

p-n Junctions in Bulk and Two-Dimensional Materials

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Abstract text goes here.

I. INTRODUCTION TO *p-n* JUNCTION

A *p-n* junction is formed when a *p*-type semiconductor is and an *n*-type semiconductor are in contact. Understanding this basic configuration creates a foundation for much of modern electronic applications and other semiconductor devices. These *p-n* junctions are fundamental to a variety of functions such as rectification, amplification, switching, and other applications which can be achieved by varying parameters of the junction.

II. *p-n* JUNCTION IN EQUILIBRIUM

In the most basic sense, one can consider a *p-n* junction under thermodynamic equilibrium with constant doping concentrations. The band diagrams of the *p* and *n*-type materials before they are brought into contact with each other are pictured in fig. ??.

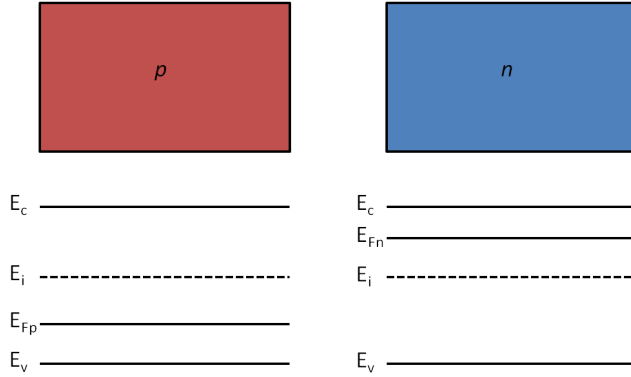


FIG. 1: Energy band diagram of the *p* and *n*-type regions taken separately.

Once the regions of differing types are brought into contact with each other the band diagram is as pictured in fig. ??.

Once the two material types are connected and the Fermi levels are aligned then the electrons diffuse from the electron-rich *n*-type (*p*-type) material to the electron-lacking (hole-lacking) *p*-type (*n*-type) region. The diffusion of charges across the junction creates an internal built-in potential denoted by Φ_0 in fig. ?? and in equilibrium is dependent upon the thermal voltage ,doping

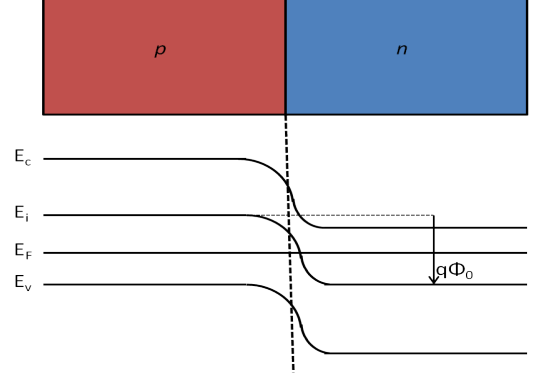


FIG. 2: Energy band diagram of a *p-n* junction.

concentrations, and intrinsic carrier concentration of the semiconductor. The built-in potential is given by

$$\Phi_0 = \frac{k_B T}{q} \ln \left(\frac{N_a N_d}{n_i^2} \right), \quad (1)$$

where the term $k_B T/q$ is the thermal voltage V_T , N_a and N_d are the acceptor and donor doping concentrations, respectively, and n_i is the intrinsic carrier concentration of the semiconductor. When the electrons (holes) diffuse from the *n*-type (*p*-type) region into the *p*-type (*n*-type) region ionized donor (acceptor) atoms are left in their place. This creates a depletion region on each side of the junction as shown in fig. 3 where W_p and W_n denotes the depletion region widths on the *p* and *n* sides, respectively. In the case of an abrupt *p-n* junction, one that

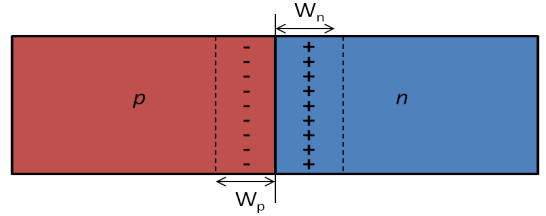


FIG. 3: Depletion region width depiction on both the *n*-side and *p*-side, W_n and W_p , respectively.

can be modeled as step-function at the transition from the depletion region to the charge-neutral *p* and *n*-type regions, there are two boundary conditions that must be satisfied. First, that the at the boundary of the depletion region, the electric field must go to zero. Written in

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a mathematical form this implies that

$$E(x = W_{p,n}) = 0. \quad (2)$$

Second, we define the point $x = 0$ to be the transition within the depletion region from the p -type to the n -type regions, at this point, the electric field must be continuous. This condition written more compactly can be expressed as

$$E(x = \delta_p) = E(x = \delta_n), \quad (3)$$

where δ_p and δ_n are some infinitesimally small distance on the p and n -side, respectively.

III. p - n JUNCTION IN NON-EQUILIBRIUM

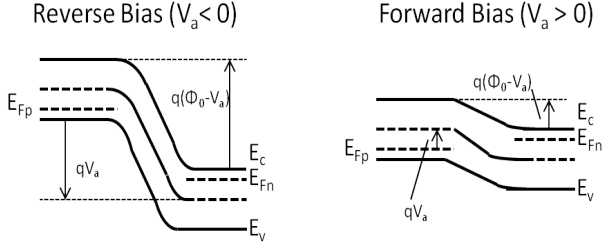


FIG. 4: Energy band diagram on p - n junction at forward and reverse bias.

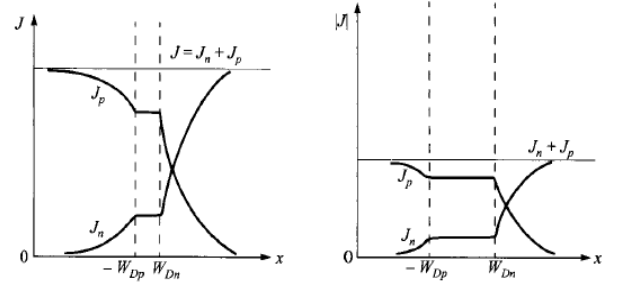


FIG. 5: Shockley current density as a function of position within the semiconductor structure at forward and reverse bias.

IV. p - n JUNCTION IN 3D AND LOWER-DIMENSIONS

V. CONCLUSION

VI. p - n JUNCTIONS IN TWO-DIMENSIONAL MATERIALS

Short literature review of p - n junctions in 2D materials.

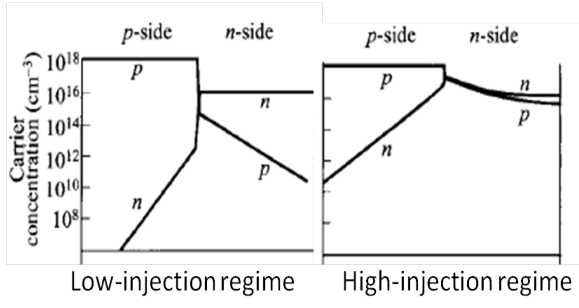


FIG. 6

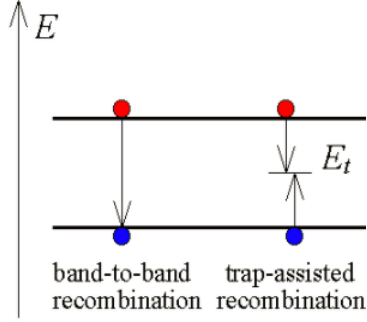


FIG. 7: Diagram of band-to-band and SRH recombination.

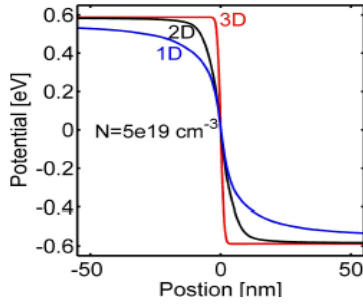


FIG. 8: Built-in potential as a function of position for 1D, 2D, and 3D.

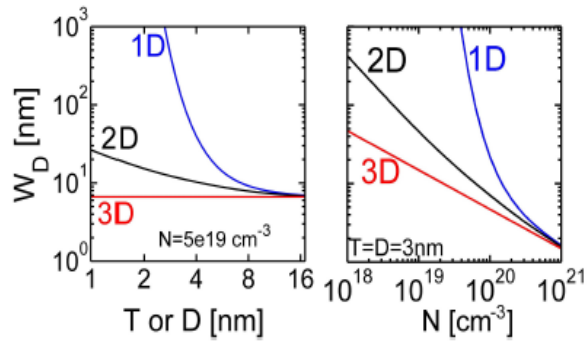


FIG. 9: Depletion width as a function of thickness (left) and carrier concentration (right) for 1D, 2D, and 3D.