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STUDIES ON NONLINEAR BEHAVIOR OF SEMICONDUCTOR FOR THE REALIZATION OF DOPING CONCENTRATION SENSOR

Bhukya Arun Kumar[1], Sanjay Kumar Sahu[2], *Gopinath Palai[3], Sarada Prasad Mohanty[4]
[1,2]School of Electronics and Electrical Engineering, Lovely Professional University
[3]Department of Electronics and Communication, Gandhi Institute for Technological Advancement, Bhubaneswar - 752054
[4]Department of Chemistry, OUTR, Bhubaneswar
Corresponding author's E-mail: gpalai28@gmail.com, gpalai_ece@gita.edu.in

Abstract. The exploration of doping concentration in p and n type semiconductors are comprehend in this article for sensing application. The mechanism of the investigation relies on the nonlinear behavior of output result pertaining to the impurity concentration. Moreover, the principle of the mechanism governs by the transportation of electric field in the photonic crystal fiber-based semiconductor materials. In this work a light source of 1550nm is applied to a photonic crystal fiber with varying concentration. A photo detector is fitted at the output end which captures the signal to measure the potential variation when the concentration is subjected to change. The results provide distinct features in terms of non-linearity which is exploited here for sensing applications.

Keywords: Doping concentration, nonlinear behavior, Sensor.

1. Introduction

Today's semiconductor technology is a research area of electronic science. Semiconductors are unique materials in that their conductivity or resistivity may be changed by adjusting certain physical parameters. Its characteristics are intermediate between those of a conductor and those of an insulator. Among other physical parameters, doping concentration and temperature, play an important role in controlling the properties of semiconductor devices. Basically, temperature changes the properties of intrinsic semiconductors, whereas doping concentration changes the properties of extrinsic semiconductors, physical properties (mobility, band gap, conductivity, and resistivity, among others) are influenced by doping level in extrinsic semiconductors. Degenerate semiconductors, for example, are generated when impurities are heavily doped (either donor or acceptors). Doping concentrations also define the concept of a compensated semiconductor, which contains both donors and acceptors. Silicon semiconductors play a significant part in the electronics sector when it comes to different types of semiconductor materials. Doping in silicon semiconductors is an important parameter in optoelectronics applications like lasers, solar cells, photo detectors, light-emitting diodes, and optical thyristor's etc. [3,8-9,14].The number of electrons in conduction band can be carefully controlled by number of impurity atoms added to silicon. Adding pentavalent impurity atoms to intrinsic silicon, the number of electrons in conduction band can be increased. In the similar fashion, the number of holes in intrinsic silicon [2,13] will rise just by adding trivalent impurity atoms. In the literature, refers to sensing, a new approachat 1550 nm is proposed which finds PECVD SiO2: N/SiO2 slab waveguide grating (SWG) [4]. In that proposition, the author considered reflected spectrum is to analyze refractive index and strain by Grating Mode R-Soft design tools suite method which depends on temperature. Further the investigation of semiconductor properties with the help of the principle of photonic is rare pertaining to the current research scenario. Basically, photonics deals with certain system which can be utilized in developing electronic devices to detect, modulate, change and moreover control the light propagation. These are artificially manufactured with a periodic arrangement explicitly useful in the area like robotics, agriculture, medicine, spectroscopy, health monitoring system, laser technology and many more [7].Materials having a periodic dielectric profile, such as photonic band-gap (PBGs) or photonic crystals (PhCs), can restrict light of specific frequencies or wavelengths from travelling in one, two, or any number of polarization directions inside the materials. This frequency range is commonly assumed to be the photonic band-gap since it resembles an electrical band-gap. Photonic crystals are sometime named as photonic band gap materials. Chemical sensors, biosensors, solar cells and optical sensors have been proposed as platforms of photonic crystals. Generally, photonic crystal is composed of periodic dielectric material capable of affecting the motion of photon. The mechanism is quite analogous to a piece of semiconductor where periodic potential creates a similar kind of impact on the behavior of electron. A proper design of this kind may suppress the flow of light to a particular direction and confine over a band of frequencies. In addition, it can also perform detection, creation, transmission which finds a phenomenal growth in the field of optoelectronics. The most interesting part for this structure in comparison to electronics system is that the interference level is quite less and this is due to the fact that photons do not interact among themselves.Further focusing on the literature review on optical fibre, new in-fibre polarisers, polarisation controllers, and grating devices, as well as increased sensitivity pressure and acoustic sensors, gas sensors with quick response and ppm level detection-limit, and unique in-fibre polarizer's, polarisation controllers are discussed [7,11]. As semiconductor is one of the constituents in designing photonic crystal, Nayak Chittaranjan uses gallium arsenide as background material to design an optical mirror behaving like a sensor as total power is reflected back to the source [10]. Mishra et al. explains about photonic sensor made up of silicon/germanium which divulge about nonlinearity which is changing as a function of temperatures. In that work they have estimated different parameters such as transmittance, reflection and absorption for sake of sensor design [5,12].Though many works have been done with respect to the sensing application for semiconductor, the present paper uses signal having wavelength of 1550nm light source for sensing as less absorption losses at this wavelength. Hollow-core type of square photonic band gap fibres offer distinct features that may be exploited to construct innovative photonic sensors and devices.

The present article is segregated as follows; introduction to semiconductor-based photonics is indicated in the section-1, where the operational mechanism of the research is discussed in the section 3, where mathematical treatment is signified in the section 4. The result and discussion are made in the section 5 and conclusion is mentioned in the section 5.

2. Operational Mechanism

The investigation of doping concentration of semiconductor can be made using the photonic crystal fibre which relies on the different components such as laser source which emanates the signal of 1550 nm, semiconductor based photonic structure and the photodiode. The entire operational mechanism is shown in the figure 1(a).

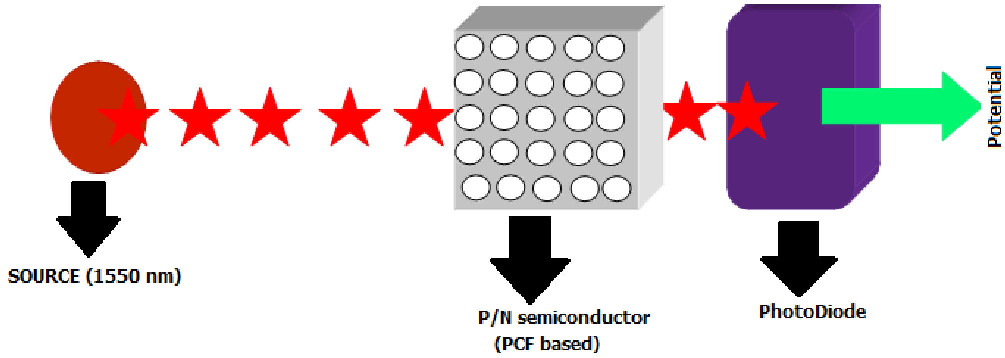

Figure 1. Experimental (proposed) setup to find out the power at the output (photometer)

In the figure 1,1550 nm wavelength of light is made available from the source and allowed to incident on silicon based photonic crystal fiber structure (P/N type), then signal would be transported in the fiber and the electric field distribution is realized inside the structure. Finally, the peak electric field reaches at the at the output end. Further the photo detectorindicates the amount of potential corresponding to each doping concentrations. A photonic crystal fiber is simply made up either p or n type of silicon-based semiconductor as background material where air is taken as column material that is running along the fiber. Similarly, the number of air holes is taken of 25 in such way that 5×5 along row × column respectively. However, the defect is made at the central region. The main cause of selecting a defect at the center is that there will be three option to fix detector position at three different positions (left, right and central region). Moreover the, the configuration of this investigation depends on the lattice spacing of the structure and diameter of air holes which is taken of 1000 nm and 800 nm respectively.

3. Mathematical Treatment

The mathematics for the realization of concentration sensor is computed using the principle of electric filed distribution in the fiber. With the help of Helmholtz equation, the field distribution of the photonic crystal fibers has been computed.

So, to compute, they can be written as

$$\frac{1}{\in(r)}\nabla\times\{\nabla\times E(r)\}=\frac{\omega^2}{c^2}\,\mathrm{E(r)} \quad (1)$$

The symbols have their usual meaning

The solution of equation (1) is expressed as

$$\mathrm{E(r)}=E_{k,r}(r).e^{\,i.k.r} \quad (2)$$

$E_{k,r}$ is defined to be the periodic function with periodicity of lattice. Bloch wave equation suffices the wave functions to make use of Fourier series over lattice vector, with an expression governed by

$$E_{kr}(x,y)=\sum E'_{kr}(G_r)\ \exp(i(k_x+G_x,r).x+(k_y+G_y,r).y) \quad (3)$$

Here $E'_{kr}(G_r)$ are Eigen vectors is calculated

Here $E'_{kr}(G_r)$ are Eigen vectors to be found during the Eigen problem solution. G_x and G_y named as Fourier coefficients for harmonics. Expressions with equation2 & 3 are utilized to solve eigen value problem and subsequently estimated the field distribution for the photonic crystal fiber. The obtained electric fields collected from the photo detector are then taken to calculate the required potential.

4. Result and Discussion

Even though nonlinear properties of semiconductor are seen in most of the cases, the final computation is considered with negleting the such behaviour for sensing applications because we are focusing on the linear behaviour of the same. More specifically, in today situation optical material using semicoductor finds operation in linear region assuming that the non linear effect plays minor role in the result. The reason for considering the linear response is that when dielectric and metals intersperse in a design it is rather difficult to solve Maxwell equation due to complex boundary condition. In addition to that in linealty condition transmittance and reflectance are most focused parameters when a source of light is allowed to pass thriugh the sample neglecting scattering and diffusion effect. On the other hand in non linear case it is customary to include the polarization control as optical material normally anisotropic in nature.So here in this work we tried to stress on nonlinear effect due to the light matter interaction which may help in designing sensors.In this process we enumerate an extensive study on silicon semiconductor where the light source is applied to it. The output potential is measured by the detector with changing the amount of dopant in the semiconductor based fiber, which is discussed in the figure 1.

Considering the internal mechanism (section-2), a signal of 1550 nm incidents to the photonic structures which leads to the distribution of electricfields in the structure which is found with help of equation (1-3) where the plane wave exapnsion is used to compute the same. To fetch the field distribution in the fiber, the different input parameters have been used which is indicated in the table 1 [6].

Table 1: Input parameters to fetch electricfield disrribution

Wavelength = 1550 nm		
Lattice Spacing = 1000 nm; Diameter of air hole=800 nm		
Impurity Concentration (cm^{-3})	Refractive Index (p type-silicon)	Refractive Index (n type-silicon)
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

In the Table 1, different input parameters have been chosen sch as wavelength of the signal (1550 nm), lattice spacing of the structure (1000 nm), diamter of the air holes, refractive indices of p and n type silicon semiconductor materials with respect to the different impurity concentrations which is indicated in the column 1 (doping concentration), column (Refractive index of p-silicon) and column 3(refractive index of n silicon) at the signal of 1550nm respectively. With the help of above said data from the table 1 and applying the plane wave exapnsion method through equations (1-3), the electricfield distribution is found [1]. Though the results for the doping conecntration have obtained, the outcome for the concetration of 10^{15} cm^{-3} (n-type) is indiacated in the figure 2.

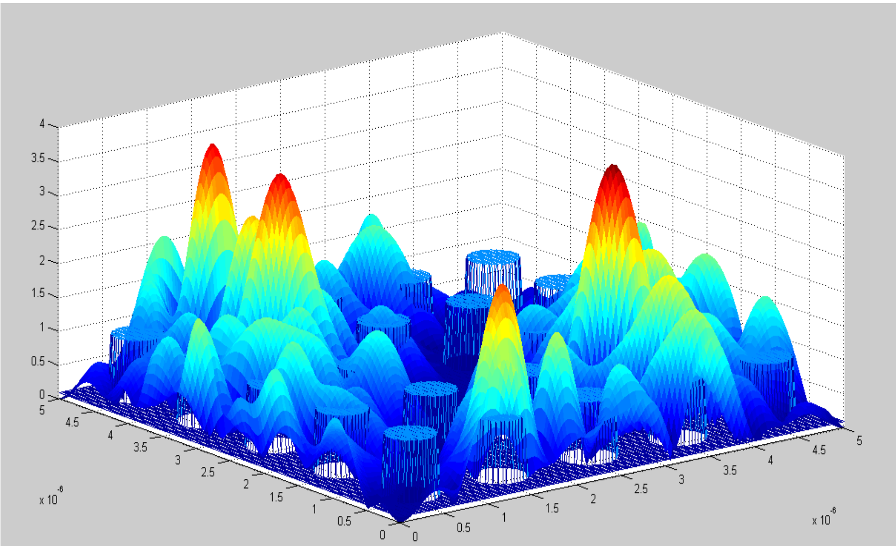

Figure 2. Simulated field distribution for concentration 10^{15} cm^{-3} for n-silicon at the signal of 1550 nm

In the figure 2, the length and breadth of the fiber is shown along x and y axis respectively where the peak electric field distribution is taken along z-axis respectively. The peak electric fields are indicated through red color where the total electric fields have been found with the combination of electric fields. Further the said electric filed appears at the output end of the fiber and finally collected by the photo detector. The photo detector converts the light in to potential. Even if we have shown the result for 10^{15} cm^{-3}, the computations for electric field distribution as well as potential are made for all other impurity concentration corresponding p and type semiconductor. The entire results for the same are indicated in the table 2(a) and 2(b) for p and n-silicon semiconductor respectively;

Table 2(a): Variation of peak electric field and potential for different doping concentration (P type semiconductor) at 1550nm

Impurity Concentration (cm^{-3})	Peak Electric Field V/m	Potential in μ-Volt
10^{15}	25.165	150.99
10^{16}	25.12547	150.75282
10^{17}	19.41947	116.51682
10^{18}	29.817	178.902
10^{19}	22.135	132.81
10^{20}	27.472	164.832
10^{21}	22.558	135.348

Table 2(b): Variation of peak electric field and potential for different doping concentration (n type semiconductor) at 1550nm

Impurity Concentration (cm^{-3})	Peak Electric Field V/m	Potential in μ-Volt
10^{15}	18.691	112.146
10^{16}	21.943	131.658
10^{17}	21.079	126.474
10^{18}	20.92259	125.5355
10^{19}	25.268	151.608
10^{20}	30.214	181.284
10^{21}	16.976	101.856

Table 2 represents the values of the peak electric field (column 2) emerging form photonic crystal fiber and potential (column 3) from photodetector with respect to the impurity concentration (column 1). To make better understanding the aforementioned outcomes, a graph is plotted for p and n type semiconductor using the data from table 2, the same results is indicated in the figure 3(a) and 3(b) for p and n material respectively.

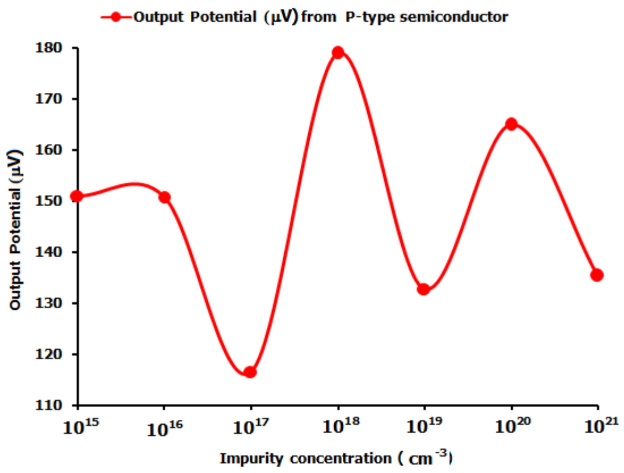

Figure 3(a) Variation of electricpotential with doping concentration for p-type silicon material

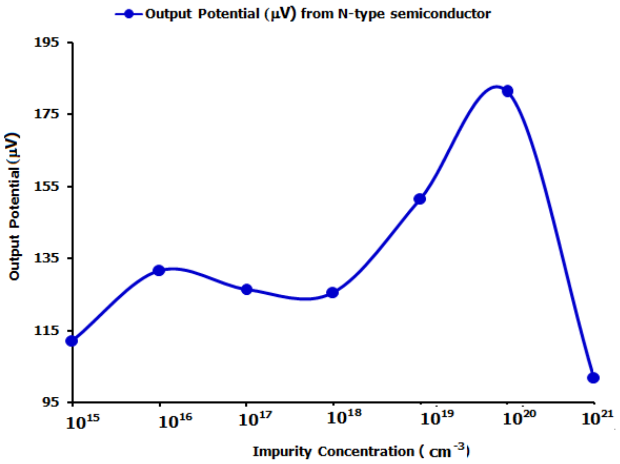

Figure 3(b) Variation of electric potential with doping concentration for n-type silicon material

In the figure 3; estimated potential (µV) are fitted along Y-axis where imprity concentration (cm^{-3}) is taken along X-axis. From these figures, it is realised that the variation of potentials are nonlinear with respect to the impurity cocentartions. The probale reason for these non- linearity is that the interaction of photon paraticles with the doping concenttion as well as lattice vibration. For example; the interaction of impurity atoms with lattice vibration takes place and simultaneoulsy the interaction of photon particles with both impurities and lattice transpires the nonlinear behaviour.

5. Conclusions

In this work a semiconductor based photonic structure with variable concentration is excited with a 1550 nm signal. During signal transmission, electric field distribution plays main role to realize the non-linear behavior of the semiconductor materials where all kind of computation have been carried out through plane wave expansion technique. It is concluded that the electric potential varies non-linearly when the impurity concentration is subjected to vary in the case of n and p silicon based photonic structures.

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