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Time-resolved photoluminescence for the measurement of the effective carrier lifetime in Si photonic structures

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Abstract

Two-dimensional photonic structures for advanced light trapping in thin film crystalline silicon solar cells are mainly studied from the optical point of view. However, the nanopatterning process can induce etching damage that can reduce the minority carrier lifetime and the cell performance. Time-resolved photoluminescence is used to evaluate the effect of photonic structures on the effective lifetime of nanopatterned silicon epi-layers. Two excitation wavelengths are used to evaluate separately the quality of the bulk and the patterned surface of the epi-layers. The measurements are discussed in connection with the carrier generation maps calculated with Finite-Difference Time Domain simulations.

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1. Introduction

Si thin-films are promising candidates to obtain high efficiency solar cells [1]. This technology still requires important improvements particularly concerning the reduction of the surface losses and the optimization of light trapping. In the literature, many papers report on the use of photonic structures to improve the light absorption of thin-films [2-7]. Because photonic structures modify the electromagnetic field distribution in the sample, the

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photogenerated carrier distribution is modified and an enhanced photogeneration in higher recombination areas may occur. Therefore, the effective lifetime is a crucial parameter to obtain solar cells with a high conversion ratio. Photonic structures are made by thin-film nanopatterning processes which can induce damage to the patterned walls or a reduction in passivation. A few papers have reported on the characterization of the effective lifetime of photonic-textured Si bulk substrates or Si epi-foils by quasi-steady state photoconductance and calibrated photoluminescence imaging [8-9]. Asymmetrical samples as thin-films deposited on a substrate limit the use of standard lifetime characterization techniques, like QSSPC (quasi-steady state photoconductance), which are mainly affected by the bulk substrate. Time-resolved photoluminescence (TRPL) can be used on a wider variety of samples for a non-destructive control during the critical steps of solar cells fabrication. We have already reported a method to extract the injection dependent effective lifetime on passivated Si substrates and Si thin-films by TRPL from the exponential signal decay [10-11]. In this work, we investigate the ability to apply TRPL to nanopatterned Si epi-layers. This method is particularly challenging because the excitation and the PL emission are affected by the nanopatterning. FDTD simulations are carried out in order to evaluate the photogenerated carrier distribution of patterned samples and explain experimental results.

2. Experimental details

2.1. Sample preparation

The samples are n-type Si epitaxial layers with very low doping levels (between $5x10^{13}$ and $2x10^{14}$ cm^{-3}) and two thicknesses (28 and 75 µm). The epitaxial layers are grown on highly doped n^+-type Si substrates with resistivity ρ in the range 0.001-0.005 Ω.cm and thickness around 500 µm. The huge difference in doping levels of the epi-layer and of the substrate is chosen to provide a good field-effect passivation at the epi-layer – substrate interface. Moreover, due to a high doping level in the substrate, Auger recombination occurs in this area and most of the excess carrier density (Δp) is located in the epitaxial layer. Consequently, the PL signal is assumed to be mainly due to the epitaxial layer as commonly acknowledged in such structures [12].

Photonic structures are etched on the front surface of Si epitaxial layers (Fig. 1). For that purpose, a 100 nm-thick SiO_2 layer is deposited on the epi-layer and will be used as a hard mask for the etching step [4]. Holographic lithography is carried out with a UV laser (at 266 nm) and a negative photoresist. The laser beam is expanded and spatially filtered through a pinhole to generate a coherent beam which illuminates the sample and a mirror in a Lloyd's mirror configuration (Fig. 2). Two-dimensional arrays are made by a second exposure of the photoresist after the sample is rotated by 90°. After the resist development, a first RIE (Reactive Ion Etching) with CHF_3 and Ar gas is performed to etch the SiO_2 layer through the resist mask. Then, a second RIE (with a combination of SF_6, O_2 and CHF_3 gas) is applied. This process is independent of the crystal orientation and produces cylindrical holes with U-shapes profiles. SEM observations of the top view and the cross-section of the nanopatterned epi-layers are shown on Fig. 3. The period of the structure is about 650 nm and the mean holes diameter is about 160 nm for the thinner epi-layer and 320 nm for the thickest one, which corresponds respectively to fill factors of 5% and 20%. Finally, the samples are passivated on the front side with a 15 nm-thick Al_2O_3 layer deposited by ALD (Atomic Layer Deposition). On Fig. 3b, we can observe that the Al_2O_3 deposition (the thin bright layer at the surface) is conformal on these structures. For comparison, epi-layers on substrates with the same characteristics were kept without patterning.