANGE DURING DEVICE OPERATION

↳ Q_{it} INTERFACE TRAPPED CHARGE DUE TO INCOMPATIBLY OXIDIZED Si ATOMS WITH DUNDLING BONDS NEAR THE SURFACE. THIS CHARGE CAN CHANGE CAPTURING e OR h DEPENDING ON THE DEVICE OPERATION.

↳ Process WITH HIGH Q_f HAS ALSO HIGH Q_{it} SO PROBABLY COMMON OXIDE, OXYGEN.

↳ Q_m MOBILE OXIDE CHARGE NOT SO SIGNANT TODAY. MOBILE IONS K⁺ OR Na⁺ ELIMINATED WITH CLEAN ROOMS

↳ Q_{et} OXIDE TRAPPED CHARGE LOCATED ANYWHERE IN THE OXIDE, LIKELY BROKEN Si-O BONDS IN TSUL OF THE OXIDE (BROKEN DUE TO PROCESS STEPS OR IONIZING RADIATION) NORMALLY DESTROYED BY HIGH TEMPERATURE ANNEAL. # This May CAPTURE e OR h DURING DEVICE OPERATION RESULTING IN TRAPPED CHARGE. (OR OR IMPORTANCE NOW DUE TO HIGH ELECTRIC FIELDS PRESENT IN DEVICES TODAY (NOT QUESTIONS))

All THESE ANNEALED AT THE END OF FABRICATION IN Ar OR N₂ AMBIENT AND THEN ANNEAL IN H₂.

- To OXIDISE BASICALLY A FURNACE UP TO 1000-1200°C AND GAS DISTRIBUTION TO CONVECT H₂O or O₂ MUST FURNACES TODAY VENUE TO SPARE SPACE. WAFERS NORMALLY LOADED INTO FURNACES ON "BOATS" OF 10-50 WAFERS CARRIED BY AUTOMATIC LOADING SYSTEMS THAT DO NOT TOUCHES THE FURNACE WALLS. TEMPERATURE CONTROL WITH THERMO COUPLES IN ORDER TO MANTAIN UNIFORM T AROUND WAFERS. TIME CONTROL OF SECONDS AND T OF $\pm 0.5^\circ\text{C}$ AND NEEDED TO PRODUCING CONSISTENT OXIDE THICKNESS. IDEALLY WE WANT VERY SHOT HIGH T SHOTS.
- RTO RAPID THERMAL OXIDATION USES CAMB HEATED CHAMBER THAT CAN HEAT UP TO 1000°C /s HOLD THE WAFER AND THAN COOL IT DOWN TO RT AGAIN IN 1000 SECONDS. USUALLY THIS SYSTEMS ARE SINGLE WAFER. BIG PROBLEM IS KNOWING EXACTLY THE WAFER TEMPERATURE (NOT POSSIBLE THE USE OF THERMO COUPLES HAVING DUE TO RST T CHANGE)
- SOME OXIDATION HAS "FAST RAMP" THAT IS A MIDDLE POINT ($10^\circ\text{C}/\text{s}$) BETWEEN CLASSIC AND RTO

DIGITAL GROWTH MODEL

LINEAR PARABOLIC MODEL USED IN PLANAR OXIDATION. THIS MODEL CANNOT EXPLAIN SHARPED OXIDATIONS OR OXIDATION IN MIXED SITES OR VARIOUS THIN OXIDE GROWTH. ALSO UNEXPLAINED HOW OXIDATION AFFECTS DOPANTS DIFFUSION.

ASSUME OXIDE ALREADY PRESENT x_0 AND ONLY PLANE SURFACE. 3 MAIN FLUXES F_1 TRANSPORT OF OXIDANT IN GAS PHASE TO OXIDE SURFACE $F_1 = h_g (C^* - C_o)$ h_g MASS TRANSFER COEFFICIENT. DEFINING C_o AS THE CONCENTRATION OF GAS JUST OUTSIDE THE SURFACE WE CAN WRITE THE HENRY'S LAW $C_o = h_p P_g$ BUT WE CAN'T KNOW P_g (PARTIAL PRESSURE OF OXIDANT AT SOLID INTERFACE SO IT'S CONVENIENT TO WRITE C_o IN FUNCTION OF P_g THE BOLLE GAS PRESSURE AS $C^* = h_p P_g$ BEING C^* THE OXIDANT CONCENTRATION THAT WILL BE IN EQUILIBRIUM WITH P_g WE CAN NOW ASSUME $C^* \approx C_o$ $P_g \approx P_s$ (THIS NOT LIMITING TERM SO WE CAN) FROM IDEAL GAS LAW $C_o = P_g / R T$ AND $C_s = P_s / R T$ USING THIS IN THE EXPRESSION OF THE FLUX WE OBTAIN $F_1 = h (C^* - C_o)$ WITH $h = h_g / R T$.

FLUX 2 IS THE DIFFUSION THROUGHOUT OXIDANT TO THE INTERFACE WITH SILICON THAT USING KELCI'S LAW $F_2 = -D \frac{dC}{dx} = D \left(\frac{C^* - C_i}{x_0} \right)$ THIS ASSUMING PROCESS AT STEADY STATE. FLUX 3 REACTION AT Si-SiO₂ INTERFACE $F_3 = k C_i$ WE FIND A LOT OF PARAMETERS. IN STEADY STATE CONDITION $F_1 = F_2 = F_3$ SO WE OBTAIN \downarrow . WE HAVE USED THE ASSUMPTION OF $h \gg 1$ MUCH LARGER THAN ALL OTHER PARAMETERS. WE CAN OBSERVE TWO REGIMES

- $V_s x_0 / D \ll 1$ $C_i \approx C^*$ OXIDANT SUPPLIED FASTER THAN IT REACTS. THIS IS REACTION RATE CONTROLLED
- $V_s x_0 / D \gg 1$, $C_i \approx 0$ OXYGEN REACTING FASTER THAN N_a

IF REGIMES, DIFFUSION CONTROLS REGIMES. WE CAN COMBINE FLUX AND STEADY STATE TO OBTAIN $\frac{dx_0}{dt} = \frac{F_1}{N_A} = \frac{k_s C^*}{N_A} \left(1 + \frac{x_0}{D} \right)$ NO NUMBER OF OXIDANT MOLECULES INCORPORATED PER UNIT VOLUME OF OXIDE GROWTH. INTEGRATING THIS WE OBTAIN $\frac{x_0^2 - x_i^2}{B} + \frac{x_0 - x_i}{B/A} = t$ WHERE $B = 2DC^*/N_A$, $B/A = C^* V_s / N_A$. COEFFICIENTS B AND B/A EXPERIMENTALLY OBTAINED AND HAVE APPROXIMATELY THE SAME SIGN. REACTION WITH SURFACE B THE TRANSPORT. WE CAN GENERATE WRITING $\frac{x_0^2}{B} + \frac{x_0 - x_i}{B/A} = t$ WHERE T IS THE TIME TO CREATE THE ALREADY PRESENT OXIDE. ACTIVATION ENERGY OF $B/A \approx 2eV$ ENERGY TO BREAK Si-Si BONDS.

\hookrightarrow CRYSTAL ORIENTATION MAY AFFECT THE PARAMETER B SINCE NONE Si ATOMS HAVE PRESENT HIGHER THE SPACE FOR REACTION WILL BE IN RACE ($B_{[AlN]} = B_{[LiClO_4]} = 1.68 \text{ } B_{[NaCl]}$) (WE HAVE MORE SILICON BONDS). CRYSTAL ORIENTATION DO NOT AFFECT B THAT TAKES INTO ACCOUNT THE DIFFUSION THROUGHOUT THE EXISTING OXIDE. THIS CAN CREATE PROBLEM IN 3D STRUCTURE SINCE MORE SURFACES WILL BE EXPOSED

\hookrightarrow OVER FIRST 20nm OF OXIDE THIS MODEL DOES NOT WORK WE HAVE TO INCLUDE ANOTHER TERM IN THE MODEL $\frac{dx_0}{dt} = \frac{B}{2x_0 + A} + C \exp(-\frac{x_0}{L})$ $L = 7nm$ THIS MODEL MATCHES THE EFFECTIVE GROWTH RATE

\hookrightarrow SUBSTRATE DOPING PROFILE WILL CHANGE DURING OXIDATION DEPENDING ON IMPURITIES DIFFUSIVITY AND SEGREGATION COEFFICIENTS (ALSO PLUGGED BURNED)

\hookrightarrow OXIDATION PROCESS CONSUMES VACANCIES AND INJECT INTERSTITIALS (VOLUME EXPANSION)

MEASUREMENT METHOD

PHYSICAL MEASUREMENTS.

ETCH THE SiO₂ (HF) AND WITH STYLUS PROFILER OXIDE THICKNESS OR ALSO SIM OR TEM MICROSCOPY BUT THIS PROVIDES ONLY THE THICKNESS OF THE SiO₂ AND NOT OTHER PARAMETERS

OPTICAL MEASUREMENTS

- MONOCROMATIC WAVELENGTH INTO SILICON AT A CERTAIN ANGLES SOME LIGHT WILL BE ABSORBED SOME TRANSMITTED AND REFLECTED BY THE INNER SURFACE SO THAT THE 2 LIGHT REFLECTED IN DIFFERENT PLACES (OPTICAL PATH) WILL

CREATE DISTORTING OR CONDUCTIVE INTEGRITY. FROM THIS ONE CAN DEDUCE THE OXIDE THICKNESS. THIS WORKS FOR THICKNESS OF A FEW FEET OR MM

- Ellipsometry same as before but with polarized light and take each thickness or polarization we can deduce to this works down to nm
- Color change (colours appear over 30nm) estimate within 10-20nm can be made with this change but oxides thinner than 5nm has no colour

↳ EMISSION MEASUREMENTS: MOS CAPACITOR (SEE BUGGON DIENES COURSE)

INTEGRATION FROM THE SLIDES

- Nitridation mainly used to form a barrier to the diffusion of B from Si to SiO₂
- ADVANCED OXIDATION TECHNIQUES:

RADICAL OXIDATION: H₂ AND O₂ INTO PTO CHAMBER WATER AND RADICALS LIKE O AND OH ARE FORMED AND THIS WITH LOW PRESSURES GUARANTEES HIGH QUALITY OXIDES

PLASMA OXIDATION: LOW THERMAL BUDGET BUT ULTRA THIN AND QUALITY OXIDES

THIN FILM DEPOSITION

- MAIN ISSUES WHEN TALKING ABOUT THIN FILM AND THIS QUALITY OF DEPOSITED FILM (IN TERMS OF COMPOSITION, CONTAMINATION LEVELS, DEFECT DENSITY AND MECHANICAL AND ELECTRICAL PROPERTIES) STRESS IN THE FILMS (THIS SHOULD BE MINIMUM) MECHANICAL STABILITY DURING SUBSEQUENT PROCESSSES AND GOOD ADHESION TO UNDERLYING FILMS.
- WE WANT ALSO UNIFORM THICKNESS ACROSS WAFER FROM WAFER TO WAFER AND AS FILM CROSS NON-PUNCHED TOPOLOGY.
- STEP COVERAGE: COVERAGE ON THE SIDE OF A STEP OR EVEN QUANTITABLY AS MINIMUM THICKNESS ON SIDE OF A STEP DIVIDED BY THICKNESS ON TOP HORIZONTAL SURFACE IF THIS RATIO = 1 CONFORMAL COVERAGE
- GAP FILLING: ABILITY TO FILL VIAS OR CONTACTS WITH HIGH ASPECT RATIO ($= \frac{h}{\ell}$). INCOMPLETE FILLING OF A GAP CAN CAUSE HIGH RESISTANCE PATHS (IF METAL LINES) STRESSES & CAN TRAP CHEMICALS LEADING TO RELIABILITY ISSUES
- TWO MAIN CATEGORIES: CHEMICAL AND PHYSICAL CVD HISTORICALLY FOR Si AND DIELECTRIC AND GOOD STEP COVERAGE WHILE PVD FOR METAL LINES.
- THIRD CATEGORY COATING A WAFER WITH A LIQUID FILM THAT FORMS A SOLID WHEN HEATED. THIS SPIN ON GLASSES
- FOURTH CATEGORY BUBBLING DEPOSITION MAINLY USED TO DEPOSIT Cu LINES.

- CVD

- GAS INTRODUCED INTO DEPOSITION CHAMBER WHERE THEY REACT AND FORM THE DESIRED FILM ON THE WAFER. GAS STREAM REACTIONS CAN CREATE PARTICLES WHICH CAN DROP DOWN onto THE SURFACE AND CREATE DEFECTS
- SIMPLEST ATMOSPHERIC PRESSURE CVD OR APCVD. WALLS OF THE CHAMBER NOT HEATED TO REDUCE DEPOSITION ON THEM BUT WAFER HEATED WITH RF COATED GRAPHITE SUSPENSIONS HEATED BY RF INDUCTION
- LOW PRESSURE CVD (LPCVD) HOT WALL REACTION WAFER PLACED IN A CHAMBER SIMILAR TO OXIDATION SYSTEMS

OTHER TYPES USE SOG GASEOUS REACTANTS AND PLASMA. VERY LOW THERMAL BUDGET.

- ATMOSPHERIC PRESSURE CHEMICAL VAPOR DEPOSITION (APCVD)

- + STEP INVOLVED BASICALLY ARE 1) TRANSPORT OF REACTANTS THROUGH CONVECTION TO DEPOSITION REGION 2) TRANSPORT BY DIFFUSION FROM GAS STREAM TO SURFACE 3) ABSORPTION OF REACTANTS ON WAFER SURFACE 4) SURFACE PROCESS 5) DESORPTION OF BYPRODUCTS FROM THE SURFACE 6) TRANSPORT OF BYPRODUCTS AWAY FROM THE SURFACE BY CONVECTION.
- + A NON MENTIONED PHASE IS THE AGRGATION THAT IS THE MOVE AWAY OF REACTING SPECIES BECAUSE THEY NEVER (COLLIGATE WITH STICKING COEFFICIENT). ALSO SURFACE MIGRATION DON'T MENTIONED.

+ IN OUR ANALYSIS WE WILL NOT CONSIDER GAS-PHASE REACTIONS.

- + THE MOST IMPORTANT STEPS ARE 2) THAT IS MASS TRANSFER OF REACTANTS THROUGH THE BOUNDARY LAYER AND STEPS 3-5 THAT WE WILL USE AS SURFACE REACTIONS.

BOUNDARY LAYER

Si + Flux 1 THAT MEANS SAYS THE FLOW OF REACTANTS SPECIES FROM BULK OF THE GAS TO THE SURFACE (THROUGH THE BOUNDARY LAYER) IS $F_1 = h_g (C_G - C_S)$ C_G CONCENTRATION IN GAS FLOW C_S CONCENTRATION AT THE SURFACE OR REACTANTS SPECIES h_g MASS TRANSPORT COEFFICIENT + Flux 2 FLOW OF REACTANTS CONSUMED AT THE SURFACE BY REACTION $F_2 = k C_S$ k CHEMICAL SURFACE REACTION RATE.

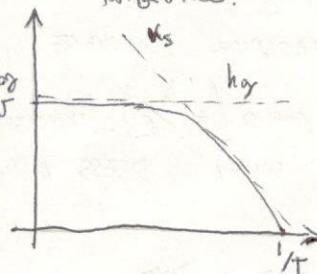
$$+ ASSUMING STATIONARY STATE CONDITIONS F_1 = F_2 = F \Rightarrow C_S = C_G \left(1 + \frac{V_S}{h_g}\right)^{-1} \text{ AND SO}$$

GROWTH RATE $\dot{V} = \frac{F}{N} = \frac{v_{\text{sho}}}{v_{\text{sho}}} \cdot \frac{C_0}{N}$ WHERE N NUMBER OF ATOMS INCORPORATED PER S
 UNIT VOLUME IN THE FILM. DIVIDING $\dot{V} = \frac{C_0}{C_T}$ WE CAN WRITE $\dot{V} = \frac{v_{\text{sho}}}{v_{\text{sho}}} \cdot \frac{C_T}{N} Y$ WHERE
 OR CONCENTRATION OF ALL MOLECULES IN GAS.

f If $v_{\text{sho}} \propto T$ $\dot{V} \propto \frac{C_T}{N} Y$ SURFACE REACTION CONTROLLED CASE } TWO REGIMES

f If $v_{\text{sho}} \propto k_B T$ $\dot{V} \propto \frac{C_T}{N} k_B Y$ MASS TRANSFER CONTROLLED REGIMES

f GROWTH IN BOTH REGIMES IS LINEAR BECAUSE REACTION ALWAYS OCCURS AT GROWTH INTERFACE.

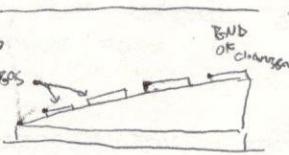


+ THE TWO REGIMES DOMINATE IN DIFFERENT TEMPERATURE RANGES DUE TO THEIR DEPENDENCE WITH T , $v_{\text{sho}} \propto \exp(1/T)$ $k_B \approx \text{constant}$ (v_{sho} HAS ARRHENIUS FORM)

f IN MASS TRANSFER REGIME THE FLOW OF GAS AND BOUNDARY LAYER CONTROL (SO THE GEOMETRY OF THE REACTION) AND FLOW RESTRICTIONS ON THE ABSORPTION OF THE WATER AND THERMAL POSITION

f IN SURFACE REACTION REGIME T IS CRUCIAL BUT THE GEOMETRY OF THE CHAMBER NOT SO WATERS CAN BE SWIRLED OUT ON ANOTHER.

f USING S_s AS THE BOUNDARY LAYER THICKNESS THIS TERM IS NOT CONSTANT THROUGHOUT THE CHAMBER BUT INCREASES AND SINCE $k_B = D_g/S_s$ WHERE D_g IS THE GAS DIFFUSION COEFFICIENT THE WATER HAS TO BE FLUID THROUGH THE FLOWFIELDS TO KEEP k_B CONSTANT FURTHERMORE THE CONCENTRATION OF REACTANTS SPECIES ALSO DECREASE ALONG THE CHAMBER. FOR THIS TWO REASON WATER HAVE TO BE PLACED ON A TILTED SURFACE.

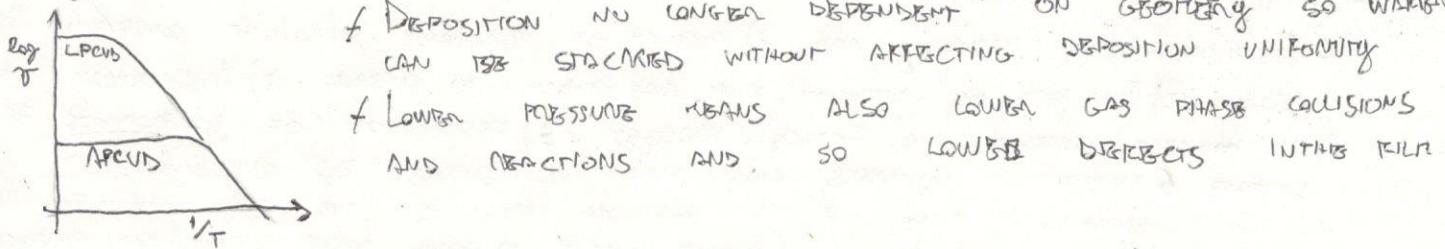


f HIGH TEMPERATURE PROCESS MEANS HIGH QUALITY FILMS THAT ARE BAD RIMS WANT LOW T (AND SO REACTION REGIME) GIVES US GOOD RIMS

- LOW PRESSURE CHEMICAL VAPOR DEPOSITION (LPCVD)

f WE WANT TO AVOID GEOMETRY PROBLEMS OR APCVD WEAVING GOOD QUALITY RIMS AND A NICE GROWTH RATE. (IN THIS WAY WE CAN STACK WATERS IN BOATS)

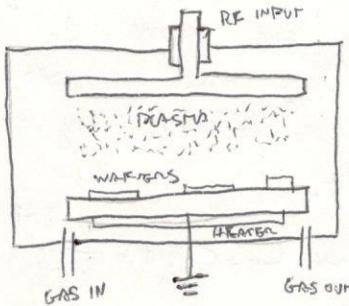
f $k_B = \frac{D_g}{S_s}$ BUT $D_g \propto 1/P$ SO DECREASING THE PRESSURE WE CAN ACTIVE HIGHER k_B AND SO INCREASE THE REACTION CONTROLLED REGIMES



- PLASMA ENHANCED CHEMICAL VAPOUR DEPOSITION (PECVD)

f SOMETIMES THERE ARE RESTRICTIONS TO TEMPERATURE PASSAGE (IF AT PRESENT NO MORE THAN 450°C CAN BE ACHIEVED)

f PECVD IN ADDITION TO A THERMAL SOURCE TO PROVIDE THE ENERGY NEEDED FOR CHEMICAL REACTIONS TO OCCUR A PLASMA SOURCE IS USED (PLASMA ARE HIGHLY IONIZED GAS)



f BY SUPPLYING ADDITIONAL ENERGY FROM THE PLASMA TO THE REACTANT GAS THE REACTION NEEDED FOR DEPOSITION CAN OCCUR EVEN AT RT

f PLASMA INTERACTION CAUSES REACTANT GASES TO DISOCIATE AND IONIZE IN A VARIETY OF SPECIES SUCH AS RADICALS THAT ARE HIGHLY REACTIVE AND WITH OTHER SPECIES TAKING FROM THE FILM.

f FREE RADICALS REACT WITH NEUTRAL SPECIES THAT HAVE INCOMPATIBLE BONDING

+ In addition to ion and ion beam bombardment from the plasma can occur.

+ PECVD can result in good coverage and filling gaps also at low T.

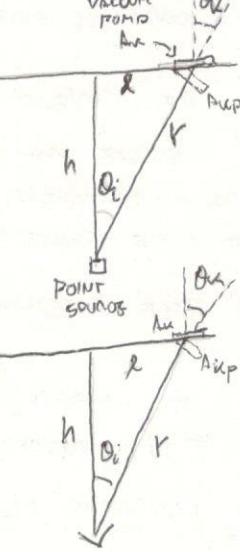
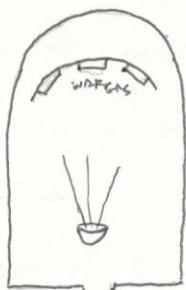
- HIGH DENSITY PLASMA CHEMICAL VAPOR DEPOSITION (HDPCVD)

- + Very high density plasma and separate DC bias applied to the substrate
- + Combines PECVD techniques with bias sputtering to obtain very good narrow gap filling
- + Mostly used for SiO_2 deposition

- PVD

- More versatile than CVD allowing almost any material deposition
- Very low gas pressure in this system so very few gas phase collisions
- Little re-arrangement of atoms usually occurs on surface so shadowing effects and gap filling problems are not

- EVAPORATION



f Source material is heated in a vacuum chamber and evaporated atoms condense on the chamber and on wafers. Heater resistance type (but this leads to contamination) or e-beam heating that can achieve heating without contamination effects (side effect of e-beam is production of X-rays that can damage oxide)

f Low pressures (10^{-5} torr) leads to few gas phase collisions and atoms travel in straight lines from surface to wafers.

f We can model our evaporation in two ways as a point source or a small planar source on a small surface

~ Point source
The flux F_p leaving the source A_s is $F_p = \frac{R_{\text{evap}}}{\pi r^2}$ where R_{evap} is the evaporation rate and $r = 2h$ for a source emitting only upwards or for a source emitting in all directions.
This flux that strike A_w depends on the normal component of the flux of a source emitting in all directions. We must multiply for $\cos \theta_i$ being the angle between the source normal and the direction of the source. Dividing this flux for the density of the material depositing we get the velocity of deposition $V = \frac{F_{\text{evap}}}{A_w \cos \theta_i}$.

~ Small surface source
The emitted flux is written for normal direction. Emission from small planar surface known as ideal cosine emission. Extra term $\cos \theta_i$ comes into play so deposition rate becomes $V = \frac{R_{\text{evap}}}{A_w} \cos \theta_i$. (ideal cosine emission also describes reflection or materials)

f For small planar surfaces more anisotropic emissions can occurs and can be modeled as $\cos^n \theta_i$ with $n > 1$. This can be due to crucible geometry or ratio melt depth vs melt surface area.

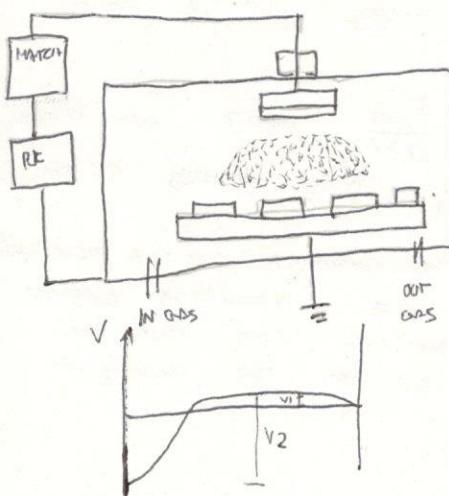
L The term $R_{\text{evap}} \propto (\frac{m}{T})^{1/2} \cdot P_e$ As angle of source m - gram-molecular mass Pe vapour pressure dramatically depending on temperature

/ Big drawback not all material is easy to deposit and no in-situ monitoring and poor step covering

/ Sticking coefficient near to 1 and poor narrow angles of annular distribution leads to low step coverage and gap filling properties.

- SPUTTER DEPOSITION
- DC SPUTTER DEPOSITION
 - INLET GAS (Ar) FLOWS INTO SPUTTERING CHAMBER AT LOW PRESSURES VOLTAGES APPLIED BETWEEN TWO ELECTRODES AND PLASMA IS COAGULATED
 - PLASMA CONTAIN NEUTRAL ATOMS AND A SUBSTANTIAL POSITION IONS AND FREE ELECTRONS.
 - TOP ELECTRODE WITH NEGATIVE VOLTAGE IS APPLIED IS THE SOURCE MATERIAL TO BE DEPOSITED (CHARGE ON TARGET). BOTTOM ELECTRODE METAL PLATE IS INTEGRAL WAFERS SURFACES ARE GROUNDED AND CALLED A NODE.
 - POSITION IONS ACCELERATED THROUGHOUT THE TARGET STRIKE AND DISLOCATE OR SPUTTER THE TARGET ATOMS THAT ARE FREE TO MOVE THROUGH THE PLASMA UNTIL THEY REACH THE WAFFER.
- TARGET MUST BE CONDUCTIVE TO DEPOSIT INSULATORS OTHER TECHNIQUES MUST BE USED.
- AN ACCELERATED SPUTTER ATOMS THAT MIGRATES THROUGH THE CHAMBER WHILE THEY CAN, STAY ABSORBED, MIGRATE TO ANOTHER SURFACE OR BE REFLECTED. AN ACCELERATED ION CAN BE REFLECTED BACKWARDS DURING SPUTTERING AND INCORPORATED DURING THE FILM.
- SECONDARY ELECTRONS CAN BE EMITTED DURING SPUTTERING BY THE TARGET THAT CAN IONIZE IMPURITIES THAT TRAVEL TO WAFERS TO IONIZE AND SUSTAIN THE PLASMA
- SPUTTERING YIELD RANGE BETWEEN O₁ AND O₃ AND DEPENDS ON MATERIAL, ION ENERGY AND ION ANGULAR ANGLES.
- SPUTTERING TARGETS USUALLY WIRE SO RIBBON PROVIDED A LARGE ANGULAR DISTRIBUTION THAT LEADS TO GOOD STEP COVERAGE.

- RF SPUTTER DEPOSITION



- To SPUTTER NON CONDUCTIVE MATERIAL WE NEED A RF VOLTAGE INSTEAD OF A DC ONE. FREQUENCY USED IS 13.5 MHz TARGET DESIGN TO BE HIGH ENOUGH SO THAT A CONTINUOUS PLASMA DISCHARGING IS MAINTAINED
- ELECTRONICS ARE NOT THE SAME BUT THE RF CURRENT MUST BE CONTINUOUS SO $\frac{V_1}{V_2} = \left(\frac{A_2}{A_1}\right)^M$ WHERE M IS EXPONENTIALLY 1-2. FINE TUNING THE RATIO BETWEEN THE 2 ANGLES WE CAN TUNE THE AMOUNT OF SCATTERING ON BOTH PLATES
- SHIELDS ARE REQUIRED AND GUARANTEE A SAFE BIASING STABILITY STATE CONDITION AT BIASING
- REACTIVE SPUTTER DEPOSITION : NEGATIVE GAS IS ADDED IN PLASMA AND HELD AND CONCERN DEPOSITION (Ti SPUTTER N GAS TiN DEPOSITED)
- BIAS SPUTTERING: WAFER SIDE BIASSED IN ORDER TO GET A SURFACE CLEANING OR WAFERS ON DEPOSITION AND SPUTTERING AT SAME TIME
- MAGNETRON SPUTTERING MAGNET ADDS TO IMPROVE IONIZATION OF THE PLASMA COLLIMATED SPUTTERING INCORPORATING GAP KILLING PERFORMANCE BY ALLOWING NARROW ANGULAR ANGLES DISTRIBUTION
- IONIZED SPUTTERING: IN SOME CASE THE MATERIAL TO BE DEPOSITED IS IONIZED AN RF COIL AROUND THE PLASMA INDUCES COLLISION TO CATCHES IONS. THIS PROVIDE NARROW ANGULAR ANGLES DISTRIBUTION.

DOPANT DIFFUSION

- PRE-DEPOSITION: DOPING OFTEN PROCEEDS BY AN INITIAL PRE-^{DEP.} STEP TO INTRODUCE THE REQUIRED DOSE OR DOPANT IN THE SUBSTRATE
- DOPING-IN: A SUBSEQUENT (TOP) DOPING-IN ANNEAL THEN DISTRIBUTES THE DOPANTS TO DESIRED FRACTIONALS.
- SOLID SOLUBILITY: MAXIMUM CONCENTRATION OF A DOPANT THAT CAN BE DISSOLVED IN Si UNDER EQUILIBRIUM CONDITIONS WITHOUT FORMING A SEPARATE PHASE (OFTEN THIS COMPLEX, TYPICALLY PRECIPITATES)
- SIMS MEASUREMENT TECHNIQUES MEASURING ALSO PRECIPITATES AND CAN'T DISTINGUISH BETWEEN ACTIVE dopants (THE IMPORTANT ONE) AND UNACTIVE dopants.
- ELECTRICAL SOLUBILITY MAY BE DIFFERENT FROM SOLID SOLUBILITY (ABOUT 10% INACTIVE dopants AND FORMED THAT DO NOT CONTRIBUTE FREE CARRIERS)
- ACTIVE CAN BE IMPLANTED IN "E-ACTIVE" POSITIONS UNTIL HIS SOLID SOLUBILITY (\gg E. SOLUB.) BUT THERE IS A HUGE FORCE THAT TENDS TO UNACTIVATE AS DOPING SUBSEQUENT THERMAL ANNEALING (As ATOMS SURROUND VACANCY AND REMAIN INACTIVE).

- DIFFUSION FROM MACROSCOPIC VIEW POINT

f FICK'S FIRST LAW: FLOW OF MATERIAL PROPORTIONAL TO CONCENTRATION GRADIENT
 $F = -D \frac{dC}{dx}$ IN A DIAMOND LATTICE AS Si D HAS THE SAME VALUE IN ALL DIRECTIONS

f FICK'S SECOND LAW: CONSERVATION LAW FOR MATTER, INCREASE OF CONCENTRATION IN A VOLUME WITH TIME IS THE DIFFERENCE OF FLUX INSIDE AND OUTSIDE THIS VOLUME $\frac{\partial C}{\partial t} = \frac{\partial F}{\partial x} = \frac{F_{in} - F_{out}}{\Delta x}$

Substituting the first law into the second we obtain $\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \left(D \frac{\partial C}{\partial x} \right)$ THAT SUPPOSING D CONSTANT (AT $T = \bar{T}$) GIVES $\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2}$ THIS IS CALLED FICK'S SECOND LAW OF DIFFUSION. SIMPLER SOLUTION OF THIS IS IN STEADY STATE CONDITION SO $D \frac{\partial^2 C}{\partial x^2} = 0$ THAT GIVES $C = a + xb$.

- ANALYTIC SOLUTIONS OF DIFFUSION EQUATION

\hookrightarrow GAUSSIAN SOLUTION IN INFINITE MEDIUM

SPRING IN A LIGHTLY DOPED REGION (LOW T EPITAXIAL GROWTH OF SINGLE CRYSTAL Si DOPED ON A Si WAFER AND INTRODUCES DOPANT GAS INTO CHAMBER FOR SHORT AMOUNT OF TIME). BOUNDARY CONDITIONS ARE $C \rightarrow 0$ AS $t \rightarrow \infty$ FOR $x > 0$ AND $C \rightarrow \infty$ AS $t \rightarrow 0$ FOR $x < 0$ AND THE DOSE $Q = \int_{-\infty}^{+\infty} C(x,t) dx$.

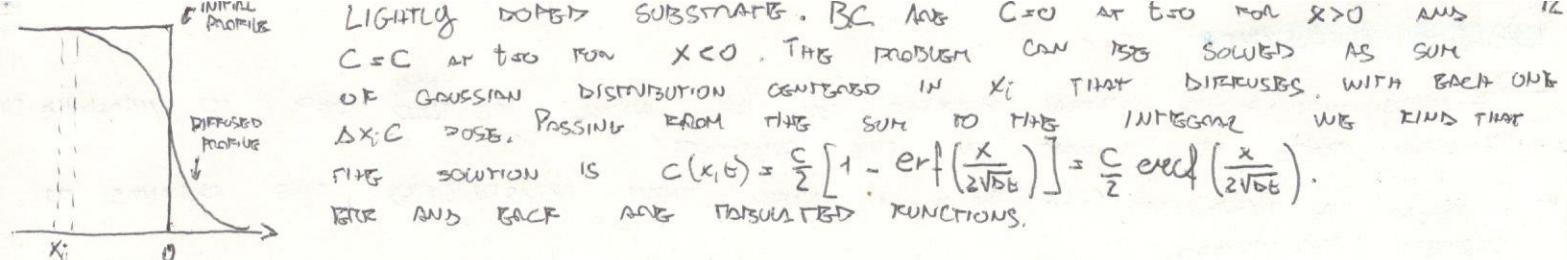
SOLUTION TO FICK'S LAW FOR THIS B.C. IS A GAUSSIAN FUNCTION PROFILE, THAT EVOLVES WITH TIME AND RETAINS THE SAME GAUSSIAN FORM $C(x,t) = \frac{Q}{2\sqrt{\pi D t}} \exp\left(-\frac{x^2}{4Dt}\right)$ RULES OF THUMB TO KNOW HOW MUCH THE DOPANTS IS DISPERSED IS LOOKING AT THE DIFFUSION LENGTH $\sqrt{4Dt}$. ION IMPLANTS MORNING AND IN FIRST ORDER GAUSSIANS.

\hookrightarrow GAUSSIAN NEAR A SURFACE

DOPANTS DOSE NEAR A SURFACE SPRING (DOSED BY LOW ENERGY ION IMPLANTATION) ASSUMPTION: NO DOPANT LOSS DOPANT DOSE CONSTANT, EVAPORATION OR SEGREGATION EFFECT EQUAL 0.
 WE CAN NEGLECT PRECONDITION PROBLEMS BY CONSIDERING A DOSE $2Q$ AND THE SURFACE A MIRROR LAYER SO THAT WE OBTAIN
 $C(x,t) = \frac{Q}{\sqrt{\pi D t}} \exp\left(-\frac{x^2}{4Dt}\right)$ EQUAL TO SOLUTION OF BOUNDARY WITHOUT $\frac{1}{2}$

\hookrightarrow GAUSSIAN FUNCTION SOLUTION IN INFINITE MEDIUM

DIFFUSION FROM AN INFINITE SOURCE OF DOPANT (HEAVILY DOPED EPITAXIAL LAYER ON



\hookrightarrow Exponential Function Solution Near a Surface

CONSTANT SURFACE CONCENTRATION ALL TIMES (DIFFUSION FROM GAS AMBIENT WITH CONCENTRATION ALONGS SOURCE SOLUBILITY) WE ARE NEAR A SURFACE. THE MIDPOINT x_i MUST REMAIN STATIONARY AND THE SOLUTION ON $x>0$ IS STILL VALID. THE SURFACE CONCENTRATION IS HELD CONSTANT AND THIS CONSIDERATIONS LEADS TO $C(x,t) = C_s \left[\text{erfc}\left(\frac{x}{2\sqrt{Dt}}\right) \right]$. THE TOTAL DOSE IMPLANTED WILL BE $Q = \frac{2C_s}{\sqrt{\pi}} \sqrt{Dt}$

- PARALLEL FUNCTION SOLUTION APPLIES WHEN THE TARGET IS AN INFINITE SOURCE OF DOPANTS WHICH IMPLIES THAT AN INCREASING DOSE OF DOPANTS IS IMPLANTED IN THE SUBSTRATE DURING DIFFUSION PROCESS TO MAINTAIN CONSTANT SURFACE CONCENTRATION.

GAUSSIAN SOLUTION APPLIES WHEN THE DOSE IS FIXED AND SO THE SURFACE CONCENTRATION MUST DEPEND AS DOPANT DISSOLVED IN THE BULK

- DIFFUSION COEFFICIENT D HAS AN Arrhenius FORM SO A STRONG DEPENDENCE WITH TEMPERATURE. SINCE THERE ARE A LOT OF PROCESSES IN A SINGLE PRODUCTION LINE THE EFFECTIVE PRODUCT D_t IS GIVEN BY $D_t = D_{t_0} e^{E_a / (RT)}$ THE TOTAL EFFECTIVE D_t IS GIVEN BY THE SUM FOR ALL t PRODUCTS AND SINCE D IS EXPONENTIALLY DEPENDENT WITH TEMPERATURE THE HIGHEST TEMPERATURE STEPS IN THE PROCESS GENERALLY DOMINATE AROUND THE OTHERS.

- CONNECTIONS TO FICK'S LAW

\hookrightarrow ELECTRIC FIELD EFFECTS

WITH AN EXTERNAL FORCE ACTING ON DIFFUSING SPECIES WE HAVE TO ADD AN ADDITIONAL TERM TO $F = -D \frac{dC}{dx} + Cv$ AND ALSO TO THE SECOND LAW $\frac{dC}{dx} = \frac{2}{kT} \left(\frac{D}{kT} \frac{dC}{dx} \right) - v \frac{dC}{dx}$. THIS ADDITIONAL FORCE IS AN ELECTRIC FORCE CAUSED BY THE FACT THAT DIFFUSING SPECIES AND E.H. HAVE DIFFERENT MOBILITIES (ACTUALLY $D_{ion} \ll D_{diff}$). EUSIONS WILL TEND TO DIFFUSE AHEAD OF DONORS LEAVING BEHIND POSITIVELY CHARGED DONOR CREATING AN ELECTRIC FIELD TO SET UP CAUSING AN ENHANCED DIFFUSION.

THIS CAN BE TAKEN INTO ACCOUNT BY A FACTOR h IN FIRST FICK'S LAW $F = -D_h \frac{dC}{dx}$ WHERE $h = 1 + C/\sqrt{C_0 + 4m^2}$ WHICH HAS AN UPPER BOUND OF 2 (THIS WHEN DOING CONCENTRATION TERM IS MUCH HIGHER THAN INTRINSIC CONCENTRATION).

\hookrightarrow CONCENTRATION DEPENDENT D EFFECTS

DIFFUSIVITY D VARIES WITH CONCENTRATION WITH HIGHER CONCENTRATION NEGON DIFFUSING RATHER THAN LOW CONCENTRATION CAUSING A MORE BOK-LIKE PROFILE RATHER THAN A GAUSSIAN ONE (OR ELSE). THE DIRECT CONSEQUENCE OF THIS PROBLEM IS THAT $\frac{dC}{dx} = \frac{D}{kT} \left(\frac{dC}{dx} \right)$ MUST BE COMPUTED NUMERICALLY SINCE $D = D(x)$

\hookrightarrow SEGREGATION EFFECTS

DOPANTS HAVE DIFFERENT SOLUBILITIES IN DIFFERENT MATERIALS AND SO REDISTRIBUTE AT THE INTERFACE UNLESS THE CHEMICAL POTENTIAL IS THE SAME IN BOTH PARTS OR THE INTERFACE. THIS DIFFERENCE IN DOPANTS SOLUBILITY IN EACH PHASE CAUSES A LOCAL DIFFUSING FLUX UNTIL CHEMICAL POTENTIAL EQUALIZES

\hookrightarrow INTERFACIAL DOPING PILEUP EFFECTS

IT HAS BEEN OBSERVED THAT DOPANTS MAY PILEUP IN A VERY NARROW INTERFACIAL LAYER BETWEEN Si AND SiO_2 . THIS PILEUP BURST IS SEPARATED FROM ANY SEGREGATION LAYER CAN BE MONOLYTIC AND ALL ATOMS IN THAT LAYER ARE ACTIVE BECAUSE OF AMOUNT OF INTERFACIAL DOSE LOSS CAN BE SIGNIFICANT FRACTION OF THE DOSE OR DOPANTS THAT ARE USED THIS EFFECT CAN TAKE ON A DOMINANT ROLE IN DETERMINING THE CRITICAL CHARACTERISTIC OF THE DEVICE.

DIFFUSION KNOW AN ATOMIC SCALE VIEWPOINT

- + POINT DEFECTS AND DOPANT DIFFUSION ARE STRONGLY LINKED
- + EASY TO THINK THAT A VACANCY ADJACENT TO DOPANT PROVIDES MECHANISM FOR THE DOPANT TO HOP TO ADJACENT SITES THIS REFLECTING A SINGLE MIGRATION STEP FOR THE DOPANT ATOM (THIS IS HAPPENS IN METALS WHICH FULL OF VACANCIES)
- + EASY TO THINK SILICON INTERSTITIAL MIGHT "WALK OUT" A SUBSTITUTIONAL DOPANT ATOM KNOW HIS LATTICE SITE AND BRINGING IT TO QUICKLY DIFFUSE DOWN FORM NEARLY OPEN CHANNELS IN SILICON LATICE.

+ DOPANTS AND A SILICON ATOM COULD SHARE A LATTICE SITE AND BY MOVING IN THIS BOND DIRECTION COULD MIGRATE AS A BOUND PAIR THROUGH THE LATICE. THE PAIR INTRASTRITAL-DOPANT MIGRATES AS A MOBILE SPECIES THROUGH THE LATICE FORMING THE PAIR BREAKS UP LEAVING THE DOPANT IN SUBSTITUTIONAL SITE AND AN INTRASTRITAL. THIS PROCESS IS REFERRED AS INTRASTRITAL ASSISTED DIFFUSION.

↳ OXIDATION ASSISTED DIFFUSION

OXIDATION INSERT INTRASTRITAL AND CONSUMES VACANCIES SO SPECIES THAT TENDS TO HAVE AN INTRASTRITAL ASSISTED DIFFUSION WILL DIFFUSE FASTER THAN OTHER VACANCY-ASSISTED WILL DIFFUSE LESS.

PREFERENCE TO MOVE WITH I OR V DEPENDS ON THE SIZE OF THE DOPANT. COHERENT INTERACTION BETWEEN A POINT DEFECT AND A DOPANT DEPENDS ON THE MISMATCH OF SIZE SO THAT A LARGE DOPANT MAY PREFER TO MIGRATE WITH VACANCY COMPARED WITH INTRASTRITAL. B, P INTRASTRITAL SB VACANCY NITURATION OF THE SURFACE HAS OPPOSING EFFECT OF OXIDATION. THIS CAN BE NORMALIZED WRITING AN EQUATION IN THESE CONDITIONS $\frac{f_I}{f_V}$ INTRASTRITAL/VACANCY TYPE CONCENTRATION AND $\frac{C_V}{C_I}$ VACANCY/INTRASTRITAL CONCENTRATION

$$D_{eff} = D^* \left(f_I \frac{C_I}{C_V} + f_V \frac{C_V}{C_I} \right)$$

- ATOMIC SCALE DIFFUSION

WE CAN CONSIDER A DOPANT A INTERACTING WITH AN INTRASTRITAL I AS $A + I \rightarrow A'I$ WITH AI INTRASTRITAL ASSISTED MOBILE SPECIES. IF WE CONSIDER THAT REACTION TO BE IN EQUILIBRIUM ($C_{AI} = k_e C_A C_I$) WE CAN DERIVE THE FOLLOWING EXPRESSION THAT LEADS TO UNK MACRO-MICRO SCOPIC PARAMETERS

$$\frac{\partial C_A}{\partial t} = \frac{\partial}{\partial x} D_A^* C_A \cdot \frac{C_I}{C_I^*} \left[\frac{\partial}{\partial x} \ln \left(\frac{C_A C_I^*}{C_I C_A^*} \right) \right]$$

- MEASUREMENT METHODS

↳ SIMS SECONDARY ION MASS SPECTROSCOPY

USED TO MEASURE THE CHEMICAL CONCENTRATION OF DOPANTS (CHEMICAL & READING ACTIVELY!) SPECIAL SIMS TIPS ARE INCORPORATED IN THE UGATE DURING PROCESS DEVELOPMENT. THIS TIPS ARE SPUNTED BY AN ION BEAM AND SPUTTERED ATOMS TYPICALLY COLLECTED FROM A PROBE. SPUTTERED ATOMS SO FAR ARE NOT IONIZED AND EXCITED AND MASS ANALYZED AND COUNTED. SINCE ONLY SMALL KINETIC OF SPUTTERED ATOMS AND ANOTHER IONIZED ION BEAM IS CHOSEN TO HAVE HIGH ION YIELD.

↳ SPREADING RESISTANCE

CUT THE SAMPLING AT A SHALLOW ANGLE AND USE A PAIR OF METAL POKERS TO COUNT THE RESISTANCE DOWN IN THE BULK. IMPORTANT THAT THE TIPS HAVE GOOD ELECTRICAL CONTACT WITH SURFACE AND DO NOT PENETRATE THE BULK. IF TIP IS TOO SHARP MICROSPONTANEOUSLY MAKES BAD CONTACT IF TIPS TOO ROUGH IT PENETRATES DEEP INTO THE SUBSTRATE AND MEASURING THE RESISTANCE OR GROWING UNWANTED ZONES.

THIS MEASURES ONLY THE BORELY ACTIVE DOPANTS DIFFUSION DISTRIBUTION THIS AND SIMS GIVES US UNACTIVE DOPANTS CONCENTRATION.

↳ SPREAD RESISTANCE ALREADY DESCRIBED BEFORE

ION IMPLANTATION

- DOPANTS IONS ARE ACCELERATED TO HUNDREDS OR THOUSANDS VOLTS OR KILOGRAY AND SHOTCHED INTO A PERFECT SILICON LATTICE CAUSING A CASCADE OF DAMAGE THAT MAY DISPLACE THOUSANDS OF SILICON ATOMS FOR EACH IMPLANTED ION. SUBSEQUENT ANNEALING REDUCES THE DAMAGE.
 - ION IMPLANTER (MACHINE)
 - + SOLID SOURCE OF MATERIAL VAPORIZED OR GAS SOURCE USED TO DELIVER MATERIAL TO ION IMPLANTER (SOLID SOURCE GOOD SINCE AMONG EVENLY MATERIAL CAN BE VAPORIZED AND IMPUNED)
 - + GAS ROOM IS IONIZED BY IONIZING ELECTRONS COMING FROM ARC DISCHARGE OR HOT PLASMA. USUALLY ALSO A MAGNETIC CIRCUIT IS ADDED SO THAT IONIZATION HAS GLOBAL TRAJECTORY TO INCREASE IONIZATION PROBABILITY.
 - + EXIT SLIT SHAPES THE ION BEAM WITHOUT ACCELERATED ATOMS ENTERS INTO AN ANALYZER CHAMBER WITH A MAGNETIC FIELD B PERPENDICULAR TO ION MOTION SO THAT WE CAN WRITE THE MOTION EQUATION OF IONS AS $\frac{m v^2}{R} = q v B$ SINCE IONS MOVE IN CIRCULAR SHAPE DUE TO B WITH A RADIUS R AND A VELOCITY v AND DUE TO THE CONSERVATION OF ENERGY CONSIDERING THE IONS ACCELERATED BY A POTENTIAL DIFFERENCE V_{ext} $\frac{1}{2} m v^2 = q V_{\text{ext}}$ WE CAN DERIVE THE FOLLOWING EQUATION $\sqrt{m} = \sqrt{\frac{q}{2v}} \cdot R B$ SO FOR A FIXED MAGNET DESIGN AND A FIXED OF THE RESOLVING APERTURE IN THE MACHINES TUNING THE ANALYZER MAGNET CURRENT WILL CAUSE DIFFERENT MASS ATOM TO BE SEPARATED
 - + FOR MOST SITUATION IONS ARE FURTHER ACCELERATED TO THEIR FINAL ENERGY OF IMPLANTATION
 - + ION PATH ELECTROSTATICALLY DEVIATE IN ORDER TO COLLECT ALL NON IONIZED ATOMS THAT CONTINUES UNDEFLECTED.
 - + IMPLANT DOSE CALCULATED BY LOCATING THE RANGE IN A RANDY CED WITH COLLECTING CURRENT AND INTEGRATES OVER TIME (NORMALIZED DOSE GIVEN BY $Q = \frac{1}{A} \int \frac{I}{q} dt$ I COLLECTING BEAM CURRENT AND A IMPLANTED AREA).
 - + WAFERS CAN BE MECHANICALLY MOVED ON ION BEAM RASTERS THROUGH ELECTROSTATIC DEFLECTION PLATES.
 - TEMPERATURE RISE IN SILICON CAUSED BY ION IMPACT. ENERGY DEPOSITED IS $E_{\text{dep}} = \sqrt{I d t} = V Q$ IMPACT T IS ABOUT 120°C WHILE THE PHOTORESIST CRACKS.
 - INCREASES THE DOSE MEANS LONGER IMPACT TIME OR HIGH BEAM CURRENT.
 - ION IMPLANTATION IS A RANDOM PROCESS EACH ION FOLLOW RANDOM TRAJECTORY. IF DIFFERENT IONS IMPLANTED AT SAME ENERGY HEAVY IONS STOP AT SHALLOW LENGTH
 - DISTRIBUTION OF ION IMPLANTATION CAN BE DESCRIBED AS A GAUSSIAN $C(x) = C_p \exp\left(-\frac{(x-R_p)^2}{2\Delta R_p^2}\right)$ WHERE R_p IS THE PROJECTED RANGE (AND IT'S DEPENDENT ON IMPLANTATION ENERGY BIGGER IS BETTER HIGHER R_p) AND ΔR_p IS THE SPREAD OF IONS, STANDARD DEVIATION, (BIGGER WITH BIGGER DOSE) AND C_p PEAK CONCENTRATION OF GAUSSIAN. WE CAN DEDUCE THE TOTAL DOSE IMPLANTED AS $Q = \int_{-\infty}^{+\infty} C(x) dx = \sqrt{\pi} \Delta R_p C_p$ AND SO $C_p = \frac{Q}{\sqrt{\pi} \Delta R_p}$
 - DEFINING THE THICKNESS OF THE MASK AS X_m TO HAVE THE CORRECT DOSE Q OVER THE MASK OR A CORRECT MASK PROPERTY WE CAN CALCULATE THE TOTAL DOSE THAT PASSES THROUGH THE MASK AS $C_p = \frac{Q}{X_m} \exp\left(\frac{X_m - R_p}{\sqrt{2} \Delta R_p}\right)$
 - IF AFTER A GAUSSIAN IMPACT WE HAVE A T ANNEALING THE GAUSSIAN DISTRIBUTION WILL DISPERSE AS IN THE ROLLING FORMULA $C(x,t) = \frac{C_p}{\sqrt{2\pi(\Delta R_p^2 + 2\Delta t)}} \exp\left(-\frac{(x-R_p)^2}{2(\Delta R_p^2 + 2\Delta t)}\right)$ WITH ALL PROBLEMS RELATED TO DIFFUSION ALREADY DISCUSSED
 - ION IMPACT IS SIMILAR TO GAUSSIAN ONLY NEAR THE PEAK TO HAVE A BETTER DESCRIPTION OF THIS SHAPE WE NEED HIGHLY ORDER MOMENTS R_p IS FIRST ORDER ΔR_p SECOND ORDER LINE SMOOTHNESS THAT IS III ORDER OR KURTOSIS FOURTH ORDER (SKW ASYMMETRY, KURTOSIS TAILNESS)
-

CHANNELING EFFECT

CRYSTALLINE STRUCTURE OF SILICON PLAYS IMPORTANT ROLE. IONS CAN KINETIC CHANNELS IN THE SILICON LATTICE AND TEND TO A LOW NUMBER INSIDE THIS CRYSTAL BEYOND THIS STOPS. EFFECT OF CHANNELING ON IMPLANT IS TO CAUSE TRAILS THAT CONTINUE MUCH FURTHER THAN EXPECTED. TO AVOID THIS EFFECT 3 SOLUTIONS: TILT THE SAMPLE, GROW SMALL SILICON DISKING (THAT IS AMORPHOUS) OR IMPLANT SOME AMORPHOUS SILICON ON TOP.

- STOPPING MECHANISM.

IONS SCATTER DETERMINISTICALLY FROM TARGET ATOMS THROUGH ANGLES DETERMINED FROM CLASSICAL TWO-BODY COLLISION THEORY SLOWING DOWN BY AN ADDITIONAL DRAG FORCE FROM ELECTROSTATIC INTERACTIONS RATHER THAN IONS LOSE ENERGY DUE TO BOTH NUCLEAR SCATTERING AND ELECTRONIC STOPPING POWERS GIVING $\frac{dE}{dx} = -N [S_n(E) + S_e(E)]$ WHERE N IS SILICON DENSITY & STOPPING POWERS, S_n AND S_e ARE KNOWN RANGE OF IONS CAN BE DETERMINED AS $R_s = \int^R dx = \frac{1}{N} \int^R \frac{dE}{S_n(E) + S_e(E)}$

+ NUCLEAR STOPPING

CAN BE MODELED AS A COULOMB SCATTERING WITH A POTENTIAL MODIFIED TO ACCOUNT FOR EJECTION SHIELD EFFECT $V(r) = \frac{q^2 Z_1 Z_2}{4\pi \epsilon_0 r} \phi(r)$ Z_1, Z_2 ATOMIC NUMBERS ANALOGOUS TO COULOMB ON COLLISION MAXIMUM ENERGY TRANSFERRED IS $E_f = \frac{4 M_1 M_2}{(M_1 + M_2)^2} E$ WHERE E IS THE IMPACT ENERGY SO $S_n(E)$ DEPENDS ON ION ENERGY. $S_n(E)$ SMALL AT HIGH ENERGY AND DOMINATES AT THE END OF THE RANGE. SMALL AT HIGH E BECAUSE FAST PARTICLES HAVE LESS INTERACTION TIME WITH SCATTERING NUCLEUS.

+ NON LOCAL EJECTION STOPPING

MAJOR COMPONENT OF ELECTRONIC STOPPING DUE TO DRAG THAT MOVING IONS EXPERIENCE IN A DISSIPATIVE MEDIUM.

POLARIZATION OF DISSIPATIVE MEDIUM OCCURS AROUND THE ION TO MINIMIZE THE OVERALL ELECTRIC FIELD. AS THE ION IS SET IN MOTION POLARIZATION FIELD MUST ADJUST BY REALIGNMENT OF ELECTRONS WHICH AT SUFFICIENT ION VELOCITY CAUSES THE POLARIZATION RIGID TO LAG BEHIND CHARGED ION LEADING TO A DRAG FORCE MOVING THE ION. IT'S ANALOGOUS WITH PARTICLES moving DOWNSLOPES IN A VISCOUS MEDIUM WHERE VISCOSEITY IS CAUSED BY SEA OR BULK CRACKS.

DRAG IS PROPORTIONAL TO ION VELOCITY AND ACTS AS DISSIPATIVE ENERGY LOSS

+ LOCAL ELECTRONIC STOPPING

COLLISION WITH ELECTRONS AND SUBSEQUENT MOTION TRANSFER REDUCING ION ENERGY. THIS CAN ALSO ALTER THE ION TRAJECTORY ALTHOUGH THIS EFFECT IS MINOR COMPARED TO NUCLEAR STOPPING DISSIPATION. ALSO THIS DEPENDS ON ION VELOCITY. CHARGE WE CAN WRITE $S_e(E) = k/E$

- DAMAGE PRODUCTION

TO CAUSE PENETRATING HOLE NEED 15eV ENERGY THAT CAN BE THOUSANDS. SOME RECOMBINATION OCCURS WITHIN THE CASCADE DUE TO ELECTRONIC DISSIPATION HOPS IN 10^{-10} TIME SONG AFTER DAMAGE HAS BEEN PRODUCED.

SOME DEFECTS GENERATED CAN BE RECOMBINED WITH DEFECTS FROM OTHER CASCADES SO THE DAMAGE ACCUMULATION ON THE EXISTING LOCAL DEFECT DENSITY. THE AMOUNT OF DAMAGE ACCUMULATED DEPENDS ON N OF DEFECTS GENERATED IN AN ISOLATED CASCADE OR F FRACTION THAT RECOMBINES WITHIN CASCADE AND OVERLAPPING CASCADES N LOCAL EXISTING DEFECT DENSITY AND N_d THE THRESHOLD DEFECT DENSITY WHERE COULD IS CONSIDERED APPROXIMATELY $\Delta N_d \propto f_{rec} \left(1 - \frac{N}{N_d}\right)$. NOTE $N \ll N_d$ $\Delta N_d = 0$ IF AMORPHOUS NO DEFECT SINCE NO CRYSTAL.

DAMAGE PRODUCTION IS MAXIMUM WHEN NUCLEAR ENERGY LOSSES HIGHEST

- SOLID PHASE EPITAXY (SPE)

IF Si AMORPHIZED DURING IMPLANTATION CRYSTALLINE STRUCTURE CAN BE RECONSTRUCTED THROUGH SPE. USE OF THE UNDAMAGED SUBSTRATE AS SEED. IT'S A QUICK PROCESS FOR (100) CUBIC CRYSTAL IF SUBSTRATE IS DOPED (EASY ANNULUS OF DEFECTS AND ACTIVATION). ACTIVATION PS: 20

GRANULAR FONTS CAN BE ALSO SURFACE COLORING CLAM-SHALL DEFECTS

- DAMAGE ANNALING

TWO STPS. FIRST STEP ANNALING AROUND 400°C WHICH VACANCY CLUSTERS BREAK UP AND ANNAL WITH INTRASTITIAL; FINAL RESULT IS REMOVE ALL DIENVAL PAIRS LEAVING ONLY INTRASTITIAL TYPE DEFECTS. I DEFECTS RESULT OF AN IRREG (DOPANT) ATOM ADDED SO +1 MOL%. INTRASTITIAL OF "+1" CONDENSE IN RD SHAPED DEFECTS EVEN AFTER FURTHER ANNALING AT $T > 500^{\circ}\text{C}$. THIS NUBBONS LIE ON $\{311\}$ PLANES. THIS CAN BE ENHANCED UPON FURTHER ANNALING BY EVAPORATION OF S-I BND OF THE DEFECTS. LARGER DEFECT EASY TO FORM DISLOCATION LOOPS THAT ARE DIFFICULT TO REMOVE.

DISLOCATION IN DEPICTION REGION OR PN JUNCTION CAN CAUSE DRIVING CURRENTS PARTICULARLY IF THEY RECOMBINE DURING THE METAL IMPURITIES.

- TO ACTIVATE ATOMS ANNALING IS FUNDAMENTAL. HIGH IMPURITY DAMAGE IS EASIER TO ACTIVATE (I COMPETES WITH B FOR SITES AND B-I AND INACTIVE COUPLES CAN BE CREATED) WITH KOR LOW IMPURITY ALSO LOW $T \approx 600^{\circ}\text{C}$ AND ON

- TRANSIENT-ENHANCED DIFFUSION (TED)

BURST OF DIFFUSION MANY THOUSAND TIMES FASTER THAN WHAT IS NORMALLY OBSERVED FOR SIMILAR ANNALS WHERE NO IMPURITY DAMAGE IS PRESENT. IT'S DOMINANT EFFECT THAT DETERMINES JUNCTION DEPTH IN SHALLOW P-N JUNCTION. BASIC MODEL ASSUMES THAT ALL DEFECTS ABOMBING RAPIDLY LEAVING ONLY A NEW INTRASTITIAL P-N DOPANT ATOM WHICH DOPANT ATOM OCCUPIES A SUBSTITUTIONAL SITE. $\{311\}$ CLUSTERS FORM RAPIDLY AND REMAINS STABILE FOR LONG DRIVING TED BY REMOVING I AND SHANNING TED DURATION INVERSELY PROPORTIONAL WITH T

- EFFECT ON DEVICES

PSCF REVERSE SHOT CHANNEL GATE GRADIENT OF INTRASTITIAL PROFILE TOWARD GATE OXIDE CAUSES CHARGE DOPANT TO PILE UP UNDER THE GATE INCREASING V_{TH} FOR SHOTCH GATE LENGTHS.

ETCHING

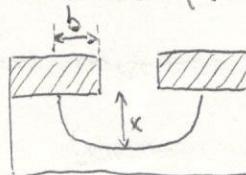
- Etch selectivity is the ratio of etch rates of different materials in an etch process.
- Etch directionality is a measure of the negative etch rates in different directions. Isotropic etching occurs when etch rates are the same in all directions both vertical and horizontal typically. Anisotropic etch is when we have more vertical etch than horizontal (commonly anisotropic no etch in horizontal directions). More physical etch being anisotropic and less selective.
- Etch process should be uniform, safe to use and should cause minimal damage to structures on the chip.

- WET ETCHING

Immersing wafer into baths of liquids chemicals exposed film could be etched away. Wet etchants work by chemically reacting with the film to be water soluble byproduct or gases.

Etch selectivity defined as $S = \frac{V_1}{V_2}$ where V etch rate of material 1 or 2. Being the material we want to etch will define $S > 1$. Selectivity for the material to be etched w.r.t. the mask important gives us the mask thickness so that it's not completely removed.

Most chemical etch isotropic with exception to those which are sensitive to crystallographic orientation ($\langle 111 \rangle$ direction). The length 'b' in figure it's called etch bias.



Some overetch is always done to ensure that etch goes completion everywhere this ensures that within some structures may be overetched no parts remain unetched. Due to this practice it's found mental the selectivity to the substrate.

- PLASMA ETCHING

Wet etch replaced with plasma etch for 2 reason 1) more vigorous etch due to formation of reactive chemical species 2) possible directional etching

Typical RF-powered plasma etch uses DC power, both chemical and ionic species have a role in etch. The electrode (without wafer) is usually smaller to have higher fields to maintain current continuity (higher RF current density)

✓ CHEMICAL ETCHING

Done typically by free radicals (electronically neutral species that have incomplete bonding so highly reactive) that react with the material to be etched. The byproducts should be volatile species that leaves the surface exposing more material to be reacted.

This component etch isotropically due to 2 main causes: 1) uniform angular distribution ($\cos^0 \theta = 1$) 2) low sticking coefficient.

The process is very selective.

✓ PHYSICAL ETCHING

Positive ions accelerated towards each electrode. Staying on wafer surface results in physical component of etching. Flux of atoms ion toward the wafer is much more bidirectional because of the directionality of E . It is usually assumed that all ions move \perp to wafer surface, meaning it very large in cosine distribution.

⚠️! One ion reaches the surface it does not strike the surface sometimes (or if with low E so nothing happens) so sticking coefficient $\neq 1$.

Ions etch material by physical sputtering. Some chemical reaction can occur if ionized species are reactive.

✓ ION-ENHANCED ETCH

CHEMICAL AND PHYSICAL SPECIES WORK IN A SINERGETIC MANNER. MORE THAN A SIMPLE SUPERPOSITION OF EFFECTS. IF CHEMICAL SPECIES INCREASED INCREASE VERTICAL ETCH AND NOT HORIZONTAL. CHEMICAL COMPONENTS AND PHYSICAL ONE IN THE PLASMA WORK TOGETHER TO GET THE MATERIAL WITH BOTH COMPONENTS REQUIRED AT ANY POINT TO WORK.

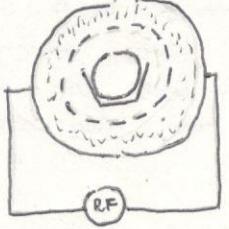
GOOD SELECTIVITY AND GOOD ANISOTROPY

Why? - CHEMICALLY INERT RESIDUE IS OFTEN FORMED AND DEPOSITED ON THE SURFACE THIS LAYER INHIBITS CHEMICAL ETCHING BY PHYSICALLY BLOCKING THEM AND BY REACTING WITH THEM MAKING THE REACTIONS POOR. THIS PASSIVATION LAYER IS REMOVED (ONLY ON BOTTOM WNL) BY ION BOMBARDMENT LEADING TO VERY ANISOTROPIC ETCH. ION BOMBARDMENT USING SIDEWALLS INHIBITION TO PROTECT AGAINST LATERAL ETCHING.
Typically provides like in figure ↗

- PLASMA ETCH SYSTEMS

- BARREL ETCHERS

NAME FOR IT'S SHAPE. NO IONIC BOMBARDMENT EXISTING DURING CHEMICAL SO VERY SELECTIVE AND VERY LITTLE DAMAGE FROM THE SURFACE. HIGH THROUGHPUT DUE TO CLOSELY STACKED WAFERS.



ETCH UNIFORMITY NOT GOOD BECAUSE OF LONG DIFFUSION PATH FROM OUTSIDE TO INNER PART OF WAFER.

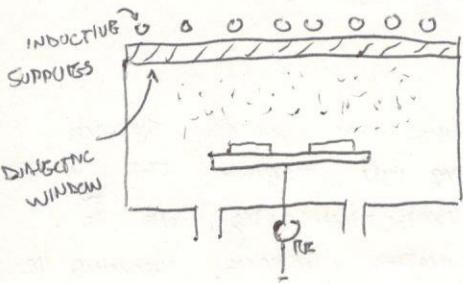
LIMITED TO NONCONDUCTING SUBSTRATES OR PHOTOABSTRACTION REMOVAL

SIMILAR AS DOWNSTREAM PLASMA ETCHERS WHERE PLASMA IS CONTAINED IN ONE CHAMBER AND NEGATIVE SPECIES DIFFUSE IN ANOTHER CHAMBER WHILE WAFERS ARE ALSO CALLED AFTER GLOW ETCHERS USED FOR NON-MASKED PROCESS LIVING NITROGEN REMOVAL AFTER LOCOS PROCESS.

- PARALLEL PLATE ETCHERS

VERY SIMILAR TO PECVD SYSTEMS EXCEPT THAT ETCH GASES ARE USED INSTEAD OF DEPOSITION GASES. MUCH BETTER ETCH UNIFORMITY THAN BARREL ETCHERS AND ALLOWS FOR ION BOMBARDMENT TOO. 2 OPERATION MODES: PLASMA MODE: SYMMETRICAL ELECTRODES LEADS TO POOR ION BOMBARDMENT DUE TO SMALL SURFACE VOLTAGE DROP AT WAFER SURFACE, HIGH REACTIVE ION BOMBARDMENT ASymMETRIC PLATES GUARANTEES ION-FOURNISHED PER ETCH

- HIGH DENSITY PLASMA SYSTEMS



PLASMA DENSITY AND ION ENERGY DECREASED BY AN IGNITION OR PLASMA USING ECR (ELECTRON CYCLOTRON RESONANCE) OR ICP (INDUCTIVELY COUPLED PLASMA) SYSTEM. WE CAN ACHIEVE HIGH ION DENSITY AND LOW ION BOMBARDMENT.

ION BOMBARDMENT DAMAGE ALSO CAN BE kept LOW WHILE MAINTAINING HIGH ETCH RATES AND GOOD ANISOTROPIC ETCH

- SPUNTER ETCHING ONLY SPUNTING COMPONENT USED (NOT USE IN INDUSTRY)

WITH CHEMICAL INERT ATOMS AS ARGON WITH HIGH ENERGIES
- ION MILLING: CONFINED PLASMA USED TO GENERATE IONS THAT GIVES TO ACCURATE IONS THE ION can ALSO BE FOCUSED (USE FOR MASK ABALING AND TEM STAMPING POSITION)

- END POINT DETECTION: USING OPTICAL EMISSION SPECTROSCOPY A SPECIFIC WAVE-

- LENGTH RELATIVE TO A REACTANT OR REACTION PRODUCT CAN BE FOCUSED (THIS AVERAGE OVER A LARGE SURFACE IT'S NOT A PUNCTUAL MEASUREMENT)
- PLASMA ETCH ISSUES
- + LOADING EFFECT ETCH RATE DEPENDS ON LOCAL PLASMA DENSITY THAT COULD BE NON UNIFORM
 - + μ-LOADING EFFECT STRUCTURES WITH DIFFERENT MASK OPENING OR ASPECT RATIOS ARE ETCHED WITH DIFFERENT ETCH RATES (SMALL BETTER FOR HIGH ASPECT RATIOS). CAN BE DUE TO: DEPOSITION OR TRAPPING OF REACTANTS SPECIES, DISTORTION OF ION PATH DUE TO CHARGING, SHADOWING EFFECTS
 - + OTHER ISSUES MAY BE MICRO TRAPPING DUE TO ION PHYSICAL DEFLECTION (F_z) RESIST & SPOTTING AND ION TRAJECTORY DISTORTION DUE TO RESIST CHARGING, WE CAN ALSO INCUR IN RADITION DAMAGE

ETCHING MODELS

- + LINEAR ETCH MODEL CHEMICAL AND IONIC COMPONENTS ACTS INDEPENDENTLY AND COMBINE IN A LINEAR FASHION. SO WE GET ETCH RATE = $(S_c V_f F_c + V_i F_i) / N$ N IS THE DENSITY OF THE FILM TO BE ETCHED F_i ION FLUX S_c STICKING COEFFICIENT F_c CHEMICAL FLUX V_f , V_i RELATIVE RATE CONSTANT FOR THE TWO FACTORS. IN PRACTICE V_f USED AS FITTING PARAMETER FOR THE PURELY CHEMICAL ETCHING AND V_i IS ION INDUCED ETCH YIELD.
- ION ENHANCED MODEL WE NEED A MODEL WHERE THE REACTANT COMPONENT IS FUNDAMENTAL, IF ONE IS MISSING THE ETCH RATE HAVE TO GO TO 0 AND IF ONE IS MUCH HIGHER THAN THE OTHER ETCH VELOCITY HAS TO SATURATE TO A LIMIT VALUE (ACCORDING TO LANGMUIR ABSORPTION THEORY) THE NUMBER OF REACTIVE NEUTRAL SPECIES THAT ABSORB ON THE SURFACE TO REACT WITH SURFACE MATERIAL IS $C = S_c (1 - \theta) F_c$ θ IS THE FRACTION OF SITES COVERED BY BY PRODUCTS AND F_c FLUX OF SPECIES ON SURFACE.
- REACTANT NEUTRALS CONTAINED IN BYPRODUCTS REMOVED PER TIME PER AREA IS $I = V_i \theta F_i$
- ASSUMING STEADY STATE CONDITION WE DERIVE $\theta = 1 / [1 + \frac{V_i F_i}{S_c F_c}]$
- THE ETCH RATE IS THE FLUX OF REMOVED SPECIES DIVIDED BY THE DENSITY OF THE FILM TO BE ETCHED SO
- ETCH RATE = $\frac{1}{N} \cdot 1 / \left[\frac{1}{V_i F_i} + \frac{1}{S_c F_c} \right]$.
- WE SEE 2 EVENTS OCCURRING IN SERIES AND NOT IN PARALLEL. THE PROCESS IS LIMITED BY SLOWEST OF THE 2 PROCESSES
- OTHER END POINT DETECTION FOR THINNING FILMS CAN BE INTERFEROMETRY.
- ETCH RATE DEPENDENCE ARE QUITE COMPLICATED BUT IN GENERAL:
 - ① DEPENDS ON GAS SPECIES
 - ② INCREASING POWER INCREASES THE ETCH RATE
 - ③ INCREASING PRESSURE DECREASES THE DENSITY BUT INCREASES CHEMICAL FLUX, DEPENDENCE ON PRESSURE NOT EASILY PREDICTABLE
 - ④ LOW RATE CAN BE INCREASED TO SUPPLY MORE REACTANT SPECIES BUT HIGH FLOW RATE CAN DECREASE TOO MUCH THE RESIDENCE TIME, FLOW RATE HAS MINOR IMPACT.
- ETCH PROFILE CAN BE CONTROLLED BY:
 - INCREASING ION BOMBARDMENT (SO POWER)
 - USING DIFFERENT ETCHANT GASES TO CONTROL BYPRODUCTS REACTIONS.



Back-end Technology

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- Back-end refers to the interconnect layers, contacts, vias, and dielectric layers that bring active devices into specific circuit configurations
- It can be divided into: local interconnects (silicided gate transistors and silicided active regions like source and drain regions), contacts (connect silicide/local interconnects to first level of metal), intermediate or global interconnect (metal lines wiring active elements into circuits), dielectrics (insulating different metal levels and lines), vias (same as contacts but connects metal lines together)

Silicides

- Used as local interconnections in 2 ways: on top of polysilicon layer they form "polycide", on top of source on drain regions and as independent local interconnect
- In polycide silicidng decreases the sheet resistance of the polysilicon gate and local interconnect while maintaining the good properties of the polysilicon/SiO₂ interface, in source drain region decreasing sheet resistance of the diffused layers.
- Silicides used because they provide low electrical resistivity status at high T (good since no implanted GaAs) good process compatibility with silicon easy to etch etc provides good contacts with other materials and having low electromigration probabilities.
- Two ways of forming silicides:
 - / Direct deposition with sputtering from a composite target, sputtering from two targets / co-sputtering from 2 targets or CVD also deposited with metal
 - / Reaction method: 1) deposit metal upon amorphous Si > than annealing process so that Si and metal react to form silicide and unreacted metal etched away 2) No Si deposited but metal only deposited and then anneal so that it will react only when it's on silicon then etch away the unreacted part (it's a self-aligned process) self aligned silicide on silicide
- For both methods annealing process needed
- Very popular silicide is TiSi_x that has a high resistivity phase "C19" that forms at moderate type dopings. We have to convert it to "C54" phase with an anneal at 800°C with low resistivity characteristics.
- Narrow width salicidation and compatibility with shallow junctions are main issues in salicidation process

Contacts

- Metal/semiconductor can in general be rectifying or ohmic. Because ideally it's a strong function of metal work function and so in theory it could be possible to choose a metal which produces small ϕ_B ; in practice impossible due to other constraints on metal (low resistivity) and the surface states induced pinning or from metal at the surface. So generally high ϕ_B for n-doped Si and low for p-type.
- If we use a low doped Si the barrier creates a depletion region that we don't want in our contact if instead we use a high doped Si the depletion zone becomes so narrow to yet not the tunneling current to negligible levels so filter our junction resistances as a small resistance. Actually $\rho_s \propto N_d^{1/2}$. In case of low doping thermionic current is type dominant term.

Measured ρ can be higher due to not clean interface, fewer dopants in Si at surface than desired due to segregation effects.

General requirements for MS-S/contacts are low resistance and good thermal

STABILITY

- Early circuits used only Al as contact material having contact with Si and heavily doped with an impurity. Al makes good contact reducing native oxide and carbon impurities with an ambient at 600°C . This in Hz ambient to "cage" also SiO_2 . But solubility of Si in Al at 500°C is 1% meaning that Al in contact with Si wants to absorb the Si up to its solubility limit. This silicon then scales up by Al to creates voids that are quickly filled by Al resulting in $0.2-0.3 \mu\text{m}$ of regeneration. This problem becomes worst if we include the fact that Al do not regenerate native oxide uniformly so creating spikes in Si or also $1 \mu\text{m}$ solutions to this problem is 1) using Al with already some silicon in it so first solubility requirement is already full-filled (but at less than 1 too much Si in Al and creates precipitates) 2) barrier layers to prevent or slow down any interaction with Si; passivating barrier layer has to be inert to both Si and Al and be good diffusion barrier as well (TiN is one example). TiN has good structure (1 nm) this has impenetrable to Si and most other species; chemically stable and inert with most species. Other layers usually first layer of Ti and then TiN to form also has silicide under.
- Contacts now ruggedized with W plugs. With Al planarity remains an issue done by "damascene" process since first we deposit a usual or direct that we etch a hole in it and then the surface with adhesion layer (TiN) then W deposition all over (CVD W gives much more conformal and filling of the contact w.r.t Al.) and finally CMP process to manage all.

- INTERCONNECTS AND VIAS

- Primary requirements are low resistivity, good adhesion to underlying ticks, stability during processing and operations and the ability to be deposited and etched.
- Al good resistivity adhering well to SiO_2 and can be etched and deposited in easy ways but melting T is low (660°C) and thermal expansion coefficient $\times 10$ than Si.
- Two phenomena happens in Al that are problems:
 - + hillock growth occurs when Al ticks is subjected to high compressive stresses. This stresses easily caused by thermal expansion coefficient difference. Due to its polycrystalline structure and can melt point of Al are caused on coating hillocks and voids resulting this stress position of Al are caused on coating hillocks and voids. Hillocks can break or can cause shorts between lines or open circuits. Hillocks can break or crack upper SiO_2 layers increasing probability of shorts. Solution is to add portion of Cu that in excess (over its solubility) segregates boundaries without diffusion of Al is enhanced an precipitates on the Al grain boundaries and avoiding hillocks or voids formation.
 - + electromigration: when electrical current flows through Al in order of mA/cm^2 electrons transfer enough momentum to Al atoms to cause them to diffuse (fast along grain boundaries) and this can cause a build-up of aluminum in some regions and voids in others and so same problems or. Because of Al diffuses mostly on grain boundaries electromigration is very dependent on grain structure, size and crystallographic orientation of grains. Adding Cu to Al slow down this process. Also multi-layer stacks and used lines Ti (helps controlling grain structure) + TiN (barrier during via processing) + Al+TiN (that can also shield metal lines in case of void or cracks formation)

- DIELECTRICS

- First usage of dielectric separates active areas from first line of metal layer integral dielectrics (IMD) dielectrics that separates global interconnections
- Good electrical isolation, low dielectric constant (so C_p low), high breakdown fields and low leakage as electrical characteristics. In addition good adhesion to Si

- METAL AND SILICIDES, LOW THERMAL STRESS, GOOD THERMAL STABILITY, LOW DOPING
DENSITY AND TiN SHOULD BE PREFERRED TO HYDROGEN FOR THE FINAL
Ti_x ALLOY
- SiO₂ OR PSG PHOSPHOSILICATE GLASS THAT IS SiO₂ DOPED WITH P USED (SiON)
ONE FOR BETTER PROPERTIES). USUALLY MULTIPLE LAYER USED BIASING FIRST SiO₂
THAN PSG AS FIRST LAYER. (PSG HAS BETTER AND SMOOTH COVERS)
 - PECVD USED FOR OXIDE DEPOSITION SINCE TiB ENERGY FROM PLASMA
ENHANCES DEPOSITION REACTION AND PROVIDES DENSE FILMS AND BETTER
COVERAGE AND RILUNG AT LOW T.
 - PLANARIZATION NEEDED TO DEPOSIT Al LINES. REFLUX OF PSG OR MOLY
COMMONLY CMP PROCESS.

- SCALING PROCESS

TIME OF A SIGNAL PROPAGATING INTO A LINE CAN BE DESCRIBED FROM DISTURBED
MODEL (TIME FROM 10% TO 90%) AS $0.89 R_{\text{Cu}} L$. RESISTANCE OF A LINE IS
ESTIMATED AS $R_{\text{line}} = \rho \frac{L}{Wt}$ AND THE CAPACITANCE AS $C = K_{\text{ox}} E_0 \frac{Wt}{R_{\text{ox}}} + K_{\text{ox}} E_0 \frac{L}{W}$ WHERE
X_{OX} AND K_{OX} ARE THICKNESS AND DIELECTRIC CONSTANT OF SiO₂ LS DISTANCE BETWEEN 2 LINES
SO THE TOTAL DEBTY WILL BE $Z = 0.89 K_{\text{ox}} E_0 \rho L^2 \left(\frac{1}{1+K_{\text{ox}}} + \frac{1}{W} \right)$ K_L ADDED TO
ACCOUNT FOR RUMMING FIELDS OR INTRACONNECTIONS ABOVE OR BELOW MULTILAYER STRUCTURES
DETERMINING F_{MN} AS THE MINIMUM DIMENSION OBTAINABLE IN A TECHNOLOGY WE CAN SAY
THAT X_{OX} H_L AND W_L ARE ALL EQUAL TO F_{MN} AND L REMAINS QUASI CONST.
DETERMINING AREA OF THE CHIP (ACCUMULATING $L^2 = A$ THAT SLIGHTLY INCREASES) SO THE TIME
~~IS $\approx 0.89 K_{\text{ox}} E_0 \rho / F_{\text{MN}}^2$~~ WE NEED TO KEEP MATERIAL PROPERTIES AS GOOD AS POSSIBLE
TO WHICH Z IS UNDER CONTROL

- COPPER PROCESS

COPPER CANNOT BE DRY ETCHED BECAUSE BYPRODUCTS ARE NOT VOLATILE AND REQUIRES
A DAMASCENE APPROACH

- SILICIDE GATES ON S/D REGIONS

SiO₂ REMOVED FROM SOURCES THAN Ti DEPOSITED BY SPUTTER ON WHOLE WAFER. FIRST
ANNEAL STEP IN NITROGEN AMBIENT SO THAT WHEN Si IS EXPOSED WILL FORM TiSi₂ AND
AND AT THE SURFACE TiN OVER SiO₂ ONLY TiN FORMS THIS LIMIT THE INTERNAL GROWTH
OF THE SILICIDE. SECOND ANNEAL AT HIGH T TO PASS FROM "C9" TO "C8" PHASE

- CONTACT FORMATION (DAMASCENE PROCESS)

OPEN UP HOLES IN FIRST METALLIC OR DIAMONICS TO FORM METAL CONTACT
ANISOTROPIC PLASMA Etch USUALLY DONG (IMPORTANT THAT ALL DIAMONICS OR BYPRODUCTS
AREN'T TO CREATE GOOD CONTACT). BIGGING HOLES RILUNG AN ADHESION BARRIER
IS FORMED WITH Ti (DEPOSITED IF SPUN NOT ALREADY PRESENT) ON BOTTOM
OF HOLES. THEN TiN DEPOSITED AS A BARRIER LAYER TO PREVENT DIFFUSION AND
SPREADING EFFECTS (TiN DONG BY SPINNING OR CVD). ANNEALING IN N₂ OR O₂
AMBIENT TO IMPROVE TiN BARRIER PROPERTIES THEN AS FINAL STEP W
IS DE POSITED

- GLOBAL INTERCONNECTS

USUALLY MADE WITH Al WITH 0.5-1% Cu ALSO Si IS ADDED EVEN IF SPINNING IS
NO LONGER A PROBLEM. Al LAYERS USUALLY CLAD WITH TiN Ti OR TiN LAYERS.
SURFACES MUST BE CLEAN TO ENSURE GOOD CONTACT PROPERTIES

- # LITHOGRAPHY
- A light sensitive photoresist is spun onto the wafer forming a thin layer at the surface. Resist film selectively exposed by illuminating light through a mask and then developing completes the pattern transfer to the wafer.
- Generally critical dimension (CD) control is required to be $\pm 10\%$ of the smallest feature size.
- About $\frac{1}{3}$ of overall cost of a wafer is due to LIO.
- Patterns that connects the various layers in an integrated circuit are designed with CADS. Once the design is complete the information for each mask used is transferred to a mask making machine (e-beam or laser pattern generator).
- Mask is fused silica plate covered with thin layer of chromium and a layer of photoresist. Laser or e-beam expose resist writer is then developed and used as reticle mask to remove excess chromium. Often usually mask replicated x1 to x5 dimension. Lateral magnification will be provided by lens system. No defects on mask will rapidly lead to a mask defect and repair (done with additional Cr or with e-beam) fundamental. Mask protected by contamination or dust particles with a thin transparent Mg membrane on the chromium side or the mask on a metal frame. Particle designed to fall out of focus and so not transferred in wafer.
- Pattern information transferred on wafer with projection exposure system. Light from high intensity source collimated and pass through the mask. Only few chips printed during one exposure.
- + Wafer physically moved to next exposure field and process repeated as step and repeat tools on steppers.
 - + Mirror slit or lights by light source system and mask and wafer simultaneously scanned together so that image is scanned along the wafer as scanner.
- Job of exposure tool best aerial image as possible in terms of resolution, exposure field, depth of focus, uniformity ...
- Job of photoresist to transfer aerial image in best 3D replica in terms of geometric accuracy, exposure speed, resist resistance to subsequent processes.
- ## - LIGHT SOURCES
- High resolution LIO requires short wavelength photons. Wavelength strongly correlated to diffraction limits that limits our technology nowadays.
- Arc lamps as primary light source usually containing Hg vapour inside sealed glass envelope. Arc is struck between electrodes applying enough voltage to ionize the gas that one of ionized behaves like a plasma.
- Light emission by two processes: 1) free electrons have high effective T and emit black body radiation but with wavelength deep in visible light so this radiation is absorbed before exit the lamp by walls 2) Hg electron excite due to collision and hop on deatoms emits energy which is giving photons at precise wavelengths in UV range.
- Most steppers use single wavelength by filtering unwanted one (optical system easy to design with single w.) Two commonly used g-line 436 nm and 365 nm i-line
- ## - EXPOSING SYSTEMS
- CONTACT DUVING
MASK PLACED STRONG SIDE DOWN IN DIRECT CONTACT WITH WAFER; OR SPINNING WAFER THROUGH MASK. ALIGNMENT DONE prior to exposing with microscope and mask a little separated from wafer.

DIFFRACTION EFFECTS MINIMIZED AND MACHING INEXPENSIVE BUT HAS CONTACT RESULT IN DAMAGE OF BOTH MASK AND RESIST LEADING TO HIGH DEFECT DENSITY

- PROXIMITY PRINTING

SOLVES THE ISSUES OF DEFECTS WITH GAP 5-25 μm BUT THIS SEPARATION DEGRADES AS RESOLUTION DUE TO DIFFRACTION EFFECTS. RESOLUTION LIMIT $\approx \sqrt{\lambda}$ OF GAP λ WAVELENGTH. BOTH CONTACT AND PROXIMITY REQUIRES XL MASK NOT EASY TO PRODUCE.

- PROJECTION PRINTING

HIGH RESOLUTION WITHOUT PROBLEMS OF CONTACT PRINTING. MASK SEPARATED FROM WAFER AND OPTICAL SYSTEM USED TO IMAGE THE MASK ON WAFER. RESOLUTION LIMITED BY DIFFRACTION BUT, OPTICAL ZOOM IN X4 X5 ONLY SMALL PORTION ON WAFER IS PAINTED. FOCUSING LENS COULD ONLY READ ONE PART OF DIFFRACTION PATTERN SO SOME INFORMATION IS LOST.

- RESIST PROCESS 1) ABLE IMAGE FORMATION ON TOP OF RESIST LAYER 2) LATENT IMAGE FORMATION INSIDE RESIST AND AT EXPOSED AREAS 3) RESIST DEVELOP EXPOSED AREAS TO ILLUMINATION BECOMES SOLUBLE TO DEVELOPER.

- PHOTONICIST

- PHOTORESIST MATERIALS DESIGNED TO RESPOND TO INCIDENT PHOTONS BY CHANGING THEIR PROPERTIES WHEN EXPOSED TO LIGHT. MATERIAL THAT CONTAINS AND MAINTAINS A LATENT IMAGE OF THE IMPRINTING PHOTONS UNTIL THE RESIST IS DEVELOPED.

- ALMOST ALL RESIST HYDROCARBON BASED MATERIALS, WHICH THIS MATERIAL ABSORBS LIGHT ENERGY. ION PHOTONS BREAKS CHEMICAL BONDS AND THE MATERIAL RESTRUCTURES IN A MORE STABLE FORM.

POSITIVE RESISTS: LIGHT-EXPOSED REGIONS BECOMES MORE SOLUBLE IN DEVELOPER (BUT IT'S RESIST).

NEGATIVE RESISTS: LIGHT-EXPOSED REGIONS BECOMES HARDER AND INSOLUBLE (BAD RESOLUTION).

- SENSITIVITY MEASURES HOW MUCH LIGHT IS REQUIRED TO EXPOSE THE RESIST. HIGH SENSITIVITY INCREASES THE THROUGHPUT OF LITHO PROCESS. SUPER SENSITIVITY ALSO CAN LEAD TO UNSTABILITY OR THE MATERIAL AND THERMAL AND DUE TO SHOT NOISE OR LIGHT.

- RESOLUTION IMPORTANT ISSUE SINCE NOWADAYS WE ARE LIMITED BY ABLE IMAGE AND DIFFRACTION PROBLEMS.

- "RESIST FUNCTION" DESCRIBES THE NEED FOR PHOTONICIST TO WITHSTAND BAKING OR ION IMPLANTATION. NEEDED A GOOD ROBUSTNESS TO THIS PROCESSES.

- G AND I-LINE PHOTONICIST USUALLY DON'T USE 3 COMPONENTS: INACTIVE RESIN USUALLY HYDROCARBON RESIN THAT BASIC OF THE MATERIAL, A PHOTOACIDIC COMPOUND (PAC) ALSO HYDROCARBON AND SOLVENT TO ADJUST VISCOSITY.

DUV RESISTS REPLACE PAC WITH PHOTO-ACID GENERATOR (PAG) WHICH ACTS AS CHEMICAL AMPLIFIER.

MOST OF SOLVENT REMAINES DURING SPINNING AND PREBAKING ONCE ACTIVATING EXCITANTS

- G/I-LINE RESISTS

MOST COMMON ARE DON MATERIALS. PACS AND DIAZOQUINONES THE ROLE OF PACS IS TO INHIBIT DISSOLUTION OF THE MATERIAL IN THE SOLVENT WITHIN EXPOSED TO LIGHT PACS CHEMICALLY CHANGES AND STABILIZES ITSELF REMOVING A CARBON ATOM WITH AN OXYGEN ATOM COVALENT BONDED WITH IT.

- DUV RESISTS DURING ULTRA VIOLET

DON HAS 2 PROBLEMS 1) FOR WAVELENGTHS BELOW I-LINE RESIST STRONGLY ABSORBS INCIDENT PHOTONS MAKING DIRECT PHOTOREACTION TO HAPPEN INSIDE THE RESIST 2) LOW SENSITIVITY DUV BASED ON CONDUCTING DIFFERENT CIRCUITRY BASED ON CHEMICAL AMPLIFICATION RESIST (CAR). SENSITIVITY INCREASE BY FACTOR 3. INCIDING PHOTONS REACTS WITH PHOTO-ACID-GENERATOR PAG CATALYZING AN ACID MOLECULE THIS ACIDS ACTS AS CATALYSTS DURING SUBSEQUENT RESIST POST BAKE TO CHANGE RESIST PROPERTIES. REACTION IN POST-BAKE.

KEY POINT REACTION AND CATALYTIC ACID MOLECULE NEGLECTED AND MAY PARASITIC WITH HUNDREDS OF REACTION.

POST-EXPOSURE BAKE (PEB) HEAT PROVIDES ENERGY NEEDED FOR REACTION AND MOBILITY TO ACID TO FIND NEW MOLECULES TO REACT WITH DURING PEB.

OPTIMAL SENSITIVITY AND RESOLUTION.

TIME DELAY BETWEEN EXPOSURE AND POSTBAKING CAN CAUSE AMMING CONTAMINATION THAT

BASIC CHAOTIC BEHAVIOR OF WAFER IS CONSIDERED. CONSIDER MEASURING RESIST ABILITY LIGHT TO
RESIST. DUE TO GAS IN THE EXPOSURE IMAGE EXPOSURE SYSTEM.
IT IS EXPONENTIALLY DECREASED.
CONSIDER IS THE SLOPE IN CONDIT OR $\gamma = 1/\log_{10}(\frac{Q_f}{Q_0})$
 $g-i-LINCS \gamma = 2-3$ DUV MUCH SMALLER

- PROCESS STEPS

- WAFER CLEANING AND HEATING TO DRIVE OFF ANY WATER VAPOR ON SURFACE
- ADHESION PROTECTOR APPLICATION HMDS MOST COMMON SUBSTANCE FOR THIS PURPOSE
- SPINNING OR RESIST IMMEDIATELY AFTER HMDS APPLICATION. UNIFORM WAFERS WITH HIGH RESIST ACCELERATIONS AND SO HIGH SPIN. SPINNING PRODUCES "EDGE BEADS" THAT IS THICK RESIST ON EDGES OF WAFER THAT HAS TO BE REMOVED BEFORE PROCEEDING
- LIQUID PRE-BAKE TO COMPLETELY CONSUME SOLVENT INCREASING RESIST ADHESION AND REGULAR SUBSTRATE STICKIES PRESENT IN PHOTOBEST
- EXPOSURE CREATES LATENT IMAGE (REQUIRING TIME DEPENDENT ON THICKNESS AND LIGHT INTENSITY)
- POST EXPOSURE BAKING IN OVEN TO MINIMIZE STANDING WAVES EFFECTS
- DEVELOP (TIME DEPENDENT ON T REGULAR CONCENTRATION)
- POST-BAKING DONE AT HIGH T NOT OTHER BALES TO HARDEN THE PHOTOBEST

- THERMAL RELAXATION IN ORDER TO REDUCE FEATURE DIMENSIONS PHOTOBEST CAN BE PROCESSED WITH CONTINUED THERMAL PROCESS THAT SHOOTS DIMENSIONS

- NOTCHING: DUE TO SUBSTRATE NON-PLANARITY OBSCURE REFLECTIONS CAN IMPACT NON EXPOSED REGIONS

- STANDING WAVES: SUBSTRATE REFLECTIVITY THIN FILM INTERFERENCES IS PRESENT WITHIN THE ASSIST THICKNESS CAUSING A "SCALLOPED" REGIONS ASSIST ANTI-REFLECTION COATING AS SOLUTION

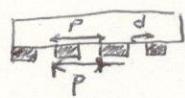
- ALIGNMENT: OPTICAL ALIGNMENT URGED TO LEVEL CRUCIAL FOR DEVICE FIDELITY. SPECIAL STRUCTURES (ALIGNMENT MARKS) ARE GENERATED. DEDICATED FEEDBACK BOX AND USED TO ENSURE MUTUAL ALIGNMENT BETWEEN 2 MASK AND ALIGNMENT SYSTEM USE MEANS TO CALIBRATE ITSELF

- RESOLUTION ENHANCEMENT TECHNIQUES (IN PROJECTION LIO)

- IF THE DIMENSIONS OF AN OPTICAL SYSTEM ARE ALL LESS THAN THE WAVELENGTH OF THE LIGHT WE CAN ASSUME THAT LIGHT CAN BE TREATED LIKE PARTICLES TRAVELING IN STRAIGHT LINES. IN OUR CASE THIS ASSUMPTION FAILS AND WE HAVE TO TAKE INTO ACCOUNT THE WAVE NATURE OF LIGHT
- DIFFRACTION HAPPENS BECAUSE LIGHT DO NOT TRAVEL IN STRAIGHT LINES, SHIELLED APERTURE MEANS WIDER SPREAD OF THE LIGHT BECAUSE THERE ARE USES WAVES TRYING TO PASS THROUGH THE APERTURE AND THIS MORE SPATIAL PROPAGATION RESULTS BEYOND THE APERTURE
- BECAUSE OF ITS FINITE DIMENSIONS FOCUSING LENS COLLECTS ONLY A PART OF TOTAL DIFFRACTION PATTERN ASSOCIATED WITH LIGHT PASSING THROUGH THE APERTURE.
- IN PROJECTION SYSTEMS UNDERRADING DIFFRACTION OR THE RIGID DIFFRACTION HAPPENS.
- NUMERICAL APERTURE NA: DEFINING IT AS THE INDEX OF REFRACTION OF THE MATERIAL BETWEEN OBJECT AND LENS (USUALLY $n=1$) AND OF THE MAXIMUM HALF ANGLE OF THE DIRECTED LIGHT THAT CAN ENTER THE LENS (MAY BE LIMITED BY PHYSICAL SIZE OF LENS) WE DEFINING NUMERICAL APERTURE AS $NA = n \sin \alpha$ THAT DETERMINES THE NUMBER OF DIFFRACTION ORDERS THAT CAN BE CAPTURED AND THUS THE QUALITY OF THE IMAGE RECONSTRUCTED. INCREASING NA HIGH PATTERN RESISTIVITY CAN BE OBTAINED.

OBJECTIVE LENS (FOR COHERENT IMAGING) FUNCTION IS TO RECONSTRUCT THE DIFFRACTION PATTERN AND TO FOCUS IT ON THE WAFER, SINCE MASK SPECTRUM IS THE FOURIER TRANSFORM OF THE PATTERN LENS NEEDS TO PERFORM AN INVERSE FOURIER TRANSFORM.

LENS CAN PRODUCE INTERFERING TONES ONLY IN THIS PORTION OF DIFFRACTED LIGHT THAT BENDS THE LIGHT SO WE GET A DIFFRACTED IMAGE WHICH IS LPI SYSTEM.



MASK SPECTRUM IS DISCRETE THE FREQUENCIES ARE SPACED WITH $\frac{1}{P}$ SEPARATION.

THEORETICAL RESOLUTION LIMIT IS DEPENDENT ONLY ON PERIOD P AND NOT BY d UNDER THIS SAME λ WITH FEATURE PITCH GIVES SMALLER (P SHARPER) THE DIFFRACTION ANGLE BECOMES LARGER FOLLOWING THE FORMULA $\sin \phi = h \lambda / p$ WITH ϕ ANGLE OF DIFFRACTED RAY AND h INTEGRAL NUMBER.

WHEN MASK IS ILLUMINATED FROM LIGHT TRAVELLING IN VARIOUS DIRECTION WE HAVE A PARTIAL COHERENT IMAGE. THE IMAGE CAN BE CALCULATED BY ADDING IMAGES ARISING FROM ALL INCIDENT LIGHT SOURCES. WE DEFINING $\sigma = \frac{\sin \phi}{\lambda}$ PARTIAL COHERENCE \rightarrow ANGLE WRT \perp OF MASK AT WHICH LIGHT ARRIVES

- FOR A COHERENT ILLUMINATION WE GET A RESOLUTION OF ($\sigma=0$) $R_c = \frac{\lambda}{NA^2}$

FOR PARTIALLY COHERENT ILLUMINATION $R_c = \frac{1}{2} \frac{\lambda}{NA(1+\sigma)}$

- MODULATION TRANSFER FUNCTION (MTF) USED TO DETERMINE THEORETICAL RESOLUTION OR LIMIT OF OPTICAL IMAGING. FOR $\sigma=0$ SYSTEM CAN CAPTURE FREQUENCY UP TO NA/λ FOR $\sigma \leq 1$ SYSTEM ABLE TO RESOLVE UP TO $(1+\sigma)NA/\lambda$

- IMAGE CONTRAST IS INDEX OF AVERAGE INTENSITY AT WAFER LEVEL $C = \frac{I_{MAX} - I_{MIN}}{I_{MAX} + I_{MIN}}$

- DEPTH OF FOCUS IS MAXIMUM AMOUNT OF CHANGE (IN \rightarrow^2 DIRECTION) THAT CAN BE TOLERATED BEFORE PRINTED PATTERN SIZE EXCEEDS OUTSIDE OF SPECIFICATIONS THAT WITH THE FRESNEL CRITERIA CAN BE EXPRESSED AS $DOF = \frac{\lambda}{2NA^2}$

- $\int R_c = k_1 \frac{\lambda}{NA}$ THIS CONSIDERING NEAR SYSTEMS AND RESIST RESPONSE. k_1 MEASURES LITH AGGRESSIVENESS $\int DOF = k_2 \frac{\lambda}{NA^2}$ DEPENDS ON RESIST LENS AND EXPOSURE TOOLS k_2 DEPENDENT ON LIGTHOUSE SHAPE AND CONCENTRATIONS...

- RESOLUTION ENHANCEMENT TECHNIQUES (RET)

- OFF-AXIS ILLUMINATION (OAI)

FILTERING SPATIAL FREQUENCIES ($\frac{1}{P}$) USEFUL TO RECONSTRUCT IMAGE AT WAFER LEVEL AND ASSURE MAXIMUM CONTRAST BECAUSE DC BACKGROUND LIGHT IS MINIMIZED. ILLUMINATION SHAPE MUST BE CUSTOMIZED DEPENDING ON CAVITY RESONANCES TO BE PRINTED

- ATTENUATED PHASE-SHIFT MASKS (ATT-PSM)

DESTRUCTIVE INTERFERING BETWEEN LIGHT TRAVELLING IN THE QUARTZ AND IN THE SHIFTED, MATERIAL IS USED TO ENHANCE AVERAGE IMAGE CONTRAST WRT COHERENT MASKS NO CROMB BUT SEMI-TRANSPARENT LAYER THAT PHASE-SHIFT

- OPTICAL PROXIMITY CORRECTIONS (OPC)

OPCS MAKE SUB-RESOLUTION CHANGES IN THE SHAPE OR THE PATTERN ON THE MASK TO COMPENSATE EFFECTS OF CURRENT WAVELENGTHS AND FEATURE SIZE THAT LOCATES AROUND CONVEX AND CONCAVE LINES

- ALTERNATING LITH TOOLS

- IMMERSION LITHOGRAPHY HAS THE ADVANTAGE OF $n > 1$ SINCE IN WATER $n=1.33$. FURTHERMORE FOR A GIVEN DIRECTION OVER THE ANGLE OF THE LIGHT INSIDE THE FLUID WILL BE USES IN AIR. SMALL ANGLE MEANS SMALL OPTICAL PATH DIFFERENCE AND SO BETTER DEPTH OR FOCUS

- ELECTRON BEAM DIRECT WRITING

PROS: ALREADY KNOWN TECHNOLOGY $\lambda \approx 0.1 \text{ nm}$ SO LOW DIFFRACTION EFFECTS AND NO NEED OF MASK

CONS: HIGH PRODUCTION COST (ELECTRONS HAVING A LOW PERCENT STOPPING EXPOSING UNWANTED AREA)

BRINGING UV (GUV)
SIMILARITY BUILT OPTICAL LITO: IL AND DOK SCANS WITH NA AND λ USES OF REDUCTION OPTICS
SUPPORT OAI PSM AND OPC EMPLOY STEP AND SCAN SYSTEMS
DIFFERENCES VERY SHINY λ ABSORBED BY ALL MATERIALS, VACUUM OPERATION USES NEGLIGIBLE
PARTICLES WITH PARTIALLY ABSORBERS AND REQUIRES REFLECTIVE OPTICS. CHALLENGES IN TOOLS
RESIST AND MASK PROPERTIES

- NANO IMPRINTING LITO (CONTACT PRINTING)
IDENTICAL TO PRODUCTION OR PSM BUT WITH 1:1 DIMENSIONS SO DYNAMIC CONTROL AND POSITIONING
IS CRUCIAL

- THE EFFECTS OF REDUCING DIMENSIONS ON THE LENS NAMES A LPF SO WE ARE LOSING HIGH F
COMPONENTS OF THE DIFFRACTION PATTERN. LOST INFRAS RESULTS IN ABERRATION IMAGING WITH
ROUNDERS COMING SHORTENING OF LENGTHS AND NARROW LINEAR FEATURES.
THIS EFFECTS CAN BE PREDICTABLE AND CAN BE COMPENSATED BY ADJUSTING FEATURES
DIMENSIONS AND SHAPES TO THIS MASK (OPTICAL PROXIMITY CORRECTION OPC)

- EJECTION BEAM LITO
E-BEAM USED FOR MANY YEARS IN MANUFACTURING. OPTIMAL RESOLUTION OBTAINED SINCE e HAVE
WAVELENGTH PROPERTIES HAVING λ LESS THAN 0.1 nm SO DIFFRACTION PROBLEMS ARE NON-LIMITING
MAJOR DRAWBACK SMALL THROUGHPUT SINCE EXPOSURE NATURE BIG PIXEL TO PIXEL IN A SERIAL
PROCESS. THIS COMES FROM A NUMBER OF PROBLEMS: 1) e-BEAM CURRENT IS LIMITED BY
WEAVING MINIMUM NUMBER OF EJECTION TO WELL EXPOSE A PIXEL AND SO UPPER BOUNDS
TO VELOCITY 2) HIGH-BEAM INTENSITY, RESOLUTION CAN BE DEGRADED BY COULOMB REPULSION OF
CHARGED e IN BEAM 3) e WITH 10-20 keV ENERGY SCATTER WITH NUCLEI AND PANEL FOR
AT LEAST 1 μ m AND THIS CAN CAUSE EXPOSURE OF UNWANTED AREAS

- X-RAY LITO
WAVELENGTHS ORDER OF THIN SO DIFFRACTION EFFECTS ARE NEGLECTIBLE BUT FOCUSING X-RAY
IT'S BIG ISSUE SO GENERALLY FOCUSING PRINTING SYSTEMS BASIC CONFIGURATION
X-RAY SOURCE AND OPERATED IN VACUUM AMBIENT.
VISUAL GOOD RESOLUTION AND THROUGHPUT COMPAREABLE WITH OPTICAL SYSTEMS
ISSUES WITH MASK AND X-RAY SOURCE.
NO MATERIAL TRANSMIT X-RAYS BASICALLY SO CLEAR AREAS DON'T BEG LOW MASS MATERIALS
(Si₃N₄) AND DARK AREAS LIVING Au OR W THAT STOPS X-RAYS. MASK LOT REQUIRE AND
NECESSARILY CONTINUOUS MANUFACTURING CONTROL FOR STRESS ISSUES.

CMOS PROCESS FLOW

- INDIVIDUAL DEVICES DO NOT INTERACT WITH EACH OTHER BECAUSE THROUGH THEIR CIRCUIT INTERCONNECTIONS WE NEED TO HAVE CERTAIN THICKNESS OF INDIVIDUAL DEVICES ON CHIP AND ELECTRICALLY ISOLATED FROM EACH OTHER. DONE BY LOCOS

- LOCOS

LOCALLY OXIDIZING SILICON SUBSTRATE PROCESS. LOCAL OXIDATION OF SILICON. THE REACTIONS BETWEEN THIS THICK SiO_2 LAYERS AND CAUSED ACTIVE REGION WHICH WE WILL BUILD OUR MOS DEVICE. THIS IS AN INITIAL STEP.

WAFER IS COATED THAN THIN LAYER OF SiO_2 GROWTH AND DEPOSITION OF Si_3N_4 . Si_3N_4 CREATS COMPRESSIVE STRESS ON SUBSTRATE SO THE MAJOR REASON OF SiO_2 GROWTH FIRST IS TO RELIEVE THIS STRESS THAT CAN LEAD TO DAMAGE OF WAFER (SiO_2 CREATS STRESS IN OPPOSITE WAY BALANCING THE THICKNESS OF THE 2 WE CAN HAVE STRESS NULLED). DEPOSITION OF PHOTORESIST AND EXPOSURE TO PATTERN LOCOS ZONES.

Si_3N_4 IS NOW DRY ETCHED USING PHOTORESIST AS MASK. RESIST STRIPPED OFF AND THEN AGAIN IN OXIDIZING AMBIENT IN ORDER TO USE Si_3N_4 TO STOP OXIDATION IN ACTIVE REGIONS AND TO OXIDIZE THE UNWANTED PART (GROWTH OF SiO_2 INSIDE Si). AFTER THIS Si_3N_4 CAN BE STRIPPED OFF.

- POLY-BURIED LOCOS

NOW $\text{SiO}_2/\text{Si}_3\text{N}_4$ BURIED LAYERS SiO_2 - POLY SILICON - Si_3N_4 . PROCESS IS THE SAME POLY SILICON USED TO RELIEVE THE STRESS DUE TO Si_3N_4 . THIS OXIDATION EXTEND FOR SOME DISTANCE UNDER Si_3N_4 (BIRD'S BEAK) IN THE UN-WANTED ZONE AND THIS CAN CAUSE PROBLEMS AND NON-MANUFACTURABILITY.

- STI SHALLOW TRENCH ISOLATION

ELIMINATES BIRD'S BEAK PROBLEMS.

SiO_2 AND Si_3N_4 DEPOSITED (SOLVED RELATED ISSUES NO BIG PROBLEM NOW SINCE WE DON'T HAVE LONG HIGH-T OXIDATION BUT THICKNESS OF 2 LAYERS COMPENSATES STRESS). PHOTORESIST APPLIED EXPOSED AND DEVELOPED. NITROGEN AND OXIDE LAYER ETCHED USING PHOTORESIST AS MASK. THEN TRENCHES ETCH THAT ARE 0.5 μm DEEP. WE CAN USE AGAIN PHOTORESIST AS MASK ON THE $\text{SiO}_2/\text{Si}_3\text{N}_4$ AND THEN DEPOT. WE CAN USE AGAIN PHOTORESIST AS MASK ON THE $\text{SiO}_2/\text{Si}_3\text{N}_4$ LAYER. IMPORTANT THAT TRENCHES WALLS ARE VERTICAL SO THERE IS LITTLE UNDERCUTTING UNDER ADJACENT REGIONS. AFTER TRENCH DONE THERMAL GROWTH OF A NATIVE OXIDE (THIN LAYER) TO HAVE GOOD Si/SiO₂ INTERFACE AND ROUND THE CORNERS THEN DEPOSITION ANOTHER OR THICK LAYER OF SiO_2 BY CVD. NO VOIDS OR GAP IN TRENCHES IS FUNDAMENTAL. AFTER THIS CMP TO PLANARIZE ALL AND REMOVAL OF Si_3N_4 LAYER.

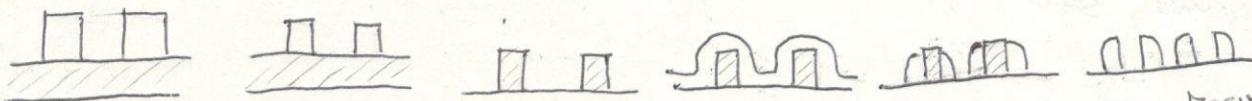
MEMORY PROCESS FLOW

- OBJECTS TO BE BUILT ON CHARGE ARE 3 : + FLOATING GATE TRANSISTORS (MEMORY CELLS)
+ LOW VOLTAGE TRANSISTORS LV BDMT P-N MOS + HIGH VOLTAGE TRANSISTORS HV BDMT P-N MOS

- DOUBLE PATTERNING

- POSSIBLE OPTION TO OVERCOME RESOLUTION LIMITS OR LWD

POSITIVE DOUBLE PATTERNING: PHOTONISRY DEBURDED ON A SECONDARY LAYER WITH MINIMUM SIZE SURVIVED BY THERMAL PROCESSSES. THEN IT IS TO TRANSFER ON IMAGE ON SECONDARY LAYER. DEPOSITION OF A SUPPORT MATERIAL ALL OVER AND THEN ANISOTROPIC Etch TO FORM SPACERS AROUND SECOND LAYERS. REMOVAL OF THIS SECOND LAYER AND USE OF THESE SPACERS AS MASK FOR NEXT PROCESS



NEGATIVE DOUBLE PATTERNING: UNTIL SPACER FORMATION THEN DEPOSITION OF SECONDARY LAYER ALL OVER PATTERNING. THEN SiNP OR SPACERS AND

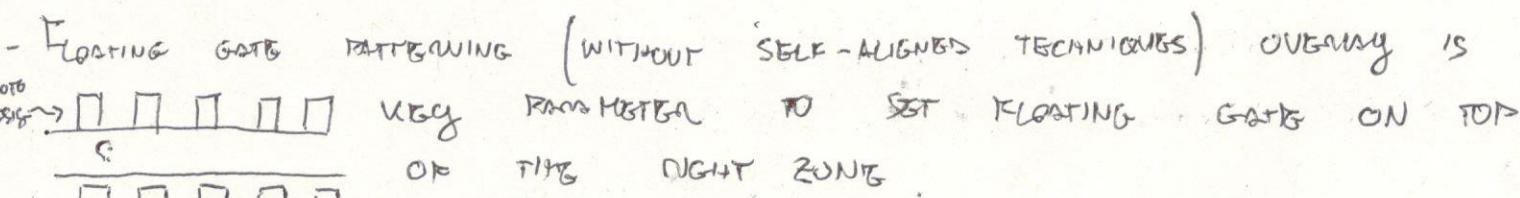
THE SAME OF POSITIVE APPROACH TO KILL GAPS AND POLISH TO USE OR REMAINING AS MASK



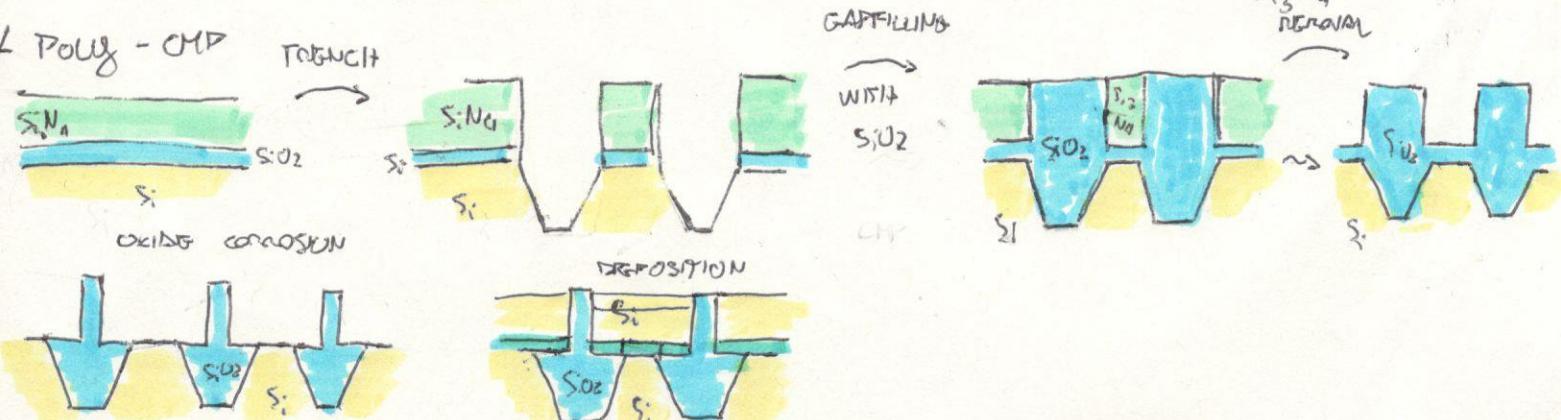
- NEGATIVE APPROACH HAS BETTER DIMENSIONAL CONTROL ON SPACES (LINES AND SPACES) PAIR WITH FIRST LWD PROCESS PAIR WITH FILLING AND PUNARIZATION)

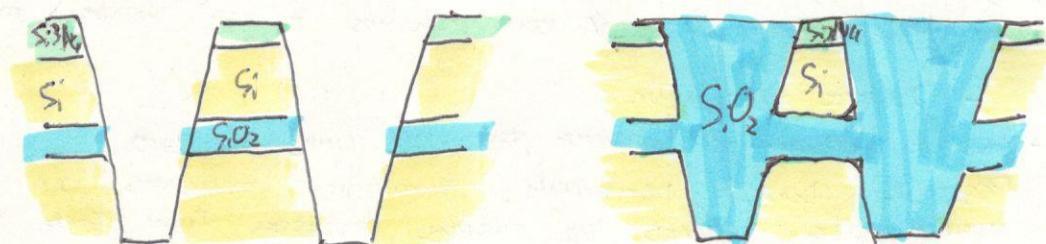
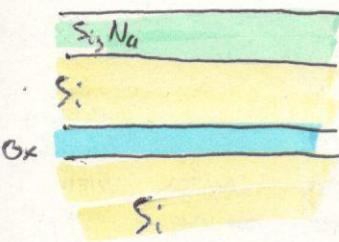
- MAIN DRAWBACK IS THERE ARE NECESSARY ADDITIONAL MASKS TO CUT THE LINES TERMINATION (THAT IN POSITIVE APPROACH AGES IN A SHORT 2 BY 2) OR TO PRINT NON PITCH STRUCTURES

- DOUBLE EXPOSURE: A MASK WITH DOUBLE PITCH WRT THE WANTED ONE IS EXPOSED 2 TYPES WITH THE SECOND EXPOSURE TRANSLATED OF $\frac{1}{2}$ PITCH WRT THE FIRST. MAIN DRAWBACK IS THAT THE LWD QUALITY DEPENDS ON THE OVERLAP OF THE 2 EXPOSURES

- FLOATING GATE PATTERNING (WITHOUT SELF-ALIGNED TECHNIQUES) OVERLAY IS PHOTO NOISE  VBG RARE METAL TO SET FLOATING GATE ON TOP OR THE RIGHT ZONE.

SELF ALIGNED TECHNIQUES ARE USED USING POLY CMP AND ASASTI





ROUNDING PROBLEMS DVS&B

- STRESS MEASUREMENT WITH NUCLEUS RAYLEIGH SPECTROSCOPY : STRESS ALONG THE SILICON RAYLEIGH SHIFT