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THE LOPE (LOCAL POINT CONTACT AND SHALLOW ANGLE EVAPORATION) SILICON SOLAR CELLS

B. Terheiden, P. Fath, G. Willeke, E. Bucher,
Universität Konstanz, Fakultät für Physik, P.O.Box X916, D-78457 Konstanz, Germany
Tel.: 0049-7531-88-2088, Fax: 0049-7531-88-3895
email: barbara.terheiden@uni-konstanz.de

ABSTRACT: Based on macroscopically V-textured silicon substrates, a completely new solar cell concept has been developed for high efficiency mono- and multicrystalline silicon - the LOPE solar cell. The local openings on the V-groove tops receive a heavy selective emitter diffusion and subsequently an interconnection by the SAFE (Shallow Angle Finger Evaporation) technique. Series of monocrystalline LOPE cells were processed and the impact of varying the point contact distance and shallow angle evaporation conditions have been investigated. The results are very good cell parameters, a low reflection and a good internal quantum efficiency.
Keywords: point contact - 1: c-Si - 2: texturisation - 3

1. INTRODUCTION

The recent record efficiencies [1], [2] that have been obtained on monocrystalline silicon solar cells are with point-like contacts to the emitter and the base. The University of New South Wales demonstrated an efficiency of 24% (1 sun illumination on a 4cm2 PERL structure) whereas SunPower reported an efficiency of 26.8% on a 1.56cm^2 point contact concentrator solar cell. Simplifications of high efficiency processing sequences are being implemented by several groups [3-7]. Some groups pursue the reduction of the number of processing steps [3], [4] while maintaining reasonable high efficiencies, others suggest novel solar cell concepts to avoid the expensive photolithographic steps [5-7] without loosing high efficiency features like low contact recombination (selective emitters or MIS contacts), fine line finger grids (buried contacts or shallow angle evaporation), low surface reflection (random pyramids or V-texturization) as well as high quality back contacts (back surface reflectors and local back contacts). In the following one of the novel solar cell concepts - the LOPE (LOcal Point contact and shallow angle Evaporation) solar cell - developed at the University of Konstanz will be presented [7].

2. THE LOPE TECHNIQUE

LOPE solar cells, as schematically shown in Fig. 1, include a mechanically formed V-groove surface texturisation which is obtained using a conventional dicing machine equipped with beveled saw blades. After shallow emitter diffusion and thermal oxidation, a regular pattern of local openings is formed at the V-grooved tops by using ultra thin dicing blades (thickness: 15 µm) The shape and width of the point-like openings can be chosen relatively freely by adjusting the cutting depth. The experimentally obtained dimensions of a point contact are in the range of 10µm in width and 15µm in length homogeneously distributed over an area of the presently used 5x5cm^2 (see also Fig. 3). After a heavy selective phosphorus diffusion in the openings and the formation of a local Al back surface field (Al-BSF), the heavily doped point contacts are interconnected by shallow angle finger evaporation (SAFE) of Ti/Ag. The SAFE technique relies on deeply V-grooved specimens, which are exposed to the metal evaporation beam under a shallow angle perpendicular to the groove direction.
In this case the previous groove serves the following one as a shadowing mask. Fine-line contact grids with a minimum finger width of below 10µm can be obtained without reflection loss due to an oblique finger metallisation.
The advantages of this new high efficiency solar cell design are the omission of expensive photolithography steps, a high front grid performance (almost no shadowing losses, very low contact recombination) and a favorable selective emitter design (very shallow emitter and heavy contact area diffusion). It is believed that LOPE high efficiency solar cells could be especially suitable for cost effective PV concentrator applications.

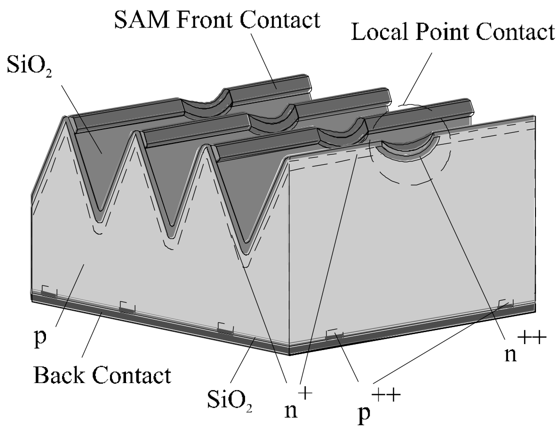

Fig. 1 Schematic representation of LOPE solar cell structure with a local Al BSF.

3. SOLAR CELL PROCESSING

Solar cell processing of monocrystalline silicon solar cells with a mechanically V-grooved front surface and LOPE front contacts have been performed at the processing facilities of the University of Konstanz.
For V-groove formation a conventional dicing saw equipped with beveled saw blades with a tip angle of 35° and a tip radius of < 10µm was utilized. The groove depth is 120µm.
The applied LOPE high efficiency cell process for monocrystalline silicon is schematically shown in Fig. 2.

1. Mechanical texturisation and saw damage etching
2. Thermal oxide masking of back side
3. $POCl_3$ emitter diffusion 100Ω/sqr.
4. TCA thermal oxidation: growth of a masking layer, passivation
5. Mechanical local point contact formation and damage etching
6. Heavy phosphorus point contact diffusion: 35Ω/sqr.
7. Photolithographical definition of local Al back contacts
8. Al evaporation at back side, lift-off and sintering/drive in
9. Shallow angle evaporation of Ti/Ag front contacts and busbar formation
10. Al evaporation at back side and sintering

Fig. 2: Process sequence for monocrystalline silicon solar cells using the LOPE technique.

The SAFE (Shallow Angle Finger Evaporation) was optimized on multicrystalline silicon with three different V-groove sequences: all V-groove tops on equal height (1), a lower one in the middle (2), two lower ones between the metallized ones (3)(Fig. 3). The different heights of V-groove tops provide the possibility of varying the point contact distances also in this direction, perpendicular to the V-texturisation.
Applying the SAFE metallisation to the LOPE cell there arises the problem of an uncomplete metallisation of the local opening themselves. In recent experiments the metallisation could be improved but it is still not perfect at present (Fig. 4). Therefore we currently implement a metal plating step into the process sequence in order to overcome these restrictions.

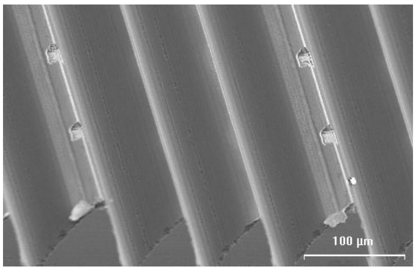

Fig. 3: SEM picture of local point contacts on the V-groove tops of a LOPE cell. The fingers, evaporated under a shallow angle, which are interconnecting the single point contacts, are visible at the V-groove tips (V-groove sequence 3, see text).

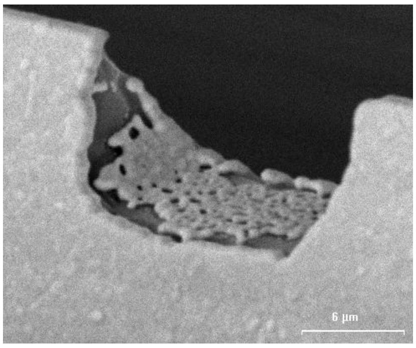

Fig. 4: SEM picture of a single local point contact, which was metallized using the shallow angle evaporation. The width of the point contact openings is approximately 15µm.

4. THREE DIMENSIONAL DEVICE SIMULATIONS

The device simulations of the LOPE cell result in a survey of which point contact distances and which shallow emitter leads to the best results.
The simulation was done with the program $DESSIS_{ISE}$ [8]. The point contact distances were varied in two dimensions, parallel and perpendicular to the V- grooves. We calculated the short circuit current (J_{sc}), open circuit voltage (V_{oc}) and the cell fill factor (FF) for three distances parallel to the V-texturisation, 50µm, 200µm, 1000µm, two distances perpendicular to it, 100µm and 200µm, and two emitter sheet resistances, 80Ω/sqr. and 300Ω/sqr.
The V-textured frontside has been simplified to a flat one with doubled point contact distances in order to reduce the number of simulation grid vertices necessary for an accurate 3D device simulation. In order to get the original short circuit current (J_{sc}) contribution from each point contact a reduced light intensity has been used.
The simulations showed the following influences of the point contact spacing. J_{sc} is highest for the lowest point contact density, because the point contact shading losses are smallest in this case. V_{oc} is mainly limited by bulk and back surface recombination and is therefore little affected by the point contact spacing. FF is highest for the small point contact spacings due to smaller emitter sheet resistance losses.

The slightly lower fill factors of the 300 Ohm/sqr. emitter solar cells are overcompensated by higher short circuit currents, which are due to the larger short wavelengths quantum efficiency.
Therefore the results show a maximum in efficiency. This maximum results from the optimisation of an V_{oc} and J_{sc} increase versus an FF decrease. This maximum lies for the 300Ω/sqr. emitter at point contact distances of 400µmx200µm. The 80Ω/sqr. emitter has not such a definite maximum (Fig. 5), because the lower sheet resistance does not reduce the cell fill factor (FF) as much as the higher sheet resistance does.

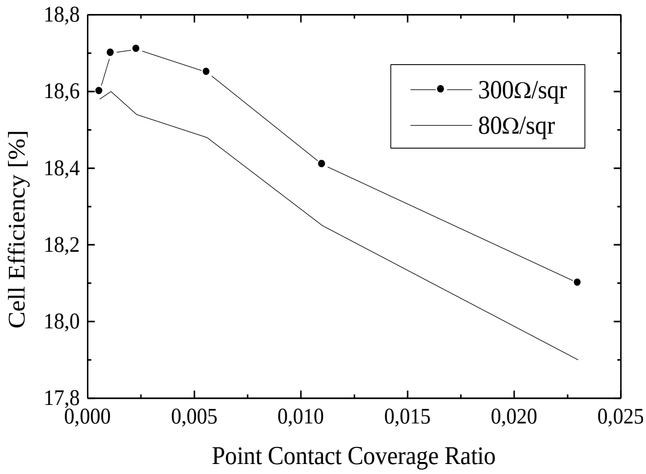

Fig. 5: Optimisation of local point contact distances and comparison of two different shallow emitters (L_D=200µm, full BSF).

5. Solar Cell Characterisation

5.1 Optimisation of the finger grid

Multicrystalline silicon solar cells were used to optimize the metal thickness on the grid finger. Tab. 1 shows the optimum achieved for each V-groove sequence.

Tab. 1: Results of the illuminated IV-measurements of multicrystalline silicon solar cells with shallow angle evaporated front grid and varying metal finger distances. (no surface passivation and ARC)

Metal finger distance [# of V-groove dist.]	Voc [mV]	Jsc [mA/cm^2]	FF [%]	η [%]
1	576	26.4	75.9	11.6
2	582	27.5	77.2	12.3
3	577	27.2	77.2	12.1

5.2 Hemispherical Reflectances

The highest reflectance is found as espected on a sequence 1 LOPE cell with 50µm point contact distance. As it is shown in Fig. 6 the reflectance is less than 7% over a wide range of wavelengths, whereas the 1000µm point contact cells showed a reflectance of less than 5%. In comparision to that the reflectance of the unmetallized LOPE cell is around 2% smaller. This means that there are almost no shadowing losses caused by the finger grid.

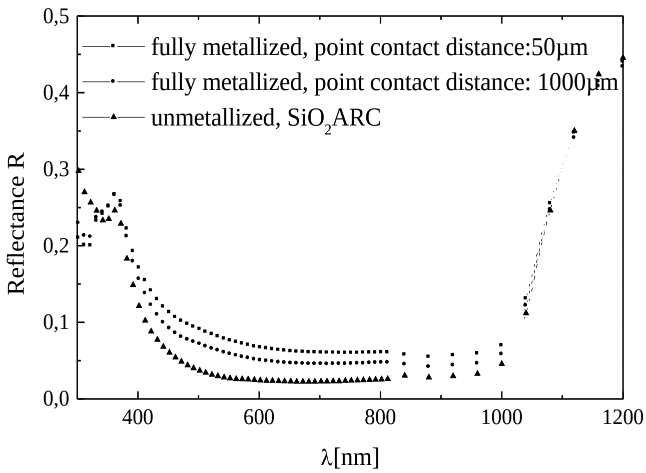

Fig. 6: Hemispherical reflectance R of a LOPE solar cell with different point contact distances compared to an unmetallized LOPE cell. All LOPE cells have got an anti-reflection coating, ARC, of SiO_2 and full Al BSF.

In Fig. 7 the hemispherical reflectance of another series of LOPE cells is compared with an untextured reference cell whereas both have a single SiO_2 ARC. The average reflectance of the metallized LOPE cell is below 4 % in this case but the reflectance of the flat reference lies at about 17% in the range of 600nm to 1000nm. This shows that the reflectance is reduced for a large part because of the V-texturisation of the frontside

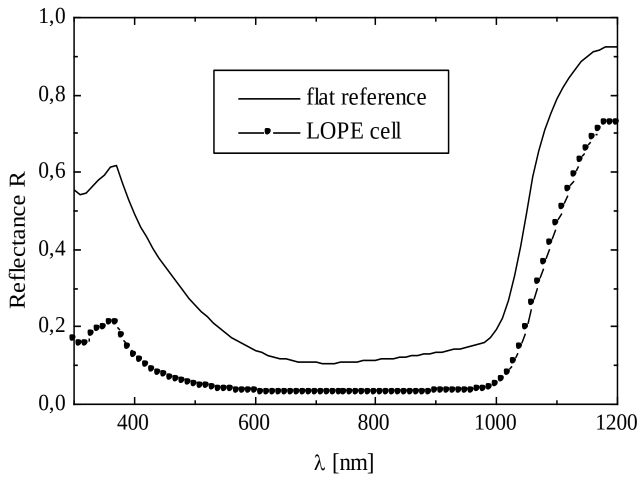

Fig. 7: Hemispherical reflectance R of a LOPE solar cell in comparison to a flat reference cell with the same single layer ARC and local BSF.

5.3. Internal Quantum Efficiency

The measured internal quantum efficieny, IQE, of a LOPE solar cell is shown in Fig. 8**.** For wavelengths larger than 1000nm the IQE of the LOPE cell is higher than that of the flat reference with the same SiO_2 single layer ARC because of an enhanced optical path length of the long wavelength photons due to the V-texturisation of the front surface and the back surface-reflector (local BSF).

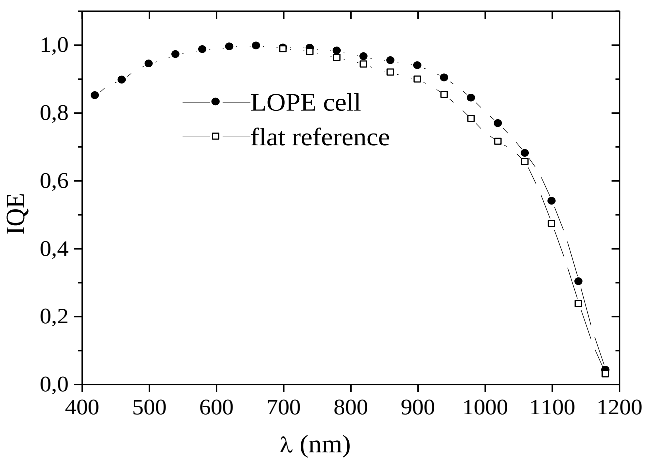

Fig. 8: IQE of a LOPE cell and a flat reference (because of technical problems the reference could not be measured over the whole range)

5.4 Illuminated IV-measurements

In Tab. 2 the results of the illuminated IV-measurements of LOPE cells with local BSF and those of a flat reference are shown.

Tab. 2: Comparison of the cell performance of LOPE solar cells (sequence 1) and untextured references.

Cell type	Voc [mV]	J_{sc} [mA/cm^2]	FF [%]	η [%]
flat reference	658	31.4	76.4	15.7
LOPE: 1000µm	646	35.9	71.6	16.3
LOPE: 300µm	650	36.8	72.8	17.4

The improved SAFE technique and the local BSF give a J_{sc} of 36.8mA. Combined with a high V_{oc} it comes to a 17.4% cell efficiency. The slightly reduced open circuit voltage of 8mV of the LOPE cell (300µm) as compared to the reference is a result of two opposing effects: an enhanced dark saturation current due to a by a factor of 3 increased cell surface and a reduced bulk recombination through removal of silicon volume during macroscopical V-texturing (effective wafer thickness after V-grooving and defect etching: 120µm). When comparing the J_{sc} of the two different point contact distances there is a difference of 1mA. The lower J_{sc} of the 1000µm LOPE cell is due to an enhanced current crowding with increasing point contact spacing. Related to this is a fill factor loss of 1.2% absolute due to series resistances. The comparable low cell fill factors of the LOPE cells are due to the series resistance as well. They are mainly caused by a not yet optimal busbar performance, since the busbar runs perpendicular to the V-grooves. This enhances the current path towards the measurement probe by a factor 3.

6. CONCLUSIONS

A novel solar cell concept has been presented which is based on local point contacts prepared by a simple and fast mechanical structuring step and a self-aligned metallisation step which omits any photolithography. First results have demonstrated a solar cell efficiency of 17.4% due to a high J_{sc} and V_{oc}. The fill factor was too small and therefore in future work the shallow angle finger evaporation technique SAFE will be combined with electro-less metal plating.

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