Fabrication and Characterization of Photodetector Based on Porous Silicon

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Electrical and photoresponse properties of Al/porous silicon/crystalline Silicon/Al structure (Al/pSi/c-Si/Al) were investigated. Unoxidized porous Si layer was made on single crystalline p-Si using anodic etching in aqueous HF at a current density of 60 mA/cm² for 20 min etching time. The structure of porous layer was investigated using SEM and FTIR. The electrical properties of the Al/pSi/c-Si/Al junction were studied using dark I-V, illuminated I-V and C-V measurements. The rise time of the detector was found to be 100 ns and its responsivity was 0.38 A/W at 600 nm and 0.44 A/W at 800 nm when the photodetector bias is at −3 V. [DOI: 10.1380/ejssnt.2010.388]

Keywords: Si; Porous; Anodization; Photodetector; Responsivity; Rise time

I. INTRODUCTION

Porous silicon (pSi) formed by electrochemical etching (anodization) exhibits a set of unique properties such as direct and wide modulated band gap, high resistivity, large surface area to volume ratio, and almost the same monocrystalline structure as bulk silicon. These valuable properties make pSi as attractive and promising material for superior opto-electronic device fabrication [1, 2]. Porous silicon plays an important role in photovoltaic characteristics through the improvement of light absorption. The optical reflectance from planar monocrystalline silicon surface is around 38% but can be minimized using KOH and NaOH texturing. Chemical texturization of single crystal silicon is ineffective due to random distribution of the grain orientations [3] but this problem was overcome by pSi formation. Up to date, few papers were published on optoelectronic properties of Al/pSi/Si/Al photodetectors made by electrochemical anodization on high resistivity Si substrate (10⁻¹⁹ Ωcm) [4–8]. The published results showed higher responsivity and quantum efficiency for these structures than that for p-n Si photodiodes.

This paper presents the results of a comprehensive experimental study of structural, electrical, and photoresponse characteristics of Al/pSi/Si/Al photodetectors made by electrochemical anodization.

II. EXPERIMENTS AND DEVICE STRUCTURE

Mirror-like monocrystalline p-type silicon wafer of 1-3 Ωcm electrical resistivity and (111) orientation was used as a substrate. The wafer was first dipped in 40% HF to remove the native oxide. The back side of the wafer was covered with wax. The porous layer was formed by electrochemical etching (anodization) in ethanoic hydrofluoric acid solution at a current density of 60 mA/cm² for 20 min in dark conditions at 300K. Ethanol was often added to evacuate the H₂ bubbles, which developed during process. The samples were then cleaned and air dried. Figure 1 shows a schematic diagram of the electrochemical anodization system used for pSi formation. The microstructure and morphology of porous layer was investigated using SEM. FTIR spectrometer (model Shimadzu IRAffinity-1) was used to characterize the surface chemical composition of the pSi layer.

Ohmic contacts were made on both porous and back surfaces by deposition of Al films through mask using thermal resistive technique after that annealing under vacuum at 300°C for 15 min was made to satisfy ohmic contact. The sensitive area of the photodetector was around 7×7 mm. The cross-sectional view of Al/pSi/Si/Al structure is depicted in Fig. 2. Dark and illuminated I-V characteristics, V_{oc} and I_{sc} of the photodetector were investigated using an electrometer, a power supply and a halogen lamp. C-V measurement was carried out using an hp LCZ meter at the frequency of 100 kHz. The photosensitivity of the photodetector was investigated in the wavelength range of 400-1000 nm with the aid of Joban-Yvon monochromator and standard Si power meter. Pulsed laser diode at minimum power (neutral density filter was used as attenuator) and storage CRO were used to measure the rise time of photodetector.
FIG. 3: FTIR absorption spectrum of porous silicon layer.

TABLE I: Chemical bonds and their IR resonance positions in porous silicon.

<table>
<thead>
<tr>
<th>Wave number (cm$^{-1}$)</th>
<th>Bond type</th>
</tr>
</thead>
<tbody>
<tr>
<td>460</td>
<td>Si–O–Si rocking vibration</td>
</tr>
<tr>
<td>650</td>
<td>SiH, SiH$_2$ bending vibration</td>
</tr>
<tr>
<td>870</td>
<td>SiH$_2$ scissors vibration</td>
</tr>
<tr>
<td>960</td>
<td>Si–O–Si stretching vibration</td>
</tr>
</tbody>
</table>

III. RESULTS AND DISCUSSION

Figure 3 shows the IR vibration spectra of pSi, the assignment of the main vibrational features is presented in Table I.

The FTIR characteristics confirmed the porosity of the etched Si in which the porous layer adsorbs oxygen from air to form vibrational Si–O bonds [8].

Figure 4 reveals an SEM topographic image of the pSi surface. A sponge-like structure is noticed and pores have an average diameter of 170 nm (macro-porous).

Dark I-V characteristics of the Al/pSi/c-Si/Al structure are shown in Fig. 5, where appreciable rectification can be noticed. The positive axis of the I-V plot corresponds to positive bias voltage (forward bias) applied to the pSi. I-V characteristics of the reverse direction exhibits noticeable saturation. Furthermore, these I-V properties are similar to those of p-n Si junction but with lower slope. This is because the Al/pSi/c-Si/Al structure consists of two junctions connected in a series; the Al/pSi Schottky (due to high resistance of porous Si layer) junction and pSi/c Si heterojunction and this in good agreement with published data [9].

The ideality factor ($n$) and the saturation current ($I_s$) were deduced from the ln$I_f$-$V$ curve and found to be around 10 and 200 nA respectively. The value of $n$ is better than that reported by Algun and Arikan [10], and this is attributed to the high series resistance that trapped the carriers at pore walls and also due to the high density of state at the pSi-cSi interface. The forward current shows a hysteresis loop (denoted by arrows); when measuring the I-V characteristics, the curve obtained when varying the voltage in an increasing manner was lower than that recorded when decreasing the voltage. This was due to the slow capture centers caused by the holes [11]. No hysteresis loop appeared on the reverse current. $C^{-2}$ versus reverse bias voltage plot is presented in Fig. 6. The relationship is linear and the extrapolation of the curve to $C^{-2} = 0$ point gave a built-in-voltage ($V_{bi}$) of 1.3 V.

The impact of white light illumination with intensity of 80 mW/cm$^2$ on the I-V characteristics of the photodetec-
The ratio of photo-to-dark current \((I_{ph}/I_d)\) was 160 at \(-3\) V bias. Increasing the bias voltage increases the photocurrent. Figure 8 demonstrates the dependence of \(I_{ph}\) on light power density. It is clear that the relationship is linear up to 50 mW/cm\(^2\) then it saturates.

The photovoltaic properties at AM1 condition show that open circuit voltage \(V_{oc}\) and short circuit current \(I_{sc}\) were 0.3 V and 6 \(\mu\)A, respectively.

The spectral photosensitivity \((S_{\lambda})\) as a function of wavelength plot for photodetector with \(-3\) V bias voltage is presented in Fig. 9. Two peaks are observed and located at 600 nm and 800 nm with sensitivities of 0.38 A/W and 0.44 A/W respectively. These values are higher than that for the standard \(p-n\) Si photodetector. The first response peak indicates that wavelength of 600 nm is absorbed in the depletion region of Al/pSi contact. The second response peak is a result of absorption of 800 nm in the depletion region of pSi/cSi contact, since the band gap of pSi is \(\sim 2\) eV and 1.12 eV for cSi at room temperature. Lower sensitivity was, however, obtained when the photodetector works in the photovoltaic mode (in absence of external bias). This result agrees with the report by Shieh et al. [7]. To find out why the photodetector has high sensitivity, we propose the following explanation: The total sensitivity of the photodetector is the sum two terms;

\[
S_{\lambda} = S_{Al-pSi} + S_{pSi-cSi},
\]  

where \(S_{Al-pSi}\) is the sensitivity of the Al-pSi Schottky contact and \(S_{pSi-cSi}\) is the sensitivity of the pSi-cSi heterojunction.

The obtained results of responsivity is higher than that reported by Svechnikov et al. [11] for porous Si photodetector made on 10 \(\Omega\)cm resistivity \(p\)-type Si substrate. The high responsivity of photodetector is arise from a fact that the porous surface is perfect in trapping photons and the surfaces are well passivated with very low concentration of surface recombination as well as the reflectivity of porous Si for visible and near infrared regions is very low [9]. From the sensitivity plot, and according to the following equation [12]

\[
\eta = 1240S_{\lambda}/\lambda (nm),
\]  

the quantum efficiency \(\eta\) of the photodetector in the spectral range 600-900 nm was found to be 63%. Figure 10 shows the pulse waveform recorded by the photodetector biased with \(-3\) V. The detectivity \(D^*\) of photodetector was calculated and found to be \(5\times10^{11} \text{ W}^{-1}\text{cm Hz}^{1/2}\). The rise time, measured from 10-90% of the signal, was found to be 100 ns. The decay time was longer than the rise time which may be caused by surface states and mismatch in lattice constant between porous Si and monocrystalline Si. The lattice expansion of the
porous layer generates lattice mismatch induced compressive strains on the porous layer at the pSi/substrate interface to pSi surface [13].

IV. CONCLUSION

Al/pSi/c-Si/Al photodetector was fabricated and characterized without any oxidation or post-annealing. The porous layer formation was confirmed by FTIR and SEM studies. The photodetector has good linearity characteristics and shows a good photoresponse in both visible and near IR regions, with a sensitivity of 0.38 A/W at 600 nm and 0.44 A/W at 800 nm. Photosensitivity was improved under reverse bias voltage of −3 V. Dark forward I-V characteristics exhibited a hysteresis loop. Fast response time of 100 ns was obtained. These results are encouraging and competitive to traditional p-n Si photodiodes. The effect of porous silicon preparation conditions on the performance of the photodetector is underway.