TANDEM AMORPHOUS SILICON SOLAR CELLS

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Abstract - Recent progress in the field of amorphous silicon tandem solar cells is reviewed. The advantages of series connected tandem cells with regard to single junction amorphous solar cells are discussed. Partitioning a thicker cell into two or three thinner cells results in higher inherent built-in electric fields in the cells with better conversion efficiency and stability. A new approach is described, utilizing parallel connection of cells in tandem structure to additionally improve efficiency, stability and sensitivity to thickness tolerances. The essential similarities and differences between series and parallel tandem cell arrangements are discussed and the present status of tandem cells fabrication is presented.

Tandemske amorfne silicijeve sončne celice

Ključne besede: energija fotonapetostna, celice sončne, celice tandemske, silicij amorfni, stanje razvoja, izkoristek konverzijski, stabilnost, tandem serijski, tandem paralelni, izdelava

Povzetek: Prikazani so dosežki s področja amorfnih silicijevih tandemskih celic. Opisane so prednosti serijskih tandemskih celic proti eni sami amorfni silicijevi sončni celici. Razdelitev debelejše celice v dve ali tri tanjše vodi do večjih vgrajenih električnih polj v posameznih celicah in k boljšim izkoristkom pretvorbe in večji stabilnosti delovanja. Opisan je novi pristop z vzporedno vezavo posameznih celic, pri kateri je pričakovati dodatno izboljšanje izkoristka, stabilnosti in neobčutljivosti na tolerance debelin celic. Prikazane so glavne podobnosti in razlike med serijsko in paralelno vezavo ter trenutno stanje tehnologije izdelave tandemskih celic.

INTRODUCTION

The majority of photovoltaic energy conversion devices on the market today are silicon solar cells, including most efficient but expensive single crystalline devices, less expensive recrystallized metallurgical silicon devices, as well as low cost thin film solar cells from amorphous silicon which received a great attention during the last decade as one of the most prospective materials for low cost solar cells.

Amorphous silicon (a-Si) can be inexpensively deposited on large substrates of various materials and shapes. During its deposition it needs to be treated to relatively low temperatures in the range of 200-300°C. Due to high light absorption of a-Si, the a-Si solar cell thickness can be very small, typically less than 1μm.

The main limitation in obtaining high solar cell conversion efficiency are poor transport properties of charge carriers in amorphous silicon. The photogenerated electrons and holes which make up the collected solar cell photocurrent have very short diffusion lengths which are much too short to provide effective collection of these carriers. Therefore, the a-Si cell has to be very thin and an aiding electric field is built inside of the cell to assist more effective charge separation and collection. On the other hand, the cell should be sufficiently thick in order to provide a suitable absorption of light flux. These opposing criteria directed to the idea of tandem a-Si solar cell structures where the individual cells are deposited sequentially forming a multilayer solar cell structure in which the unit cells are optically and electrically connected in series /1/. Since the collected photocurrent must be the same in all unit cells, each consecutive cell in a series tandem structure must be thicker than the preceding one.

A parallel connected tandem a-Si cell structure in which the individual cells are optically connected in series and electrically in parallel has been proposed recently /2/. This configuration which is presently under intensive investigations is hoped to outperform its series tandem counterpart with respect to conversion efficiency and stability promising also lower sensitivity of solar cell efficiency on nonuniform a-Si deposition rate in large area solar cell modules /3/.

SERIES TANDEM CELL STRUCTURE

In series tandem structures two or three cells are optically and electrically connected in series, as shown in Fig. 1 /1/. The front p^+in^+ cell is covered by a transparent conductive oxide (TCO) layer providing electric contact to the p^+ layer of this cell. The metal on n^+ layer is serving for electric contact to the back p^+in^+ cell. Junctions n^+p^+ interfacing consecutive unit cells are acting as ohmic contacts, electrically interconnecting succeeding p^+in^+ cells.

The individual cells in such serially stacked devices can use the same amorphous material in all unit cells. Such structure which affords a sufficient absorption of photon flux and enables a satisfactory collection of photogenerated carriers is regarded as one of the most practical solutions. The fact that the electric current in a series connected tandem cell is the same in all unit cells demands a greater thickness of each consecutive cell. Consequently, a practical stacked a-Si cell structure consists of only two cells. A triple tandem structure would require an unacceptably thin front and thick back unit cell. Most frequently these double stacked cells are fabricated by depositing thin layers of TCO, amorphous

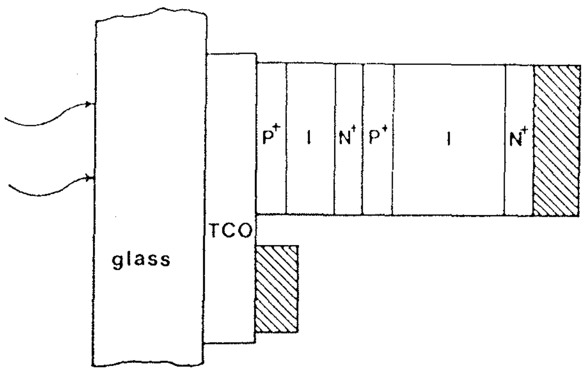

Fig. 1: The basic series tandem structure.

silicon and metal on a glass substrate, as shown schematically in Fig. 2. The p^+ and n^+ layers are indispensable for creating the built-in electric field in i-layers assisting charge carrier separation and collection. Since the diffusion lengths in highly doped a-Si are extremely short, these dead layers must be very thin, usually in the range between 15 and 30nm.

Even a very thin p^+ layer of the front cell parasitically absorbs a large amount of photons at short wavelenghts. For this reason the energy gap of the front p+ layer is increased to about 2eV by mixing amorphous silicon with carbon, resulting in a sort of optical window. In spite of a wider band-gap a relatively large part of light flux is absorbed in this so-called p^+ window layer, as shown in Figs. 3.a and b, representing the calculated portions of the absorbed sunlight flux in specific layers of a double stacked tandem cell for two sets of solar cell thicknesses, given in Table I. It can be noticed from these plots that the absorbed fluxes in i-layers of both cells are matched when the top cell is much thinner than the bottom cell.

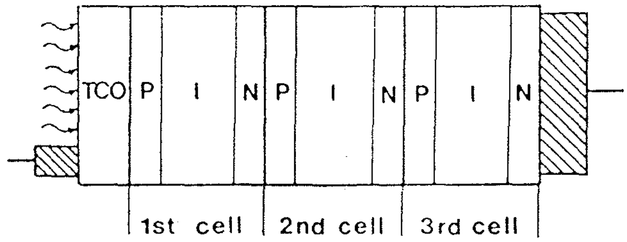

Fig. 2: Schematic presentation of double-stacked a-Si/a-Si series tandem solar cell.

The absorbed photons in both i-layers generate electrons and holes which are collected at opposite electrodes. The effectiveness of this charge collection greatly depends on the density of localized states in the gap of a-Si. Higher is the density of states in the i-layer, greater is the decrease of the built-in electric field and higher are thermal recombinations of photogenerated carriers, resulting in a decreased collection efficiency. The so-called Staebler-Wronski effect (SW effect), which originates from increased states density in the gap during a strong illumination, is the main cause of unstable operation of a-Si cells. When decreasing the thicknesses of individual cells in a-Si tandem structures, the built-in electric field in i-layers increases, and the solar cell degradation due to SW effect is reduced.

Table I Thicknesses of thin layers selected for calculation of absorptance

		Thickness (nm)
layer(s)	case (a)	case (b)
TCO	200	200
P_1	15	15
I_1	30	470
N_1	15	15
$P_1/I_1/N_1$	60	500
P_2	15	15
I_2	370	570
N_2	15	15
$P_2/I_2/N_2$	400	600

The initial efficiency of double stacked a-Si/a-Si cells has been obtained around 11% /4/. However, after light induced degradation the stabilized efficiencies of 8% were obtained in large area modules.

The second kind of series tandem cell structure consists of two or three p^+in^+ amorphous cells having different band-gaps. This so-called multi-gap amorphous solar cell uses the principle of spectral splitting. As shown in Fig. 4, the incident light enters the first cell made from a wide band-gap material, absorbing only the blue portion

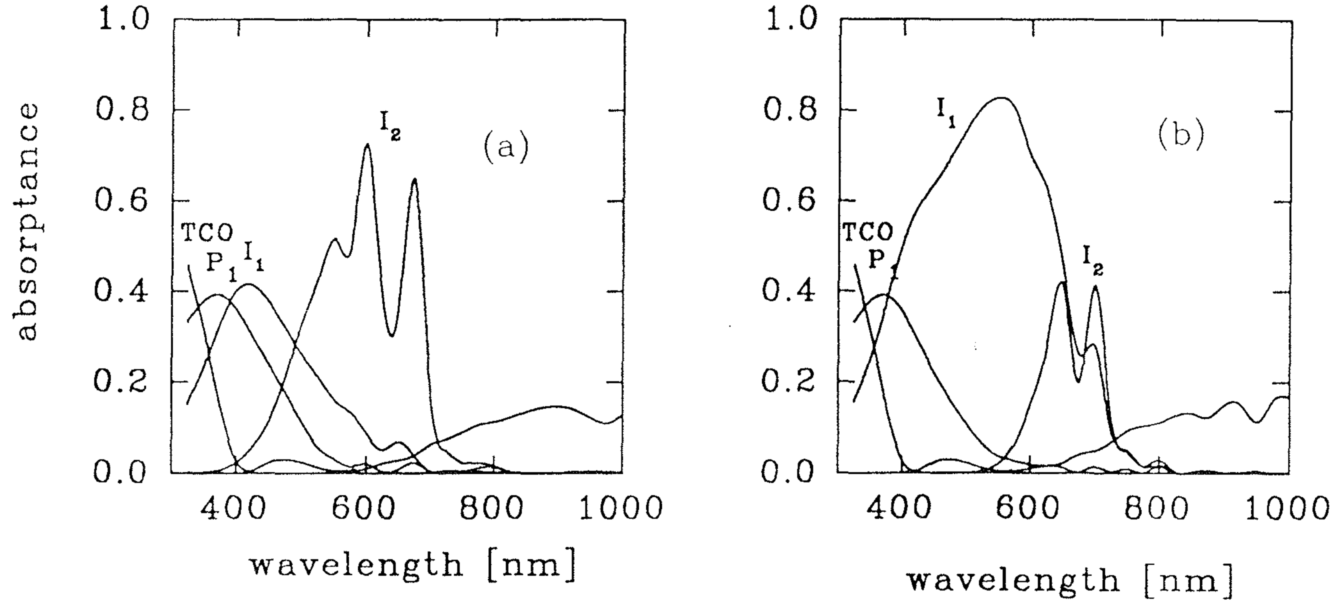

Fig. 3: Absorptance of sunlight in various layers of a double-stacked a-Si/a-Si solar cell in cases of an unmatched (a) and a matched (b) structure.

of the solar spectrum and producing inherently high open-circuit voltage. Higher wavelength light passes through the first cell without being absorbed and generates charge carriers in amorphous material of the second cell having smaller band-gap. The rest of the long wavelength flux which passes also the second cell is finally absorbed in the third cell made from the smallest band-gap material. A typical three cell configuration uses amorphous silicon-carbon, amorphous silicon, and amorphous silicon-germanium as semiconductor materials in such tandem configuration. As in case of double stacked a-Si/a-Si tandem structure the photogenerated currents in all cells in series must be equal, so that the thicknesses of individual cells are tailored with regard to their light absorption properties and carrier collection capabilities.

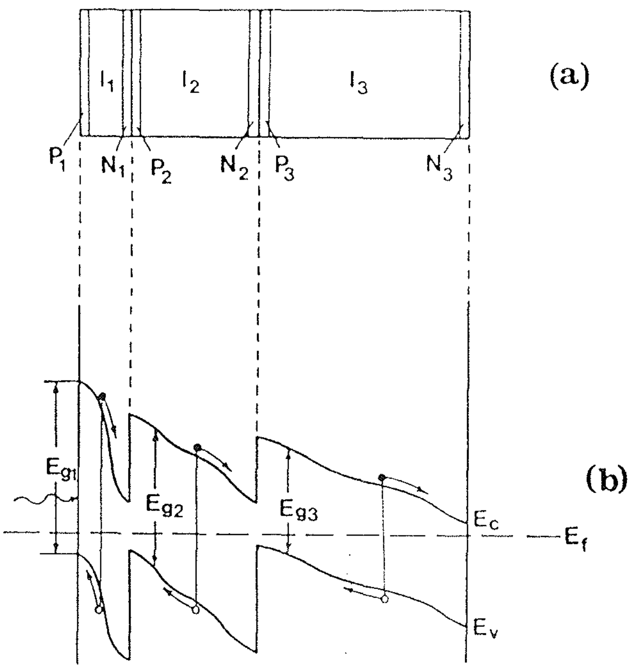

Fig. 4: Multi-gap stacked solar cell structure (a) with its band-gap representation (b).

Triple cell modules have been fabricated with initial conversion efficiencies between 10 and 11%, which degraded for less than 20% after extended light soaking /5/.

PARALLEL TANDEM CELL STRUCTURE

A new a-Si tandem solar cell structure has been proposed recently in which individual cells are optically connected in series and electrically in parallel /2/. This structure, shown schematically in Fig. 5, consists of two or more a-Si cells stacked in the sequence pin-nip-pin-...etc. At each interface between consecutive cells the electric contact to both joining cells is provided by a thin transparent conductive layer.

In contrast with series tandem structure in which the current passing all unit cells is the same, the parallel tandem arrangement requires equal photovoltages in all cells. This voltage, being in the vicinity of the open-circuit voltage, does not vary strongly with different light generated and collected charge carrier densities. This is because the voltage at the maximum cell collection efficiency markedly depends on strongly varying dark current and much less on gradually changing photocurrent component. This suggests that all unit cells in a parallel tandem arrangement must have equal dark characteristics, demanding the same amorphous semiconductor for all unit cells.

Intensive studies and experiments are currently carried on in fabricating a double stacked parallel tandem structure, and computer simulation of parallel tandem cell has also been initiated /3/. Computer modelling of a-Si tandem cells has indicated that the expected sensitivity of a parallel tandem arrangement on the thickness variations of individual cells is much lower than in case of series tandem structure. As an example, Fig. 6 shows

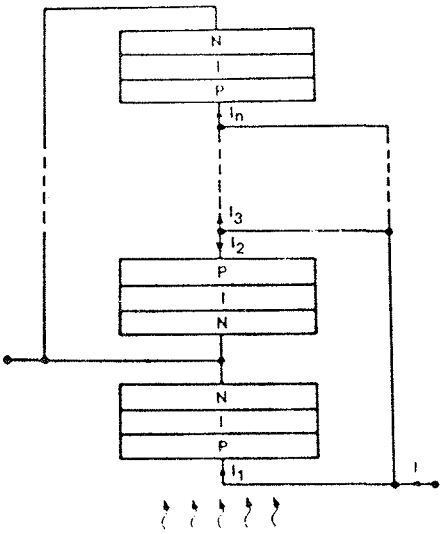

Fig. 5: *Parallel tandem a-Si cell connection.*

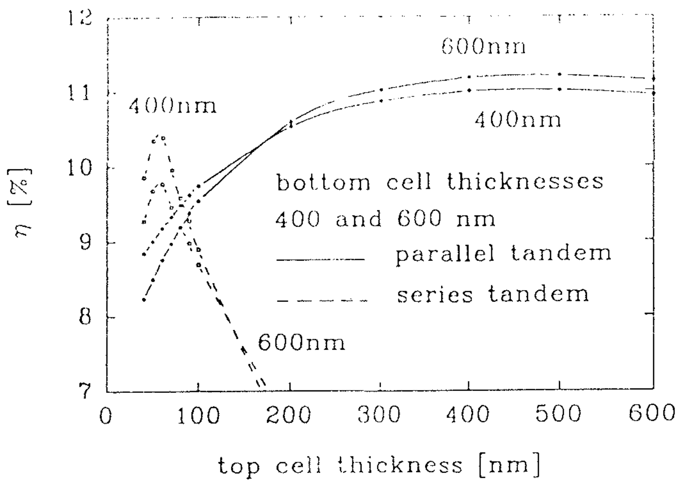

Fig. 6: *Series and parallel tandem cell efficiency as function of top cell thicknesses.*

the computed conversion efficiency of parallel and series tandem cells having a fixed bottom cell thickness and a varying top cell thickness. It can be noticed that in contrast with series tandem cell the thickness of the front cell in parallel connection can vary broadly not affecting strongly the conversion efficiency. Since the thickness of unit cells in parallel tandem connection is not critical it can be expected that this tandem arrangement will outperform the series tandem structure by having a smaller decrease of conversion efficiency due to nonuniform a-Si deposition rate in large area solar cell modules. Considering the fact that all unit cells in a parallel tandem structure can be made equally thin it can be expected that a structure consisting of multiple thin cells in parallel connection will behave very stable after strong illumination, having a very weak SW effect.

FABRICATION OF TANDEM CELL STRUCTURES

A variety of methods, such as chemical vapor deposition and sputtering, could be used to deposit a-Si based solar cells. However, the only technique which produced ac-

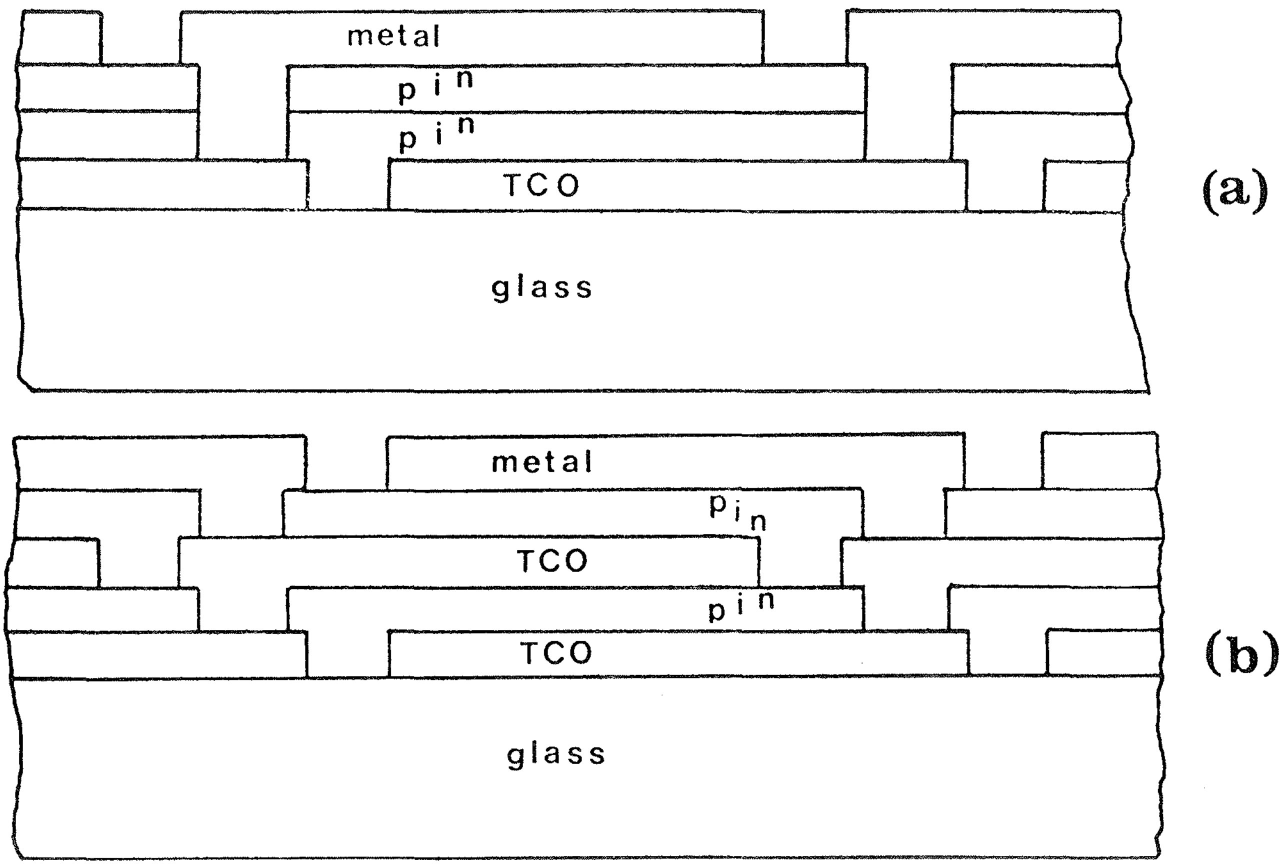

Fig. 7: *Cross-sectional view with laser scribe pattern of double stacked series connection (a) and parallel connection (b).*

ceptable undoped and doped amorphous silicon layers is plasma enhanced chemical vapor deposition or shortly glow-discharge process. The existing reactors can produce today the monolithic modules with active areas greater than 40cm x 100cm where the individual cells are patterned and interconnected into panels. The delineation of the monolitic pattern can be achieved by photolitography, mechanical abrasion, lift-off techniques or laser scribing. The most attractive approach for large area photovoltaic modules is that of laser scribing process, where laser cuts off the layers that have been deposited on the substrate. The typical laser scribe pattern of a two cell series tandem connection is shown in Fig. 7.a. The same patterning principle can be used for delineation of parallel tandem arrangement, shown in Fig. 7.b. Multiple cell panels can be made as extensions of cross sectional presentations in Figs. 7.a and b.

CONCLUSIONS

Tandem amorphous solar cell consisting of serially connected unit cells presents an improvement of electrical characteristics when compared to those of single amorphous silicon cell. The partition of a single cell into two or three cells connected in series results in smaller thickness of each unit cell while maintaining long enough path for photons to be moderately absorbed. The consequence of thinner intrinsic layers of individual cells are higher built-in electric field strengths with an improved collection efficiency of photogenerated carriers. Higher internal electric field causes also smaller cell instability due to Staebler-Wronski effect. The concept of parallel connected stacked solar cell represents a meaningful alternative to the conventional series connected arrangement. The parallel connected structure promises a higher conversion efficiency and a smaller sensitivity to unit cell thickness variations and will seemingly suffer a lower Staebler-Wronski effect.

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