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A 3 terminal parallel connected silicon tandem solar cell

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Abstract

A new tandem structure based on a silicon solar cell is presented. This structure works with two or three junction levels, being the silicon cell in this last case the intermediate cell. The different levels have been interconnected in parallel and for that a greater number of the lower band gap cells would be needed in order to equalize the operating voltage of all the structure. However, the presented three terminals structure only needs a maximum of 4 pn junctions for the 3 levels structure or even only 2 for a two level structure. This structure can be easily included in a conventional 2 terminal flat module without complicating the internal wiring. The maximum technological efficiency has been estimated in 39.4 % for the three levels structure and using well known materials for each level a 30 to 32% efficiency level sounds possible.

Keywords: heterojunction; tandem device; parallel connected; silicon solar cell

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1. Introduction

Since the early 90’s it was shown that the technological limit to efficiency for crystalline silicon technology is close to 26% [1]. This limit was early reached [2] getting to laboratory cells with 25% of conversion efficiency. Even in mass production there are technologies producing silicon cells with efficiencies of 24% [3] and only very recently has been surpassed this efficiency world record with a 25.6% for a silicon solar cell has been announced by Panasonic utilizing the IBC solar cell design [4]. This paper shows structures of silicon solar cells capable of produce efficiencies values in the 35-40% range. Obviously these structures uses tandem configurations mixing several materials but being a silicon solar cell the support for all of those. Technical approaches followed so far have been monolithically interconnected or mechanically stacked [5] tandem solar cell structures, getting at the date to

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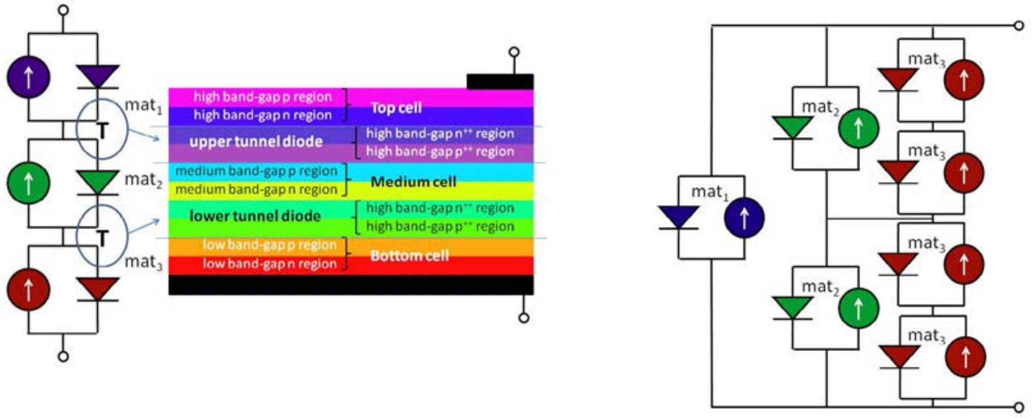
devices with efficiencies close to that of single silicon solar cell. There is a great challenge to exceed 25% of efficiency using tandem solar cells with silicon as one of their components. In series connected tandem solar cells the total current supplied from the device is that from the worst cell. Single silicon solar cells are capable of recovering up to 42 mA/cm^2 from the upper part of the solar spectrum ($\leqslant$1100 nm). In the lower part another 26 mA/cm^2 can be achieved and obviously there is not any other material capable of the improvement in efficiency to a silicon cell when it is used as low band-gap material in a series-connected 2-junction structure. For the high band-gap there are not so rigorous restrictions. It is possible to divide the upper part of the spectrum in two parts of around 18 to 24 mA/cm^2 each. The upper material must have an optimum band-gap in the 1.65 to 1.85 eV range. All these restrictions will be relaxed if a parallel connection is used, as we suggest in this work.

2. Series and parallel connected tandem cells

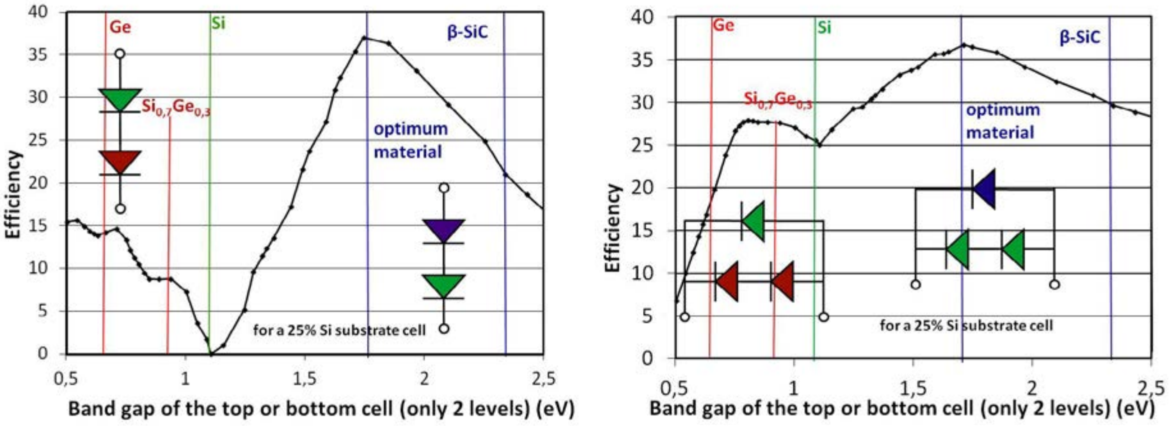
The electrical connection of tandem solar cells is currently made in a series circuit. The current flowing by the device go through all their components and in this way if any of them limits this flow that compromises the behavior of the full device. In counterpart these devices are simple to use because they present only two terminals and the resulting devices, incorporating two, three or even four materials, actives from different light wavelengths, have given cells with superb efficiencies, exceeding the 40% value. Although the idea of series connected tandem cells is simple that is not their implementation. To put different cells of different materials in series imply the contact of the p and n type of different cells, developing a voltage of opposite direction to the main voltage cell. To avoid that a new component must be added in these cells, the tunnel diode. This tunnel diode must allow the flow of current in a opposite direction to their pn junction with unappreciable voltage losses, they dielectric constant must be close to those of the surroundings materials in order to allow the flow of light, their lattice constant must be also in concordance with their neighbors and finally their band gap must be large enough to not produce appreciable light absorptions. Figure 1 (a) shows the equivalent circuit and the structure of a three materials series connected solar cell. As it has been there indicated a minimum of 10 different layers would be needed and usually this number of layers is close to their double value. On the contrary, parallel connected tandem cells, as indicated in figure 1 (b), have a different number of pn junctions for each material. Instead of matching the current in this structure each material level must provide the same voltage and we can say that they are voltage matched.



a

b

Fig. 1. Structure for a 3 levels, (a) series connected, (b) parallel or voltage matched connected.

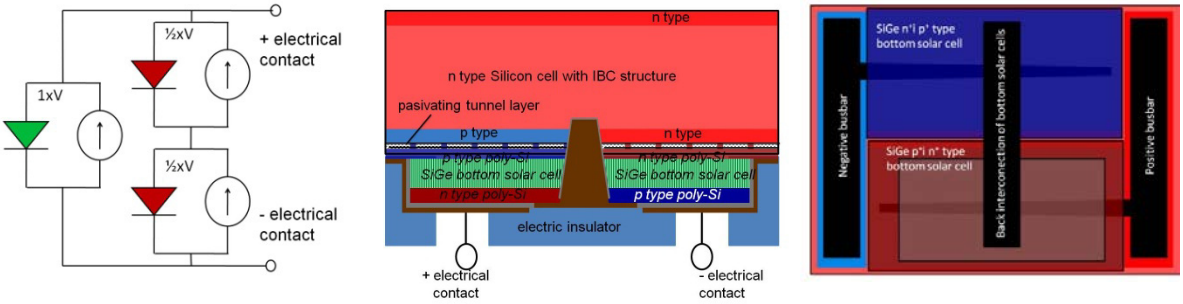


a b

Fig. 2. Maximum achievable efficiency with a 2 level solar cell, using a 25% efficient silicon solar cell, being (a) series or (b) parallel connected.

Particular cases of voltage matched structures have been reported previously [6-9], but never before analyzed their exact behavior and potential. Although the appearance of a higher complexity than their equivalent series connected ones, due to the necessity of a larger number of pn-junctions, this work will show that the implementation of the parallel solution is simpler. To start, as it can be seen in figure 1 (b) the concurrence of different materials is always done by the same type region and not tunnel diodes are required.

Figure 2 (b) shows the corresponding efficiency for a two materials parallel connected structure. It can be seen that there is a full 0.73 to 3 eV region within the efficiency is over the 25 % value. Even being in competence for the same part of the spectrum in the parallel connection this fact is not dramatic because at the end the current form both cells are added. Because the voltage of a pn junction depends as the logarithmic of the current these structures are less sensitive to irradiation level, solar spectrum and device degradation than traditional series connected devices. Also, even in the case of using materials with band-gap values far from the optimum values for a given light spectrum the limitation from the different operating voltages is less restrictive than the current limitation of traditional devices, giving to gains in efficiency for a wide range of band-gap values.



a b c

Fig. 3. (a) electrical equivalent circuit, (b) section of the structure and (c) rear view of a 2 levels, 3 pn junctions parallel connected solar cell with a top IBC silicon solar cell and two bottom SiGe cells.

3. The bottom cell

Existing a wide range of materials that can be used to supplement the silicon solar cell in their bottom side, the SiGe is a good material for that. It can be modulated in band-gap values from 0.66 to 1.12 eV filling the full region of 0.75 to 0.95 eV where, according to figure 2 (b), there is a net gain of 1.7 to 2.7 % absolute in efficiency. SiGe has a well established technology, first introduced form IBM for the manufacturing of high speed transistors [10] and more recently for the manufacturing of solar cells [11]. It can be growth by LPCVD at moderate temperatures, under 600ºC on silicon and producing epitaxial monocrystalline layers.

However, to supplement a silicon solar cell two SiGe cells are required. A previous patent [12] shown that there is a simple structure if the silicon one is a back contact cell. Figure 3 (a) shows the electrical circuit of a parallel connected tandem cell composed by a silicon cell and other two SiGe as bottom cells. As it was previously explained there is not any tunnel or accommodation device or interface between the Si and the SiGe cells. Due to the lower band gap of the SiGe material this could add an extra surface recombination on the silicon back surface, however that is avoided if that is growth on a polysilicon layer accommodating the interface of both material and that is already incorporated in any of silicon back contact cells [3]. In this way, and being the polysilicon a material of larger band-gap than the SiGe, this would be a good passivating material for that in the same manner than the a-Si is for the x-Si. Figures 3 (b) and (c) show the section and the rear view of a silicon IBC structure incorporating the two SiGe cells, parallel connected to the first as shown in fig. 3 (a).

4. Materials for the top cell

The optimum material for the top cell, with the restriction of working at double voltage, is around 1.7 eV. However, using materials of higher band gap, like beta-SiC (2.4 eV), gives to lower increase on efficiency but also to a more secure behavior in the silicon solar cell, which efficiency is not affected by the addition of this top cell.

Regarding figure 4 (a) it can be shown that for the top cell and depending of their band gap there is a short range of efficiencies from this top cell in which the total tandem efficiency benefits for the inclusion of this top cell. That is due to the fact that not all the cells of 1.7 eV can work at double voltage than the silicon cell. However, the total efficiency of the tandem cell is reduced if the top cell doesn't reach this minimum efficiency. For example, for a material with the optimum band-gap of 1.7 eV we can get the maximum efficiency of 36.7 % if the individual top cell presents 24.6 % efficiency. However for efficiencies lower than 16.3 % of this top cell the final device always will have efficiency under 25%, degrading the electrical behavior of the single silicon cell. Figure 4 (a) represents also the current efficiency of different technologies and curiously none of the current amorphous technologies is capable of supplement the efficiency of the silicon cell. The situation is the opposite if a crystalline top cell is used.

The final efficiency depends on the relation $\Delta V_{oc}/\Delta E_G$ of the top cell, what is a factor depending of physical and technological facts. The red line on figure 4 (a) shows the frontier from an improving or degrading top cell. Several values of efficiency vs. band-gap from different technologies are represented in figure 4 (a) and none of the amorphous materials analyzed and represented by blue triangles fulfill the requirement of the minimum efficiency. However that is not the case of crystalline materials represented by the red diamonds. We suspect that polycrystalline materials would also be in the region of a net efficiency gain but we don't have evidence of that. Regarding the optimum materials it appears that III-V compounds give a clear opportunity for high efficiency devices, however until now mixing silicon and III-V materials is a challenge topic and always solved by not large throughput techniques like MOCVD. However, silicon carbide is a well known material, used in their amorphous state as passivant for silicon surfaces; it can be epitaxially deposited on silicon substrates at relatively low temperatures (around 900 ºC) and used in microelectronics for large temperature devices. It can be doped in the same manner than silicon, using the same dopants, and also oxidized and with full technology developed to work with that. The only problem is that their band-gap of 2.34 eV is far from the optimum material, but even in this case a final efficiency of 29.6 % would be obtained for a 2 materials device and 32.5 % for a 3 layers device. But as in the SiGe case, SiC would be non stoichiometrically deposited giving to Si_xC_{1-x} materials, currently used for LED manufacturing with control of the band-gap by the Si to C proportion. Finally, ternary alloys of SiCGe are used for a better fitting to the silicon lattice.

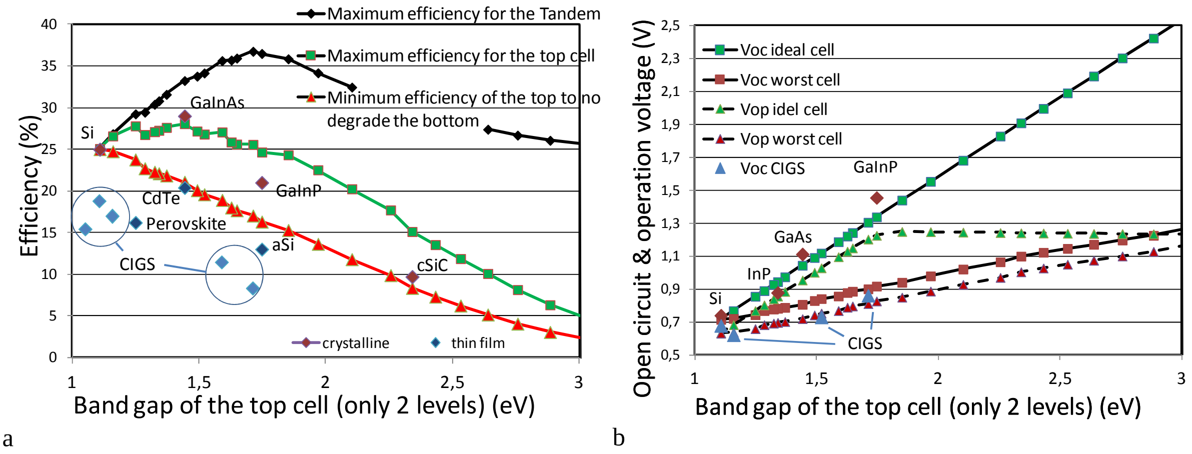


Fig. 4. (a) maximum achievable efficiency for a 2 levels parallel connected solar cell, being the bottom one a 25% efficient silicon solar cell and indicating the range of efficiencies of the top cell to reach an ensemble with more than 25% and (b) open circuit and operating voltages of the top cell under the same assumptions than (a) figure.

In order to understand the limitations of each material, figure 4 (b) represents the open circuit voltage of the top cell and their operating voltage in the case of being parallel connected to two 25% silicon solar cells. As in figure 4 (4) green lines represents the ideal case and red ones the limit for the degradation of the silicon behavior of 25%. For the ideal case it can be saw that the operating voltage follows to the open circuit voltage from the lower E_G values to the maximum 1.7 eV and saturates for larger values. We can say that the total structure is limited by the top cell for E_G values under 1.7 eV and from the silicon cell for larger E_G values. Also, the green line has a behavior of $\Delta V_{oc}/\Delta E_G=1$, while the red line, corresponding to the case of degrading the full structure presents this tendency $\Delta V_{oc}/\Delta E_G=0.5$. The region under 1.7 eV presents a low range in terms of efficiency of acceptable top materials, because as previously explained the device is limited from this, but there is more tolerance to the quality of that in the upper region and sounds more convenient to work with materials with wider band gap. Figure 4 (b) also includes results of record cells. In blue they are represented the V_{oc} values from different CIGS cells with different ban gaps [13]. Surprisingly all these devices accommodate to the lower red line and cannot upgrade any good silicon solar cell. But the good accommodation to this $\Delta V_{oc}/\Delta E_G=0.5$ tendency seems to indicate the existence of any fundamental limitation, probably extendable to other amorphous materials. For crystalline record materials [14], in contrary, there is near to perfect accommodation to the ideal behavior represented in line green in figure 4 (b).

5. Top cell and the three terminal approach

As it was previously explained the main problem of the presented structure is their complexity in terms of number of components. However in the case of each material level works at a voltage double or half regarding the next or the previous layer it is possible to have simpler approaches. As in the bottom case the best solution for the top cell is having this top cell a back contact structure, and in this way the lower band gap devices, the two silicon cells, would accommodate together their p or n type regions. However a top device with a back contact structure nowadays is not available.

A new and very simple approach is if a three terminal approach is implemented instead the classical two terminal cell as previously discussed. Figure 5 shows a couple of paths to separate a structure of 2 different materials, 3 pn junctions and 2 terminal into basic cells of 2 different materials, 2 pn junctions and 3 terminals. A previous work of Gee [6] also had shown another couple of ways to do that. In any case the resulting basic cell is a three terminal device with 2 materials or even 3, as it was shown in figure 6 with ability to be incorporated in a classical two terminal module as they are nowadays the standard PV modules.

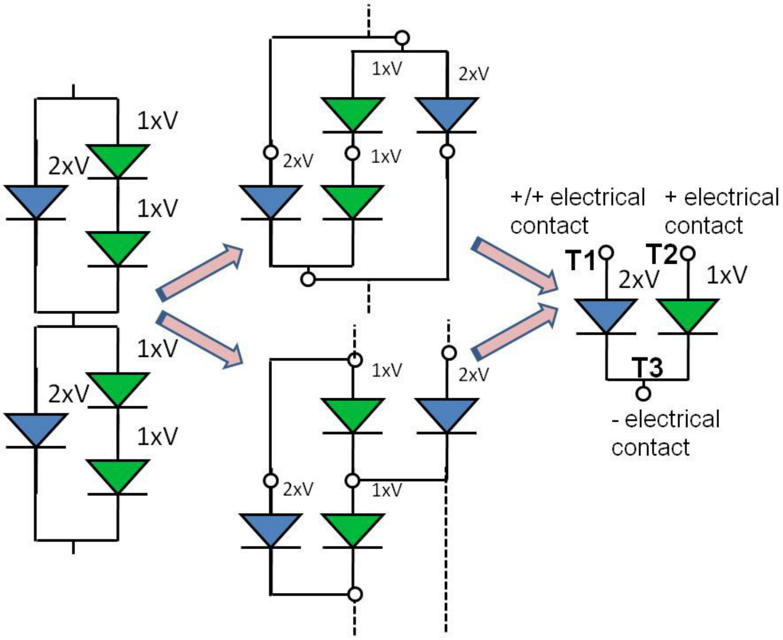


Fig. 5. Simplifications from the 2 levels, 2 terminals and 3 junctions parallel connected cell to the 2 levels, 3 terminals and 2 junctions device.

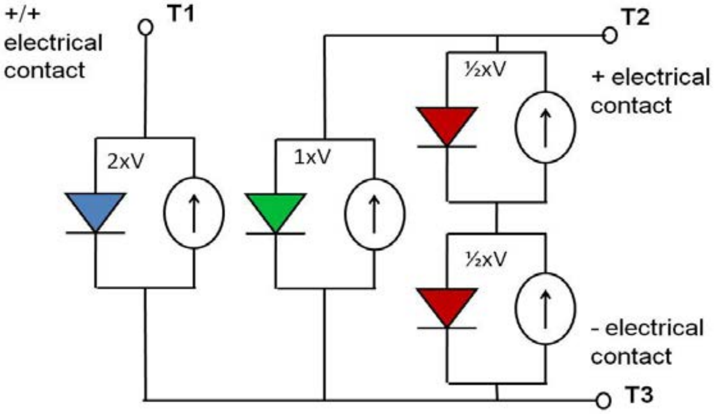


Fig. 6. Structure of a three different band-gap sub-cells parallel connected in a three terminal device according to this work..

At last, figure 6 shows the basic cell of a device with 3 different materials, 4 pn junctions and 3 terminals. For the bottom, materials, structures and technologies as presented in [12] would be used. For the top different configurations and materials have been studied but currently are under a request of patent from the authors. The obtainable final efficiency is, with this structure, close to 40 %. This value is obtained using a 25 % silicon cell as intermediate sub-cell, a top cell in the 1.71 eV optimum point with a gain of 11.7 % and a SiGe bottom cell with an extra contribution of 2.7 % giving to a total efficiency of 39.4 %. All these values have been obtained using realistic parameters from existing solar cells as it can be saw in figures 4 (a) and (b). For practical device with not optimized devices in term of material's band gap and technology and reaching an intermediate efficiency of 32%, as tentative, this value would come from a 25 % silicon cell, would imply an extra efficiency of around 6 % from the top cell and a 1% from their bottom ones. That suggests that the top material requires the main research effort because more of the final efficiency depends of this material and also because all the light entering to the device passes through this top cell and that compromises not only the behavior of the top cell but of the full structure. As indicated in figure 4 (b) working in the upper region from the 1.71 eV maximum gives to the easiest devices in terms that the efficiency limitation is produced by the silicon device with a well known technology. In our understanding β-SiC is a good candidate, with enough band gap, good passivation of the silicon front surface and well developed technology from the microelectronic sector. Also, there are possibilities to shift their band-gap changing the proportion of Si/C and also there are other similar structures to the here presented, currently in study, that could move the maximum from 1.71 eV to higher values.

The interconnection in a two terminals PV-module is simple if the operating voltage of each individual solar cell component is a multiple of the lower voltage cell. Some approaches to do that would be found in [6], however the approach from this work is unique and new (currently in a patenting process).

6. Conclusions

A new structure of tandem solar cell has been presented. This structure gives to devices with two or three terminals but easily connected into two terminal modules. Although the concept presented is independent from their realization this structure would implement materials deposited in silicon by standard industrial techniques, like LPCVD. The new approach of connecting the cells in parallel is less restrictive than the conventional series connected giving to a continuous improving on efficiency from the full region of 0.75 to 3 eV for the extra cells added. This relaxation of this configuration from the top and bottom materials used gives to being less critical to manufacturing tolerances, degradations or exposition to different light spectrums. In addition the parallel connection avoids the use of tunnel diodes for the interconnecting different materials, resulting in simpler structures.

From the top cell we shown that an extra of 11.7 of absolute efficiency would be added to the tandem device, however not all materials and cells with adequate band gap can do that. We demonstrate that crystalline solutions, like that made on InP, GaAs, GaInP or even β-SiC can improve the final results over the starting silicon cell efficiency, however those cells based on amorphous materials, like CIGs cells, aSi or maybe perovskites seem to not be able for this purpose. We have found that any fundamental phenomenon is under this limitation and more research seems necessary in order to overcome that.

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