Investigations of a novel front contact grid on poly silicon solar cells

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ABSTRACT: Using poly silicon wafers as starting material 3 cm x 3 cm solar cells were made. Pairs of solar cell devices were processed simultaneously using sets of subsequent wafers which exhibit essentially the same grain structure. The front metallisation of the reference cell was done by painting a conventional grid structure with silver ink whereas onto the other cell the metal structure was painted along the grain boundaries. Current - voltage measurements on a series of cell pairs were made in the dark and under illumination. Diodeparameters - recombination current, j_{01}, diffusion current, j_{02}, shunt conductance, G_{SH}, and series resistance, R_S - as well as solar cell parameters - short circuit current, i_{SC}, open circuit voltage, V_{OC} , and curve fill factor, CFF, were determined. The comparison of the statistically evaluated results shows, that the series resistance of the reference cells is more than 20 per cent larger than the one found for the cells which have a front contact grid along the grain boundaries, resulting in an average increase of the curve fill factor of more than 5 per cent. Furthermore the individual results of these two parameters as well as of the load resistance at conditions of maximal power output differ considerably less from the mean value for these cells compared to the values of the reference devices.

1. INTRODUCTION

Most of the reduction of the conversion efficiency observed on solar cells made from polycrystalline silicon compared to solar cells manufactured from monocrystalline wafers can be attributed to the presence of grain boundaries [1]. A simplified explanation of the influence of grain boundaries on the solar cell output can he given by assuming that the whole solar cell is divided into individual devices as given by the grains. The grain boundaries then can be considered as crystal surfaces. As a consequence dangling bonds and surface defects cause an enhanced recombination of free carriers along the grain boundaries. Therefore grain boundary passivation becomes an important item in poly silicon solar cell preparation [2,3]. Due to the metallisation of the backside and the front side metal grid the individual grains are electrically connected together in a parallel circuit. Usually the front side grid is not made in such a manner that every grain has its own metal contact. As a consequence the current generated by the incident light within the grain has to pass through grain boundaries which can be assumed to he regions of enhanced electrical resistance thus contributing to the overall series resistance of the solar cell. Since grain boundaries without passivation are mostly regions of enhanced recombination for the light generated minority carriers the internal overall quantum efficiency is reduced near grain boundaries, whereas regions within the grain with high quantum efficiency may be shaded by the front metal grid. The basic idea of the present work was to form the front metal grid along the grain boundaries expecting that this shall he advantageous compared with a conventional metal grid for the two effects described above which contribute to the reduction of the total solar cell output.

2. EXPERIMENTAL

As a starting material we used wafers of commercially available polycrystalline p-type silicon from Wacker Heliotronic. The 10 cm x 10 cm wafers were cut into 3 cm x 3 cm squares for solar cell manufacturing. Two subsequent wafers were selected in order to obtain pairs of substrates with essentially the same grain structure. These pairs were processed simultaneously. This was done to minimize the influence of the substrate as well as of the preparation techniques other than the front side metallisation on the finally measured current-voltage characteristics. The substrates were chemically polished and cleaned. Diffused planar p/n junctions on the front side were made by standard phosphorous diffusion techniques. An aluminum layer was applied onto the backside of the devices. The front side metal grid of one cell of the cell pair was made by painting a conventional metal structure with a silver ink onto the surface. Further on this type of cell will be refered to as the reference cell. The thickness of the lines was 0.5 to 0.6 mm. On top of the other cell named the test cell the metal grid was painted along the major grain boundaries. The firing of the silver ink at 700° C for 1 min again was done simultaneously for the cell pairs. Finally an antireflection coating was applied to the solar cell by evaporating silicon monoxide onto the front side of the devices. A pair of finally processed solar cells is shown in Fig.1 as a high contrast black and white picture in order to illustrate the difference of the two front contact grids. Metallised areas appear white whereas the active AR coated area appears to be black. Some of the cell pairs were contaminated with well known minority carrier lifetime killers such as iron prior to the diffusion of the p/n-junction. This was done to ensure to a high degree that the differences in the finally measured solar cell and diode parameters do not depend on occasional fluctuations of the local minority carrier diffusion length within the grains in the two cells. All our samples were prepared without any grain boundary passivation. Current - voltage measurements in the dark as well as under illumination were made on a series of 20 pairs of solar cells. This was done by the use of a Keithley 224 current source which is capable to act as a current sink for currents below 100 mA. Due to this limitation the I(V) curves under illumination were performed using a tungsten halogen lamp with a slightly reduced light intensity compared to simulated AM I irradiation. Both, light intensity and temperature were kept constant during the measurements of all samples. Some selected sample pairs were scanned with a light beam at a wavelength of the emitted light of 940 nm. The induced current was recorded as a function of the lateral location of the incident light on the solar cell.

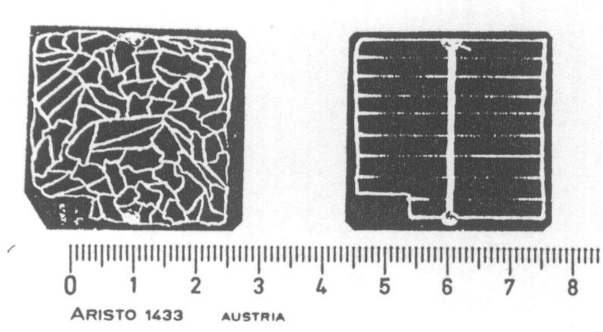

Fig. 1:High contrast picture of a pair of solar cells.The front metal grid appears white whereas the active cell area is shown in black. On the left a test cell with contacts along the grainboundaries and on the right a cell with a conventional grid structure is displayed.

3. RESULTS

Using a DC equivalent circuit model the current-voltage curve in the dark can be used to determine the diode parameter given by equation 1 [4]:

$$i = i_{01}\left[\exp\left\{\frac{q(V-R_S i)}{2k_B T}\right\}-1\right] + i_{02}\left[\exp\left\{\frac{q(V-R_S i)}{k_B T}\right\}-1\right] + G_{SH}(V-R_S i)$$

In the above equation q is the elementary charge and k_B the Boltzmann constant. The first term on the right side of Eq.1 is due to the recombination current induced by deep recombination centres within the deple-

Table 1: Mean values and standard deviations - in paranthesis - of diode and solar cell para

	j_{01} [µA]	j_{02} x 10^{-11} A	G_{SH} [mS]	R_S [Ω]	CFF [-]	i_{SC} [mA]	V_{OC} [V]
Test cell	1.0 (0.5)	8.6 (2.8)	0.62 (0.48)	0.43 (0.06)	0.72 (0.09)	63.9 (5.9)	0.520 (0.013)
Reference cell	1.1 (0.7)	8.1 (2.8)	0.30 (0.08)	0.52 (0.17)	0.68 (0.13)	73.1 (6.6)	0.520 (0.015)

tion region of the p/n-junction, The second term describes the current contribution arising from the diffusion current determined by the dopant concentration on each side of the p/n- junction. The last part contributes in an ohmic way to the total current and is characterised by the shunt conductance, G_{SH}. The expression $V-R_Si$ takes into account the voltage drop across the series resistance, R_S. Under illumination eq.1 describes the internal current losses from a constant light generated current, i_L:

$$i_{tot}(V) = i_L - i(V)$$

The shunt conductance was determined from the first derivative of the i(V) curve in the dark at V=0. As can be seen from eq.1 the series resistance will dominate the i(V) curve at high current values. Above current densities of approximately l0mAcm^{-2} our i(V) curves nearly are linear and R_S was determined from the slope. In order to keep the temperature constant at high current densities the measurements were carried out with pulsed current. Correcting the measured i(V) curve for G_{SH} and R_S the two parameters, i_{01} and i_{02} , characterising the recombination and the diffusion current respectively were obtained from a semi-logarithmic plot of i(V) for V=0. The i(V) curves taken under illumination were used to obtain the short circuit current density, i_{SC} at V=0, the open circuit voltage, V_{OC}, at i=O. From the plot of P(V), where P = i x V the maximal power output, $P_{max} = i_{max} \times V_{max}$ was determin-ed and used to calculate the curve fill factor, CFF= P_{max} / (i_{sc}xV_{oc}), and the load resistance, $R_{load} = V_{max} / I_{max.}$ A comparison of all our cell pairs shows that for more than 2/3 of the pairs, R_S and CFF of the cells which have a front contact grid along the grain boundaries are cleary improved compared to the reference samples. The short circuit current however was found to be reduced. This may very likely due to the fact that our test cells have larger shaded areas due to the front contact grid than the reference cells. The shaded area of the test cells was typically 5 per cent larger than the one of the reference cells. With the exception of the shunt conductance all other parameters were found to be unaffected from the method of the front contact metallisation. This can be considered a proof for the relevance of the statistical data evaluation since there cannot be any influence of the front metallisation expected on recombination current, diffusion current or open circuit voltage. These parameters are essentially determined by the p/n-junction characteristics. For most of the pairs the shunt conductance too was about equal however there have been some samples of test cells which exhibit up to 2 orders of magnitude increased values of G_{SH}. It appears to be likely that during the firing of the silver ink silver particles can penetrate more easily along grain boundaries across the p/n-junction than they do within the grains thus shunting the diode. The overall mean values and standard deviation of the diode and solar cell parameters are summarized in table 1. The mean value of the load resistance for the test cells was 8.2 Ω ± 16 per cent whereas for the reference cells a value of 7.8 Ω ± 51 per cent was found. The much smaller standard deviation for the test cells indicates that the influence of individual grains on the overall solar cell output is clearly reduced.

4. CONCLUSIONS

The method to form the front contact grid along the grain boundaries of a poly silicon solar cell has been found to be advantageous in order to reduce the series resistance of the device. A reduction of more than 20 per cent was observed. As a consequence we have found an improvement of typically more than 5 per cent of the curve fill factor of our lest cells compared to the reference cells. Against our expectation the short circuit current measured on the test cells exhibit smaller values than the ones observed on the reference cells. This can be explained by the fact that the top surface area of the reference cells was less shaded by the front metal grid than it was on the test devices. An improved method for the application of the front metal grid along grain boundaries is under progress. Besides the observed improvement of R_S and CFF a clearly reduced variation of the individual solar cell parameters of the test cells was found. This could become important for the solar cell array fabrication since it bears the potential for improved module efficiency.

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