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The Effect of Doping Concentrations on the Thickness of the Depletion Layer on Some Semiconductor Materials

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Abstract

In this work, the code "Poisson" written by Silsbee and Drager, developed at Cornell University was used to Simulate band bending and carrier concentrations in the inhomogenous semiconductors: Gallium nitride, Zinc oxide, Cadmium sulfide, Cadmium selenide, Cadmium telluride, Indium phosphide, Gallium arsenide and Silicon. The energy gap for these semiconductors is generally greater than 1eV. Simulation of doping concentrations was run on preset four (4) on the code "Poisson". The effect of doping concentrations on the thickness of the depletion layer width and charge displacement of the semiconductor materials was obtained. The width of depletion layer decreases with increase in doping concentrations while increase in doping concentrations leads to increase in the charge displacement. The relationship between depletion layer width and the doping concentrations (from 1×10^{20} to 1×10^{16} cm^{-3}) is best described by a power function of the form $y = ax^b$. On the other hand, wide band gap results in increase in depletion layer width.

***Keywords*:** Poisson code, doping concentrations, depletion layer, charge displacement

1. Introduction

A semiconductor is a solid substance that has a conductivity between that of an insulator and that of most metals either due to addition of an impurity or because of temperature effects. They are also crystalline or amorphous solids with distinct electrical characteristics. Technically, a semiconductor is simply an insulator in which the temperature is high enough to excite electrons into the bottom of an empty band, or from the top of a full band, to give a medium with mobile charge carriers. Impurity doping of the material provides the control of concentrations essential for device fabrication. Semiconductor devices rely on control of the spatial distribution of carrier concentrations through a combination of electrode geometry an inhomogenous composition achieved both by alloying and doping [1]. There are two basic groups or classifications of semiconductors: they can either be intrinsic or extrinsic in nature. An intrinsic semiconductor material is chemically pure in nature, thus it possesses a very low conductivity level having very few number of charge carriers, that is the holes and the electrons which are equal in quantities. Extrinsic semiconductor materials are those where a small amount of impurity has been added to the basic intrinsic material. N-type semiconductor has an excess of electrons, in this way, free electrons are available within the lattices and their overall movement in one direction under the influence of a potential difference result in an electric current flow. P-type semiconductor has a shortage of electrons, that is there are holes in the crystal lattice. Most commonly used semiconductors materials are crystalline inorganic solids. They are often classified according to their position or group within the periodic table. Semiconductors can be used to offer optimum performance. Silicon which is the most widely used type of semiconductor is easy to fabricate and provides good general electrical and mechanical properties. It is also used for integrated circuit to form high quality silicon oxide used for insulation layers between different active elements of the IC. Cadmium sulfide is used in photo-resistors and also in solar cells.

The optical properties of semiconductors are an important factor in understanding the performance of optical sensors and solar cells. These properties are based on the interaction of electromagnetic waves with matter [2].

Another important general characteristics of the widely employed semiconductors is compositional purity. It is an established fact that even extremely minute traces of impurity atoms can have detrimental effect on the electrical properties of the semiconductors. For this reason the compositional purity of semiconductors must be very carefully controlled: In fact, modern semiconductors are some of the purest solid materials in existence [3]. Gallium arsenide (GaAs) is a compound of two elements, gallium and arsenic. Proliferation of consumer communication products such as digital mobile phones, personal communication systems, satellite and fiber optic communications and wireless network have driven demand for semiconductor devices manufactured with Ga-As [4]. Usually if a forward bias is applied on a p-n junction, the potential barrier is lowered, and the majority current is reduced to zero, the voltage at which the resultant current is obtained is called the photovoltaic potential. Germanium semiconductor detectors were first introduced in 1962 and are now the detectors of choise for high energy-resolution gamma-rays studies. These detectors directly collect the charges produced by the ionization of semiconductor material [5]. The band gap energy E_v is perhaps the most important parameters in the study of semiconductors[3]. In semiconductor physics the depletion region is also called depletion layer or space charge layer. It is an insulating region within a conductive doped semiconductor material where the mobile charge carriers have been diffused away, or have been forced away by an electric field. The only elements left in the depletion region are ionized donor or acceptor impurities. Understanding the depletion region is the key to explaining modern semiconductor electronics: diodes, bipolar junction transistors, and variable capacitance diodes all rely on depletion region phenomena. The depletion width describes the width of the depletion region in a semiconductor, particularly in geometries that are one dimensional like the p-n junction and MOS capacitor. Associated with the depletion layer in an effect known as band bending. This occurs because the electric field in the depletion layer varies linearly in space from it maximum value at the gate to zero at the edge of the depletion width. p-n junction are of great importance both in modern and electronic applications and in understanding other semiconductor devices. The code ”poisson” was used to simulates the band bending and carrier concentrations of some semiconductor materials by varrying the voltage applied and concentrations with measurements of the energy gap of the semiconductor materials.

A key element in a semiconductor is the ability to control the spatial distribution of mobile charge carriers, the electrons and holes. This is achieved by a combination of inhomogenous doping and appropriate electrode geometries and applied fields. The code poisson, written by Silsbee and Drager, (1997) Cornell University, Cambridge, and being employed in this work illustrates the important physics for configurations amenable to a one dimensional analysis. The basic problem is to know the effect of the voltage applied on the thickness of the depletion layer when the concentrations of the donor and acceptor are known and the energy gap of the semiconductor material is also given. Understanding the effect of the applied voltage and the depletion layer is the fundamental to a study of some main classes of semiconductor amplifiers.

The poisson code was used to simulate the band bending and carrier concentration of the following inhomogenous semiconductors Gallium nitride, Zinc oxide, Cadmium sulfide, Cadmium selenide, Cadmium telluride, Indium phosphide, Gallium arsenide and Silicon. The results obtained was used to analyze the effect of doping concentrations on the depletion layer and charge displacement. The computation involves running the presets in the in the poisson code using applied voltage and doping concentrations as the input parameters.

2. Theory

In semiconductor physics, the depletion region also called depletion layer, depletion zone or space charge layer, is an insulating region within a conductive doped semiconductor material where the mobile charge carriers have diffused away or have been forced away by an electric field, the only element left in the depletion region are ionized donor or acceptor impurities. The depletion region is so named because it is formed from a conducting region by removal of all free charge carriers, leaving none carry current. Understanding the depletion region is the key to explaining modern semiconductor electronics, example, diodes, bipolar junction transistors, field effect transistor and variable capacitance diodes all rely on depletion region phenomena. In order to calculate the band bending depletion region for normal semiconductor , we make use of the poisson equation [6].

$$\nabla^2 V = -\frac{\rho}{\varepsilon_o \varepsilon_r} \qquad (1)$$

where V is the potential difference corresponding to the band bending, ρ is the space-charge density in the semiconductor, ε_o is the permittivity of free space and ε_r is the dielectric constant of the semiconductor. The depletion width describes the width of the depletion region in a semiconductor, particularly in geometries that are one dimensional like the p-n junction and MOS capacitor. The width of the depletion region is governed by the principle of charge neutrality . The principle of charge neutrality states that the sum of the positive charges must be equal the sum of the negative charges.

$$n + N_A = p + N_D \qquad (2)$$

where n and p are number of free electrons and holes, and $N_D$and N_A are number of ionized donors and acceptors. The electric field is zero outside the depletion width and therefore Gauss law implies that the charge density in each region balances[7].

Treating each region separately and substituting the charge density for each region into the poisson equation eventually leads to a result for the depletion width is.

$$w \approx \left[\frac{2\varepsilon_0\varepsilon_r}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)(V_{bi} - V)\right]^{\frac{1}{2}} \qquad (3)$$

where V_{bi} is build in voltage and V is the applied voltage and w is the depletion width

Associated with the depletion layer is an effect known as band bending. This occurs because the electric field in the depletion layer varies linearly in space from it (maximum) value E_m at the gate to zero at the edge of the depletion width [8].

$$E_m = \frac{qN_A w}{A\varepsilon_o} \qquad (4)$$

where A is the gate area. This linearly varying electric field leads to an electrical potential that varies quadratically in space. The energy levels or energy band bends in response to this potential. The band gap energy E_v is perhaps the most important parameters in semiconductor physics [3].

Poisson's equation is widely useful because many problems in physics involve devices in which applied potential differences are known, and in which constant potentials occur at the boundaries [9]. The poisson equation is necessary to simulate the electronic characteristics of devices for semiconductors without remanant polarisation (referred to as normal semiconductors here). The band bending strongly affects the current-transport mechanism and the capacitance in devices. When the impurity concentration in a semiconductor changes abruptly from acceptor impurities N_A to donor impurities N_D. One obtains an absruct juction in particular, if $N_A \gg N_D$ or $N_D \gg N_A$, one obtains a one side abrupt $n^+ - p$ or $p^+ - n$ junction respectively.

Next, we proceed to calculate the field and potential distribution inside the depletion region. To simplify the analysis, the depletion approximation is used which assumed that the depleted charge has a box profile. Since in thermal equilibrium the electric field in the neutral regions (far from the junction at either side) of the semiconductor must be zero, the total negative charge per unit area in the p-side must be precisely equal to the total positive charge per unit area in the n-side.

$$N_A W_{DP} = N_D W_{DA} \qquad (5)$$

The equation below is obtained from Poission equation:

$$-\frac{d^2\psi_i}{dx^2} = \frac{d\xi}{dx} = \frac{\rho(x)}{\varepsilon_s} = \frac{q}{\varepsilon_s}\left[N_D^+(x) - n(x) - N_A^-(x) + p(x)\right] \qquad (6)$$

Inside the depletion region, $n(x) \approx p(x) = 0$, and assuming complete ionization,

$$\frac{d^2\psi_i}{dx^2} \approx \frac{qN_A}{\varepsilon_s} \quad \text{for } -W_{DP} \leq x \leq 0 \qquad (7a)$$

$$-\frac{d^2\psi_i}{dx^2} \approx \frac{qN_D}{\varepsilon_s} \text{for } 0 \leq x \leq W_{DP} \qquad (7b)$$

ψ_i is the potential of the semiconductor ${E_i}/{q_i}$ (V)

ε_s is the permitivity of the semiconductor $({F}/{cm})$

x is theee distance of thickness

The electric field is obtained by integrating the above equations that is;

$$\xi(x) = -\frac{qN_A(x+W_{Dp})}{\varepsilon_s} \text{ for } -W_{DP} \leq x \leq 0 \qquad (8)$$

$$\xi(x) = -\frac{qN_A(W_{Dp}-x)}{\varepsilon_s} \text{ for } 0 \leq x \leq W_{DP} \qquad (9)$$

Integrating Eqs(3.4a) and (3.4b) gives the potential distribution $\psi_i(x)$, with these the potential across different regions can be found as:

$$\psi_p = \frac{qNW_{Dp}^2}{2\varepsilon_s} \qquad (10a)$$

$$|\psi_n| = \frac{qN_DW_{Dn}^2}{2\varepsilon_s} \qquad (10b)$$

ψ_n is relative to the n-type bulk and thus is negative

From the above equation the depletion width is calculated to be :

$$W_{Dp} = \sqrt{\frac{2\varepsilon_s\psi_{bi}}{q}\frac{N_D}{N_A(N_A+N_D)}} \qquad (11a)$$

$$W_{Dn} = \sqrt{\frac{2\varepsilon_s\psi_{bi}}{q}\frac{N_A}{N_D(N_A+N_D)}} \qquad (11b)$$

$$W_{Dp} + W_{Dn} = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{N_A+N_D}{N_AN_D}\right)\psi_{bi}} \qquad (12)$$

$$W_D = \sqrt{\frac{2\varepsilon_s\psi_{bi}}{qN}} \qquad (13)$$

depending on whether $N_A \ll N_D$ or vice versa

3. Methodology

The code Poisson is one of the simulation for Solid State program (SSS). The code calculates and displays one dimensional numerical solutions for the band bending and carrier concentrations in inhomogenous semiconductors. It simulates both the p-n junction and sub-gate region of the metal insulator semiconductor field effect transistor (MISFET) for a wide range of material parameters under both equilibrium and biased conditions. ‘Poisson’ was programmed by Russ Thompson. The simulations were developed at Cornell University. A preset system is included which leads the user to the available parameter space and gives a way to become acquainted with the program, there are eight (8) presets on the program, numbered 1 to 8 [1]. The code calculates and displays one dimensional solutions for the band bending and carrier concentrations in inhomogenous semiconductors. It simulates both the p-n junction and the sub-gate region of the MISFET for a wide range of material parameters under both equilibrium and biased conditions. On preset four (4), the doping concentrations N_d and N_a (which are the same) were varied from 1×10^{20} to 1×10^{16} cm^{-3} for Zinc oxide, Gallium arsenide, silicon, Indium phosphide, Cadmium telluride and Cadmium selenide and in each case the values of the depletion layer width and charge displacement were taken.

4. Results and discussion

The depletion widths and Charge displacements obtained from the variation of doping concentrations for the various semiconductor materials were tabulated in tables 1 and 2 respectively.

Table 1 The doping concentrations and depletion width

		Depletion Width (cm)							
S/N	**Concetration (cm^{-3})**	Gallium-Nitride	Zinc-Oxide	Cadmium-Sulfide	Cadmium-Selenide	Cadmium-Telluride	Indium-Phosphide	Gallium-Arsenide	Silicon
1.	1.00×10^{20}	7.72×10^{-07}	7.66×10^{-07}	6.29×10^{-07}	4.75×10^{-07}	4.43×10^{-07}	4.01×10^{-07}	4.12×10^{-07}	3.48×10^{-07}
2.	1.00×10^{19}	2.44×10^{-06}	2.34×10^{-06}	1.97×10^{-06}	1.47×10^{-06}	1.37×10^{-06}	1.24×10^{-06}	1.27×10^{-06}	1.06×10^{-06}
3.	1.00×10^{18}	7.39×10^{-06}	7.28×10^{-06}	5.93×10^{-06}	4.35×10^{-06}	4.03×10^{-06}	3.63×10^{-06}	3.72×10^{-06}	2.95×10^{-06}
4.	1.00×10^{17}	2.32×10^{-05}	2.26×10^{-05}	1.83×10^{-05}	1.29×10^{-05}	1.18×10^{-05}	1.04×10^{-05}	1.09×10^{-05}	8.22×10^{-06}
5.	1.00×10^{16}	7.12×10^{-05}	6.88×10^{-05}	5.51×10^{-05}	3.74×10^{-05}	3.43×10^{-05}	2.86×10^{-05}	3.07×10^{-05}	2.28×10^{-05}

Table 2 The doping concentrations and Charge displacement

		Charge displacement, D (Cm^{-2})							
S/N	**Concetration (cm^{-3})**	Gallium-Nitride	Zinc-Oxide	Cadmium-Sulfide	Cadmium-Selenide	Cadmium-Telluride	Indium-Phosphide	Gallium-Arsenide	Silicon
1.	1×10^{20}	$4.6x10^{13}$	$4.6x10^{13}$	$3.7x10^{13}$	$3.2x10^{13}$	$3.1x10^{13}$	$3.0x10^{13}$	$3.0x10^{13}$	$2.6x10^{13}$
2.	1×10^{19}	$1.5x10^{13}$	$1.4x10^{13}$	$1.2x10^{13}$	$1.0x10^{13}$	$9.6x10^{12}$	$8.9x10^{12}$	$9.1x10^{12}$	$8.1x10^{12}$
3.	1×10^{18}	$4.5x10^{12}$	$4.4x10^{12}$	$3.6x10^{12}$	$3.1x10^{12}$	$2.9x10^{12}$	$2.7x10^{12}$	$2.8x10^{12}$	$2.4\ x10^{12}$
4.	$1.\times10^{17}$	$1.4x10^{12}$	$1.4x10^{12}$	$1.1x10^{12}$	$9.3x10^{11}$	$8.8x10^{11}$	$8.0x10^{11}$	$8.3x10^{11}$	$7.0x10^{11}$
5.	1×10^{16}	$4.3x10^{11}$	$4.3x10^{11}$	$3.4x10^{11}$	$2.8x10^{11}$	$2.6x10^{11}$	$2.4x10^{11}$	$2.5x10^{11}$	$2.1\ x10^{11}$

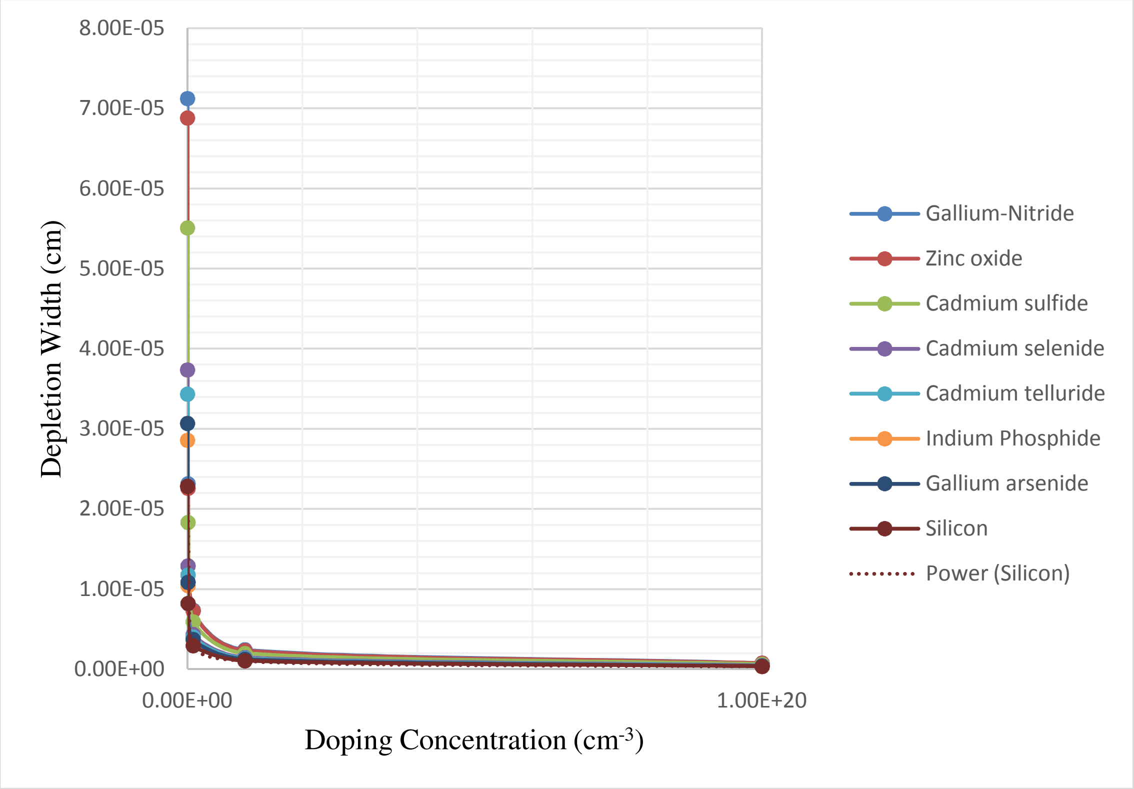

Figure 1 Graph of doping concentrations against depletion width

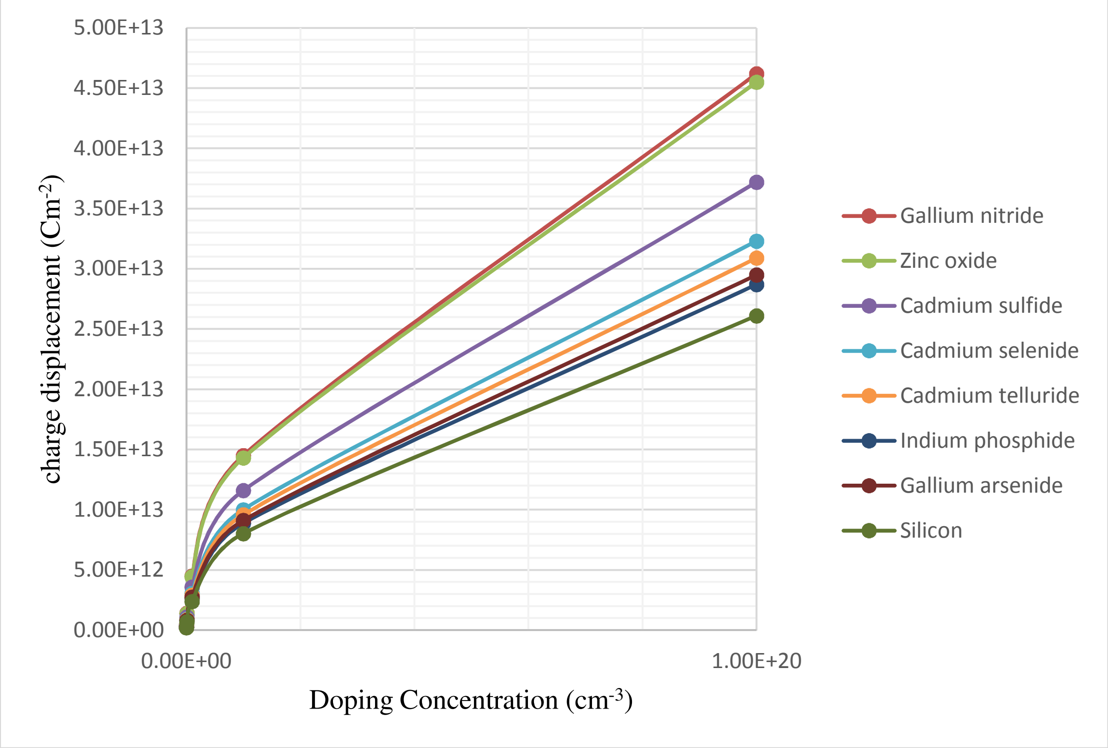

Figure 2 Graph of doping concentrations against charge displacement

From **figure 1**, it was observed that increase in doping concentrations leads to decrease in the depletion layer width. Also, it shows that semiconductor material with a wide band gap (high energy gap), such as gallium-nitride and zinc-oxide, have a higher depletion layer. But From **figure 2**, increase in doping concentrations leads to increase in the charge displacement. From **figuire 1** it is obvious that the relationship between doping concentration and depletion layer width is described by power function [10] of the form $y = ax^b$, y is the dependent variable and x is the independent variable. Here y is depletion width (in cm), x is doping concentration (in cm^{-3}) while a and b are constants. Table 3 contains the Band gap (eV) and constants a and b for each of the semiconductors. The constant a decreases as band gap decreases while the constant b increases as band gap decreases.

Table 3 Bandgap and power function constants

Semiconductors	**Bandgap (eV)**	**a**	**b**
Gallium-Nitride	3.44	5078.4	-0.491
Zinc oxide	3.35	4615.8	-0.489
Cadmium sulfide	2.50	3246.7	-0.485
Cadmium Selenide	1.70	1423.7	-0.473
Cadmium telluride	1.56	1202.6	-0.471
Gallium arsenide	1.42	955.69	-0.468
Indium Phosphide	1.35	758.77	-0.463
Silicon	1.12	403.86	-0.452

5. Conclusion

The effect of doping concentrations on the thickness of the depletion layer investigated using the Poisson code. From the results, it is clear that increasing the doping concentrations of a semiconductor material, result in a decrease in the depletion layer. Thus the applied voltage and doping concentrations has effect on the depletion layer while an increase in doping concentrations leads to increase in the charge displacement. And that the relationship between doping concentration and depletion layer width is described by power function.

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