

Thin silicon interference solar cells for targeted or broadband wavelength absorption enhancement

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Abstract: We present the concept of interference solar cells reliant on spectrum filtering or splitting to enhance absorption in thin ($<13\ \mu\text{m}$) silicon absorber layers, both for targeted wavelengths and broadband absorption. Absorption enhancement in the long wavelength regime is achieved by fine-tuning of device layer thicknesses to provide destructive interference between reflected and escaped waves. We suggest this concept is also suitable for broadband absorption enhancement when combined with spectrum splitting optics through gradual thickness changes laterally across the device. Using the example of silicon heterojunction solar cells, we have computationally demonstrated a short circuit current density enhancement of 19% (from $25.8\ \text{mA}/\text{cm}^2$ to $30.7\ \text{mA}/\text{cm}^2$) compared to a silicon heterojunction cell of the same absorber layer thickness.

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1. Introduction

Silicon has been dominating the photovoltaic (PV) industry since its beginnings in the 1970s [1,2]. Despite the rise of numerous alternative technologies, more than 90% of newly installed PV plants are still silicon-based [2] and these are likely to remain the most deployed PV technology. In recent years, great effort has been devoted to decreasing the silicon absorber thickness [3–11]. This stems from both economic motives—as Si contributes an average of 14% to the total \$ per Watt costs of assembled modules across relevant cell technologies [12]—as well as electrical performance and mechanical functionality incentives. Decreased thickness has been shown to improve open circuit voltage and fill factor of silicon (heterojunction) solar cells [4,6,11]. Additionally, for thicknesses approximately $10\ \mu\text{m}$ or smaller, silicon becomes mechanically flexible and can be cut with scissors [9,13,14], enabling fabrication of flexible modules.

However, silicon is an indirect semiconductor and therefore exhibits poor absorption for low energy photons—thinner absorber layers exacerbate this issue. Poor absorption results in low external quantum efficiency and thereby, significant losses of short circuit current density. To ensure complete absorption of the above-band-gap solar spectrum, the path length of light within the silicon must be increased. Strategies that increase the path length and mitigate photon escape are referred to as light trapping methods. It can be shown that for cells with a thickness significantly greater than the involved wavelength and coherence length, i.e., in the ray optical regime, optimum light trapping is achieved for perfect randomization of the light direction [15]. In this case and for weakly absorbing conditions the path length enhancement amounts to $4n^2$, where n is the refractive index of the medium [15]. The formula has to be modified when accounting for strongly absorbing conditions [16]. In silicon solar cells, this ray optical limit can be approached by texturing the front and rear side of the silicon solar cell with random pyramids [17]. Texturing can be achieved via anisotropic KOH etching, and the resulting pyramids are

typically on the order of 1–5 μm . While this approach works well for standard silicon solar cells, smooth surfaces pose several benefits. For example, textured surfaces become problematic if the silicon absorber thickness is reduced to a value close to the pyramid size, or if a different material is integrated on top, such as in perovskite [18] or III-V tandem solar cells. An on-chip integrated photonic power converter would require an additional processing step to obtain a textured surface. In these cases, a smooth front and even rear surface might be required. Smooth surfaces also facilitate surface passivation allowing enhanced open circuit voltage. Enhancing absorption in thin silicon with a smooth surface has previously been achieved through coupling into guided modes via gratings [19], photonic crystals [20,21] and nanowire arrays [22], or through restricting escape [23,24]. In strongly absorbing media, it has been shown that coupling into an optical cavity can lead to near-unity absorption [25]. However, in the weakly absorbing regime, i.e., long wavelength absorption in silicon, strict interference conditions must be met for each involved wavelength separately. In some applications such as for data transmission, only one specific wavelength is employed and the solar cells acting as photonic power converters have to be optimized for only one targeted wavelength [26–28]. Similarly, solar cells used in combination with luminescent solar concentrators (LSCs) only need to operate with narrow spectrum light [29]. For broad spectrum light, enhancing absorption through interference can only be successful through spectrum splitting optics and subsequent optimization per wavelength. Spectrum splitting optics such as gratings also enable multibeam interference requiring temporal coherence [30,31]. The spatial separation of the different wavelengths provides narrow bandwidth light with temporal coherence, where the product of bandwidth and coherence time amounts approximately to unity [31,32].

In this paper, we present the computational design of a smooth front and rear surface silicon solar cell, which provides enhanced light trapping in the long wavelength regime through a wavelength-tuned optical cavity. A silicon heterojunction (SHJ) solar cell architecture is chosen to demonstrate this concept, as SHJs offer high V_{OC} , high current densities, and are the present single-junction, Si-based efficiency record technology. For a system in which we adjust the layer thickness for each wavelength, we demonstrate a short circuit current density enhancement of 4.9 mA/cm^2 (+19%) for a cell with a gradient absorber layer thickness between 8.8 μm and 12.9 μm . Design parameters are highly tunable, allowing fabrication for multiple solar cell applications, including non-SHJ devices.

2. Design of the interference silicon heterojunction solar cell

To enhance internal light intensity in a solar cell, the superposition of waves reflected at layer interfaces should cancel external to the cell. This is the goal of the interference solar cell. The light intensity inside the solar cell is enhanced and in the best case, all this light is fully absorbed. In a standard thick absorber solar cell, this interference-induced enhancement is performed by a simple wavelength/4 ($\lambda/4$) antireflection coating. The wave reflected on the first interface and the wave reflected on the second interface will cancel out if the refractive indices are chosen appropriately. This principle is schematically shown in Fig. 1(a) using a SHJ solar cell layer stack, which includes crystalline silicon (c-Si) passivated by 10 nm intrinsic a-Si (i-a-Si) on the front and rear. Selective contacts are created through 10 nm p-doped a-Si (p-a-Si) on the rear and 10 nm n-doped a-Si (n-a-Si) on the front. ITO on both front and rear simultaneously serves as a charge transport and optical antireflection layer. The portion of the wave reflected on the air/indium tin oxide (ITO) interface (Fig. 1(a), ray 1) and the wave reflected on the ITO/Si interface (Fig. 1(a), ray 2) have a relative phase difference of $\lambda/2$ and will destructively interfere. The third ray (of sufficiently high energy) that enters the (sufficiently thick) crystalline silicon will be fully absorbed. Since the solar spectrum contains a broad range of wavelengths, the described destructive interference conditions are not met for all wavelengths in the spectrum. Instead, the optimum λ to produce the highest current density from the Si absorber layer is found through

weighting the wavelength-dependent absorption with the solar spectrum. In SHJ solar cells, usually an ITO thickness of ~ 70 nm is used [33]; this fulfills destructive interference conditions for $\lambda = 580$ nm wavelength and it is also the optimum when weighting the wavelength-dependent absorption with the solar spectrum.

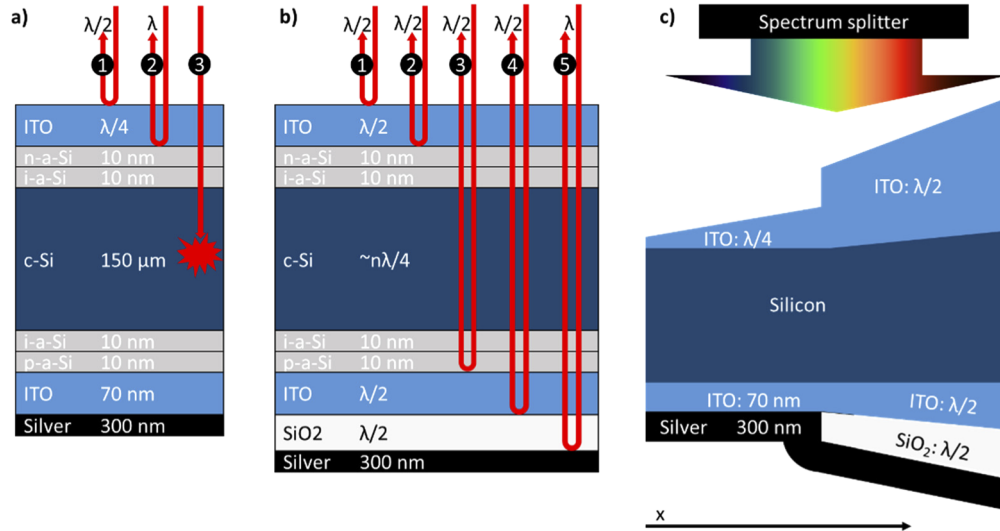


Fig. 1. a) Schematic of a standard SHJ solar cell stack with a $\lambda/4$ antireflection coating operating in strong absorption regime. b) Light trapping (LT) design and resulting phase relation for waves reflected on each interface presented for the case of thin and weakly absorbing conditions, considering a single impinging wavelength. c) Schematic of the solar cell for broadband light absorption enhancement. A spectrum splitter separates the wavelengths in a continuous manner with increasing wavelength in increasing x -direction. The layer thicknesses increase respectively to maintain proper phase relation.

However, this scenario cannot occur for long wavelengths in thin crystalline silicon. For a thickness of $10\ \mu\text{m}$, light with wavelength >670 nm will not be fully absorbed. These long wavelengths will pass through the solar cell, reflect on the rear mirror, and eventually escape out the front surface. This is shown in Fig. 1(b). In this weakly absorbing regime, it is necessary to design the layer thicknesses such that all reflected wave components, including the escaped ones, cancel out by destructive interference. The approach shown in Fig. 1(b) will be referred to as the light trapping (LT) design. The interference conditions can only be met for one wavelength at a time and the design must be adjusted for each wavelength in the spectrum. In our study, we used a layer stack mimicking the materials used in a SHJ solar cell. We include an additional SiO_2 at the rear between ITO and the silver rear mirror to lower reflections. This will potentially suppress plasmonic parasitic absorption by optically separating the higher refractive index ITO from the silver and allows increased tunability in the optical design—however, our general design also works without this SiO_2 layer. Figure 1(b) schematically indicates reflections occurring on each interface by a red arrow. This is a simplified picture; in reality, multiple reflections occur at each interface. For example, light that enters the ITO and is reflected by the silicon will not completely escape but can be partially reflected on the air/ITO interface. In our computational design, we employ the finite difference time domain (FDTD) method to account for all these reflections.

In Fig. 1(b), only the final resulting components that eventually escape out the front are shown. While it is not possible to quantify their magnitude without accounting for multiple reflections, the phase difference can easily be determined from the layer thicknesses. The relative phase is shown on each arrow, without counting integer multiples of λ . In this schematic, we assume

reflection at the a-Si/c-Si interfaces is negligible due to 1) the very thin a-Si layer thickness and 2) the nearly identical refractive indices of a-Si and c-Si. However, our simulations take these layers explicitly into account, as this is crucial for quantifying parasitic absorption. While an intuitive quantification of each component is not possible, a qualitative assessment can be performed. For weakly absorbing conditions, the escaped ray (Fig. 1(b), ray 5) will have the highest intensity. To cancel out this ray, all other components require a phase difference of $\lambda/2$ as shown in Fig. 1(b). Counterintuitively, this means it is better to have a $\lambda/2$ reflection coating to obtain high reflection by the front that cancels out the escape. For very weakly absorbing conditions, a specific silicon thickness is required to absorb and lower the intensity of ray 5 so it does not dominate compared to the other components. Depending on the magnitude of the different components, it may be beneficial for ray 3 and 4 to have a phase difference of λ and ray 5 to have a phase difference of $\lambda/2$. To find the optimum optical performance for a single wavelength, we simulate the c-Si absorption, reflection, and parasitic absorption of the ITO, a-Si, Ag, and SiO_2 as a function of c-Si thickness.

So far, we have presented the principle of interference SHJ solar cells for a single wavelength in the regime where silicon is weakly absorbing. To meet the inference conditions, each layer requires a specific thickness related to the wavelength within the medium. Such an approach is intrinsically not suited for broadband application. It is instead necessary to use spectrum splitting optics such as prisms and gratings to separate the impinging spectrum into its individual components and design the solar cell respectively. In other words, at each location x (Fig. 1(c)), a monochromatic, temporally coherent wave will be incident and layer thicknesses must be designed accordingly. In the following, we only focus on the design of the solar cell, as the design and application of spectrum splitters has been extensively discussed in literature [34–37].

To design the broadband interference solar cell, we assume spectrum splitting optics that lead to a gradually increasing wavelength in the x -direction as shown in Fig. 1(c). It should be noted, that the use of photon energy conserving spectrum splitting or concentrator optics in solar energy conversion technologies generally requires direct sunlight and sun tracking. As explained above, there is a wavelength regime in which light that enters the c-Si will be fully absorbed. In this case, the ITO has to be designed as an antireflection coating, with the thickness corresponding to $\lambda/4$ of the wavelength within the medium. We chose the rear ITO to be 70 nm as this is commonly used in SHJ solar cells and does not influence the optical properties for fully absorbing conditions. Once the threshold wavelength where the c-Si is no longer fully absorbing is reached, layer thickness gradients that offset photon escape for longer wavelengths are introduced laterally in the stack. This can be done in two different ways: 1) by designing a reflection coating, i.e. changing the front ITO thickness to $\lambda/2$ or 2) by adjusting both front and rear ITO thickness while introducing an SiO_2 layer, the latter providing more design flexibility. The design in Fig. 1(c) uses option 2). The c-Si thickness must also be graded to provide the required optical path length.

Note that Fig. 1(c) is only presenting a schematic on the functioning principle. In reality, the thickness depends on wavelength and refractive index, as the wavelength within the medium determines the optical path length difference. Hence, layer thickness changes might not be as trivial as displayed here. We will present an example of realistic layer thicknesses below. In the following, we are presenting calculations for individual wavelengths. The design of a full device with gradient layer thickness would also depend on the electrical properties, which we did not model in this work.

3. Optical performance of an interference solar cell

To assess the optical properties of our interference solar cell, we performed 2-dimensional finite difference time domain (FDTD) simulations using the commercial software Lumerical. For the SHJ solar cell, we used the same material refractive index data as in [24]. The simulations used a

mesh size of 4 nm of auto, non-uniform type and 0.0129324 fs time step. A monochromatic planewave light source was incident from the top of the simulation cell (same orientation as schematics in Fig. 1) and simulations were performed for light with wavelengths between 300 nm and 1100 nm in 20 nm steps. We chose perfectly matched layers as boundary conditions for the top and bottom, and periodic boundaries for the left and right to represent a spatially extended, free-standing solar cell.

We set the thickness of ITO, a-Si, and SiO₂ layers to correspond to either $\lambda/4$ or $\lambda/2$ and swept the c-Si thickness to find an optimum in absorption. At 840 nm and a thickness of 10 μm or thinner, the escape is significant which is detrimental for the short circuit current density due to the high solar flux in this wavelength regime. Therefore, parameters were chosen to obtain 90% absorption at a wavelength of 840 nm. This optimization resulted in a c-Si thickness of approximately 9.5 μm . This thickness ensures that the intensity of the escaping wave is low enough to be cancelled out by the front reflection while simultaneously, the optical path length difference provides destructive interference outside of the solar cell.

In Fig. 2(a), the c-Si thickness-dependent absorption within c-Si, reflection/escape, and parasitic absorption are presented, using an example calculation performed for 840 nm wavelength light. Reflection and escape cannot be separated as they result from the superposition of all involved partial waves. An absorption peak of 91.9% occurs at a thickness of 9555 nm, while rapidly decreasing to 25.9% at 9500 nm. This demonstrates the significant influence of the optical path length difference on absorption for incident wavelengths of 840 nm.

The decrease of c-Si absorption both above and below 9555 nm thicknesses is caused almost entirely by an increase in reflection, as seen in Fig. 2(a). Figure 2(a) also shows the parasitic absorption within all layers; maximum parasitic absorption coincides with the maximum of absorption within the c-Si. At these wavelengths, reflection accounts only for 0.2% of the losses and hence, the requirements for complete destructive interference outside of the solar cell were almost perfectly met.

We also investigated the detailed nature of the parasitic absorption, shown in Fig. 2(b). The a-Si passivation and selective contacts do not contribute to the parasitic absorption for such long wavelengths, where parasitic absorption is solely originating from front and rear ITO, SiO₂, and silver. ITO absorption in the infrared originates from free carriers [38]. While the front ITO absorption remains relatively constant for all c-Si thicknesses, the rear ITO absorption increases significantly at the resonance condition, and even surpasses the front ITO contribution to parasitic absorption. The strongest absorption occurs within the silver and the second strongest in the SiO₂. This suggests an optical cavity is created by the rear ITO/SiO₂/silver stack, with absorption enhanced through the creation of surface plasmons at the respective interfaces. The parasitic absorption within all a-Si layers is negligible at 840 nm.

As seen in Fig. 2, the optimum c-Si thickness to absorb 840 nm wavelengths is 9555 nm. This thickness corresponds to approximately 41.49 times the wavelength within the c-Si. In order to optimize a design for broadband spectral absorption rather than a single wavelength (e.g., 840 nm), precise thickness parameters for the optical path length should ideally be determined. However, the 40 nm of a-Si necessary for a SHJ solar cell complicates determining whether the total silicon stack yields an odd or even number of $\lambda/2$ for the optical path length. For our broadband absorption design, we fixed the c-Si thickness to be 41.49λ in combination with the light trapping structure for all wavelengths between 780 nm and 1100 nm. By choosing a constant multiple of the wavelength, we ensure that the resulting c-Si thickness will be a gradient without exhibiting discrete steps. Such steps could lead to scattering, as well as complicate fabrication. For wavelengths <780 nm, we adjusted only the antireflection coating to be $\lambda/4$ for each wavelength and otherwise kept all layer thicknesses constant. In this short wavelength regime, the c-Si thickness was set to 8767 nm. This is the thickness used for the threshold wavelength of 780 nm and facilitates a smoother transition between the short-wavelength-optimized regime

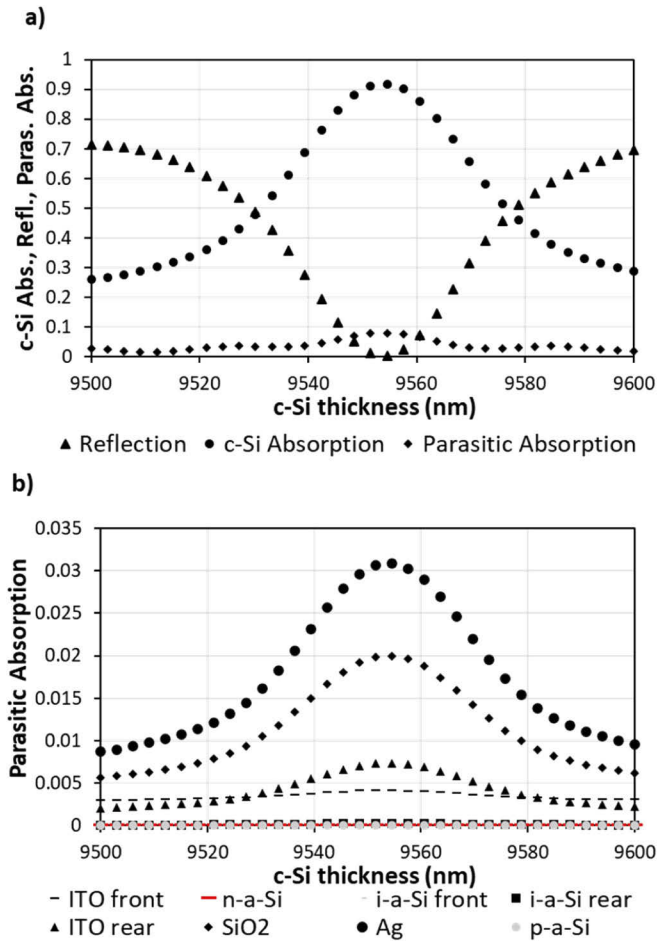


Fig. 2. a) Absorption within c-Si, overall reflection/escape, and parasitic absorption depending on the crystalline silicon thickness. b) Parasitic absorption in each individual layer. The parasitic absorption within all a-Si layers is negligible at 840 nm.

and long-wavelength-optimized regime. All resulting layer thicknesses are presented in Fig. 3. Note that 8000 nm were subtracted from the c-Si thickness to allow visualization of all layer thicknesses in a single plot. In the simulations, each wavelength was simulated separately; a full device with gradient thickness was not modeled.

The real and imaginary refractive indices of c-Si, SiO₂ and ITO are presented in Fig. 3(b) and 3(c). The real refractive index of SiO₂ stays nearly constant in the investigated regime, so thickness changes proportionally with the wavelength. Similarly, the real refractive index of silicon is nearly constant between 780 nm and 1100 nm, meaning the thickness also increases linearly. The real refractive index of ITO changes with the wavelength, and therefore the ITO increase is not strictly proportional to the wavelength increase. The imaginary refractive index of c-Si drops with increasing wavelength explaining the decreasing absorption coefficient. The ITO imaginary refractive index first drops due to decreased interband transition but then increases again due to free-carrier absorption. The imaginary refractive index of SiO₂ always stays lower than 0.004 but is not zero. This means that with strong field enhancement, such as in the case for surface plasmon polaritons, absorption within the SiO₂ is possible.

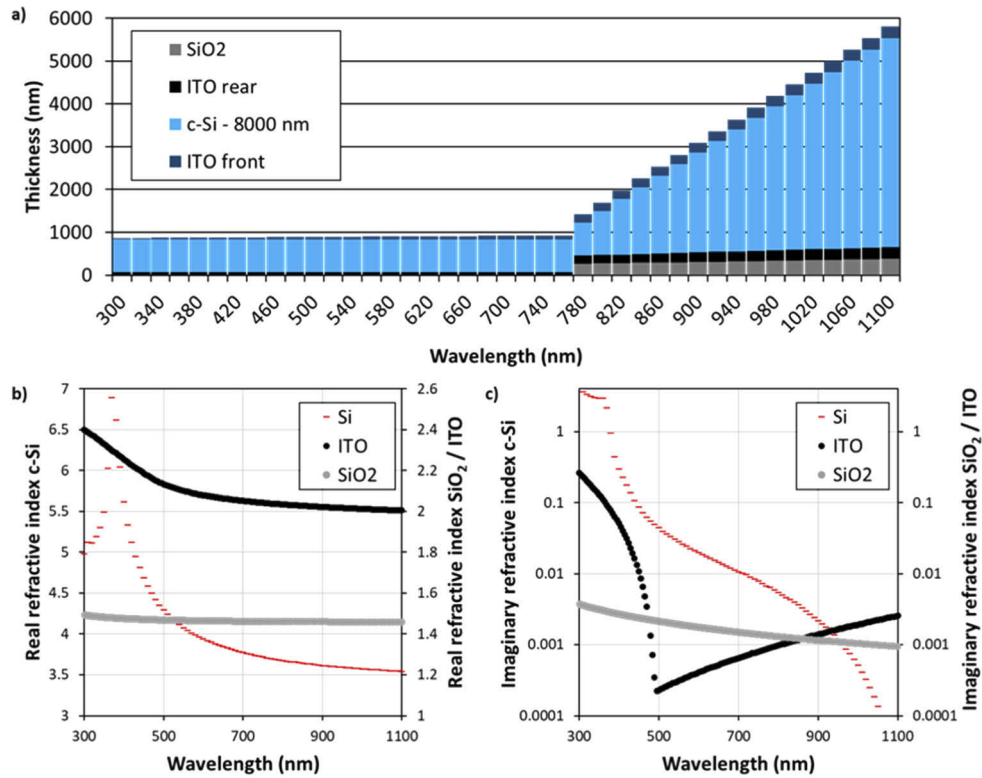


Fig. 3. a) Thicknesses for each wavelength as used to calculate data presented in Fig. 4. Note that 8000 nm were subtracted from the c-Si values for graphical presentation with other layer thicknesses. b) Real and c) imaginary refractive index of c-Si, ITO and SiO₂ used in the simulations.

In Fig. 4(a) the absorption within c-Si, the reflection/escape, and the parasitic absorption are presented for two different thin SHJ solar cell designs. The black markers refer to a cell without the light trapping (LT) structure, i.e., without the approach described in Fig. 1(b). The rear ITO was kept at 70 nm for all wavelengths, but the front ITO was adjusted to be $\lambda/4$ for each wavelength respectively. The c-Si thickness was kept constant at 8767 nm for wavelengths < 780 nm, as explained above. Between 300 nm and 600 nm wavelengths, the results follow a similar trend as for standard thick SHJ solar cells, as the light is absorbed within the first few micrometers of the structure. Losses are primarily dominated by parasitic absorption (components detailed in Fig. 4(b); discussed below). Beyond 660 nm, light is no longer fully absorbed in the c-Si, with both escape and interference effects starting to occur. Thus, the absorption begins decreasing, and the discontinuous absorption decreases observed in Fig. 4(a) can be explained by interference. Starting at 660 nm the c-Si absorption, reflection/escape, and parasitic absorption for a structure with a LT design are presented using red markers. This structure uses a $\lambda/2$ front ITO reflection coating as well as $\lambda/2$ ITO and SiO₂ in the rear. At wavelengths < 840 nm, front reflection dominates, but for > 840 nm, the escape dominates. Figure 4(a) also shows that 780 nm is the shortest wavelength for which the LT structure performs better than a $\lambda/4$ AR coating, and hence, 780 nm was used as the transition wavelength between the two regimes.

Parasitic absorption plays a substantial role for wavelengths > 840 nm. In Fig. 4(b) the parasitic absorption in each individual layer is presented for the design shown in Fig. 3(a), i.e., 1) regime 300 nm-760 nm: no LT and a $\lambda/4$ coating, 2) regime 780 nm-1100 nm LT and $\lambda/2$ coating. Black

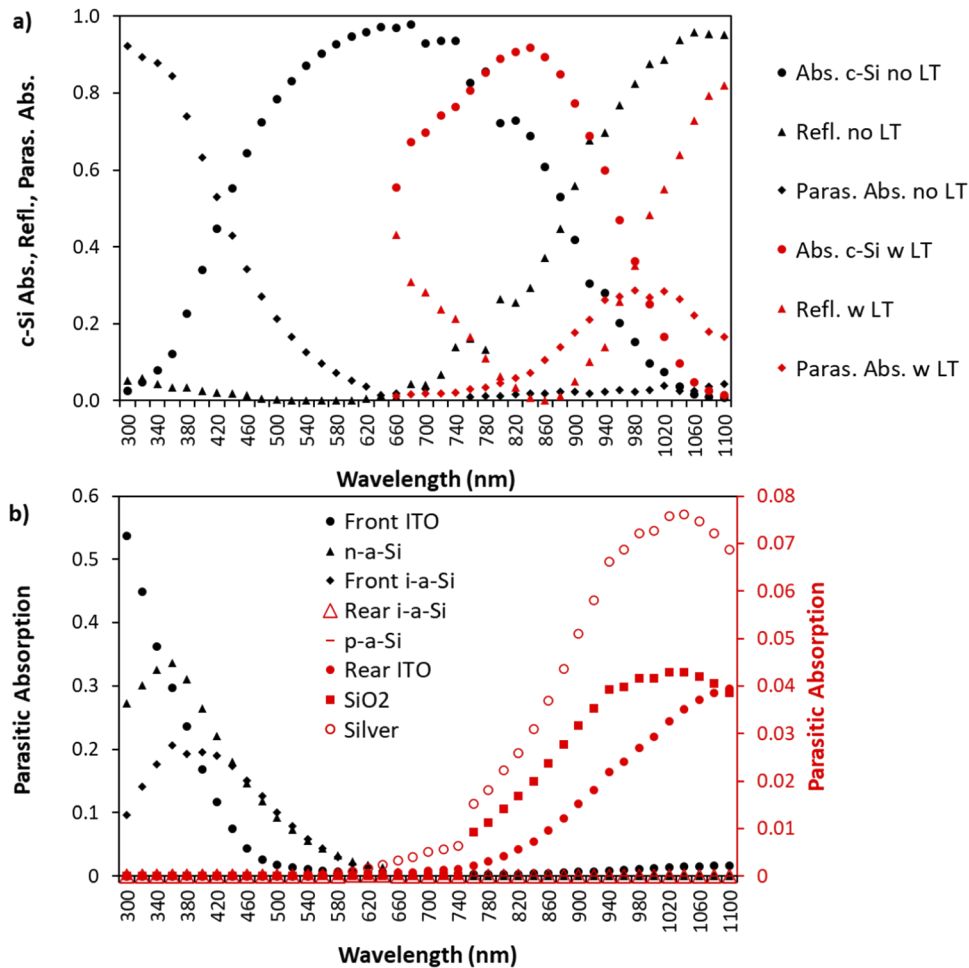


Fig. 4. a) Wavelength dependent absorption within thin c-Si (c-Si Abs.), overall reflection/escape (Refl.), and parasitic absorption (Paras. Abs.). Black markers refer to the layout without light trapping (LT) structure, using ITO with thickness $\lambda/4$ adjusted for each wavelength, and constant thickness of c-Si (8767 nm), rear ITO (70 nm), and silver (300 nm). The red markers refer to the results with light trapping structure, i.e. $\lambda/2$ ITO in front and rear, and SiO₂ between the rear ITO and Ag. b) Parasitic absorption in each individual layer for the design shown in Fig. 3. Black markers refer to the left y-axis, red markers refer to the right y-axis.

markers refer to the left y-axis and red markers refer to the right y-axis. For short wavelengths, the parasitic absorption is dominated by front ITO, n-a-Si and front i-a-Si, which is consistent with previous studies [33]. The absorption occurs through interband transitions within the ITO and a-Si layers. Between approximately 600 nm and 660 nm the parasitic absorption becomes almost negligible, but then increases for longer wavelengths due to free carrier absorption within the ITO and silver. This is consistent with the results of the layer stack optimized for 840 nm absorption shown in Fig. 2(b), which may suggest an optical cavity and plasmon enhanced absorption at the rear ITO/SiO₂/Ag stack enhance the parasitic absorption in our design.

To quantify the advantage over conventional optical designs, we compared the results of our structure with several different scenarios. We obtained data on the transmission through the front layers into the c-Si without any interference contributions from the c-Si by using the online solver OPAL2 from PV Lighthouse. In this solver, thin films are treated with a Maxwell equation solver, while the propagation of light through c-Si is considered to be of ray optical nature. This is an accurate treatment for broadband light and c-Si thickness larger than the coherence length of unfiltered sunlight. Subsequently, we calculated the absorption based on single pass, dual pass and $4n^2$ absorption enhancement for different c-Si thicknesses. This approach does not take parasitic absorption in the rear into account, which causes an overestimation of the total absorption calculated by OPAL2. In Fig. 5(a) the wavelength dependent absorption is plotted for our design as described in Fig. 3(a) and for a cell with the same c-Si thickness but with constant front ITO of 70 nm and either single pass, dual pass or $4n^2$ absorption enhancement inside the c-Si. Note that the $4n^2$ enhancement is merely plotted for comparison. It does not constitute a physical limit, but a broadband enhancement approaching the $4n^2$ has not previously been demonstrated in such thin, non-textured silicon. Exceeding $4n^2$ enhancement in a narrow wavelength regime has been demonstrated with various photonic strategies for specific wavelengths [23,39]. Our design exceeds $4n^2$ enhancement at the design wavelength of 840 nm but also provides broadband enhancement between 780 nm and 1100 nm. In the short wavelength regime, our design suppresses reflection due to adjusting the $\lambda/4$ AR coating for each wavelength respectively. This is also seen in Fig. 5(b) which presents 1-reflection for the same cases as presented in Fig. 5(a). Reflection is almost completely suppressed in our design between 300 nm and 680 nm and near 840 nm. Figure 5(a and b) show that our design provides a significant improvement compared to a cell with the same c-Si for which no LT strategies are performed.

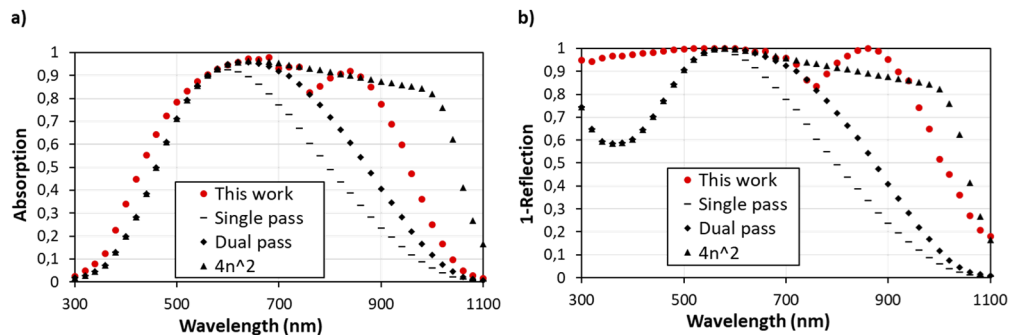


Fig. 5. a) Absorption and b) 1-reflection of silicon assuming transmission into c-Si as simulated using PV Lighthouse Opal2 and the same c-Si thickness as in Fig. 3 for each wavelength respectively, in the case of single pass (dashes), dual pass (diamonds), and with $4n^2$ path length enhancement. The circles show absorption (a) and 1-reflection (b) for the design presented in this work.

To quantify these results further, we determined the short circuit current density by assuming all photons absorbed in the c-Si of the SHJ contribute one electron-hole pair and all parasitically

absorbed photons do not contribute to the current density. Different scenarios yielding the current density are shown in Table 1.

Table 1. Description of different SHJ solar cell designs and their respective calculated short circuit current densities.

LT scheme \ Si thickness	180 μm	8767 nm	12885 nm	Gradient according to Fig. 3(a)
No reflection, full absorption	43.1 mA/cm ²	43.1 mA/cm ²	43.1 mA/cm ²	43.1 mA/cm ²
4n ² LT	39.7 mA/cm ²	33.4 mA/cm ²	33.8 mA/cm ²	33.8 mA/cm ²
Flat front and rear, single pass		21.6 mA/cm ²	23.8 mA/cm ²	21.9 mA/cm ²
Flat front and rear, dual pass		25.3 mA/cm ²	27.0 mA/cm ²	25.8 mA/cm ²
$\lambda/4$ AR coating		27.4 mA/cm ²	29.3 mA/cm ²	
$\lambda/4$ AR coating & interference LT				30.7 mA/cm ²

Perfect absorption of the AM 1.5G spectrum between 300 nm to 1100 nm yields a maximum current density of 43.1 mA/cm². A 180 μm thick SHJ solar cell with random pyramid front texture and 4n² absorption enhancement would generate a short circuit current density of 39.7 mA/cm², which was simulated with the OPAL2 calculator of PV Lighthouse (which, as noted, is an over-estimate as it does not properly account for parasitic absorption at the rear of the solar cell). A SHJ solar cell with 8767 nm thickness, standard constant AR coating and perfect rear mirror (i.e., dual pass light path length as noted in Table 1) would generate 25.3 mA/cm². Adjusting the ITO to be $\lambda/4$ for each respective wavelength enhances the generated current density to 27.4 mA/cm². Including our proposed design with a graded Si thickness and LT architecture achieves a current density of 30.7 mA/cm² (where parasitic absorption is properly accounted for).

We can similarly compare the current density improvements of our design over those of an SHJ solar with a 12885 nm thick absorber layer, which is the thickest portion of our proposed, graded c-Si device. An SHJ with this thickness and an ideal back mirror (i.e., dual pass) would generate 27.0 mA/cm². Including the $\lambda/4$ AR coating yields 29. mA/cm², % less than the 30.7 mA/cm² achieved in our full design (which features far thinner Si for a majority of the absorber layer gradient).

If the thickness of the c-Si is adjusted as in our design and the same light trapping scenarios to calculate absorption in Fig. 5 are used, resulting current densities are 21.9 mA/cm² for single pass, 25.8 mA/cm² for dual pass and 33.8 mA/cm² for the hypothetical case of 4n² absorption enhancement (as shown in the last column of Table 1).

4. Discussion of the results

Overall, our spectrum splitting light trapping design enhances the short current density of a structure with the same graded silicon absorber thickness and ideal rear mirror by 19% from 25.8 mA/cm² to 30.7 mA/cm² (and indeed is slightly >19%, as the 25.8 mA/cm² does not account for parasitic absorption in the rear of the cell, whereas the 30.7 mA/cm² does). As a note, evaluating current densities of our proposed design to those of a cell with constant Si absorber thickness does not provide a physically consistent comparison of the improvements provided by the overall light trapping design. The majority of our design features $\leq 10 \mu\text{m}$ thin silicon and therefore, a solar cell fabricated with such a design would be mechanically flexible. By keeping the front and rear smooth, the c-Si/a-Si interface area is minimized, which decreases surface recombination

and results in higher open circuit voltage. The fabrication of such thin silicon and thin SHJ solar cells has been demonstrated previously [6–8,40].

Comparing these results to previously reported values, Pathi et al. computationally demonstrated up to 30 mA/cm² for 20 μm cells in which the crystalline silicon was not textured [41]. Yan et al. experimentally demonstrated for a 20 μm cell 24.7 mA/cm² without texture, 31.7 mA/cm² with standard texture, and 32.5 mA/cm² with nanoarray rear texture [42]. Yang et al. reported 34.6 mA/cm² for a nanotextured silicon solar cell with effective thickness of 2 μm [10].

Nevertheless, the presented design is not trivial, as layer thicknesses change throughout the device. For a given wavelength, the optimum Si thickness range of the LT design is quite narrow, as can be seen in Fig. 2. It is always possible to broaden the response by removing layers, such that less beams participate in the interference. The ideal scenario depends on the type of technology and application that is desired. Here, we wanted to show excellent current generation at specific wavelengths in a SHJ solar cell. As one other example, in a standard back surface field silicon solar cell, significantly less layers would participate in the interference which would lead to less narrow response. In our example, all layer thicknesses scale with the wavelength in first order approximation. Therefore, slight inaccuracies in the manufacturing process can later be compensated by proper positioning of the spectrum splitting optics. In the design presented here, the ITO thickness gradient also needs to be compatible with the silicon thickness. The accuracy with which the ITO thickness and optics need to be aligned depends on the length scale over which the thickness gradient occurs, i.e. the length of the x-axis in Fig. 1(c). The shorter this length scale, the more accurate the assembly needs to be. On the other hand, smaller features also mean smaller and less bulky optical components which could be an economic advantage. This trade-off needs to be assessed in a thorough feasibility and techno-economical study which is beyond the scope of this paper. The length scale over which the thickness changes occur also affects the electrical properties. The photon flux within the solar spectrum strongly depends on the wavelength. Therefore, different areas of the cell will receive different photon flux which will lead to position dependent charge carrier injection levels. Photon fluxes fluctuating on micrometer scale do not influence the macroscopic device properties of SHJ solar cells. This is seen from studies in which front contacts either partially shade or enhance illumination [43]. If the flux fluctuation occurs on length scales comparable or larger than the diffusion length of charge carriers, the front contact design will play an important role in the overall device performance. There will also be an interplay between front contact layout and ITO thickness. It might be possible to reduce the number of fingers if the cell can be designed such that the area with the thinnest ITO lies in the center between two front contacts and the ITO thickness increases closer to the contacts, where more current has to be carried. For a quantitative analysis accounting for all electrical effects, a three-dimensional distributed resistance equivalent circuit model, such as SPICE [44], needs to be employed.

Thickness gradients during thin film growth are readily attainable in various vapor phase deposition techniques. For example, the use of a non-rotating substrate holder during sputtering results in tunable thickness gradients laterally across a substrate, and is a common method for rapidly achieving large sets of oxide films with composition gradients proportional to (co)sputtered thickness gradients [45–48]. Techniques such as liquid-phase-crystallized Si can be leveraged to obtain 5–40 μm thin silicon with excellent V_{OC} obtained by high quality surface passivation [49]. Other promising pathways for kerfless, high quality (i.e., respectable lifetime), thin Si absorber layers include various spalling [50–52] or epitaxial growth [53] methods. Such thinly spalled or grown layers can undergo etching to obtain the necessary thickness gradients without significant material loss. For SiO₂ linear increases in thickness have been demonstrated [54–56]. The ITO refractive index changes with wavelength and the changes are not linear. While this complicates the optimal ITO thickness profile maintaining precise ITO thicknesses is not crucial in the $\lambda/4$ AR coating regime as there are only two waves interfering which inherently leads to a broad peak.

5. Summary and conclusions

We have introduced the concept of interference solar cells to enhance absorption in thin ($<13\ \mu\text{m}$) silicon absorber layers, both for targeted wavelengths and broadband absorption in combination with spectrum splitting optics. Using the example of silicon heterojunction (SHJ) solar cells, we have demonstrated both short wavelength and long wavelength absorption enhancement compared to a SHJ cell with the same silicon thickness. Absorption enhancement in the short wavelength regime was achieved through a $\lambda/4$ antireflection coating optimized for each wavelength by gradually changing the thickness. In the long wavelength regime, a $\lambda/2$ reflection coating and a rear light trapping structure of $\lambda/2$ ITO and $\lambda/2$ SiO_2 were introduced. This long wavelength design structure is showcased for an example wavelength of 840 nm; for a c-Si thickness of $9.6\ \mu\text{m}$, 840 nm wavelength light is nearly fully absorbed by having reflection and escape cancel out through destructive interference. For a broadband device weighted with the solar spectrum, we calculated a short circuit current density enhancement of 19% (from $25.8\ \text{mA}/\text{cm}^2$ to $30.7\ \text{mA}/\text{cm}^2$) compared to a standard device with the same c-Si thickness gradient. The presented design is highly tunable allowing optimization for various (silicon) solar cell technologies and for specific fabrication requirements. The presented simulation methods did not investigate the light intensity distribution within the device layers, giving another route for further enhancements through this novel design.

As the economics of silicon solar manufacturing pushes for thinner silicon layers, our approach provides a means to significantly enhance absorption to offset inherent decreases when using thinner absorption layers, enabling higher efficiency thin solar cells. While manufacturing of lateral thickness gradients across a device stack may prove challenging, the tunability of the presented design allows for a vast set of applications and parameters specific to manufacturing needs.

Acknowledgments. RS acknowledges tenure track start-up funding provided by the University of Twente.

Disclosures. The authors declare no conflicts of interest.

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