Crib sheet 3: (MOS devices, Schottky junctions, CMOS)

Electrostatic potentials for MOS capacitors

$$\phi(x) = \frac{1}{q}\left[E_{\mathrm{i}}(\mathrm{bulk}) - E_{\mathrm{i}}(x)\right]$$

Potential at position x

$$\phi_{\mathrm{S}} = \frac{1}{q}\left[E_{\mathrm{i}}(\mathrm{bulk}) - E_{\mathrm{i}}(\mathrm{surface})\right]$$

Potential at semiconductor/oxide interface

$$\phi_{\mathrm{F}} = \frac{1}{q}\left[E_{\mathrm{i}}(\mathrm{bulk}) - E_{\mathrm{F}}\right]$$

Bulk potential in semiconductor (ϕ_{F} depends on doping concentration)

Gate-Voltage relationship

$$V_{\mathrm{G}} = \phi_{\mathrm{S}} \pm \frac{\varepsilon_{\mathrm{Si}}}{\varepsilon_{\mathrm{ox}}} x_{\mathrm{ox}} \sqrt{\frac{2qN_{\mathrm{A/D}}}{\varepsilon_{\mathrm{Si}}}|\phi_{\mathrm{S}}|}$$

+/– and $N_{\mathrm{A}}/N_{\mathrm{D}}$ for NMOS/PMOS

Threshold voltage $V_{\mathrm{G}} = V_{\mathrm{T}}'$ if $\phi_{\mathrm{S}} = 2\phi_{\mathrm{F}}$ (V_{T}' doping dependent, see ϕ_{F} above)

Depletion layer width: $W = \sqrt{\dfrac{2\varepsilon_{\mathrm{Si}}|\phi_{\mathrm{S}}|}{qN_{\mathrm{A/D}}}}$ ($W = W_{\mathrm{T}}$ if $\phi_{\mathrm{S}} = 2\phi_{\mathrm{F}}$)

MOS-Capacitances: $C_{\mathrm{ox}} = \dfrac{\varepsilon_{\mathrm{ox}}}{x_{\mathrm{ox}}}$; $C_{\mathrm{S}} = \dfrac{\varepsilon_{\mathrm{Si}}}{W}$; $C_{\mathrm{G}} = \dfrac{C_{\mathrm{S}} C_{\mathrm{ox}}}{C_{\mathrm{S}} + C_{\mathrm{ox}}}$

***I-V* relationships for NMOS devices:** Z = gate width, L = gate length, A = gate area = $Z \times L$

$$I_{\mathrm{DSat}} = \frac{Z\mu C_{\mathrm{ox}}}{2L}(V_{\mathrm{G}} - V_{\mathrm{T}})^2 \text{ for } V_{\mathrm{D}} > V_{\mathrm{DSat}} \text{ and } V_{\mathrm{G}} \geq V_{\mathrm{T}} \text{ with } V_{\mathrm{DSat}} = V_{\mathrm{G}} - V_{\mathrm{T}}$$

$$I_{\mathrm{D}} = \frac{Z\mu C_{\mathrm{ox}}}{L}\left[(V_{\mathrm{G}} - V_{\mathrm{T}})V_{\mathrm{D}} - \frac{V_{\mathrm{D}}^2}{2}\right] \text{ for } 0 \leq V_{\mathrm{D}} \leq V_{\mathrm{DSat}} \text{ and } V_{\mathrm{G}} \geq V_{\mathrm{T}}$$

Small-signal parameters and cut-off frequency:

Below pinch-off: ($V_{\mathrm{D}} \leq V_{\mathrm{DSat}}$) $g_{\mathrm{d}} = \dfrac{Z\mu C_{\mathrm{ox}}}{L}(V_{\mathrm{G}} - V_{\mathrm{T}} - V_{\mathrm{D}})$ $g_{\mathrm{m}} = \dfrac{Z\mu C_{\mathrm{ox}}}{L} V_{\mathrm{D}}$

Under saturation: ($V_{\mathrm{D}} > V_{\mathrm{DSat}}$) $g_{\mathrm{d}} = 0$ $g_{\mathrm{m}} = \dfrac{Z\mu C_{\mathrm{ox}}}{L}(V_{\mathrm{G}} - V_{\mathrm{T}})$

cut-off frequency: $f_{\mathrm{t}} = \dfrac{g_{\mathrm{m}}}{2\pi C_{\mathrm{G}}} \approx \dfrac{g_{\mathrm{m}}}{2\pi C_{\mathrm{ox}} A}$

Relationships for real MOS devices:

Flatband voltage $$V_{\mathrm{FB}} = \frac{1}{q}\Phi_{\mathrm{MS}} + \left(-\frac{Q_{\mathrm{i}}}{C_{\mathrm{ox}}}\right) \text{ with } \Phi_{\mathrm{MS}} = \Phi_{\mathrm{M}} - \Phi_{\mathrm{S}}$$

Real threshold voltage: $V_{\mathrm{T}} = V_{\mathrm{FB}} + V_{\mathrm{T}}'$ (V_{T}' = threshold voltage of ideal device)

Relationships for MS (Schottky) junctions (n-type semiconductor):

Schottky barrier height: $\Phi_{\mathrm{B}} = \Phi_{\mathrm{M}} - \chi$ (independent of applied voltage)

Schottky-diode built-in potential: $$qV_{\mathrm{bi}} = \Phi_{\mathrm{B}} - (E_{\mathrm{c}} - E_{\mathrm{F}}) = \Phi_{\mathrm{B}} - \left[\frac{E_{\mathrm{G}}}{2} - (E_{\mathrm{F}} - E_{\mathrm{i}})\right]$$

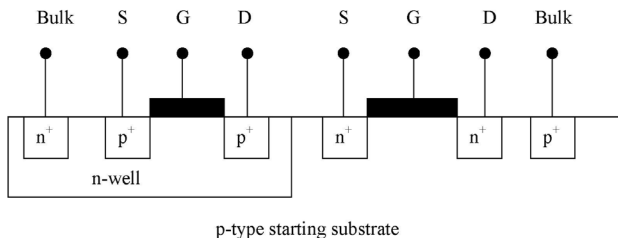
Ion implantation

Ion implantation profile: $$N(x) = \frac{iondose}{\sqrt{2\pi}\Delta R_{\mathrm{p}}} \exp\left[-\frac{1}{2}\left(\frac{x - R_{\mathrm{p}}}{\Delta R_{\mathrm{p}}}\right)^2\right]$$ $[iondose]$ = # of ions/cm^2

V_{T}-shift by ion-implantation: $$|\Delta V_{\mathrm{T}}| = \left|\frac{q\ iondose}{C_{\mathrm{ox}}}\right|$$

Boron ions in Si → acceptors: $\Delta V_{\mathrm{T}} > 0$ (positive shift)
Phosphorous ions in Si → donors: $\Delta V_{\mathrm{T}} < 0$ (negative shift)

CMOS schematic for p-type starting substrate
(for n-type starting substrate change conductivity types appropriately)



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