Size-Controlled Silicon Nanocrystal Superlattices for Tandem Solar Cells

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Abstract

We have developed silicon nanocrystals superlattices (Si-NC SLs) in both SiC and SiO_x matrices to implement the upper cell of a tandem solar cell with adjustable band gap. We report detailed analysis of the electrical and optical properties of such Si-NC SLs, which have been deposited on Si substrate by means of plasma-enhanced chemical-vapor deposition (PECVD). The samples were submitted to a post-deposition annealing treatment to produce phase separation, precipitation and growth of the Si-NC, which are size controlled by the thickness of the Silicon-rich layer. We further discuss the effect of the NC size on absorption and on the injection and electrical transport. We also present some preliminary results of the stand-alone upper nanocrystal finalized cell. This work demonstrates that Si-NCs are a promising photovoltaic material system; especially in the case of a SL-based approach.

Introduction

Silicon nanocrystals (Si-NCs) embedded in silicon-based insulator matrices have great interest owing to the properties arising from quantum confinement effects in the absorption and emission characteristics. Emerging application fields of Si-NC are third-generation photovoltaics, visible light emitters and integrated silicon photonics [1-3]. If the size of the Si-NC is well controlled so that size distribution is narrow, band-gap enlargement allows tuning sharply the absorption and emission of the Si-NC. This can be done from about 2.5 eV to the near infrared at around 1.3 eV. The tuning of the Si-NC band gap can be graded even in a single device and it has very interesting applications such as using Si-NC ensembles for the upper cell of a silicon tandem solar cell [1]. The upper cell should absorb in the high energy part of the solar spectrum with band-gaps in the range 1.7-2.0 eV so that it is complementary to the standard silicon solar cell below which should absorb the low energy part of the solar spectrum.

A very new and most interesting type of structure for the upper part of the tandem solar cell is the Si-NC superlattice (SL). It is essentially an amorphous superlattice in which Si-NC are embedded in one of the sublayers. As the Si-NCs precipitate and grow during annealing, its final size is limited by the thickness of the Si-rich containing sublayer. The other sublayer acts as a barrier from a double point of view: i) As a material barrier to limit the growth of the Si-NC and ii) As an electronic barrier as the band gap of the barrier sublayer is larger than that of the Si-NC sublayer (see Figure 1 for a sketch). The barrier layers must be very thin for the formation of minibands and for good carrier transport and current extraction. We have experimented with two material systems: i) Si-NC embedded in SiO_x with very thin SiO_2 barriers and ii) Si-NC embedded in SiC_x with SiC thin barriers [4-7].

Experimental

Alternating Si-rich silicon oxide (SRON)/SiO_2 and Si-rich silicon carbide (SRC)/SiC superlattices were deposited on *p*-type Si substrate by means of PECVD. The thickness of the silicon rich layers and the barrier layers (SiO_2 and SiC) were initially varied in a wide range. After optimization they were finally adjusted for a tradeoff having: i) *Thick enough layers* for good Si-NC formation and sharp interfaces without compositional mixing and ii) *Thin enough barriers* for electrical transport to be possible within the minibands. The superlattices were then submitted to a standard procedure to finalize the upper cell structure and contacts. A vertical device structure was attained by sputtering 70 nm of ITO (Indium Tin Oxide) on top of the SL stack and Al at the bottom of the Si substrate. Further details on sample preparation and device fabrication can be consulted elsewhere [5-7]. Many experiments were performed to assess the material composition, structure, optical and electrical properties: i) Energy-filtered transmission electron microscopy (EFTEM); ii) Photo and electroluminescence; iii) Elipsometry, absorption and Raman spectroscopies for the optical properties and iv) Electrical conduction and solar simulator response.

Results and discussion

The Si-NC embedded in SiO_2 present strong photoluminescence (PL) emission, making this technique suitable for analyzing their emission properties [see Fig. 2(c)], which is closely related to the absorption edge energy. Thus, both EFTEM (Fig. 1a) and PL [(Fig. 2c)] are useful for determining optimum Si-NC absorption edge 1.7-1.9 eV: between 3 and 4 nm in diameter for both SiC and SiO_x matrices. The high absorption coefficients found for these systems (10^4–10^5 cm^{-1}) ensure the efficient absorption of the most energetic region of the solar spectrum [see Fig. 2(b) and 2(d)]. Detailed current-voltage *I*(*V*) electrical measurements under dark and illumination conditions were performed in all test devices containing Si-NC SLs, either in SiC or SiO_2 matrices. The electrical and electro-optical results are summarized in Fig. 2. High current densities were obtained when devices are polarized in accumulation regime. We found that the conduction between Si NCs is mainly achieved by thermal hopping through localized traps. The variation of the Si-rich layer thickness, i.e. the NC size, allowed for the in-depth study of the electrical transport within each matrix, as well as the electrical response to light excitation. In particular, a photoconductivity absorption edge could be evaluated in both material systems, resembling the optical absorption results.

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Figures

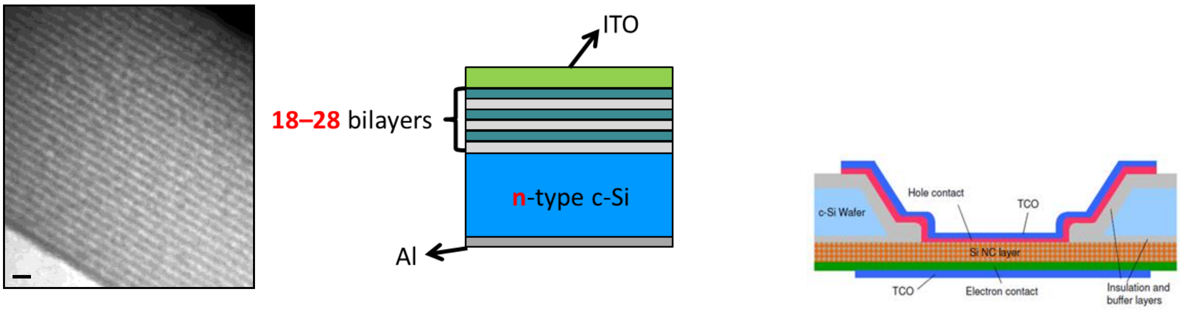

Figure 1. Left is a Si-NC superlattice with SiC matrix. Middle and right: a sketch of the upper cell device.

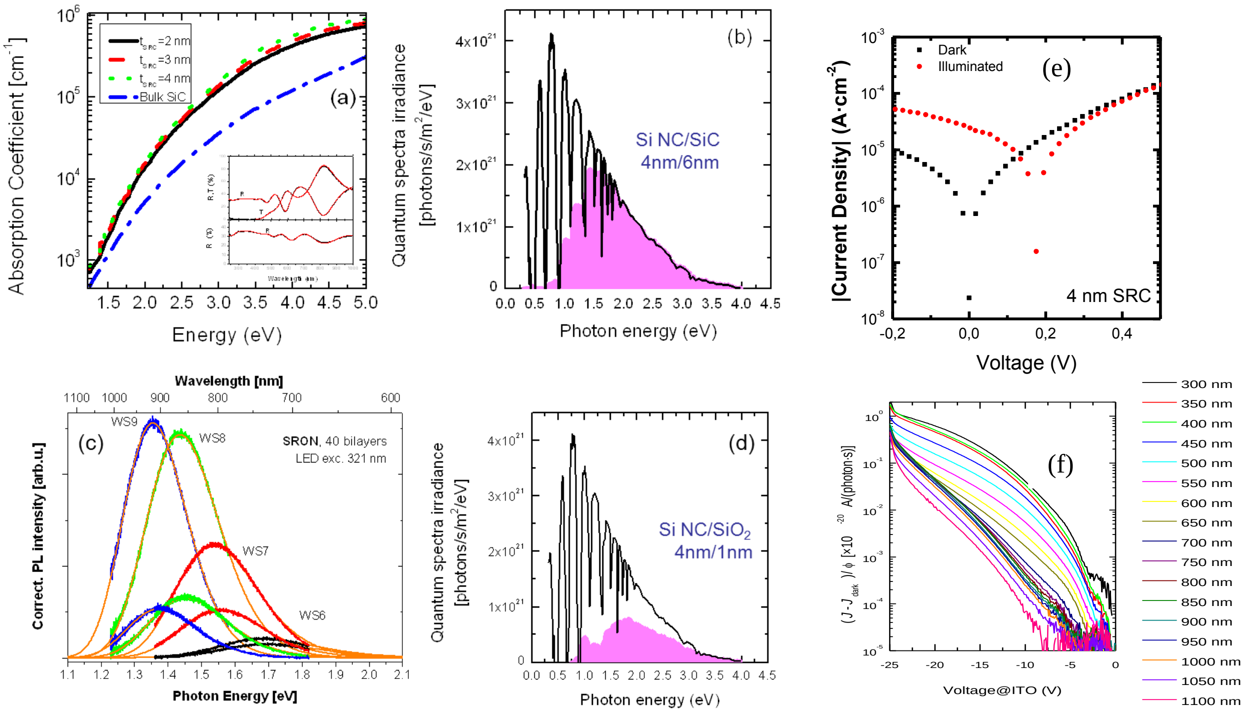

Figure 2. Absorption coefficient, spectrum and electrical response of the superlattices