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Materials Science and Engineering C 26 (2006) 427 – 430
MATERIALS SCIENCE & ENGINEERING C
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Silicon nanostructured layers for improvement of silicon solar cells' efficiency: A promising perspective

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Available online 5 January 2006

Abstract

The photovoltaics industry is dominated by silicon solar cells technology mainly because of the low manufacturing cost. However, these solar cells show an important limiting factor on conversion efficiency due to the inefficient absorption of high energy photons as a consequence of the indirect bandgap structure of bulk silicon. In this article, we discuss about different possibilities to improve the efficiency of solar cells and we propose the use of silicon nanostructured layers to achieve this goal. We present the fabrication methods as well as the characterization results of two kinds of layers which can be used for solar cells' efficiency improvement, namely non-stoichiometric silica layers (SiO_x) and non-stoichiometric silicon nitride layers (SiN_x). We demonstrate that the photoluminescence (PL) properties and/or the increased photocurrent (PC) signal at high-energy photon could be used to improve this efficiency. Finally, the major asset of these methods lies in their possibility to be incorporated to the solar cell processing for an insignificant cost.

1. Introduction

Solar cell silicon technology is the most widely used for the fabrication of photovoltaic modules nowadays. However, the manufacturing cost which is mostly dominated by material costs demands a reduction of the amount of high-quality material for solar cell manufacturing. This reduction can be achieved by reducing the cell thickness (thin film technology) or by improving the solar cell efficiency. In silicon solar cells, one of the main limiting processes of energy conversion is the lost of excess energy of generated carriers during the absorption of high energy photons due to thermalisation losses [1]. Therefore, it would be very attractive that high energy photons could be absorbed more efficiently. In order to achieve this, we propose in this work the use of silicon-based non-stoichiometric insulating layers. These layers are usually based in silicon nitride or silicon dioxide matrix containing silicon nanostructures (ns-Si) and being fabricated by a variety of different methods [2–4]. As it has been widely discussed during the last decade, ns-Si show enhanced luminescent properties compared to bulk silicon as well as an increased bandgap as a consequence of confinement effects. In this work, we report on the optical characterization of non-stoichiometric silica (SiO_x) and non-stoichiometric silicon nitride (SiN_x) layers containing ns-Si. We demonstrate that not only the improvement of the photoluminescence (PL) properties but also the significant enhancement of high-energy photon absorption via the photocurrent signal (PC) observed in these layers could be capitalized for the improvement of silicon-based solar cells.

2. Experimental details

Off-stoichiometric SiO_x ($x = 1.5$) layers were deposited by low pressure chemical vapor deposition (LPCVD) on a 63-nm thick SiO_2 layer previously grown by thermal oxidation onto a silicon substrate. The silicon excess was introduced by adjusting the N_2O/SiH_4 gas flow ratio and the conditions were controlled to obtain a 200 nm thick SiO_x film. After deposition a first annealing step in N_2 at 1000 °C was performed in order to assure the good Si/SiO_2 phase separation. A final annealing step was performed at 1000 °C during

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0928-4931/$ - see front matter © 2005 Published by Elsevier B.V.
doi:10.1016/j.msec.2005.10.029

30∼120 min under O_2 atmosphere to synthesize and passivate the ns-Si. In addition, non-stoichiometric silicon nitride layers (SiN_x) were fabricated by deposition of ∼15 nm thick layers on 700-nm thick SiO_2 layers previously grown by thermal oxidation of silicon substrates using the photo-assisted chemical vapor deposition (UVCVD) technique. The thickness and the stoichiometry of the deposited layers were adjusted by varying the flowing gas ratio Si_2H_6/NH_3 and the substrate temperature. PL spectra were obtained using a laser line excitation at 244 nm from a frequency doubled Ar^+ laser, a spectrometer (Jobin-Yvon HRS-2) and a GaAs cathode photomultiplier (Hamamatsu H5701-50) for light detection. The PC spectra acquisition was performed in MIS-type devices fabricated by evaporating a 15-nm thick circular shape Au layer on the SiO_x or SiN_x layer. The current produced in the device for each incident wavelength coming from a tungsten lamp attached at the exit slit of the spectrometer was collected by a current amplifier (Keithley 428) using a lock-in amplifier to improve the signal/noise ratio. Finally, the PL and PC spectra were corrected for the spectral response of the system.

3. Results and discussion

The first set of samples analyzed by PL and PC corresponds to SiO_x layers. As it can be observed from Fig. 1, the PL peak of these layers shows a blueshift as oxidizing annealing time increases, which is in good agreement with a reduction of the ns-Si size. Besides, as we have reported for these samples [5], it has been confirmed that the PL emission energy correspond well to the optical gap predicted by the quantum confinement theory and in consequence the radiative mechanism is most probably related to the extinction of quantum confined excitons within ns-Si core. This finding is quite surprising as it is clearly different from the generally reported mechanism (self-trapped exciton extinction at the ns-Si/SiO_2 interface) observed in ns-Si imbedded in an oxide matrix [6–8]. In addition, the PC spectra of our SiO_x samples shown in Fig. 2, reveals that the samples containing the nanostructured layer show a clear enhancement of absorption at high photon energy compared to the reference samples (without the nanostructured layer).

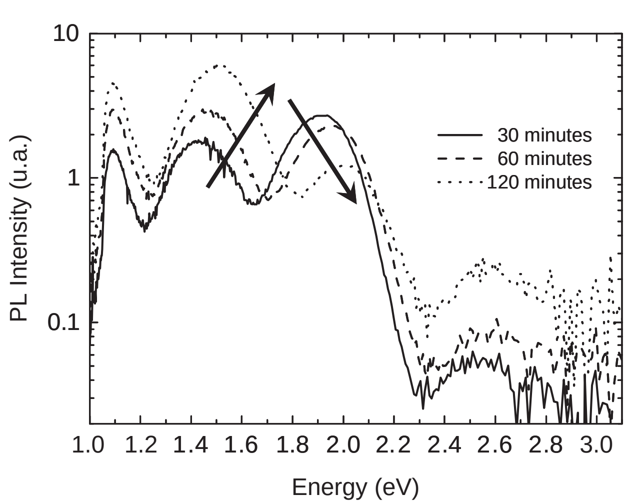

Fig. 1. PL spectra obtained from LPCVD-deposited SiO_x layers containing silicon nanostructures for 3 different O_2 annealing times. The arrow indicates the PL energy shift with annealing duration.

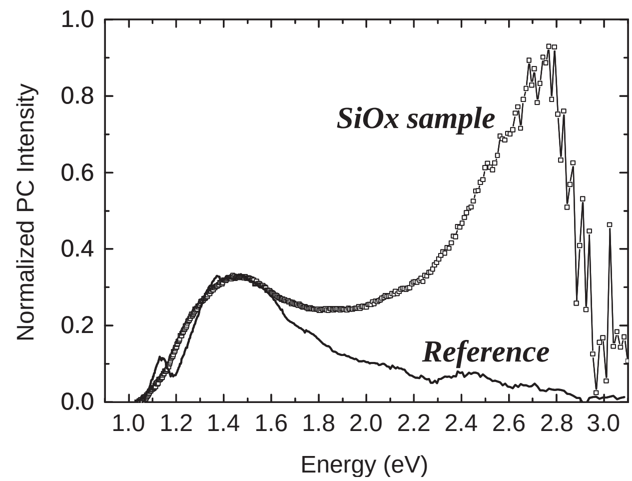

Fig. 2. Photocurrent spectra comparison between a reference sample (without the SiO_x layer) and a sample with the SiO_x film containing ns-Si. It is clearly observed the increase of the PC signal at high photon energies in the samples containing ns-Si.

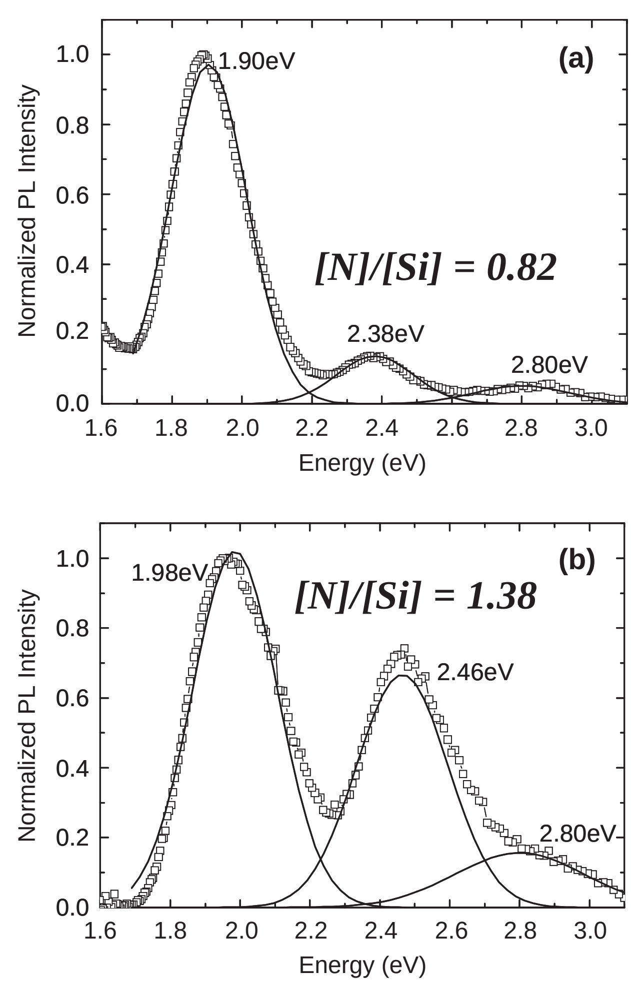

Fig. 3. Gaussian deconvolution of PL spectra of a SiN_x films with an atomic ratio of [N]/[Si] = 0.82 (a) and [N]/[Si] = 1.38 (b). Note that only the emission bands at 1.9 and 2.4 eV show an energy-dependence with silicon content.