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Technical and economic assessment of perovskite solar cells for large scale manufacturing

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In this paper, we have carried out detailed technical and economic assessment of perovskite solar cells for large scale manufacturing. For ultra-small area of the order of 0.1 cm^2, efficiency of 20% or so are reported. However, for area of 25 cm^2, the efficiency is about 10%. Based on the photovoltaic module manufacturing requirements of no constraint on the supply of raw materials, low variability of every key process and process-induced defects, low cost of manufacturing, prospects for further cost reduction in the future, green manufacturing, and long-term reliability, there are absolutely no prospects of manufacturing perovskite solar cells. No one has commercialized perovskite solar cells. Thus, contrary to hype in the literature, there is no truth that perovskite solar cells will replace silicon solar cells. We have also examined the role of perovskite solar cells for increasing the efficiency of silicon solar cells and found unsuitable both for two and four terminal device architectures. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4927329]

I. INTRODUCTION

For sustainable global economic growth, electricity is a vital resource that enables and empowers individuals and societies. Free incident solar power per year on earth is 23 000 TWy,[1] and can be a sustainable energy source to humanity.[2] 1 h of incident solar energy is equal to all the energy used in 1 year on our planet. Commercially, solar energy can be converted into electricity by following two approaches: (i) use of photovoltaic (PV) devices with or without concentration, and (ii) use of concentrated solar power (CSP). We have explained the limitations of CSP at length to compete with PV devices.[3] Very recent economic data further support the limitations of CSP to compete with PV devices for generating electricity.[4] The global cumulative installed PV capacity has reached the 180 gigawatt (GW) milestone at the end of year 2014, and is expected to increase by 177% from 2014 levels to reach almost 500 GW (498 GW) mark by the end of 2019.[5] Over 90% of PV market share consists of non-concentrator bulk silicon solar cells.[3] Thus, the future direction of research in photovoltaic devices must take into consideration the current manufacturing trends of the PV devices in the global context of electricity generation.

In recent years, perovskite solar cells or organo-metal halide perovskite (OHP) have received lot of attention.[6–8] The general field of photovoltaics is 60 years old (started in 1954 with the report of 6% efficient silicon solar cell), and the terrestrial photovoltaics is 42 years old (a lot of research started just after oil embargo of 1973). Future research direction of PV must follow the path that will lead to the capability of providing the cheapest electricity in the 21st century.[9] Based on the existence of a wide variety of fundamental technical and economical knowledge base, the purpose of this paper is to examine the potential of perovskite solar cells for large scale manufacturing.

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II. POTENTIAL OF PEROVSKITE SOLAR CELL

The perovskite materials, mostly composed of organic, metal, and halogen, are easy to synthesize. The common formula includes $CH_3NH_3(Pb,Sn)X_3$, where X = halogen (mostly I, Br, or Cl). It is also common to use $MAPbI_3$ to indicate $CH_3NH_3PbI_3$ where M = CH_3(methyl) and A = NH_3 (amino). One of the early works in 2009, Ref. 10, demonstrated the efficiency of 3.81% (with $CH_3NH_3PbI_3/TiO_2$), and open circuit voltage of 0.96 V (with $CH_3NH_3PbBr_3/TiO_2$) was reported. The work of Ref. 10 sparked interest among chemist, material scientists, and engineering community. As shown in Fig. 1, the efficiency of perovskite solar cells has made steady progress, and is now higher than organic solar cells and it competes with other thin film solar cells.

Progress in reported efficiency of small area devices and the increase in the number of publications are the key reasons for media attention.[12–14] However, it should be noted that the exponential growth in publications and increase in efficiency do not necessarily translate into real world success, and it does not guarantee that the product will be manufactured. There are many such examples in the semiconductor world. As an example, the names of "nano material," "nano technology," and carbon nano tubes (CNTs) have received tremendous attentions from academic and industrial researchers. CNT based transistors were proposed for replacing silicon complementary metal oxide (CMOS). As early as 2002, it was stated[15–17] that due to manufacturing related fundamental limitations, CNT based transistors cannot replace silicon CMOS. The fundamental reason is that there is a need for a higher level of control of the process variation which is far beyond than what is currently achievable through conventional methods.[17] Thus, without inventing a fundamentally new process control, CNT cannot be used in semiconductor devices where the performance of integrated system depends on acceptable manufacturing variation of each CNT.[18] Attempt to start a commercial process of manufacturing CNT based flash memory by a startup company called "Nantero" failed miserably to launch the proposed new product.[19] Thus, it is very important to examine the fundamental manufacturing requirement of a solar cell. In Sec. III, we have examined key manufacturing considerations.

III. MANUFACTURING CONSIDERATIONS FOR PEROVSKITE SOLAR CELLS

The key considerations for large scale manufacturing of any new solar cell (including perovskite solar cells) are following:

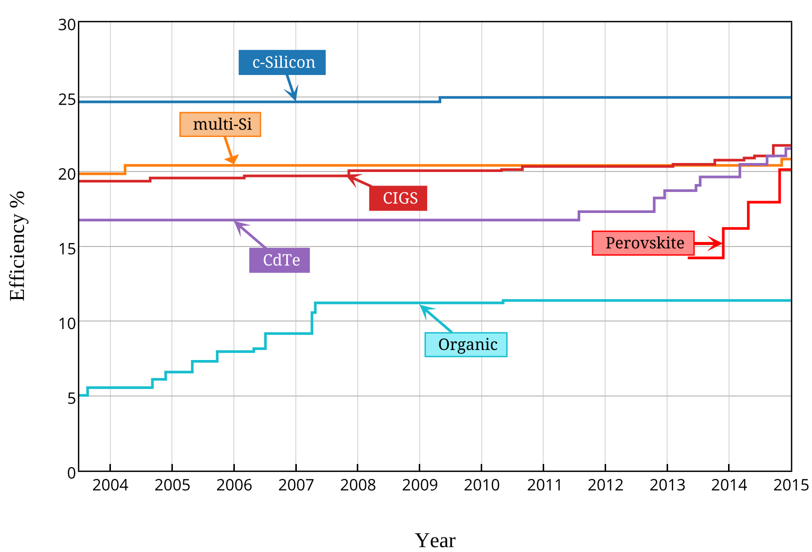

FIG. 1. Perovskite cells have demonstrated a very rapid rise in efficiency in few years. Data from Ref. 11.

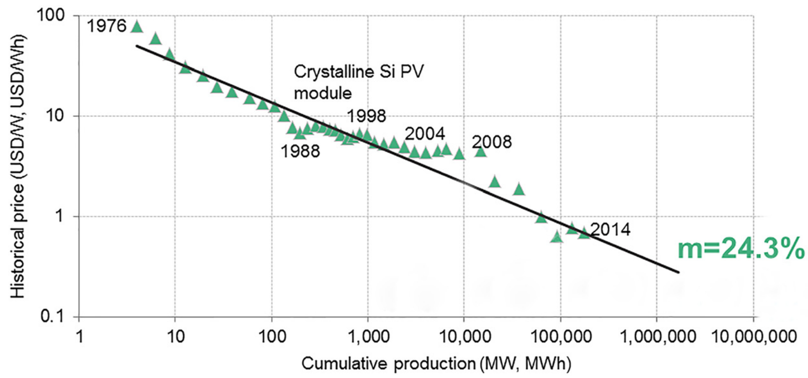

FIG. 2. Learning experience curve of bulk silicon PV module manufacturing. Adapted with permission from V. Sivaram, "Why Moore's law doesn't apply to clean energy technologies," 2015, see http://www.greentechmedia.com/articles/read/why-moores-law-doesnt-apply-to-clean-technologies (last accessed May 20, 2015). Copyright 2015 Bloomberg New Energy Finance.

A. Efficiency considerations and variability

In case of non-concentrated silicon solar cells, the highest efficiency reported to date is 25%.[3] With huge investment already on bulk silicon solar cells, perovskite solar cells will need to demonstrate more than 30% efficiency as a large area single junction cell.[3] In addition, the manufacturing cost of PV modules based on perovskite solar cells must be lower than the cost of bulk silicon PV modules. As shown in Figure 2,[20] the cost of PV modules based on bulk silicon is reduced by about 24% when the cumulative manufacturing production is doubled. In any manufacturing, controlling the process variability is very crucial.[21] The issue of process variability and its effect on the performance of photovoltaic module has been discussed at length in our previous publication.[3] The worst performing cell will dominate the power output, and pull down the overall power output and performance of the entire module. Fig. 3 shows the percentage difference of laboratory scale reported cell efficiency and manufactured module efficiency.[22–29] The variation of voltage, current, and resistance contribute to this decrease in efficiency of the manufactured modules.

In a news article, the best perovskite solar cell efficiency of 20.1% has been reported.[8] The authors referenced in news article of Ref. 7 have also published a recent article in open

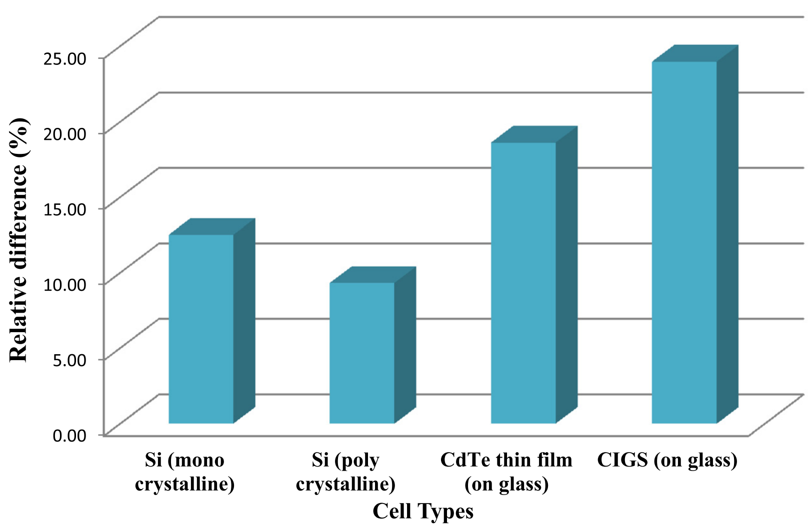

FIG. 3. Relative difference in module efficiency and cell efficiency of some single junction solar cells. Data from Refs. 22–29.

literature and claimed efficiency of 18.4%.[30] A careful study of Ref. 30 (specifically Figure 3(a) in Ref. 30) shows that 18.4% efficiency of solar cell with an area of 0.096 cm^2 is the average of forward and reverse bias sweep of 17.8% and 19%, respectively. Such practice of averaging forward and reverse bias sweep is not in line with real world application of solar cells for generating power. In addition, the hysteresis curve obtained in reverse and forward bias indicates inherent reliability problem of the devices reported.[30] When a module with 10 perovskite solar cells (each cell is postage stamp size) is fabricated, the module efficiency is only 12%.[31] A statistical analysis showed that increase in standard deviation of solar cell parameters has direct impact on power output, and power loss is a function of parametric variation.[3] In worst case scenario, a severe fault in one or few cells may even render a module unusable.

To provide controlled process variability, semiconductor industry uses advanced process control in place of statistical process control.[32] This adds to the capital cost of manufacturing equipment and operating cost of particular process equipment. In addition to that, for a new type of solar cells, the cost of custom built processing equipment is much higher than "off the shelf" equipment used by silicon solar cell manufacturers. This issue of process control has been one of the fundamental reasons for failure of over 200 companies that started in 2008 with the goals of inventing and commercializing disruptive PV technologies; most of these companies have either gone bankrupt or do not exist anymore.[3]

B. Large area device performance and series resistance

Besides the scaling up issues mentioned above, there are series resistance issues that get masked when cells of smaller size are tested and reported. As shown in Ref. 33, if a solar cell is smaller than a certain size, the measurements will not reflect the effects of series resistance. This is due to the fact that the resistance of the solar cell is a non-linear function of current as the current-voltage relation is given by

$$I - \frac{V - IR_s(I)}{R_{sh}} = I_0\left[e^{\frac{V-IR_s(I)}{V_{th}}} - 1\right] - I_L\,, \tag{1}$$

where

$$R_s(I) = R_1 + R_2 + R_3 + \frac{I_L R_3}{I}\,. \tag{2}$$

Here, I_0 is the reverse saturation current, I_L is photo-generated current, V_{th} is thermal voltage, R_{sh} is shunt resistance, V is external voltage, and I is external current. R_1, R_2, and R_3 are linear contact resistance, lumped value for front layer sheet resistance, and base resistance, respectively. Based on the methodology of Ref. 33 and using AM 1.5 G spectrum, the minimum area to demonstrate series resistance effects for a solar cell of band gap of 1.5 eV (under ideal condition when all photo generated carriers are collected) should to be at least 0.35 cm^2 in size.[9] However, many studies on perovskite cells are done on much smaller cells. For 0.09 cm^2 perovskite solar cell, the reported efficiency was 12.04%, but for 0.98 cm^2 size, it dropped to 8.27%.[34] In contrast, 25.6% efficiency was reported for 143.7 cm^2 Si solar cells.[35] In another investigation,[36] a 5 cm × 5 cm perovskite module with 12 cells was reported, and the resulting efficiency was only 9.9%. The lower efficiency of less than 10% on area as small as 25 cm^2 is one of the fundamental reason that the hype of perovskite solar cells has no relevance of manufacturing these devices for commercialization.

C. Lead-free manufacturing

When selecting the candidate material for solar cell, the material should be nontoxic and lead-free.[3] Most of the perovskite research has been conducted with Pb based materials. In Ref. 37, news on lead free perovskite is reported. However, no data have been reported about

the efficiency and electrical properties of Pb-free perovskite solar cells. Comparison of performances of halides of Pb, Sn, and Pb-Sn alloys revealed that the complete elimination of Pb from the perovskite compound causes a significant drop in photo conversion efficiency.[38] Another investigation reported Pb-free perovskite cells with several halogen combinations of $CH_3NH_3SnI_{3-x}Br_x$ (x = 0, 1, 2, 3), but the efficiency was below 10%.[39] Lead based perovskite solar cells do not meet the environment, health, and safety criterion of manufacturing solar cells.[3]

D. Stability and reliability

The stability issues will be a major roadblock for commercialization of perovskite solar cells. For increasing stability, the use of mixed halide $CH_3NH_3PbI_{3-x}Cl_x$ had been proposed, and its use also makes the diffusion paths longer.[40] In Ref. 41, it was reported that the higher Br content (>20%) provides better stability, but lower Br content (<10%) leads to better efficiency. These two conditions are contradictory to each other. In another study, the authors reported that even after encapsulation, perovskite cells lost 20% of initial photo conversion efficiency after 500 h of exposure.[42] Another investigation pointed out that the instability in cells with TiO_2 may arise from light-induced desorption of surface-adsorbed oxygen and proposed the use of Al_2O_3.[43] Moreover, Al_2O_3 has also been reported to aid power conversion efficiency.[44] However, encapsulation or the use of Al_2O_3 could not prevent the degradations which were identifiable in 5 h exposure of light.[43] It is worth mentioning that for competing current commercial PV modules, the perovskite PV modules must have a life time of at least 30 years. A report prepared by the U.S. National Renewable Energy Laboratory (NREL) revealed that c-Si modules have an average degradation rate of only 0.47% per year (installed before year 2000) to 0.36% per year (installed after year 2000).[45] In another study, Si solar modules that were exposed to sunlight for 25 years lost only 3.8% in between measurements in 1985 and 2006.[46] Si based solar cell manufacturers provide warranties that state the modules would keep operating within a small and defined degradation.[47] The best warranty in the market promises 95% and 87% of their peak performance in first 5 years and at the end of 25 years, respectively.[48] The reliability data of silicon solar cells have shown that silicon solar cells can operate very well beyond the 25 years warranty given by the manufacturers. Sun Power has published[49] that useful life of their modules is more than 40 years, which is defined as 99% of modules producing at least 70% of their power.

E. Cost of ownership (COO) issues

Before establishing the technology of any new type of solar cell, there are many established capital cost and operating cost issue that need to be dealt carefully. Among those, the COO of any equipment is very crucial.[50] Detailed cost analysis of perovskite solar cell is not available except some comments about expected prices.[37] However, it should be noted that this is just a projection, and no mathematical details or supply chain data are available for perovskite solar cells.

IV. FUTURE GROWTH OF THIN FILM SOLAR CELLS IN THE CONTEXT OF GLOBAL PV MARKET

Falling prices of PV modules[51] are largely responsible for exponential growth of PV industry in recent years.[52] As shown in Fig. 1, there has been no major improvement in the efficiency of silicon solar cells since 1999. The thin film market share has been decreasing every year, and is expected to decrease in the future.[53] The thin-film PV module share is expected to decline from 8% in 2014 to 7% in 2015, compared to 15% market share in 2010.[5]

We do not wish to convey the message that there is no future of thin film PV module manufacturing. We have shown in Sec. III that thin film PV modules have limited success in competing directly with bulk silicon PV modules. The most successful thin film company, First Solar, is not only a PV module manufacturer but also project developer, and eventually

involved directly or indirectly in selling electricity to the customers.[54] There are niche markets where thin film PV modules have the potential of playing a very important role. Building integrated PVs (BIPV) and throw away products are two markets where thin films PV may make a very important contribution.[3] To date, there is no thin film technology that can penetrate the above mentioned markets.

V. PERFORMANCE EVALUATION OF PEROVSKITE PV AS TOP LAYER IN TWO-JUNCTION AND FOUR-TERMINAL ARCHITECTURE

Due to lattice matching and ultra-low interface defects features, conventional tandem cells have been successful only in the case of III–V compound semiconductor solar cells. For other structures, no significant progress has been made in the last 60 years. In a previous publication,[3] we have demonstrated that the only way to increase the efficiency of bulk silicon solar cells is to use the multi-junction multi-terminal architecture.

In Fig. 4,[3] we have shown the use of thin film as top junction material in the fabrication of two-junction and four-terminal (TJFT) device architecture. In this section, we have examined the role of perovskite solar cells in the development of architecture shown in Fig. 4. The absorption coefficient of Si,[55] along with another perovskite material[56] is shown Fig. 5.

We have used ideal conditions to calculate the efficiency of TJFT structure. Following are the key assumptions: (a) The thickness of silicon solar cells is 180 μm; (b) each absorbed photon contributes to one electron-hole pair, and only one minority carrier contributes to photocurrent; (c) all generated minority carriers are collected at electrodes, and no bulk or surface recombination takes place; (d) no photons are reflected; and (e) the presence of electrodes, hole

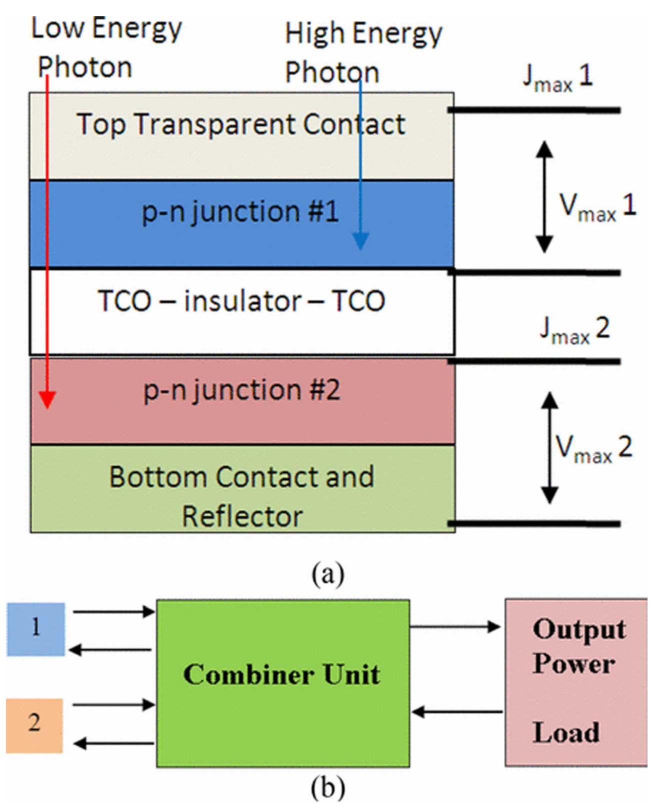

FIG. 4. (a) Schematic of the proposed two-junction four terminal solar cell. (b) External circuitry to combine electricity from two junctions. Reprinted with permission from Singh *et al.*, "Making solar cells a reality in every home: Opportunities and challenges for photovoltaic device design," IEEE J. Electron. Devices Soc. **1**(6), 129–144 (2013). Copyright 2013 IEEE.

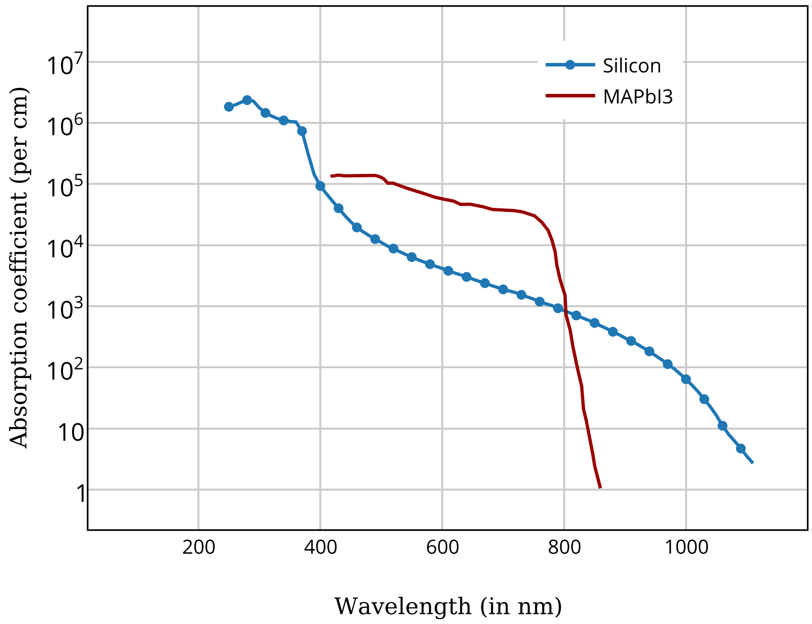

FIG. 5. Absorption coefficient of silicon and a perovskite material ($MAPbI_3$) at different wavelengths. Data from Refs. 55 and 56.

transport layer, glass, etc., are ignored, and only perovskite material ($CH_3NH_3PbI_3$) and Si absorb the photons. These assumptions do not represent the real world situation, but allow us to visualize the highest possible performance that can be achieved by the combination of perovskite material and Si.

In Fig. 6, we have calculated theoretical efficiency of individual cells (individual layers) in TJFT structure as a function of thickness of the top $CH_3NH_3PbI_3$ perovskite solar cell. The absorption coefficient data of Fig. 5 are used to calculate the theoretical efficiency of top and

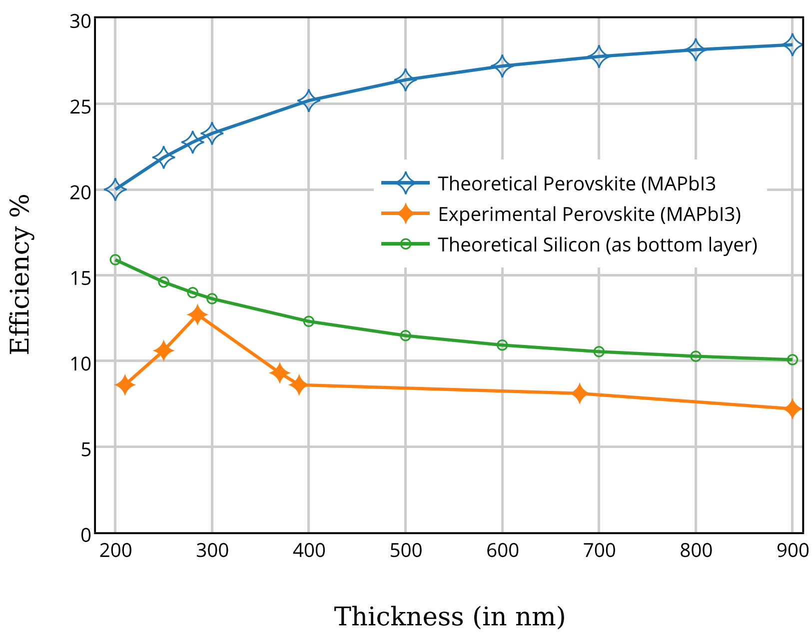

FIG. 6. Efficiency of perovskite (top layer) and Si (bottom layer) as individual cells as parts of TJFT structure. Experimental perovskite data from Ref. 57.

bottom cells. For different values of thickness, the theoretical efficiencies of Si cell and $MAPbI_3$ cell are compared against the experimental values of efficiency of $MAPbI_3$ solar cells from Ref. 57. Due to the absence of bulk and surface recombination in theoretical calculations, the efficiency of perovskite solar cells keeps increasing with thicker solar cells. However, as the experimental data[57] of Fig. 6 show, after certain thickness, the efficiency starts decreasing for perovskite cells with the increase in thickness.

Fig. 7 shows a comparison of internal photon conversion efficiency (IPCE) of Si, $CH_3NH_3PbI_3$ ($\approx MAPbI_3$), $CH_3NH_3PbI_2Br$ ($\approx MAPbI_2Br$), and $CH_3NH_3SnI_2Br$ ($\approx MASnI_2Br$) solar cells.[34,39,58,59] If we compare $CH_3NH_3PbI_2Br$ and $CH_3NH_3SnI_2Br$, it is evident that the substitution of Pb by Sn causes drop in IPCE. The data clearly show that except at certain wavelengths, the IPCE's of perovskite solar cells is far below than that of Si solar cell. Due to high absorption coefficient (Fig. 5), the top layer perovskite cell will absorb more photons, yet produce less photocurrent due to lower values of IPCE.

In Fig. 8, we have compared the theoretical performances of 2-terminal and 4-terminal devices where the top layer is perovskite solar cell and the bottom layer is silicon solar cell. As can be seen from Fig. 8, the efficiency of 2-terminal solar cell is lower than the efficiency of 4-terminal device. In 2-terminal arrangement, both layers have different photocurrent, but the smaller current becomes the current for the whole arrangement. These results demonstrate that only for ultra-thick and ultra-high performance materials (not invented yet), under ideal conditions, it is possible to achieve efficiency of perovskite/silicon solar cells of the order of about 35%. However, in real world, due to limited diffusion length of perovskite solar cells, such high efficiency values cannot be achieved. Experiments performed on 2 terminal perovskite/silicon solar cells support our prediction. The efficiency of perovskite/silicon solar cell is only 13.7%.[60] One can argue that the cost of 4 terminal perovskite/silicon soar cell will be significantly higher than the cost of silicon solar cells. This will not be true, since the major cost contributor of silicon solar cells is glass. As compared to 25% efficiency of silicon solar cells, if the four terminal architecture can achieve additional 10% efficiency, the additional cost will be justified. With silicon as the base material, the optimum energy gap for top solar cell is about 2.0 eV,[3] which is not the case of perovskite solar cells.

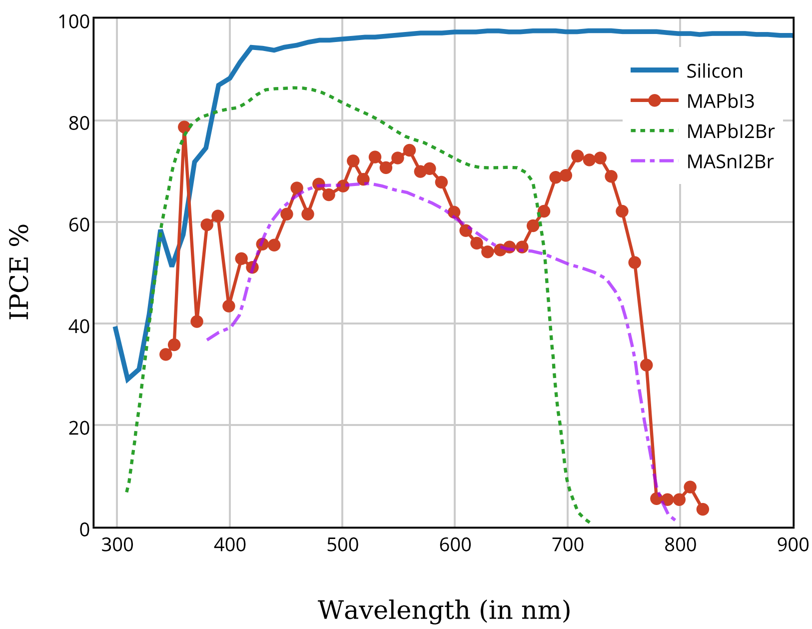

FIG. 7. IPCE of Si, $CH_3NH_3PbI_3$, $CH_3NH_3PbI_2Br$, and $CH_3NH_3SnI_2Br$ solar cells. Data from Refs. 34, 39, 58, and 59. (Here, M = CH_3 and A = NH_3).

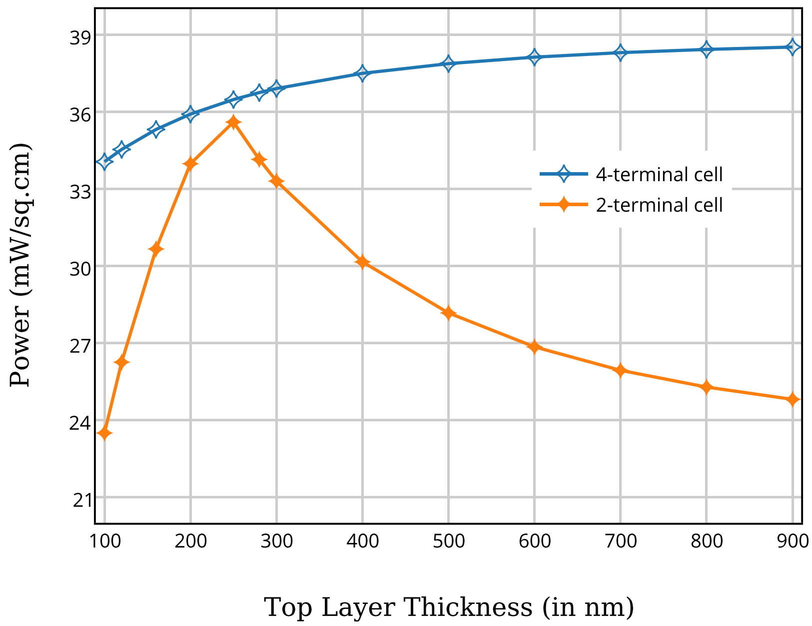

FIG. 8. Theoretical maximum power that can be harvested by 2-terminal and 4-terminal tandem cell (with Si and $MAPbI_3$). Si thickness is 180 μm.

VI. ECONOMIC ASSESSMENT

A convergence of distinct forces namely, low cost photovoltaics system for power generation, falling prices of batteries for storing electrical power, carbon emission problems, rising cost of residential electricity, and the dominance of semiconductor based electronics in every sector is making it possible to transform the aging centralized alternating current (ac) electivity infrastructure in the United States and other developed economies by local direct current (dc) power based electricity infrastructure without the need for a long-range transmission and distribution network. Using free fuel of Sun, the local dc power generated by PV and stored in batteries is the only way to remove global energy poverty. Photovoltaics industry is one of the highest growth industries. Silicon based PV modules have taken the same role in power industry as has been the role of silicon CMOS based integrated circuits in microelectronics and nanoelectronics. In an earlier publication,[3] we have outlined the following economic requirement for manufacturing any PV module: (a) no constraint on the supply of raw materials, (b) the low variability of every key process and process-induced defects, (c) low cost of manufacturing, (d) prospects for further cost reduction in the future, (e) green manufacturing to avoid environmental, health, and safety problems, and (f) long-term reliability of PV modules. An examination of the performance and reliability data of perovskite based solar cells shows that these solar cells are not meeting manufacturing criterion. With huge investment in bulk silicon based PV module manufacturing and the success of PV industry, it is impossible for perovskite solar cells ever to enter into manufacturing. The hype created in the literature has no economic evidence to support the claim that silicon solar cells will be replaced by perovskite solar cells.

VII. CONCLUSION

In this paper, we have investigated the prospects of perovskite solar cell technology for practical applications. High efficiencies in the 20% range have been reported for ultra-small device areas of the order of 0.1 cm^2. For device area of 25 cm^2, the efficiency is of the order of 10%. In addition to the low efficiency, there are major issues of stability and toxicity of Pb. PV market is growing exponentially, and is based almost entirely on bulk silicon solar cells. The thin film share of the PV market is constantly decreasing. Thus contrary to the hype in the literature, there is no truth that perovskite solar cells will replace silicon solar cells. There is no

future of perovskite solar cells to increase the efficiency of silicon solar cells either by using two or four terminal device structure.

ACKNOWLEDGMENTS

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