Available online at www.sciencedirect.com

ScienceDirect

Solar Energy 132 (2016) 143–149

SOLAR ENERGY

www.elsevier.com/locate/solener

Investigation of parasitic absorption and charge carrier recombination losses in plasmonic silicon solar cells using quantum efficiency and impedance spectroscopy

Eshwar Thouti, Vamsi K. Komarala *

Centre for Energy Studies, Indian Institute of Technology Delhi, New Delhi 110016, India

Received 10 November 2015; received in revised form 23 February 2016; accepted 1 March 2016
Available online 19 March 2016

Communicated by: Associate Editor Frank A. Nüesch

Abstract

Quantum efficiency and impedance spectroscopy tools are employed for understanding the influence of parasitic absorption losses and partial field effect surface passivation by the silver nanoparticles (Ag NPs) on electrical properties of textured silicon solar cells without and with Si_3N_4 spacer layer. The parasitic absorption losses from Ag NPs reduced the internal quantum efficiency near the surface plasmon resonance region. The passive components like; series and parallel resistances, chemical capacitance of solar cells without and with Ag NPs are estimated after fitting impedance semicircles, which are further used for estimating effective carrier lifetime (τ_{eff}) values. Under AM1.5G illumination, cells with Si_3N_4 spacer layer showed a large decrease in the τ_{eff} due to the strong parasitic absorption losses from the Ag NPs. But, the cells without Si_3N_4 spacer layer showed a small decrease in the τ_{eff} due to the reduced surface recombination after partial field effect passivation from near-fields of Ag NPs' surface plasmon resonances on the emitter surface.

Keywords: Silicon solar cell; Silver nanoparticles; Impedance spectroscopy; Effective carrier lifetime; Parasitic absorption

1. Introduction

Recently, metal nanoparticles (NPs) are considered as an alternate for confining light/enhancing optical absorption in various types of solar cells with the excitation of localized surface plasmon resonances (SPRs). In the literature, much has been reported about optical properties of metal NPs for light trapping in solar cells. A few configurations are proposed for integrating metal NPs in cell structure; placing directly on front surface, embedding in active medium, and also integrating at rear side of cell structure (Atwater and Polman, 2010). For silicon based cells, researchers have employed metal NPs, mainly either on front or rear surface (Pillai et al., 2007; Beck et al., 2009; Tan et al., 2012; Spinelli et al., 2012; Pudasaini and Arturo, 2013; Manisha et al., 2014a,b). When the metal NPs are integrated at rear side of silicon cell for light trapping, minimal plasmonic related losses like; interband transitions and parasitic absorption losses are observed (Beck et al., 2009; Atwater and Polman, 2010; Tan et al., 2012; Manisha et al., 2014a,b). When metal NPs integrated on front surface of silicon cell, the detrimental factors (parasitic absorption) associated with NPs are overshadowed the beneficial effects (Beck et al., 2009; Pudasaini and Arturo, 2013; Thouti et al., 2014; Das et al., 2015), which curtailed the light trapping efficiency in the silicon. Apart

---

* Corresponding author.
E-mail addresses: eshwariitd@gmail.com (E. Thouti), vamsi@ces.iitd.ac.in (V.K. Komarala).

http://dx.doi.org/10.1016/j.solener.2016.03.002
0038-092X/

from the parasitic absorption losses from metal NPs (Spinelli and Polman, 2012), other loss mechanism related to modified carrier surface recombination process at silicon surface-NPs interface without/with a thin spacer layer has been overlooked (Yang et al., 2012; Barugkin et al., 2013; Tong et al., 2014; Thouti et al., 2014).

There is no such experimental study, which can distinguish the parasitic absorption losses and modified charge carrier recombination at the interface due to the metal NPs. Since, these two mechanisms have strong influence on any opto-electronic device performance after integrating the metal NPs (Thouti et al., 2014; Sero et al., 2009), so, there is a need to understand the individual loss mechanism on device performance. For understanding the optical and/or electronic losses of plasmonic cells, conventional DC characterization techniques such as current–voltage and quantum efficiency measurements are routinely employed. Some basic studies of plasmonic silicon cells related to incident wavelength dependent photocurrent reduction in SPR region, and modification of minority carrier diffusion lengths in off-resonance region of metal NPs are reported recently (Thouti et al., 2014).

The aim of this work is to understand plasmonic silicon cells' performance modification after integration of silver (Ag) NPs due to the parasitic absorption losses and partial field effect passivation at the cell emitter-Ag NPs interface. We made an attempt to segregate these two mechanisms by investigating effective carrier lifetime (τ_{eff}) values of Ag NPs integrated textured silicon cells without and with Si_3N_4 spacer (anti-reflection) layer using quantum efficiency and impedance spectroscopy (IS) techniques. The AC frequency analysis of plasmonic cell can help for quantifying passive components like; recombination resistance and junction capacitance; these parameters are further used for estimating of τ_{eff} (Sero et al., 2009; Kumar et al., 2014). Since, these passive components of device are sensitive to any variation in the physical structure, which can provide some microscopic insights related to the cell emitter-metal NPs interface.

2. Experimental procedure

The textured silicon solar cells without and with Si_3N_4 layer of thickness ~75 nm were used in this study, which are obtained from different sources. The Si_3N_4 thin film acts as surface passivation layer as well as anti reflection coating (ARC) on cells, and the fabrication procedure of these cells is similar to the details reported elsewhere (Thouti et al., 2014). Before the Ag NPs preparation on the cell front surface, cells were pre-annealed at 300 °C for 1 h in nitrogen ambient to avoid any temperature dependent modifications during experimentation in device structure, these cells are called in the discussion as C0 (cells without ARC) and ARC0 (cells with ARC). The Ag NPs were prepared from thermally evaporated discontinuous/continuous Ag thin films having mass thicknesses of ~5 and ~10 nm, followed by an annealing at 300 °C for 1 h in nitrogen ambient; these samples are called as C5/ARC5 and C10/ARC10, respectively. Surface morphological studies of Ag NPs were carried out using Carl Zeiss scanning electron microscope (SEM). The Ag NPs were also prepared on glass substrates with the similar experimental conditions for transmittance measurements.

Total transmission (TT) and total reflectance (TR) measurements were performed using Perkin Elmer Lambda 1050 double beam UV–Vis–NIR spectrophotometer having 150 mm integrating sphere as an attachment. The current density–voltage (*J*–*V*) graphs of cells were carried out under the standard test conditions of the AM1.5G incident light spectra using Oriel Sol3A solar simulator from Newport Corporation, USA. A Keithley 2440 sourcemeter was used for *J*–*V* measurements. External Quantum Efficiency and TR spectra were recorded using SpeQuest quantum efficiency measurement system having an integrating sphere as an attachment from ReRa Solutions, The Netherlands. For IS measurements, Zahner Zennium model potentiostat equipped with frequency response analyser was used. Impedance spectra were recorded from 1 Hz to 1 MHz frequency range with perturbation voltage of 10 mV, and by applying 0.6 V forward DC bias voltage under AM1.5G light illumination from a solar simulator. The IS measurements were carried out on the same cell before (C0/ARC0) and after Ag NPs integration (C5/ARC5 and C10/ARC10), in order to avoid area dependent variations during measurements. The obtained impedance semicircles were fitted using ZView program, with different combinations of inductor, resistor, and capacitor in an equivalent circuit model. All the characterization experiments were conducted at room temperature.

3. Results and discussion

The SEM micrographs of the Ag NPs prepared on textured silicon cells without ARC (C5 and C10) and with ARC (ARC5 and ARC10) are presented in Fig. 1. Relatively larger size NPs formation can be seen in the case of cell C10 when compared to on cell C5, which is due to the large initial Ag film mass thickness. There is no considerable variation in the size or surface coverage of Ag NPs when prepared on the Si_3N_4 layer coated textured silicon surface. Due to large surface coverage of NPs, it appears like 2-dimensional Ag NPs layer.

The *J*–*V* measurements for cells without (C0) and with the Ag NPs (C5 and C10) are presented in Fig. 2a, the inset table shows the photovoltaic parameters of corresponding cells. From Fig. 2a, it is apparent that the cell efficiency is slightly decreased after the Ag NPs integration. The decreasing trend in current density and efficiency of cells after Ag NPs integration is also presented in Fig. 2c in the form of standard box plot. This represents distribution of current density and efficiency values of three cells corresponds to Ag film thickness of ~5 and 10 nm. Internal quantum efficiency (IQE) and TR spectra of cells C0, C5 and C10 are presented in Fig. 2b, from which one can