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Effect of Indium Tin Oxide on Hydrogenated n-doped amorphous silicon heterojunction solar cells.

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Abstract—**The High efficiency of HIT structure (Heterojunction with Intrinsic Thin layer between the hydrogenated amorphous silicon a-Si:H emitter and crystalline silicon c-Si) are recently under intensive investigations since they are combining the low cost and low temperature process of a-Si:H deposition coupled with the high efficiency and high stability of c-Si. In order to study and analyze the band bending at the transparent conductive oxide/hydrogenated n-doped amorphous silicon (n-a-Si:H), we have varied the surface band bending by changing the E_{sbb} in order to reduce the surface potential barrier between the Indium Tin Oxide (ITO) and adjacent n-layer. We showed that with an increase on the front contact barrier height at the interface ITO/n-a-Si:H (band-banding reduced) which leads normally to a better ohmic contact, the characteristics J(V) remain unchanged.**

Index Terms—**Simulation, HIT solar cells, potential barrier height, band bending, *J(V)* characteristics**.

I. INTRODUCTION

The HIT Structure (Heterojunctions with Intrinsic Thin layers) created by the group of research SANYO has a principal advantage compared to the conventional cells: the use of silicon amorphous deposited at low temperature. p and n-type substrates are recently under intensive investigations since they are combining the low cost and low temperature process of a-Si:H deposition coupled with the high efficiency and high stability of c-Si. An important scientific and technological progress on HIT has led to solar cells with efficiencies up to 21% [1, 2,3,4].

In spite of this progress, the solar cell efficiency is greatly limited by the recombination at the Transparent Conductive Oxides TCO/a-Si:H interface. TCO: Tin Oxide (SnO2) and Indium Tin Oxide (ITO) deposited on glass are widely used as window layer in the fabrication of a-Si:H based solar cells because of their low sheet resistively and high transparency in the visible region. However, many problems are associated with the use of these transparent conductive oxides. It is thus necessary to reduce the ohmic and optical losses generated by this interface.

It has been shown that it is possible to form a good Schottky diode between TCO and a-Si:H without a decrease of optical transmission if we interpose tin Palladium or Chrome film [5,6]. In agreement with these experimental results, computer models on the effects of the height of the front contact barrier have shown that the front barrier ϕ_{b0} has to be increased (band-banding reduced) to increase the efficiency of the p-i-n and HIT n-type c-Si substrates solar cells [7,8]. In order to simulate and study the effect of the surface band bending on the structure HIT p-type c-Si substrates: ITO/n-a-Si:H/i-polymorphous (pm-Si:H)/p-c-Si/Al, we have varied this band bending by changing the E_{sbb} in order to improve the ohmic contact between the ITO and n-layer. We chose the polymorphous silicon as an intrinsic thin layer because of its excellent electric properties [9]. Figure 1 illustrates the schematic band diagram of interface region.

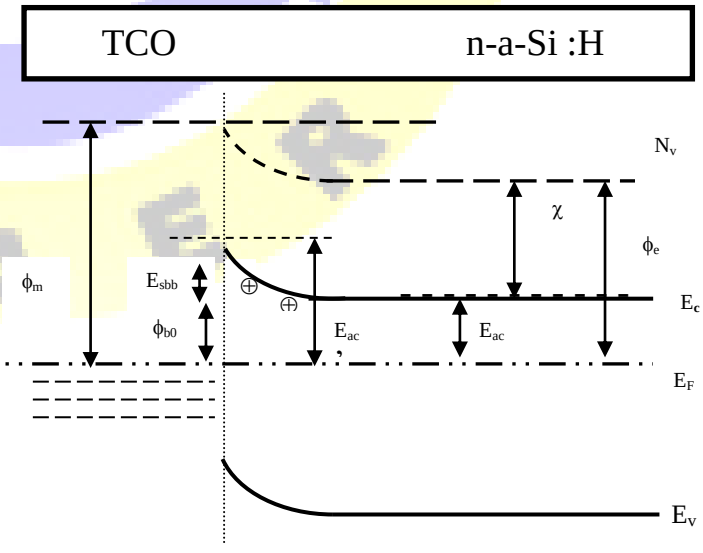


Fig. 1: The schematic band diagram of TCO/n-a-Si:H interface region.

ϕ_m is the work function of TCO, ϕ_e is the work function of n-a-Si:H. ϕ_{b0} is the front contact barrier height, E_{sbb} is the TCO/n-surface band bending, E_{ac} *(n)* is the activation energy of the n-layer, χ is the electron affinity of the n-a-Si:H.

II. SIMULATION MODEL

The different parameters of our device were determined by ASDMP [10,11] (Amorphous Semiconductor Device Modeling Program). Prof. Roca's group at École polytechnique de Paris, France, has demonstrated experimentally that ASDMP model mimics the performance of p-i-n and HIT solar cells with data from solar cell performance [12,13].

ASDMP examines the behaviour of semiconductor device structures under steady state in one dimension by solving simultaneously Poisson's equation, the continuity equations for free electrons and the continuity equation for free holes using finite differences and the Newton-Raphson technique, and yields the *J(V)* characteristics and the quantum efficiency. These equations are:

$$\frac{d}{dx}\left(\varepsilon(x)\frac{d\psi(x)}{dx}\right)=\rho(x). \quad (1)$$

$$0=\frac{1}{q}\frac{dJ_n(x)}{dx}+G_{opt}(x)-R_{net}(x). \quad (2)$$

$$0=\frac{1}{q}\frac{dJ_p(x)}{dx}+G_{opt}(x)-R_{net}(x). \quad (3)$$

In Poisson's equation "Eq. (1)", $\varepsilon(x)$ is the dielectric permittivity of the semiconductor. $\Psi(x)$ is the potential energy of an electron at the vacuum level in electron volts, and $\rho(x)$ is the space charge density in the semiconductor. In the continuity equations "Eq. (2)-(3)", J_n *(x)* and J_p *(x)* are the electron and hole current, respectively, and q is the charge of electron. The term G_{net} *(x)* represents the net optical generation of free electron-hole pairs per unit volume, while $R_{net}(x)$ denotes the net recombination of free carriers per unit volume. The expression of free and trapped charges, the recombination term, the boundary conditions and the solution technique in this program, are similar to the AMPS computer program [14,15,16] developed by Professor Fonash's group.

The boundary conditions used for the Poisson's equation are:

$$\psi(0)=\phi_{b0}+\chi_0-\phi_{bL}-\chi_L-V \quad (4)$$

And

$$\psi(L)=0 \quad (5)$$

Where $\Psi(0)$ [$\Psi(L)$] is the vacuum level at $x = 0$ (L), ϕ_{b0} (ϕ_{bL}) the front (back) contact barrier height and χ_0 (χ_L) the electron affinity of the material at $x = 0$ (L). For light through the n layer ϕ_{b0}, χ_0 represent the contact barrier height and the electron affinity of the n-a-Si:H layer, while ϕ_{bL} , χ_L are those of p-c-Si. V is the applied forward biased potential. The contact barrier heights for a cell with the n-layer in contact with ITO at $x = 0$ and the p-layer in contact with a metal at $x = L$, are given by:

$$\phi_{b0}=E_{ac}(n)\pm E_{sbb} \quad (6)$$

And

$$\phi_{bL}=E_g-E_{ac}(p)-E_{sbb} \quad (7)$$

TABLE 1
PRINCIPAL INPUT PARAMETERS

Parameters	n-a-Si :H	i-pm-Si :H	p-c-Si
d (A°)	80	30	300 x10^4
χ (eV)	4.00	3.95	4.22
E_μ (eV)	1.80	1.96	1.12
E_{ac} (eV)	0.21	0.92	0.06
ND, NATOT (cm^{-3})	9.0x10^{18}	1.0x10^{14}	4.0x10^{18}
E_D (eV)	0.050	0.050	0.005
E_A (eV)	0.030	0.030	0.003
G_{D0}, G_{A0} (cm^{-3} eV^{-1})	4.0x10^{21}	4.0x10^{21}	4.0x10^{20}
μ_n (cm^2/V s)	20	30	1000
μ_p (cm^2/V s)	4	12	450
ϕ_{b0} (eV)	0.12-0.28		
ϕ_{bL} (eV)	1.06		

These contacts are characterized by surface recombination speeds for each carrier (taken here to be S_{n0}, S_{p0}, S_{nL} and S_{pL} = 10^7 cm/sec for holes and electrons). $E_{ac}(n)$ et $E_{ac}(p)$ are the activation energy of the n and p layers. E_{sbb} is the band bending. The barrier height ϕ_{b0} at the front contact ($x = 0$) is depicted in figure 1, which shows this contact in a solar cell structure in thermodynamic equilibrium. This barrier height value and the other important parameters that we use in these simulations are listed in table 1.

The typical gap-state distributions used in the calculations consists of U-shaped model, and two Gaussian distribution functions to simulate the dangling bond states. The generation term in the continuity equations has been calculated using a semiempirical model [17] that has been integrated into the odelling program. Both secular interference effects and diffused reflectances and transmittances due to interface roughness are taken into account. The principal parameters used in this study are summarized in table 1.

III. RESULTS AND DISCUSSION

The device used in the present work consists of a HIT structure ITO/n-a-Si:H/i-pm-Si:H/p-c-Si /Al. In these cells, the parameters of each layer are summarized in table 1.

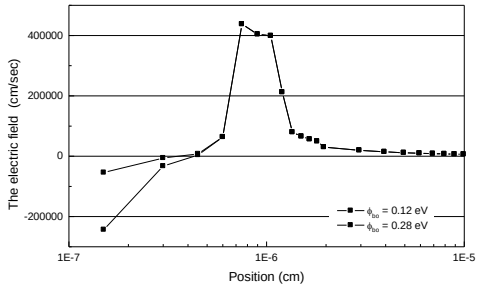
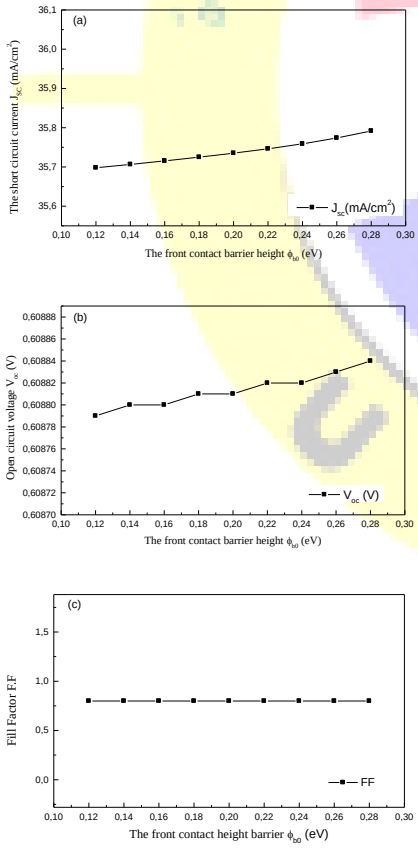


Fig. 2: The electric field vs. position for cells with 80 A° of n-layer and the front contact height barrier ϕ_{b0}=0.12 eV and 0.28 eV.

We notice a decrease of the electric field on the contact (ITO/n-a-Si:H) when we increase the ϕ_{b0} value (Fig.2). This decrease of the electric field let more electrons able to pass from the n-layer to the ITO which leads normally to an improvement on the *J(V)* characteristics of our solar cells.

In the contact ITO/p-a-Si:H, the front barrier height ϕ_{b0} has to be increased to increase the efficiency of the HIT n-type c-Si substrates solar cells [8], whereas for contact ITO/n-a-Si:H we hardly notice any change on the *J(V)* characteristics of our solar cells "Fig. 3". Indeed, the Open circuit voltage V_{oc} and the Fill factor *FF* remain unchanged. A decrease of the electric field on the contact (ITO/n-a-Si:H) doesn't give any change in efficiency η of our cells.



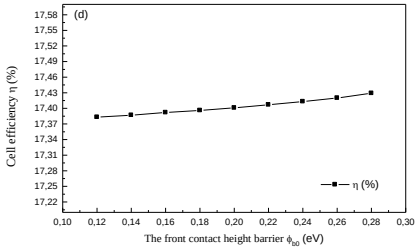


Fig. 3: Plot of (a) Short circuit current J_{sc}, (b) V_{oc} Open circuit voltage, (c) Fill factor *FF* and, (d) Cell efficiency η as a function of the front contact height barrier ϕ_{b0}.

Indeed, the electron affinity of hydrogenated n-doped amorphous silicon (n-a-Si: H) is between 3.9 and 4 eV and its activation energy is about 0.2 eV, which gives us a work function equal to about 4.20 eV. Knowing that the work function of ITO is higher than the semiconductor ϕ_{ITO} = 4.30 eV, the formation of this contact (ITO/n-a-Si:H) is likely to drive the n-layer (n-a-Si:H) in depletion, causing a drop in open circuit voltage V_{oc}. We consider the potential barrier for such contact (ITO/n-a-Si: H) between 0.2 and 0.4 eV (Fig. 4). An increase of work function of ITO in this case (for example ϕ_{ITO}=5 eV), led to a sharp depletion of n-layer, which significantly affects the band bending. It grows up, and it only increases the potential barrier, which opposes the diffusion of electrons.

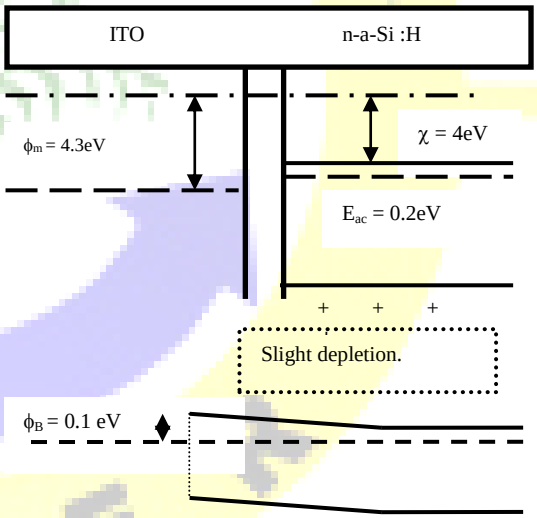


Fig. 4. Contact ITO/n-a-Si :H at thermodynamic equilibrium f or work function of ITO ϕ_{ITO} = 4.30 eV

IV. CONCLUSION

In summary, we have found that the cell performance don't depends on the front contact barrier on indium tin oxide/hydrogenated n-doped amorphous silicon heterojunction solar cells. Indeed, we have shown that an increase of the front contact height barrier ϕ_{b0} (the band-banding reduced) don't give any change on the *J(V)* characteristics of our solar cells.. The simplest explanation is that an increase of work function of ITO led to a sharp

depletion of n-layer and than an increase of the potential barrier, which opposes the diffusion of electrons.

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