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Radial microwire array solar cell with pyramidal structure

Bindu Priyadarshini*, Mukul Kumar Das, Mrinal Sen, Subindu Kumar

SAP Research Laboratory, Department of Electronics Engineering, Indian Institute of Technology (Indian School of Mines), Dhanbad, India

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ABSTRACT

In this work, a theoretical model for radial p-n junction microwire array solar cell with pyramidal structures in the space between microwires has been developed. Incorporation of pyramidal structures results in reflection of light, which would otherwise be unused, and illuminates side walls of the microwires. This additional illumination enhances absorption and, hence, efficiency of the whole structure. Efficiency enhancement is analyzed by varying different device parameters e.g., radius and length of each microwire and packing fraction of the structure. Results show that the maximum fractional efficiency enhancement can be obtained as 30% by suitable choice of these parameters.

1. Introduction

Reduction of cost and, at the same time, enhancement of efficiency of solar cell is a big challenge [1–3]. Low cost material is always preferred to reduce the overall device cost [4]. But low cost materials have either a large density of imperfections or a large-scale of impurities which reduce the diffusion length of minority carriers [5]. Now, efficiency of solar cell is mainly limited by the factors like absorption of light and collection of photo generated carriers. Collection of carriers is again limited by the diffusion length of the carriers. In conventional planar solar cell structure, thickness of active layer may be increased to enhance the light absorption. But, due to the low diffusion length of carriers in such materials, carrier collection becomes limited. Hence, the efficiency cannot be enhanced much by increasing the thickness of active layer in a planar solar cell. Solar cell structure consisting of radial p-n junction wires has attracted a great deal of interest among researchers in recent times to overcome this problem [6–12]. This is because, p-n junction in the radial direction enables decoupling of the requirements for light absorption and carrier collection into orthogonal spatial directions [13–16]. So each wire in the array could be long enough in the direction of light incidence for enhanced absorption but, thin in other dimension for effective carrier collection. It is also predicted that the structure would be capable to reduce the overall recombination loss [13,14]. Moreover, wire-array enables stronger light harvesting [10,16,17], resonant-mode-enhanced absorption [18], improved stability against light-soaking [19], higher material quality tolerance etc [20]. Orthogonal wire-array structures have an extra advantage of small reflectance property across a wide optical spectrum, which can be achieved without using any antireflection coating [21]. So, the structure consisting array of radial p-n junction micro-wires is effective for materials like Si which has low absorption coefficient and low minority carrier diffusion length [3,22]. In spite of various advantages of wire-array solar cell, it has a serious disadvantage that light incident in the space between wires is completely wasted. The problem can be encountered a lot, if a reflecting structure, like pyramidal reflector with high reflectivity, is incorporated between the vertical wires [23].

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* Corresponding author.

E-mail addresses: bindup2k4@gmail.com (B. Priyadarshini), das_mkdas@yahoo.co.in (M.K. Das), mrinal.sen.ahm@gmail.com (M. Sen), subindukumar@yahoo.com (S. Kumar).

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Because, the light which is incident on reflecting structures between wires (which would otherwise be wasted without the pyramidal mirror) is reflected by its slant surface and illuminates the side walls of wires. Thus absorption of additional light in the side wall of wires is expected to offer enhanced efficiency. To the best of authors' knowledge, theoretical modeling of such solar cell structure has not yet been reported in literature, though the radial p-n junction wire-array solar cell structures have already been reported in literature [24–26]. Modeling of such wire-array solar cell with sub-micrometer wire diameter requires consideration of wave-optics which involves huge computational complexity. Because, though the periodic boundary condition can be imposed on the optical modes at the open-end side of the wires but that fails at the portion of wires where they are attached with the substrate. Hence, it is very hard to obtain a generalized analytical solution for the structure through wave-optics. On the other hand, a ray-optical approach results in a simplified model which gives reasonable accuracy for a wire-array structure with wire diameter in the range of 4 μm and above [27]. Moreover, higher conversion efficiencies are observed in wire-arrays with wire diameter in the range of several micrometers compared to that with wire diameter in sub micrometer range [28,29]. This is due to enhanced open circuit voltage in microwires (i.e., wires with diameter in the range of micrometer) than nanowires (i.e., wires with diameter in the range of nanometer) which occurs due to rapid saturation of current in the latter [29]. Therefore, ray-optical approach is considered for modeling the structure of this work as its prime objectives is to establish the importance of pyramidal reflectors between the rods.

In this work, a theoretical model for silicon microwire array solar cell with pyramidal reflecting structure between microwires is developed. The efficiency of the whole structure is analyzed by varying different device parameters like length of each microwire and spacing between microwires. Rest portion of this paper is organized as follows. The proposed theoretical model is elaborated in Section II, results are described in Section III and finally conclusion is given in Section IV.

2. Theoretical model

Device structure considered in our analysis is a two dimensional array of p-n junction microwires with some pyramidal reflectors between two rods, as shown in Fig. 1(a). Microwire solar cells are basically array of cylindrical shaped, small, independent cells with micro dimensional radial geometry. The axes of the microwires are considered to be parallel to each other and are oriented to the direction of incident light but the abrupt p-n junction is along its radial direction. So it can be considered to be made of two concentric cylinders with opposite polarity doping in core and shell regions (e.g. p-type core and n-type shell). For clear visualization of the whole structure, an expanded version of two microwires and their intermediate space, which incorporates a single pyramid, is shown in Fig. 1(b). The energy band diagram of a single microwire with radial p-n junction is shown in Fig. 1(c). Device parameters used in our model are also shown in these figures. Light is assumed to be incident on top surface of the microwire along normal to the surface as shown in Fig. 1(a). On incidence of light on the rod, carriers are generated along the length of the rod but, they are separated out in the radial direction traversing a micro-dimensional thickness and hence with a very less chance of recombination. Length of the rods can be increased to absorb sufficient light but that will not hamper the carrier separation unlike in planner solar cell. The p-n junction in the microwire is assumed to be abrupt, and so the depletion approximation is assumed to be valid. The estimation of one-dimensional carrier transport is also valid because the variation of concentration of generated carriers along the length (z direction) is much lower than that in the radial direction. However, this is a quite good assumption for a radial p-n junction microwire made of materials in which the optical thickness is much greater than the diffusion length of minority carriers. Based on the above assumptions, continuity equation in cylindrical coordinate system for minority holes in n-type shell can be written as:

$$\nabla^2 p' - \frac{p'}{L_p^2} = \frac{\partial^2 p'}{\partial r^2} + \frac{1}{r}\frac{\partial p'}{\partial r} - \frac{p'}{L_p^2} = \underbrace{\frac{-\alpha_n \Gamma_0 (1 - R_n)}{D_p} e^{-\alpha_n z}}_{I} \tag{1}$$

where, p′ is the excess minority-hole concentration with respect to its equilibrium value p_0, R_n is reflectivity of the top surface of microwire, Γ_0 is incident photon flux density on top surface, L_p and D_p are the diffusion length and diffusion coefficient of minority holes respectively, α_n is the absorption coefficient of material in n-region. Now, light incident in the gap between microwires is reflected by the slant surface of pyramid. This reflected light is absorbed by the curved surface of cylindrical rods and as a result, some additional carriers are generated within the wires. Generation of these additional carriers due to presence of pyramidal structure has been taken into account in our model by incorporation of an additive term in the right hand side of the continuity equation. Hence, the one dimensional modified continuity equation can be represented as:

$$\nabla^2 p' - \frac{p'}{L_p^2} = \frac{\partial^2 p'}{\partial r^2} + \frac{1}{r}\frac{\partial p'}{\partial r} - \frac{p'}{L_p^2} = \underbrace{\frac{-\alpha_n \Gamma_0 (1 - R_n)}{D_p} e^{-\alpha_n z}}_{I} - \underbrace{\frac{\alpha_n C_n}{D_p}}_{II} \tag{2}$$

where, C_n represents the rate of additional electron generation per unit area due to the absorption of light, reflected from the pyramidal surface, by the sidewall of the microwire at a particular z. Therefore the right hand side (RHS) of Eq. (2) can be categorized into two parts namely, Term I and Term II. Term I is due to the absorption of incident light on top surface of the rod and the Term II is due to the presence of pyramidal surface. Similarly, the modified continuity equation for minority electrons in p-type core can be written as–