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Innovative Silicon Based PV Technologies to Reduce Electricity Production Costs

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The cost/watt of the solar cell has dropped so fast that manufacturing cost is a small fraction of the total costs for energy production, which are mainly driven by balance of system and commodity materials. Actually, increasing efficiency and average energy generation are the most powerful levers for overall cost reduction in photovoltaics (PV).

Silicon Heterojunction Technology (HJT) is an innovation in PV, which can win the competition with mainstream technologies. By leveraging on high efficiency, thermal stability, lower degradation per year and high bifacial factor, HJT solar cell can lead to a remarkable reduction of the levelized cost of energy (LCOE) in €/kWh. [1, 2].

The fabrication process of HJT solar cells is simpler and makes it the most performing technology based on silicon. HJT can rely on the compatibility with several advances enabling the solar cell to overcome the theoretical limits of silicon, aiming at achieving more than 30% energy conversion efficiency.

Tandem solar cells are the most promising path to increase PV module performances, several approaches are explored to find a tandem structure, which can be industrialized. Coupling with an HJT bottom cell can be a viable path to obtain an industrial application.

We report on the efforts for the development and industrialization of innovative Si heterojunction technology towards more than 25% efficiency, as well as on the activities to overcome the theoretical limits of silicon, aiming at more than 28%, through implementation of multiple junction structures.

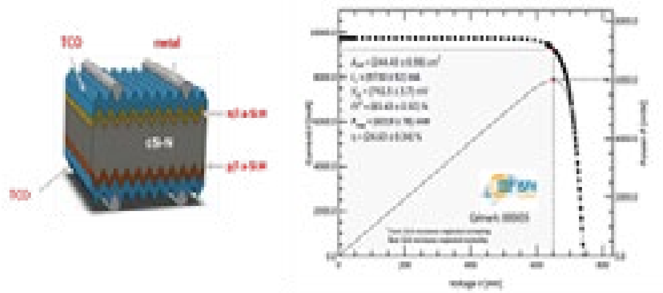

Fig.1: (a) Structure of a Si-HJT solar cell consisting of thin intrinsic and n or p doped hydrogenated amorphous silicon layers (few nanometers) deposited on the front and on the back surfaces of a n-type silicon wafer. (b) Recent efficiency record for a bifacial HJT solar cell obtained with an industrial process on commercial size solar cell (156.75 mm 156.7 mm Wafer). The development activities have been performed within a joint development program of Enel Green Power with the CEA-INES Technology of LITEN.

Actually, silicon HJT combines the advantages of monocrystalline solar cells with the good light absorption and excellent passivation of hydrogenated amorphous silicon. The cell takes benefit from the high band gap (Eg) of the hydrogenated amorphous silicon (Eg =1.75 eV), which due to the hetero-junction with the crystalline silicon (Eg =1.15eV), ensures a better passivation of surface states. With respect to most common approaches (Al-BSF and PERC [3]), HJT cell passivation is achieved with non-metallic contacts that act as contact and passivating layer at the same time. Recently, Si HJT record efficiency has been obtained by our group, in collaboration with the CEA-INES Technology Center. We have shown that around 25% efficiency can be achieved on commercial solar cells and with high throughput industrial equipment [4].

Further margin of efficiency increase is expected in the near future by implementing our technology roadmap. HJT solar cell has a very symmetric structure and the passivation is obtained with the deposition of thin layers of similar thickness on cell front and the backside, for this reason it exhibits the highest bifacial ratio, exceeding 90%. This means that considering an adequate albedo a solar plant with HJT can gain more than 20% in terms of average energy produced. Beside high efficiency and bifacial gain, HJT cells show other advantages in terms the average electricity produced by a PV solar field. The behavior of HJT solar modules is even better with time because of a sort of regeneration effect leading to increase the performances after exposition to the light [5]. HJT resilience is related to the charming combination of high quality n-type silicon, passivation effects of amorphous silicon on both surfaces and of the good barrier behavior against Na+ of the transparent conductive oxide (TCO) sued as contact. The barrier to sodium improves robustness against detrimental Potential Induced Degradation. Moreover, the use of n-type wafer for HJT cells avoid the drawbacks that affect conventional solar cells such as Light Induced Degradation and Light and Elevated Temperature Induced Degradation [7].

Amorphous silicon used in HJT is a good selective contact, nevertheless the recombination losses associated to the contacts can be further reduced by developing contact structures that improve surface passivation at the same time, extracts more carriers in a selective way. In the region close to the electrodes, holes are extracted from the p-type silicon layer and electrons from the n-type electrode. Using materials with high work function (WF) and bandgap it is possible to create, in correspondence of the electrodes, an offset in the conduction band for electrons or in the valence band for holes. The WF difference of the heterojunction formed between the contact material and the absorber induces a band bending into the absorber, leading to the formation of an induced junction [6]. In addition, the detrimental influence of very high carrier densities in the contact region, i.e. heavy doping effects like Auger recombination and band gap narrowing will be further diminished. The applicability of high WF transition metal oxides adopted from organic electronics (such as MoOx, WOx, etc.), has been investigated for silicon thin film, and is now under investigation for c-Si [7].

In a high efficiency crystalline silicon PV module the wafer cost covers about 25-30% of the full module cost. The reduction of several tens of microns can lead to a significant cost reduction. Thinning the silicon wafer below the industry-standard (~160 μm), in principle reduces both manufacturing cost and capex, and accelerates economically sustainable expansion of PV manufacturing. Technologies of making thin wafers down to 100 mm thickness are viable. Cost of manufacturing steps upstream of wire sawing are reduced with the amount of silicon. Further thickness reduction to 50 μm or thinner wafers may require novel kerfless wafer growing processes, such as epitaxial mono-wafer and directly-grown multi-wafer technologies. However, thickness reduction renders silicon wafers less mechanically robust, causing the breakage during high temperature treatments. In case of HJT cells the low thermal budget used in the fabrication process (<200°C) enables the use of thin wafers, with thickness of 100 μm or even below. Wafer thinning decreases the volume of absorber material and hence the ability to absorb light thus reducing the generation of photo-current. To compensate the current loss it is necessary to increase the light capturing by using photon management concepts, which enhance the optical path of light or increase the light trapping in the absorber material. There are different approaches using nano-patterning or metallic nanoparticles that enable a coupling between photons and plasmons [8, 9].

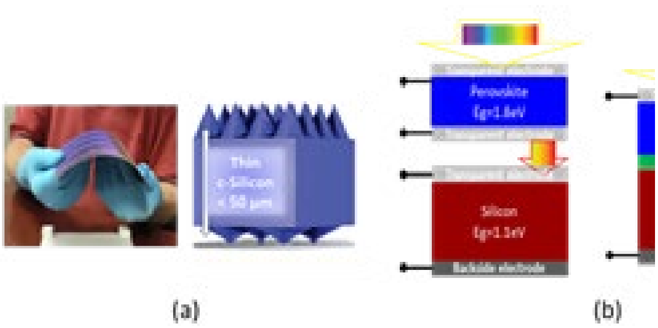

Fig.2: (a) Thin HJT solar cell obtained with very thin crystalline silicon wafers. To maintain good short circuit current in the solar cell when the silicon absorber is decreased below 50μm, nanopatterning is necessary to increase the optical path of the light in the silicon and compensate the loss of absorption due to the thickness reduction. Plasmonic enhancement is studied as alternative. (b) Tandem structures with perovskite top cell and silicon bottom cell. 4T structure is on the left, monolithic 2T is on the right.

The maximum conversion efficiency of silicon solar call in ideal conditions is given by Shockley-Queisser limit, that is of about 29% [10-12]. The limit is defined by considering the Auger recombination and the intrinsic losses as transparency of silicon to photons that have energy lower than the bandgap, and the thermalization losses for high energy photons that generate high energy electrons and holes (hot carriers) wasting energy as heat. An interesting technological approach is given by the tandem structure, in which two or more cells with different band gap are overlapped. From a practical viewpoint, the double junction approach is more feasible and can be implemented in industrial manufacturing process.

Solar cells are devices that generate current by converting photons with energy higher than Eg in electrons. Basically, the highest efficiency is achieved when the voltage reaches 60-70% of bandgap value. In general, cells with low band gap generate higher current, cells with high band gap provide a higher voltage output and lower current. Optimum condition is achieved at intermediate values, in the 1.0÷1.6 eV range. Silicon solar cells (Eg=1.1eV) and CIGS cells (Eg=1.08eV) have bandgap close to the lower value of the optimal range, GaAs cells (Eg=1.45eV) and CdTe (Eg=1.5eV) are closer to the higher value.

The top cell in the tandem sequence absorbs high-energy photons and is transparent to lower energy photons, which are absorbed by the underlying cells. If the bandgaps are matched in a way that both the cells absorb approximately the same number of photons, they can be arranged in series. For the practical two junctions approach, silicon solar cells are excellent bottom cells. On the other hand, it is quite difficult to find an ideal counterpart as top cell. An interesting approach to industrial tandem application can come from the exploitation of perovskite solar cells. Perovskite material used for solar cells is a hybrid organic-inhorganic material with crystalline structure ABX3, where X is an oxygen or a halogen atom. A represent the big cation, which occupies a cubic-octahedral site shared with twelve X anions. The smaller cation B is stabilized in an octahedral site shared with six anions X. Halogen elements perovskites exhibit very interesting characteristics with semiconductor-metal transitions with increasing dimensionality [13]. In order to allow perovskite solar cells to be employed in a commercial tandem solar cell structure it is necessary to solve the drawbacks related to scalability, non-toxicity (most performing perovskite solar cells contains a high amount of Pb) and reliability of the material. The scientific community is enthusiastically concentrated to find a solution to the mentioned drawbacks and every few months there is a significant result in that direction. Using the detailed balance principle, described before, the theoretical Shockley-Queisser limit for a perovskite/silicon tandem cell can be attained. This limit value is of about 40%. From a practical viewpoint the cell could achieve more than 30% efficiency (still an outstanding target). Tandem solar cells can be developed following two main architectures that are described as 4T and 2T, respectively. The 4T structure is obtained by mechanically overlapping top and bottom cells with a four terminals configuration. The cells are realized independently and stacked one on top of the other, each with their terminals. This configuration implies problems related to the transparency of the contacts traversed by the light in the suitable wavelength range in order to be absorbed by the top cell and the bottom one. During the operation, both the cells of 4T tandem can be taken independent at their maximum power points, with distinct tracking systems. In particular, this reduces the limitations on the choice of the top cell band gap and makes the system less sensitive to the spectral variations. The 2T structure consists of a monolithic tandem cell with two terminals (2T) in which the perovskite cell is deposited on top of the silicon cell. Top and bottom cells are series connected, with an interface layer allowing the current flowing between the two cells with recombination mechanism or with quantum tunneling. With respect to the 4T structure, a 2T tandem requires only one transparent electrode by reducing the impact of parasitic optical absorption and in principle reduces the number of process steps and fabrication cost. Top and bottom cells must be designed to generate similar currents, because the cell with a lower current will limit the overall current of the series. This implies more constraints in the top cell bandgap that has to be between 1.7÷1.8 eV. Moreover, when the top cell is deposited on top of the bottom cell it is important that the process does not degrade the performances of the bottom cell. When the top cell is deposited on the bottom cell it must behave as a good substrate during top cell deposition, and this is rather difficult due to the texturing of the silicon bottom cell.

In conclusion, the huge manufacturing volume increase of PV modules and the corresponding reduction of the costs have remarkably improved the perspectives for a fast transition towards a more sustainable future. Silicon solar cell technology will continue its evolution until the achievement very close to the theoretical limit of 29%, calculated for the silicon bandgap.

Advanced passivation schemes use in heterojunction cells, which can use very thin silicon, will facilitate such a transition. This will lead to a further cost reduction, also supported by new development of PV modules architecture.

In the next years, we will assist to the transition towards a new technology, which will enable to overcome silicon solar cell theoretical limits. Likely, the best option will be the tandem architecture that will couple an ultra-thin silicon bottom cell with a consolidated industrial process with a top cell made with a low cost thin film material. The challenge will be to find a suitable material from the viewpoint of stability, non-toxicity and of the wide availability of the materials.

Keywords: Photovoltaics, solar cells, hetero-junction technology, selective contacts, very thin solar cells, perovskite, tandem solar cell.

References

1. G. Condorelli et al. 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC).

2. C. Colletti et al. 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC).

3. International Technology Roadmap of Photovoltaics. VDMA Engineering Federation. 11th Edition. 2020. (www.itprv.org).

4. TaiyangNews, February 05, 2020.

5. E. Gerritsen et al. PV Power Plant Technology and Business, Vol 20, 103-110, 2019.

6. J. Berghold, et.al. Proceedings of the 25th European Photovoltaic Solar Energy Conference and Exhibition, Valencia, Spain, 2010, pp. 3753–3759.

7. M. Pander et al., 35th European Photovoltaic Solar Energy Conference and Exhibition, Brussels, Belgium (2018).

8. J. Melsken et al. J. of Photovoltaics, 8, 373-388 (2018).

9. A. Gentile et al. J Mater Sci, 49, 8498–8507 (2014).

10. S. Lombardo et al. Appl. Phys. Lett. 101, 123902 (2012)

11. W. Shockley and H. J. Queisser, J. Appl. Phys., 32, 510–519, (1961).

12. M.A. Green et al. “Nature Materials. 16, 23-34 (2016).

13. C.H. Henry. J. Appl. Phys. 51 4494 – 4500 (1980).

14. N-G Park, Materials Today. 18, 65 (2015).