Theoretical Investigation of Doping Concentration in Silicon Semiconductor Using Optical Principle

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ABSTRACT— This paper investigates the amount of doping concentration in silicon semiconductor using optical principle. Both donor and acceptor impurities of n type and p-type silicon semiconductor materials are computed at wavelength of 1550 nm. During the computation of donor and acceptor impurities, both reflection and absorption losses are considered. Theoretical result showed that transmitted intensity through both n-type and p-type silicon structure increases with respect to doping concentration (10^{15} cm^{-3} to 10^{21} cm^{-3}). It is also seen that transmitted intensity increases slowly up to 10^{20} cm^{-3} and then increases rapidly with the increase of doping concentration. Finally an experimental set up is proposed to estimate the doping concentration in silicon semiconductor.

KEYWORDS: doping concentration, silicon semiconductor, Reflectance, transmitted intensity

I. INTRODUCTION

Now a day's semiconductor technology is a remarkable research in the field of electronic science. Semiconductor is a special type of materials because its conductivity or resistivity can be increased or decreased by varying different physical parameter. Its properties lie between conductor and insulator. Out of different physical parameters, temperature and doping concentration play vital role to control different properties of semiconductor devices. Basically temperature makes vary the properties of intrinsic semiconductor where the properties of extrinsic semiconductor are varied with the variation of doping concentration.

The physical properties (mobility, band gap, conductivity and resistivity etc.) of an extrinsic semiconductor depend on doping concentration. For example degenerate semiconductor is formed under heavy doping of impurities (either donor or acceptors). Beside this, doping concentrations also define the concept of compensated semiconductor, where both donor and acceptors are present. As far as different types of semiconductor materials are concerned, silicon semiconductor plays an important role in the electronic industry. Doping in silicon semiconductor is a key parameter to realize optoelectronics applications such as Lasers, Solar cells, Photodetectors, Light-emitting diodes, and Optical Thyrister, etc. [1-4]. Apart from optoelectronics applications, the properties and applications of all silicon based electronics devices are controlled by doping concentration. As far as pn junction is concerned doping concentration plays significant role to investigate the built in potential, depletion layer width, electric field and electric potential in depletion region, junction capacitance and IV characteristics etc. [5]. Similarly doping concentration controls the operation of bipolar junction transistor because doping concentration in an emitter, base, and collector region is different for suitable transistor operation [6]. Also the doping concentration determines the width of M-S (metal-semiconductor) junction for an example; heavy doping concentration makes junction thin (ohmic contact) and light doping junction makes junction thin (Schottky barrier diode). Moreover the application of SBD (Schottky barrier diode) and ohmic contact are different [7]. As far as the operation of MOSFET (metal oxide field effect transistor), MESFET (metal semiconductor field effect transistor) and/or HEMT (high electron mobility transistor) is concerned, doping concentration on substrate or body controls the efficiency of the same transistor [8]. As far as literature survey on similar type of research is concerned, recently a few papers deal with related types of work [9,10,11]. In reference [9], authors discuss the impurity concentration in chalcogenide glasses using plane wave expansion method. Similarly, temperature in semiconductors materials are investigated in reference [10]. Also authors bestow the concentration of indium in indium antimony materials in reference [11].

In view of the importance of doping concentration in silicon electronics devices, this paper investigates the doping concentrations (donor and acceptor impurities) in p and n type semiconductor. Though this work is restricted with theoretical study only, here for the first time we are dealing with silicon semiconductor materials to estimate the doping concentrations with respect to transmitted intensity of light.

This paper is organized as follows; section II describes the mathematical treatment to find out reflectance and transmitted intensity. Results and discussion including experimental set up are discussed in section III. Finally, conclusions are given in section IV.

II. MATHEMATICAL TREATMENT

Before going to discuss the mathematical treatment to obtain transmitted intensity, let us focus into the ray diagram of incident, reflected and transmitted light including their directions, which is shown in Fig. 1.

In Fig. 1, it is seen that, 'I_0' be the intensity of incident light, which falls on the left side of this silicon (220 nm×200 nm) structure (both n and p semiconductor). Assuming 'R' to be the reflectance from left side then the intensity of reflected light (I_R) can be written as

$$I_R = RI_0 \quad (1)$$

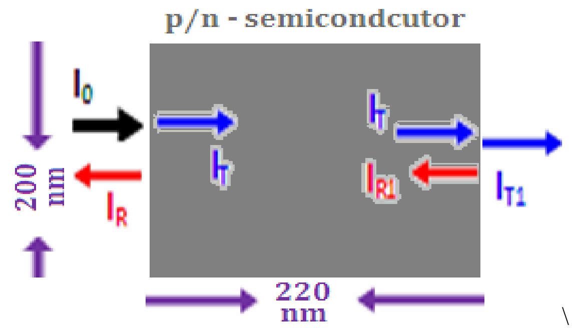

Fig. 1, silicon structure

Using Eq.(1), light transmitted (I_T) through the left side of silicon structure will be:

$$I_T = I_0 - I_R = I_0 - RI_0 = I_0(1-R) \quad (2)$$

Eq.(2) is represented **as** incident light for right side of the semiconductor So the amount of light reflected (I_{R1}) from this end is:

$$I_{R1} = RI_T = RI_0(1-R) \quad (3)$$

So the amount of light transmitted through the structure is

$$I_{T1} = I_T - I_{R1} = I_0(1-R)^2 \quad (4)$$

Considering absorption loss by silicon structure, equation (4) can be modified using Maxwell's equation and can be written as [12]

$$I_{T1} = I_0(1-R)^2 e^{-\beta t} \quad (5)$$

where $e^{-\beta t}$ is known as absorption factor and 'β' is called as absorption coefficient of silicon, which is found zero at wavelength 1550 nm [13]. Since 'β' is zero, the absorption factor is '1'. So the equation (5) is modified as

$$I_{T1} = I_0(1-R)^2 \quad (6)$$

The reflectance 'R' from such structure can be found using Fresnel's formula [14], i.e.

$$R = \left(\frac{n_{si} - n_{air}}{n_{si} + n_{air}}\right)^2 \quad (7)$$

where n_{si} and n_{air} are the refractive index of silicon and air medium respectively.

The refractive indices of silicon (p type and n type) are found using following formula [15]:

The refractive index of n-silicon in term of donor is given by

$$n_{Nsi} = n_0 - 8.8\times10^{-22} N_D \tag{8}$$

The refractive index of p-silicon in term of acceptor is given by

$$n_{psi} = n_0 - 8.5\times10^{-18} N_A^{\ 0.8} \tag{9}$$

where n_{Nsi} and n_{Psi} is the refractive index of n type and p type of silicon and n_0 be the refractive index of pure silicon (zero doping) , which is equal to 3.46. N_D and N_A are donor and acceptors concentrations. Knowing the values of n_{si}, n_{air} and R, the resultant intensity (I_{T1}) can be determined.

III. Results and Discussion

From Eq. (7), it is seen that the reflectance from silicon structure depends on refractive index of p and n type materials with different concentrations (donor and acceptors). The values of refractive indices of p and n type of semiconductor are found using equation (8) and (9), which is mentioned in table 1.

Table 1, Variation of refractive index of silicon with doping concentration

Concentration (C) (cm^{-3})	Refractive index at wavelength of 1550 nm	
	p-Silicon (n_{Psi})	n-Silicon (n_{Nsi})
10^{15}	3.4614	3.4595
10^{16}	3.4613	3.4594
10^{17}	3.4612	3.4593
10^{18}	3.4602	3.45885
10^{19}	3.4473	3.4506
10^{20}	3.3734	3.3714
10^{21}	2.9208	2.5794

Using data from Table 1 and with the help of equation (7) simulations are made to obtain reflectance corresponding to each doping concentration (acceptor and donor impurities). After finding reflectance, the transmitted intensity is found by using equation (6)

The same result is shown in Fig. 2.

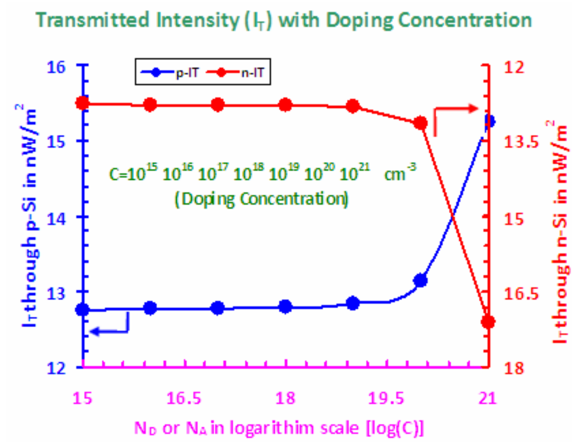

Fig. 2, Variation of transmitted intensity through p-si and n-si with donor and acceptor concentration.

In Fig. 2, it is seen that transmitted intensity in nW/m^2 through p-silicon semiconductor structure is taken along primary y-axis (left vertical axis) , where transmitted intensity in nW/m^2 through n- silicon semiconductor structure is taken along secondary y-axis (right vertical axis). Similarly, logarithm of concentration [log (C)] is taken along primary x-axis where 'C' is donor and acceptors concentration, which varies from 10^{15} cm^{-3} to 10^{21} cm^{-3}.

From Fig. 2 it is found that both transmitted intensities (transmitted intensity through n and p-structure) increases with the increase of doping concentration, for example transmitted intensity through n-silicon semiconductor increases from 12.775 nW/m^2 to 17.12 nW/m^2 as doping concentration (donor) increases from 10^{15} cm^{-3} to 10^{21} cm^{-3} and transmitted intensity through p-silicon semiconductor increases from 12.76 nW/m^2 to 15.25 nW/m^2 as doping concentration (acceptor) increases from 10^{15} cm^{-3} to 10^{21} cm^{-3}. From above variation, it is inferred that though the nature of variation of transmitted intensity through p and n semiconductor are same, the path of variation is not same. Moreover it is found that transmitted light through n-type semiconductor is more than p-type silicon semiconductor.

Aside this , it is observed that transmitted intensity slowly increases up to 10^{20} cm^{-3} and further increases rapidly. The reason for slow variation of transmitted intensity with respect to donor and acceptors concentration of 10^{15} cm^{-3} to 10^{20} cm^{-3} is that the change of refractive index is found less (from Table 1) with respect to same concentrations (both donor and acceptors). Since the change of refractive index with respect to concentration from 10^{20} cm^{-3} to 10^{21} cm^{-3} is found more , the transmitted intensity through p and n type of semiconductor is suddenly increased with same concentrations. In Fig. 3, it is also observed that though both variations of transmitted intensities intersect at same value of concentration (log(C)=20.4), the transmitted intensities are not same . It also indicates that the transmitted intensity through p-silicon semiconductor is 14.0 nW/m^2 , where transmitted intensity through n-silicon semiconductor is 15.0 nW/m^2 at concentration $10^{20.4}$ cm^{-3}.

Though this paper explores theoretical study only, here we want to divulge an experimental set up by which one can design the same set up to measure the concentrations experimentally. The same proposed experimental set up is shown in Fig. 3.

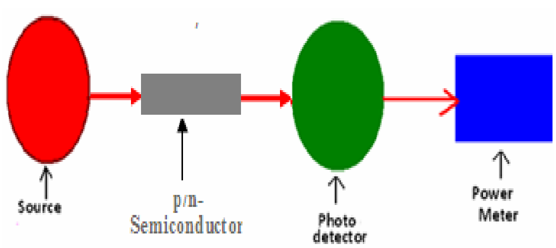

Fig. 3. Experimental set up to compute the concentration of donor and acceptor concentrations in n and p silicon semiconductor materials.

Figure 3 represents an experimental arrangement to measure the transmitted intensity directly, which leads to estimate the donor and acceptor concentrations, which is stated bellow:

Light having wavelength of 1550 nm incidents on silicon structure (p-type or n-type), then some amount of light will be reflected from it and some will be absorbed by it and rest amount of light will be reached at photo detector and subsequently measured at power meter. In this case, the transmitted intensities in the power meter are differed from different doping concentrations. Since there is no absorption loss accomplished with semiconductor, the output intensities depend on reflectance only. The same reflectance is determined using equation (7).

IV. Conclusion

The computation of donor and acceptor concentrations in silicon semiconductor is thoroughly investigated in this paper. Reflections as well as absorption losses are cogitated to measure the transmitted intensity. Analytical results revealed that transmitted intensities through p and n type of semiconductors increase with the increase of doping concentration. This result is also divulged that these transmitted intensities slowly vary up to certain donors and acceptors (10^{20} cm^{-3}) and further increases suddenly. This peculiar variation of transmitted intensities depends on both refractive indices and thickness of semiconductor structures. Experimental setup is also proposed to find out the same concentration. It is found that both acceptor and donor impurities of silicon semiconductor can be determined by knowing the values of transmitted intensity of light.

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