Oxide and interface trapped charges in MOS-C
Outline

• Introduction
• Tools for measurement
• 4 types of oxide impurities
  - Fixed Oxide Charge (FOC)
  - Mobile Oxide Charge (MOC)
  - Oxide Trapped Charge (OTC)
  - Interface Trapped Charge (ITC)
• Fundamental techniques for characterization
• Homework
About me

• First year PhD student
• Charge capturing in silicon quantum dot single-electron pumps

• My motivation:

$t_{ox} = 4 \text{ nm}, T_{operation} < 200 \text{ mK} \& f > 1 \text{ GHz}$
Introduction

Metal-Oxide-Semiconductor

If we have imperfections:
- Stronger 1/f noise
- Oxide turns to be amorphous
- Field effect mobility changes

Description is applicable to all insulator-semiconductor systems, but we aim for learning SiO$_2$-Si (p-type).

1) Interface Trapped Charge
2) Fixed Oxide Charge
3) Oxide trapped charge
4) Mobile Oxide Charge
Capacitance in MOS

Applying $V_G > 0$

$V_G = V_{FB} + V_{ox} + \phi_s$

$C = \frac{dQ}{dV}$

$C = \frac{C_{ox}(C_p + C_b + C_n + C_{it})}{C_{ox} + C_p + C_b + C_n + C_{it}}$

$\phi_s$ - surface potential (total bending of $E_i$)

- $V_{ox}$ - oxide voltage
- $V_{fb}$ - flatband voltage

$C_{ox}$ – oxide capacitance
$C_p$ – hole capacitance
$C_n$ – electron capacitance
$C_b$ – space-charge density bulk charge
$C_{it}$ – interface trap capacitance

Aalto University
School of Science
Quantifying oxide imperfections

• $Q$ – charge per unit area ($\text{C cm}^{-2}$)
• $N$ – number of charges per unit area ($\text{cm}^{-2}$)
• $D$ – charge density ($\text{cm}^{-2} \text{eV}^{-1}$)
• $\rho$ – number of charges per volume ($\text{cm}^{-3}$)

$$V_{FB} = \phi_{MS} - \frac{Q_f}{C_{ox}} - \frac{Q_{it}(\phi_s)}{C_{ox}} - \frac{1}{C_{ox}} \int_{t_{ox}}^{t_{ox}} \frac{x}{t_{ox}} \rho_m(x) \, dx - \frac{1}{C_{ox}} \int_{t_{ox}}^{t_{ox}} \frac{x}{t_{ox}} \rho_{ox}(x) \, dx$$

Metal – Semiconductor work function difference
Capacitance in MOS

4th floor lab

Hewlett Packard 4192A LF impedance analyzer

- Frequency range: 5 Hz – 13 MHz
- $V_{pp} = 2$ V
- $V_{bias} = -40$ V to +40 V

![Image of equipment and graph](image-url)
Capacitance measurement

- **High frequency:**
  
  \[ v_o \approx (RG + j\omega RC)v_i \]

  $G$ – conductance of scr and oxide

  Two phases: on phase $RG$, and $90^\circ$ phase component $RC$, $C$ and $G$ can be extracted

- **Quasi-static:**
  
  not so efficient, strong $1/f$ noise

  can be measured using op-amp, linear ramp on gate voltage

  \[ I = \frac{dQ_G}{dt} = \frac{dQ_G}{dV_G} \frac{dV_G}{dt} = C \frac{dV_G}{dt} \]

  constant
C – V curves in theory

- High frequency ac voltage on $V_g$ (10 kHz – 1 MHz)

$$C_{S,hf} = \sqrt{\frac{q^2 K_s \varepsilon_0 N_A}{2kT[2|U_F| - 1 + \ln(1.15(|U_F| - 1))]}}$$

- Low frequency ac voltage on $V_g$

$$U_F = \frac{q\phi_F}{kT}$$
$$U_S = \frac{q\phi_s}{kT}$$
$$\phi_F = \frac{(kT/q) \ln(N_A/n_i)}{2L_{Di}}$$
$$L_{Di} = \sqrt{\frac{K_s \varepsilon_0 kT}{2q^2 n_i}}$$

- Rapidly changed dc bias → no inversion charge generation → Deep depletion

$$C_{S,dd} = \frac{C_{ox}}{\sqrt{1 + 2(V_G - V_{FB})/V_0}}$$

$$C = \frac{C_{ox} C_S}{C_{ox} + C_S}$$

$$V_G = V_{FB} + \phi_s + V_{ox} = V_{FB} + \phi_s + \hat{U}_S$$
$$\frac{kT K_s l_{ox} F(U_S, U_F)}{q K_{ox} L_{Di}}$$
1) Fixed Oxide Charge \((Q_f, N_f)\)

Positive charges near the Si-SiO\(_2\) interface

Origin: created during oxidation

Indistinguishable from Interface Trapped Charges → measurable after annealing

Cure:
1. Use high temperature oxidation → reduces \(Q_f\)
2. Anneal after oxidation with N\(_2\) or Ar

*Deal triangle*: effect of annealing on \(Q_f\)
How to measure FOC?

Remove other oxide charges

Measure high frequency $C - V$ curve

Compare with theory curves

$Q_f = (\phi_{MS} - V_{FB})C_{ox}$

How to know $\phi_{MS}$?
Indirectly from photoemission measurements

An other approach:
No need for work function!
Just measure at different $t_{ox}$

$V_{FB} = \phi_{MS} - \frac{Q_f}{C_{ox}} = \phi_{MS} - \frac{Q_f t_{ox}}{K_{ox} \varepsilon_o}$
2) Mobile Oxide Charge \( (Q_m, N_m) \)

Ionic impurities in oxide such as \( \text{Na}^+, \text{Li}^+, \text{K}^+, \text{H}^+ \)
- Lithium: vacuum pumps oil
- Potassium: chemical-mechanical polishing
- Sodium: most common contaminant
Origin: negative ions and heavy metals

Mobility: Electric field in oxide \( \rightarrow \) drift velocity of mobile ions through the oxide

Transit time:
\[
\tau = \frac{t_{ox}}{v_d} = \frac{t_{ox}^2}{\mu V_G} = \frac{t_{ox}^2}{\mu_o V_G} \exp\left(\frac{E_A}{kT}\right)
\]

Mobility:
\[
\mu = \mu_o \exp\left(-\frac{E_A}{kT}\right)
\]
Measuring Mobile Oxide Charge:

- **Bias-Temperature Stress**: High temperature (150 – 250 °C) and $V_G$ applied electric field $E=10^6 \text{V/cm}$ for 5-10 min $\rightarrow V_{FB}$ shifts (repeated with opposite bias polarity)
  
  Direct charge measurement, *Area* independent

  \[ Q_m = -C_{ox} \Delta V_{FB} \]

- **Triangular Voltage Sweep**: High temperature (200 – 300°C)
  low-frequency $C-V$ curve is measured $\rightarrow$ charge flow through the oxide $\rightarrow$
  slow $V$ ramp makes sure current is due to mobile charges

- Other methods: sodium detection or neutral impurities - SIMS
3) Oxide Trapped Charge ($Q_{ot}$, $N_{ot}$)

Positive or negative charges due to holes or electrons in the oxide
Origin: Ionizing radiation, avalanche injection or other mechanisms (even operation)
No cure
Not routinely measured

Oxide trapped charge distribution:
- **Etch-off**: etching one layer → $C - V$ curve is measured → repeat it → spacial distribution (destructive)
- **Photo I-V**: electron injection to oxide → depends on the barrier and injecting surface distance & barrier height → monitor $V_{FB}$ and measure

$$Q_{ox} = -C_{ox} \Delta V_{FB}$$
4) Interface Trapped Charge \((Q_{it}, \ N_{it})\)

Positive or negative charges in \(\text{SiO}_2\) – Si interface

Origin: Structural defects, oxidation-induced defects, metal impurities or radiation caused bond breaking (hot electrons)

Symptoms: electrostatically coupled to the conducting channel in MOSFET

Cure: low-temperature (\(~450^\circ\text{C}\) hydrogen annealing
Interface Trapped Charge

1) *Low frequency methods*: traps and minority carrier inversion charges are responding to ac signal

- Compare low frequency \( C - V \) curve with *theory predicted* trap free curve
  - Capacitance in depletion-inversion case:
    \[
    C_{if} = \left( \frac{1}{C_{ox}} + \frac{1}{C_S + C_{it}} \right)^{-1}
    \]
  - Trap density \( D_{it} = C_{it}/q^2 \)
    \[
    D_{it} = \frac{1}{q^2} \left( \frac{C_{ox} C_{if}}{C_{ox} - C_{if}} - C_S \right)
    \]
- Compare low frequency \( C - V \) curve with *high frequency* \( C - V \) curve
  - Measure it at high frequency, but not too high – series resistance effect may arise
2) **High frequency methods:**

- **Terman method:**
  High frequency $C-V$ measurement (no $C_{it}$), where dc gate voltage is swept slowly.
  The additional depletion or inversion charges induces extra charges in the semiconductor → hf curve “stretches out”

- **Gary-Brown method:**
  Measuring $C-V$ at reduced temperature (77K) → interface trap time increases → traps are not responding to the room temperature ac anymore

- **Jenq method:**
  MOS is biased to accumulation at $T_{room}$ → cooling down to 77 K, bias is swept to inversion → again back to accumulation → The hysteresis between the two curve is propotional to the average interface trap density
3) **Conductance method**

ITC: capture and emission of carriers, loss is represented by $G_p$, $C_S$ and $C_{it}$ are combined to $C_p$.

Measure $G_p$ at different $f$ and $V_{BL} \rightarrow D_{it}$ can be extracted.

No $C_S$ dependency in conductance.

A: Acceptors, $D$: Donors.
## Summary

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### Pro
- Easy to measure
- High sensitivity for mobile oxide charges
- Spatial distribution of impurities
- Non-destructive and better accuracy
- Large surface potential range → better $D_{it}$ estimation
- Easy to measure
- High sensitivity, no need for $C_s$ estimation

### Con
- Other oxide charges appear
- Oxide leakage current for thin oxide
- Destructive method
- Not efficient
- Current measurement is required
- Requires cooling
- Limited surface potential range

### Sensitivity
- Pro: $10^9 \text{cm}^2$
- Oxide Trapped Charge: $10^9 \text{cm}^2$
- Interface Trapped Charge: $3 \times 10^{10} \text{cm}^2 \text{eV}^{-1}$
Consider an MOS capacitor with $t_{ox} = 40$ nm and $V_{FB} = 0$.

(a) Now consider a similar device except the oxide is contaminated with mobile ions. These are very peculiar mobile ions. The upper half of the oxide (the side nearest the gate) contains a uniform density of positively charged ions with $\rho_{m1} = 0.04$ C/cm$^3$. The lower half of the oxide (the side nearest the substrate) contains a uniform density of negatively charged ions with $\rho_{m2} = -0.06$ C/cm$^3$. Determine $V_{FB}$ for this case.

(b) The device undergoes a bias-temperature stress at elevated temperature with positive gate voltage and all charges move. Determine $V_{FB}$ for this case. (Problem 6.5)