Thin Solid Films 615 (2016) 358–365

Contents lists available at ScienceDirect

Thin Solid Films

journal homepage: www.elsevier.com/locate/tsf

Indium as a *p*-type dopant of thin film silicon solar cells

D.J. Paez *, E. Huante-Ceron, A.P. Knights

McMaster University, Department of Engineering Physics, Hamilton, ON L8S 4L7, Canada

ARTICLE INFO

Article history:
Received 23 September 2015
Received in revised form 21 July 2016
Accepted 21 July 2016
Available online 22 July 2016

Keywords:
Photovoltaic
Thin-film photovoltaic
Impurity photovoltaic effect
Thin-film silicon solar cells
Crystalline silicon
Indium as *p*-type

ABSTRACT

The effect of using indium, a deep-level acceptor in silicon, as a dopant for an ultra-thin film (2.5 μm thick) single-crystalline silicon solar cell has been investigated. Indium acts as a *p*-type dopant in silicon with an energy level 0.157 eV above the valence band and the use of this deep-level acceptor has been proposed as a method to enable sub-bandgap transitions via the impurity photovoltaic (IPV) effect. In the current work, a maximum conversion efficiency under 1 sun illumination, air mass 1.5, of 4.74 ± 0.2% is measured for a solar cell using indium as a *p*-type dopant. An equivalently processed cell using boron in place of indium has a maximum efficiency of 4.16 ± 0.2%. Similar relative increases in efficiency have been observed for nine individual devices. The area of the cells is 0.5 × 0.5 cm^2 with 7% covered by the metal contacts. A dual-junction analytical model is used to show that for all indium-doped cells in this study there exists an enhancement in the generation of charge carriers compared to boron-doped cells. External-Quantum-Efficiency measurements of both boron and indium doped cells shows an enhancement in optical to electrical conversion for wavelengths of ~470–1000 nm when indium is used as a dopant. No significant conversion is observed for wavelengths >1100 nm, in contradiction of an IPV effect existing in these devices.

1. Introduction

Efficient optical to electrical conversion is a fundamental requirement of a range of silicon device applications such as photodetection, solid-state-imaging and most notably, photovoltaics. Solar cell fabrication has evolved from cell production at relatively high-cost with low-efficiency (generation I) to the implementation of novel techniques that replace the limiting single silicon based PN junction. The most recent generation of photovoltaic devices combines cost-efficient, thin-film absorbers (generation II) with structures that enhance absorption of light from the solar spectrum (generation III) to create low-cost, highly absorbing cells [1]. Silicon-On-Insulator (SOI) is a potential platform that can aid in achieving a reduction in cost while maintaining high efficiency. For example, crystalline Silicon-On-Glass mini-modules, using electron-beam deposition to create the silicon thin film region (~2 μm thick), have been reported with a conversion efficiency (η) per cell of 6.7% [2] and a mini-module conversion efficiency of 10.5% [3]. In the general case though, ultra-thin (<10 μm) SOI solar cells have not been able to achieve efficiencies to date >10% [4]; their limiting factor being the relatively weak absorption of crystalline silicon (c-Si) in the visible region of the optical spectrum.

The introduction of a deep-level impurity in the silicon bandgap (E_g) was initially proposed as a method to improve the efficiency of a solar cell by allowing carrier generation via that impurity level (E_T), with a resulting increase in current density [5,6]. However, Shockley and Queisser argued that an increase in efficiency is unlikely because these same deep-level states also act as recombination centers [7] and hence reduce open-circuit voltage (V_{oc}). A detailed balance limit study from Würfel [8] using silicon solar cells with mid-gap defects supports this argument. The Würfel model accounts for possible photocurrent generated by photons with energies greater than $E_g/2$, but less than E_g, since the deep-level is assumed to be in the middle of the bandgap. The electrical circuit resembles a parallel connection of a solar cell (with bandgap E_g) with two further solar cells (each with a bandgap of $E_g/2$) connected in series. The configuration reflects the advantage in absorption from the cells connected in series, but the overall system is not effective as the study shows that mid-gap levels are not improving the overall efficiency of the cell since they increase the recombination rate [8]. However, there have been theoretical studies more recently that suggest that if the energy level is carefully chosen at approximately one-third the bandgap energy either above the valence band or below the conduction band [9,10], the IPV effect can contribute to an improvement in cell efficiency [11,12]. The thin-film structure of the cells reported in this paper are designed to makes use of the Impurity Photo-Voltaic (IPV) effect to enhance the absorption of photons.

The IPV effect has to date been assumed to be a two-step excitation process, as described schematically in Fig. 1. Photons with energy greater than the difference between E_T and the valence band are assumed to excite an electron to the impurity level. The second step is the electron excitation from E_T to the conduction band (E_C) due to the

* Corresponding author at: McMaster University, Department of Engineering Physics, 1280 Main Street West, JHE-A315, Hamilton, ON L8S 4L7, Canada.
E-mail address: paezcadj@mcmaster.ca (D.J. Paez).

http://dx.doi.org/10.1016/j.tsf.2016.07.053
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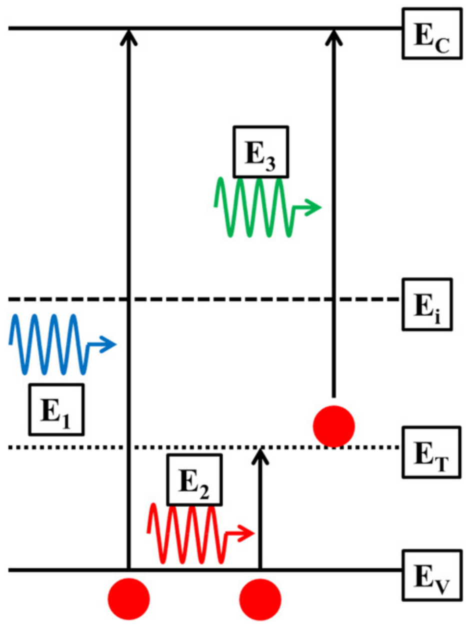

Fig. 1. Impurity photovoltaic (IPV) effect. In addition to a single band-to-band transition as represented by the absorption of a photon with energy E_1, the IPV effect is assumed to be a two-step excitation process with the absorption of a photon with energy $E_T < E_2 < E_g$ and a photon with energy $(E_g - E_T) < E_3 < E_g$, where E_g = bandgap energy.

absorption of a photon with energy greater than the energy difference between E_C and E_T [5].

Indium is considered a deep-level acceptor in silicon at an energy level of 0.157 eV [5,11] above the valence band. Keevers and Green presented a modified Shockley-Read-Hall (SRH) model of enhanced absorption in silicon cells in which electrons and holes can be optically excited to and from an indium level in addition to the thermal capture and excitation from it [5]. They suggested that the incorporation of indium leads to a significant increase in short-circuit current due to sub-bandgap wavelength absorption that outweighs the reduction in V_{oc}. They computed a maximum increase of absolute efficiency of 1–2% due to the IPV effect when indium is used in a bulk cell with a single horizontal PN junction. They further suggested that the limiting enhancement factor is the electron photoemission from the indium level, which competes with the entire photoemission and intrinsic band-to-band absorption [5] from the available photon flux. In order to provide a more efficient IPV effect, and therefore an increase of current output, it is better to maintain the indium levels as fully occupied. This can be achieved by ensuring an *n*-type background doping concentration higher than that of the indium.

In this paper, we describe the fabrication of solar cells using a vertical PN junction configuration, designed to enhance the collection of optically generated carriers. The material used is micro-electronic, device grade SOI, which consists of a thin layer of high quality silicon on a thin layer of SiO_2, supported by a passive silicon substrate. Although this material system is relatively high in cost to produce and is thus unsuitable for mass production of silicon-based solar cells, it provides an excellent method for investigation of the effects of indium doping of thin film cells, which in this case are not related to the crystallinity of the silicon itself. The silicon overlayer is always of high quality single crystal, here with a thickness of 2.5 μm. Given that it is possible to dope the entire 2.5 μm thickness with indium, the effects of the doping

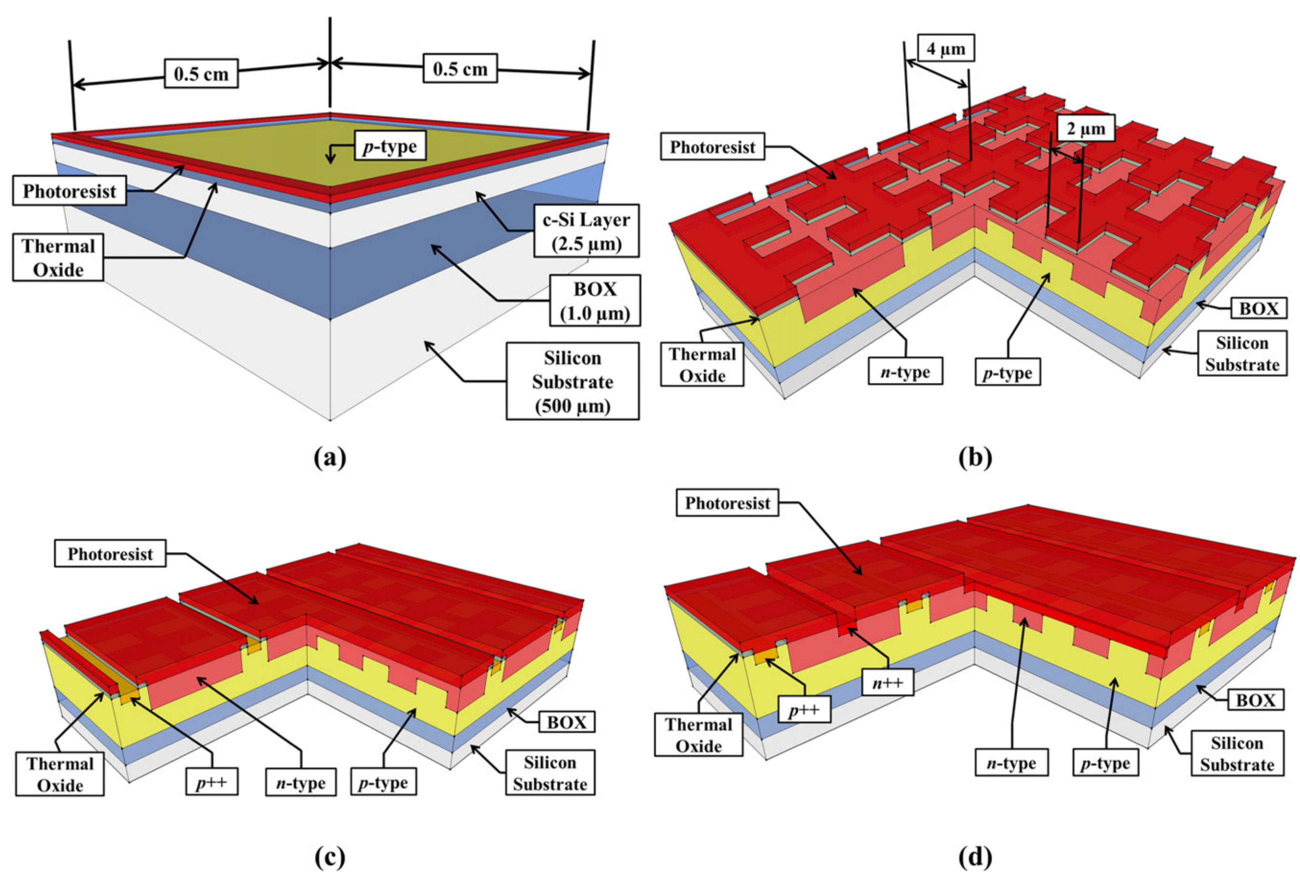

Fig. 2. Thin film solar cell fabrication process. (a) 0.5 × 0.5 cm^2 window and implanted *p*-type dopant. (b) Periodic comb finger patterned and *n*-type region formed by ion implantation. (c) Heavily doped $p{+}{+}$ windows and implanted boron region. (d) Heavily doped $n{+}{+}$ windows and implanted phosphorus region.