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Impact of Nanometer Air Gap on Photon Recycling in Mechanically Stacked Multijunction Solar Cells

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Abstract

We investigate photon recycling at the top subcell in mechanically stacked multijunction solar cells with nanometer air gap between the subcells. We calculate the incident-angle-dependence of the reflectivity at the rear surface of the top subcell, which shows that more than 30% of luminescence at the top subcell is reflected at the air gap even with 10 nm thickness. Our findings indicate that the high efficiency photon recycling can occur at the nanometer air gaps.

1. Introduction

Light management for designing the optical properties of solar cells has gained much attention for achieving high conversion efficiency. In the devices with high-quality materials, the radiative recombination exhibits a primary recombination channels, which shows a significant impact to the performance of photovoltaic devices. Luminescent coupling between subcells has been extensively studied in stacked multijunction devices. Photon recycling originates from the re-absorption of luminescence (i.e. photons generated by radiative recombination) in the same subcell; by contrast, in luminescent coupling, luminescence in higher-bandgap subcells can be re-absorbed by lower-bandgap subcells beneath [Fig. 1]. Re-absorption of luminescence leads to an increase in photocurrent in the subcell.

The assessment of light management for photon recycling results in a significant increase in conversion efficiency of thin film solar cells through photon recycling [1,2]. In addition to single-junction solar cells, the design of optical coupling between subcells has received increased attention in multijunction solar cells to boost the performance further. Monolithic devices with no gaps between the subcells exhibit strong optical coupling between the subcells. The luminescent coupling efficiency depends on the device structure, that is, an inverted grown p-n structure [3]. In contrast, when a gap, such as air gaps [4], exists between the subcells, light with a large incident angle is reflected due to total internal reflection. More than 90% of the luminescence is reflected at the semiconductor/air interface due to total internal reflection. In mechanically stacked multijunction solar cells that are bonded using metal nanoparticle (MNP) arrays [5], nanometer air gaps between the subcells exist and can affect the optical properties. So far, even though the coverage of MNP is ~10%, normal incident light can transmit through the interface with 10-nm air gap [6]. However, the impact of nanometer air gaps to photon recycling and luminescent coupling have not been understood well.

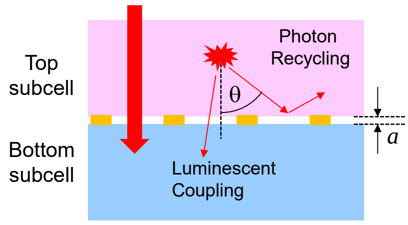

Fig. 1. Schematic illustration of photon recycling and luminescent coupling in multijunction solar cells with nanometer air gap.

In this study, we investigated the effects of air gap thickness between the stacked subcells on photon recycling at the top subcell to understand the optical properties in the mechanically stacked multijunction solar cells via metal-nanoparticle arrays. We calculated the incident-angle dependence of the reflectance at the interface between the top and bottom subcells, which determines the efficiency of photon recycling at the top subcell and luminescent coupling from the top subcell to the bottom subcell.

2. Results and Discussions

Reflectance at the air gaps

Transmittance and reflectance for light with a large incident angle is sensitive to the nanometer air gaps between dielectrics of high refractive indices [7]. The wave vector $\boldsymbol{k}$ makes an angle θ with the normal incidence to dielectric/air interface [Fig.1], and has components $k_{\parallel}$ and $k_{\perp}$ parallel and perpendicular to the interface, respectively, i.e., $k_{\parallel}=nk_0 \sin\theta$ and $k_{\perp}= nk_0 \cos\theta$, where the wave number k is given by $n(2\pi/\lambda_0)$ with the refractive index of the dielectric media n and wavelength in air λ_0. When θ is sufficiently large, $k_{\parallel}$ exceeds k_0 and gives rise to the evanescent wave on the air side with $\beta=\sqrt{n^2\sin^2\theta-1}k_0$. The transmissivities for a transverse electric (TE) wave and transverse magnetic (TM) waves are given by [7]:

$$T_E=\left[1+\frac{\left(k_\perp^2+\beta^2\right)^2}{4k_\perp^2\beta^2}\sinh^2\beta a\right]^{-1} \quad (1)$$

and

$$T_M = \left[1 + \frac{\left(k_\perp^2/n^4 + \beta^2\right)^2}{4k_\perp^2\beta^2/n^4}\sinh^2\beta a\right]^{-1}, \qquad (2)$$

where a is the air gap thickness.

As a test structure, here we use the stacked GaAs//Si multijunction solar cells with the air gap between the GaAs and Si layers. Here, we initially ignore the metal-nanoparticle array between the GaAs and Si layers. For luminescence, the reflectance for light with a large incident angle is more important because the direction of luminescence exhibits random distribution. To investigate the luminescence of the GaAs subcell appearing at 800 nm wavelength, we calculate the reflectance R = 1 - T for light with an incident angle θ using the refractive index of GaAs (n = 3.7) and Si (n = 3.7) for 800 nm wavelength light. For simplicity, we ignore the optical absorption here.

Figure 2 shows the incident angle dependence of reflectance for different air gap thicknesses. Above the critical angle of 15.7°, the reflectance increases with incident angle. The reflectance above the critical angle increases with the air gap thickness. Note that the GaAs/Si interface with no air gap exhibits zero refractive index difference, resulting in no reflectance even for a large incident angle. Because of the enhanced reflectance, the reflection of luminescence at the rear surface of the top GaAs subcell increases, which means that even the nanometer air gap can improve the photon recycling. Consequently, the enhanced photon recycling efficiency can increase the minority carrier density in the top GaAs subcell resulting in enhanced open-circuit voltage.

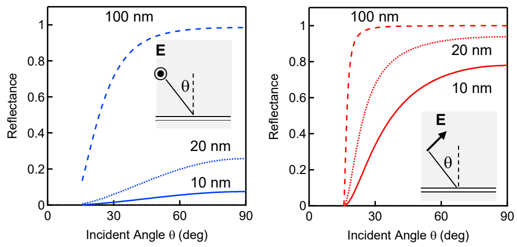

Fig. 2. Reflectance at the air gap of the GaAs//Si structure with 10, 20, and 100 nm gap thickness for light with different incident angles.

Photon recycling efficiency

Based on the angle-dependent reflectance, we discuss the photon recycling efficiency in the GaAs subcell. Note that in single-junction solar cells, the probability densities of escape from the front are determined by the angle-dependent Fresnel coefficients for specular reflection and transmission at the front and back interfaces [1]. To evaluate the reflectance efficiency of the luminescence at the rear surface of the top subcell, we calculated the reflectance efficiency at the rear surface of the top GaAs subcell for incident light with random distribution, R, as

$$R = \int_0^{\pi/2} R(\theta)\sin\theta d\theta \cdot \qquad (3)$$

From Eq. (3), we obtained a total reflectance efficiency for the GaAs//Si structure with air gaps [Fig. 3]. The reflectance values are the averages of the transverse-electric (TE) and transverse-magnetic (TM) modes. For infinite gap thickness, only 3.7% luminescence is transmitted thus more than 95% is reflected at the GaAs/air interface. In contrast, in the case of zero gap thickness, no reflection of the luminescence appears because of zero refractive index difference. For 10 nm gap thickness, more than 30% of luminescence is reflected at the rear surface of the top GaAs subcell, and thus a part of the reflected luminescence is re-absorbed at the GaAs subcell, resulting in the enhanced minority carrier density and open-circuit voltage.

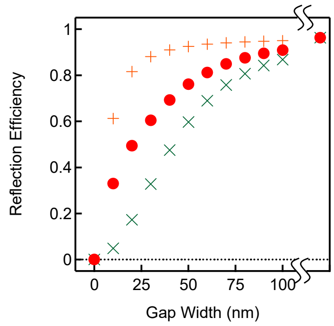

Fig. 3. Reflection efficiency for luminescence at the rear surface of the GaAs top subcells as a function of air gap thickness.

3. Conclusions

We investigate the impact of nanometer air gaps between the subcells on photon recycling effect in mechanically stacked multijunction solar cells. The photon recycling and luminescent coupling efficiencies depend strongly on the air gap thickness, which is a key parameter of tuning luminescent effects in multijunction solar cells. The similar approach can be used to calculate the photon recycling in the lead halide perovskite/Si multijunction solar cells.

Acknowledgements

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