Simulation of Optimized High-Current Tandem Solar-Cells With Efficiency Beyond 41%

MOHAMED MOUSA1, FATHY Z. AMER2, ROAA I. MUBARAK2, AND AHMED SAEED1, (Senior Member, IEEE)
1Electrical Engineering Department, Future University in Egypt, Cairo 11835, Egypt
2Department of Electronics and Communications Engineering, Faculty of Engineering, Helwan University, Cairo 11792, Egypt
Corresponding author: Mohamed Mousa (mohamed.mossa@fue.edu.eg)

ABSTRACT Two-terminal tandem solar-cells have a high efficiency of power conversion. One of their main limitations is the operating current density as the two-terminal tandem solar-cell is equivalent to electrically connected series subcells. Increasing the top absorber layer’s thickness will lead to an increase in the top subcell current and a decrease in the bottom subcell’s current. The subcell with the minimum current forces the tandem cell to operate at its value, limiting the overall performance. In this paper, a proposed solution for such a problem is introduced using a bottom subcell consisting of germanium-telluride (GeTe), which gives a high current and matches the top subcell at a thicker absorber layer. A proposal of three different tandem cells with perovskite (MAPbI₃)/CIGS, perovskite (MAPbI₃)/GeTe, and perovskite (MAPbI₃₋ₓClₓ)/GeTe have been presented. The proposed perovskite (MAPbI₃)/CIGS has an efficiency of 30.52%, whereas the replacement of the CIGS bottom subcell by GeTe led to a significant enhancement of the efficiency to reach 35.9%. High efficiency of 41.7% is obtained by replacing the perovskite (MAPbI₃) top subcell with perovskite (MAPbI₃₋ₓClₓ). A modified numerical algorithm is proposed to obtain the optimum thickness of the top subcell to achieve higher power-conversion efficiency. The performance evaluation and simulation of the designed tandem cells were carried out using SCAPS-1D. The temperature effects on the proposed cells have been encountered in simulation. The results show that the proposed tandem solar-cells have comparable performance and higher efficiencies relative to the published works.

INDEX TERMS CIGS, GeTe, high-current tandem-cell, optimized thickness, perovskite, two-terminal tandem-solar cell, SCAPS-1D.

I. INTRODUCTION
The demand for energy has risen dramatically in the last century. In the next few decades, it is expected that this demand will be doubled. The main source of the used energy now is fossil fuels, which has a terrible impact on the environment and leads to global warming. Clean energy devices are promising for the commercial market, especially photovoltaics, due to their advantages of providing clean energy, converting sunlight into electricity without pollution, and operating for a long time without maintenance [1].

Nowadays, the different forms of crystalline silicon (Si) solar cells dominate the market of photovoltaic. More than 25 % efficiency can be achieved by the silicon solar cells [2]. Copper indium gallium selenide (CIGS) is considered to be one of the most promising and efficient thin-film solar cells with a thin window layer of tungsten disulfide (WS₂) to have a simulated efficiency of about 26.4% [3], also perovskite solar cells have demonstrated fast development and opened new ways for photovoltaic as it is reported efficiency has increased in the recent few years up to more than 30% [4]. The reasons behind the increase of perovskite cells’ performance are their lower recombination rates, broad absorb spectrum, long diffusion lengths, high open-circuit voltage, and bandwidth tuning.

The performance of this type of solar cells is limited as it can only absorb the photons with the energies greater than or equal to the energy gap of the used material, while the other part of the incident spectrum will be lost, and even...
photons with higher energies will lose the energy difference as a thermalization loss. This limit can be overcome by the promising tandem (multi-junction) photovoltaic devices as they consist of sub-cells, each of which absorbs different wavelengths of the incident spectrum [5].

In this work, three different proposed tandem solar cells are tested and simulated at different conditions using SCAPS-1D (SC Capacitance Simulator-one dimension) [6]. High efficiency of 30.5% is obtained using (MAPbI$_3$)/CIGS tandem cell.

The replacement of the CIGS bottom subcell by GeTe subcell with the same doping level and thickness has solved the current limiting problem, which improved the efficiency to reach 35.9%. Then, the perovskite (MAPbI$_3$) top subcell is replaced with the perovskite (MAPbI$_{3-x}$Cl$_x$) subcell, which has higher performance parameters, as the mixed iodide/chloride perovskite have higher thermal stability and better carrier diffusion lengths, which led to a very high efficiency of about 41.7%.

In addition, the performance of the three tandem cells are tested at different temperatures, and the results show that the tandem cells with GeTe as a bottom subcell is more immune to temperature variations than the tandem cell with the CIGS as a bottom subcell.

The rest of this work is structured as follows: the methodology is discussed in section II; section III presents the simulation results and discussion; section IV shows the effects of the temperature on the performance parameters; a comparison of the results of this work and the recently published results are presented in section V; finally, section VI provides the concluding remarks.

II. METHODOLOGY

A. CELL STRUCTURE

Through the investigation of the performance of the tandem solar cells, the top and bottom subcells are simulated independently. Following the widely used approach in simulating the tandem cells, it is assumed that the tunnel junction is ideal, and the electrical losses and optical losses in each interface are neglected [7]–[12].

The current matching condition is achieved by adjusting the thickness of the top subcell while fixing the thickness of the bottom subcell. The structure of perovskite (MAPbI$_3$), perovskite (MAPbI$_{3-x}$Cl$_x$) top subcells and CIGS, and GeTe bottom subcells are shown in Fig. 1.

In the perovskite (MAPbI$_3$) subcell, copper oxide (Cu$_2$O) is used as a Hole Transport Layer (HTL), PCBM (fullerene derivative of the C$_{60}$ buckyball) is used as an Electron Transport Layer (ETL), and the MAPbI$_3$ as an active layer. Transparent Conductive Oxides (TCO) are used as an optically-transparent electrode that allows photons to penetrate the cell and carry the generated electrons to the external terminals of the cell. In contrast, the IDLs are used between the active layer (MAPbI$_{3-x}$Cl$_x$) and the HTL layer, and between the active layer (MAPbI$_{3-x}$Cl$_x$) and the ETL layer to make the device more practical. In the CIGS and GeTe subcells, zinc oxide (ZnO) and Cadmium sulfide (CdS) are used before the absorption layer.

The simulation parameters of the top and bottom subcells are based on the models used in [4], [7], and [13], which are listed in Tables 1, 2, and 3.
**TABLE 1.** Simulation parameters of perovskite (MAPbI$_3$) top subcell.

| Parameters                 | CuO  | MAPbI$_3$ | PCBM |
|----------------------------|------|-----------|------|
| $E_g$ (eV)                 | 2.45 [15] | 1.50 [16] | 1.80 [17] |
| Thickness (nm)             | 20 (variable) | 25 |
| Relative permittivity      | 7.11 [18] | 6.50 [19] | 3.90 [19] |
| Affinity of the electrons  | 2.6 | 3.9 | 4.2 |
| Effective density of states of CB (cm$^2$V$^{-1}$) | $2.02 \times 10^{17}$ [18] | $2.75 \times 10^{14}$ [20] | $10^2$ [21] |
| Mobility of the electrons $\mu_e$ (cm$^2$V$^{-1}$s$^{-1}$) | 200 [22] | 10 [23] | $10^3$ [19] |
| Concentration of donors $N_D$ (cm$^{-3}$) | 0 | $10^{13}$ [24] | $10^2$ |
| Effective density of states of VB (cm$^2$V$^{-1}$) | $1.1 \times 10^{17}$ [18] | $3.9 \times 10^{14}$ [20] | $10^2$ [21] |
| Mobility of the holes $\mu_h$ (cm$^2$V$^{-1}$s$^{-1}$) | 80 [25] | 10 [23] | $2 \times 10^7$ [19] |
| Concentration of acceptors $N_A$ (cm$^{-3}$) | $10^{16}$ [26] | $10^{13}$ [24] | 0 |
| Density of defects $N_i$ (cm$^{-3}$) | $10^{14}$ | $10^{14}$ | $10^{14}$ |

**TABLE 2.** Simulation parameters of perovskite (MAPbI$_3$−$x$Cl$_x$) top subcell.

| Parameters                 | CuO  | MAPbI$_3$−$x$Cl$_x$ | ZnOS | TCO |
|----------------------------|------|---------------------|------|-----|
| $E_g$ (eV)                 | 2.1 [27] | 1.55 [28] | 2.83[29] | 3.5 |
| Thickness (nm)             | 500 | 10 (variable) | 20 | 500 |
| Relative permittivity      | 7.11 [27] | 6.5 [27] | 9 [29] | 9 |
| Affinity of electrons(eV)  | 3.2 [27] | 3.9 | 3.9 [30] | 3.6 [31] | 4 |
| Effective density of states of CB (cm$^2$) | $2.2 \times 10^4$ | $2.2 \times 10^4$ | $2.2 \times 10^4$ | $2.2 \times 10^4$ |
| Mobility of the holes $\mu_h$ (cm$^2$V$^{-1}$s$^{-1}$) | 3.4 | 2 | 2 [27] | 100 [29] | 20 |
| Concentration of donors $N_D$ (cm$^{-3}$) | 0 | $10^{15}$ | $10^{15}$ [4] | $10^{15}$ [4] | $2 \times 10^9$ |
| Effective density of states of VB (cm$^2$) | $1.8 \times 10^8$ | $1.8 \times 10^8$ | $1.8 \times 10^8$ | $1.8 \times 10^8$ |
| Mobility of the holes $\mu_h$ (cm$^2$V$^{-1}$s$^{-1}$) | 3.4 | 2 | 2 [27] | 25 [29] | 10 |
| Concentration of acceptors $N_A$ (cm$^{-3}$) | $10^{20}$ | 0 | 0 | 0 | 0 |
| Density of defects $N_i$ (cm$^{-3}$) | $10^{15}$ | $10^{15}$ [32] | $10^{15}$[33] | $10^{15}$[33] | $10^{15}$[33] |

The power density of the light spectrum transmitted from the top subcell to the bottom subcell, $S(\lambda)$ (W/m$^2$), is given by (1) [8];

$$S(\lambda) = S_o(\lambda) \cdot \prod_{x=1}^{n} e^{-\alpha_x d_x}$$

where $S_o$ is the incident spectrum (AM 1.5), $x$ is the layer number, $n$ is the total number of layers of the subcell, $d$ is the thickness of each layer (cm), and $\alpha$ is the absorption coefficient (cm$^{-1}$) of each material (with a pre-factor $A_{\alpha}$) given by [14];

$$\alpha(E) = A_{\alpha} \sqrt{h\nu - E_g}$$

where $E_g$ is the energy gap of the material (eV), $h$ is the Planck’s constant (eV sec), and $\nu$ is the spectrum frequency.

**B. THICKNESS OPTIMIZATION OF THE TOP SUBCELL**

In this subsection, a modified numerical method based on the concept given by [36] is proposed. The proposed modification in the algorithm uses two phases for thickness ($t_s$) optimization with two steps: course step $t_{cs}$ of 50 nm, and fine step $t_{fs}$ of 5 nm. The flowchart of the proposed algorithm is shown in Fig. 2. In each step, all the performance parameters of the junction is calculated based on the resulting thickness.

This proposed change leads to faster response in finding the optimum top subcell thickness for the two junction tandem cell, as the number of total calculations decreases. Moreover, it can find more accurate optimum thickness as the step of the second phase is reduced to 5 nm. The bottom subcell layer thickness must be thick enough to absorb as much as possible from the transport photons from the top subcell and was not taken into considerations in the optimization process, but the overall thickness of the tandem structure must not be greater than 50 $\mu$m (an assumed diffusion length to ensure free charge transport to electrodes) [36].
III. SIMULATION RESULTS AND DISCUSSION

A. PEROVSKITE (MAPbI$_3$) SUBCELL

In this section, the study of simulating perovskite (MAPbI$_3$) subcell is performed. The Cu$_2$O layer valence band maximum is $-5.05$ eV, i.e., higher than the Highest Occupied Molecular Orbital (HOMO) energy level of the MAPbI$_3$ layer ($-5.5$ eV), thus leading to the extraction of the holes at the interface between MAPbI$_3$ and Cu$_2$O layers. Furthermore, the edge of conduction of the Cu$_2$O film is ($-2.60$ eV), which is much higher than the Lowest Unoccupied Molecular Orbital (LUMO) level of the MAPbI$_3$ ($-3.9$ eV). This blocks electrons from MAPbI$_3$ to reach the Cu$_2$O layer effectively. On the other side, the HOMO level of the PCBM layer is lower than that of the MAPbI$_3$ layer, and PCBM shows a slightly deeper LUMO level than MAPbI$_3$. This causes the holes and electrons to be successfully drifted to the contacts. The perovskite (MAPbI$_3$) subcell performance is studied for different active layer (MAPbI$_3$) thickness range of 50 nm to 600 nm. The variation of Power Conversion Efficiency (PCE), open-circuit voltage ($V_{OC}$), short-circuit current density ($J_{SC}$), and Fill Factor (FF) with MAPbI$_3$ thickness variations are shown in Fig. 3.

B. PEROVSKITE (MAPbI$_{3-x}$Cl$_x$) SUBCELL

In this section, the study of simulating perovskite (MAPbI$_{3-x}$Cl$_x$) subcell is performed. The variations of PCE, $V_{OC}$, $J_{SC}$, and FF with (MAPbI$_{3-x}$Cl$_x$) thickness are shown in Fig. 4. The perovskite (MAPbI$_{3-x}$Cl$_x$) subcell is more complicated than the perovskite (MAPbI$_3$) subcell; however, the simulation results show higher PCE, $J_{SC}$, and FF at any absorber layer thickness. On the other hand, the $V_{OC}$ of perovskite (MAPbI$_{3-x}$Cl$_x$) is lower than perovskite (MAPbI$_3$) at a small layer thickness. However, unlike the perovskite (MAPbI$_3$) subcell, the $V_{OC}$ of the perovskite (MAPbI$_{3-x}$Cl$_x$) subcell does not decrease by increasing the absorber layer thickness; instead, it increases until reaching saturation.
C. CIGS SUBCELL

Figure 5 presents the CIGS subcell’s simulated $J/V$ curve; the other used simulation conditions are the same as those used for the previous simulations. The simulated CIGS subcell exhibits a $PCE = 21.57\%$ with $FF = 81.94\%$, $V_{OC} = 0.621\ V$, and $J_{SC} = 42.38\ mA/cm^2$.

D. GeTe SUBCELL

Figure 6 shows the simulated $J/V$ curve of the GeTe subcell. The simulated GeTe subcell exhibits a $PCE = 26.21\%$ with $FF = 81.92\%$, $V_{OC} = 0.6\ V$, and $J_{SC} = 53.3\ mA/cm^2$.

The results show that GeTe is a promising material as it has a high short-circuit current density; which is the key to solve one of the main limitations of the two-terminal tandem solar cells; as the current density of the two-terminal tandem solar cells is limited by the lowest current of the subcells (mostly the bottom subcell). Therefore, GeTe is a better choice, especially for the bottom tandem subcells (low incident power spectrum). In addition to its electrical conductivity, the reason that GeTe has high current density is it has a low energy gap, which leads to the ability to absorb more of the incident spectrum.

E. TANDEM PEROVSKITE (MAPbI$_3$)/CIGS CELL

To perform the simulation of the optimized perovskite (MAPbI$_3$)/CIGS two-terminal tandem solar cell, the
proposed numerical method was used, and the tandem output efficiency with top subcell absorber layer thickness is shown in Fig. 7. The results show the optimum (highest) tandem cell efficiency is 30.52% at top subcell absorber layer thickness 230 nm. Also the current density of both subcells was examined with varying the thickness of the absorbing layer of the top subcell and the results shows the matching point at perovskite thickness of 230 nm as shown in Fig. 8; the perovskite (MAPbI$_3$) subcell with this absorber layer thickness exhibits a $PCE = 20.58\%$, $FF = 82.67\%$, $VOC = 1.2143V$, and $JSC = 20.5 mA/cm^2$.

Then the highest efficiency of the tandem cell is at the matching point of the current density of both subcells with a top subcell absorber layer thickness of 230 nm.

FIGURE 7. Perovskite (MAPbI$_3$)/CIGS tandem cell efficiency with top subcell absorber layer thickness.

FIGURE 8. $J_{SC}$ of perovskite (MAPbI$_3$) and CIGS subcells with top subcell absorber layer.

The structure of perovskite (MAPbI$_3$)/CIGS tandem cell with AM1.5 incident spectrum to the top subcell and filtered AM1.5 to the bottom subcell (after part of the spectrum is filtered out) is shown as Fig. 9.

FIGURE 9. Perovskite (MAPbI$_3$)/CIGS tandem solar cell as AM1.5 and filtered AM 1.5 is illuminated on the subcells.

FIGURE 10. Band diagrams of Perovskite (MAPbI$_3$)/CIGS top and bottom subcells.
absorbed by the top subcell) is shown in Fig. 9. The figure shows that most of the AM 1.5 spectrum (up to 826 nm) is absorbed by the top subcell, and the rest of the spectrum is transmitted to the bottom subcell. The band diagrams of top and bottom subcells are shown in Fig. 10 a and b, respectively.

J/V curves of perovskite (MAPbI$_3$), CIGS subcells and perovskite (MAPbI$_3$)/CIGS tandem solar cell are shown in Fig. 11. CIGS subcell with incident filtered AM 1.5 spectrum exhibits a $PCE = 19.67\%$ with $FF = 81.19\%$, $V_{OC} = 0.603$ V, and $J_{SC} = 20.5$ mA/cm$^2$. Perovskite (MAPbI$_3$)/CIGS tandem solar cell exhibits a $PCE = 30.52\%$ with $FF = 81.98\%$, $V_{OC} = 1.817$ V, and $J_{SC} = 20.5$ mA/cm$^2$. Figures 12 and 13 show the spectrum absorbed by perovskite (MAPbI$_3$), CIGS subcells and perovskite (MAPbI$_3$)/CIGS tandem solar cell, and the external quantum efficiency (EQE) of both subcells, respectively.
FIGURE 16. The perovskite (MAPbI$_3$)/GeTe tandem solar cell as AM1.5 and filtered AM 1.5 is illuminated on the subcells.

FIGURE 17. The band diagrams of Perovskite (MAPbI$_3$)/GeTe top and bottom subcells.

F. TANDEM PEROVSKITE (MAPbI$_3$)/GeTe CELL

In the perovskite (MAPbI$_3$)/GeTe tandem solar cell, the bottom CIGS subcell of the previous tandem cell was replaced by a GeTe subcell with the same doping level and thickness.

The thickness of the top subcell absorber layer (685 nm) is obtained using the proposed optimization numerical method, which results in 35.9% efficiency for the perovskite (MAPbI$_3$)/GeTe tandem cell, as shown in Fig. 14. The current densities of both subcells are examined with the top subcell thickness variation showing that the matching point is located at the optimum thickness obtained by the proposed algorithm, as shown in Fig. 15.

The perovskite (MAPbI$_3$) subcell with this absorber layer thickness exhibits a PCE = 23.87% with FF = 78.71%, $V_{OC} = 1.1657$ V, and $J_{SC} = 25.88$ mA/cm$^2$. It is clear replacing the CIGS bottom subcell by the GeTe bottom subcell allows the top perovskite (MAPbI$_3$) to operate at a higher current density, which, in turn, improves the overall performance parameters of the tandem cell.

The structure of perovskite (MAPbI$_3$)/GeTe tandem cell, with AM1.5 incident spectrum to the top subcell and filtered AM1.5 to the bottom subcell, is shown in Fig. 16.

The band diagrams of top and bottom subcells are shown in Fig. 17a, and b respectively. As expected, the spectrum absorbed by the top subcell (with 685 nm) is greater than...
that whose absorber layer thickness is about 230 nm. The new AM 1.5 filtered spectrum transmitted to the bottom subcell is lower than the previous tandem cell. However, because of the GeTe properties, the bottom subcell generates a higher current density of about 25.90 mA/cm², which almost matches the top subcell current density.

$J/V$ curves of perovskite (MAPbI₃), GeTe subcells and perovskite (MAPbI₃)/GeTe tandem solar cell are shown in Fig. 18. GeTe subcell with incident filtered AM 1.5 spectrum exhibits a $PCE = 29.79\%$ with $FF = 81.11\%$, $V_{OC} = 0.581$ V, and $J_{SC} = 25.9$ mA/cm², perovskite (MAPbI₃)/CIGS tandem solar cell exhibit a $PCE = 35.9\%$ with $FF = 79.40\%$, $V_{OC} = 1.747$ V, and $J_{SC} = 25.88$ mA/cm².

Figures 19 and 20 show the spectrum absorbed by perovskite (MAPbI₃), GeTe subcells and perovskite (MAPbI₃)/GeTe tandem solar cell, and the external quantum efficiency (EQE) of both subcells, respectively.

**G. TANDEM PEROVSKITE (MAPbI₃₋ₓClₓ)/GeTe CELL**

The perovskite (MAPbI₃₋ₓClₓ)/GeTe tandem solar-cell is as the previous tandem cell with the top perovskite (MAPbI₃) subcell replaced by the optimized perovskite (MAPbI₃₋ₓClₓ) subcell [4]. The thickness of the top subcell absorber layer (525 nm) is obtained using the proposed optimization numerical method, resulting in a higher efficiency of 41.7% as shown in Fig. 21. At this thickness, both subcells’ current densities are found to be almost the same as shown in Fig. 22.

As the perovskite (MAPbI₃₋ₓClₓ) has a higher open-circuit voltage relative to perovskite (MAPbI₃), the overall open-circuit voltage of the perovskite (MAPbI₃₋ₓClₓ)/GeTe tandem cell is greater than perovskite (MAPbI₃)/GeTe tandem cell.
FIGURE 24. The band diagrams of Perovskite (MAPbI$_{3-x}$Cl$_x$) subcell.

FIGURE 25. $J$/$V$ curves of perovskite (MAPbI$_{3-x}$Cl$_x$), GeTe subcells, and perovskite (MAPbI$_{3-x}$Cl$_x$)/GeTe tandem solar cell.

FIGURE 26. The absorbed spectrum of perovskite (MAPbI$_{3-x}$Cl$_x$), GeTe subcells and perovskite (MAPbI$_{3-x}$Cl$_x$)/GeTe tandem cell.

FIGURE 27. EQE of perovskite (MAPbI$_{3-x}$Cl$_x$) and GeTe subcells.

FIGURE 28. $J$/$V$ curves of the three tandem cells MAPbI$_3$/CIGS, MAPbI$_3$/GeTe, and MAPbI$_{3-x}$Cl$_x$/GeTe with PCE 30.52%, 35.9%, and 41.73%, respectively.

The perovskite (MAPbI$_{3-x}$Cl$_x$) subcell with this absorber layer thickness exhibits a $PCE = 29.61\%$ with $FF = 88.99\%$, $V_{OC} = 1.254$ V, and $J_{SC} = 26.54$ mA/cm$^2$. It is clear that replacing the perovskite (MAPbI$_3$) top subcell with the perovskite (MAPbI$_{3-x}$Cl$_x$) top subcell leads to a higher matching current density point and higher open-circuit voltage. As expected, this improves the overall performance parameters of the tandem perovskite (MAPbI$_{3-x}$Cl$_x$)/GeTe cell.

The structure of perovskite (MAPbI$_{3-x}$Cl$_x$/GeTe tandem cell, with AM1.5 incident spectrum to the top subcell and filtered AM1.5 to the bottom subcell, is shown in Fig. 23. The spectrum absorbed by the top perovskite (MAPbI$_{3-x}$Cl$_x$) subcell is almost of the same wavelength (826 nm) as perovskite (MAPbI$_3$). The band diagram of top subcell is shown in Fig. 24.

The $J$/$V$ curves of perovskite (MAPbI$_{3-x}$Cl$_x$), GeTe subcells and perovskite (MAPbI$_{3-x}$Cl$_x$)/GeTe tandem solar cell are shown in Fig. 25. GeTe subcell with incident filtered AM 1.5 spectrum exhibits a $PCE = 29.79\%$ with $FF = 81.14\%$, $V_{OC} = 0.582$ V, and $J_{SC} = 26.57$ mA/cm$^2$. perovskite (MAPbI$_{3-x}$Cl$_x$)/GeTe tandem solar cell exhibits a $PCE = 41.7\%$ with $FF = 85.66\%$, $V_{OC} = 1.836$ V, and $J_{SC} = 26.54$ mA/cm$^2$. Figures 26 and 27 show the spectrum absorbed by perovskite (MAPbI$_{3-x}$Cl$_x$), GeTe subcells and perovskite (MAPbI$_{3-x}$Cl$_x$)/GeTe tandem solar cell spectrum, and
TABLE 4. Performance parameters of three tandem cells.

| Parameters | MAPbI3/CIGS | MAPbI3/GeTe | MAPbI3-xClx/GeTe |
|------------|-------------|-------------|-------------------|
| n (%)      | 30.52       | 35.90       | 41.73             |
| FF (%)     | 81.98       | 79.40       | 85.66             |
| Jsc (mA/cm²) | 20.50     | 25.88       | 26.54             |
| Voc(V)    | 1.816       | 1.747       | 1.835             |

the external quantum efficiency (EQE) of both subcells, respectively.

H. PERFORMANCE COMPARISON OF THE THREE PROPOSED TANDEM CELLS

This section shows a comparison between the proposed three-tandem cells. First, the J/V curves of the three-tandem cells are given in Fig. 28, then a comparison between the performance parameters of the proposed three-tandem solar cells are given in Table 4.

The results show that replacing the CIGS bottom subcell in MAPbI3/CIGS tandem cell by GeTe subcell leads to increasing the current density by almost 25%. This, in turn, improves the overall performance of the MAPbI3/GeTe tandem cell, and the power conversion efficiency increases from 30.5% to 35.9%, but at the same time, the MAPbI3/GeTe tandem cell has a lower open-circuit voltage than MAPbI3/CIGS tandem cell by about 0.07 V.

This can be attributed to the fact that the short-circuit current density matching point using GeTe as bottom subcell occurs at a thicker absorber layer of top MAPbI3 subcell, and as shown in Fig. 2(b) the open-circuit voltage of the MAPbI3 top subcell decreases as the absorber layer thickness increases.

To increase both the voltage and current, and optimize the performance of the tandem cell, an optimized MAPbI3-xClx cell [4] is used as a top subcell with GeTe bottom subcell. This, in turn, increases the cell’s overall efficiency and makes it closer to the ideal cell.

IV. THE EFFECTS OF THE TEMPERATURE VARIATION ON THE PARAMETERS OF PERFORMANCE

Temperature change has a significant impact on the performance of solar cells, so this section is dedicated to the study of this effect on the main parameters of the proposed cells.

Figures 29 and 30 show the performance parameters of the subcells and tandem cells with temperatures varying from 260 K to 360 K, respectively. The temperature variation effect is examined by changing the temperature by step 5K on SCAPS-1D simulator.

The results show that increasing the temperature decreases the PCE of subcells and tandem cells in a linear manner. It is clear that both perovskite (MAPbI3 and MAPbI3-xClx) subcells are more immune to the temperature variation than CIGS and GeTe subcells.

The degradation of tandem cell efficiency is dominated by the effect of the bottom subcell, which is more affected by the change in temperature.

The open-circuit voltage and fill factor decrease with temperature; MAPbI3-xClx and GeTe subcells are more immune to temperature variations than MAPbI3 and CIGS subcells, especially at high temperatures. The short-circuit current density of MAPbI3-xClx and GeTe subcells have higher immunity to temperature variations than MAPbI3 and CIGS subcells. This enables the tandem cell MAPbI3-xClx/GeTe to have almost the best performance parameters relative to the other proposed tandem cells.

V. COMPARISON WITH THE RECENTLY REPORTED RESULTS

This section is dedicated to comparing the results of the recently published tandem solar cells and the results of this research; this comparison focuses on the tandem cell.

TABLE 5. Comparison of the recently published results with the proposed tandem cells.

| PCE (%) | FF % | Jsc (mA/cm²) | Voc(V) | The material of Top/Bottom subcells | Ref. - Year |
|---------|------|-------------|--------|-----------------------------------|----------|
| 21.4    | 79.9 | 15.8        | 1.692  | MAPbI3/SHJ                        | [37] - 2016 |
| 22.8    | 77.5 | 16.8        | 1.751  | CA0.15FA0.85PbI3/SHJ              | [38] - 2017 |
| 22.8    | 73.8 | 17.6        | 1.75   | CA0.16PbI3(FA0.85Mn0.15)/PbI3(FA0.85Mn0.15)/BRx/Si | [39] - 2017 |
| 23.6    | 79   | 18.1        | 1.65   | CA0.17FA0.83PbI3(BR(0.17,0.83))/SHJ | [40] - 2017 |
| 25.2    | 77   | 18.4        | 1.77   | FA0.05Ca0.2PbI3(BR0.25)/3V/CA0.15 | [41] - 2018 |
| 25.2    | 73.1 | 19.5        | 1.788  | CA0.15PbI3(BR1.5)/textured Si     | [42] - 2018 |
| 25.4    | 79.4 | 17.8        | 1.8    | CA0.15(FA0.85MA0.15)0.5PbI3BR0.5/Si | [43] - 2018 |
| 25.5    | 78.5 | 18.5        | 1.76   | CA0.05(MA0.17FA0.83)PbI3(BR0.17,0.83)/Si | [44] - 2018 |
| 28.8    | 78.7 | 19.5        | 1.78   | Perovskite/Si (monolithic)         | [45] - 2018 |
| 30.2    | 68.9 | 22.4        | 1.94   | Se/CZTS/Se                        | [46] - 2019 |
| 30.5    | 81.9 | 20.49       | 1.81   | MAPbI3/CIGS                       | This work |
| 31.1    | 88   | 17.04       | 2.07   | GaInP/Si                          | [47] - 2020 |
| 33.3    | 83.5 | 12.7        | 3.127  | Triple-junction (GaInP/InGaAs)    | [48] - 2018 |
| 35.9    | 87.5 | 13.6        | 2.52   | Triple-junction (GaInP/GaAs)      | [49] - 2017 |
| 35.9    | 79.4 | 25.88       | 1.747  | MAPbI3/GeTe                      | This work |
| 39.2    | 83.5 | 8.457       | 5.459  | Six junction (monolithic)         | [50] - 2017 |
| 41.73   | 85.66| 26.54       | 1.835  | MAPbI3-xClx/GeTe                 | This work |

The efficiency increases to be 41.73%, and FF becomes 85.66%. To the best of our knowledge, this cell has one of the highest performance’s parameters.
FIGURE 29. Performance of subcells with temperature: (a) PCE, (b) $V_{OC}$, (c) $J_{SC}$, and (d) $FF$.

FIGURE 30. Performance of tandem cells with temperature: (a) PCE, (b) $V_{OC}$, (c) $J_{SC}$, and (d) $FF$. 
main parameters of performance as listed in Table 5. It is noticed that the efficiency of the tandem solar cells is doubled in the last few years, and the new proposed tandem cells (MAPbI₃/CIGS, MAPbI₃/GeTe, and MAPbI₃₋ₓClₓ/GeTe) have high PCE relative to the other double junction two-terminal tandem cells. The triple (and more) junction solar cell shows high performance, but it is more complicated with a higher cost. The proposed MAPbI₃/GeTe, and MAPbI₃₋ₓClₓ/GeTe tandem cells have one of the highest PCEs, and best performance parameters for two-terminal double junction tandem cells, which is comparable to those of the conventional and the complicated (triple-junction and more) one. Up to our knowledge, this work reports one of the highest power conversion efficiency in recent years for two-junction tandem cells using incident spectrum AM 1.5.

VI. CONCLUSION
Along the road to manufacture solar cells with high powerconversion efficiency, multi-junction solar cells show a better choice as they can absorb a broader spectrum than single-junction solar cells. Increasing the number of junctions enhances the ability to absorb a wide spectrum and have a higher power-conversion efficiency. Still, at the same time, this increases the complexity and the cost of the cell. Only two-junction solar cells are used in this work and results in high efficiency. This is achieved by solving one of the main problems facing the two-terminal tandem solar cells, as the subcell with a lower current (almost the bottom) forces the tandem cell to operate at its current density. As the GeTe is used as an absorber in the bottom subcell, this shows a high current-density for the bottom subcells and allows the tandem cell to operate at a higher current, and this, in turn, increases the overall tandem cell performance. Also, a modified algorithm is proposed for optimizing the thickness of the top subcell layer. The simulations of the proposed tandem cell of MAPbI₃/CIGS show an efficiency of 30.5%; then, GeTe is used as a bottom subcell to replace the CIGS (with the same doping and thickness), which increased the efficiency to 35.9%. Replacing the MAPbI₃ top subcell by MAPbI₃₋ₓClₓ shows a higher efficiency of 41.73%; which is one of the highest power-conversion efficiencies reported for tandem cells to the best of our knowledge. All the proposed cells have the advantages of using only two junctions, which greatly impact reducing the complexity and cost of solar cells.

REFERENCES
[1] N. T. Raj, S. Inyian, and R. Goic, “A review of renewable energy based cogeneration technologies,” Renew. Sustain. Energy Rev., vol. 15, no. 8, pp. 3640–3648, 2011.
[2] K. Yoshikawa, H. Kawasaki, W. Yoshida, T. Irie, K. Konishi, K. Nakano, T. Uto, D. Adachi, M. Kanematsu, H. Uzu, and K. Yamamoto, “Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion efficiency over 26%,” Nature Energy, vol. 2, no. 5, 2017, Art. no. 17032.
[3] K. Sobayel, M. Shahnazizaman, N. Amin, M. R. Karim, M. A. Dar, R. Gul, M. A. Alghoul, K. Sopian, A. K. M. Hasan, and M. Akhtaruzzaman, “Efficiency enhancement of CIGS solar cell by WS₂ as window layer through numerical modelling tool,” Sol. Energy, vol. 207, pp. 479–485, Sep. 2020.
[4] M. M. Salah, M. Abouelatta, A. Shaker, K. M. Hassan, and A. Saeed, “A comprehensive simulation study of hybrid halide perovskite solar cell with copper oxide as HTM,” Semicond. Sci. Technol., vol. 34, no. 11, Nov. 2019, Art. no. 115009.
[5] R. Yasodharan, A. P. Senthilkumar, P. Mohankumar, J. Ajayan, and R. Singhalakrishnan, “Investigation and influence of layer composition of tandem perovskite solar cells for applications in future renewable and sustainable energy,” Optik, vol. 212, Jun. 2020, Art. no. 164723.
[6] M. Burgelman, K. Decock, S. Khelifi, and A. Abass, “Advanced electrical simulation of thin film solar cells,” Thin Solid Films, vol. 535, pp. 296–301, May 2013.
[7] M. Mousa, M. M. Salah, E. Z. Amer, A. Sased, and R. J. Mubarak, “High efficiency tandem perovskite/CIGS solar cell,” in Proc. 2nd Int. Conf. Smart Power Internet Energy Syst. (SPIES), Sep. 2020, pp. 224–227.
[8] K. Kim, J. Gwak, S. K. Ahn, Y.-J. Eo, J. H. Park, J.-S. Cho, M. G. Kang, H.-E. Song, and J. H. Yun, “Simulations of chalcopyrite/c-Si tandem cells using SCAPS-ID,” Sol. Energy, vol. 145, pp. 52–58, Mar. 2017.
[9] K. Kim, J. S. Yoo, S. K. Ahn, Y.-J. Eo, J.-S. Cho, J. Gwak, and J. H. Yun, “Performance prediction of chalcopyrite-based dual-junction tandem solar cells,” Sol. Energy, vol. 155, pp. 167–177, Oct. 2017.
[10] G. K. Gupta and A. Dixit, “Theoretical studies of single and tandem Cu₂ZnSn(S/Se)₄ junction solar cells for enhanced efficiency,” Opt. Mater., vol. 82, pp. 11–20, Aug. 2018.
[11] M. M. Lunardini, J. P. Alvarez-Gaitan, J. I. Bilbaoa, and R. Corkish, “Life cycle assessment of solar photovoltaics and their end-of-life,” IJoLCAS, vol. 2, no. 2, 2018.
[12] J. Madan, Shivaniv. Pandey, and R. Sharma, “Device simulation of 17.3% efficient lead-free all-perovskite tandem solar cell,” Sol. Energy, vol. 197, pp. 212–221, Feb. 2020.
[13] M. A. A. Noman, M. J. Abden, and A. M. Islam, “Germanium telluride absorber layer, a proposal for low illumination photovoltaic application using AMPS 1D,” in Proc. Int. Conf. Comput., Commun., Chem., Mater. Electron. Eng. (IC4ME2), Feb. 2018, pp. 1–5.
[14] U. Mandadapu, S. V. Vedanayakam, and K. Thyagarajan, “Simulation and analysis of lead based perovskite solar cell using SCAPS-ID,” Indian J. Sci. Technol., vol. 10, no. 11, pp. 65–72, 2017.
[15] K. P. Ganesan, N. Anandhan, V. Dharuman, P. Sanil, R. Panerselvam, and T. Marimuthu, “Electrochemically modified crystal orientation, surface morphology and optical properties using CTAB on CuO thin films,” Results Phys., vol. 7, pp. 82–86, Jan. 2017.
[16] J.-Y. Jeng, Y.-F. Chiang, M.-H. Lee, S.-R. Peng, T.-F. Guo, P. Chen, and T.-C. Wen, “Methylammonium lead iodide perovskite/fullerene-based hybrid solar cells,” SPIE Newsroom, vol. 10, Aug. 2013, Art. no. 005033.
[17] G. Xing, N. Mathews, S. Sun, S. S. Lim, Y. M. Lam, M. Gratzel, S. Mhaaisalkar, and T. C. Sum, “Long-range balanced electron- and hole-trapping lengths in organic-inorganic CH₃NH₃PbI₃,” Science, vol. 342, no. 6156, pp. 344–347, Oct. 2013.
[18] L. Zhu, G. Shao, and J. Luo, “Numerical study of metal oxide heterojunction solar cells,” Semicond. Sci. Technol., vol. 26, Jun. 2011, Art. no. 085026.
[19] U. Mandadapu, “Simulation and analysis of lead based perovskite solar cell using SCAPS-ID,” Indian J. Sci. Technol., vol. 10, no. 1, pp. 1–8, Jan. 2017.
[20] G. Giorgi, J.-I. Fujisawa, H. Segawa, and K. Yamashita, “Small photocarrier effective masses featuring ambipolar transport in methylammonium lead iodide perovskite: A density functional analysis,” J. Phys. Chem. Lett., vol. 4, no. 24, pp. 4213–4216, Dec. 2013.
[21] K. Akaike, K. Kanai, H. Yoshida, J. Tsutsumi, T. Nishi, N. Sato, Y. Ouchi, and K. Seki, “Ultraviolet phototransistor spectroscopy and inverse photoemission spectroscopy of [6,6]-phenyl-C₆₁-butyric acid methyl ester in gas and solid phases,” J. Appl. Phys., vol. 104, no. 2, Jul. 2008, Art. no. 023710.
[22] P. A. Kozhaviy and B. Johansson, Literature Review on the Properties of Cuprous Oxide Cu₂O and the Process of Copper Oxidation. Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Company, 2011.
[23] C. Wehrenfennig, G. E.Eperon, M. B. Johnston, H. J. Snaith, and L. M. Herz, “High charge carrier mobilities and lifetimes in organolead trihalide perovskites,” Adv. Mater., vol. 26, no. 10, pp. 1584–1589, Mar. 2014.
[24] Q. Zhou, D. Jiao, K. Fu, X. Wu, Y. Chen, J. Lu, and S.-E. Yang, “Two-dimensional device modeling of CH₃NH₃PbI₃ based planar heterojunction perovskite solar cells,” Sol. Energy, vol. 123, pp. 51–56, Jan. 2016.
[25] H. Matsumura, A. Fujii, and T. Kitatani, “Properties of high-mobility CuO films prepared by thermal oxidation of Cu at low temperatures,” Jpn. J. Appl. Phys., vol. 35, p. 5631, Nov. 1996.
[26] Y. S. Lee, J. Heo, M. T. Winkler, S. C. Siah, S. B. Kim, R. G. Gordon, and T. Buonassisi, “Nitrogen-doped cuprous oxide as a P-type hole-transporting layer in thin-film solar cells,” J. Mater. Chem. A, vol. 1, no. 48, p. 15416, 2013.

[27] N. Kour, R. Mehrz, and Chandhi, “Efficient design of perovskite solar cell using mixed halide and copper oxide,” Chin. Phys. B, vol. 27, no. 1, Jan. 2018, Art. no. 018801.

[28] J. Chae, Q. Dong, J. Huang, and A. Centrone, “Chloride incorporation process in CH$_3$NH$_3$PbI$_3$-Cl$_x$ perovskites via nanoscale bandgap maps,” Nano Lett., vol. 15, no. 12, pp. 8114–8121, Dec. 2015.

[29] M. Gloczekker, “Device physics of CuIn$_x$Ga$_{1-x}$Se$_2$ thin-film solar cells,” Ph.D. dissertation, Dept. Phys., Colorado State Univ., Fort Collins, CO, USA, 2005.

[30] S. Bansal and P. Aryal, “Evaluation of new materials for electron and hole transport layers in perovskite-based solar cells through SCAPS-1D simulations,” in Proc. IEEE 43rd Photovoltaic Spec. Conf. (PVSC), Jun. 2016, pp. 1–4.

[31] S. I. Rahman, S. Faisal, S. Ahmed, and T. I. J. Dhrubo, “A comparative study on different HTMs in perovskite solar cell with ZnO:Sn electron transport layer,” in Proc. IEEE Region Humanitarian Technol. Conf. (R10-HTC), Dec. 2017, pp. 546–550.

[32] T. Minemoto and M. Murata, “Theoretical analysis on effect of band offsets in perovskite solar cells,” Sol. Energy Mater. Sol. Cells, vol. 133, pp. 8–14, Feb. 2015.

[33] M. M. Salah, K. M. Hassan, M. Abouelatta, and A. Shaker, “A comparative study of different ETMs in perovskite solar cell with inorganic copper iodide as HTM,” Optik, vol. 178, pp. 958–963, Feb. 2019.

[34] A. O. Pudov, A. Kanevce, H. A. Al-Thani, J. R. Sites, and F. S. Hasoon, “Secondary barriers in CdS-CuIn$_x$Ga$_{1-x}$Se$_2$ solar cells,” J. Appl. Phys., vol. 97, no. 6, 2005, Art. no. 064901.

[35] S. Wagner, J. L. Shay, P. Miglierato, and H. M. Kasper, “CuInSe$_2$/CdS heterojunction photovoltaic detectors,” Appl. Phys. Lett., vol. 25, no. 8, pp. 434–435, Oct. 1974.

[36] R. I. Rabady and H. Mansareh, “Thicknisses optimization of two- and three-junction photovoltaic cells with matched currents and matched lattice constants,” Sol. Energy, vol. 158, pp. 20–27, Dec. 2017.

[37] J. Werner, C. H. Weng, A. Walter, L. Fesquet, J. P. Seif, S. De Wolf, B. Niesen, and C. Bailiff, “Efficient monolithic perovskite/silicon tandem solar cell with cell area> 1 cm$^2$,” J. Phys. Chem. Lett., vol. 7, no. 1, pp. 161–166, 2016.

[38] F. Sahli, B. A. Kamino, J. Werner, M. Bräuninger, B. Paviet-Salomon, L. Barraud, R. Monnard, J. P. Seif, A. Tomasi, Q. Jeangros, J. P. Mailloa, D. P. McMeekin, R. L. Hoye, and C. Ballif, “Improved optics in monolithic perovskite/silicon tandem solar cells with a nanocrystalline silicon recombination junction,” Adv. Energy Mater., vol. 8, no. 6, Feb. 2018, Art. no. 1701609.

[39] Y. Wu, D. Yan, J. Peng, Y. Wan, S. P. Fang, H. Shen, N. Wu, C. Barugkin, X. Fu, S. Surve, and D. Grant, “Monolithic perovskite/silicon-homojunction tandem solar cell with over 22% efficiency,” Energy Environ. Sci., vol. 10, no. 11, pp. 2472–2479, 2017.

[40] K. A. Bush, A. F. Palmstrom, J. Y. Zhengshan, M. Boccard, R. Checharoen, J. P. Mailloa, D. P. McMeekin, R. L. Hoye, C. D. Baille, T. Leijtens, and I. M. Peters, “23.6%-efficient monolithic perovskite/silicon tandem solar cells with improved stability,” Nature Energy, vol. 2, no. 4, pp. 1–7, 2017.

[41] K. A. Bush, S. Manzoor, K. Frohna, Z. J. Yu, J. A. Raiford, A. F. Palmstrom, H. P. Wang, R. Prasanna, S. F. Bent, Z. C. Holman, and M. D. McGehee, “Minimizing current and voltage losses to reach 25% efficient monolithic two-terminal perovskite-silicon tandem solar cells,” ACS Energy Lett., vol. 3, no. 9, pp. 2173–2180, 2018.

[42] F. Sahli, J. Werner, B. A. Kamino, M. Bräuninger, R. Monnard, B. Paviet-Salomon, L. Barraud, L. Ding, J. J. D. Leon, D. Sacchetto, and G. Cattaneo, “Fully textured monolithic perovskite/silicon tandem solar cells with 25.2% power conversion efficiency,” Nature Mater., vol. 17, no. 9, pp. 820–826, Sep. 2018.

[43] B. Chen, Z. Yu, K. Liu, X. Zheng, Y. Liu, J. Shi, D. Sprok, P. N. Rudd, Z. Holman, and J. Huang, “Grain engineering for perovskite/silicon monolithic tandem solar cells with efficiency of 25.4%,” Joule, vol. 3, no. 3, pp. 177–190, 2019.

[44] M. Jošt, E. Köhen, A. B. Morales-Vilches, B. Lipovský, K. Jäger, B. Macco, A. Al-Ashouri, J. Kré, L. Korte, B. Rech, S. Schlattmann, M. Topič, B. Stannowski, and S. Albrecht, “Textured interfaces in monolithic perovskite/silicon tandem solar cells: Advanced light management for improved efficiency and energy yield,” Energy Environ. Sci., vol. 11, no. 12, pp. 3511–3523, Dec. 2018.

[45] Oxford PV. (2018). Oxford PV Perovskite Solar Cell Achieves 28% Efficiency. [Online]. Available: https://www.oxfordpv.com/news/oxford-pv-perovskite-solar-cell-achieves-28-efficiency

[46] H. Ferhati and F. Djellal, “Exceeding 30% efficiency for an environment-friendly tandem solar cell based on Earth-abundant Se/CZTS materials,” Phys. E, Low-Dimensional Syst. Nanostuct., vol. 109, pp. 52–58, May 2019.

[47] M. Benaitcha, L. Dehimi, F. Pezzimenti, and F. Bouzid, “Simulation analysis of a high efficiency GaNP/Si multijunction solar cell,” Semicond., vol. 41, no. 3, 2020, Art. no. 032701.

[48] R. Curior, J. Benick, F. Feldmann, O. Höhn, H. Hauser, P. Beutel, N. Razeck, M. Wimpminger, B. Bläsi, D. Lackner, and M. Hermle, “III-V-on-silicon solar cells reaching 33% photovoltaic conversion efficiency in two-terminal configuration,” Nature Energy, vol. 3, no. 4, pp. 326–333, 2018.

[49] S. Essig, C. Allebé, T. Remo, J. F. Geisz, M. A. Steiner, K. Horowitz, L. Barraud, J. S. Ward, M. Schnabel, A. Descouedres, and D. L. Young, “Raising the one-sun conversion efficiency of III-V/Si solar cells to 32.8% for two junctions and 35.9% for three junctions,” Nature Energy, vol. 2, no. 9, 2017, Art. no. 17144.

[50] J. F. Geisz, M. A. Steiner, N. Jain, K. L. Schulte, R. M. France, W. E. McMahon, E. E. Perl, and D. J. Friedman, “Building a six-junction inverted metamorphic concentrator solar cell,” IEEE J. Photovolt., vol. 8, no. 2, pp. 626–632, Mar. 2018.

M. Mousa et al.: Simulation of Optimized High-Current Tandem Solar-Cells