Infrared response of the lateral PIN structure of a highly titanium-doped silicon-on-insulator material*

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(Received 29 March 2011; revised manuscript received 19 May 2011)

The intermediate band (IB) solar cell is a promising third-generation solar cell that could possibly achieve very high efficiency above the Shockley–Queisser limit. One of the promising ways to synthesize IB material is to introduce heavily doped deep level impurities in conventional semiconductors. High-doped Ti with a concentration of 10^{20} cm^{-3}–10^{21} cm^{-3} in the p-type top Si layer of silicon-on-insulator (SOI) substrate is obtained by ion implantation and rapid thermal annealing (RTA). Secondary ion mass spectrometry measurements confirm that the Ti concentration exceeds the theoretical Mott limit, the main requirement for the formation of an impurity intermediate band. Increased absorption is observed in the infrared (IR) region by Fourier transform infrared spectroscopy (FTIR) technology. By using a lateral p–i–n structure, an obvious infrared response in a range of 1100 nm–2000 nm is achieved in a heavily Ti-doped SOI substrate, suggesting that the improvement on IR photoresponse is a result of increased absorption in the IR. The experimental results indicate that heavily Ti-implanted Si can be used as a potential kind of intermediate-band photovoltaic material to utilize the infrared photons of the solar spectrum.

Keywords: infrared response, ion implantation, rapid thermal annealing, intermediate band solar cell

PACS: 61.72.u–, 78.40.Fy, 80.40.jj **DOI:** 10.1088/1674-1056/20/10/106104

1. Introduction

The intermediate band solar cell (IBSC)[1] is a promising third-generation solar cell that could possibly achieve very high efficiency over the limit established by Shockley and Queisser in 1961. The novel solar cell is based on inserting a half-filled intermediate band in the traditional forbidden band of a semiconductor that permits sub-bandgap low energy photons to be absorbed, increasing the current while preserving the output voltage. Prototype IBSCs reported to date have been demonstrated using InAs/GaAs quantum dot materials[2] and highly mismatched alloys based on the band anticrossing model, such as ZnTe:O[3] and GaInNAs.[4] In principle, it is a predictable way to form an IB material by introducing a sufficiently high concentration of impurities into a semiconductor. The main requirement for obtaining an IB material is to reach an impurity concentration level beyond the Mott limit, which is much higher than the solid solubility limit.

Due to the predominant role of Si, Si-based IBSCs are attractive. Highly titanium-doped silicon material with the Ti concentration above the Mott limit has been realized by a combination of ion implantation and pulse laser annealing as the non-equilibrium techniques. The infrared property of an As^+ ion implanted and annealed Si wafer has been studied before.[5,6] So far the structural[7] and the electrical transport properties[8] of Ti-implanted Si have been reported. However, its photoresponse property has been seldom investigated. In this paper, using a lateral pin structure on SOI substrate, we investigate the infrared photo-induced response of highly Ti-doped Si material. It is found that the increased absorption in the IR region can result in the enhancement of the IR response in a range of 1100 nm–2000 nm.

2. Experiment

P-type SOI (100) wafer with a thickness of 625 μm (ρ = 14 Ω·cm–22 Ω·cm, $p = 6.0 \times 10^{15}$ cm^{-3}–9.4×10^{15} cm^{-3}) was used here. The buried oxide layer was 1 μm, and the top p-type Si layer with

*Project supported by the National Natural Science Foundation of China (Grant Nos. 61036001, 51072194, and 60906035).

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a resistivity of 14 Ω·cm–22 Ω·cm and a thickness of 1 μm was implanted at room temperature by Ti ions at a high dose of 1.7×10^{15} cm^{-2} and with an energy of 45 keV. Then the implanted sample was annealed at a temperature of 850 °C for 15 s in N_2 atmosphere by rapid thermal annealing (RTA), to recover the damaged crystalline structure and activate the Ti impurity. Double-polished p-type Si (100) substrate ($\rho = 10$ Ω·cm, $p = 1.32\times10^{15}$ cm^{-3}) with a thickness of 350 μm was implanted and annealed in the same condition of counterpart SOI samples.

Secondary ion mass spectroscopy (SIMS) measurements were performed to determine the depth profile of the Ti concentration of the annealed sample. To avoid the effect of the cavity formed by SOI wafer on the absorption spectrum, Fourier transform infrared spectroscopy (FTIR) technology was used to measure the optical properties of the annealed implanted Si sample and the un-implanted reference Si sample. It is considered that the IR response change between un-implanted Si and annealed implanted Si samples is the same as that between un-implanted SOI and annealed implanted SOI ones.

In order to eliminate the influence of the substrate, a buried SiO_2 layer was used which could prevent the collection of electron–hole pairs produced by substrate absorption. In addition, a lateral p–i–n structure was designed to investigate the photoresponse property of the highly doped Ti-implanted SOI wafer. Its schematic cross section is shown in Fig. 1. A square mesa with a length ranging from 300 μm to 1000 μm was fabricated by dry-etching technology stopping in the SiO_2 layer of SOI substrate. The top silicon layer was selectively implanted with B at a dose of 4×10^{15} cm^{-2} and an energy of 45 keV, forming an N-doped region with a thickness of about 400 nm. Selective implantation with P at a dose of 4×10^{15} cm^{-2} and an energy of 85 keV in the top silicon layer can form a P-doped region with a thickness of about 240 nm, followed by RTA at 950 °C for 5 s. A 500-nm-thick Si_3N_4 film was deposited by plasma-enhanced chemical vapour deposition (PECVD) with three functions such as passivation, isolation and an antireflection layer for an infrared wavelength of 1550 nm. Metal contacts on Si were formed with a 500-nm aluminum layer, followed by RTA at 450 °C for 5 s. The micrograph of the lateral pin photodetector is shown in Fig. 1(b).

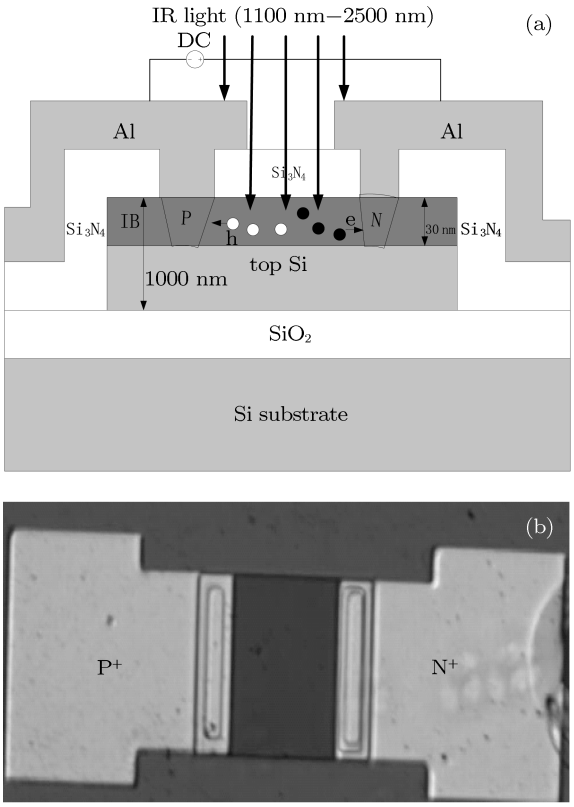


Fig. 1. Schematic diagram of the cross section of the lateral pin structure of Ti-implanted SOI material (a), and optical microscopic image of the lateral pin PD (b).

3. Results and discussion

Figure 2 shows the depth profiles of Ti atoms in the annealed sample, measured by SIMS and simulated in the as-implanted sample by the Monte Carlo simulation program (TRIM).

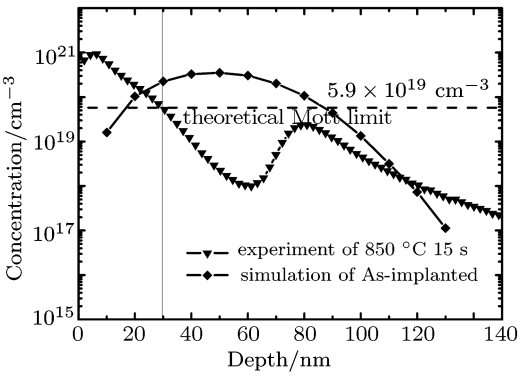


Fig. 2. Depth profiles of Ti concentration in Si for as-implanted and annealed samples.

The summit of concentration is at 50 nm below the surface for as-implanted sample, while the peak shifts to the surface after annealing. From the surface to a depth of 30 nm, the Ti concentration of 10^{20} cm^{-3}–10^{21} cm^{-3} is higher than the Mott limit of

5×10^{19} cm^{-3} at 300 K,[9] meeting the essential condition to form IB material. Furthermore, the integration of the Ti concentration depth profile shows that about 74% of the Ti atoms still remain at the top Si layer.

Optical absorption spectra were measured by FTIR technology as shown in Fig. 3. It indicates the enhanced absorption in a range of 1000 nm–2000 nm for the annealed Ti-implanted Si sample compared with an un-implanted Si wafer, while the absorption edges of both samples remain unchanged at about 1100 nm of common bulk Si material. Although free carrier absorption, generally proportional to the square of the wavelength, is stronger at longer wavelengths as shown in Ref. [10], no obvious free carrier absorption is observed at longer wavelengths above 2000 nm in Fig. 3. The noises at around 1380 nm and 1870 nm are attributed to the absorption bands of CO_2 and H_2O, respectively.

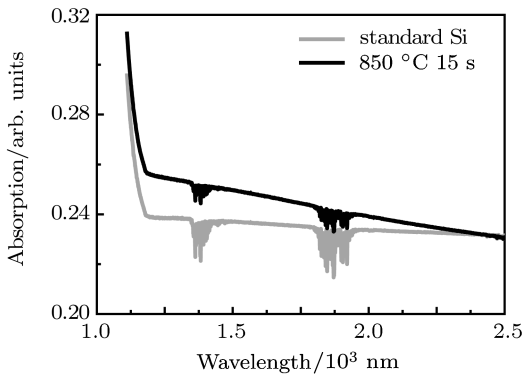


Fig. 3. Absorption spectra of un-implanted Si and annealed implanted Si wafers.

The current–voltage characteristics for the lateral PD with a square size of 300 μm were tested using the halogen lamp with one double-polished Si wafer with a thickness of 350 μm serving as filter 1 and two such Si wafers used as filter 2. The double-polished Si wafers were used to filter out visible light and allow infrared light of about 1100 nm–2500 nm to pass through. As shown in Fig. 4, there is an obvious IR photo-generated current, which increases with voltage increasing. The current reaches 24.63 μA at −20 V with filter 2 and increases to 46.1 μA with filter 1. The main reason for the large reversed voltage is due to the fact that a large mesa size on the order of 300 μm can make the drift field too weak to collect the carriers at low voltage. Reducing the mesa size will make the carrier collection easier. However the large dark current may indicate large recombination centres in Ti-implanted SOI material, which may be attributed to a region where there is a large amount of Ti but the concentration is still too low to induce the delocalization transition of the Mott limit as shown in Fig. 2.

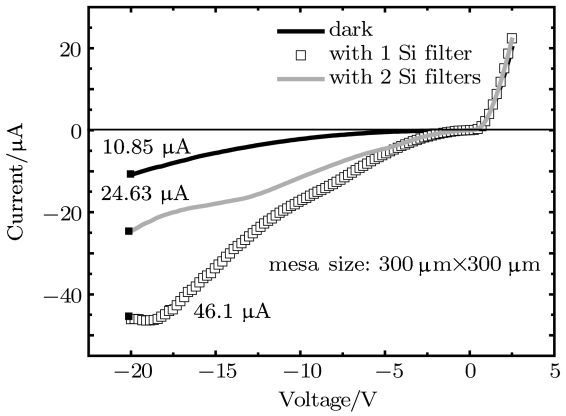


Fig. 4. *I–V* curves of lateral PIN Ti-implanted SOI PD with a size of 500 μm at different illumination conditions.

A monochrometer with 0.5-nm resolution was used to select the excitation wavelength from a chopped tungsten light source and the signal was measured by an SR830 lock-in amplifier. The full spectrum response of the PD at zero applied voltage is shown in Fig. 5. There are three current peaks, one main current peak at near 1120 nm, while other tiny peaks at 1420 nm and 1945 nm. An obvious response is observed in a range of 1100 nm–2000 nm, although at wavelengths below 800 nm ir is dramatically reduced. Although the native Fabry–Perot cavity, formed between the top-Si/air and buried SiO_2/SOI interface, may have a strong resonant-cavity effect on the light emission spectra with peak interval of about 50 nm,[11] there seems to be little effect on the photo-current spectra. The significant decrease in the response below 800 nm suggests that charges generated near the detector surface become trapped, while charges generated from photons at longer wavelengths, and thus absorbed deeper in the Si, have a higher possibility of being collected. A similar infrared response enhancement phenomenon has been found in a Si avalanche photodiode microstructured with femtosecond laser in SF_6 atmosphere,[12] which is supposed to be due to sulfur atom-induced deep level states in the forbidden band. It was reported that Ti has a deep level centre in Si with an acceptor level at 0.09 eV below conduction band (CB) and two donor levels at 0.30 eV below CB and 0.26 eV above the valence band (VB),[13] thus peak wavelengths of 1200 nm, 1550 nm, and 1440 nm may be expected. It was also reported recently that Ti has a defect level

at (0.49±0.03) eV below CB,[14] thus the peak wavelength of 1879 nm–2067 nm may be expected. Therefore, the observed peaks at around 1114 nm, 1416 nm, and 1906 nm may be related to Ti-induced deep levels.

Although the IR response is still far away from the expectation, it is a step towards our understanding of IB material and its application in solar cells as well as photodetectors. Recently, similar work has been done by Si^+ implantation and annealing to make infrared waveguide Si photodiodes[15] and micro-ring resonator,[16] utilizing the impurity-induced IR response. Moreover, work on optimized device structures and optimized fabrication processes with better carrier collecting ability are underway. Further studies are required to identify the existence of the impurity band and answer the remaining questions about its mechanism.

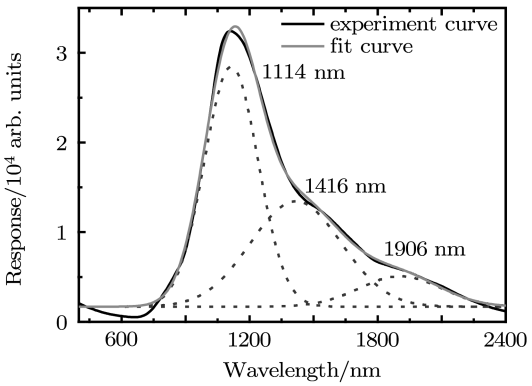


Fig. 5. Spectrum responses of lateral pin Ti-implanted SOI PD.

4. Conclusion

An obvious infrared response in a range of 1100 nm–2000 nm is achieved in heavily Ti-doped SOI substrate, using a lateral p–i–n structure, suggesting that the improvement in IR photoresponse is a consequence of increased absorption in IR. The experimental results indicate the possibility to utilize the infrared low-energy photons of the solar spectrum by using an impurity intermediate band solar cell. Further studies are under way in order to better understand the mechanisms of Ti-implanted Si IB materials.

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