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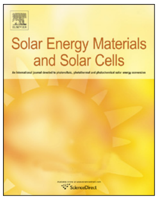

Angular reflection study to reduce plasmonic losses in the dielectrically displaced back reflectors of silicon solar cells

Y. Yang*, S. Pillai, H. Kampwerth, M.A. Green, H. Mehrvarz, A. Ho-Baillie

Australian Centre for Advanced Photovoltaics, School of Photovoltaic and Renewable Energy Engineering, University of New South Wales, Sydney, NSW 2052, Australia

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ABSTRACT

Metals are an integral part of solar cell structures—as a metal contact and/or a back reflector. However it is a less known fact that there are plasmonic losses associated with these structures and it is important to minimise such losses especially when placed in proximity to scattering media like textures on the front of the cell that can introduce an angular dependence to the light incident on the rear. This study investigates the losses in a metal reflector when placed adjacent to a dielectric layer in a typical solar cell rear geometry. The experimental measurement was realised using a novel custom built optical setup for characterising intensity of the reflected light at various internal incident angles at the Si–dielectric interface. Our results show that the thickness of the dielectric layer, the refractive index of the dielectric layer and the type of the rear metal can all affect the degree of such losses and the distribution of the angular reflection. Both measured and simulation results indicate that a 250–320 nm SiO_2 along with an Ag back reflector gives the best internal rear angular reflection in Si but is dependant on the wavelength of interest. It also shows that textured or scattering front interfaces with internal incident angles greater than 28° have the potential to provide light trapping through total internal reflection and at the same time minimise plasmonic losses at the metal reflector interface.

1. Introduction

An effective light trapping scheme is critical to boost light absorption within solar cells, increasing the short circuit current as well as the overall conversion efficiency. In conventional solar cells light trapping is normally achieved by two optical components: a textured front surface and a highly reflective rear reflector [1], as shown by Fig. 1. Surface texture leads to multiple reflections at the front surface and deflects incident light at oblique angles, enhancing light path length and overall light absorption. A rear reflector redirects the weakly absorbed low energy photons back into the bulk Si (specular reflection) for further electron–hole pair generation, with a small portion being lost by absorption in the metal, (A_b in Fig. 1). In fact, light propagating towards the rear surface due to the deflection from the front strikes the rear at a range of angles, resulting in a rear reflection that is angularly dependent. Textured interfaces along with plasmonic and dielectric scatterers either on the front or rear of solar cells are gaining a lot of importance in light trapping as the trend is for thinner solar cells. The principle in all these cases relies on large angle scattering to achieve total internal reflection (TIR). This highlights the importance of the angular reflection characteristics for the rear of the cell, which is the focus of this study.

Very few measurements of the angular reflection dependence of rear reflectors in cells have been reported previously. The difficulties lie primarily in the significant difference in the refractive index between air and silicon when a flat wafer is measured. This constrains incident light of any angle to a 17° cone after the light enters the silicon (see Fig. 2(a)). Another measurement restriction comes from the reflected light detection process where the front surface of the wafer again introduces unwanted reflection. In this study a novel optical setup is built to allow light illumination and detection over a broad angular range. The angularly dependent reflection intensities R_b (Φ_i) are reported, with the effect of dielectric layer thicknesses and metal used as reflectors being experimentally examined, and the effect of the refractive index of dielectric layer being investigated via simulation. The aim is to increase the reflection into Si at the rear interface facilitating better light absorption.

2. Surface plasmon polaritons losses

Surface plasmon polaritons (SPP) refer to longitudinal oscillations of electron charges at the metal–dielectric interface on excitation by light. Such excitations propagate along the metal surface, with the

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* Corresponding author. Tel.: +61 433 264 753; fax: +61 2 9385 5412.
E-mail address: yang.yang@unsw.edu.au (Y. Yang).

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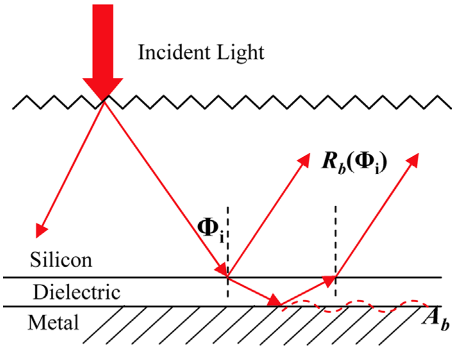

Fig. 1. A schematic of the light trapping scheme formed by a textured front surface and a dielectrically displaced reflector used in high performance silicon solar cells. Rear surface reflection R_b is angularly dependent due to front surface deflection.

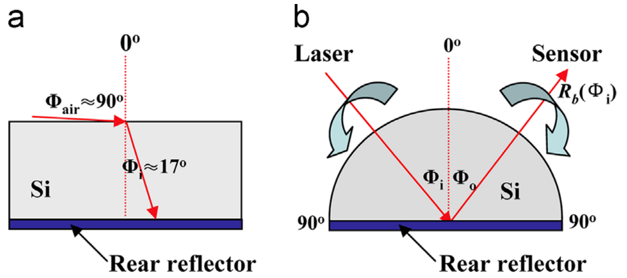

Fig. 2. (a) A schematic showing the measurement limitations of using a flat wafer. The angle of incidence is restricted to within a 17° cone inside Si due to the difference in the refractive index between air and silicon. (b) A schematic of the proposed measurement with a Si hemisphere allowing light illumination and detection at any angle between 0° and 90°. Φ_i and Φ_o are the light incoming and outgoing angles within silicon respectively, with $\Phi_i = \Phi_o$ for specular reflectors. Φ_{air} is the angle of incidence of light in air.

electromagnetic field strength decaying exponentially on either side with a maximum value at the surface. Only *p*-polarised light effectively couples to SPPs [2]. For a smooth metal surface, a SPP cannot be excited at the air–metal interface by light due to the mismatch in the momentum with plasmons ($k_x > \omega/c$ where k_x is the momentum along the surface direction as shown in Fig. 3(b), ω is the radial frequency of light and c is its velocity). Two general methods adopted to excite SPPs are coupling via a grating and by attenuated total reflection (ATR) [2–4]. Coupling using a grating is most often achieved by incorporating a rough metal surface and is beyond the scope of the study as we investigate smooth interfaces only. ATR generally employs two different geometries–a prism coupler adjacent to the metal surface (known as the Kretschmann configuration) excites plasmons on the air–metal interface of the prism and the metal surface separated by a small gap of air or dielectric (known as Otto configuration) excites SPPs at the metal–dielectric interface by frustrated total reflection. In both cases, proper choice of the incidence angle above the critical angle for TIR allows matching of the wave vector of the SPP with that of light.

A commonly used Otto configuration is composed of a dielectric prism with refractive index larger than that of air and a thick metal slab separated by a small air gap in between [5]. A solar cell rear structure involving a Si/dielectric/metal layer stack resembles such a configuration with the index of Si (representing the prism) larger than that of the dielectric (representing the air gap), as shown in Fig. 3(a). Campbell [6] first noted a strong dip in the calculated reflection of the rear Si/SiO$_2$/Al structure of solar cells at angles near the critical angle for total internal reflection at the Si–SiO$_2$ interface. This reflection dip is believed to be caused by the excitation of surface plasmon polaritons (SPP) at metal interface. In the Otto configuration, when the angle of incoming light

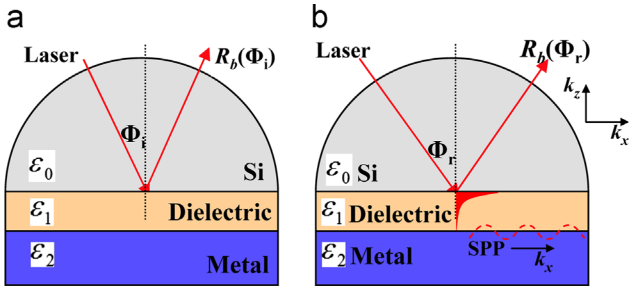

Fig. 3. (a) Schematic of a dielectrically displaced rear reflecting system of solar cell and (b) system at resonance resembling an Otto configuration. SPPs are excited by a laser beam when $\Phi_i = \Phi_r$, the resonance angle, at the metal interface.

approaches the resonance angle ($\Phi_i = \Phi_r$, Φ_r indicating the angle of maximum SPP coupling to the dielectric–metal interface) of the system, the evanescent waves travel parallel along the Si–dielectric interface. The tail of the evanescent wave (originating at the onset of TIR) is brought into contact with a metal–dielectric interface that supports SPPs, see Fig. 3(b) [7].

When light (free space wave vector, $k = \omega/c$) passes through Si with angle of incidence $\Phi_i > \Phi_c$ the critical angle at Si–dielectric interface, TIR occurs. In the process light gains an additional momentum equivalent to $(\omega/c)\sqrt{\varepsilon_0}$. TIR results in an evanescent wave propagating at the Si–dielectric interface with the wave-vector projected to the surface (x-direction) being $(\omega/c)\sqrt{\varepsilon_0}\sin\Phi_r$. Since the two waves have the same characteristics, the wave-vector k_x for SPP excitation at the metal–dielectric interface is then matched for the system shown in Fig. 3(b), when $\Phi_i = \Phi_r$ according to the SPP dispersion relation [2]

$$k_x = \frac{\omega}{c}\sqrt{\varepsilon_0}\sin\Phi_r = \frac{\omega}{c}\sqrt{\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}} \tag{1}$$

ε_0, ε_1, and ε_2 are the complex permittivities of the three media, Si ($\varepsilon_0 = \varepsilon'_0 + i\varepsilon''_0$) dielectric ($\varepsilon_1 = \varepsilon'_1 + i\varepsilon''_1$) and metal ($\varepsilon_2 = \varepsilon'_2 + i\varepsilon''_2$) respectively (see Fig. 3). ε_2 has a largely real negative value, whereas constant ε_1 has a smaller real positive value ($\varepsilon'_2 < 0$ and $|\varepsilon'_2| > \varepsilon_1$). Therefore k_x is primarily real, with a minor imaginary component k_{xi}, causing the wave amplitude in direction parallel to the dielectric–metal interface to decay due to absorption in the metal and therefore conversion to heat energy [8]. The SPP resonance condition in Eq. (1) can be rewritten as:

$$\sin\Phi_r = \sqrt{\frac{\varepsilon_1}{\varepsilon_0}}\sqrt{\frac{\varepsilon_2}{\varepsilon_1+\varepsilon_2}} \tag{2}$$

The condition for TIR at the Si/dielectric interface from Snell's law is

$$\sin\Phi_c = \frac{n_1}{n_0} \tag{3}$$

Assuming the imaginary part of ε_0 and ε_1 can be neglected, the first term in Eq. (2) is simplified to n_1/n_0 (same as right side of Eq. (3)). As $\varepsilon'_2 < 0$ for metals in the wavelengths of interest, $\varepsilon'_1 > 0$ and $|\varepsilon'_2| > |\varepsilon'_1|$, the condition for an interface mode to exist is satisfied. This would mean that $\varepsilon'_1 + \varepsilon'_2 < 0$ and $|\varepsilon'_1 + \varepsilon'_2| < |\varepsilon'_2|$, therefore the second term of Eq. (2) is real and larger than unity. This indicates that resonance angle Φ_r is always larger than critical angle Φ_c.

The propagating SPP causes light to be trapped at the metal interface resulting in absorption loss in the metal. This is an optical loss mechanism for solar cells which needs to be avoided and can occur on smooth surface as well contrary to belief that this occurs only on rough surfaces. In this work, we have experimentally confirmed the existence of such SPP excitation in a standard solar cell rear structure and have discussed factors those can affect the degree of such losses.