SOLAR CELL AS A WAVEGUIDE: QUANTUM EFFICIENCY OF AN ULTRATHIN CRYSTALLINE SILICON SOLAR CELL

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ABSTRACT: An analysis of an ultra-thin crystalline silicon solar cell with 200 nm thick active layer fabricated in our laboratory shows that the behavior of quantum efficiency as a function of wavelength is primarily determined by the absorption of light in the active layer, showing a series of interference peaks. We have now modeled this solar cell in detail, perceiving the solar cell as a waveguide. Intriguingly we find that the peaks in the quantum efficiency lie close to the frequencies of the trapped (internal) modes of the waveguide. This paper provides a detailed explanation of how these modes, normally inaccessible to external observation, can be detected in external quantum response, in terms of the position of poles of the absorbance in the complex wave number plane.
Keywords: Absorption, optical properties, quantum efficiency, waveguide.

1 INTRODUCTION

Much research is currently under way to reduce the material usage, and therefore the cost, in the manufacture of crystalline silicon solar cells. Many novel approaches exist to overcome the principal challenge to improve the optical absorption. These include the deposition of fluorescent molecules or quantum dots, or building dielectric/metallic nanostructures either on the surface or inside silicon solar cells. Their common feature is to couple the incident solar radiation into the waveguide modes trapped by total internal reflection (TIR) in the planar solar cell. The optical path length in the solar cell can then be enhanced, thereby substantially reducing the thickness of silicon solar cells.

In this paper we present an in-depth study of an ultra-thin crystalline silicon solar cell with 200 nm thick active silicon layer. The measured quantum efficiency is modeled numerically and we find that, intriguingly, it reveals peaks which lie close to the waveguide modes corresponding to the active silicon layer. We give an explanation of why these normally hidden internal modes are available to external observation.

2 ABSORBANCE OF THE SOLAR CELL

An ultra-thin crystalline silicon solar cell has been fabricated in the clean room of Southampton Nanofabrication Centre and the experimental procedure is described in [1]. The structure of the solar cell and the nominal thickness of each layer are shown in Fig. 1. By using the transfer matrix method, the measured quantum efficiency has been modeled successfully. We show below how this cell can be modeled analytically as a waveguide.

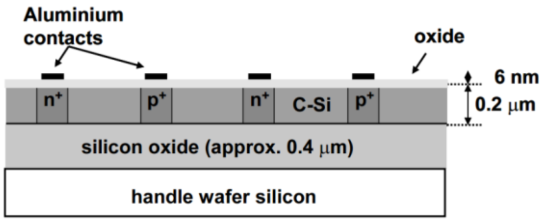

Figure 1: Structure of the fabricated ultra-thin crystalline silicon solar cell [1]

The planar solar cell can be modeled as a silicon waveguide layer sandwiched by two layers of silicon dioxide. As shown in Fig. 2, the incident light from layer 1 (silicon oxide) undergoes multi-reflection in layer 2 (silicon) and is finally transmitted into layer 3 (silicon oxide). Also shown in Fig. 2 are the refractive indices and light propagation angles in each layer.

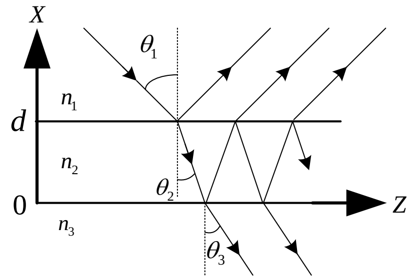

Figure 2: Light propagation near a layered structure

By using Airy's summation [2] for the reflectance and transmittance of a planar slab, the absorbance of the active silicon layer can be obtained as

$$A = 1 - \left| \frac{r_{12} + r_{23} e^{2i\phi}}{1 + r_{12} r_{23} e^{2i\phi}} \right|^2 - \frac{n_3 \cos\theta_3}{n_1 \cos\theta_1} \left| \frac{t_{12} t_{23} e^{i\phi}}{1 + r_{12} r_{23} e^{2i\phi}} \right|^2 \quad (1)$$

where r_{ij} and t_{ij} are the Fresnel reflection and transmission coefficients at the interface of layer i and layer j, respectively, $\phi = k_{2x} d = n_2 k_0 \cos\theta_2 d$ the phase retardation for light travelling through layer 2 of thickness d and k_0 the wave number in vacuum. It is apparent from Eq. (1) that the absorbance has singularities when the denominator of the second and the third term vanishes. These singularities are poles in the complex wave number plane whose position is given by $1+r_{12}r_{23}e^{2i\phi}=0$; in other words, when the wave number component in the x direction ($k_{2x}=n_2k_0\cos\theta_2$) equals to

$$k_{2x}=\frac{2m\pi+2\phi_{21}+2\phi_{23}+i\ln|r_{21}||r_{23}|}{2d}\quad(m=0,1,2,3....)\quad(2)$$

where k_0 the wave number in vacuum, $r_{21}=|r_{21}|e^{-i2\phi_{21}}$, $r_{23}=|r_{23}|e^{-i2\phi_{23}}$ and m is an integer. For the waveguide modes trapped by TIR, $\theta_2>\theta_c$ (critical angle for TIR) and $|r_{21}|=|r_{23}|=1$, Eq. (2) can be rewritten as

$$2k_{2x}d-2\phi_{21}-2\phi_{23}=2m\pi\quad(m=0,1,2,3....)\qquad(3)$$

This is exactly the characteristic dispersion relation for the waveguide modes and m represents the mode index number [3]. For light propagating in the escape cone, $\theta_2<\theta_c$ and $|r_{21}|=|r_{23}|<1$, the singularities of the absorbance move to the complex plane of k_{2x}. Thus, the absorbance has poles in the complex plane of k_{2x}. The poles locate on the real axis correspond to the trapped waveguide modes, while the poles in the complex plane correspond to the escape cone modes.

Because the extinction coefficient of silicon is small relative to the real part of the refractive index in the spectral range of interest [4], the phase angles for the escape cone modes are close to zero, i.e. $\phi_{21}=\phi_{23}\approx0$. This condition corresponds to the waveguide modes propagating near the critical angle for TIR. Thus, the poles related to the escape cone modes lie close to the poles related to the waveguide modes propagating near the critical angle.

The poles related to the trapped waveguide modes propagating near the critical angle are given by

$$2k_{2x}d\approx2m\pi\quad(m=0,1,2,3....)\qquad(4)$$

with the condition

$$\theta_2\approx\theta_c\qquad(5)$$

The poles related to the escape cone modes are given by

$$k_{2x}=\frac{2m\pi+i\ln|r_{21}||r_{23}|}{2d}\quad(m=0,1,2,3....)\qquad(6)$$

with the condition

$$\theta_2=0\sim\theta_c\qquad(7)$$

The real part of Eq. (6) is close to the result given by Eq. (4) even when the propagation angle θ_2 changes from θ_c to 0. This is due to the small variation of $\cos\theta_2$, i.e. $\cos\theta_2\approx1$ for any $\theta_2<\theta_c$ or any escape cone modes in silicon. The imaginary part is given by the Fresnel reflection coefficients, which is dependent on the angle of propagation, and the thickness of the active silicon layer.

3 CALCULATION RESULTS AND DISCUSSION

For our thin solar cell, the thickness of the active silicon layer is only 200 nm and thus Eq. (4) only has a few discrete solutions. Using the refractive index for silicon and silicon dioxide from [4], the wavelength and mode index number for the poles related to the waveguide modes can be obtained and the result is shown in Tab. 1.

Table I: Waveguide mode pole parameters

m	5	4	3	2
Wavelength (nm)	410	448	524	698

The poles related to the escape cone modes are dependent on the propagation angle θ_2. The movement of these poles is plotted in the complex plane of k_{2x} in Fig. 3 (b) as θ_2 increases from 0 to the critical angle θ_c. It is seen from Fig. 3 (b) that the poles related to the escape cone modes move away from the poles on the real axis, which corresponds to the trapped waveguide modes. Thus, under normal excitation of light ($\theta_2=0$), the absorbance of the solar cell should show local peaks close to the wavelength corresponding to these poles. Since the solar cell has unity carrier collection efficiency throughout most of the device [1], the quantum efficiency should be proportional to the solar cell absorbance and it should show the local peaks corresponding to the poles.

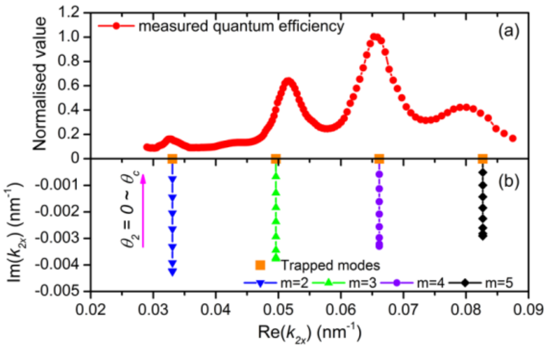

Figure 3: (a) The measured quantum efficiency of the solar cell; (b) poles of the solar cell absorbance in the complex plane of k_{2x}

Fig. 3 (a) plots the measured quantum efficiency under light excitation in the normal direction to the solar cell surface against the related wave number $k_{2x}=n_2k_0\cos(0)$. It is seen that the local peaks of the quantum efficiency lie close to the poles corresponding to the trapped waveguide modes propagating near the critical angle for TIR in the complex plane of k_{2x}.

4 CONCLUSION

The absorbance of a fabricated ultrathin silicon solar cell has been modeled analytically. By studying the poles of the absorbance in the complex plane of wave number, we find that the peaks of the quantum efficiency of the solar cell lie close to the wavelength of the trapped waveguide modes propagating near the critical angles for total internal reflection. The normally inaccessible feature of the waveguide modes to external observation can thus be detected in external quantum response, in terms of the poles of the absorbance of the active silicon layer in the complex wave number plane.

5 REFERENCE

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6 ACKNOWLEDGEMENTS

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