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RESEARCH ARTICLE

Suntulip: New Tool to Simulate Solar Cells

JASURBEK GULOMOV[1], OUSSAMA ACCOUCHE[2], (Associate Member, IEEE), BILEL NEJI[2], AND JAKHONGIR ZIYOITDINOV[1]

[1]Department of Physics, Andijan State University, Andijan 170100, Uzbekistan
[2]College of Engineering and Technology, American University of the Middle East, Egaila 54200, Kuwait

Corresponding author: Jasurbek Gulomov (jasurbekgulomov@yahoo.com)

ABSTRACT The article underscores the role of simulation in solar cell research, focusing on the newly-developed solar cell simulation program, Suntulip, which was written in C#. Given, the escalating significance of solar energy, optimizing solar cell efficiency and reducing costs has become vital for sustainability. Simulation has proven to be extremely efficient and cost-effective method compared to experimental and theoretical approaches. The introduction of Suntulip addresses the lack of a simulation library in C# and its potential contribution to solar cell research. Notably, the program's reliability is substantiated through optical simulations and a comparison with Wafer Ray Tracer, demonstrating accurate and consistent results. The article emphasizes Suntulip's user-friendly interface and versatile capabilities in calculating reflection, transmission, and absorption coefficients, hence providing valuable insights into solar cell behavior. As Suntulip continues to demonstrate its accuracy, it holds promises in advancing solar cell technology and facilitating sustainable energy solutions.

INDEX TERMS Fresnel reflection, simulation, software, refractive index.

I. INTRODUCTION

Maximizing the full potential of solar energy depends on increasing solar cell efficiency and reducing production costs, a critical task in today's pursuit of sustainability. Solar cell research generally employs three main methods [1]: experiments, theory, and modeling. However, experimental research demands substantial time and financial resources, while theoretical analysis encounters limitations in solving complex equations. Enter solar cell simulation, a remarkably optimal research approach. By employing advanced computational techniques, modeling is highly cost-effective and efficient, alleviating the need for extensive financial and temporal investments. Researchers can swiftly propose and evaluate various solar cell structures, expediting the identification of optimal designs [2].

Depending on the subject of research, the appropriate modelling program is selected. Basically, programs are divided into codes and tools that simulate materials and devices. Lumerical TCAD [3], Sentaurus TCAD [4] and Silvaco TCAD [5] programs are widely used in the simulation of semiconductor devices. These programs have the ability to simulate in 3D and 2D dimensions. A total of 338,1497, and 2578 articles in Scopus-indexed journals are published using obtained results in Lumerical TCAD, Sentaurus TCAD, and Silvaco TCAD, respectively. Since Lumerical TCAD is mainly designed for modeling the optical properties of solar cells, which accounts for fewer studies conducted with it. In TCAD programs, the experimentally determined parameters of the materials in the solar cell are mainly taken as input parameters in the simulation of the solar cell. In the simulation of materials, 2 different methods are mainly used: Molecular Dynamics (MD) [6] and Density Functional Theory (DFT) [7]. The material synthesis process is modeled in MD and the material properties are calculated in DFT. In material simulation, coordinates, vectors, pseudopotentials and basis sets of atoms are taken as input parameters. LAMMPS [8] for MD and Quantum Espresso [9], CASTEP [10], VASP [11] codes for DFT are widely used. If the material properties of the solar cell

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are calculated by DFT and entered into TCAD as material properties, a modeling chain from atom to device can be created [12].

The maximum efficiency of solar cells is theoretically determined using the Shockley-Quisser limit (SQ) [13]. The SQ limit determines the maximum efficiency of the solar cell based on the band gap of material. For example, since the band gap of silicon is 1.12 eV, the maximum efficiency of a silicon-based solar cell is 29%. In laboratory experiments, it is equal to 26.81% [14] and in industry 24% [15]. Theoretical studies can mainly optimize the solar cell in a particular case. That is why the results obtained in theory are less likely to be confirmed in experiment. For example, the optimal value of the base angle of the upright pyramidal textures formed on the surface of silicon-based solar cells is 73.120 according to theory and 70.350 according to the results of simulation in Sentaurus TCAD [16]. This is because theoretical analysis primarily considers the solar cell's optical properties, whereas simulations take into account both optical and electrical property variations.

The significance of this article lies in highlighting the paramount importance of simulation, particularly in the realm of solar cell research and development. As previously discussed in the preceding literature, simulation stands as one of the most crucial methodologies in the scientific world today. The emergence of numerous simulation programs, especially those in Python and Matlab, has propelled the advancement of solar cell simulation, fostering broader accessibility and application for researchers. The article goes a step further by introducing a novel solar cell simulation program named Suntulip, expertly developed in C#. By addressing the existing gap of C# libraries for solar cell simulation, Suntulip holds immense potential in facilitating future design projects through its Transfer Matrix Method (TMM) capabilities. The program's adaptability to function as a TMM library further contributes to the expanding repertoire of solar cell simulation tools available in C#, promising to advance the field and drive the solar cell simulation progress.

II. THEORETICAL BACKGROUND OF THE TRANSFER MATRIX METHOD

Fresnel's equations [17] describe the reflection and transmission at the boundary between two media. However, in the case of a layer with a specific thickness, as depicted in Figure 1, the situation becomes more complex. Within this layer, light undergoes nearly infinite reflections and transmissions.

In this case, it is difficult to use Fresnel's laws for each refracted, reflected ray. Because there is light absorption in the layer. We can use linear algebra to solve this easily.

To simplify the images, we change the drawing a little. As shown in Figure 2, we make it appear that the incoming electric field and the outgoing electric field appear on a specific surface.

At the interface, we assume that the electric field is downward and upward. In Formula 1, we express the electric field

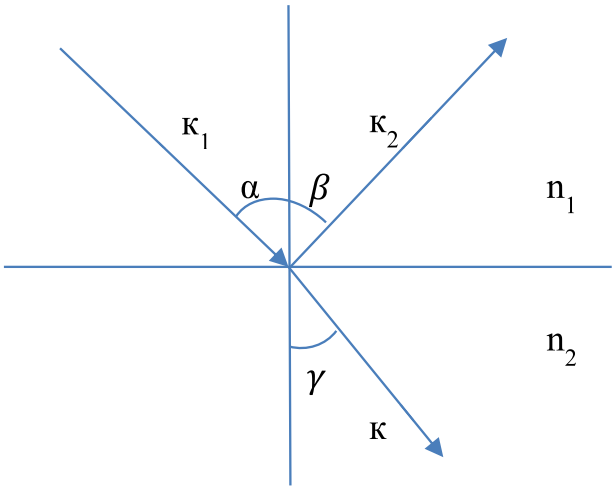

FIGURE 1. Refraction and reflection of light rays on the interface. k_1, k_2 and k_3 are incident, reflected and refracted rays. α, β and γ are angles of incident, reflected and refracted rays with vertical axe. n_1 and n_2 is refractive index of first and second medium.

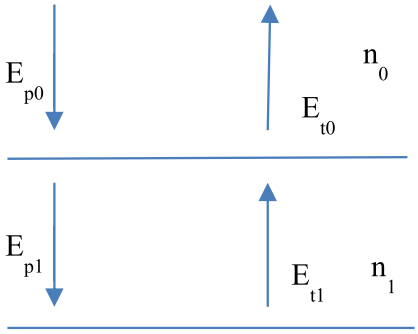

FIGURE 2. A diagram of the expression of a light beam through the electric field. E_{p1} and E_{t1} are electric field of rays going to downside and upside in second medium as well as E_{p0} and E_{t0} are in first medium.

strengths leaving the surface by the incoming ones.

$$\begin{cases} E_{p1} = t_{01} \cdot E_{p0} + r_{10} E_{t1} \\ E_{t0} = r_{01} \cdot E_{p0} + t_{10} E_{t1} \end{cases} \tag{1}$$

Here: t_{01} and t_{10} are Fresnel transmission coefficient as well as r_{01} and r_{10} are Fresnel reflection coefficient for rays going to downside and upside.

Let's put the system in such a state that those in group 0 are separate and those in group 1 are separate. According to the Fresnel formulas, there is a condition given in formula 2 between the Fresnel coefficients of rays of order 0 and 1.

$$r_{01} = -r_{10}, \quad r_{01}^2 + t_{01} t_{10} = 1 \tag{2}$$

Using the conditions given in formula 2, if we change the equation system given in formula 1, a system of equations that can be written in the form of a matrix equation given in

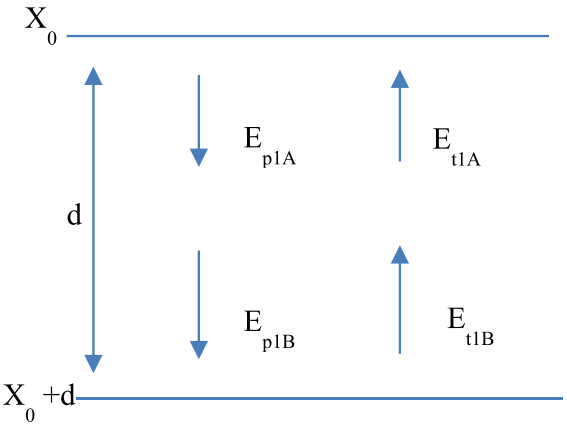

FIGURE 3. Diagram of the representation of the light beam through electric field in the layer. E_{p1A} and E_{p1B} are electric field of entering and exiting downward rays and E_{t1B} and E_{t1A} are that of upward rays. d is thickness of layer. X_0 is coordinate of the front side of layer.

formula 3 is formed.

$$\begin{bmatrix} E_{p0} \\ E_{t0} \end{bmatrix} = \frac{1}{t_{01}} \begin{bmatrix} 1 & r_{01} \\ r_{01} & 1 \end{bmatrix} \begin{bmatrix} E_{p1} \\ E_{t1} \end{bmatrix},$$
$$\frac{1}{t_{01}} \begin{bmatrix} 1 & r_{01} \\ r_{01} & 1 \end{bmatrix} \equiv D_{01} \tag{3}$$

Here: D_{01} is transmission matrix.

It is known that an electromagnetic wave is absorbed when passing through a medium. Let's bring this absorption into matrix form. Figure 3 shows the electric field of rays entering and leaving the layer. E_{PA} is the electric field near the light source, while E_{PB} is located further away from the source. If we consider light falling downward from the top, the electric field at the lower part of the medium is weaker.

E_{P1A} and E_{P1B} can be expressed as a complex function according to the Burger-Lambert law [18] as given in formula 4.

$$E_{P1A}(x) = E_0 \cdot e^{i(\omega t - kx_0)}$$
$$E_{P1B}(x) = E_0 \cdot e^{i(\omega t - k(x_0+d)} \tag{4}$$

Here: ω is frequency of the light, E_0 is amplitude of the electric field, t is time, k is the absorption coefficient of the medium, i is complex number.

Using the functions in formula 4, the relationship between E_{P1A} and E_{P1B} given in formula 5 can be found.

$$E_{P1A} = E_{P1B} \cdot e^{ikd} \tag{5}$$

The relationship between E_{t1A} and E_{t1B} can be determined in the same way as the relationship between E_{P1A} and E_{P1B} above. A system of equations was created between E_{t1} and E_{P1}. The system of equations can be written in the form of a matrix equation given in formula 6.

$$\begin{bmatrix} E_{P1A} \\ E_{t1A} \end{bmatrix} = \begin{bmatrix} e^{ikd} & 0 \\ 0 & e^{-ikd} \end{bmatrix} \begin{bmatrix} E_{P1B} \\ E_{t1B} \end{bmatrix}$$
$$\begin{bmatrix} e^{ikd} & 0 \\ 0 & e^{-ikd} \end{bmatrix} \equiv P_1 \tag{6}$$

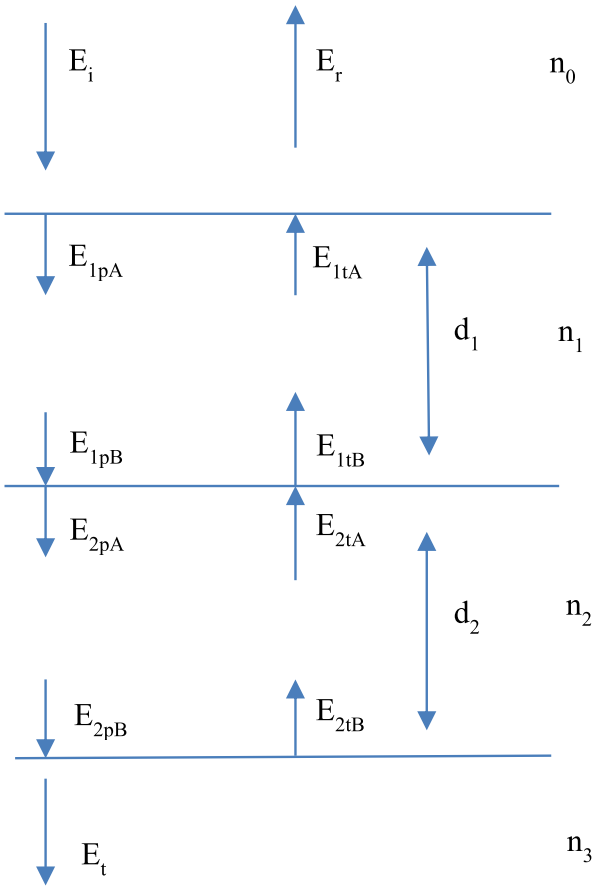

FIGURE 4. Diagram of representation of light in a 2-layer structure by electric field. E_i, E_r and E_t are electric fields of incident, reflected and transmitted rays. d_1 and d_2 are thicknesses of the first and second layers. n_0, n_1, n_2 and n_3 are refractive indices of the media.

Here: P_1 is propagation matrix.

Let's calculate the reflection and transmission coefficients of the 2-layer system given in Figure 4. For this, it is necessary to write the electric field of the rays entering and exiting the layer, as shown in figure 2.

As given in formula 7, we express the relationship between the rays entering and leaving the boundary of each medium by the D matrix and the relationship between the electric field intensity of the rays entering and leaving the layer by the P matrices.

$$\begin{bmatrix} E_i \\ E_r \end{bmatrix} = D_{01} \begin{bmatrix} E_{1PA} \\ E_{1tA} \end{bmatrix}, \quad \begin{bmatrix} E_{1PA} \\ E_{1tA} \end{bmatrix} = P_1 \begin{bmatrix} E_{1PB} \\ E_{1tB} \end{bmatrix}$$
$$\begin{bmatrix} E_{1PB} \\ E_{1tB} \end{bmatrix} = D_{12} \begin{bmatrix} E_{2PA} \\ E_{2tA} \end{bmatrix}, \quad \begin{bmatrix} E_{2PA} \\ E_{2tA} \end{bmatrix} = P_2 \begin{bmatrix} E_{2PB} \\ E_{2tB} \end{bmatrix}$$
$$\begin{bmatrix} E_{2PB} \\ E_{2tB} \end{bmatrix} = D_{23} \begin{bmatrix} E_t \\ 0 \end{bmatrix} \tag{7}$$

By substituting the matrix equation given in formula 7 one after the other, it is possible to determine the relationship

between E_i, E_r and E_t given in formula 8.

$$\begin{bmatrix} E_i \\ E_r \end{bmatrix} = D_{01} \cdot P_1 \cdot D_{12} \cdot P_2 \cdot D_{23} \begin{bmatrix} E_t \\ 0 \end{bmatrix}$$
$$D_{01} \cdot P_1 \cdot D_{12} \cdot P_2 \cdot D_{23} \equiv M \tag{8}$$

Here: M is transfer matrix.

Since D and P matrices are 2nd-order matrices, their mutual multiplication which is M matrix, is also a 2nd-order matrix as given in formula 9.

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \tag{9}$$

Here: M_{11}, M_{22}, M_{21} and M_{12} are elements of transfer matrix.

Previously, we only considered how to calculate a 2-layer optical system using the transfer matrix method. However, if the number of layers is n, then a transfer matrix can be formed by multiplying n D and P matrices. Finally, for n layers, the matrix M given in formula 9 is formed. The required optical parameters are determined using the elements of the M matrix.

Natural light can be divided into two transversal and parallel polarized rays. Therefore, the Fresnel coefficients for both parallel and transversal polarized rays can be written as given in formula 10.

$$\begin{cases} r_{um}^{\perp} = \dfrac{M_{21}^{\perp}}{M_{11}^{\perp}} \\ t_{um}^{\perp} = \dfrac{1}{M_{11}^{\perp}} \end{cases}, \quad \begin{cases} r_{um}^{\parallel} = \dfrac{M_{21}^{\parallel}}{M_{11}^{\parallel}} \\ t_{um}^{\parallel} = \dfrac{1}{M_{11}^{\parallel}} \end{cases} \tag{10}$$

Here: r and t are Fresnel coefficients.

Using the Fresnel coefficients of a parallel and transversal polarized beam, the reflection and transmission of the light from the general optical system can be calculated as given in formula 11.

$$R_{um} = \frac{(r_{um}^{\parallel})^2 + (r_{um}^{\perp})^2}{2}$$
$$T_{um} = \frac{n_{n+1} \cos \gamma_{n+1}}{n_0 \cos \alpha} \left(\frac{(t_{um}^{\perp})^2 + (t_{um}^{\parallel})^2}{2} \right) \tag{11}$$

Here: R_{um} and T_{um} are reflection and coefficients of the optical system, n_{n+1} is refractive index of the media where is downside of the optical system, n_0 is refractive index of the media where is upside of the optical system, γ_{n+1} is refraction angle of the ray where is downside of the optical system.

Considering that the sum of the energy of the reflected, transmitted and absorbed light from optical system is equal to the energy of the incident light. So, the light absorption coefficient in the optical system can be calculated using formula 12.

$$A_{um} = 1 - R_{um} - T_{um} \tag{12}$$

Here: A_{um} is absorption coefficient of the optical system.

III. EXISTENT TOOLS TO SIMULATE SOLAR CELLS

Solcore [19], as a comprehensive open-source solar cell simulation software, possesses several advantages and disadvantages compared to other tools such as SCAPS [20], PC1D [21], TMM-FT [22], TMatrixOpt [23], and OPV Lab [24]. One of its major strengths lies in its incorporation of the Transfer Matrix Method (TMM), allowing for accurate optical modeling of solar cells. Solcore combines TMM with carrier transport and detailed balance, providing a holistic approach for simulating solar cell performance. As an open-source tool, Solcore encourages collaboration and community-driven improvements. This enhances accessibility and flexibility and allows users to tailor the code to their specific research needs. Moreover, Solcore supports various material models and includes a range of optoelectronic device functionalities, making it versatile for different types of solar cells and devices. However, Solcore may have a steeper learning curve for new users due to its feature-rich environment, especially for those who are not familiar with programming or scripting languages. The extensive capabilities of Solcore can lead to complexities in setting up simulations and analyzing results for beginners. Therefore, documentation and user support may be essential to help users navigate and harness the software's full potential effectively.

SCAPS boasts a user-friendly interface and extensive material properties modeling, which can be advantageous for researchers looking for a more straightforward approach to solar cell simulations. PC1D, on the other hand, is known for its focus on silicon solar cells, making it a suitable choice for those working specifically with silicon-based devices. TMM-FT provides a specialized MATLAB-based tool for thin-film optics, offering a user-friendly environment for researchers who prefer working with MATLAB and require optical simulations for thin-film devices. TMatrixOpt offer open-source options with a TMM emphasis, which can be beneficial for researchers seeking transparency, customization, and the ability to modify the code for their unique requirements. Furthermore, OPV Lab excels in its specialization for simulating organic photovoltaic devices, making it an ideal choice for researchers focused on organic solar cells. Its features cater specifically to the complexities of organic materials, which may not be as comprehensive in other more generalized software tools. GPVDM [25] is developed to simulate organic and perovskite solar cells.

Table 1 shows the website of the solar cell simulation software, the number of articles published, the year of the first article, their capabilities, and brief descriptions. The number of articles published based on the results obtained using these programs was sourced from the Scopus database. For instance, using the SCAPS program, a total of 1,942 articles were published in journals indexed in Scopus. This indicates that it is widespread software in simulation of solar cells among 1D-simulation tools due to its straightforward interface and versatile simulation capabilities. For example, if a material's complex refractive index is not available in a solar cell simulation, SCAPS can calculate the photogeneration in

TABLE 1. Various tools developed to simulate solar cells.

Tools	Description	Features/Capabilities	Number of articles	First article published year	Website/Source
Solcore	Open-source solar cell simulation software with optical modeling	Transfer Matrix Method, Carrier transport, Detailed balance	6	2018	Solcore GitHub
SCAPS	Comprehensive solar cell simulator with optical properties	Transfer Matrix Method, Device simulation, Material properties modeling	1942	1999	SCAPS Website
PC1D	Device simulation software with optical modeling for silicon solar cells	Transfer Matrix Method, Device simulation, Silicon-specific models	366	1984	PC1D Website
TMM-FT	MATLAB-based tool for thin-film optics	Transfer Matrix Method, Thin-film modeling	-	-	TMM-FT Mathwok
TMatrixOpt	Open-source software for TMM-based simulation of thin-film optical devices	Transfer Matrix Method, Thin-film optical device design	-	-	TMatrixOpt GitHub
OPV Lab	Software for simulating organic photovoltaic devices (OPVs)	Optical modeling, Charge transport, Material properties	51	2017	OPV Lab Website
GPVDM	Software for modeling and simulation of photovoltaic devices	Device simulation	56	2011	GPVDM Website

that material using the material's bandgap. Since TMM-FT and TMatrixOpt are new tools, articles have not yet been published using results obtained from them in journals indexed in Scopus. However, despite the fact that OpvLab is a new program, the rate of popularity is increasing sharply, as Table 1 shows.

IV. CODES WRITTEN FOR THE SUNTULIP

The core of the code involves intricate matrix operations to compute the optical properties of solar cells. The functions 'otish', 'qaytish', and 'yutulish' play pivotal roles in determining the reflection, transmission, and absorption coefficients, respectively. These coefficients are derived from the input data on the solar cell's refractive indices and other parameters. The code efficiently performs multiple matrix multiplications to calculate intermediate values, which are then used to obtain the final ratios of reflection, absorption, and transmission. This numerical approach offers valuable insights into the behavior of solar cells, enabling researchers to optimize their design for enhanced energy conversion efficiency.

Calculation of Reflection, Transmission, and Absorption Coefficients: In this part, the code calculates the optical constants (tm1, tm2, and tm3) for different solar cell configurations using the 'otish' function. It then populates three matrices (rm1, rm2, and rm3) with specific values derived from these optical constants. Additionally, the code calculates matrix elements for the absorption coefficients (alm1 and alm2) using the 'yutulish' function with different parameters.

```
for (int t = 1; t <= i; t++)
{
 // Calculate optical constants for different solar cell configurations
```

```
    double tm1 = otish(n[0, t], n[1, t]);
    double tm2 = otish(n[1, t], n[2, t]);
    double tm3 = otish(n[2, t], n[0, t]);
    // Populate matrices with calculated values
    double[,] rm1 = {{1 / tm1, qaytish(n[0, t], n[1, t]) / tm1 },
{qaytish(n[0, t], n[1, t]) / tm1, 1 / tm1 } };
    double[,] rm2 = {{1 / tm2, qaytish(n[1, t], n[2, t]) / tm2 },
{qaytish(n[1, t], n[2, t]) / tm2, 1 / tm2 } };
    double[,] rm3 = {{1 / tm3, qaytish(n[2, t], n[0, t]) / tm3 },
{qaytish(n[2, t], n[0, t]) / tm3, 1 / tm3 } };
    // Calculate matrix elements for absorption coefficients
     double[,] alm1 = {{yutulish(k[1, t], d1, l[t]), 0 }, {0,
yutulish(k[1, t], -d1, l[t]) } };
     double[,] alm2 = {{yutulish(k[2, t], d2, l[t]), 0 }, {0,
yutulish(k[2, t], -d2, l[t]) } };
  }
```

Matrix Multiplication to Calculate Optical Properties: In this part, the code performs matrix multiplication to calculate the intermediate values required for reflection, transmission, and absorption calculations. It initializes a matrix y to store the results of the matrix multiplications. The code then performs matrix multiplication of rm1 with alm1, and the result is stored in y. Afterward, the values of y are copied back to rm1. The same process is repeated for the matrix multiplication of rm1 with rm2, and the result is again stored in y.

```
  double[,] y = new double[2, 2];
  for (int f = 0; f < 2; f++)
  {
    for (int u = 0; u < 2; u++)
     {
       for (int h = 0; h < 2; h++)
        {
           y[f, u] += rm1[f, h] * alm1[h, u];
        }
     }
  }
  for (int f = 0; f < 2; f++)
  {
    for (int u = 0; u < 2; u++)
     {
       rm1[f, u] = y[f, u];
     }
  }
  for (int f = 0; f < 2; f++)
  {
  for (int u = 0; u < 2; u++)
   {
    for (int h = 0; h < 2; h++)
     {
      y[f, u] += rm1[f, h] * rm2[h, u];
       }
     }
  }
  for (int f = 0; f < 2; f++)
  {
   for (int u = 0; u < 2; u++)
    {
     rm1[f, u] = y[f, u];
    }
  }
```

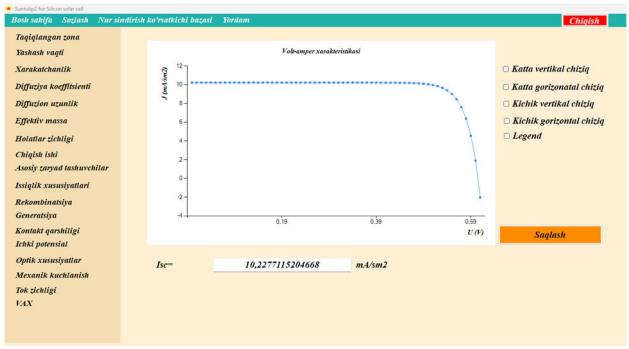

FIGURE 5. Interface of suntulip.

In the final part of the code, optical properties such as reflection, absorption, and transmission coefficients are computed. The results are obtained by iterating through the matrices using a loop operator.

```
double tum = 1 / rm1[0, 0];
tum * = tum;
double rum = Math.Pow((rm1[1, 0] / rm1[0, 0]), 2);
double alum = 1 - rum - tum;
rat[0, t] = rum;
```

V. CAPABILITIES OF SUNTULIP

Suntulip is a simulation software to determine the physical properties of silicon-based solar cells. The program is designed with simple user-friendly interface. making it an ideal choice even for those who do not possess programming skills. It presents a straightforward and convenient means for solar cell simulations.

During a solar cell simulation, a graph, as shown in in Figure 5 appears in the center of the screen. On the left side of the display, user will see a menu strip labeled with the names of the physical features a. By selecting the desired physical characteristic from the left side, the software generates the corresponding value and displays graphs illustrating its dependence on temperature and input concentration. On the right side of the graph, several checkboxes can be used by the user to customize the graph based on their preferences, such as showing the graph with or without grid. Additionally, a ''Save'' button to enable user to store the generated graph on the computer's memory. User has the option to save the graph in two formats - ''png'' and ''jpeg''.

Graphs of dependence of all physical properties on temperature and input concentration are created. And it allows us to save and analyze them and use them where necessary.

In the base of the refractive index, there is a graph of the dependence of the complex refractive index of 132 materials on the wavelength.

TMM was used to calculate the optical properties of the solar cell. This method is particularly adept at simulating

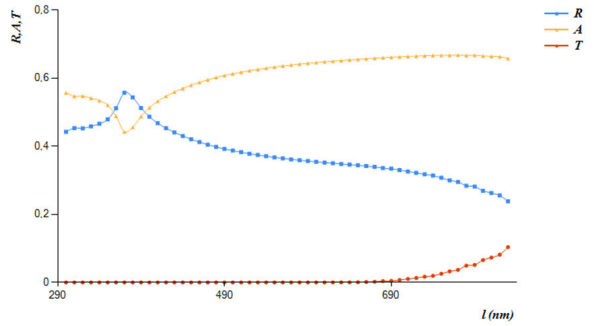

FIGURE 6. Dependence of the absorption, transmission and reflection coefficients of the silicon-based solar cell on the wavelength of light.

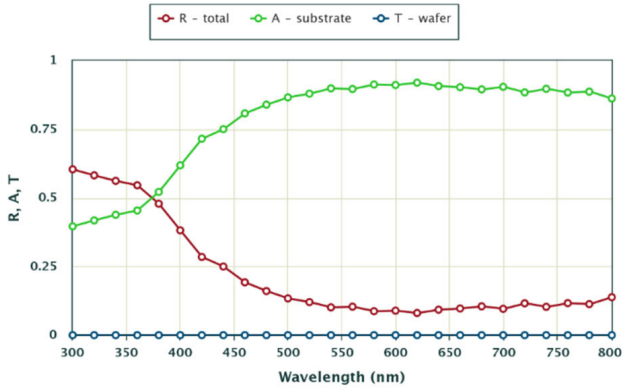

FIGURE 7. Dependence of the absorption, transmission and reflection coefficients of the silicon-based solar cell on the wavelength of light.

planar structures, given its capacity to account for internal interference within the layers. Figure 6 shows the dependence of calculated reflection, transmission and absorption coefficients of a 175-μm silicon-based solar cell coated with a 100 nm thick SiO_2 layer on the light wavelength.

Figure 7 shows the absorption, transmission and reflection coefficients of a 100 nm SiO_2-coated 175 μm silicon-based solar cell as a function of light wavelength, calculated in Wafer Ray Tracer module of PVLightHouse [26].

It turned out that the absorption and reflection coefficients calculated in Suntulip and Wafer Ray Tracer are almost identical depending on the wavelength of light. Remarkably, at a wavelength of 375 nm, there is a peak in the reflection coefficient and a sharp decrease in the absorption coefficient according to the result obtained in Suntulip. However, the Wafer Ray Tracer results did not show such a dramatic increase and decrease.

The refractive index of silicon reaches a maximum of 6.7 at a wavelength of 375 nm [27] and then decreases almost exponentially depending on the wavelength of light. The refractive index of SiO_2 is 1.47, almost constant and independent of the wavelength [28]. According to the refractive index of silicon and SiO_2, at a wavelength of 375 nm, the SiO_2/Silicon structure showed the maximum reflection and the minimum absorption. This phenomenon is consistent with Fresnel's theory, it is known that if the difference in refractive index of two media increases, the coefficient of reflection increases. The largest difference between the refractive indices of SiO_2 and silicon corresponds to the wavelength of 375 nm. Therefore, the results obtained in the Suntulip that we have developed gave more accurate result. Which indicates a higher level of reliability in our software.

Suntulip's distinct edge over Wafer Ray Tracer lies in result accuracy, a critical aspect in solar cell simulation. While both tools offer similar absorption and reflection coefficients at various wavelengths, Suntulip excels in capturing pronounced variations, such as the peak in reflection coefficient and sharp absorption decrease at 375 nm. This discrepancy highlights Suntulip's enhanced accuracy. Recognizing these differences underscores the paramount importance of accurate simulation outcomes, particularly in nuanced scenarios. Suntulip's ability to precisely depict optical behavior at key wavelengths enhances its reliability, guiding design decisions and optimizing solar cell performance with more informed insights.

Suntulip's distinction from SCAPS extends to a pivotal aspect that underscores its versatility. While SCAPS offers the ability to study temperature and doping concentration effects on solar cell parameters, Suntulip adds a unique dimension by facilitating the direct observation of material property shifts in response to changes in doping concentration and temperature. Unlike SCAPS, which primarily centers on solar cell parameters, Suntulip empowers researchers to visually track the evolution of essential material properties—such as band gap, density of states, SRH, Auger and Radiative recombination, carrier concentration, contact resistivity, electron affinity, diffusion length, and carrier lifetime—concomitant with variations in doping concentration and temperature. This innovative feature furnishes a holistic comprehension of how transformations in material attributes across diverse conditions intricately influence solar cell performance. Consequently, Suntulip enriches solar cell optimization endeavors by encompassing the intricate interplay between material properties, temperature, and doping concentration, pivotal for refined design strategies. Notably, Suntulip's distinctive capability broadens further; it enables the calculation of absorption, reflection, and transmission spectra of solar cells—an aspect that SCAPS lacks. This capability enables researchers to comprehend optical behavior of solar cells and to find optimal optical structure. Ultimately, Suntulip's multifaceted functionalities position it as an invaluable tool, not only for advancing solar cell research and development but also for paving the way towards enhanced solar cell performance and design precision.

Differences among tools might appear minor, these nuances can often address specific gaps in simulations, adding value to the toolset available to researchers. Our intention is not to claim superiority over all tools, but to emphasize Suntulip's unique contributions. By focusing on specific features such as a user-friendly interface, comprehensive material property analysis, and the ability to visualize

material property changes, we aim to highlight Suntulip's relevance in bridging a specific gap.

VI. CONCLUSION

In conclusion, this article underscores the pivotal role of simulation in advancing solar cell research and development. The pressing need to enhance solar cell efficiency and reduce production costs in the pursuit of sustainable energy solutions calls for innovative methodologies. Simulation, exemplified by the newly developed Suntulip program in C#, emerges as a cost-effective and efficient alternative to traditional experimental and theoretical methods. Its ability to swiftly propose and evaluate various solar cell structures streamlines the process of identifying optimal designs, ultimately accelerating progress in the field. The reliability of Suntulip is showcased through optical simulations and a robust comparison with Wafer Ray Tracer, yielding accurate and consistent results. By providing a user-friendly interface and versatile capabilities in calculating reflection, transmission, and absorption coefficients, Suntulip empowers researchers to gain valuable insights into solar cell behavior. Moreover, its open-source nature fosters collaboration and customization, further driving advancements in solar cell technology. As the demand for sustainable energy solutions intensifies, Suntulip's potential to contribute to the wider development of solar cell simulation tools becomes increasingly evident. By equipping researchers with a reliable and accessible platform, Suntulip plays a vital role in expediting the optimization of solar cell performance, paving the way towards a cleaner and more sustainable world.

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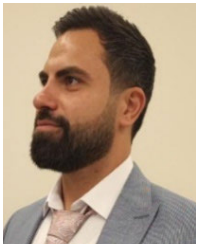
JASURBEK GULOMOV was born in Andijan, Uzbekistan, in 1999. He received the B.S. degree in physics and the M.S. degree in physics of renewable energy sources and sustainable environment from Andijan State University, Uzbekistan, in 2021. He is the author of 21 articles and seven inventions. His current research interests include numerical simulation, DFT, perovskites, nanoplasmonic solar cells, metal nanoparticles, metal oxides, heterojunction solar cells, computational material science, and programming. He is a holder of a national scholarship after being named Mirzo Ulugbek and winner of the 2021 Student of the Year. Besides, he is winner of the President Scholarship, in 2022.



OUSSAMA ACCOUCHE (Associate Member, IEEE) received the degree in electrical engineering from Lebanese University, Beirut, Lebanon, in 2011, and the master's and Ph.D. degrees in smart grids from Grenoble-Alpes University, Grenoble, France, in 2016. He has several years of industrial and international experience, including France, Italy, and Japan, as a Supervisor Engineer. Since September 2018, he has been an Assistant Professor with the Electrical Engineering Department, American University of the Middle East, Egaila, Kuwait. His current research interests include smart grids, renewable energies, solar cells, artificial intelligence, and smart cities.

BILEL NEJI was born in Tunisia, in May 1983. He received the B.Eng. degree in electrical engineering from the National Engineering School of Sfax, Tunisia, in cooperation with Valenciennes University, France, in 2007, the M.S. degree in new technologies in computer systems from the National Engineering School of Sfax, in cooperation with Lille University, France, in 2008, the Ph.D. degree in electrical engineering, focused on scientific satellites' subsystems from the National Engineering School of Sfax, in cooperation with Wurzburg University, Germany, in 2014, and the Ph.D. degree in electrical engineering, focused on MEMS and micro/nano sensors design and fabrication from The State University of New York at Buffalo, USA, in 2015. He has co-founded the BAK USA Technologies Corporation, NY, USA, in 2014, where he was the Director of engineering, until 2018. He joined the American University of the Middle East (AUM), Kuwait, in September 2018, as an Assistant Professor. He is currently an Associate Professor with AUM, where he is also the Research Office Coordinator of the College of Engineering and Technology. He has been conducting research in different areas, including embedded systems, MEMS and sensors design, artificial intelligence, and renewable energy. He received the Fulbright Science and Technology Award from the U.S. Department of States, USA, in 2011, and several other prestigious awards worldwide.

JAKHONGIR ZIYOITDINOV was born in Andijan, Uzbekistan, in 1988. He is currently the Secretary of the Scientific Council, Andijan State University, and an Associate Professor with the Physics Department. He has ten years of teaching experience. He has extensive experience in republic projects. He was involved in the following projects, such as "Improved Solar Energy Usage.". He has participated in a seminar of various countries, such as Italy, Germany, and China. He has more than 70 scientific publications in international and local journals, conference proceedings, and periodicals. His current research interests include numerical simulation, temperature effect on silicon, and the cooling systems of PV panels.