INVESTIGATIONS OF A NOVEL TYPE OF INVERSION LAYER SILICON SOLAR CELL

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ABSTRACT: A novel type of inversion layer silicon solar cell was investigated. The cell consists of a highly doped polycrystalline silicon layer - the thickness is about 250*nm* - which was grown onto the thermally oxidized surface of a monocrystalline n-Si substrate (the oxide thickness is about 100*nm*). Due to the low sheet resistivity - less than $20\Omega/\square$ - of the polysilicon layer it serves as the front contact of the photovoltaic device. The interferences of the incident light caused by the optical properties of the silicon dioxide/polysilicon system reduces the reflectance to zero at a wavelength of 630*nm* without any additional antireflection coating. Currently the solar cell output of the devices mainly suffers from the low tunneling probability of the light generated current through the oxide. An improved solar cell design with respect to the optical and electrical properties of the silicon dioxide and the polysilicon layer is suggested.

Keywords: c-Si - 1: Inversion-layer - 2: Polycrystalline - 3

1. INTRODUCTION

Metal-Insulator-Semiconductor inversion layer (MIS-IL) solar cells are an attractive alternative to high conversion efficiency photovoltaic cells with a pn-junction. In the late seventies MIS-IL crystalline silicon solar cells were the first cells with an open circuit voltage above 650*mV* and a conversion efficiency of more than 17 per cent [1]. Despite the promising results on laboratory devices most of the solar cell manufacturers have not adapted the MIS inversion layer solar cell technology for commercial solar cells. One of the reasons probably is the difficulty to keep the high concentration of the fixed charges in the oxide layer stable over the lifetime of the solar cell [2,3]. In the present work we report about the first results we have obtained for SOS - Semiconductor-Oxide-Semiconductor - cells based on crystalline silicon. The thin surface layer consists of a highly phosphorous doped polycrystalline silicon film. The absorbing substrate was single crystal silicon. It has to be pointed out that originally the devices were not designed for solar cell applications. That means that the choice of the material parameters are not optimized for a large area photovoltaic solar cell. Therefore the solar cell parameters reported later on must not be compared directly to the parameters currently obtainable with crystalline silicon solar cells. However we believe that this type of SOS solar cell offers several advantages compared to the well known MOS photovoltaic cell. The polycrystalline silicon layer

(i) protects the sensible oxide from environmental damage.

(ii) can act together with the underlying silicon dioxide as an antireflective coating as will be explained later.

(iii) reduces due to its high electrical conductivity the necessary space width of the metallic front grid.

2. EXPERIMENTAL

We got a set of about 1cm^2 samples from J. Lutz (University of Leoben, Austria). The crystalline n-silicon substrate was thermally oxidized. The preparation of the polycrystalline silicon layer was typical for integrated circuit applications. The undoped silicon was deposited by a low pressure CVD process. Then phosphorous was ion implanted followed by a subsequent recrystallisation step. No further details were available. The whole rear side of the substrate was covered by an ohmic contact consisting of a gold/germanium alloy. Onto the polycrystalline silicon layer dots with a diameter of 0.5*mm* of chromium/gold were evaporated. The spacing between the quadratically placed contacts was 5*mm*. A cross sectional diagram of the device is shown in figure 1.

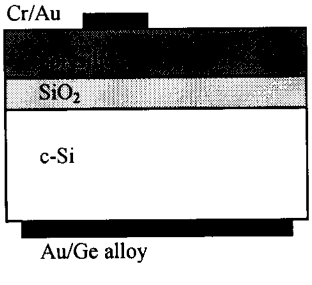

Figure 1: Diagram of the cross section of the inversion layer device (not to scale).

First the electrical properties of the polycrystalline silicon layer were determined with a Hall experiment at room temperature in Van der Pauw geometry. In addition the reflectance of the structure in the wavelength range from 200*nm* to 2600*nm* was measured. The measured data were used to evaluate the thickness of the polycrystalline layer and the thickness of the underlying oxide layer. The index of refraction of SiO_2, n_{SiO} was assumed to be 1.459, for the polysilicon the published values for single crystal silicon were taken [4]. The results are summarized in table I. In addition a cross section was prepared from sample #611 and characterized by TEM. The difference between the optical and the structural thickness of the silicon oxide was a factor of 2 and for the polycrystalline silicon the two thicknesses differ by 10 per cent. This discrepancy arises from the deviation of the index of refraction for polycrystalline silicon from the values for single crystal silicon. For a tunneling probability of 1 for the light generated current across the oxide the thickness of the oxide layer however is much to high. Two samples - #98 and #611 - out of the set were light sensitive.

Table I: Parameters of the polycrystalline silicon layer

sample	ρ_{SHEET} [Ω/□]	d_{polySi} 1) [nm]	d_{SiO} 1) [nm]	$n \times 10^{26}$ [m^{-3}]	$\mu_{Hall} \times 10^{-4}$ [$m^2V^{-1}s^{-1}$]
#611	28.685	252	50	6.0	14.5
#98	19.068	298	50	7.8	14.2

1) calculated from optical interferences assuming an index of refraction $n_{SiO_2} = 1.459$ and $n_{poly\text{-}Si}$ equaling the index of refraction for crystalline silicon. A TEM picture of the cross section of sample #611 however results in d_{polySi}=230*nm* and d_{SiO}=100*nm*.

As can be seen in table I the free electron concentration is as high as $6\times10^{26}m^{-3}$ which means that the semiconductor is degenerated - The Fermi level is above the conduction band - and to a first approximation can be considered to be metallic.

3. RESULTS

The current voltage characteristics of the devices were measured in the dark and under illumination for different illumination intensities up to $200Wm^{-2}$. The results for sample #98 are shown in figure 2. Sample #611 showed a smaller photovoltaic effect. Since we have no information about the differences in the sample preparation no explanation can be given in this paper.

The active area of the photovoltaic device has not yet been determined, therefore no current densities are reported. From locally resolved light beam induced current measurements, which exhibit a nearly position independent signal amplitude over the whole sample surface, we conclude, that the cell area is given by the sample area - about $1cm^2$ - rather than by the area of the front contact metal dots. Taking into account the thickness of the oxide layer the current which has to tunnel through the oxide is astonishing large indicating a high defect density in the oxide layer.

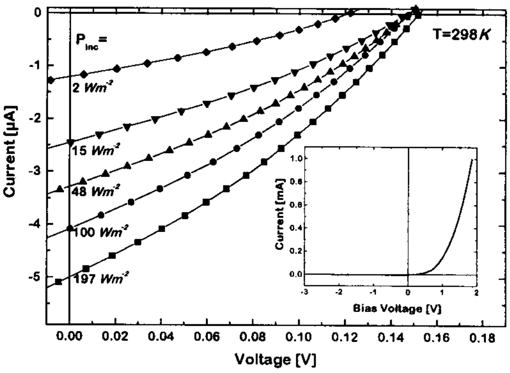

Figure 2: Current voltage characteristics of cell #98 for different illumination intensities of the incident light. The inset shows the dark *i*(*V*) curve.

The saturation of the open circuit voltage at about 140*mV* suggests that it is rather limited by the difference of the work functions of the n-Si substrate and the n^+-polysilicon layer [5]. However that can not explain the high values of the built-in voltage derived from capacitance measurements.

The differential conductance and capacitance have been determined for two frequencies - 10*kHz* and 50*kHz* respectively - with the help of a phase sensitive lock-in amplifier for bias voltages in the range between -3*V* and +2*V*. The frequencies are well above the frequency range where inversion can take place. Therefore for the reverse biased device the region in the monocrystalline substrate at the oxide interface can be considered completely depleted. After correcting the measured capacitance for the constant oxide capacitance C_{ox}, which is placed in series with the depletion capacitance C_{depl} in the electrical circuit, a plot of C_{depl}^{-2} versus the bias voltage was made in order to derive the built-in voltage V_{bi} [5]. The result for sample #611 is shown in figure 3.

The built-in voltage for sample #611 was found to be 0.75*V* and for sample #98 it was 0.81*V*. These high values show the potential of the cells for high open circuit voltages. Furthermore it can be deduced that the properties of the space charge region below

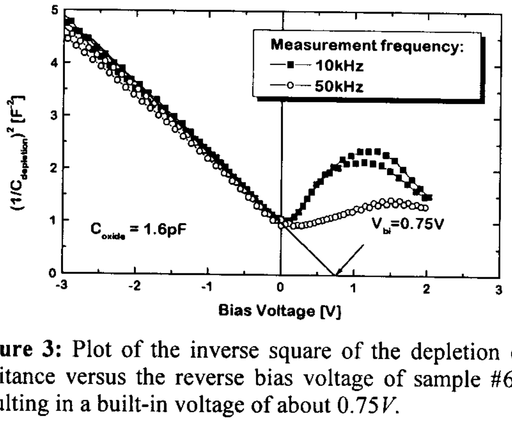

Figure 3: Plot of the inverse square of the depletion capacitance versus the reverse bias voltage of sample #611 resulting in a built-in voltage of about 0.75*V*.

the oxide is governed by fixed oxide charges rather than by a Schottky effect since the differences in the work function between the monocrystalline n-Si substrate and the polycrystalline n^+-Si surface layer is estimated to be less than $0.5V$ [5]. The kind and origin of this fixed oxide charges are not yet determined. The obtained value for the oxide capacitance C_{ox} of 1.6pF for sample #611 suggests that the active device area is given solely by the area of the front contact points. The capacitance for the forward biased cell measured at 10*kHz* showed a hysteresis whereas at 50*kHz* no hysteresis was observed. The origin of the hysteresis can be attributed to mobile surface charges at the oxide-substrate interface.

Locally resolved measurements of the quantum efficiency were carried out. By the use of fibre optics the light of a monochromator was focused onto the cell. The diameter of the light spot was about 0.5*mm*. The light induced current was measured with a lock in amplifier using a current sensitive preamplifier at an intensity modulation frequency of 631*Hz*. Simultaneously to the photocurrent the locally resolved surface reflectance was recorded. Several locations of the cell area were examined. The reflectance showed slight variations due to thickness variations of the oxide and/or polycrystalline silicon film. The photocurrent however remained almost constant independently of the distance between the front metal dot and the light excited region of the device. This indicates that the polysilicon layer acts as a front contact. A result of the wavelength resolved photocurrent measurement obtained on sample #98 is shown in figure 4.

The pronounced maxima in the external quantum efficiency are due to the interference minima of the reflectance as can be seen in figure 5. At the maxima of the external quantum efficiency the reflectance of the oxide/polycrystalline silicon layer approaches zero what will be expected for a high quality antireflection coating. Rather surprisingly the external quantum yield at photon energies greater than 2.8*eV* is still measureable although the calculated transmittance of the polycrystalline silicon layer fastly decreases to zero towards higher photon energies as shown in figure 5. As mentioned above for the first calculations of the reflectance - shown in figure 5 - and transmittance of the oxide/polysilicon system optical data for monocrystalline silicon were taken. A more extended data evaluation with the help of the computer program „FilmWizard“ allowing the variation of the optical parameters of the polycrystalline layer was yielding in a much better agreement between the measured and the calculated reflectance and transmittance. In the case of sample #611 this modified assumptions were leading to thicknesses of the oxide and the polysilicon layers which differ less than 5 per cent from the structural thicknesses observed with TEM. It has been frequently reported that the extinction coefficient as well as the index of refraction for polycrystalline silicon slightly differs from the values of single crystal silicon which is attributed to density variations in the polycrystalline silicon [6,7]. A recalculation of the transmittance showed a clear enhancement in the blue and ultraviolet wavelength region as has been expected from the observed external quantum efficiency data at high photon energies. The local internal quantum efficiency was obtained from the measured external quantum efficiency dividing it by (1-*R*) where *R* is the measured reflectance. The slight variations of the internal quantum efficiency arise from the difficulty to calibrate the experimental setup for absolute reflectance measurements on a spot size of $0.2mm^2$.

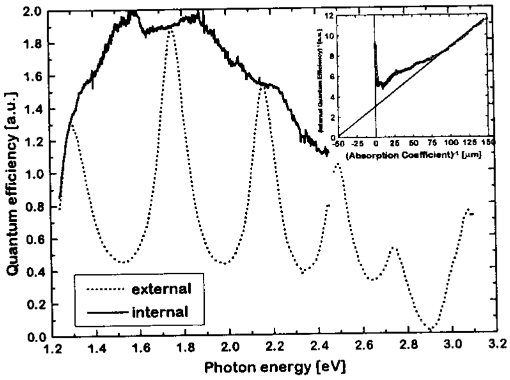

Figure 4: External and internal quantum efficiency as a function of the photon energy for cell #98. The inset shows the evaluation of the minority carrier diffusion length from a plot of the inverse internal quantum efficiency versus the reciprocal absorption coefficient of silicon.

From the internal quantum efficiency the minority carrier diffusion length was determined to be 54μm for the sample #98 and 93μm for the sample #611 (see inset in figure 4).

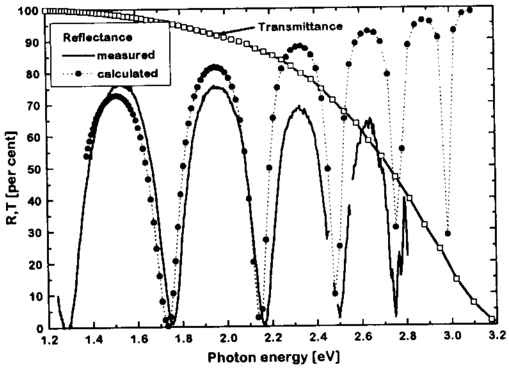

Figure 5: Measured reflectance and calculated reflectance and transmittance of the 250*nm* thick polycrystalline silicon layer assuming optical constants for single crystal silicon.

4. CONCLUSIONS

We have investigated the photovoltaic response of simple planar SOS structures which are in no way optimized for solar cell applications. However some properties of the polycrystalline silicon layer on top of the oxide appear to be promising for the application in the preparation of inversion layer photovoltaic cells.

At the present state of our work the results do not allow to attribute the photovoltaic behaviour of the device exclusively to the formation of an inversion layer in the substrate at the semiconductor-insulator interface. It seems that both mechanism - the formation of an inversion layer due to fixed charges and the Schottky effect arising from the differences in the work function of the two semiconductors - contribute to the overall electrical performance of the device. In the future it will be unavoidable to investigate test structures with a p-Si substrate.

As has been demonstrated a highly doped polysilicon film - carrier concentrations as high as $8\times10^{26}m^{-3}$ are obtainable - can act as a front side contact thus reducing the need of a narrow spaced metallic grid. A properly designed combination of a polysilicon layer on top of a silicon dioxide layer can replace an additional antireflective coating, thus reducing the process steps of the solar cell manufacturing. Since the effective optical parameters of the polycrystalline silicon strongly depend on the sample preparation conditions transmittance and reflectance can be adjusted in order to optimize the silicon dioxide/polysilicon layers (i) for an antireflection coating and (ii) for a high ultraviolett transmittance if necessary. A calculation based on an AM1.5 spectra assuming the transmittance (for monocrystalline silicon) of the polysilicon as indicated in figure 5 shows that only 13 per cent of the total number of incident photons in the energy range from $1.12eV$ (band gap of the crystalline silicon substrate) to $4eV$ is absorbed by the polysilicon layer. This means about 90 per cent of the incident photons are transmitted through the polycrystalline silicon film and can contribute to the photovoltaic energy conversion in the substrate. The most important improvement of the SOS device can be expected when the $100nm$ thick silicon dioxide layer will be locally thinned to a thickness of about $2nm$ which results in a tunneling probability of one for the light generated carriers.

ACKNOWLEDGEMENT

We want to thank Dr. J. Lutz from IMS (Vienna) for supplying of the samples. The financial support of the authorities of the city of Vienna is kindly acknowledged.

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