Optical Response of UV Laser Irradiated Extrinsic Semiconductor

Maryam Sardar, Zaka Ullah*, Anwar Latif, Bushra Jabar, Abida Perveen, Muhammad Shahid Rafique, and Muhammad Khaleeq-Ur-Rahman

Laser and Optronics Centre, Department of Physics, University of Engineering & Technology, Lahore - 54890, Pakistan

*email: mail2zaka@gmail.com

Received 4 February 2015

Abstract — Fine polished samples of p-silicon were irradiated in ambient air using Excimer Laser and Spectroscopic Ellipsometry was employed to investigate their various optical properties. The changes in optical constants (refractive index and extinction coefficient) and optical band gap energy were noticed in incident wavelength range 500–1000 nm. Both refractive index and extinction coefficient decrease exponentially before and after irradiation. A fall in the optical band gap energy of p-silicon was also observed after laser exposure, which makes the materials suitable for variety of optoelectronics applications.

Keywords: p-silicon; Excimer Laser; Irradiation; Spectroscopic Ellipsometry.

1. Introduction

Semiconductors are playing vital role in electronic industry due to their interesting and significant properties such as optical imaging, optical recording, integrated optics, etc., investigated over last few decades [1-3]. The photo or laser induced phenomena along with laser annealing affects, make these materials quite useful for diversity of optoelectronics components like photos resist, optical memories, optical interconnects, optoelectronics circuits, etc. [4-6]. The material exposure can also result in excitation of electron-hole pairs. Physiochemical properties of silicon materials change due to the structural changes caused by laser irradiation [7-9]. Laser produced defects and variations in grain size also change the optical parameters of irradiated materials, such as refractive index, absorption coefficient, optical band gap energy, etc. [10].

The effect of UV laser irradiation on these optical parameters of p-type semiconductor is presented in this paper, to make these materials more suitable for the fabrication of optoelectronic devices.

2. Experimental technique

Fine polished p-silicon targets with dimensions 1 cm × 1 cm × 0.2 cm were irradiated by UV Excimer laser (λ = 248 nm, τ = 20 ns, E = 57 mJ) having rectangular
profile beam at fluence 1.085 J/cm\(^2\) in ambient air. Irradiation was performed in ambient air for 200 laser shots at a repetition rate 100 Hz.

The area exposed on the samples was 1 cm\(^2\) in grid formation. Rotating compensator auto aligned Ellipsometer (M-2000, J.A. Woolam Co., Inc.) was used to measure the optical constants of irradiated materials. It has broad range of incident wavelength from 193 nm to 1690 nm and provides a mapping of about 300 mm. The samples were scanned at an angle 60° to the incident beam with respect to the surface of target. The elliptical beam spot size having a length of 5 mm on semi-major axis, was used. The experimental setup is shown in Fig. 1.

![Experimental Setup](image)

Fig. 1: Schematic of the experimental setup.

3. Results and discussion

Spectroscopic Ellipsometry measures the two values \((\Psi, \Delta)\) that express the amplitude ratio and phase difference between p- and s-polarizations, respectively. The variation in light reflection with p- and s-polarizations is measured as the change in polarization state, where p-polarized waves have electric field parallel to the plane of incidence and s-polarized waves have electric field perpendicular to the plane of incidence. In particular, when a sample structure is simple, the amplitude ratio \(\Psi\) is characterized by the refractive index \(n\), while \(\Delta\) represents light absorption described by the extinction coefficient \(k\). In this case, the two values \((n, k)\) can be determined directly from the two Ellipsometry parameters \((\Psi, \Delta)\), obtained from the measurements using Fresnel equations [11].

The data obtained from Spectroscopic Ellipsometry of unexposed and exposed p-silicon targets reveal a change in refractive index, extinction coefficient and optical band gap energy.
Cauchy-Sellmeir model was used to derive these parameters [11]. The variation in refractive index $n$ for un-exposed and exposed p-silicon is shown in Fig. 2. Trend shows exponential decrease in both cases, for incident waves ranging from 500 nm to 1000 nm. At 500 nm, the values of ‘$n$’ for un-exposed and exposed samples are 4.10 and 3.76, respectively, and then a gradual decrease is observed up to 700 nm where these values become 3.70 and 3.54 respectively. With further increase in the wavelength, refractive index decreases and gets its minimum value 3.54 at 1000 nm for un-irradiated p-silicon and 3.46 for irradiated p-silicon.

![Fig. 2: Influence of Wavelength $\lambda$ on Refractive Index $n$](image)

![Fig. 3: Influence of Wavelength $\lambda$ on Extinction Coefficient $k$](image)
The variations in $k$ for un-irradiated and irradiated p-silicon are shown in Fig. 3. There is an exponential decrease for both un-irradiated and irradiated samples. At 500 nm incident wavelength, the values of $k$ for un-irradiated and irradiated samples are 0.66 and 1.09, respectively. In both, visible and IR regions, $k$ decreases as the wavelength of incident wave is increased. It has a minimum value of 0.23 at 1000 nm for un-irradiated p-silicon and 0.44 for irradiated p-silicon, respectively.

Tauc’s relation, which relates absorption coefficient ($\alpha$) and the incident photon energy ($h\nu$), was used to find out the band gap energy ($E_g$) of p-silicon materials. The relation is given below [12]:

$$\alpha h\nu = A (h\nu - E_g)^n$$  \hspace{1cm} (1)

Here, $E_g$ is the band gap energy, $A$ is a constant which is different for different transitions, $h\nu$ is energy of photon and $n$ is an index which assumes the values 1/2, 3/2, 2 and 3, depending on the nature of the electronic transition responsible for the reflection [9]. $\alpha$ is the absorption coefficient and can be calculated using the relation [13,14],

$$\alpha = (4\pi k/\lambda) \times 10^9 \text{ m}^{-1}$$  \hspace{1cm} (2)

where $k$ is the extinction coefficient and $\lambda$ is the incident wavelength.

The values of optical band gap energy $E_g$ were obtained by extrapolating their straight portions towards $\alpha h\nu$ axis up to $(\alpha h\nu) = 0$ [3, 15]. The band gap energy values obtained are 3.1 eV for un-irradiated and 2.8 eV for irradiated p-silicon samples. The UV laser irradiation on the surface of p-Si produces defects that cause variations in
optical parameters, thus altering the optical properties. There is also a remarkable change in grain size as shown in Fig. 4, which effects various properties of the materials [16-17]. The variation in refractive index $n$, extinction coefficient $k$ and band gap energy $E_g$ of un-irradiated and laser irradiated p-Si materials is given in Table 1.

Table 1. Variation in refractive index $n$, extinction coefficient $k$ and band gap energy $E_g$ of un-irradiated and laser irradiated p-Si materials

<table>
<thead>
<tr>
<th>p-Silicon</th>
<th>Wavelength dependent ‘$n$’ and ‘$k$’</th>
<th>Band gap Energy $E_g$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelengths $\lambda$ (nm)</td>
<td>Refractive index $n$</td>
<td>Extinction coefficient $k$</td>
</tr>
<tr>
<td>Un-irradiated</td>
<td>500</td>
<td>4.10</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>3.54</td>
</tr>
<tr>
<td>Irradiated</td>
<td>500</td>
<td>3.76</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>3.46</td>
</tr>
</tbody>
</table>

It is clear from Table 1 that the band gap of un-irradiated sample is wider than that of laser irradiated sample. This can be attributed to the high-energy laser beam, which was sufficient to cause electronic excitations from the lone pair and bonding states to higher energy states [4]. It is suggested that the vacancies created in these transition energy states can be immediately occupied by the outer electrons via Auger Recombinations. This can lead, of course, to production of more holes and subsequently electron vacancy cascades. This affect always brings about ionizations of atoms due to structural defects, hence to the reduction of energy band gap of the semiconductor irradiated with laser. This has equally been observed to be responsible for the changes in the magneto-optical properties in some multi-layer hetero-structures [18].

The actual band gap energy of pure silicon is 1.11 eV at 302 K, but our measured band gap energy of extrinsic silicon in case of un-irradiated sample was 3.1 eV and 2.8 eV in case of irradiated sample. The changes in band structure depend on the position and shape of conduction and valence bands which are influenced by the doping level and concentration [19,20].

4. Conclusion

The p-silicon samples were irradiated with UV Excimer laser ($\lambda = 248$ nm, $\tau = 20$ ns, $E = 57$ mJ) for 200 laser shots at repetition rate 100 Hz. The refractive index and extinction coefficient, both decrease exponentially for both un-irradiated and irradiated p-silicon samples. A decrease in optical band gap energy was also observed for p-silicon after irradiation, which is desirable for many optoelectronic applications.

Acknowledgements

We are thankful to Center of Excellence in Solid State Physics, University of the Punjab, Lahore, Pakistan, for providing us the facility of Spectroscopic Ellipsometry.
References