

Capacitance-voltage profiling/ Measurement

Is a technique for characterizing semiconductor materials and devices. The applied voltage is varied, and the capacitance is measured and plotted as a function of voltage. The technique uses a metal-semiconductor junction (Schottky barrier) or a p-n junction or a MOSFET to create a depletion region, a region which is empty of conducting electrons and holes, but may contain ionized donors and electrically active defects or traps. The depletion region with its ionized charges inside behaves like a capacitor. By varying the voltage applied to the junction it is possible to vary the depletion width. The dependence of the depletion width upon the applied voltage provides information on the semiconductor's internal characteristics, such as its doping profile and electrically active defect densities.^{[2], [3]} Measurements may be done at DC, or using both DC and a small-signal AC signal or using a large-signal transient voltage.

C-V characteristics metal-oxide-semiconductor structure

A metal-oxide-semiconductor structure is critical part of a MOSFET by controlling the height of potential barrier in the channel via the gate oxide.

An *n*-channel MOSFET's operation can be divided into three regions, shown below and corresponding to the right figure

Depletion

When a small voltage is applied to the metal, the valence band edge is driven far from the Fermi level, and holes from the body are driven away from the gate, resulting in a low carrier density, so the capacitance is low.

Inversion

At larger gate bias still, near the semiconductor surface the conduction band edge is brought close to the Fermi level, populating the surface with electrons in an inversion layer or n-channel at the interface between the semiconductor and the oxide. This results in a capacitance increase.

Accumulation

When a negative gate-source voltage (positive source-gate) is applied, it creates a *p*-channel at the surface of the *n* region, analogous to the *n*-channel case, but with opposite polarities of charges and voltages. The increase in hole density corresponds to increase in capacitance.

C-V Characteristics

The low frequency and high frequency C-V characteristics curves of a MOS capacitor are shown in fig1. below,

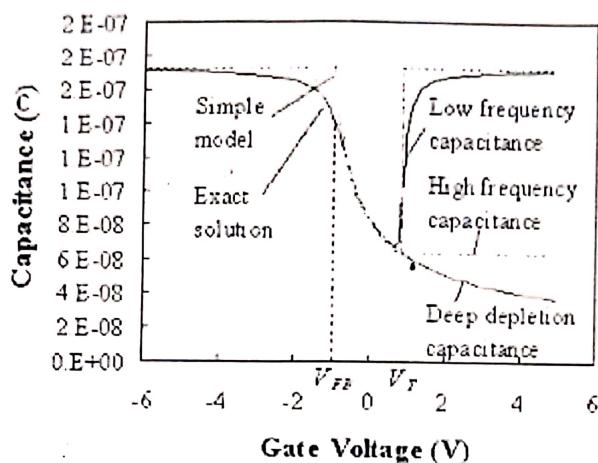


Fig 1 : Low & High Frequency C-V curves

The **low frequency** or quasi-static measurement maintains thermal equilibrium at all times. This capacitance is the ratio of the change in charge to the change in gate voltage, measured while the capacitor is in equilibrium. A typical measurement is performed with an electrometer, which measures the charge added per unit time as one slowly varies the applied gate voltage.

The **high frequency** capacitance is obtained from a small-signal capacitance measurement at high frequency. The bias voltage on the gate is varied slowly to obtain the capacitance versus voltage. Under such conditions, one finds that the charge in the inversion layer does not change from the equilibrium value corresponding to the applied DC voltage. The high frequency capacitance therefore reflects only the charge variation in the depletion layer and the (rather small) movement of the inversion layer charge.

Applications-

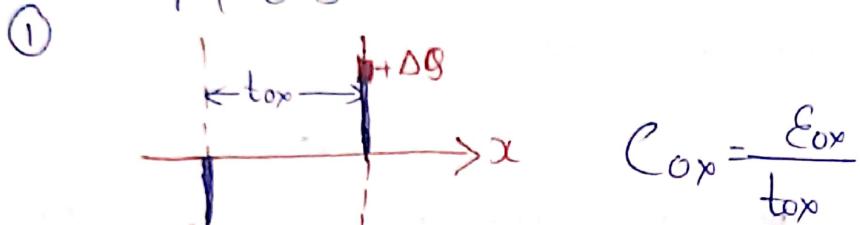
1. used to analyze the doping profiles of semiconductor devices by the obtained C-V graphs.
2. used to characterize threshold voltages and other parameters during reliability and basic device testing and to model device performance.
3. used to characterize other types of semiconductor devices and technologies, including bipolar junction transistors, JFETs, III-V compound devices, photovoltaic cells, MEMS devices, organic thin-film transistor (TFT) displays, photodiodes, and carbon nanotubes (CNTs).

C-V Profiling of MOSFET

- Observed in MOS-capacitor or MOS-Diode

$$V_g + \Delta V \quad Q + \Delta Q \quad \therefore C = \frac{\Delta Q}{\Delta V} \quad \text{DC voltage or small signals}$$

① MOS



① Accumulation

Vg (-Ve)

~~ε~~ ~~ox~~

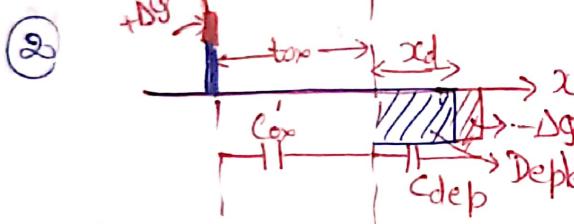
∴ ϵ_{ox} = Epsilon of oxide

② Depletion

~~ε~~ ~~ox~~ ~~ε~~ ~~o~~

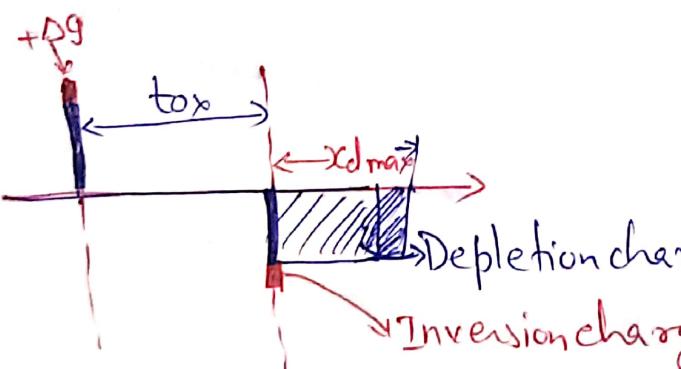
$$\epsilon_{ox} = \epsilon_{r,ox} \cdot \epsilon_0$$

MOS



Depletion charge

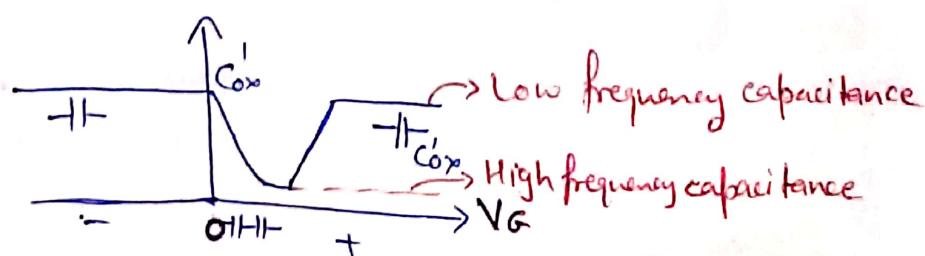
Vg (+ve Small)
② Depletion



③ - Inversion.

Vg (+ve)

$$C'_{ox} = \frac{\epsilon_{ox}}{t_{ox}}$$



Accumulation - With ΔV increase, $-\Delta Q$ is there & correspondingly $+\Delta Q$ is there. So $+Q$ & $-\Delta Q$ is separated by t_{ox} & $C'_{ox} = \frac{E_{ox}}{t_{ox}}$

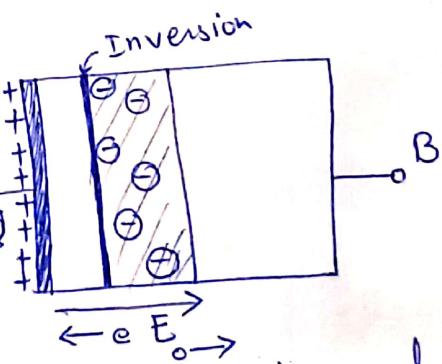
Depletion - On applying $+\Delta V$, $+\Delta Q$ is there and receive $-\Delta Q$ near the depletion layer. Now, $+Q$ & $-\Delta Q$ is now separated by t_{ox} & x_d (with two materials in between) i.e. there are two capacitance in series. So

$$\frac{1}{C'} = \frac{1}{C'_{ox}} + \frac{1}{C'_{dep}} \quad \& C'_{dep} = \frac{E_{si}}{x_d}$$

Inversion - On applying $+\Delta V$ we get $+\Delta Q$ which is balanced by $-\Delta Q$ in the inversion (as depletion region is with maximum width). Now $+Q$ & $-\Delta Q$ is separated by t_{ox} so $C'_{ox} = \frac{E_{ox}}{t_{ox}}$. With these three modes graph is plotted for ideal MOSFET.

Note → Creation of Inversion charge -

When we increase the potential which increases $E_{electric}$ (electric field) disturbing the equilibrium condition creating the generation & recombination of e^- hole. e^- moves towards the surface & holes moves away from the surface. When ΔV changes very fast w.r.t time, the process will not take place place as it is, as thermal generation takes time.



UNIT-IV

Monte-Carlo Method— A mathematical method for calculating probabilities of several alternative outcomes in an uncertain process via repeated sampling. It also works well in sensitivity analysis and ~~co~~correlation of input variables.

It can be applied to any field for risk analysis, to solve probabilistic problems & in prediction models, including business, project management, finance, science, engineering, etc.

Applications add-on — Material science, statistical physics, chemical and Bio-physics, nuclear physics, flow of traffic etc.

Steps involved in Monte-Carlo method —

1. To set up the probability distribution for important variables or Establish the mathematical model.
2. To develop / generate a cumulative probability distribution for each variable or Determine the input variables.
3. To establish an interval of random numbers for each variable or Create a sample dataset.
4. Generate random numbers or create Monte Carlo Simulation software
5. Analyze the result

Challenges— # Highly dependent on input variables/values and distribution

leads to inaccurate results, if one wrongly selects the input & probability distribution.

Example - let there be a square of side length '2r'.

$$S_{\text{square}} = (2r)^2 = 4r^2 \quad \text{--- ①}$$

Draw a circle inside the square with radius 'r'

$$\text{the } S_{\text{circle}} = \pi r^2 \quad \text{--- ②}$$

$$\text{Ratio is now given as} - \frac{S_{\text{circle}}}{S_{\text{square}}} = \frac{\pi r^2}{4r^2} = \frac{\pi}{4} \quad \text{--- ③}$$

Multiply '4' on b.h.s of eqn ③ we get -

$$4 \cdot \frac{S_{\text{circle}}}{S_{\text{square}}} = \frac{\pi}{4}$$

$$\text{i.e } \pi = 4 \cdot \frac{S_{\text{circle}}}{S_{\text{square}}}$$

i.e $4 \times \frac{\text{points within the circle}}{\text{points within the square}}$

This Monte Carlo method is shown to calculate value of π .

Ex - Draw a square on a paper & then a circle inside it.
Sprinkle some uniform objects over the square.

- Now count total no. of objects and the number of objects inside the circle.
- Now take ratio of the two countings. This gives ratio of the estimate of two areas i.e $\pi/4$. Further, multiply by 4 to get ' π '.

Monte-Carlo Method for solving Boltzmann Transport Equation (BTE)

Boltzmann transport equation is the main tool in the analysis of transport in semiconductors. Boltzmann transport equation describes the behaviour of a fluid with temperature. It also describes the change of macroscopic quantity in a thermodynamic system such as energy, charge or particle number.

Monte-Carlo method is choice for solving BTE in the field of rarefied gas dynamics due to factors as -

- (i) High dimensionality associated with $f(t, x, v)$, a function of time 't', molecular positions 'x' & velocities 'v' in phase space. This is considering the conservation of particles in phase space.

General form as

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla_x f + \mathbf{F} \cdot \nabla_v f = \left[\frac{\partial f}{\partial t} \right]_{\text{coll}}. \quad \text{---(1)}$$

This serves to highlight its physical interpretation as a balance between collisionless advection (l.h.s) and the effect of collisions (r.h.s) of eqn ①. Here \mathbf{F} = force per unit mass acting on gas molecules.

- (ii) This is ideal for accurately & stably capturing the propagation of traveling discontinuities in the distribution function resulting from the advection (horizontal movement of mass of fluid) operator in Boltzmann equation.

Overall, The Direct solution Monte Carlo method (DSMC) algorithm combines simplicity with an intuitive formulation that naturally employs importance sampling for improved computational efficiency.

DSMC solves BTE using discretization in time; each time step of length Δt is split into a collisionless advection and a collision ~~at~~ substep. Eqn ① corresponds to collisionless advection substep integrates & collision substep integrates

$$\frac{\partial f}{\partial t} = \left[\frac{\partial f}{\partial t} \right]_{\text{coll}}.$$

During the horizontal flow substep, particles move according to their velocities & accelerations.

(4)

During collision substep, the distribution function is updated by processing binary collisions between collision pairs chosen from within same computational cell of same size using acceptance & rejection method.

(4)



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①

Boltzmann Transport Equation —

We know Electron in metal = Atoms in Gas. (Both are free & without any force).

We know distribution function = No. of e- per unit vol^m or ~~cell~~ cell.

When Electric field is applied, force changes & average velocity = v_d ($\langle v_x \rangle = v_d$)

So, Boltzmann transport eqn tells that due to electric field whatever changes in force is there, ~~there~~ is how much? We will derive it.

We know phase space - Six dimension space
 $(x, y, z) \& (p_x, p_y, p_z)$.

f = distribution function ie $f(x, y, z, p_x, p_y, p_z)$

When electric field is applied, f changes.

$$\text{So } \left(\frac{df}{dt} \right)_{\text{force}} = \frac{\partial f}{\partial x} \left(\frac{-dx}{dt} \right) + \frac{\partial f}{\partial y} \left(\frac{-dy}{dt} \right) + \frac{\partial f}{\partial z} \left(\frac{-dz}{dt} \right)$$

for time $t = f$.
 $tf dt = df$.
charge = $\frac{df}{dt}$?

$$+ \frac{\partial f}{\partial p_x} \left(\frac{dp_x}{dt} \right) + \frac{\partial f}{\partial p_y} \left(\frac{dp_y}{dt} \right) + \frac{\partial f}{\partial p_z} \left(\frac{dp_z}{dt} \right)$$

Note: e- moves opp. to direction of applied electric field.
& same for e- momentum.

$$\text{or } \frac{\partial f}{\partial x} (-v_x) + \frac{\partial f}{\partial y} (-v_y) + \frac{\partial f}{\partial z} (-v_z) + \frac{\partial f}{\partial p_x} (-F_x) + \\ \frac{\partial f}{\partial p_y} (-F_y) + \frac{\partial f}{\partial p_z} (-F_z)$$



$$\text{or} - \left[\frac{\partial f}{\partial x} v_x + \dots \right] - \left[\frac{\partial f}{\partial p_x} f_x + \dots \right]$$

$$\text{or} - \left[\frac{\partial f}{\partial x} v_x + \frac{\partial f}{\partial y} v_y + \frac{\partial f}{\partial z} v_z \right] - \left[\frac{\partial f}{\partial p_x} f_x + \frac{\partial f}{\partial p_y} f_y + \frac{\partial f}{\partial p_z} f_z \right]$$

$$\text{or} - \left\{ \left[i \frac{\partial}{\partial x} + j \frac{\partial}{\partial y} + k \frac{\partial}{\partial z} \right] \vec{f} \cdot \{ i \hat{v}_x + j \hat{v}_y + k \hat{v}_z \} \right\}$$

$$\text{or} \left(i \frac{\partial f}{\partial x} + j \frac{\partial f}{\partial y} + k \frac{\partial f}{\partial z} \right) \cdot (i \hat{v}_x + j \hat{v}_y + k \hat{v}_z)$$

$$\text{or} \quad \frac{\partial f}{\partial x} v_x + \frac{\partial f}{\partial y} v_y + \frac{\partial f}{\partial z} \cdot v_z$$

$$\text{or} - (\vec{\nabla} f) \cdot (\vec{v}) = (\vec{v}) \cdot (\vec{\nabla}_p f)$$

$$\text{2} \quad - \left[\left(i \frac{\partial}{\partial p_x} + j \frac{\partial}{\partial p_y} + k \frac{\partial}{\partial p_z} \right) \vec{f} \right] \cdot (i f_x + j f_y + k f_z)$$

On Solving

$$- (\vec{\nabla}_p \cdot f) \cdot (f) = - (\vec{f}) \cdot (\vec{\nabla}_p f)$$

Finally:

$$\left(\frac{df}{dt} \right)_{\text{force}} = - \vec{v} \cdot \vec{\nabla}_p f - \vec{f} \cdot \vec{\nabla}_p \vec{f}$$

(Note)

$$\text{Here } \vec{\nabla}_r = i \frac{\partial}{\partial x} + \dots$$

$$\vec{\nabla}_p = i \frac{\partial}{\partial p_x} + \dots$$

Now due to collision the change in distribution function. ⁽³⁾

$$\left(\frac{df}{dt}\right)_{\text{coll.}} = ?.$$

ie $\frac{df}{dt} = \left(\frac{df}{dt}\right)_{\text{force}} + \left(\frac{df}{dt}\right)_{\text{coll.}}$

$$\text{or } \frac{df}{dt} = -\vec{v} \cdot \vec{\nabla}_v f - \vec{F} \cdot \vec{\nabla}_p f + \left(\frac{df}{dt}\right)_{\text{coll.}}$$

for steady state $\frac{df}{dt} = 0$

Now $\left(\frac{df}{dt}\right)_{\text{coll.}} = \vec{v} \cdot \vec{\nabla}_v f + \vec{F} \cdot \vec{\nabla}_p f$

Boltzmann Transport Equation.

Now in presence of Magnetic field

$$f = -q[\vec{E} + \vec{v} \times \vec{B}] \quad (\text{Lorentz force})$$

$$\left(\frac{df}{dt}\right)_{\text{coll.}} = \vec{v} \cdot \vec{\nabla}_v f + (-q[\vec{E} + \vec{v} \times \vec{B}]) \cdot \vec{\nabla}_p f$$

Ans

Now during collision time, 'f' changes from f to f_0
(initial) (final)

$$\text{ie } \left(\frac{df}{dt}\right)_{\text{coll.}} = \left(\frac{f_0 - f}{T}\right)$$

Collision time = T .

Introduction to Technology Computer-Aided Design

"Technology Computer Aided Design" (TCAD) is a numerical modelling method for semiconductor devices.

TCAD is a branch of Electronic design automation (EDA) which models semiconductor fabrication and semiconductor device operation. Fabrication modelling is termed as Process TCAD while the modelling of the device operation is termed device TCAD.

Purposely, TCAD designs up semiconductor processes and devices to fulfill some given specifications -

Process TCAD - Modelling of semiconductor-chip, process manufacturing steps like lithography, deposition, etching, ion implantation, diffusion, oxidation, mechanical stress etc.

It needs complete modeling of the physical principles of manufacturing and usually also the modeling of specific equipments used.

Device TCAD - Modelling of electrical, thermal, optical and mechanical behaviour of semiconductor devices (e.g. diode, BJT, MOSFET, Solar cell etc. -)

(7)

Device TCAD focusses on the physical principles at the basis of carrier transport & of optical generation in semiconductor devices.

Note:- Process Simulations - This simulate doping profiles obtained by specific processing techniques, calibrate model with experimental data and then optimize the process to obtain desired profile.

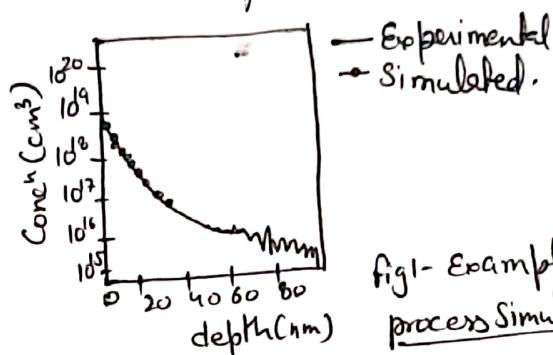
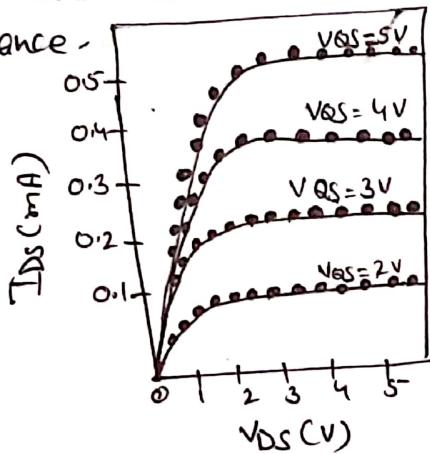


fig- Example of process Simulation.

Device Simulations -

Simulate the output characteristics of a MOSFET device & calibrate the device architecture to fine-tune the performance -



W.M.

- Advantages - (i) Better quality design (ii) Increase in productivity
(iii) Easy change of design using CAD.
(iv) Design Documentation is easy.

Disadvantages (i) Work can be lost due to sudden computer breakdown.

- (ii) Documented work is very prone to viruses.
- (iii) Running of software may consume little more time
- (iv) Updation must be regular
- (v) Costly to purchase new system.

1

(B)

⑧

for whom TCAD is useful - Architects, engineers, construction managers.



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Significance of Band Gap in Semiconductors -

Band gap is the minimum amount of energy required for an e^- to be free from its bound state. Once the band gap is fulfilled, e^- is excited into free state and take part in conduction. It determines the energy needed for conduction and energy generated.

- Band Gap helps in understanding characteristics of metals (conductors), semiconductors & insulators (non-metals). Band gap is a way of visualizing the electronic configuration in outermost shells.

Probability of finding valence electrons is highest also called as "Highest Occupied Molecular Orbital (HOMO)". It represents the ground state or unexcited energy level of the material. Electrons in the valence band are not moving till they move to conduction band.

~~Note~~. Secondly, Conduction band does not have e^- and so, called as "lowest Unoccupied Molecular Orbital (LUMO)". It is the highest energy level discretely separated from valence band. Electrons once reach conduction band can travel freely through the matter piece & conduct electricity.

Gap between valence & conduction band is called as Band Gap / Electron Band Gap. Band Gap is expressed in (eV) electron Volts.

Larger the band gap, greater is the difficulty for the valence e^- to jump to the conduction

⑩

band. It gives poor conductivity of non-metals (insulators)

When valence band and conduction bands overlap e⁻ are able to move freely as it takes place in metals (conductors). If the band gap is narrow, the e⁻ can be elevated to the conduction band i.e. materials are semiconductors.

Band Gap concept is useful in understanding the interaction of light with matter, predictor of wavelength of light absorbed by material. Narrow band gap absorbs high wave length visible range due to lower energy requirement for e⁻ movement into conduction band.

Large band gap materials absorbs short wavelength UV region due to high energy required by the valence e⁻ to go across the gap to conduction band. Semiconductors have band gap of 1~3eV & these generally absorb near UV region.

On nanoscale, band gap & its

dependent properties alters.



Soln