CV profiling

Introduction: pn junction diodes

- What is the depletion capacitance of a diode? Capacitance caused by dopants in depletion region.
- What is the diffusion capacitance of a diode? Capacitance caused by minority carrier injection into the neutral regions.
- Under what bias conditions does depletion capacitance dominate? Reverse bias.
- Under what bias conditions does diffusion capacitance dominate? Forward bias.
- Which of the two capacitances is larger? Diffusion capacitance.

Depletion approximation

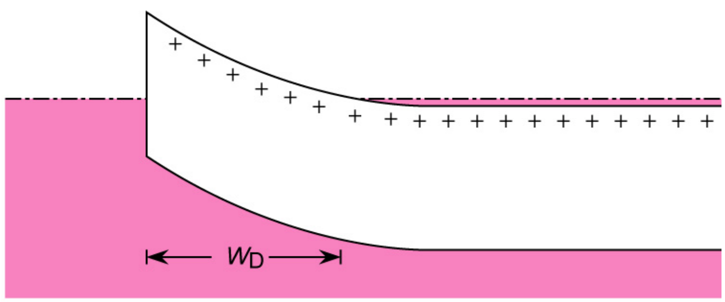
- The depletion layer thickness of a pn junction is given by:

$$W_D = \sqrt{\frac{2\,\varepsilon_r \varepsilon_0}{e}\left(\frac{N_A + N_D}{N_A N_D}\right)(V_D - V)}$$

- For asymmetrically doped pn junctions (and for Schottky contacts), the depletion layer on only one side need to be considered.
- For $N_A >> N_D$, one obtains:

$$W_D = \sqrt{\frac{2\,\varepsilon_r \varepsilon_0}{e N_D}(V_D - V)}$$

- Application of equation to Schottky contact on n-type semiconductor:



- Depletion approximation assumes that the doped semiconductor is depleted slice-by-slice.

Small signal approximation

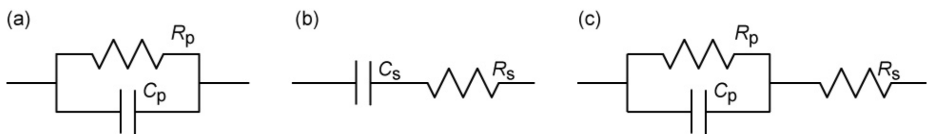
- What is a linear circuit? A circuit whose magnitude of the output signal is proportional to the magnitude of an input signal.
- Name examples of elements that can make up a linear circuit. Resistor, capacitor, inductor.
- Name examples of elements that can make up a non-linear circuit. Diodes, transistors, varactors, Zener diodes, etc.
- For small signals, any non-linear circuit can be linearized. Why? In the infinitesimal limit any function can be linearized.

Circuits

- Explain: Resistance, conductance, impedance, admittance, reactance, inductance, and capacitance.
- What is the dimension (unit) of: Resistance, conductance, impedance, admittance, reactance,

inductance, and capacitance?

- How would you measure the resistance of a circuit? Measure current and voltage of circuit.
- How would you measure the impedance of a circuit? Measure AC current and voltage of the circuit and the phase between current and voltage.
- How would you measure the capacitance of a circuit? The capacitance can be deduced from the imaginary component of the impedance
- What would be the best frequency to measure the capacitance in the circuits below?



- (a) Zero frequency, low frequency, medium frequency, high frequency, or $f \to \infty$
- (b) Zero frequency, low frequency, medium frequency, high frequency, or $f \to \infty$
- (c) Zero frequency, low frequency, medium frequency, high frequency, or $f \to \infty$

Depletion and diffusion capacitance measurement

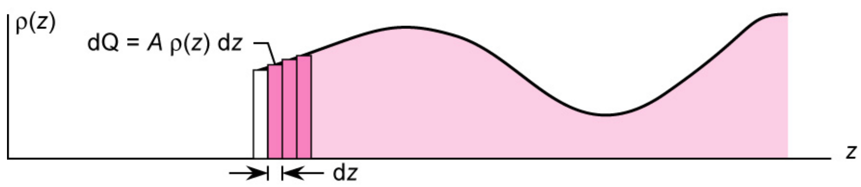
- Can one easily measure the depletion capacitance of a diode? Low leakage in reverse direction.
- Can one easily measure the diffusion capacitance of a diode? Forward current will make measurement difficult. Capacitor is "bypassed" by the low-resistance forward-biased diode.

CV profiling

- Draw the schematic C versus V curve of a pn-junction diode.
- Explain the CV profiling technique.
- What information is obtained from CV profiling?

CV profiling on classical semiconductors (no quantum wells)

- Depletion approximation is used
- Semiconductor is depleted "slice by slice".



- Potential change dV results in depletion of dQ.
- Depletion approximation: dQ = A ρ(z) dz (where A is area of device).
- Charge is completely depleted on length dz.

CV concentration and depth

- The CV concentration, N_{CV}, is defined as:

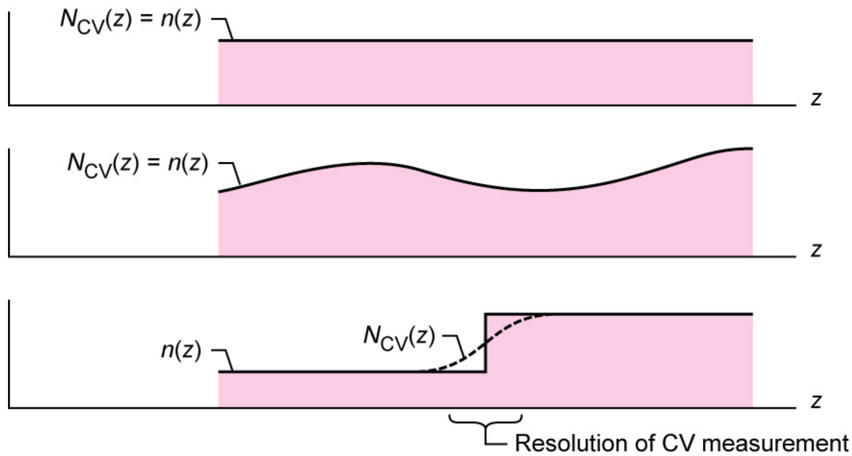
$$N_{CV} = \frac{2}{e\,\varepsilon_s}\left[-\frac{1}{d(1/C_{UA}^2)\,/\,dV}\right]$$

where C_{UA} is the capacitance per unit area (measured in F/m^2).

- The CV depth, z_{CV}, is defined as:

$$z_{CV} = \varepsilon_s / C_{UA}$$

- Because the CV measurement yields C_{UA} as as a function of V, the two quantities N_{CV} and z_{CV} can be determined. That is we can plot N_{CV} versus z_{CV}.
- One can show that $n = N_{CV}$ for a *uniformly* doped semiconductor (n being the free carrier concentration).
- However, for a *non-uniformly* doped semiconductor, this is not the case.



- One can show that the resolution of the CV measurement is given by the screening length (Debye or Thomas-Fermi screening length for non-degenerately doped and degenerately doped semiconductors, respectively).
- Although the CV profile may not reproduce the true free-carrier profile *exactly*, it reproduces the free-carrier profile *approximately*.
- *Postulate*:

$$\int_{-\infty}^{\infty} N_{CV} \, dz_{CV} = \int_{-\infty}^{\infty} n \, dz$$

Proof:

It is $$N_{CV} = \frac{C_{UA}^3}{e\,\varepsilon_s} \frac{dV}{dC_{UA}}$$

and $$z_{CV} = \frac{\varepsilon_s}{C_{UA}} \quad \Rightarrow \quad \frac{dz_{CV}}{dC_{UA}} = \frac{-\varepsilon_s}{C_{UA}^2} \quad \Rightarrow \quad dz_{CV} = \frac{-\varepsilon_s}{C_{UA}^2} dC_{UA} \, .$$

Therefore

$$\int N_{CV} \, dz_{CV} = \int \frac{C_{UA}^3}{e\,\varepsilon_s} \frac{dV}{dC_{UA}} \frac{-\varepsilon_s}{C_{UA}^2} dC_{UA} = \frac{-1}{e} \int C_{UA} \, dV$$

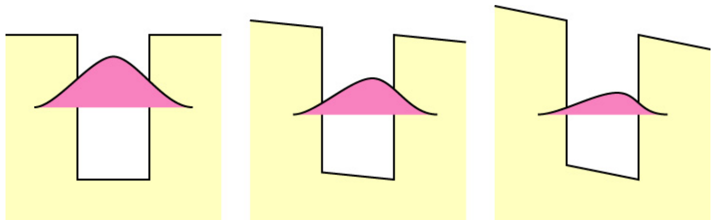
$$= \frac{-1}{e} Q = \int n \, dz$$

"*q.e.d*." or "*Quid erat demonstrandum*" or "*what was to be shown*".

CV profiling on quantum-mechanical semiconductors (quantum wells and superlattices)

- Depletion approximation is no longer applicable, because the carrier wave function cannot be depleted “slice by slice”.

- Instead the entire carrier system will react to the perturbation exerted by the voltage.



- The figure shows an electron wavefunction under the influence of an increasingly negative bias. The figure reveals that the entire wavefunction reacts to the external perturbation by (i) a changing position expectation value (centroid) and by (ii) decreasing the amplitude.
- Potential change dV results in depletion of dQ.
- The depth measured by the CV profile is the depth of the position expectation value (centroid of electron distribution). The resolution limit is given by the spatial extent (spatial width) of the wavefunction.