The Electrical Performance of Thin $n^+$-Window Layers in $a$-$Si: H$ Solar Cells

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Abstract. The electrical properties of $n^+$-window layers in $p-i-n$ $a$-$Si: H$ solar cells were characterised as a function of $n^+$-layer thickness, $d_{n^+}$, by measuring firstly the activation energy $E_a$ of the dark conductivity and secondly the built-in potential $V_{bi}$ of the cells. $E_a$ was found to increase with decreasing $d_{n^+}$, attaining values as high as 0.8 eV for $d_{n^+} \approx 5$ nm; bulk values, e.g. $E_a \approx 0.2$ eV in the amorphous and $E_a < 0.01$ eV in the microcrystalline case, were only observed for $d_{n^+} > 20$ nm and for $d_{n^+} > 200$ nm, respectively. In contrast, $V_{bi}$ did not depend on $d_{n^+}$ at all and was further found to be consistent with expectations based on the Fermi level positions in bulk $n^+$- and $p^+$-material. As a consequence $E_a$ in very thin films can no longer be considered as a measure of $(E_C - E_F)$, the distance of the Fermi level from the conduction band edge. The apparent inconsistency inherent to the $E_a$ and the $V_{bi}$ results can be resolved by assuming that the deposition of the $n^+$-material proceeds via the growth and coalescence of small islands.

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In recent years there has been an increasing interest in the development of $a$-$Si: H$ thin-film solar cells. Due to improvements in material preparation and in cell design it has so far been possible to reach efficiencies in the 7 % to 8 % range [1]. In $p-i-n$ cells the value of the built-in potential is determined by the position of the Fermi level $E_F$ in the heavily doped boundary layers. These layers have very poor photogeneration properties and can be considered as dead layers in a solar cell. As a consequence entrance windows in solar cells of the $p-i-n$ type have to be made extremely thin in order to minimize absorption losses [2]. On the other hand, the window layer has to be made thick enough in order to ensure a reasonably large value of the built-in potential $V_{bi}$. The highest efficiency has been found for window thicknesses in the range of 5–10 nm [2, 3]. Investigations of thickness dependent conductivity and photoconductivity have indicated pronounced surface effects in $n$-type films with moderate phosphorus doping. The principal finding was that thinner films have lower dark conductivities and higher activation energies [4]. Since $E_a$ was shown to be a measure of $E_C - E_F$ in $a$-$Si: H$ [5, 6] these results were interpreted in terms of an upward bending of the bands within 0.1 $\mu$m distance from both the free surface and the film-to-substrate interface [7]. Surface effects have also been found in measurements of hydrogen profiles on similarly prepared films which showed that both the free surface as well as the film-to-substrate interface of $a$-$Si: H$ films are partially depleted from hydrogen within a distance of again about 0.1 $\mu$m [8, 9].

In view of the observed boundary effects it is reasonable to ask, how far the electrical properties of extremely thin and heavily doped window layers differ from the bulk properties of $a$-$Si: H$ films and how possible differences would influence the performance of $a$-$Si: H$ cells.

To this end we first measured the dark conductivity of thin amorphous and microcrystalline $n^+$-layers deposited onto an $i$-layer in dependence on the $n^+$-layer thickness $d_{n^+}$. The underlying $i$-layer was chosen to provide growth conditions similar to those given in the deposition of $p-i-n$ cells. The measurements of the dark conductivity which probe transport parallel to the film,
Fig. 1a and b. The dark conductance (a) and the activation energy (b) of the i-n+ Si:H sandwich structure (see inset) at room temperature are shown as a function of the n+-layer thickness d+n. The full and open circles refer to amorphous (a-Si:H) and “microcrystalline” (µc-Si:H) n+-layers (PH3/SiH4=1%), respectively. The solid and dashed lines are guides to the eye.

reveal a major increase of the activation energy Ea for both kinds of n+-films with d+n→0. The main results are presented and discussed with respect to space charge layers in Sect. 2.1. In Sect. 2.3 we discuss measurements of the built-in potential Vbi of p-i-n cells having n+-window thicknesses in the same range. Vbi which probes electrical properties perpendicular to the n+-layer was found to be independent of d+n. This result implies that Ea no longer a measure of (Ec−Ep) in very thin n+-films (Sect. 2.4). The apparent inconsistency between the Ea and Vbi measurements is finally resolved in Sect. 2.5 by considering an island structure in the growth process of the α-Si:H films.

1. Experimental Details

The measurements of the conductivity activation energy were performed on i-n+ sandwich structures of Si:H deposited onto 7059 Corning glass. Si:H was prepared by plasma decomposition of SiH₄ in a capacitively coupled system run at about 13 MHz and at a substrate temperature of about 300 °C. The i-layer, kept at a constant thickness of about 1 µm, was first deposited in a pure SiH₄-plasma at rf-power densities of ≤0.04 W/cm². Then the n+-layer was deposited by adding 1% PH₃ to SiH₄ at the same power density resulting in amorphous n+-layers. n+-layers with polycrystalline properties (again 1%PH₃ in SiH₄) were obtained by diluting the SiH₄ in H₂ to a ratio of SiH₄/H₂≈0.03 and by increasing the rf-power density [10] to ≤0.4 W/cm². The thickness d+n of the n+-layer was determined by the length of the deposition time and covered the range 5 nm≤d+n≤1 µm. By depositing the n+-layer onto the i-layer we provided growth conditions for the n+-material similar to those encountered in a-Si:H cells of the p-i-n-structure.

For the conductivity measurements (current flow parallel to the film) Ti/Ag electrodes, having a length of 20 mm and separated by a gap of 4 mm, were evaporated on top of the Si:H-sandwich structure. The dark conductivity was determined during cooling down from a temperature of about 250 °C in a chamber with a residual pressure of about 10⁻² Torr. The n+-Ti–Ag contacts were found to behave Ohmic.

The measurements of the built-in potential Vbi were performed on solar cells of the structure p-i-n/ITO (ITO: indium tin oxide). Cells with both amorphous and “microcrystalline” n+-windows of varying thicknesses were prepared under conditions identical to those described above. The ITO layer had a thickness of about 67 nm and a sheet resistance of ≈60 Ω/□. The open circuit voltage V₀c of the cells was measured in dependence on the light intensity I in the temperature range 80 K≤T≤300 K. Decreasing the temperature below 200 K V₀c was found to saturate with increasing light intensity. For example, at T≈100 K V₀c was independent on the light intensity I within 3 orders of magnitude (Iₘ₉ₙ≈50 mW/cm²). The saturated values of V₀c at T<200 K thus can be considered as values for the built-in potential.

2. Results and Discussion:

2.1. The Dark Conductivity of Thin n+-Films

Figure 1a summarises data on the dark conductance of i-n+-sandwich structures at room temperature both for amorphous (full lines) and for microcrystalline n+-material (dashed lines). The activation energy of the conductance as evaluated around room temperature is plotted in Fig. 1b as a function of the thickness of the n+-layer, d+n.

Turning to the data for amorphous n+-material first it is seen that for d+n≈1 µm Ea is about 0.2 eV.