PROCESS AND TECHNOLOGY DEVELOPMENT FOR BACK CONTACT SILICON SOLAR CELLS

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ABSTRACT

Back contact solar cells promise several advantages over conventional solar cells such as easier module fabrication, higher efficiencies and excellent optical appearance. We investigated several industrial processing sequences for the manufacturing of Emitter Wrap Through, Metallization Wrap Through (η=17.2%) and Metallization Wrap Around (η=17.5%) solar cells. These new devices require novel process technologies for the definition of rectifying p/n junctions on the rear. Therefore three different methods were applied in EWT solar cells: screen printed diffusion barriers (η=16.1%, screen printed metallization, 10x10cm^2), laser patterning of a dielectric (η=16.6%, buried contacts, 5x5cm^2) and P-Al co-diffusion (η=10.1%, no ARC, 5x5cm^2). Additionally, the EWT concept was applied to monolithically integrated high voltage solar cells.

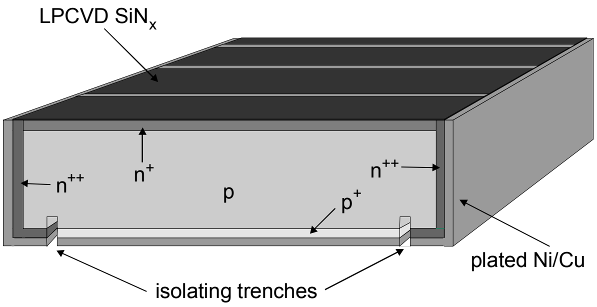
INTRODUCTION

Back contact solar cells have considerable advantages as compared to conventional solar cells like the potential for higher conversion efficiencies, easier module assembly as well as homogenous optical appearance. The device designs are also considered to solve problems associated with future crystalline silicon solar cells with reduced thickness and larger substrate sizes.

In the last years various designs of back contact solar cells have been suggested for different electronic qualities of the silicon base materials and different metallization techniques e.g. Interdigitated Back Contact (IBC) [1,2], Emitter Wrap Through (EWT) [3-6], Metallization Wrap Through (MWT) [7,8], Metallization Wrap Around (MWA) [9,10] as well as PUM solar cells [11]. In this paper we report on the work carried out at the University of Konstanz in the field of back contact solar cell development. Besides the evolution of processing sequences for different back contact device designs the main focus of this work was to develop and investigate process technologies which can help to transfer these new device designs into industrial manufacturing.

DEVICE DESIGNS

Three different device designs have been investigated. The MWA concept is closest to conventional solar cells. Only the busbars are moved from the front surface to the edge region on the rear. The current collected in the front fingers is conducted around metallized edges to the busbar on the rear (for a schematic illustration see Fig. 1, left). In MWT solar cells the n-type metal fingers on the front side are connected to the busbar on the rear by one laser drilled via located at the position of the busbars in conventional cells. In



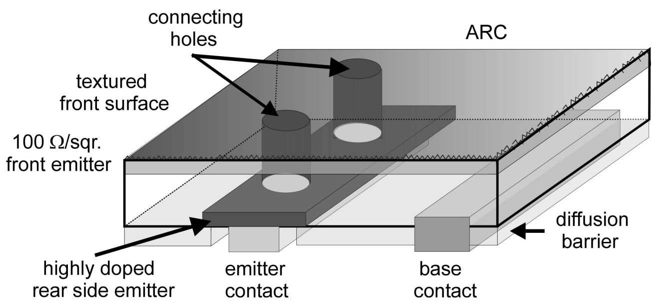


Fig.1: Schematic illustration of (left) BC-MWA solar cell: The front fingers are connected to the emitter contact on the rear around two opposite edges. External p- and n-contact definition was realized by isolating trenches. (right) Screen printed EWT solar cell. The front side emitter is connected to the rear side emitter contact through laser drilled vias. P/n contact separation is accomplished by a screen printed diffusion barrier.

MWA and MWT solar cells the finger metallization remains on the front surface. In the design of the EWT solar cell, the front side emitter is connected to the rear side emitter contact through a larger number of laser drilled vias (see Fig. 1, right). In this design metal contacts are only located at the rear in an interdigitated pattern.

PROCESS TECHNOLOGIES

Interconnection of front emitter to rear emitter contact

In MWA solar cells, the electrical interconnection between front and rear is achieved over metallized edges. In the electroless plating sequence of Buried Contact Solar Cells (BCSCs) this is achieved without further effort. The chemical reaction of the electroless plating deposition occurs on the semiconductor surfaces therefore only the dielelectric layer has to be removed at the edges e.g. by plasma etching. In the processing of MWT and EWT solar cells vias have to be introduced into the wafer. This was performed by a fast Q-switched Nd:YAG laser.

p/n-junction definition on the back

One of the key tasks to be solved in the processing of back contact solar cells is the definition of rectifying p/n-junctions on the rear. The techniques for junction definition can be divided into three main groups: removal

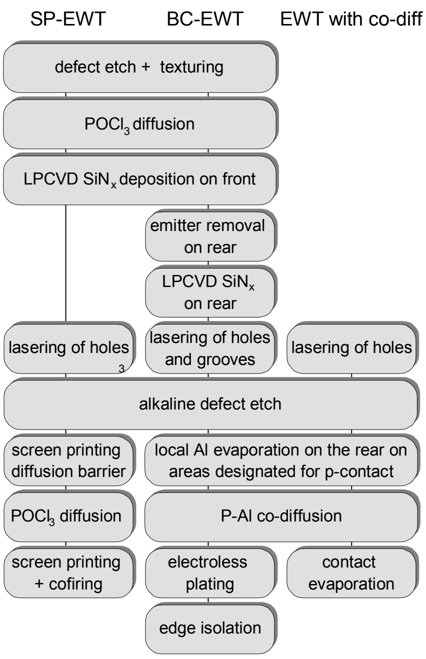


Fig. 2: Processing sequences for EWT cells applying different technologies for junction definition and metallization. (left) Screen printed metallization, selective emitter and screen printed diffusion barrier, (middle) electroless plating, selective emitter and the laser patterning of SiN_x, (right) evaporated contacts, homogenous emitter and co-diffusion.

of the doped n^+-layer after diffusion (e.g. by abrasive methods), prevention of n^+-diffusion on certain areas on the rear (diffusion barrier) and the direct formation of rectifying p/n-junctions (e.g. by P-Al co-diffusion, self-doping contacts). The main difference between the three technologies is the state of the p/n-junction on the rear after cell processing. If abrasive methods are used, the p/n-junction, which borders the surface in these regions, is in a highly damaged part with a high surface recombination velocity. This affects the saturation current density of the second diode J_{02}. Numerical investigations showed that the influence of these regions on J_{02} is linear with the contact length of the p/n-junction and increases with the surface recombination velocity [12]. The length of the p/n-junction on the rear is large for EWT solar cells (at least a factor of 10 higher as for conventional solar cells) whereas it is about the same for MWT and MWA solar cells. Therefore abrasive methods for junction isolation can be applied for MWA/MWT solar cells. In the processing of MWA and MWT cells mechanical abrasion was applied using thin dicing blades (about 100 µm) for p/n-contact isolation. However this method is not well suited for EWT solar cells, since J_{02} significantly increases and therefore FF and V_{oc} decreases. The focal point of our investigations on junction definition for EWT cells were on the other two techniques: diffusion barriers as well as P-Al co-diffusion.

Diffusion barriers have been investigated using screen printed metallization and electroless plating (see Fig. 2). For screen printed EWT solar cells a screen printable diffusion barrier was deposited locally and fired prior to the second $POCl_3$ emitter diffusion. In the processing of Buried Contact BC-EWT solar cells, LPCVD-SiN_x was deposited on the rear. This dielectric was opened locally for the p- and n-contacts by laser ablation in parallel with the via drilling. In both cases the p/n-junctions are passivated by a dielectric layer.

A completely different approach is the formation of rectifying p/n-junctions by the simultaneous diffusion of P and Al in one thermal cycle. The transition between the p and n-doped regions has rectifying properties when certain process parameters are applied (for a more detailed description see [5,13]).

SOLAR CELL PROCESSING

Emitter Wrap Through solar cells

EWT solar cells have been processed with the techniques mentioned in the previous section. The applied processing sequences are given in Fig. 2. In the first process, screen printed metallization, selective emitters and screen printed diffusion barriers were applied, in the second one electroless plating (buried contacts), selective emitter and locally opened SiN_x diffusion barriers. In the third process, the concept of P-Al co-diffusion for the formation of rectifying junctions was investigated in a rather simple process. In this process the front surface remained untextured, a homogenous emitter was diffused and no ARC was deposited. Solar cells were processed on Cz-Si as well as mc-Si.

The results of the illuminated IV-measurements are given in Tab. I and the parameters of the

Tab. I: Illuminated IV-parameters and parameters of the Two-Diode model for three different EWT solar cell designs processed according to Figure 2 with screen printed (SP), buried contact (BC) and evaporated metallization on Cz-Si and mc-Si. The solar cells with co-diffusion are untextured and without ARC.

Process	material	Size [cm^2]	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	η [%]	J_{01} [pA/cm^2]	J_{02} [nA/cm^2]	R_s [Ωcm^2]	R_{sh} [Ωcm^2]
SP	Cz	10x10	599	37.6	71.6	16.1	2.2	37	1.5	1150
SP	mc	10x10	585	35.7	68	14.2	3.4	100	1.9	1600
BC	Cz	5x5	591	37.7	74.6	16.6	2.5	89	0.72	1600
Co-diff.	Cz	5x5	593	23.9	71.1	10.1	1.5	95	1.3	1100

Two-Diode-model extracted from the dark, illuminated and J_{sc}-V_{oc} characteristics are also shown in Tab. I.

Each individual process leads to very high J_{sc}, moderate V_{oc} and good efficiencies. The efficiencies of 16.1% (SP) and 16.6% (BC) are the highest efficiencies reported for EWT solar cells using industrial processing techniques without photolithography. The high J_{sc} can be attributed to almost zero grid shading losses and a second carrier collecting junction on the rear surface. A slightly reduced V_{oc} as compared to conventional solar cells is a consequence of the second carrier collecting junction if materials with a small ratio of diffusion length to cell thickness are used. The moderate FF has different reasons. For screen printed solar cells a rather high series resistance R_s prevents a higher FF and therefore efficiency. Simulations show that with a higher conducting finger grid and a reduced finger spacing (1.8 mm instead of 2.4 mm) the efficiency will enhance well above 16 %. The buried contact technology (finger spacing 2 mm) indicates that a low R_s can be obtained if a good cell metallization is realized. Currently the FF is limited by a rather high J_{02}. At this stage, the cause of the increase in J_{02} is not fully understood, but it is expected that an incompletely removed laser damage has contributed significantly [6].

The high shunt resistances R_{sh} (normally in the range of several thousand Ωcm^2) of the EWT solar cells using co-diffusion shows that junction definition can also be accomplished without the deposition of diffusion barriers using this rather simple technique. High R_{sh} could be achieved independent of the p/n contact length [5,13].

Buried Contact MWA and MWT solar cells

MWA and MWT solar cells have been processed applying the BCSC technology. The manufacturing of these devices is very similar to the one of conventional solar cells and is described in [7,9]. Efficiencies of η=17.5/17.2 % were achieved for MWA/MWT solar cells on a cell area of 5x5 cm^2, and an efficiency of 16.6 % (MWA) was reached on 10x10 cm^2 using Cz-Si. As mentioned in [9], these back contact can be described as conventional solar cells with differences only in shadowing losses as well as R_s. Since the interconnections (edges, vias) are sufficiently metallized, additional contributions to R_s due to the interconnection between front fingers and rear side busbar are not present. Model calculations were performed to estimate the efficiency gain in the module for BC-MWA and BC-MWT solar cells compared to conventional BCSCs for different substrate sizes by the definition of a normalised efficiency η_n. The only parameters to be considered for η_n are shading as well as resistive losses. The defined normalised efficiency η_n is given by:

$$\eta_n = \eta_{shad} \cdot \eta_{R_s} = (1 - M) \cdot (1 - \frac{R_s}{R_{char}})$$

η_{shad} is due to the shadowing losses of the front metallization and M denotes the metallized fraction of the front surface. η_{Rs} determines the reduction in FF due to R_s. The calculations were performed for a line resistance of the finger metallization of 500 mΩ/cm and a groove width of 30 µm. R_{char} is given by V_{oc}/J_{sc}, and a value of 17.6 Ωcm^2 was taken. For the calculations of R_s contributions of the emitter $R_{emitter}$, busbar R_{busbar} and the finger metallization R_{finger} were considered. For the tabbed busbars (Cu ribbons) of the conventional BCSCs, a thickness of 125 µm was taken, whereas the width was 1.5 mm (2.0 mm, 2.5 mm) for 10x10 cm^2 (12.5x12.5 cm^2, 15x15 cm^2) solar cells. For MWA/MWT cells it was assumed, that the interconnection on the rear side leads to negligible resistive losses. For MWT and conventional BCSCs two busbars were taken independent of the wafer size. For each device design and cell area, the optimum finger spacing was determined and $R_{emitter}$, R_{finger} and the shadowing losses M were calculated. For MWA solar cells a design with wrap around contacts at all four wafer edges was taken leading to no silicon material losses due to edge isolation. The cells have to be cut into two halves for interconnection [9]. For MWT and conventional solar cells 1 mm is removed during edge isolation and cleaving. The results of the calculations are illustrated in Fig.3. For 10x10 cm^2, the MWA and MWT solar cell designs leads to the same performance. For larger cell areas the MWT cells reaches the highest η_n. The

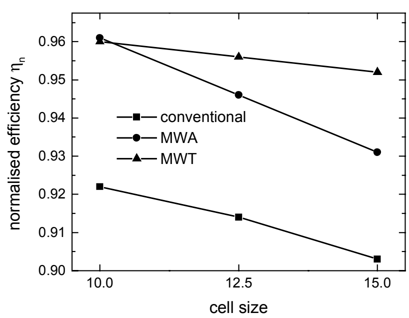


Fig 3: Calculated normalised efficiency of BC-MWA, BC-MWT and conventional BCSCs (see text).

decrease in η towards larger substrate sizes is only minor for MWT solar cells and can be reduced if more busbars are taken. Hence, the increase in efficiency for a back contact module will be between 4 and 5%rel.

HIGH VOLTAGE SOLAR CELLS

Rear contacting schemes can also be applied to monolithically integrated crystalline Si solar cells. The work on these devices is motivated by the demand of small area network independent energy sources for mobile electronic applications (telecommunication and portable computer). This market is currently served by monolithically series interconnected thin film solar cells. The objective is the development of a monolithically integrated device with the advantages of crystalline silicon solar cells: high electrical performance, long-time stability, sufficient efficiencies at low illumination levels in conjunction with high cell aesthetics. Monolithically integrated High Voltage (HighVo) solar cells have been investigated using the EWT device design [14]. A schematic illustration of these devices is given in Fig. 4. The HighVo cell consists of several Unit Cells UCs. Each individual UC has its own discrete emitter (2) and back contact region (5). The front side emitter is connected to the rear side emitter contact by laser drilled vias as illustrated for the EWT solar cells in the previous section. A similar interdigitated contact pattern of the UCs is present on the rear (see Fig. 4). These UCs are defined and partially isolated by trenches. The remaining narrow bridges guarantee the integrity of the HighVo cell and hold the wafer together. These trenches are used for the series interconnection of the individual UCs during metallization by screen printing. Hereby the emitter metallization (3) is printed over the isolation trench (4) to contact the base metallization (5) of the neighboring UC. A shortening of the UCs themselves is prevented by the emitter which also reaches via the trenches from the front to the backside. The metal filled trenches return some of the stability of the initial wafer.

Cell processing starts with the as-cut saw damage removal followed by the deposition of SiN_x as diffusion barrier and patterning. The isolating trenches as well as

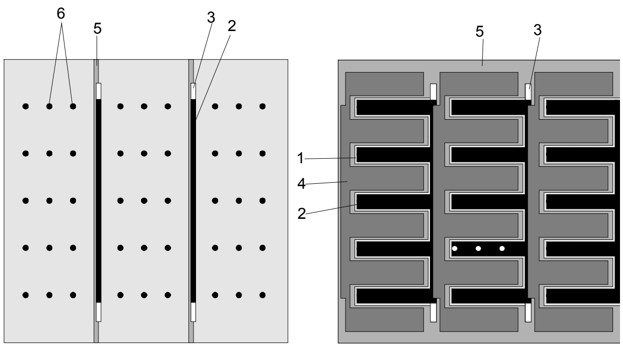


Fig. 4: Front (left) and backside view (right) of an EWT-HighVo solar cell. 1: emitter, 2: emitter contact, 3: isolation trench, 4: base contact, 5: diffusion barrier, 6: holes. The white dots in the lower sketch symbolise the holes lying underneath the emitter contact metallization.

holes are inserted by laser ablation followed by laser damage removal. Emitter diffusion was carried out using a $POCl_3$ source (R_{sheet}=30 Ω/sqr) followed by screen printing of front and rear contact and co-firing. Additionally a single layer ARC of SiN_x was deposited.
HighVo solar cells were processed with ten UCs. An aperture corrected efficiency of η=11.9% was obtained with a V_{oc} of 5.58 V, a voltage at maximum power point V_{mpp} of 4.3 V and a FF of 67.1%. These solar cells have a high effective shunt resistance of approx. 2000 Ωcm^2, which is important at low illumination levels.

CONCLUSIONS

In this work we reported on the successful development of processing sequences and technologies for three different back contact devices of MWA, MWT and EWT solar cells. The obtained efficiencies are amongst the highest reported so far for back contact solar cells using industrial production techniques. The definition of rectifying p/n-junctions is the major task to be solved in the fabrication of EWT solar cells. Three different methods have been successfully developed: screen printed diffusion barriers (η=16.1%, screen printed metallization, 10x10cm^2), laser patterning of a dielectric (η=16.6 %, buried contacts, 5x5cm^2) and P-Al co-diffusion (η=10.1%, no ARC, 5x5 cm^2). Additionally, the EWT concept was applied to monolithically integrated high voltage solar cells.

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