p-n Junctions in Bulk and Two-Dimensional Materials

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(Dated: December 3, 2017)

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. **??**.

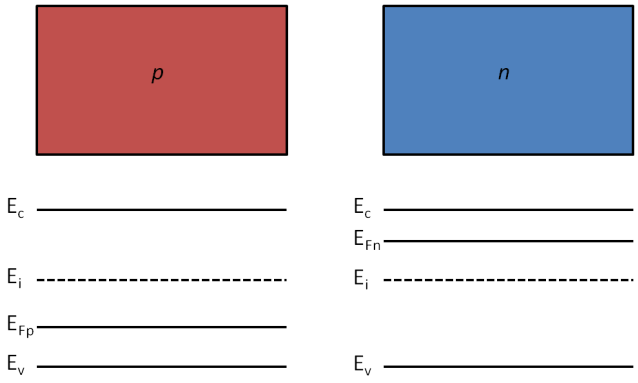

FIG. 1: Energy band diagram of the p and n-type regions taken separately.

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

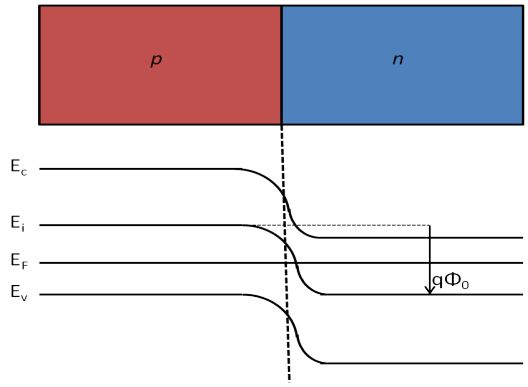

FIG. 2: Energy band diagram of a p-n junction.

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

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

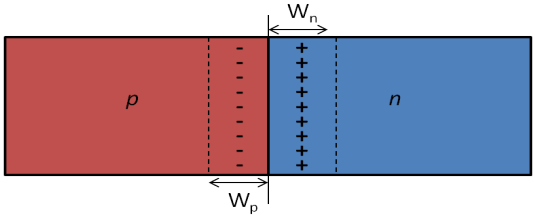

FIG. 3: Depletion region width depiction on both the n-side and p-side, W_n and W_p, respectively.

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

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

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

$$E(x = \delta_p) = E(x = \delta_n), \tag{3}$$

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

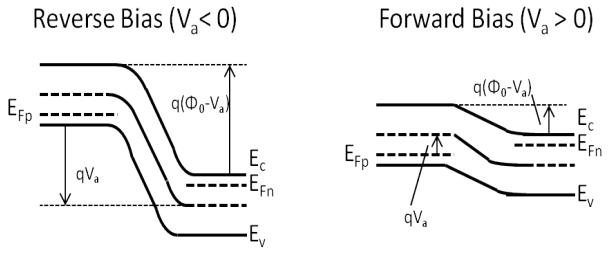

FIG. 4: Energy band diagram on p-n junction at forward and reverse bias.

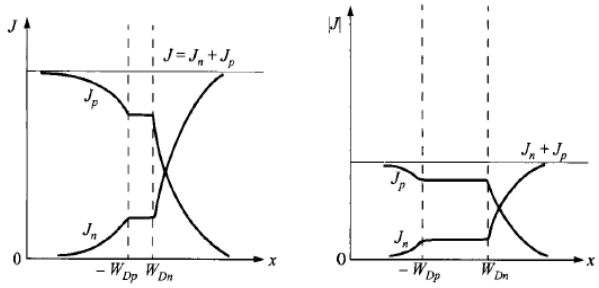

FIG. 5: Shockley current density as a function of position within the semiconductor structure at forward and reverse bias.

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

V. CONCLUSION

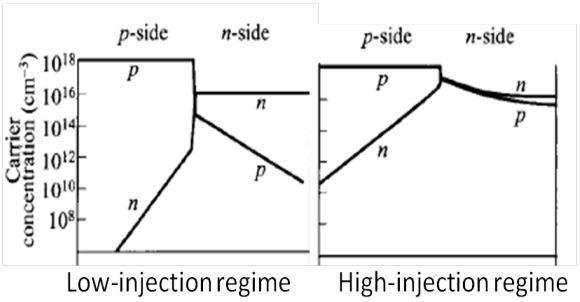

FIG. 6

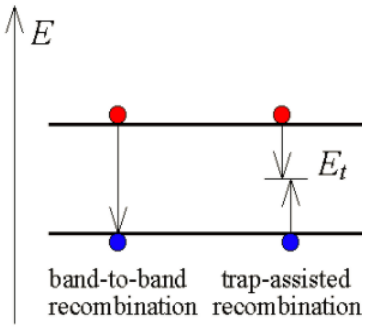

FIG. 7: Diagram of band-to-band and SRH recombination.

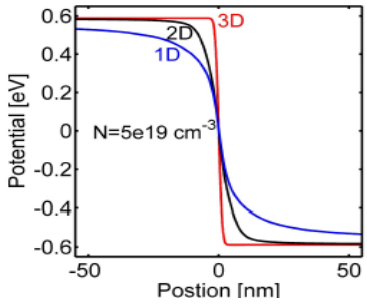

FIG. 8: Built-in potential as a function of position for $1D$, $2D$, and $3D$.

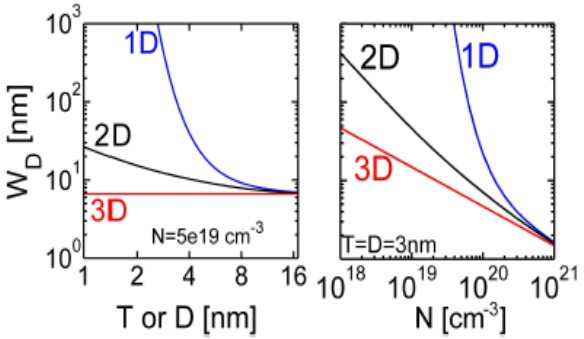

FIG. 9: Depletion width as a function of thickness (left) and carrier concentration (right) for $1D$, $2D$, and $3D$.