Strained Engineered-Induced Mobility P^+IN^+ Photodiode—A Novel Opto-sensor for Biomedical Application

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Abstract Nowadays, electrical switching circuits depend on PIN diode extensively. Non-invasive biomedical circuits are greatly influenced by the sensitivity of biosensors. The optical sensors are the key components in those circuits. The potential of PIN devices such as opto-sensors is studied in this paper. Si technology is the most mature one in modern industry. Therefore, the opto-sensitivity and photo-responsivity of the devices are studied by developing a quantum modified drift diffusion model. In this paper, the characteristics of PIN diode are studied which is made of silicon with a very small amount of carbon doping within it, and this strained material shows immense promise to the field of MMW and THz science and technology, and more precisely in biomedical domain for its modified band structure and electron transport characteristics, due to incorporation of artificial strain within this. Authors have studied the prospect of carbon doping selectively in Si PIN devices so as to increase the sensitivity of its application.

Keywords Strained band gap · Photo-responsivity · Mm-wave propagation

1 Introduction

Nowadays, electrical switching circuits depend on PIN diode extensively. Non-invasive biomedical circuits are greatly influenced by the sensitivity of biosensors. The optical sensors are the key components in those circuits. The potential of PIN devices such as opto-sensors is studied in this paper. Si technology is the most mature one in modern industry. Therefore, the opto-sensitivity and photo-responsivity of the devices are studied by developing a quantum modified drift diffusion model. In this

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paper, the characteristics of PIN diode are studied which is made of silicon with a very small amount of carbon doping within it, and this strained material shows immense promise to the field of MMW and THz science and technology, and more precisely in biomedical domain for its modified band structure and electron transport characteristics, due to incorporation of artificial strain within this. Authors have studied the prospect of carbon doping selectively in Si PIN devices so as to increase the sensitivity of its application. Microwave switches are widely used in different communication and detection systems. But the conventional classical drift diffusion (CLDD) model has certain limitations like inter-sub-band tunneling, hot carrier effect, quantum size effect, realistic field and temperature-dependent carrier density effect which degrade the overall performance of PIN diode (Chen 1993). To overcome this, efforts have been made to design PIN diode model using strained band gap.

2 Theory

The band gap engineering relies on the developments in the crystal growth (Perelman et al. 2001). As the band structure determines several important electronic and optical characteristics, so band gap engineering is one of the most powerful techniques for designing new semiconductor materials and devices. When two different materials are used to form the junction of the diode, then there may be a mismatch between both the lattices (Rahmani et al. 2016). And the lattices try to make them fit anyhow, which create strain at or near the interface of two different materials. The strain between two layers of material is simply a force acting in plane which is compensated by the attractive/repulsive forces between the atoms in the lattice. Li and Zang (2017) represent the electric field of the intrinsic region of the PIN diode and numerically expressed as

$$E(x,t) = \frac{-\partial V(x,t)}{\partial x} \tag{1}$$

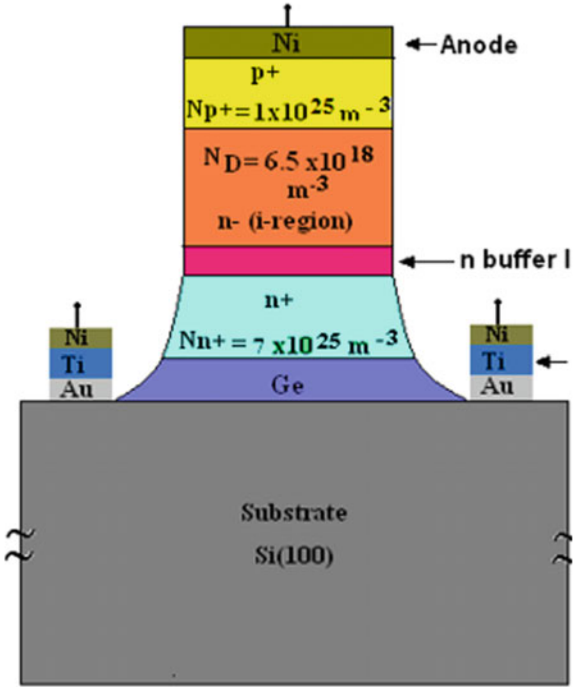
The instantaneous voltage, at intrinsic region, is determined from the electric field profile

$$V_i(t) = \int_{x=0}^{x=W} E(x,t) \tag{2}$$

So, the hole and electron current density can be expressed as

$$J_p(x,t) = -q\mu_p\left[C_p(x,t)\frac{\partial}{\partial x}V(x,t) + \left(\frac{K_B T_j}{q}\right)\frac{\mathrm{d}}{\mathrm{d}x}C_p(x,t)\right] \tag{3}$$

Fig. 1 Structure of PIN diode



$$J_n(x,t) = -q\mu_n\left[C_n(x,t)\frac{\partial}{\partial x}V(x,t) + \left(\frac{K_B T_j}{q}\right)\frac{\mathrm{d}}{\mathrm{d}x}C_n(x,t)\right] \tag{4}$$

From the above equations, the total current density due to holes and electrons can be given by Fig. 1.

The doping profile of designed P+IN+ diode is shown in Fig. 2.

The strain, ε, in the layer due to the lattice mismatch can be expressed in terms of the lattice constants of the layer and the substrate and is given by (Sahbudin 2004):

$$\varepsilon = a_{\text{substrate}} - \frac{a_{\text{layer}}}{a_{\text{substrate}}} \tag{5}$$

$a_{\text{substrate}}$ is the lattice constant of the substrate, and a_{layer} is the lattice constant of the layer.

Strain induces a shift in the energy levels than that of the unstrained conduction and valence bands. Here, in this paper, we have investigated the band structure of strained SiC (Khan and Copper 2000), where the heterojunction is made by silicon with 10% of carbon doping in it. We have extracted band parameters and analyzed electron transport phenomena which shows much higher performance than the unstrained SiC (Kundu et al. 2021; Atabaev and Juraev 2018) in terms of critical electric field distribution at breakdown, I–V characteristics, series resistance, power dissipation and

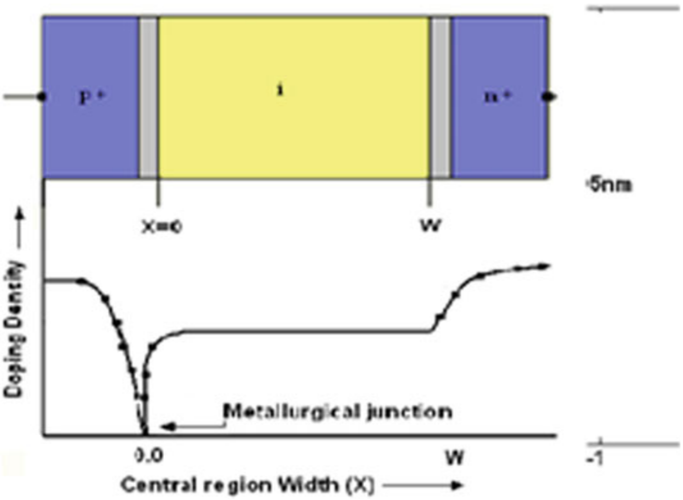


Fig. 2 Doping profile of designed P⁺IN⁺ diode

reverse recovery current, photo-responsivity and quantum efficiency. The proposed PIN model works in THz frequency region and may be used for medical imaging purposes.

3 Result

In recent year, the dynamics of carriers induced by electric field in the semiconductor superlattices is the much-interested area of research. The photoelectrical characteristics of the designed PIN photodiode are obtained by solving Poisson's equation and continuity equation (Figs. 3, 4, 5, 6 and 7; Table 1).

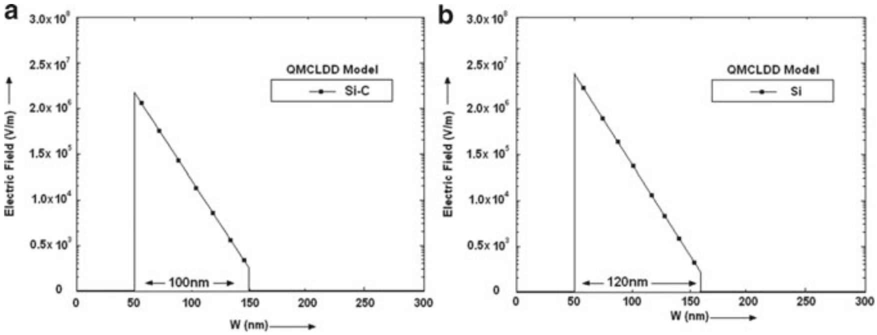


Fig. 3 Response of electric field with wavelength for **a** strained Si and **b** unstrained Si

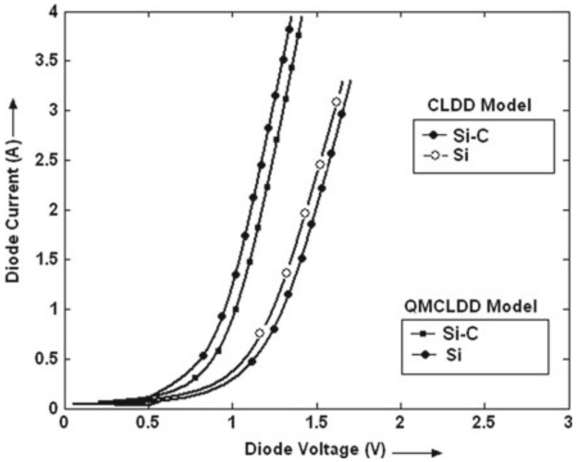


Fig. 4 V–I characteristics for unstrained Si and strained Si

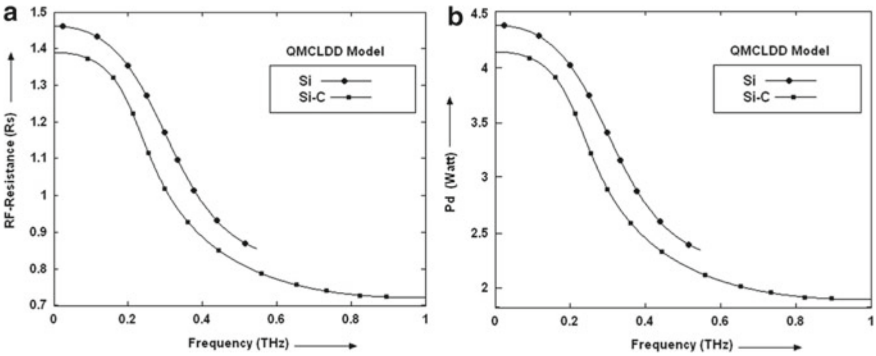


Fig. 5 Response of **a** RF resistance with frequency, **b** dissipated power with frequency for strained Si and unstrained Si

4 Conclusion

The concept of band gap engineering in enhancing the photo-current response of strained PIN devices is studied thoroughly in the report. It is observed that compared to unstrained silicon, strained (carbon doped) silicon is more efficient in THz frequency region. The future and larger study will fix immense application in case of medical instruments and electronics industry.

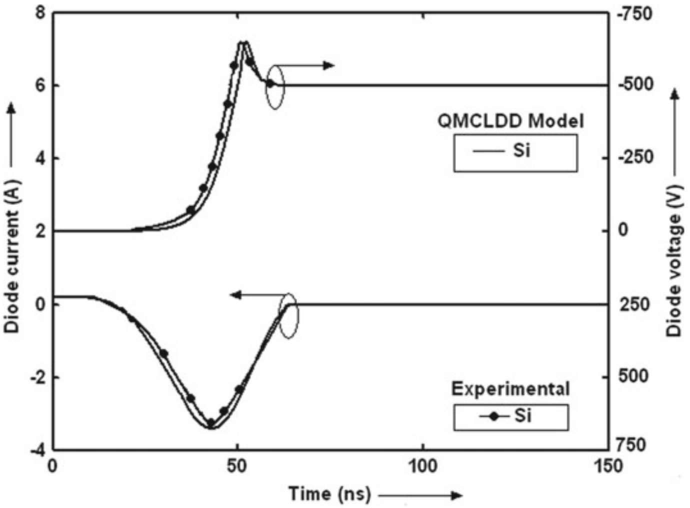


Fig. 6 Response of diode current and voltage with time

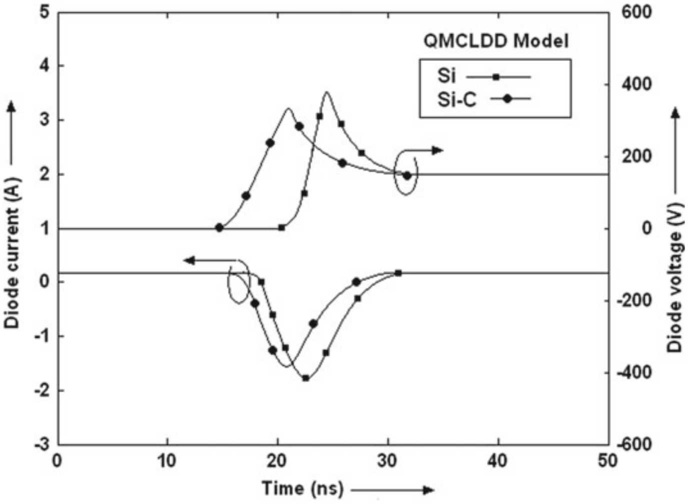


Fig. 7 Response of diode current and voltage with time compared with strained Si

Table 1 Design specifications for strained Si and unstrained Si

Device under test (DUT)	Design frequency (f_d) (THz)	i region /low-doped (n^-) region width (W) (nm)	Doping concentration of i region (n^-) (10^{18}) (m^{-3})	Doping concentration of heavily doped n region (Nn^{++}) (10^{25}) (m^{-3})	Doping concentration of heavily doped p region (Np^{++}) (10^{25}) (m^{-3})
Si	0.35	120	4.0	6.0	4.0
Si–C	0.75	100	6.5	7.0	5.0

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