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Light-trapping properties of the Si inclined nanowire arrays

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ABSTRACT

The light trapping performance of Si nanowire with different inclination angles were systematically studied by COMSOL Multiphysics. The inclined nanowires with inclination angles smaller than 60° show greater light trapping ability than their counterparts of the vertical nanowires. The Si solar cell with the inclined nanowires of the optimal parameters, whose $\theta=30°$, $P=400$ nm, $D=140$ nm, can achieve a 32.395 mA/cm^2 short circuit photocurrent density and a 35.655% conversion efficiency. The study of the inclined nanowire provides an effective way for further utilization of the incoming light.

1. Introduction

Photovoltaics is popularized at a rapid speed and has a promising outlook. More and more solar panels are installed in power plants, commercial premises, and residential houses [1,2]. Thin film solar cell, with better flexibility, lighter weights, less usage of raw material, cheaper processing and ease of integration, gains larger proportion in the solar cell market [3]. However, light management and carrier management are still two main problems [4]. The decrease in thickness may also be accompanied by incomplete absorption of photons and a corresponding decrease in efficiency. Nanowire is widely used in improving the light management duo to their unique optical properties and compatibility with inexpensive fabrication techniques. As the light trapping ability is sensitive to the morphology of the nanowire structure, the nanowires' diameter, period and ratio of diameter/period have been extensively studied both theoretically and experimentally to boost the light harvesting ability of the solar cells [5–9]. The major preparation methods of nanowires include etching by acid solutions, oblique angle deposition (OAD), molecular beam epitaxy (MBE), vapor-liquid-solid(V-L-S), reactive ion etching (RIE) etc. Apart from the vertical nanowires (VNW), inclined nanowires (INW) with varying inclination angles are obtained [10–13]. To our knowledge, there are insufficient studies to investigate the inclination angles of Si inclined NW on light trapping so far. In this paper, systematic simulations were conveyed by COMSOL Multiphysics to study the light harvesting ability of INW. The results reveal that the Si INW arrays outperform the vertical counterpart in certain angle range.

2. Methods

By employing Maxwell equations, the COMSOL Multiphysics is widely used in the analysis of the electromagnetic wave propagation in the nanostructures. Air Mass 1.5G (AM 1.5G) was used. Perpendicular incident light (the propagation direction was along the *-z* direction) of transverse electric (TE) and transverse magnetic (TM) wave were calculated separately. TE polarized plane wave had its electric field along the *-y* direction, while TM polarized case had its electric field in the *x* direction. Simulations were carried out at the wavelength regime of 310–1127 nm with a 5 nm step size, which is the corresponding wavelength range of the Si band gap. The silver back reflection layer was added to reduce the light transmission. To model the periodic array structure, the simulations were carried out by introducing the periodic boundary conditions (PBC) in both the $\pm x$ and $\pm y$ directions (the PBC in the *-y* direction is not shown in Fig. 1(a) to have a clear view of the model) [14]. To model a semi-infinite Si substrate, the periodic match layer (PML) was added in the vertical direction, which the transmission light was totally absorbed [15]. The short current density and efficiency are denoted as J_{sc} and η respectively [16,17].

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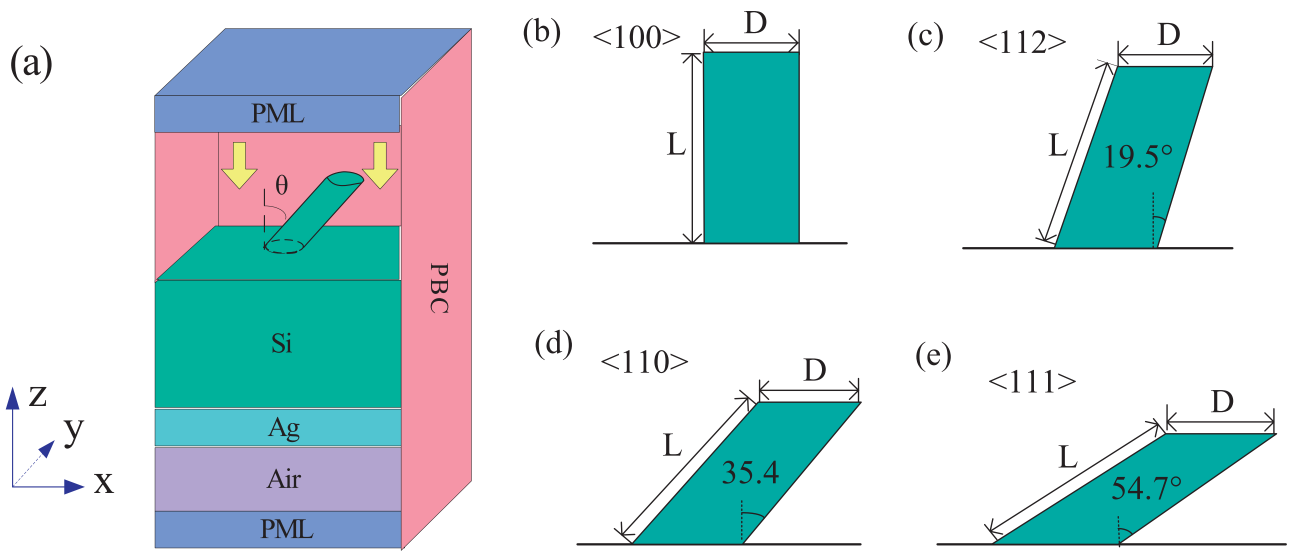

Fig. 1. The diagram of the model, the nanowires are 500 nm in length and on the silicon substrates of 1 μm thick (a), nanowires with the orientation of < 100 > (b), < 112 > (c), < 110 > (d), < 111 > (e).

$$J_{sc} = \int_{310\text{nm}}^{\lambda_g} I(\lambda)A(\lambda)\frac{e\lambda}{hc}d\lambda \tag{1}$$

$$\eta = \frac{\int_{310\text{nm}}^{\lambda_g} I(\lambda)A(\lambda)\frac{\lambda}{\lambda_g}d\lambda}{\int_{310\text{nm}}^{4000\text{nm}} I(\lambda)d\lambda} \tag{2}$$

where λ_g is the corresponding wavelength of the Si band gap, i.e. 1127 nm, $I(\lambda)$ is the standard solar irradiance spectrum of AM1.5 G, $A(\lambda)$ is the optical absorption of the structure at the wavelength λ, e is the elementary charge, h is the Planck constant, c is the velocity of light in vacuum.

The cross sectional view of the model is depicted in Fig. 1, the VNW and INW Si nanowire arrays on crystalline silicon substrates were devised for comparative analysis. As is illustrated in Fig. 1(b)–(e), comparative simulations were made between the vertical (< 100 > -oriented) and inclined NWs with growth direction along three common crystal orientation of silicon (< 110 >, < 111 > and < 112 >). The corresponding parameters are labeled clearly, where θ is the inclination angle to the vertical direction. When θ equals 0°, it is the VNW array. D, L and P are the diameter, length and period of the nanowires respectively. The diameter is taken to be $D=100$ nm, the length is set to $L=500$ nm and the period is fixed at $P=600$ nm. All the NWs are on the silicon substrates of 1 μm thick.

3. Results and discussion

3.1. The effect of inclination angle on the Si INW light-trapping ability

The absorption diagrams of the NWs are sketched in Fig. 2. The diameter and period of the NW are fixed at 100 nm and 600 nm respectively. For the INW, the discrepancy of the absorption between TE and TM polarized light results from the anisotropy in the x–y plane of the NW. That differs from the VNW, which the absorption has no obvious difference between TE and TM for it is not sensitive to polarization [18]. The INW shows no obvious advantage over the VNW for the TE polarized light. However, apparent from Fig. 2(b) of the TM-absorption, it's totally a different case. The INW Absorption-TM curves are almost uniformly higher than the VNW of the consistent parameters throughout the

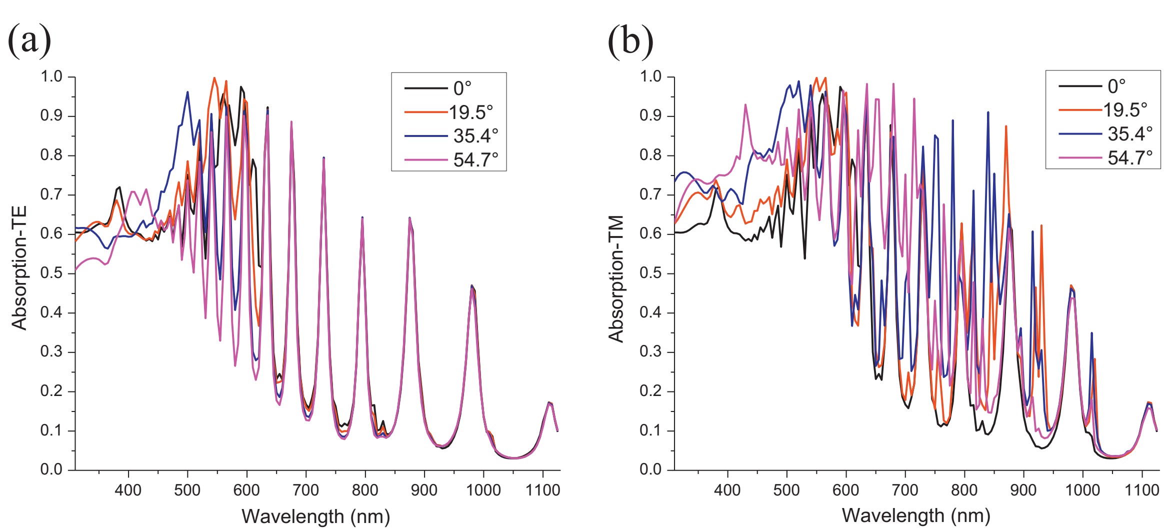

Fig. 2. Absorption of NW with four different inclination angles (vertical, < 110 >, < 111 > and < 112 > -oriented) as a function of wavelength, TE (a) and TM (b).