Lecture 10

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- Some Important Facts
  - Intrinsic (pure) silicon: number of electrons = number of holes
    * Equal electron and hold concentrations ($n_i = n_p$)
- Band Gap Energy
  - Band gap energy is the energy required to break a covalent bond and to free an electron
    * $E_g = .66$[eV] germanium
    * $E_g = 1.12$[eV] silicon
    * $E_g = 3.36$[eV] gallium nitride, used in LEDs
  - Metals have $E_g = 0$
    * Very large number of free electrons $\rightarrow$ high conductance
  - Insulators have $E_g > 5$[eV]
    * Almost NO free electrons $\rightarrow$ zero conductance
- Doping
  - The intentional addition of impurities to a semiconductor to create more free electrons or more holes
    * Creates extrinsic material
  - n-type material
    * More electrons than holes ($n > p$)
  - p-type material
    * More holes than electrons ($p > n$)
- n-type Silicon

- Elements in column V of the periodic table have 5 valence electrons
- Example: Phosphorus (P) is a popular electron donor
- The phosphorus atom has donated an electron to the semiconductor
  - Column V atoms are called donors
- The phosphorus is missing one of its electrons, so it has a positive charge (+1) $\rightarrow$ phosphorus ion (P+)
  - P+ is bound to the silicon $\rightarrow$ this +1 charge can not move
- The extra electron concentration is equal to the concentration of donor atoms (N_d)
- The overall net charge is zero, requiring that:

$$n = p + N_d$$

- *p*-type Silicon
  - Elements in column III of the periodic table have 3 valence electrons
  - Example: Boron (B) is a popular electron acceptor
    - 3 electrons (from the boron) form covalent bonds with the Si
    - A 4th electron is needed for each boron atom
      - This 4th electron creates a hole
  - The boron atom has accepted an electron from the semiconductor $\rightarrow$ column III atoms are called acceptors
  - The boron atom has one extra electron, so that it has a negative charge (-1) $\rightarrow$ boron ion (B-)
- Additional info for doped Si
  - The mass-action law hold for both n and p-type Si
    - After doping, the increased electron concentration makes hole recombination more likely (and vice versa)
    - $pn = p_i n_i$
    - $\sin(p_i) = n_i$ in intrinsic Si: $pn = n_i^2$ (at a specific temperature)
- The pn Junction
  - At zero bias ($V_D = 0$), neither electrons not holes can overcome the built-in voltage barrer of $\approx .7$[V] (for Si), so $I_D = 0$
  - As the bias (V_D) increases toward .7[V], the electrons and holes can overcome the built-in voltage barrier ($I_D > 0$)
  - As the bias (V_D) becomes negative, the barrier becomes larger

      * Only electrons and holes due to broken bonds in the depletion region contribute to the diode currnt ($I_D = I_s$)

  - As V_D becomes very negative, the barrier increases even more
      * Free electrons and holes (due to broken bonds) in the depletion region are accelerated to high energy ($> E_g$)
          · Breaking of other covalent bonds

- Junction Capacitance
  - Parasitic (unwanted) junction capacitance: $C \approx \varepsilon A/W$), where:
      * The depletion layer width (W) depends on the bias voltage
      * $\varepsilon \approx \varepsilon_r \varepsilon_o$ ($= 11.9\varepsilon_o$ for Si)
          · ε_r is the relative dielectric constant (permittivity) of a material
          · Dielectric constant for a vacuum: $\varepsilon_o \approx 8.85 \cdot 10^{-12}$[F/m]

- Depletion Capacitance

$$C_j = \frac{C_{j0}}{[1 - (V_{DQ}/\Phi_o)]^m}$$

  - C_{j0} is the incremental depletion capacitance from zero bias
  - V_{DQ} is the operating point (Q-point) voltage (DC bias voltage)
  - M is the grading coefficient (typically 1/3 to 1/2)
  - Φ_o is the built-in barrier potential
  - C_j models the depletion capacitance with bias dependence
      * Note: C_j is a small-signal parameter (most accurate for small AC signal changes around a fixed DC Q-point)