IMPLEMENTATION OF PHOTOVOLTAICS IN THE PHYSICS COURSE AT THE UNIVERSITY OF VIENNA

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ABSTRACT: As part of a second level experimental course in physics students prepare a silicon solar cell. Beginning with a $3cm\times3cm$ unpolished multicrystalline silicon wafer the students perform a cleaning and polishing step. The n^+p-junction is produced by the use of a solid state phosphorous diffusion. For the metallisation of the front and backside aluminum- and silverpastes are used. The antireflection coating consists of a $80nm$ thick silicon monoxide layer evaporated under high vacuum conditions. Current-voltage measurements are carried out in the dark and under illumination. The solar cell parameters, short circuit current density j_{sc}, open circuit voltage V_{oc}, maximal electrical power output P_{max}, load resistance R_{load} and curve fill factor CFF, as well as the current loss mechanism characterized by the diode parameters, saturation current density j_0 and diode ideality factor n, the series resistance R_S and the shunt conductance G_{SH} are determined. The best cell obtained by the students exhibit a conversion efficiency of more than eight per cent.

Keywords: Education and Training - 1: Multi-crystalline - 2: Silicon - 3

1. INTRODUCTION

The decision to utilize photovoltaic energy conversion depends on the knowledge about photovoltaics. Since future physicists are requested to decide about modern energy management a comprehensive education involving the physics of a photovoltaic solar cell is desireable. Currently at the Physics Institutes of the University of Vienna young physicists can graduate for a diploma or PhD as well as for the teaching permission in high schools. At the second level of their study the students have to select two experimental courses out of six. Since 1967 we offer a practical training in solid state physics which from the very beginning emphasizes experiments on semiconductors. For example the well known Haynes-Shockley experiment [1] which allows to determine the diffusion, recombination and drift properties of the minority carriers in semiconductors was and still is a part of the experimental training. In the past an average of 15 students per year selected our experimental course. During the last years the attempt was made to enhance the understanding of the practical importance of the experiments. Since renewable energy conversion is an important environmental factor and the technology of a photovoltaic solar cell is rather simple compared to integrated circuits the decision was made to adapt some of the experiments with respect to photovoltaic applications using a part of the laboratory equipment for solar cell characterization. Beside the preparation and characterization of a solar cell made from multicrystalline silicon - which will be described in more detail later on - another experiment is the measurement of the photoconductance decay with the help of a microwave bridge and a pulsed laserdiode in order to calculate minority carrier lifetimes of solar silicon. An additional experiment is the determination of the Hall properties of different samples of solar grade silicon. The space charge region of solar cells is characterized at low frequencies - $100Hz$ to $10kHz$ - differential conductivity and capacitance measurements.

2. EXPERIMENTAL

The preparation and characterization of a photovoltaic solar cell by the students is planned to take place on two subsequent days. The experiment is done in groups of two to four students and one instructor who simultanously carries out all the required steps for the solar cell preparation using two to three samples. These samples are intended to be handed over to a student in case his sample is broken during the cell processing. The experiment is prepared by cutting commercially available $10cm\times10cm$ multicrystalline silicon wafers to $3cm\times3cm$ samples. The thickness is about $300\mu m$ to $500\mu m$ and the surface is not grinded or polished. The wafers were optically inspected and only samples with a homogeneous grain size distribution are selected for the solar cell preparation. For one group of students 10 to 12 wafers are prepared. Every student gets his own set of preparation tools consisting of plastic tweezers, a glass and a plastic baker and a sample storage container. Usually before this experiment, the students had no experience in the handling of a silicon wafer. So the students are allowed to select their personal sample and pick them up with a tweezer and put it in the sample container. Usually 50 per cent of the wafers will survive. After picking one's wafers, the first step is to blow them with nitrogen and rinse them in ethanol. Black wax is dissolved in trichloroethylene. With a sharpened piece of wood every student draw a little mark on one corner of his sample. Then the black wax is dried at 100°C. This mark has two purposes: (i) the student can identify his sample and (ii) the front side can easily be distinguished from the back side. A chemical polishing solution consisting of (roughly) 1 part HF, 2 parts HNO_3 and 2 parts of acetic acid is prepared. All chemicals are analytic grade. The students are instructed on the toxicity and handling precautions of these chemicals before the samples are picked up with the tweezers and merged into the polishing solution. The polishing duration is approximately three minutes. However, it is individually adapted due to the differences in the composition of the etches. In any case the appearance of a brownish vapour signals the end of the chemical polishing. The wafers are picked with the tweezers and merged and rinsed in pure H_2O. After the removal of the black wax in trichloroethylene the later front side appears shiny with the unetched mark in the corner which makes a good contrast. The next step is the preparation of the diffusion furnace. A three zone furnace is used. The samples are introduced in a quartz tube. The back side of the tube is filled with quartz wool. The tube is placed in the furnace and at the beginning of the tube, which is located in the first heating zone, some P_2O_5 powder is put. The front end of the tube is then filled with quartz wool. The whole diffusion process is carried out in ambient air and consists of two steps. First the temperature is slowly increased up to 400°C. The first and the last heating zone is kept 50°C above the center zone where the wafers are placed. In this step the P_2O_5 is evaporated and transfered onto the cooler wafer surfaces. After the first step the furnace is heated up to 925°C and kept at this temperature for 10 minutes. Then the heating is stopped. When the furnace temperature has cooled down to below 200°C, the tube is taken out and the samples are immersed in ethanol in order to prevent water vapour from the air to react with the phosphorous glass layer on the samples. The diffusion parameters given above produce a n^+p-junction which is about $0.5\mu m$ deep in order to avoid shunting problems. The glassy layer is removed from the wafers by etching with HF. Then the front side except a small border at the edges and the mark is covered with black wax which is applied to the surface with the help of a brush. Backside and edges are etched in a deliberately composed mixture of HF and HNO_3. After the black wax is removed, a thin layer of a paste containing aluminum, is put on the cell's backside and dried with the help of an infrared lamp. Onto the front side a grid is painted by the use of a silver paste. The students are encouraged to design individual grid structures with respect to (i) the electrical connection of the solar cell, which will favour to cover the whole front side and (ii) the optical needs to minimize shadowing of the front side. The percentage of metallized front side will be determined after the solar cell is completely processed with the help of a scanner and a picture manipulation program. The metallized area covers typically 20 per cent to 30 per cent of the front side. Figure 1 shows the cells with the front grid during the drying step of the silver paste. The burn-in for both pastes is done simultaneously at 725°C for three minutes in ambient air. After the burn-in the wafers are transfered to a high vacuum deposition unit and placed with the front side facing the evaporation unit for the application of an antireflection coating. The chamber is evacuated during night down to less than $2\times10^{-6} mbar$.

The second day of the experiment starts with the evaporation of silicon monoxide, which has an index of refraction n_{SiO} of approximately 1.9 which closely matches the condition for minimal reflection losses of crystalline silicon at a wavelength of $600nm$, assuming n_{Si} about 3.6.

$$n_{AR} = \sqrt{n_{Si}} \qquad (1)$$

n_{AR} is the index of refraction of the antireflection coating.

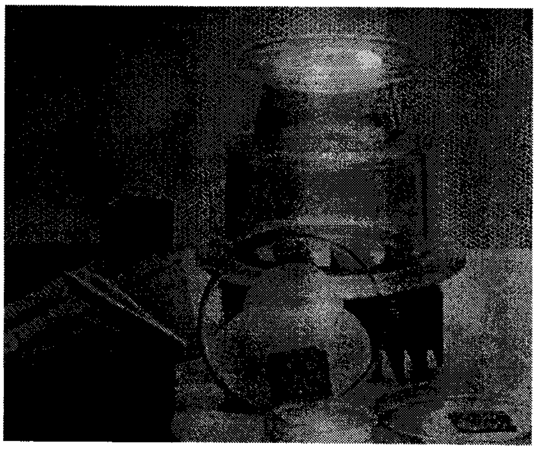

Fig. 1: Drying the grid structure on the front side of the solar cell

According to the condition of an antireflection coating as given by equation 2, the thickness d of the silicon monoxide layer is $79nm$ for a wavelength λ, about $600nm$.

$$n_{AR}\, d = \frac{\lambda}{4} \qquad (2)$$

The thickness of the thermally evaporated SiO is monitored with the help of a quartz oszillator based thickness monitor.

Before the solar cells are mounted onto copper covered substrates, the shadowed area due to the front grid is determined with the help of a simple scanner and a picture manipulation program. Afterwards a simple test of the open circuit voltage is carried out. With artificial light a value well above $200 mV$ shall be seen. In case the open circuit voltage is too small, the cell is inspected by the instructor if there are potential shunting paths across the edges. Sometimes the solar cell can be „revived“ by carefully scratching away shunted areas at the edges of the cell. Finally the aluminum covered backside of the solar cell is slightly scratched with metal tweezers in order to remove the aluminum oxide and pasted with a conducting ink onto the substrate. The front contact grid is connected with a copper wire to the electrically isolated edge of the substrate. Before pasting the copper wire to the front grid, the overlaying SiO is scratched away.

3. RESULTS

The test setup for the characterization of the solar cell consists of a low voltage halogen lamp with an integrated cold light reflector. The lamp current can be externally controlled. In order to keep the experimental setup simple, the remaining infrared radiation is filtered away and the distance between the solar cell and the lamp is about $0.5 m$. This ensures that the whole cell area is illuminated homogeneously to within ±5 per cent and that heating of the solar cell is reduced. A cooling fan intended to cool computer components further reduces the heating of the solar cell to below 1 K above the ambient temperature during illumination. A disadvantage is, that the highest obtainable illumination intensity is about $200 Wm^{-2}$ which is only 1/5 of the AM1.5 intensity. Before the cells are mounted, the light intensity is recorded as a function of the lamp current with the help of a thermopile detector. Then the detector is replaced by the photovoltaic solar cell which is connected to a Keithley 224 current source. This current source can be used as an electric load for currents up to $\pm 100 mA$. A digital voltmeter is used to determine the cell voltage. The whole setup is computer controlled. The program is adapted for the use by the students. That means that it is not an automated test routine. The students have to do all the individual settings, controlling the lamp current and the current through the solar cell, by themselves. This is intended to make the students aware of what is going on during the measurement. The data are stored to files which easily can be processed by a scientific data evaluation software. First the current-voltage characteristics in the dark is determined. Then the current-voltage characteristics for different illumination intensities is recorded. In the last measurement the short circuit current i_{sc}, and open circuit voltage V_{oc}, is determined for 30 to 50 different illumination intensities and stored as current-voltage pairs. For crystalline silicon solar cells where nearly all the light generated current is coming from the base, a plot of $i_{sc}(V_{oc})$ can be considered as the diode current without the additional voltage drop due to the series resistance R_S [2]. Therefore by comparing $i_{sc}(V_{oc})$ with the dark forward biased current - voltage curve, R_S can be determined. A result of the measurements is shown in figure 2.

The current-voltage measurements under illumination are transformed to electrical power and load resistance values which are plotted in figure 3.

Table I: Solar cell parameter for different illumination intensities

P_{inc} $[Wm^{-2}]$	V_{oc} [V]	j_{sc} $[Am^{-2}]$	P_{max} $[Wm^{-2}]$	R_{load} $[\Omega{*}m^2]$	CFF [-]
5	0.22	0.14	0.012	1.523	0.39
15	0.38	1.72	0.375	0.211	0.57
42	0.44	7.25	2.18	0.056	0.68
108	0.48	21.1	7.23	0.020	0.72
205	0.50	46.7	16.94	0.010	0.73

As can be seen the load resistance for maximal power output varies over several orders of magnitude with varying light intensity. The solar cell parameters are summarized as a function of the illumination intensity in table I for the best cell obtained by the students.

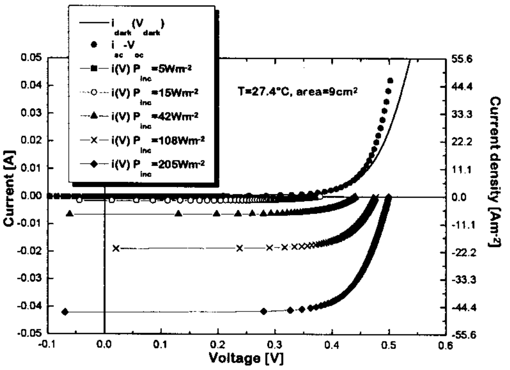

Fig. 2: Measured current-voltage characteristics of a solar cell in the dark and under five different illumination intensities and short circuit current vrs. open circuit voltage for 30 illumination intensities.

At an incident intensity of 205 Wm^{-2} the efficiency is more than eight per cent. Surprisingly almost each cell made by the students exhibits a conversion efficiency between five per cent and six per cent with small deviations as determined by the measurements described above. Although most of the conditions for the solar cell preparation are not critical to the results, it turned out that the age of the silver paste is the most critical parameter. The use of an expired, more than six month in-use silver paste was leading to drastically more shunting effects of the pn-junction and increased series resistance values.

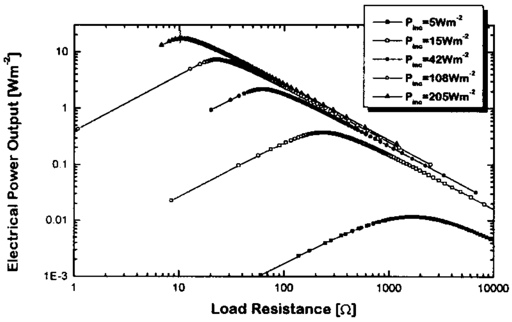

Fig. 3: Log-log plot of the electrical output of a solar cell (area = $9cm^2$) versus the load resistance for five illumination intensities at 27.4°C.

The internal loss mechanisms, diode current described by equation 3, series resistance R_S, and shunt conductance G_{SH}, are derived from the dark current-voltage characteristics and the curve given by $i_{sc}(V_{oc})$.

$$i_{diode} = i_0 \left\{ \exp\left(\frac{q(V_{ext} - i_{ext} R_S)}{n k_B T} \right) - 1 \right\} \qquad (3)$$

i_0... Reverse saturation current
q... Elementary charge
n... Diode ideality factor
k_B.. Boltzmann constant

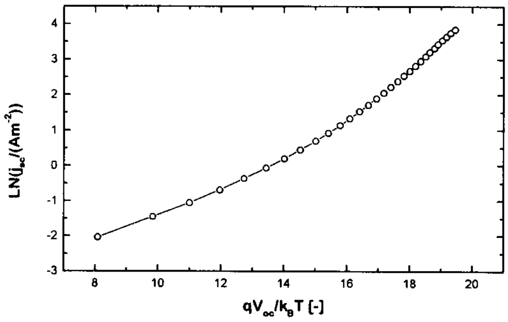

Fig. 4: Semilogarithmic plot of short circuit current density versus the normalized open circuit voltage. The linear fit gives the diode ideality factor n, and the saturation current density j_0.

i_0 and n are determined from a semilogarithmic plot of i_{sc} versus V_{oc} (fig.4). As mentioned above for crystalline silicon solar cells, the curve represents the diode characteristics without the influence of the series resistance.

In a final experiment the solar cells are connected in series and/or parallel capable to drive a small engine. The students are requested to make a written report about the experiment. They are allowed to keep their own selfmade solar cell as a souvenir.

4. CONCLUSIONS

Besides the understanding of the semiconductor physics of a solar cell the experiments are aiming at the self experience of the students with the principals of the manufacturing process as well as the problems related with the use of photovoltaic cells as electric power generators. This practical experience shall enable the future physicists and high school teachers to judge and to report about photovoltaics with a profound insight in the technical requirements for large scale photovoltaic applications.

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