ECE571 MicroFab

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1 Miscellaneous

Si atom density	$5 \times 10^{22}\mathrm{cm}^{-3}$
Boltzmann constant	$\kappa_B = 8.62 \times 10^{-5}\mathrm{eV/K}$
Vacuum permittivity	$\epsilon_0 = 8.854 \times 10^{-12}\mathrm{F/m}$
$^\circ C \rightarrow {}^\circ K$	$+273^\circ$
Capacity	$C = \frac{\epsilon_r \epsilon_0 A}{d}$
Diffusivity	$D = D_0 \cdot \exp(-E_a/k_B T)$

2 Ingot

2.1 Czochralski

Crystalgrowth process:

1. Polyxtals melted in a Qz crucible (>1500°C)
2. Seedxtal put in contact with surface (seed determines orientation)
3. Si atoms nucleate; ingot grows while being pulled up out of melt

2.2 Ingot Dopant Profile

Czochralski - CZ
Segregation coefficient $k_0 = \frac{C_s}{C_l}$ *(solid side / liquid side concentration)*

Dopant concentration profile: $\boxed{C_s(x) = C_0 k_0 (1-x)^{k_0 - 1}}$

Higher $k_0 < 1$ are often preferable ⇝ flatter profile = more wafers with uniform dopant concentration

Floating Zone - FZ
A ring heats up a small section of ingot and goes through ingot in **one** direction. Impurities move towards current liquid section. Used to clean ingot of impurities if a high ρ ingot is wanted. Process drives impurities to one end of ingot. Repeat process to get better results.

Dopant concentration profile: $\boxed{C_s(x) = C_0[1 - (1-k_0)exp(-\frac{-k_0 x}{L})]}$

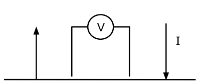
3 Wafer

Crystal Orientation and Flats
TODO better image with same orientations as in lecture

3.1 Electrical Characterization

Dopant type – Dopant type of wafer can be determined using a **hot probe**. This is a setup with two connected probes on surface of wafer. One probe is heated and drives majority carriers away of itself. Direction of the resulting current tells the carrier type (e^- or hole).

Impurity concentration – Impurity concentration can be inferred from resistivity. Use **four-point-probe** to measure resistivity. Outer probes enforce I, inner probes measure V. This setup prevents contanct resitance to distort result (contact resitance only at outer probes).



$R = \frac{V}{I}$

4 Silicon Oxide

4.1 Oxide Growth – Deal-Grove Model

Oxide thickness $\boxed{d_{ox} = \frac{A}{2}\left(\sqrt{1 + \frac{t+\tau}{A^2/4B}} - 1\right)}$

$\tau = \frac{d_i^2 + A d_i}{B}$; d_i is initial thickness

Standard Simplifications

1. $t \gg A^2/4B$ ⇝ "Thicker" oxides (parabolic growth): $\boxed{d_{ox} = \sqrt{Bt}}$
2. $t + \tau \ll A^2/4B$ ⇝ "Thinner" oxides (linear growth): $\boxed{d_{ox} = \frac{B}{A}(t+\tau)}$

Also, note $\left(\frac{B}{A}\right)_{(111)} = 1.68 \left(\frac{B}{A}\right)_{(100)}$

4.2 Oxide to Silicon Relationship

A unit cube of Si will become SiO_2 with a volume that is 2.24 times bigger. If the growth is constrained to one dimension, this is the relationship of thickness.
Using this relationship: Of 100

4.3 Electrical Characterization of Oxide

C-V profile – The capacity of the wafer can be measured. When the MOS structure is in **accumulation** or **inversion at low frequency**, the measured capacity $C = C_{ox}$. For **depletion** or **inversion at high frequency**, the measured capacity is smaller (capacitances in series).

To measure the capacity, a small alternating voltage is added to the DC voltage at the wafer. The resulting current will have a part that is phase-shifted compared to the voltage ($+90^\circ$ or $+\pi/2 leadsto$ current precedes voltage).

Calculate C using $i(t) = C\frac{dv(t)}{dt}$

4.4 High-k Dielectric Materials

Recall $C = \frac{\epsilon A}{d}$. "High k" materials with ϵ_r greater than SiOx allow to get the same electrical behavior (capacity C) for the gate oxide with **thicker** spacing. **More space between channel and gate electrode ⇝ smaller leakage current!**

5 Lithography

5.1 System Parameters

Rayleigh criterion/limit $R = \frac{1.22\lambda}{d} f$; d: *aperture diameter*

⇝ for lithography, **resolution** $\boxed{R = W_{min} = k_1 \frac{\lambda}{NA}}$; k_1: *process parameter*

Numerical aperture $\boxed{NA = n \cdot \sin(\alpha)}$; n: *refractive index of medium between objective - wafer*; α: *objective lens acceptance angle*

Depth of focus (DOF) $\boxed{DOF = \frac{n\lambda}{NA^2}}$

Modulation transfer function (MTF) $\boxed{MTF = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}}$

Strive for: $R \downarrow, DOF \uparrow, MTF \rightarrow 1$

5.2 Photoresist

Contrast $\boxed{\gamma = \frac{1}{\log(D_{100}/D_0)}}$

Critical modulation transfer function (CMTF) $\boxed{CMTF = \frac{D_{100} - D_0}{D_{100} + D_0} = \frac{10^{-\gamma} - 1}{10^{-\gamma} + 1}}$

$CMTF < MTF$ must hold for the image to resolve!

5.3 Improving Resolution

Methods without reducing λ:

- **Immersion lithography** – Add a liquid (DI water) between lens and PR ⇝ $NA \uparrow$
- **Off-axis illumination**
- **Phase shift mask**
- **Optical proximity correction**
- **Double/multi patterning**

Reducing λ:

- **Extreme ultraviolet (EUV)** – $\lambda = 13\mathrm{nm}$ or lower. At these wavelengths there is no material that can act as a lens (it will all be absorbed). System of mirrors used instead (compare to astronomy).
- **X-ray**

Alternative: **Nano imprint lithography** uses a mold to print pattern into resist.

6 Doping

6.1 Thermal Diffusion

Typically, source on wafer surface. Drive-in by thermal diffusion. Two different cases:

Unlimited/constant source, predeposition – Dopant concentration at wafer surface held constant over whole diffusion process (normally **solid solubility!**).

$C(z,t) = C_S \mathrm{erfc}\left(\frac{z}{2\sqrt{Dt}}\right)$
$Q_T(t) = \frac{2}{\pi} C(0,t)\sqrt{Dt}$
$x_j = 2\sqrt{Dt}\mathrm{erfc}^{-1}\left(\frac{C_S}{C_B}\right)$

Limited source, drive-in – A fixed amount of dopant Q_T is applied to wafer surface. Amount given as surface concentration (cm^{-2}).

$C(z,t) = \frac{Q_T}{\sqrt{\pi D t}} \mathrm{e}^{-z^2/4Dt}$

$x_j = \sqrt{4Dt \ln\left(\frac{Q_T}{C_B\sqrt{\pi D t}}\right)}$

A case that often appears is a predeposition step followed by drive-ins (normally parasitic thermal processes). If $\sqrt{Dt_p redep} \ll \sqrt{Dt_d rive-in}$*, then the dose is given by the predeposition, while the resulting concentration profile and junction depth can be approximated using the drive-in model.*
To combine multiple diffusion steps in a sequence use the sum of all Dt*'s:* $Dt_{eff} = Dt_1 + Dt_2 + \ldots$

6.2 Ion Implantation

Impurity concentration $\boxed{N(x) = N_p \mathrm{e}^{-(x-R_p)^2/2\Delta R_p^2}}$

R_p: projected range
ΔR_p: projected straggle

For implant completely in silicon $\boxed{Q = \sqrt{2\pi} N_p \Delta R_p}$

Junction depth $\boxed{x_j = R_p \pm \Delta R_p \sqrt{2\ln(N_p/N_B)}}$