

Counterbalancing light absorption and ionic transport losses in the electrolyte for integrated solar water splitting with III-V/Si dual-junctions

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ABSTRACT

Recently, significant progress in the development of III-V/Si dual-junction solar cells has been achieved. This not only boosts the efficiency of Si-based photovoltaic solar cells but also offers the possibility of highly efficient green hydrogen production via solar water splitting. Using such dual-junction cells in a highly integrated photoelectrochemical approach and aiming for upscaled devices with solar-to-hydrogen (STH) efficiencies beyond 20%, however, the following frequently neglected contrary effects become relevant: (i) light absorption in the electrolyte layer in front of the top absorber and (ii) the impact of this layer on the Ohmic and transport losses. Here, we initially model the influence of the electrolyte layer thickness on the maximum achievable solar-to-hydrogen efficiency of a device with an Si bottom cell and show how the top absorber bandgap has to be adapted to minimize efficiency losses. Then, the contrary effects of increasing Ohmic and transport losses with the decreasing electrolyte layer thickness are evaluated. This allows us to estimate an optimum electrolyte layer thickness range that counterbalances the effects of parasitic absorption and Ohmic/transport losses. We show that fine-tuning of the top absorber bandgap and the water layer thickness can lead to an STH efficiency increase of up to 1% absolute. Our results allow us to propose important design rules for high-efficiency photoelectrochemical devices based on multi-junction photoabsorbers.

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Hydrogen produced from water and sunlight offers the potential to significantly contribute to the decarbonization of the energy sector on a global scale.^{1,2} One possible route toward solar hydrogen is photoelectrochemical (PEC) water splitting. In short, a dual-junction photoabsorber immersed in an electrolyte captures the incident sunlight, generates a photocurrent as well as a photovoltage, and drives the oxygen and hydrogen evolution reactions at the respective semiconductor–electrolyte interfaces. Despite decades of research, however, no material system was demonstrated that fulfills all of the following requirements for a commercially viable PEC system: (i) a lifetime on the timescale of years, (ii) high abundance of the absorber and catalyst materials, and (iii) a high solar-to-hydrogen (STH) efficiency. The latter is especially important, since efficiency becomes a key factor determining the hydrogen production cost, when the balance of system (BOS) and land costs shift away from the materials costs. Moreover,

technoeconomic analyses imply that only highly efficient PEC water splitting might compete with the technologically more mature approach of powering an electrolyzer by photovoltaics via the grid.³ The current record PEC device with respect to efficiency is based on a GaInP/GaInAs dual-junction cell, reaching 19% STH.⁴ However, the relatively low stability and the high cost of the required GaAs-substrate are currently preventing practical applications.^{5,6}

One possible way to significantly reduce the cost of III-V-based devices is to replace the GaAs-substrate with Si that also acts as a bottom absorber.^{6–8} Indeed, demonstrated efficiencies of III-V/Si multi-junction photovoltaic solar cells have significantly increased in recent years. Also for integrated solar water splitting, there has been an increased interest for this approach over the last few years.^{8,9} In 2018, Cariou *et al.* achieved a photovoltaic conversion efficiency of 33.3% with a wafer-bonded two-terminal GaInP/GaAs/Si solar cell under

AM1.5G illumination, which was further improved to 34.1%.^{7,10} Only recently, a new record of 35.9% was achieved using a wafer-bonded two-terminal GaInP/GaInAsP//Si cell.¹¹ Direct growth of the III-V cell(s) on top of a Si bottom cell offers potential cost and scalability benefits but is also more challenging due to defects at the III-V/Si interface, which is why achieved efficiencies are still lower than those reported for the wafer-bonding approach.^{12,13} These developments pave the way for the development and fabrication of III-V/Si dual-junction cells for solar water splitting that promise similar high efficiencies as recent PEC record devices. Moreover, there has been significant progress in perovskite/Si dual-junction devices,^{14,15} which are also considered potential candidates for highly efficient solar water splitting. It should, however, be noted that the long term stability of direct or integrated approaches is still a major challenge that needs to be addressed before III-V/Si or perovskite/Si photoelectrochemical dual-junction cells can reach large-scale commercial applications.¹⁶

With STH efficiencies above 20% within reach, a number of effects become relevant that are frequently neglected in lower-efficiency devices, but cannot be ignored when approaching the physical limits. In a dual-junction, two-terminal cell, the two absorbers are connected in series and the overall efficiency is determined by the absorber with the lowest current (current matching). Hence, the efficiency is highly sensitive to changes in the solar spectrum. In any PEC

device, the incident light has to pass through a—typically aqueous—electrolyte before reaching the absorber. Since water absorbs near-infrared light, the effective illumination spectrum onto the cell deviates from the AM1.5G spectrum. Efficiency losses are, therefore, unavoidable and can be even more emphasized when the bandgaps of the multi-junction cells are perfectly matched to the AM1.5G spectrum instead of to the effective spectrum.^{16–19} An obvious strategy to minimize the parasitic absorption in the electrolyte is to decrease the water layer thickness in front of the absorber. However, with the decreasing electrolyte thickness, Ohmic and transport losses may in turn decrease the efficiency representing a typical non-linear optimization problem, leading to a global maximum of the theoretical efficiency as a function of the electrolyte layer thickness. Due to the current-matching condition in a monolithic dual-junction, this will then directly impact the ideal bandgaps of photoabsorbers.

In this work, we deconvolute the effects of the electrolyte layer thickness on the efficiency of a III-V/Si dual-junction device. Therefore, we initially investigate the influence of the electrolyte layer thickness on the maximum achievable solar-to-hydrogen efficiency and show how the top absorber bandgap has to be adapted to minimize efficiency losses under idealized conditions. Next, we model the Ohmic and transport losses with the decreasing electrolyte layer thickness. We use experimental III-V//Si dual-junction device data (as the

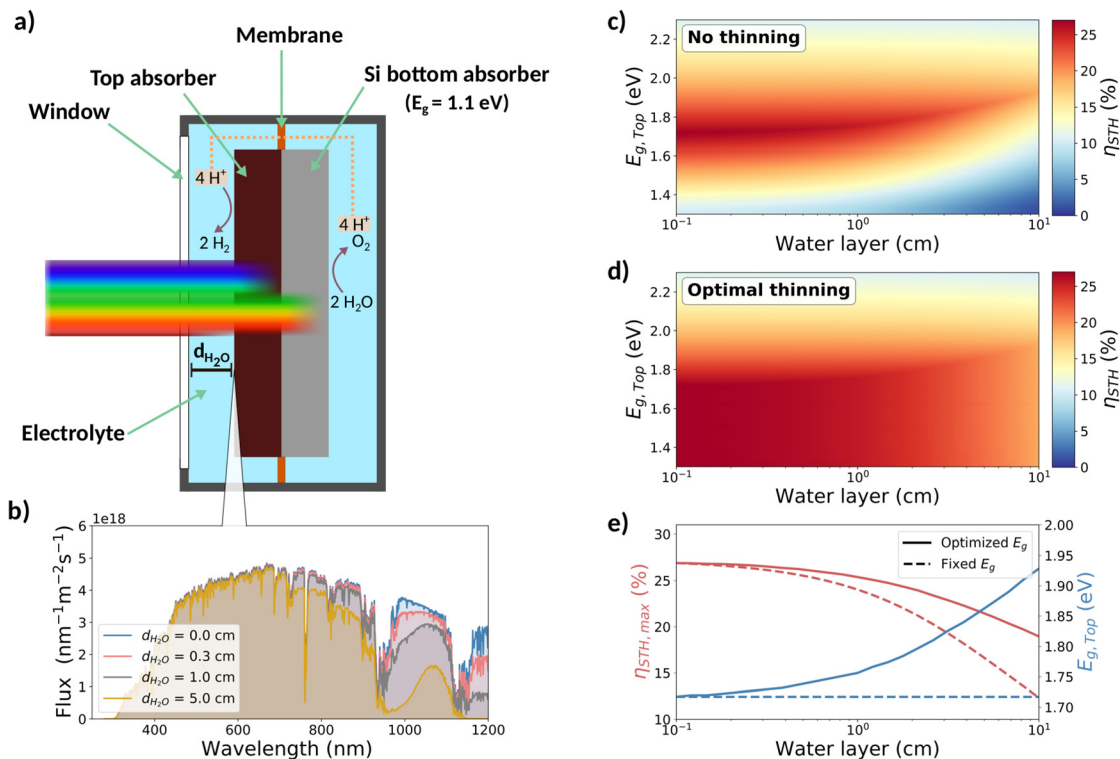


FIG. 1. (a) Sketch of a dual-junction cell for PEC solar water splitting indicating the absorption of the incident light in the electrolyte. (b) Effective AM1.5G spectra (reference data from the American Society for Testing and Materials²²) modified by the water layer (absorption data from Refs. 20 and 23) with different thicknesses hitting the top absorber of the dual-junction cell. (c) STH efficiencies modeled for an ideal case as a function of the water layer thickness and the top absorber bandgap from the detailed balance limit and Pt- and IrO_x-catalyst characteristics without thinning of the top absorber, and (d) with optimal thinning. (e) Maximum achievable STH efficiency for a fixed (dashed lines) and optimized (solid lines) top absorber bandgap as a function of the water layer thickness. The Ohmic cell resistance is assumed to be constant in all calculations (i.e., water layer thickness-independent).

performance target for directly grown III–V/Si) and combine the effects of parasitic absorption and Ohmic/transport losses. We hereby show that fine-tuning of both the top absorber bandgap and the water layer thickness can enable an absolute STH efficiency increase in up to 1%.

Figure 1(a) shows a sketch of a monolithic dual-junction PEC device with Silicon as a bottom absorber, indicating the near-infrared light absorption in the electrolyte under AM1.5G illumination. The effective spectra that reach the cell as a function of the water layer thickness in the relevant wavelength-range ($E_{g,\text{Si}} = 1.1$ eV, i.e., 1127 nm) is shown in Fig. 1(b). Even a thin water layer of 0.3 cm decreases the effective intensity for wavelengths >980 nm. When the water layer thickness is 5 cm, the intensity is drastically decreased for wavelengths >700 nm. The absorption coefficient stays finite also for lower wavelengths,²⁰ but the effect becomes negligible as water layers of several cm are practically not reasonable, also due to the resulting weight of the device. However, it emphasizes the need for a reliable benchmarking protocol for the characterization of PEC multi-junction devices in the lab.²¹

To initially only assess the influence of light absorption in the electrolyte layer on the device efficiency, a constant (i.e., water layer thickness-independent) Ohmic cell resistance is assumed in our calculations shown in Figs. 1(c)–1(e). This ideal case scenario that is modeled with our open-source Python package YaSoFo²⁴ is based on the following conditions: highly efficient Pt- and IrO_x catalysts (see Fig. S1 for I–V-characteristics), neglected concentration overpotentials, open circuit voltages obtained from the detailed balance limit, IV solar cell characteristics following the single diode equation, and an operating temperature of 25 °C (see the supplementary material Table S1 for full list of input parameters and the YaSoFo documentation for full model description²⁴). Figure 1(c) shows the STH efficiency as a function of the top absorber bandgap and the water layer assuming that all photons with an energy higher than the bandgap are absorbed and contribute to the photocurrent. The same plot in which the thickness of the top absorber is allowed to be optimized from growth to be not fully absorbing (i.e., “thinned”) so that more photons can reach the Si bottom absorber to ensure current matching conditions is shown in Fig. 1(d). The maximum theoretical efficiency decreases with the increasing water layer thickness from 26.9% (0.1 cm), 26.3% (0.4 cm), and down to 18.9% (10 cm). This represents an intrinsic efficiency loss in the photoelectrochemical solar water spitting approach. The red dashed line in Fig. 1(e) shows the higher efficiency losses, when the top absorber bandgap is not adapted to the water layer thickness (blue dashed line). Interestingly, Figs. 1(c) and 1(d) imply that there are two ways to minimize these losses and reach the maximum theoretical efficiency: (i) decrease the thickness of the top absorber so more photons can reach the Si bottom absorber or (ii) increase the bandgap of top absorber [solid blue line in Fig. 1(e)]. While both approaches have the same maximum achievable efficiency for a given catalyst performance, the latter would increase the photovoltage allowing for higher Ohmic losses in the device, or the use of less catalyst loading or catalysts with a lower activity, respectively.

To model the influence of the water layer thickness on voltage losses, we used a simplified 2D cell geometry as shown in Fig. 2(a). The calculations assume a stagnant 1 M HClO₄ electrolyte, a more realistic operation temperature of 40 °C, no membranes, and anodes that are placed on the sides of the cell. Note that this highly idealized cell geometry does not represent a practical water splitting device (e.g.,

no safe product separation). However, it gives a first impression on the voltage losses associated with a thin water layer. Note that the size of the gas bubble plume²⁵ creates another boundary condition for the minimum thickness of the water layer, but this is currently neglected in the model. To assess the Ohmic losses and concentration overpotentials in the cell, the steady-state conservation, Nernst–Planck (diffusion and migration), and the concentration-dependent Butler–Volmer equation were solved employing the finite element method in COMSOL Multiphysics (see the supplementary material note 1 and Table S2 for more details and input parameters, respectively).

As expected, our calculations show that the voltage losses (sum of the Ohmic and concentration overpotentials) increase with the decreasing electrolyte thickness and increasing cathode size [see Fig. 2(a)]. This is caused by the reduced cross section of the conductive water layer leading to higher Ohmic losses and mass-transport

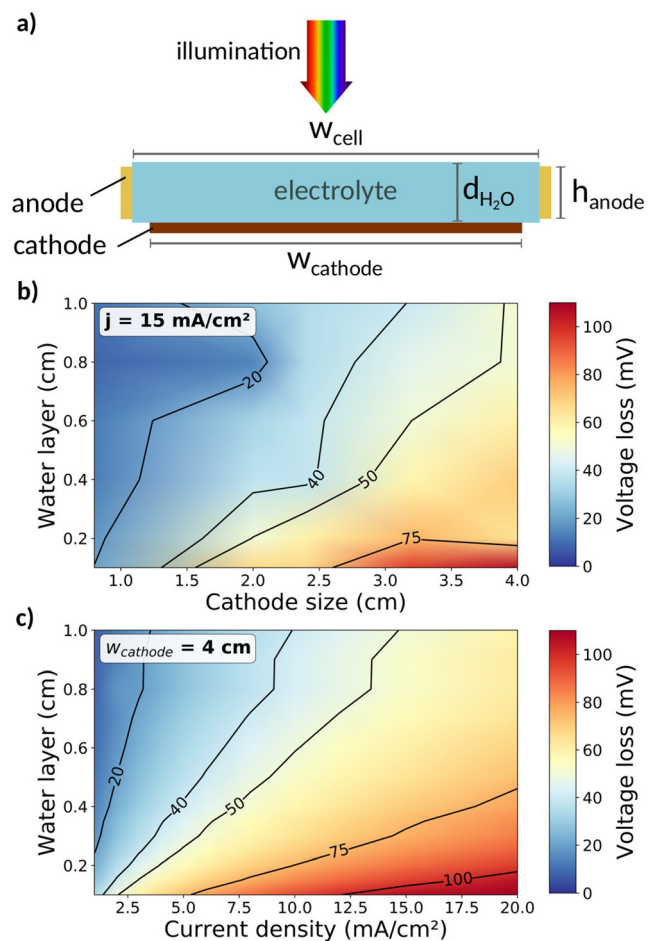


FIG. 2. (a) Sketch of the idealized 2D cell geometry used for the modeling indicating the dimensions and arrangement of the cathode, the anodes, and the electrolyte. (b) Sum of the Ohmic and concentration voltage losses for a constant current density of 15 mA/cm² as a function of the cathode size simulated with COMSOL. (c) Respective calculations varying the current density for a constant cathode size of 4 cm. The individual contributions of the Ohmic and concentration losses are shown in supplementary material Fig. S2.

limitations. For example, the voltage loss doubles from 51 to 106 mV while decreasing the water layer thickness from 1 to 0.1 cm for a fixed current density of 15 mA/cm^2 and a cathode size of 4 cm. For smaller cathode sizes, the voltage losses also double, but the absolute losses are lower. These results emphasize the need for PEC device configurations that allow short ion path lengths. Since the absolute voltage losses increase with the increasing cathode size, this is especially important for upscaled devices. The influence of the current density shown in Fig. 2(c) also reveals the expected trend: The voltage losses increase with the increasing current density and decreasing water layer thickness. For a cathode size of 0.4 cm, the voltage loss increases from 58 to 116 mV with decreasing water layer thickness from 1 to 0.1 cm for a current density of 20 mA/cm^2 . Note that the individual contribution of Ohmic and concentration losses is similar in the considered parameter space (see the [supplementary material](#) Fig. S2).

In order to determine the optimal condition, we now combine the two effects of the electrolyte layer: parasitic light absorption and the voltage losses caused by the Ohmic and concentration overpotentials. For a more realistic analysis, experimental state-of-the-art III-V//Si dual-junction device data instead of the previously employed detailed balance limit is used. Figures 3(a) and 3(b) show the IV characteristics under AM1.5G illumination and the external quantum efficiency (EQE) spectrum of an AlGaAs//Si solar cell, respectively. The AlGaAs top absorber ($E_g = 1.75 \text{ eV}$) was joined with the Si bottom absorber via wafer bonding resulting in photovoltaic conversion efficiencies of up to 29.1% (see Ref. 10 for experimental details). In the

calculations shown in Figs. 3(c)–3(f), the experimental IV and EQE data are used as an input to inter alia account for parasitic absorption, recombination losses, as well as Ohmic and finite shunt resistances in the absorber (see the [supplementary material](#) note 2 and Table S1 for full list of input parameters). The assumed operating temperature of 40°C is implemented via the temperature coefficient of the open circuit voltage. Note that for an even more realistic device modeling, the optics of the total stack (i.e., air/window/water/catalyst/protection layer/absorber) as well as the exact cell geometry would have to be considered. However, this is out of the scope of the current study and is left for future work.

Figure 3(c) shows the STH efficiency based on the experimental AlGaAs//Si cell characteristics as a function of the top absorber bandgap (no thinning) and the water layer thickness without taking the additional voltage losses due to a thinner water layer into account. The extracted maximum STH efficiency and the associated top absorber bandgap is illustrated in Fig. 3(d). As expected, the calculations show a similar trend as those shown in Fig. 1(c) based on the detailed balance limit. However, a lower maximum STH efficiency of 20.5% is achieved for the smallest considered water layer of 0.1 cm. Figures 3(e) and 3(f) show the respective calculations considering the additional voltage losses caused by the thinned water layer from Fig. 2(c). The effect is clearly visible. The overall maximum achievable STH efficiency has shifted away from the lowest considered water layer thickness of 0.1 cm to a value of around 0.7 cm. In this thickness region, the effects of the parasitic absorption and voltage losses are counterbalanced. Figures 3(e) and 3(f)

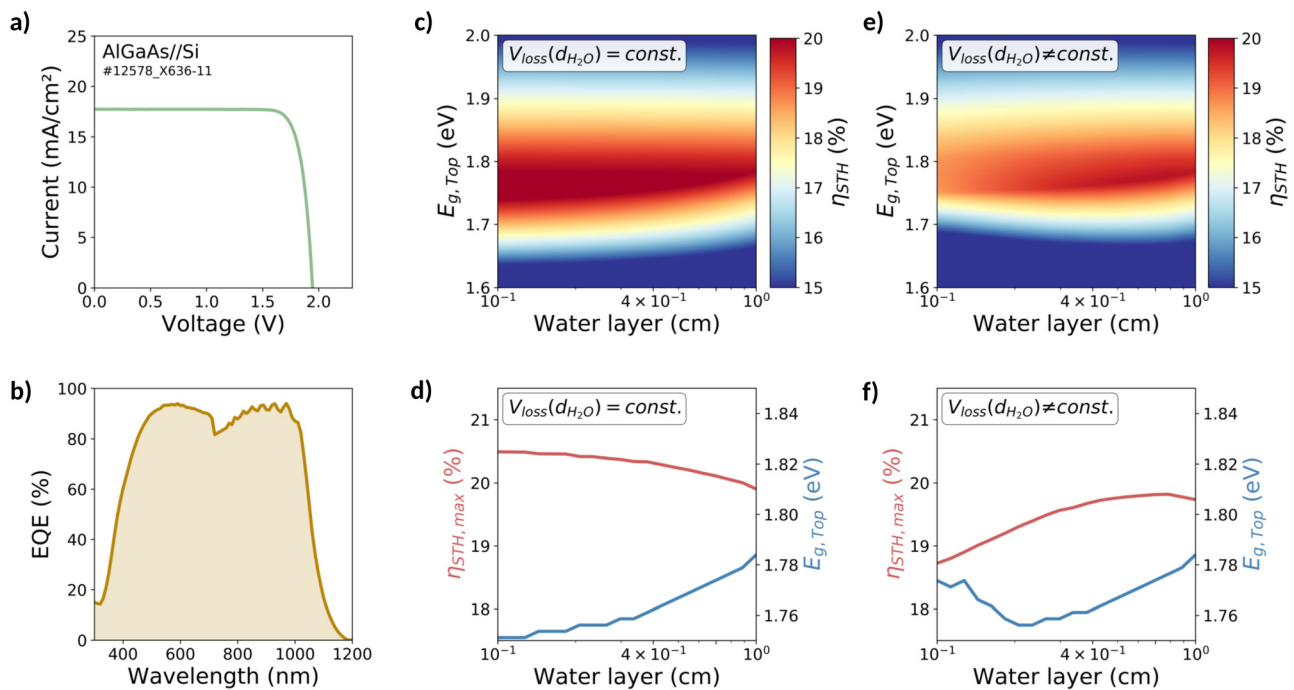


FIG. 3. (a) I–V characteristics under AM1.5G illumination of a AlGaAs//Si solar cell prepared by wafer bonding measured in the Fraunhofer ISE CalLab. (b) Sum of the EQEs of the two subcells measured at Fraunhofer ISE CalLab. (c) STH efficiencies modeled by YaSoFo²⁴ as a function of the water layer thickness and the top absorber bandgap assuming a constant voltage loss. (d) Extracted maximum efficiency and the associated top absorber bandgap. (e) and (f) Respective calculations considering the voltage losses modeled with COMSOL shown in Fig. 2(c) for a cathode size of 4 cm. All calculations were performed without the possibility of top absorber thinning. Full list of input parameters and the resulting two-electrode water splitting IV characteristics are shown in [supplementary material](#) Table S1 and Figs. S3 and S4, respectively.

reveal the important conclusion that fine-tuning of both the top absorber bandgap and the water layer thickness can lead to an absolute STH efficiency increase on the order of 1%.

Another parameter that influences the trade-off between parasitic light absorption and ion transport losses in the water layer, which was not discussed until now, is the two-electrode water splitting catalyst performance (see Fig. 4). In the model, the catalyst performance was varied by changing the exchange current density of the oxygen evolution reaction (OER) catalyst (x-axis), while keeping the exchange current density of the hydrogen evolution reaction (HER) catalyst constant. The resulting kinetic overpotential to achieve a two-electrode water splitting current density of 20 mA/cm^2 is indicated on the upper x-axis as a more tangible value. The red and blue solid lines show the optimized water layer thickness (left y-axis) and the corresponding overall maximum STH efficiency (right y-axis) as a function of the catalyst performance, respectively. For clarification, these values correspond to the maximum of the STH efficiency vs water layer thickness plot shown in Fig. 3(f). Note that each optimized water layer thickness also has a corresponding optimized top absorber bandgap (not shown). Furthermore, the distribution of the current density flowing in the electrolyte is assumed to be not affected by the exchange current density [i.e., the voltage losses shown in Fig. 2(c) are independent of the catalyst performance].

When the overall efficiency is limited by current matching in the dual-junction cell and not by the catalysis, the solar cell generates more voltage than required (larger top absorber bandgap to allow more photons to reach the Si bottom absorber). In other words, the system operates at potentials below the maximum power point (MPP) of the solar cell. This extra voltage, which is otherwise transformed into heat, can be used to counterbalance the voltage losses caused by a thin water layer (see Fig. 2). Hence, maximum STH efficiencies are reached at low water layer thicknesses due to a lower parasitic

absorption for a very good catalyst performance (right-hand side of Fig. 4). If, on the other hand, the catalyst performance is limiting and defines the magnitude of the top absorber bandgap, every additional ion transport voltage losses will lower the maximum achievable STH efficiency. Hence, the maximum efficiency is reached at elevated water layer thicknesses. Note that for a realistic device, it is more likely that the catalyst performance will be the limiting factor. For comparison, the dashed blue line shows the respective maximum STH efficiency when the water layer is fixed, i.e., not adapted to a reduced catalyst performance (dashed red line). The maximum achievable efficiency gains are again on the order of 1% (absolute), when the water layer is optimized with respect to the catalyst performance.

In summary, we modeled and deconvoluted the effect of the water layer on the maximum achievable STH efficiency of a III-V/Si dual-junction device for PEC solar water splitting. We showed that fine-tuning of both the top absorber bandgap and the water layer thickness to counterbalance the effects of parasitic absorption and voltage losses can lead to an STH efficiency increase of up to 1%. Moreover, our study emphasizes the need to explore device designs that minimize the Ohmic and transport losses associated with a thin water layer. This work lays the foundation for the development of a realistic PEC device model. Extending our calculations with experimentally obtained optical properties of the total stack (air/window/water/catalyst/protection layer/absorber), a practical and upscaled cell geometry, and including the influence of convection will be the subject of follow-up work. From a broader perspective, our results give important insights into the challenges of designing any highly efficient multi-junction PEC system, also beyond solar water splitting.

See the [supplementary material](#) for further data as well as the description of the model and all the input parameters.

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DATA AVAILABILITY

The data that support the findings of this study are openly available in Zenodo repository at <https://doi.org/10.5281/ZENODO.1489157>, Ref. 24.

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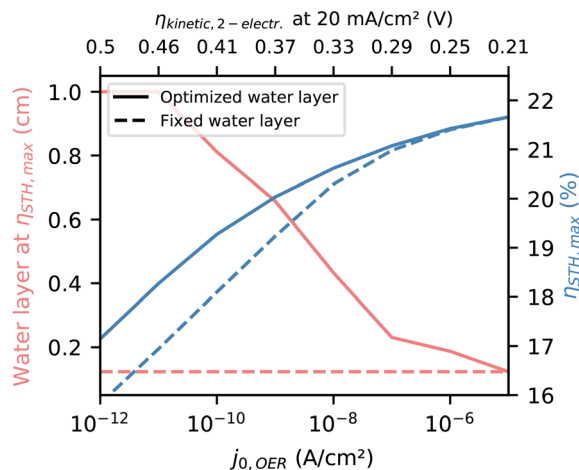


FIG. 4. Water layer thickness (red solid line) for which the overall maximum STH efficiency (blue solid line, right y-axis) is achieved as a function of the OER exchange current density used as a figure of merit for the overall two-electrode catalyst performance. The top x-axis indicates the kinetic overpotential to achieve a two-electrode water splitting current density of 20 mA/cm^2 . The blue dashed line represents the respective maximum efficiency values for a fixed water layer of 0.1 cm.

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