RECORD EFFICIENCIES ABOVE 21% FOR MIS-CONTACTED DIFFUSED JUNCTION SILICON SOLAR CELLS

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ABSTRACT

High-efficiency solar cells obtained by a simple cost-effective manufacturing process are required for a drastic reduction of the costs of solar electricity. In this paper an improved and yet simple processing sequence for highly efficient MIS-contacted diffused n^+p junction (MIS-n^+p) silicon solar cells is presented. The process is characterised by: (i) formation of a metal-insulator-semiconductor (MIS) contact on an n^+-diffused emitter, (ii) aluminium metallisation for front and rear electrodes, and (iii) low-temperature surface passivation by PECVD silicon nitride. For MIS-n^+p solar cells with the front grid defined by Al evaporation through a shadow mask efficiencies of up to 20.6% have been obtained. Furthermore, mask-free metallised cells with a mechanically grooved front surface have been fabricated. These cells have reached an confirmed efficiency of 21.1%, the highest value to date reported for MIS-n^+p silicon solar cells.

INTRODUCTION

The metallisation process of state-of-the-art high-efficiency silicon solar cells with energy conversion efficiencies of up to 24% [1] involves numerous aligned photolithography steps and plating steps [2], which can be doubted to be suitable for a large-scale industrial production. Avoiding obstacles associated with screen printing and electroless plating for highest efficiencies, a promising alternative for simple fabrication of high-quality metal contacts is the deposition of metal through a shadow mask by means of vacuum evaporation. Using this fabrication technique, photolithography steps as well as plating steps can be completely eliminated from the metallisation process. Conventionally Ti/Pd/Ag-contacted single-diffused *p-n* junction silicon solar cells incorporating this photolithography-free contact scheme have recently demonstrated independently confirmed efficiencies of up to 20.9% on 4-cm^2 FZ silicon [3].

Recently it has been demonstrated that expensive Ti/Pd/Ag-contacts can be replaced by Al-contacts on top of a thin tunnel oxide, resulting in MIS-contacted diffused n^+p-junction (MIS-n^+p) solar cells [4]. The novel fabrication procedure offers the possibility of using an inexpensive metal such as aluminium, which also allows a less aggressive cleaning procedure for the shadow masks, so that they can be re-used for a large number of evaporation cycles. An improved and yet simple processing sequence for highly efficient MIS-contacted diffused n^+p-junction silicon solar cells using aluminium for both electrodes is presented in this paper. In the literature efficiencies of 19.5% on 4-cm^2 FZ silicon [5] and 16.5% on industrially relevant 98-cm^2 CZ silicon [4] have been reported for the MIS-n^+p cell structure. In the course of this work, cells of the MIS-contacted diffused n^+p-junction type metallised by the shadow mask technique reaching 1-sun energy conversion efficiencies of 20.6% have been fabricated and characterised.

To even further increase the industrial feasibility in an innovative approach presently investigated at ISFH, the use of shadow masks is completely eliminated from the cell fabrication process by the use of oblique evaporation in conjunction with a mechanically grooved wafer surface [5,6]. Due to the shadowing effect of the ridge tops, this method is self-aligning and yields a strongly enhanced utilisation of the vacuum chamber volume as well as the evaporated metal [7]. By optimising the front grid pattern and subsequent reduction of the shadowing losses, it was possible to improve our maximum efficiency for this cell type with mask-free front grid metallisation in the course of this work to an independently confirmed value of 21.1% for MIS-contacted silicon solar cells using only aluminium for front and rear electrodes.

EXPERIMENTAL

Cell design

The most important features of the cell structure discussed in this work are:

- Aluminium front and rear electrode
- Homogeneous emitter formation by a single diffusion
- Front surface passivation by low-temperature silicon nitride deposition

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Fig. 1 shows a schematic cross section of the MIS-n^+p solar cell with the front grid deposited by metal evaporation through a shadow mask.

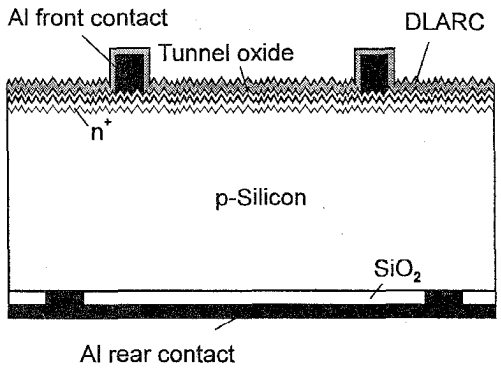

Fig. 1. Schematic cross section of a MIS-contacted diffused junction silicon solar cell with front grid deposited by metal evaporation through a shadow mask.

To reduce perimeter recombination losses, which are not negligible at present cell sizes (~4 cm ^{2}), a diffusion window is used. For large-area cells this window can be omitted, since with increasing area-to-perimeter ratio the perimeter losses become less important. As at the present stage of development the work is focused on the optimisation of the front surface of the solar cells, an oxide-passivated rear contact configuration is used.

Fabrication sequence of mask evaporated cells

Starting material are 0.5-Ω cm float-zone p-silicon wafers with shiny etched surfaces and a thickness of 400 µm. After an RCA clean a 250 nm thick thermal oxide is grown, serving as diffusion mask. Subsequently the diffusion window is opened and the wafers are immersed in a solution of KOH and Isopropanol at 75°C, resulting in a front surface texture consisting of upright random pyramids. The phosphorous diffusion is performed at 830°C using a $POCl_3$ source, leading to an emitter with a sheet resistance of around 100 Ω/□. After the definition of contact holes through the rear passivating oxide and the removal of the P_2O_5 layer from the front surface the rear electrode is formed by evaporation of Al onto the entire rear surface. A thin tunnel oxide is grown in a 15-min thermal oxidation step at 500°C, which also provides the sintering of the back contact. Subsequently, the front grid is deposited by vacuum evaporation of Al through a shadow mask. The front electrode consists of 20 µm wide fingers and contacts about 4% of the front surface (including the busbar). As final step, a double-layer antireflection coating (DLARC) consisting of excellently passivating silicon nitride (SiN) [8] and silicon oxide is deposited onto the front surface of the cell by means of plasma-enhanced chemical vapour deposition (PECVD).

RESULTS AND DISCUSSION

Cells with mask-evaporated front electrode

Fig. 2 shows the measured 1-sun current-voltage characteristics of the MIS-n^+p solar cell of Table I with the front grid formed by Al evaporation through a shadow mask. The cell parameters reach values very close to the ones obtained for similarly processed Ti/Pd/Ag-contacted diffused junction cells [3], as can be seen in Table I.

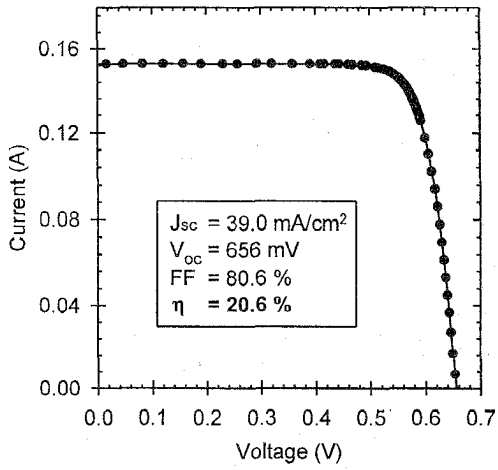

Fig. 2. Measured 1-sun current-voltage (AM1.5G, 100 mW/cm^2, 25°C, aperture area 3.9 cm^2) of the MIS-n^+p cell of Table I.

Table I. Comparison of measured 1-sun parameters of Al-contacted and Ti/Pd/Ag-contacted diffused junction cells [3].

Cell type	MIS-n^+p	n^+p
Metallisation	Al shadow mask	Ti/Pd/Ag shadow mask
J_{SC} [mA/cm^2]	39.0	39.5
V_{OC} [mV]	656	657
FF [%]	80.6	80.5
η [%]	20.6	20.9

The slightly lower energy conversion efficiency of the MIS-n^+p cell is mainly due to the lower short-circuit current density (ΔJ_{SC} ≅ 0.5 mA/cm^2) of the cell. This can be attributed to variations of the front surface texture and the DLARC. Since the other cell parameters (open-circuit voltage V_{OC} and fill factor *FF* are identical within the uncertainty of the measurement, it is been demonstrated that Ti/Pd/Ag-contacts can be replaced by Al-contacts virtually without any loss in efficiency.

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Fig. 3 shows the measured hemispherical reflectance R of the MIS-n^+p cell of Table I between 300 nm and 1150 nm wavelength. The AM1.5G-weighted front surface reflectance is about 4.3%. This relatively low value results from the good antireflection properties of the front surface texture consisting of random pyramids in conjunction with the DLARC. Also shown in Fig. 3 is the external quantum efficiency (EQE) of the cell measured with about 100 mW/cm^2 of 'white' bias light. The internal quantum efficiency (IQE) considers the measured hemispherical reflectance of the cell and the absorption by the front metal grid. However it does not consider the absorption within the SiN film on the cell. This film absorbs significantly at wavelengths below 500 nm, and this effect causes an apparent decrease of the IQE wavelengths < 500 nm.

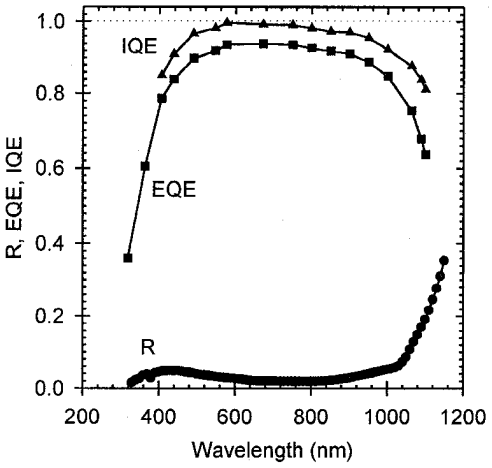

Fig. 3. Measured hemispherical reflectance and the external and the internal quantum efficiency of the MIS-n^+p cell of Table I.

Mask-free metallised cells

As an important step towards the development of a fabrication process for high-efficiency silicon solar cells consisting of only few and simple steps, suitable for large-scale industrial production, cells with mask-free metallisation are presently under investigation at ISFH [5,6,7]. The fabrication process is characterised by: (i) mechanical surface grooving, (ii) emitter formation by a single diffusion (iii) self-aligned oblique metal evaporation, and (iv) low-temperature surface passivation by silicon nitride deposition. Fig. 4 shows the measured 1-sun current-voltage characteristics of a mechanically grooved MIS-n^+p silicon solar cell with the front grid formed by mask-free oblique evaporation of aluminium. The cell exhibits an efficiency of 21.1%, which is a remarkable result considering the simplicity of the fabrication process and the non-ideal fill factor. Further grid optimisation in order to improve the relatively low fill factor seems likely to produce cell efficiencies above 21.5%.

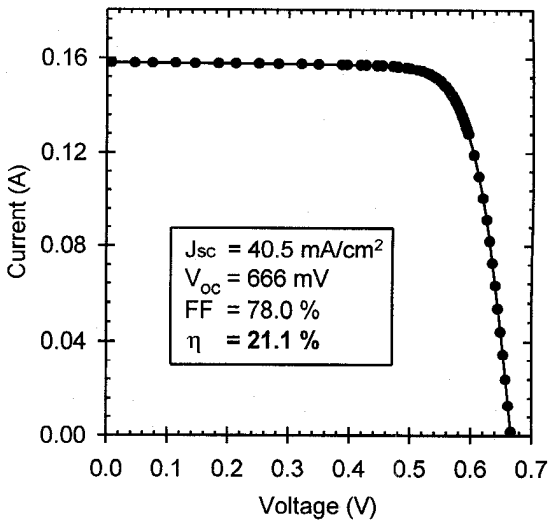

Fig. 4. Measured 1-sun current-voltage characteristics of a mechanically grooved MIS-n^+p solar cell with the front grid formed by mask-free oblique evaporation of aluminium (cell aperture area 3.9 cm^2).

Summary of cell results

Table II summarises the measured 1-sun performance parameters of the cells investigated in this work.

Table II. Measured 1-sun parameters (AM1.5G, 100 mW/cm^2, 25°C, aperture area 3.9 cm^2) of the best shadow mask evaporated and the best mask-free metallised MIS-n^+p silicon solar cells (0.5-Ω cm FZ p-silicon) fabricated in the course of this work.

Cell type	MIS-n^+p	MIS-n^+p
Metallisation	Al shadow mask	Al mask-free
J_{SC} [mA/cm^2]	39.0	40.5
V_{OC} [mV]	656	666
FF [%]	80.6	78.0
η [%]	20.6	21.1*

* Confirmed by Fraunhofer-ISE [9]

The shadow mask metallised cell shows 20.6% energy conversion efficiency. Reducing shadowing losses of the front grid by means of mechanical surface grooving in conjunction with mask-free oblique metal evaporation resulted in an increase of J_{SC} by 1.5 mA/cm^2. The improvement of V_{OC} of the cells by 10 mV can in this case be attributed to a reduced metal-semiconductor contact area of the front grid. Despite of a fill factor reduction of 2% due to a not yet optimal grid design these cells show an increase in efficiency of 0.5% (absolute), reaching a confirmed value of 21.1%.

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CONCLUSIONS

In this work, an improved and yet simple processing sequence for highly efficient MIS-contacted diffused n^+p-junction silicon solar cells, using only a single diffusion and inexpensive aluminium for front and rear electrodes has been presented. MIS-n^+p silicon solar cells with the front grid defined by Al evaporation through a shadow mask, reaching efficiencies of up to 20.6%, have been characterised. It has been demonstrated that Ti/Pd/Ag-front contacts can be replaced by Al-contacts with negligible loss in cell efficiency.

Furthermore, results for mechanical grooved MIS-n^+p cells with mask-free and obliquely evaporated front contacts have been reported. Despite the simplicity of their fabrication process (single diffusion, mask-free grid formation, all aluminium electrodes, low-temperature front surface passivation by SiN), these cells have reached independently confirmed 1-sun efficiencies of up to 21.1%. This is the highest value ever reported for MIS-contacted diffused junction cells using only aluminium for both electrodes. Further grid optimisation should result in more ideal fill factors, so that for this simple cell fabrication process efficiencies above 21.5% seem to be within the reach of presently established technology.

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