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Study of the development of tandem solar cells to achieve higher efficiencies

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ABSTRACT

Tandem solar cells are the brand-new age revolution within the photovoltaic (PV) enterprise thanks to their higher power conversion efficiency (PCE) capability as compared to single-junction solar cells, which are presently dominating, however intrinsically restrained. With the appearance of steel halide perovskite absorber substances, manufacturing extremely efficient tandem solar cells at an inexpensive price can profoundly regulate the future PV landscape. It has been formerly seen that tandem solar cells primarily based on perovskite have confirmed that they can convert mild more efficiently than stand-alone sub-cells. To reap PCEs of greater than 30%, numerous hurdles have to be addressed, and our understanding of this interesting era has to be accelerated. On this, a technique of aggregate of substances was followed and via a modified numerical technique, it was decided what preference of substances for the pinnacle and bottom sub-cell consequences in a better fee of electricity conversion efficiency (PCE). Through this study, it was discovered that the use of germanium telluride (GeTe) backside subcellular together with perovskite (MAPbI3-xClx) as pinnacle subcell can offer an excessive performance of 46.64% compared to a tandem mobile with perovskite (MAPbI3)/CIGS and perovskite (MAPbI3)/GeTe which produce decrease efficiencies. SCAPS-1D was used to evaluate and simulate the overall performance of the developed tandem cells.

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1. INTRODUCTION

Solar electricity is an abundant supply of energy. Solar cells, which straightforwardly exchange over daylight hours into power via the photovoltaic (PV) effect, are extensively identified as the most suitable method for tapping into solar-powered power. In 1954, Bell Labs invented the primary solar cellular with a 6% power conversion efficiency (PCE) primarily in light of a silicon (Si) p-n intersection [1]. Considering that at that factor, there were noteworthy progressions in Si-primarily based solar-powered cellular innovation. Right now, multi-crystalline Si cells have a performance of 23.3%, single-crystal Si cells have an effectiveness of 26.1%, and Si-primarily based heterostructure solar cells have a performance of 26.7%. Be that as it could, developed in progress the PCE of Si-primarily based single-junction solar cells has been obliged through the shockley-queisser (S-Q) constraint of 29% for such devices [2]. Furthermore, copper indium gallium selenide (CIGS) might be a profoundly promising skinny-movie solar-powered mobile innovation that consolidates a lean tungsten disulfide (WS2) window layer and accomplishes a reenacted effectiveness of around 26.4% [3].

Recently, a becoming PV period dependent absolutely upon regular inorganic crossover metal halide perovskite substances (along with CH3NH3PbI3) has checked huge capacity to get more PCE than Si single-intersection cells [4]. From one viewpoint, steel halide perovskite substances flaunt magnificent optoelectronic capacities which incorporate an exorbitant ingestion coefficient, an extended supplier dissemination length, an inordinate help lifetime, and a low exciton restricting strength [5], [6]. Perovskite PV time, notwithstanding, has gotten monstrous interest for the explanation that starter statement of a perovskite-based thoroughly color sharpened sun oriented portable with a device execution of 3.8% in 2009 [7], [8]. From that point forward, broad endeavors in device structure enhancement [9], [10], perovskite synthesis designing [11], perovskite gem increment controlling [12], [13], perovskite mass and floor surrenders passivation [14], charge-shipping layer streamlining [15], [16], and gadget interface designing [17] were made to quickly increment instrument execution to an approved worth of 25.5% in 10 years of progress [18]. In this work, three unique proposed couples of solar cells are assessed and recreated at phenomenal settings using SCAPS-1D [19]. The (MAPbI3)/CIGS couple cell has an inordinate exhibition of 30.5%. The perovskite (MAPbI3) top sub-cell is then different from the perovskite (MAPbI3-xClx) sub-cell, which has better general execution boundaries due to better warm solidness and higher transporter dispersion lengths, resulting in an extreme execution of roughly 41.7%.

2. STRUCTURE OF PEROVSKITE TANDEM SOLAR CELL

Perovskite substances are significant for gentle assimilation and photoelectric change in solar cells. Straightforward perovskites are perovskite creations with single particles involving everything about A-, B-, and X-destinations. The five National Renewable Energy Laboratory (NREL) measurements with freely accessible data utilized A-site as well as X-site joined half and half perovskites. Improvement of substances and frameworks is prime to developing photoelectric change execution. One well-researched binary combined perovskite is MAPbI3-xClx, a perovskite shape created via doping Cl atoms with partly substituted I atoms. It has been stated in [20] that Cl doping expanded the stableness and conductivity of perovskite substances, and the diffusion duration of electrons and holes became higher than 1 m [20], [21]. The structures of the proposed tandem cells are as follows:

- Inside the main proposed couple solar cell, i.e., perovskite (MAPbI3)/CIGS, p.c filled in as a top subcell, and a CIGS solar cell filled in as the most minimal subcell. The perovskite (MAPbI3) goes about as an enthusiastic layer and is stacked among copper oxide (Cu2O) and PCBM (fullerene side-effect of the C60 buckyball), which act as the opening vehicle layer (HTL) and electron transport layer (ETL) separately.
- The second proposed tandem cell i.e., perovskite (MAPbI3)/GeTe includes the perovskite (MAPbI3) because the lively top subcell, while the germanium telluride (GeTe) subcell acts as the bottom subcell.
- In the 1/3 proposed tandem cell i.e., perovskite (MAPbI3−xClx)/GeTe, the perovskite (MAPbI3−xClx) acts as the top sub mobile sandwiched between CuO and ZnOS, which act as HTL and ETL, respectively.

Interface defect layers (IDLs) and transparent conductive oxides (TCO) are hired [22], [23]. The TCO is highlighted as an optically clear cathode, allowing photons to avoid the versatile and transporting the delivered electrons to the phone's external terminals. To make the device extra advantageous, the IDLs are utilized among the dynamic layer (MAPbI3-xClx) and the HTL layer, as well as among the lively layer (MAPbI3-xClx) and the ETL layer. The construction of the perovskite (MAPbI3), perovskite (MAPbI3-xClx) top subcells, and CIGS and GeTe rear subcells are displayed in Figure 1.

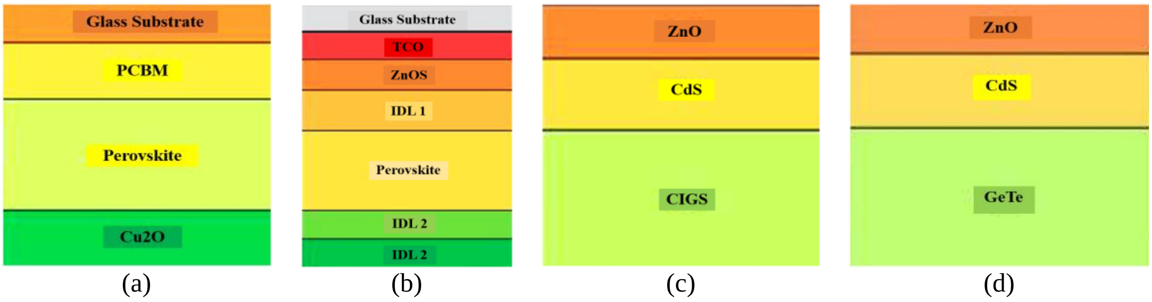

Figure 1. Cross section of (a) perovskite (MAPbI3), (b) perovskite (MAPbI3-xClx), (c) CIGS, and (d) GeTe subcells

3. EVOLUTION OF PEROVSKITE TANDEM SOLAR CELL

Interest in perovskite-based solar cells has flooded lately because of their superb photon assimilation effectiveness. Perovskite is an adaptable material equipped for accomplishing high change efficiencies for minimal price and is appropriate for the development of strong state solar cells because of its long lifetime of charge transporter partition, quick charge division, expansive ingestion range, and bigger mean freeways of electrons and openings [24]. The productivity of perovskite solar cells has worked decisively lately, arriving at more than 25% in 2021. Let us take a gander at the different perovskite solar cells present in the ongoing situation.

3.1. Perovskite/Silicon tandem solar cells

The most famous minimal expense pair choice currently being created consolidates a silicon base cell accompanying a mixture of perovskite top units. Analysis of perovskite-silicon sunlight-located containers has skillful abundant experience records, the ultimate current being by Oxford PV, a startup that got nearly 29.5% [25], [26]. It may be broadly classified into two types that is to say two terminal (2T) and four terminal (4T) perovskite/Si solar cells. The first perovskite-on-silicon 4T solar cell with a PCE of 17.9% was demonstrated by Bailie and partners in 2014. Given underneath is a figure illustrating the short timetable of the improvement of 2T and 4T Perovskite/Si couple cells. Figure 2 represents the stage diagram for the evolution of tandem perovskite silicon solar cell.

3.2. Perovskite/CIGS tandem solar cells

CIGS is a thin-film semiconductor material that has been used in solar cells since the 1980s. The first perovskite/CIGS tandem solar cell was reported in 2015 by researchers at the University of Oxford and achieved a power conversion efficiency (PCE) of 17.8%. Since then, the efficiency of perovskite/CIGS tandem solar cells has continued to improve. They are a successful, versatile, practical, and lightweight option [27], [28] because of their low carbon impression per kWh created. They can be created and interconnected straightforwardly on huge, super dainty polyimide sheets, making them promise for an extensive variety of earthly and space applications [29]. In 2018, scientists at École Polytechnique Fédérale de Lausanne (EPFL), a Swiss public research university specializing in science and innovation, revealed a perovskite/CIGS pair solar cell with a PCE of 23.26% [30]. In 2020, specialists at the NREL revealed a perovskite/CIGS pair solar cell with a PCE of 24.45%. Overall, the evolution of perovskite/CIGS pair solar cells has been driven by advances in both perovskite and CIGS solar cell technology, as well as improvements in tandem cell design and fabrication techniques [31], [32].

3.3. Perovskite/GeTe tandem solar cells

Perovskite/GeTe tandem solar cells are another turn of events in the field of perovskite solar cells that combine a perovskite solar cell with a germanium telluride (GeTe) solar cell. The efficiency of Perovskite/GeTe tandem solar cells has improved rapidly since the first report, with a PCE of 23.26% for a two-terminal tandem cell and a PCE of 26.7% for a three-terminal tandem cell. Researchers have been working to improve the stability of the perovskite layer by stabilizing additives and encapsulation materials. Companies such as Swift Solar and Oxford PV are actively developing tandem perovskite solar cell technologies.

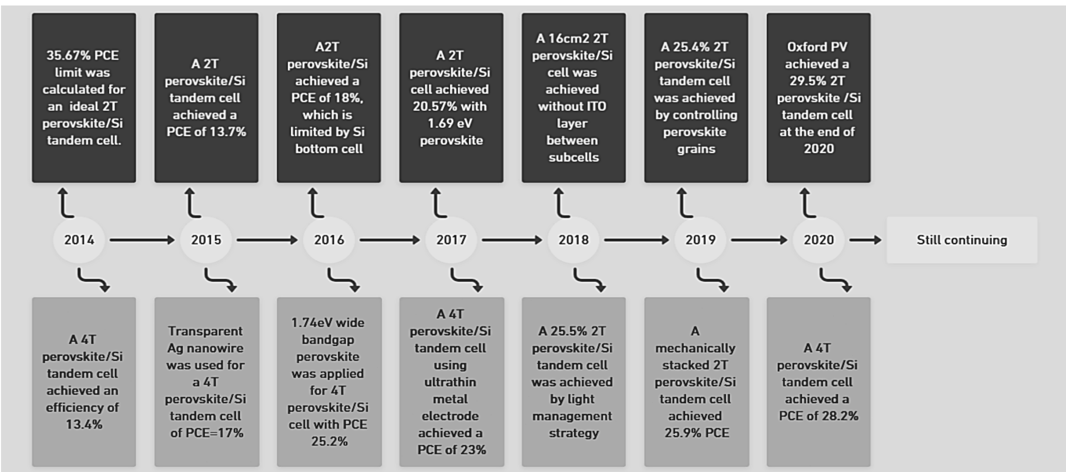

Figure 2. Stage diagram for the evolution of tandem perovskite silicon solar cell

3.4. MAPbI3-xClx/GeTe tandem solar cells

Mixed-halide perovskite materials, like $MAPbI_{3-x}Cl_x$, have attracted significant interest as a more effective option compared to pure $MAPbI_3$ in perovskite solar cells. The addition of chloride ions to the perovskite structure improves film formation, stability, and charge transport, resulting in enhanced overall device performance. Tandem solar cells incorporating $MAPbI_{3-x}Cl_x$ with germanium telluride (GeTe) have shown significant advancements in power conversion efficiency (PCE), rising from 17.3% in 2018 to 20.3% in 2019. This consistent progress underscores the promise of mixed-halide perovskites and tandem structures in advancing the frontiers of next-generation solar energy technologies.

4. THICKNESS OPTIMIZATION OF THE TOP SUBCELL

An improved numerical technique constructed at the idea offered by way of [33] is usually recommended in this paragraph. The proposed method improvement includes two phases for thickness (ts) optimization with two steps: a coarse step (tcs) of 50 nm and a fine step (tfs) of 50 nm. Primarily based on the anticipated thickness in each level, all of the junction's performance standards are determined. With fewer overall computations, the counseled adjustment quickens the process of determining the satisfactory pinnacle sub-cell thickness for the 2-connection tandem cellular. In addition, because of reality, the subsequent section's step is basically 5 nm, the best thickness not set in stone with more prominent exactness. the general thickness of the pair shape should not be more prominent than 50 m (an expected dispersion span to make specific free rate delivery to cathodes) [34], [35], but the posterior sub-cell layer thickness ought to be thick enough to accept in all in all parcel of the vehicle photons from the top sub-cell as plausible and become now not taken into worries in the streamlining framework.

5. SIMULATION AND RESULT

5.1. Tandem perovskite (MAPbI3)/CIGS cell

The proposed numerical method was used to perform simulations of optimized two-terminal perovskite (MAPbI3)/CIGS pair solar cells. In Figure 3(a), PCE=19.29%, FF=82.93%, VOC=1.2113 V, and JSC=19.1986 mA/cm^2. The most elevated proficiency of the paired cell happens when the ongoing densities of the two sub-cells are related, accompanying the safeguard coating density of 230 nm in the top sub-cell. The creation of a perovskite (MAPbI3)/CIGS couple container shows that the boundless bulk of the AM 1.5 range is exhausted for one top subcell and so forth is communicated to the base subcell. In Figure 3(b), PCE=21.82%, FF= 2.15%, JSC=42.55 mA/cm^2, VOC=0.6243 V for CIGS base subcell with occurrence sifted AM 1.5 range, VOC=0 V, JSC=19.33 mA/cm^2. PCE = 30.367% for perovskite (MAPbI3)/CIGS tandem solar cell in Figure 3(c).

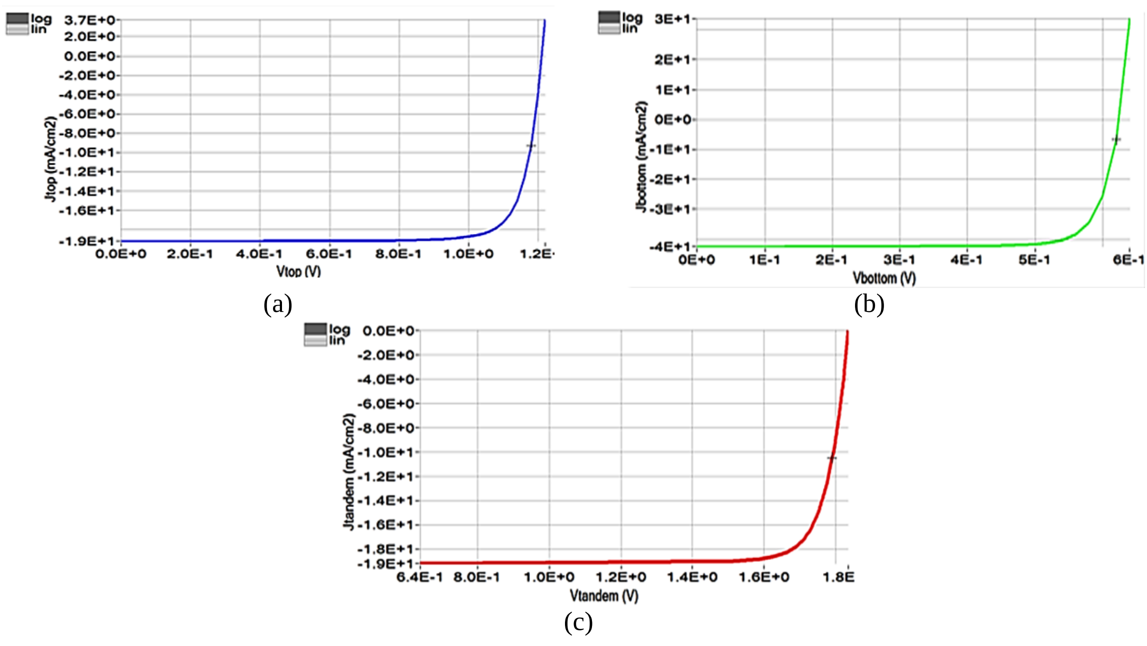

Figure 3. Structures of perovskite ($MAPbI_3$)/CIGS solar cells: (a) top cell, (b) bottom cell, and (c) tandem cell

5.2. Tandem perovskite (MAPbI3)/GeTe cell

The top subcell safeguard layer's thickness (685 nm) was resolved utilizing a streamlining mathematical methodology, yielding 37.489% productivity for the perovskite (MAPbI3)/GeTe pair solar cell. Top subcell thickness variation analysis revealed the optimal thickness attained by the suggested approach. With this absorber layer thickness, the perovskite (MAPbI3)/GeTe top subcell displays a PCE of 23.57%, FF of 78.76%, VOC of 1.1657 V, and JSC of 25.678 mA/cm^2. As expected, the top subcell's range of ingestion (at 685 nm) is bigger than that of the lower subcell, whose safeguard layer thickness is around 230 nm. The base subcell is getting a lower AM 1.5 separated range than the earlier couple cells. The base subcell, notwithstanding, yields a more noteworthy current thickness of around 25.90 mA/cm^2 because of the GeTe qualities, which are equivalent to the top subcell current thickness.

Figure 4 shows the J/V bends of perovskite (MAPbI3), GeTe, and perovskite (MAPbI3)/GeTe pair solar cells. Perovskite (MAPbI3)/CIGS tandem solar cells have a PCE of 30.367% with a JSC of 19.33 mA/cm^2. GeTe bottom subcells have a PCE of 16.46% with FF of 82.10%, VOC of 0.6035 V, and JSC of 53.39 mA/cm^2. VOC = 1.764 V, JSC = 25.92 mA/cm^2, FF = 81.81%, and PCE = 37.48% for perovskite MAPbI3/GeTe tandem cell.

5.3. Tandem perovskite (MAPbI3-xClx)/GeTe cell

The perovskite (MAPbI3-xClx)/GeTe tandem solar cell has been replaced with an optimized perovskite (MAPbI3-xClx) sub-cell, resulting in a 46.64% efficiency and identical densities of both sub-cells, as illustrated in Figure 5. The projected optimization mathematical approach was used to gain the density of the top subcell safeguard coating (525 nm). The perovskite (MAPbI3-xClx)/GeTe pair cell usually has a bigger usually open-circuit voltage than the perovskite (MAPbI3)/GeTe tandem cell. With this safeguard layer thickness, the perovskite (MAPbI3-xClx) top subcell has a PCE of 31.65%, FF of 89.73%, VOC of 1.345 V, and JSC of 26.22 mA/cm^2. This outcome in a more prominent corresponding current density points and greater open-circuit generated power, which enhances the tandem perovskite (MAPbI3-xClx)/GeTe cell's overall performance metrics. The top sub-cell absorbs nearly equal to perovskite (MAPbI3) in awareness (826 nm). Figure 5(a) shows the band diagram of the top subcell responsible for high-energy photon absorption, Figure 5(b) illustrates the bottom subcell optimized for low-energy photons, and Figure 5(c) presents the tandem configuration that integrates both subcells for improved efficiency. Figure 5 portrays the J/V bends of perovskite (MAPbI3-xClx), GeTe subcells, and a perovskite (MAPbI3-xClx)/GeTe pair solar cell. In a GeTe sub-cell, PCE is 26.46% with FF = 82.10%, VOC = 0.603 V, and JSC = 53.397 mA/cm^2. In a perovskite (MAPbI3-xClx)/GeTe tandem solar cell, PCE is 46.64% with FF = 80.09%, VOC = 1.947 V, and JSC = 29.61 mA/cm^2.

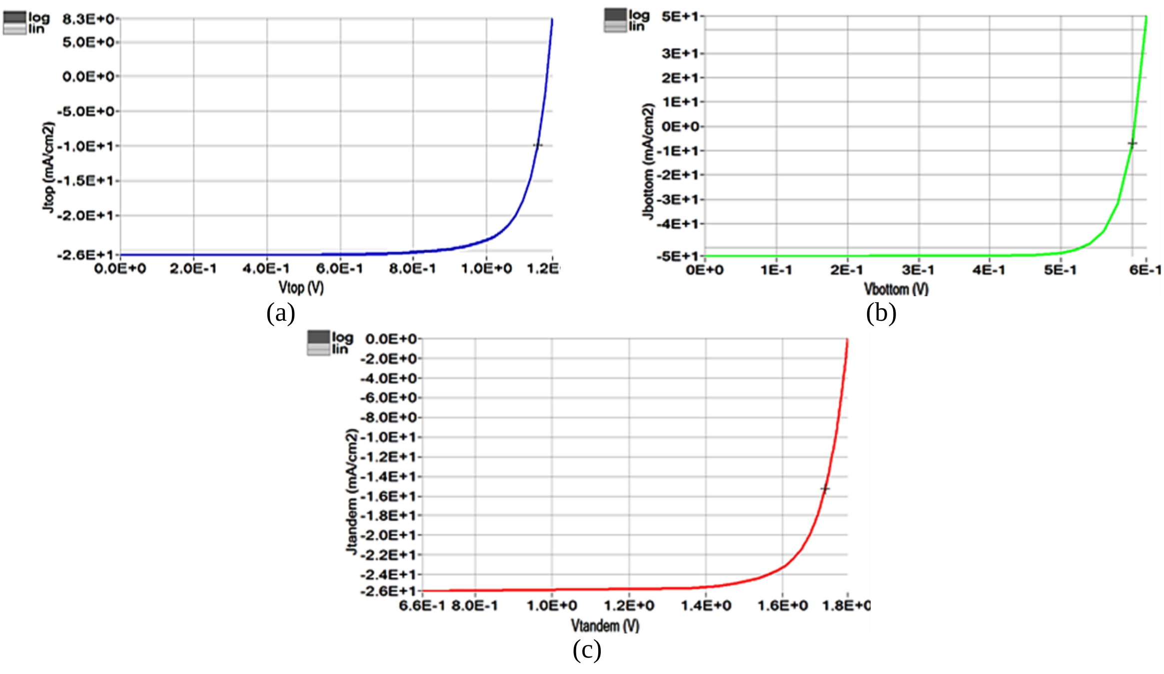

Figure 4. Structures of perovskite ($MAPbI_3$)/GeTe solar cells: (a) top subcell, (b) bottom subcell, and (c) tandem structure

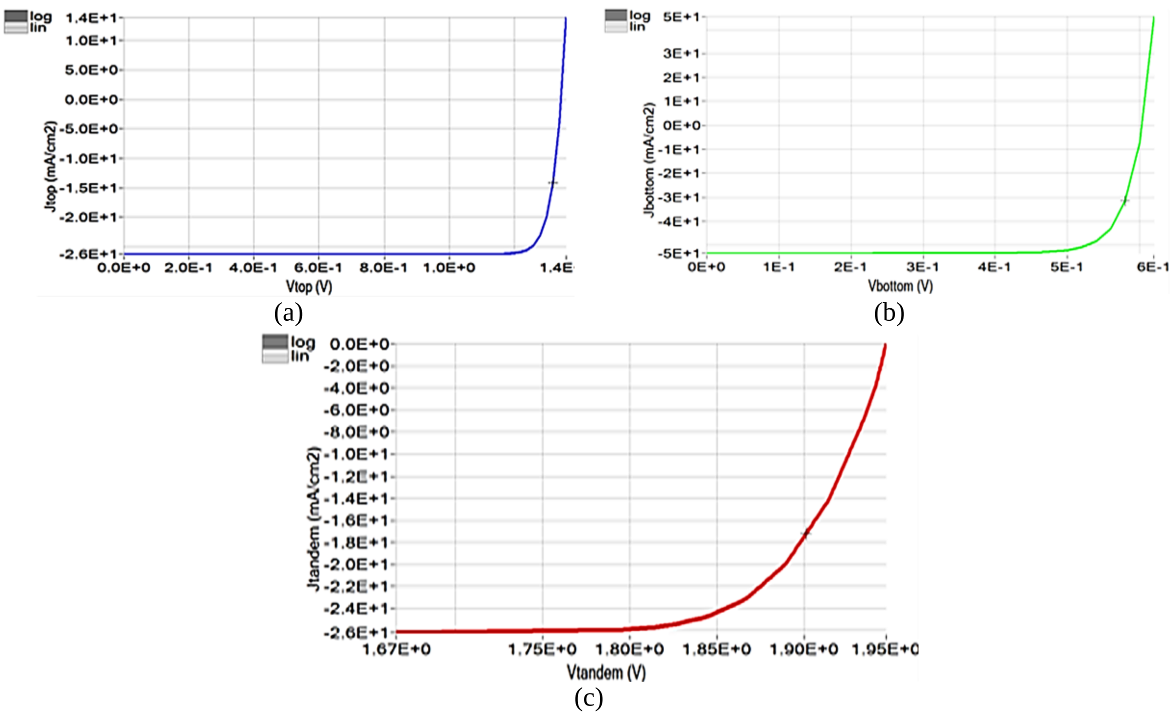

Figure 5. Schematic structures of perovskite ($MAPbI_{3-x}Cl_x$)/GeTe solar cells: (a) top subcell configuration, (b) bottom subcell configuration, and (c) tandem cell configuration

6. FUTURE CHALLENGES AND STRATEGIES

Perovskite solar cells have proven promise in photovoltaics because of their excessive performance, low-price fabrication approaches, and capability for flexible and light-weight packages, but a couple of challenges should be overcome earlier than they can be extensively applied and positioned into providers. These encompass balance and staying power, risky and ecological effects, flexibility and production, efficiency and performance, interface and interfacial engineering, standardization and reproducibility, and device characterization strategies. Tandem solar cells manufactured from perovskite and CIGS require stability and durability, a suitable tandem tool structure, manufacturing and scaling capability, and interface engineering. Tandem perovskite/GeTe solar cells combine the advantages of perovskite and GeTe substances to supply accelerated performance and stability. But numerous obstacles must have triumphed over earlier than can be successfully carried out and commercialized, including interface optimization, balance and durability, band alignment and absorption matching, cloth selection, and device engineering. Manufacturing techniques must be scalable and cost-effective, with defect and first-class management, a green and optimized tandem structure, and upscaling and reliability. Collaboration amongst academia, enterprise, and research institutions is essential to overcoming these limitations and progressing Perovskite/GeTe tandem solar cell generation.

7. CONCLUSION

Multi-crossing solar cells are a superior selection for producing solar cells accompanying extreme power-change adeptness because they can swallow a bigger range than single-intersection solar cells. The capacity to retain a more extensive range and have more powerful change effectiveness improves as the number of connections increases. Simultaneously, this adds to the intricacy and price of the cell. This work employs just two-intersection solar cells, resulting in high efficiency. This is accomplished by addressing one of the primary issues with two-terminal couple solar cells, as the subcell accompanying the lowest current (fundamentally) pushes the coupled cell to run at its ongoing thickness. Since GeTe is utilized as a safeguard in the base subcell, the base subcells have a high current thickness, permitting the two cells to work at a larger current, which further develops couple-cell execution. A changed calculation for enhancing the dimension of the head sub-cell layer is likewise proposed. The projected couple cell of MAPbI3/CIGS has a proficiency of 30.5% in recreations; from that point, GeTe is employed in the role of a base sub-cell to displace the CIGS (accompanying the equivalent doping and denseness), extending the output to 35.9%.

Supposedly, supplanting the MAPbI3 top subcell accompanying MAPbI3-xClx causes success with a higher output of 41.73%, which is an individual of ultimate powerful transformation effectiveness known for pair cells. Each of the proposed cells enjoys the benefit of just having two associations, which essentially lessens the complexity and expense of sun-powered cells.

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AUTHOR CONTRIBUTIONS STATEMENT

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Umamani Subudhi		✓	✓		✓	✓		✓	✓	✓	✓			
Arun Kumar Sahoo		✓	✓		✓	✓		✓	✓	✓	✓			
Surender Reddy Salkuti	✓	✓		✓		✓	✓	✓	✓	✓		✓	✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

DATA AVAILABILITY

The datasets used and/or analyzed during the current study are available from the corresponding author, [SRS], on reasonable requests.

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