Oxide and Process Characterization Using C-V Methods

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Agenda

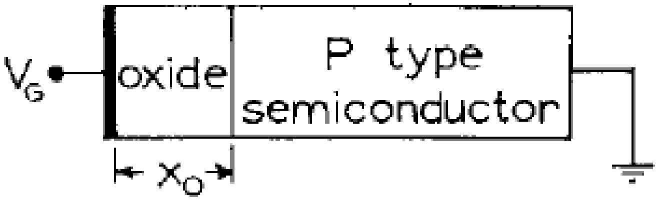
- Introduction
- MOS Capacitor Fundamentals
- Parameter Extraction Using C-V Techniques
- Conclusions

Introduction

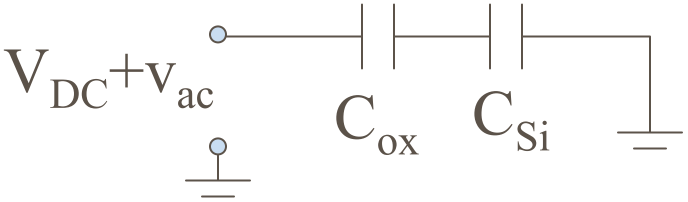
- **Oxide Characterization**
  - Oxide Capacitance (C_{ox}) → V_{TH}, γ, k
  - Fixed Oxide Charges (Q_f)
  - Interface Trap Charges (Q_{it})
- **C-V Method (MOS Capacitor)**
  - Extraction from Capacitance vs. Voltage Plots
- **C-V Method Merits**
  - MOS Cap – Natural by-product of CMOS Technology
  - Wealth of Device and Process information can be extracted → N_{sub}, V_{FB}, τ_{gen}

MOS Capacitor Fundamentals

- **Non-Linear Capacitance**
  - Capacitance varies with voltage



- **Modeled as C_{ox} in series with C_{Si}**
- **Three Basic Regimes of Operation**
  - Accumulation
  - Depletion
  - Inversion



MOS Capacitor Fundamentals

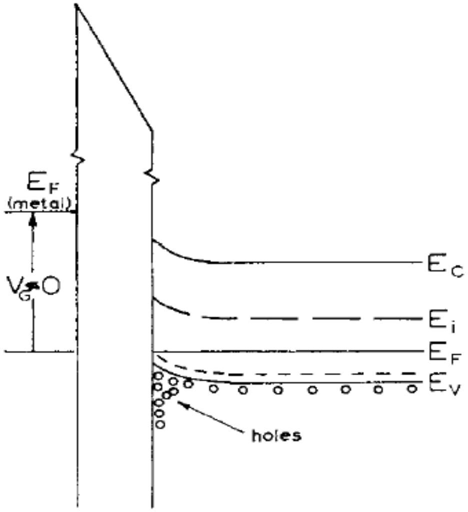
p-type Semiconductor

Accumulation[1]

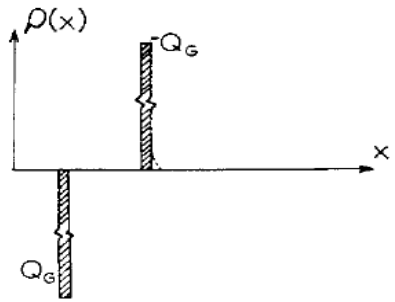
$$\frac{1}{C} = \frac{1}{C_{ox}} + \frac{1}{C_{Si}}$$

$$C_{Si} = \left| \frac{dQ_{Si}}{d\psi_s} \right|$$

$$C(accum) = \frac{1}{\dfrac{t_{ox}}{\varepsilon_{ox}} + \dfrac{L_D}{\varepsilon_{Si}} \dfrac{\sqrt{2}}{\exp\left[q|\psi_s| / 2kT \right]}}$$



(a) ACCUMULATION of majority carriers near surface



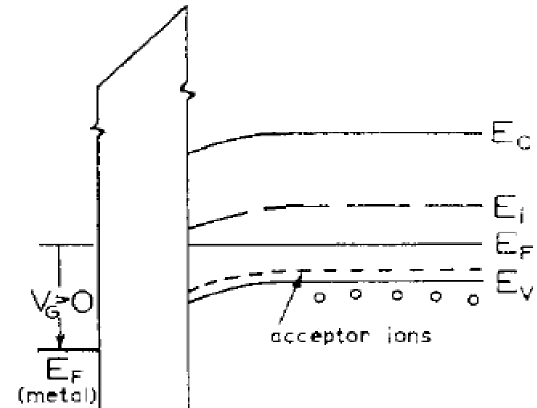
[1]H.Craig Casey Jr., *Devices for Integrated Circuits – Silicon and III-V Compound Semiconductors*, John Wiley & Sons, Inc., NY 1999

MOS Capacitor Fundamentals

p-type Semiconductor

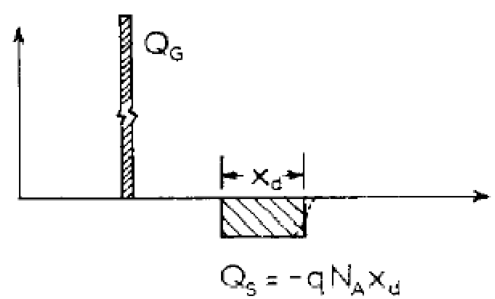
Depletion[1]

- Pos. V_G → Depletion Region
- Depletion extends with voltage
- Capacitance Decreases
  - Min. at Max. Depletion



(b) DEPLETION of majority carriers from surface

$$C(x_{d\max}) = \frac{1}{\dfrac{t_{ox}}{\varepsilon_{ox}} + \dfrac{x_{d\max}}{\varepsilon_{Si}}} \qquad x_{d\max} = \sqrt{4\varepsilon_{Si}|\psi_B| \big/ qN_A}$$



[1] H.Craig Casey Jr., *Devices for Integrated Circuits – Silicon and III-V Compound Semiconductors*, John Wiley & Sons, Inc., NY 1999

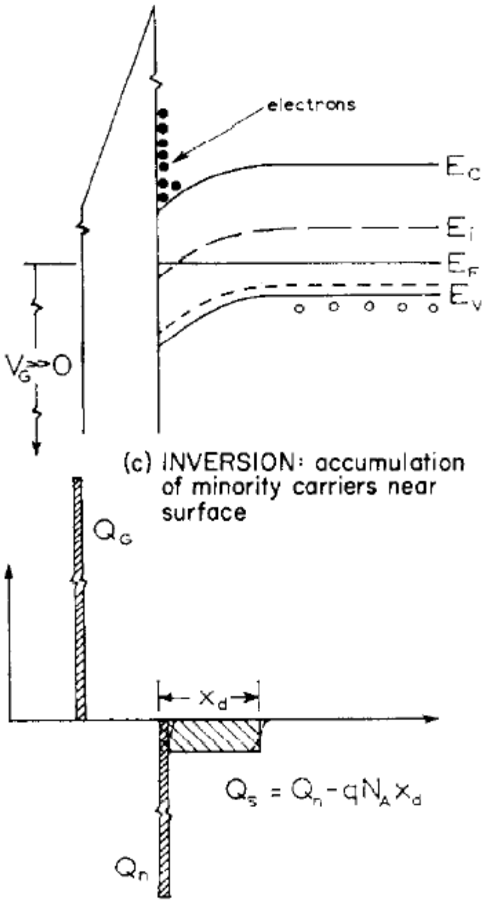
MOS Capacitor Fundamentals

p-type Semiconductor

Inversion[1]

- Further Increases in V_G
  - Surface gets Inverted
  - Minority Carriers are formed
    - Time Dependent Thermal Generation

Low Freq. Sweep | High Freq. Sweep



[1]H.Craig Casey Jr., *Devices for Integrated Circuits – Silicon and Semiconductors*, John Wiley & Sons, Inc., NY 1999

MOS Capacitor Fundamentals

High Frequency AC Signal

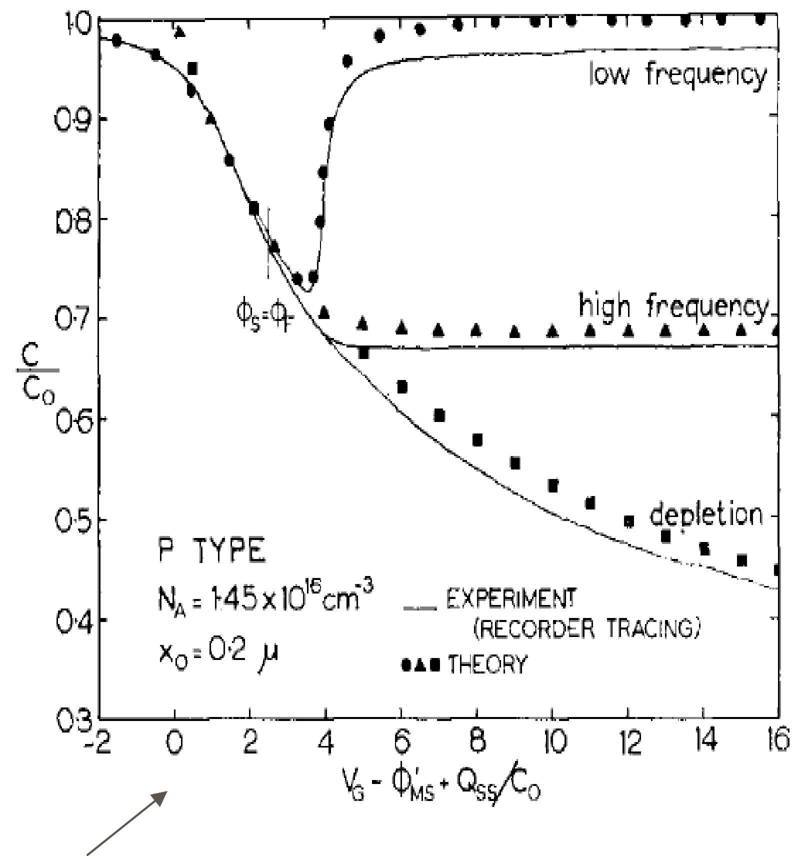
- Minority Carriers in Equilibrium with DC Signal
- Measured Cap saturates to value determined by x_{dmax}

Low Frequency AC Signal

- Minority Carriers in Equilibrium with AC Signal
- Charge on Gate compensated by inversion layer

Non-Equilibrium

- DC Sweep really fast
- Charge on Gate compensated by Depletion region width increase



[2]Grove et. al.,Solid-State Electronics, Vol.8, pp.145-163

Parameter Extraction

Oxide Thickness (T_{ox})

- Extracted from the capacitance in deep accumulation → Valid for thick oxides
- For thin oxides (< 5nm)[3]
  - QM employed for describing the SC beneath the Oxide
  - QM shifts charge centroid away from the substrate/oxide interface → Equivalent oxide thickness increase

$$\frac{1}{C_{hf}} = \frac{1}{C_{ox}} + \frac{1}{C_{Si}} + \frac{1}{C_{poly}}$$

QM Effects Incorporated

  - T_{ox} → Comparing Theoretical with Measured C_{hf} value

[3] Dmowski.K et. al.,Journal of Non-Crystalline Solids, 216 pp. 185-191, 1997

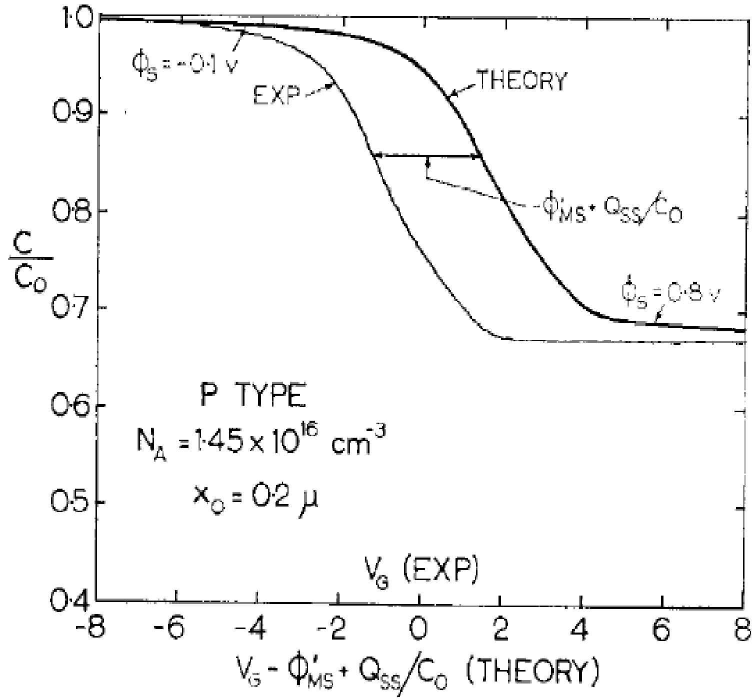
Parameter Extraction

Oxide Fixed Charge (Q_{fixed})

- Extracted from the shift in the theoretical and measured Curves
- Lateral Shift also due to Mobile Charges - Limitation

Interface Trapped Charge (Q_{it})

- Affects the slope of the C-V
- Estimated by comparison of theoretical and measured curves



[2]Grove et. al.,Solid-State Electronics, Vol.8, pp.145-163

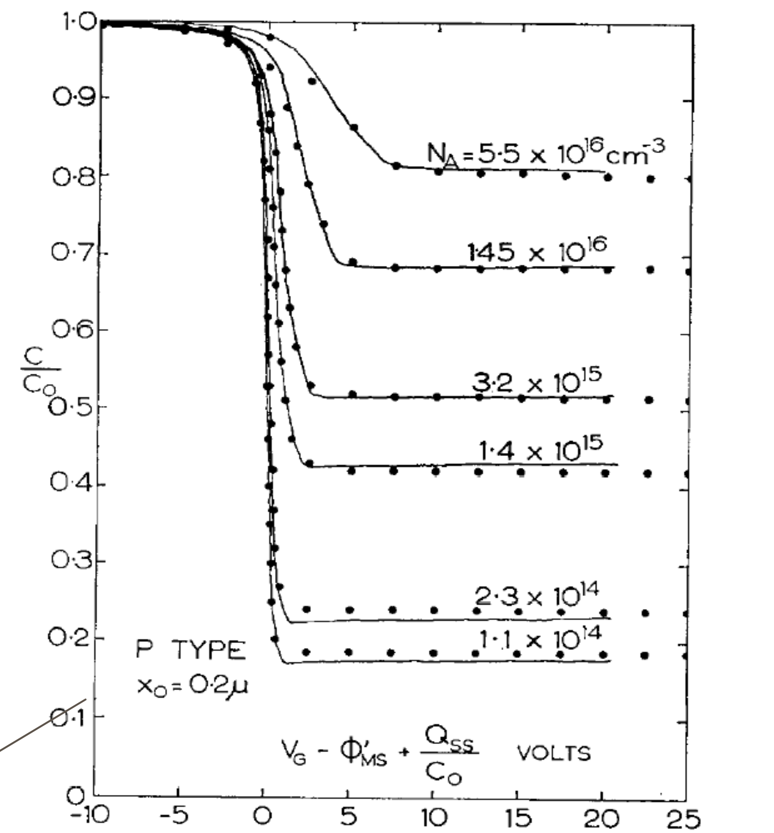
Parameter Extraction

Average Substrate Doping (N_{sub})

- C_{max}-C_{min} Method[4]

$$\frac{N_{sub}}{\ln\left(\frac{N_{sub}}{n_i}\right)+0.5\ln\left(2\ln\left(\frac{N_{sub}}{n_i}\right)-1\right)}=\frac{4kT\varepsilon_{ox}^2}{q^2\varepsilon_{Si}t_{ox}^2}\left(\frac{C_{max}}{C_{min}}-1\right)^{-2}$$

$C_{min} \rightarrow C(x_{dmax})$ and $C_{ox} \rightarrow C_{max}$



[2] Grove et. al.,Solid-State Electronics, Vol.8, pp.145-163

[4] Deal B.E. et al., J.Electrochemical Soc., 112, 1965

Parameter Extraction

Flat Band Voltage (V_{FB})

$$C_{FB} = \frac{1}{\frac{t_{ox}}{\varepsilon_{ox}} + \frac{L_D}{\varepsilon_{Si}}} \qquad L_D = \sqrt{\frac{\varepsilon_{Si} kT}{q^2 N_A}}$$ [1]

- V_{FB} → Extracted by reading off C_{FB} from the C-V curve[5]

[1] H.Craig Casey Jr., *Devices for Integrated Circuits – Silicon and III-V Compound Semiconductors*, John Wiley & Sons, Inc., NY 1999

[5] Keithley Application Note #2239

Conclusions

- MOS C-V Measurement widely used to extract parameters and for process monitoring
- Parameters extracted include
  - C_{ox} and hence T_{ox}
  - Fixed Oxide Charge and Interface Trapped Charges
  - Average Doping concentration near the oxide
  - Flat Band Voltage
  - Minority Carrier Generation Lifetimes