Master in Photonics

MASTER THESIS WORK

TRANSPARENT ELECTRODES BASED ON ULTRA THIN DIELECTRIC-METAL-DIELECTRIC MULTILAYER STRUCTURE

ELOI ROS COSTALS

Supervised by Prof. VOZ, (UPC-MNT)

Presented on date 11th July 2019
Transparent electrodes based on ultra thin Dielectric-Metal-Dielectric multilayer structure.

Eloi Ros Costals¹

¹ Electronic Engineering Department, Micro and Nano technology group, Universitat Politècnica de Catalunya (UPC), Barcelona, Spain

E-mail: eloi.ros@upc.edu

Abstract

Photonics has been the focus of an increasing amount of research resources and funding since technological demands of solutions to complex problems can be solved within its scope. In this paper we will specifically focus on the demand of Transparent Conductive Materials in an specific field of photonics (i.e. opto-electronics). Particularly, we are going to fabricate and characterize thin film stacks called DMD (i.e. Dielectric Metal Dielectric), and using simulations as a guide we will integrate this materials inside electronic devices (i.e. Silicon solar cells). The devices will use a combination Transition Metal Oxides (e.g. V2O5, MoO3) for the dielectric layers, and soft metals (Ag, Au, Al) deposited either by thermal Evaporation or Sputtering. Several ideas regarding the coalescence thickness of metallic thin films, which represents a limiting factors of this technology are tested in this work, achieving an enhancement of optical and electrical properties.

Keywords: Transparent Conductive Oxides (TCO), Transition Metal Oxides (TMO), Dielectric Metal Dielectric (DMD), Solar cells.

1. Introduction

1.1 Transparent conductive layers: A State of the Art

Electronic devices, and particularly semiconductor based electronic devices such as transistors, phototransistors, diodes, photodiodes, light emitting diodes (LED) and solar cells, are used in a variety of applications such as: Computing and performing logical operations, Optical signal processing, Domestic and Industrial lightning, and Solar energy harvesting.

Some of this applications derive from a complex packing of the aforementioned devices (e.g. Microprocessors, microcontrollers etc.), however some other applications require an intimate interaction of the device with light, and the response of the device to light will be a determinant factor.

Optoelectronics is the particular field of photonics that studies the interaction of light with electronic devices, and will be the main scope of this work.

The most basic light interactions in optoelectronic devices are: the photoelectric or photovoltaic effect (used in photodiodes and solar cells), photoconductivity (used in sensors), stimulated emission (used in Lasers) and radiative recombination or the Lossev effect (used in LED)[1].

In many of the devices requiring Lossev or photovoltaic effects will require a transparent but electrically conducting electrode. This electrode will allow the transmission of light as well as the flow of charge carriers. Some notorious applications of this electrodes can be seen in OLEDs, Liquid Crystal Displays (LCDs), Touch screens, Electro-Magnetic Shielding, and Solar Panels. [2]

A variety of materials can offer both this optical and electrical properties. For instance, Transparent Conductive Oxides (TCOs), Conductive organic polymers, graphene, carbon nanotubes and metallic nanowire mesh, and finally dielectric embedded ultra thin metallic layers.[3]
Nevertheless, the industry is at this point mainly focused on the use of TCO thin films. This can be due to the fact that TCO can be deposited by RF Sputtering offering a low cost, fast and easy scalable deposition technique.

Amongst TCOs, Tin Doped Indium Oxide (ITO) has had a dominant position due to its extraordinary optical an electrical properties. For instance, a thin film of 160nm of ITO provides an averaged transmittance up to 95% and a resistivity 20 orders of magnitude lower than an insulator (i.e. 10⁶ ohms cm) [4].

However, limited supply of indium and growing demand of ITO makes the resulting fabrication costs increase, a feature not desirable for the technological market.[5] Furthermore, a new market of opportunities arise with the fabrication of flexible devices using organic and in a close future 2D electronics. This is often an impediment for using ITO thin films, as is known to be brittle and when the substrate is bended the ITO layer loses conductivity[6].

Therefore, a different approach must be taken in order to integrate flexible optoelectronic devices into the current electronic market.

1.1 DMD and its value in Photovoltaics: Reflectivity, conductivity and selectivity.

While most of the previously introduced solutions may seem appealing and fit the requirements listed for Transparent Conductive Electrodes, we believe that DMD can offer serious advantages, particularly in Photovoltaics (PV).

DMDs are a down to earth solution easy to scale up to industrial scale since one can use several Physical Deposition methods such as Evaporation and Sputtering that fits with current equipment available for most of the electronics industry. This would mean a safe in investment when changing from ITO electrodes to DMD. Thus, making the solution quite appealing.

Particularly for PV, DMDs are also offering several advantages with respect to other alternatives, and this relates to the basic physics of how electronic devices work. A modern way to understand the carrier movement inside a solar cell, and by all means any junction based device, is breaking with the idea that a solar cell consists in a PN junction. We can conceptually think of a solar cell as an absorber (i.e. a semiconductor) and two selective contacts (i.e. an electron and a hole contact)[7]. Each contact will provide an enhanced conductivity of one carrier with respect to the other one. The asymmetry in conductivity will generate energy barriers for the predominant carrier and therefore create a diode type characteristic Fig(1). This implies that without the explicit need of any doping, and only with the tuning of the materials used at the contacts one can fabricate all types of junction based devices (e.g. photodiodes, floating gate transistors…) and particularly solar cells.

![Fig(1) Band diagram schematics of an n type silicon solar cell with doped amorphous silicon as ETL and MoO₃/Ag/MoO₃ front selective conductive antireflection electrode](image)

One of the most extended selective contacts used in Silicon PV are thin films of Transition Metal Oxides (TMO). Molybdenum, Vanadium, Tungsten and Titanium oxides offer a very good performance on c-Si solar cells for hole/electron transport layers (HTL/ETL)[8].

Generally, TMO layers are used before the ITO electrode, so from a device perspective it is an interesting idea to combine the TMO layers in the DMD structures to replace the ITO as the conductive transparent electrode and antireflection coating, by directly depositing an integrated selective, conductive antireflection coating (i.e. DMD). This would offer several advantages over non selective TCOs, even ITO depending on the application as the multilayer can be deposited in one stack with the same equipment. And if the application required different properties, optical and electrical properties of the multilayer stack can be tuned by changing the electrode dielectric layers.

1.1 Simulating DMD phase interference: Transfer Matrix Method

Even though the DMD multilayer is meant to be 3D structure, the only optical change will be seen in depth and generally normal to the surface, therefore reflection and transmission coefficients can be obtained by a the cascade calculation used in Transfer Matrix Method (TMM) [9]. In this method we will be including the individual optical properties of each layer (i.e. complex refractive index and thickness) and computing the reflection and transmission

\[
\left(\frac{E^+_{m}}{E^-_{m}}\right) = \frac{1}{t_m} \left( T_m e^{i\delta_{m-1}} r_m e^{-i\delta_{m-1}} \right) \left(\frac{E^+_{m-1}}{E^-_{m-1}}\right)
\]

Eq [1] coefficient.
We can write the forward field in the mth layer as $E_{m+}$ and the backward field as $E_{m}^-$. Where $t_m$ is the thickness of the $m_{th}$ layer and $\delta_m$ is the phase change in the $m_{th}$ layer.

If the multilayer has a total of $k$ layers the total transmitted and reflected field become proportional to the initial incoming field as expressed in following equation.

$$
\left( \frac{E_{k+1}^+}{E_{k+1}^-} \right) = \frac{M_k M_{k-1} \ldots M_1}{t_k t_{k-1} \ldots t_1} \left( \frac{E_{0}^+}{E_{0}^-} \right)
$$

Eq [2]

The cascade matrix method therefore yields the total Reflection and Transmission coefficients.

$$
R = \frac{|E_{k+1}^-|^2}{|E_{k+1}^+|^2}
$$

Eq [3]

$$
T_{||} = \frac{n_0}{n_{k+1}} \frac{|E_{0}^+|^2}{|E_{k+1}^+|^2}
$$

1.2 Introduction to thin film growth: Coalescence threshold in Volmer-Webber growth

It is very desirable for the metallic layer in DMDs to be as thin as possible in order to avoid large optical losses. Nevertheless, homogeneity problems are present when ultra thin films (i.e. less than 10 nm) are deposited either via Sputtering and thermal evaporation.

The presence of interatomic/intermolecular cohesion forces, characteristic of each material, as well as the surface topography and rate deposition may influence the final roughness of the deposited layer. This defines 3 type of thin film growing when going to ultra thin thickness. Frank-Van der Merwe is a layer by layer growth and due to great wetability of the deposited materials one achieve an homogeneous layer[10].

Volmer-Weber is an island growth, and it occurs with low wetability materials where the deposited layer coalescence and forms isolated islands. This is the typical growth displayed by soft metals onto insulators.

Stranski-Krastanov is an intermediate case and consists on a firs Frank-Van der Merwe nucleation stage followed by a Volmer-Webber.

Coalescence threshold in the metallic layer of the DMD will be the main challenge faced in this work, and several strategies are used to decrease this phenomenon and enhance the smoothness of the metallic layer and decrease the metallic thickness.

2. Experimental

The deposited DMDs were designed as V2O5/metal/V2O5 (VMV) electrodes and they were deposited by thermal evaporation in a vacuum system with a base pressure below 10−6 mbar. The films were grown at low deposition rates in the range of 1–4 A/s and the substrates were maintained at room temperature. The thickness of the evaporated layers was measured by means of an INFICON SQC-310 deposition controller. In that case of very thin layers that have not coalesced, the thickness measured by the quartz microbalance must be interpreted just as the amount of material evaporated onto the substrate. Optical and electrical characterizations were done for structures deposited onto borosilicate glass after ultrasonic bath, and typical organic cleaning with acetone isopropanol and deionized water. The DMD structures were examined by field-emission scanning electron microscopy (FESEM).

The sheet resistance ($R_{sh}$) was evaluated using a 4-point probe. The optical transmittance was measured using an UV-visible-near infrared response Shimadzu 3600 spectrophotometer.

Regarding the fabricated solar cells, the devices were fabricated on polished (100) n-type (2 Ω cm) c-Si wafers of 280-µm thickness. The DMD structures developed in this paper were deposited on the front side to perform as HTL as well as frontal transparent electrode.

The rear electrodes consisted of a stack of Aluminium and Titanium oxides (Al2O3/TiO2) deposited by Atomic Layer Deposition (ALD), followed by a thin magnesium layer, and a final thick aluminium capping. Such structure behaves as a good dopant-free electron selective contact, as reported in a previous work [11]. The active area of the solar cells (1 cm2, 4 cm2) was defined by conventional photolithography and wet-etching steps. Finally, a 2-µm-thick Ag grid was thermally evaporated through a shadow mask as a front contact. The metallic grid covered 4% of the VMV active area. A schematic of the device structure is shown in Fig(2).

On complete devices, the current density versus voltage (JV) electrical characteristics were measured using a Newport solar simulator and Keithley 2400 dc source-meter. Additionally, quasi-steady-state open-circuit voltage (QSSVoc) measurements [12] were done with a system made by the group. Using this technique, the actual electrical characteristics can be compared with pseudo-JV curves with no influence of the series resistance. The, external-quantum efficiency (EQE) curves of the solar cells was measured by means of a QEX10 PV measurement equipment.
Finally a set of Aluminum doping in Ag thin films was done by co-sputtering in RF magnetron sputtering (ATC ORION 8 HV) with 3 targets at RT in different pressures in the mTorr range using both Al and dilute hydrogen in Argon as dopants during deposition process.

**Fig(2)** Solar cell architecture used in this work.

### 3. Results and Discussion

#### 3.1 Effect of a gold seed layer on VAV DMDs

The aim of this work is mainly its use in silicon solar cell, thus we are going to use Vanadium Oxide and not other TMOs since V2O5 yields the best surface passivation in Si solar cells. As a first step one can assume that since the extinction coefficient of the metal is the largest of the multilayer, the larger contribution to the optical properties of the stack will be the thickness of the metallic layer. Therefore, to see what is the effect of thickness on the stack we fabricated a series of V2O5/Ag/V2O5 (VAV) DMDs with steady dielectric thickness and changing the metallic thickness.

Different samples were deposited on glass substrates to measure their optical transmittance. The thicknesses of the bottom and top V2O5 layers were fixed at 20 and 35 nm, respectively. As an intermediate metal, we started to study the use of silver layers with a thickness between 6 and 12 nm. As one can be seen in **Fig(3)** in average, transmittance decreases with the thickness of the intermediate Ag layer.

This behaviour is expected as previously commented owing to the optical absorption of the metallic layer. Nevertheless, the transmittance in the infrared region was unexpectedly low for very thin Ag layers. Besides, in the wavelength region of 700–900 nm, transparency was not in direct correlation to the metal thickness.

This can be due to the characteristic growth mechanism of Ag films when evaporated onto a dielectric substrate (i.e. Volmer-Weber [13]). Isolated islands of Silver are likely to scatter the incoming light and moreover cause a parasitic absorption of photons and excitation of localized surface plasmons [14]. Equivalent behavior has been already reported for other DMD structures, where silver was also used as the intermediate metal [15]. The initial formation of islands can be explained because Ag atoms prefer to bond with each other rather than with the substrate. Therefore, the nominal thickness displayed in the graph, obtained by the quartz sensor during the evaporation would only be a reference value for the amount of evaporated metal. A successful approach to promote the formation of a continuous film (Frank–Van der Merwe growth) is to use a seed (wetting) layer [16], [17]. It has been previously studied how the use of wetting layers of Germanium and Copper and Gold may enhance the wettability of ultrathin silver layers, but in order to maintain the same deposition equipment (i.e. thermal evaporation) we used Gold which is a soft metal easy to evaporate. Therefore, we evaporated an ultrathin (1 nm) gold seed preceding the Ag layer. We can see how the dissociation energy of the Au–Ag bond (202.9 kJ/mol) is higher than that of a diatomic Ag–Ag bond (160.3 kJ/mol) [18]. Thus, impinging Ag atoms are expected to bond tightly with the gold seed rather than migrate over the surface to form Silver clusters.

Consequently, a series of VAuAgV multilayers was prepared to compare their characteristics with the previously studied VAgV structures. The Au seed layer (1 nm) was combined with 5, 7, and 9 nm Ag layers for total metal thicknesses or the total amount of metal equivalent to those of VAgV samples (6, 8, and 10 nm). A comparison of the optical transmittance evidences the interest in using a seed
The VAuAgV multilayers were noticeably more transparent in the visible and infrared regions. The optical transmittance was slightly reduced only at short wavelengths ($\lambda < 400$ nm) because of the gold absorption. Nevertheless, the improved optical properties of VAuAgV multilayers with respect to VAV is clear.

![Transmittivity of VAuAgV samples](image)

**Fig(4) Transmittivity of VAuAgV samples evaporated on top of Borosilicate glass.**

The wetting effect of the Au seed over the Ag layer could be confirmed in the FESEM images **Fig(5).**

Left image corresponds to the VAgV sample with an 8-nm-thick Ag layer, where isolated clusters of silver can be clearly resolved. In contrast, the sample with an intermediate Au/Ag stack (1 nm/7 nm) shows a continuous and a much more homogeneous film. The FESEM image is very revealing as the homogeneity of the metallic layer can also be related to the electrical conductivity of the stack.

Each of the DMD layers are fundamentally contributing to the stack with its characteristic features. For instance, from an optical point of view the top dielectric layer is meant to smooth the refractive index change before light reaches the metallic layer and therefore increase the optical transmittance, however from an electrical point of view it can’t offer high carrier mobility neither a high carrier concentration so its thickness must be maintained at the minimum value possible. The bottom dielectric layer from an optical point of view is meant to tune the maximum of the optical transmittance to match the AM 1.5 solar spectrum in a similar way to the top dielectric layer, however it is far more important to the electrical properties as it must provide the stack with hole selectivity.

**Fig(5) FESEM imaging of bare 8 nm deposited Ag film (left) and 1 nm Au/7nm Ag stack (right).**

A direct contact of the Metallic layer with the c-Si would provide a Shotky type of junction. While this junction may be suitable for signal applications, it is very undesirable from a PV point of view. Therefore, the bottom Vanadium oxide layer must be at all cost maintained at a value close to the literature (i.e. 15-20 nm)

In conclusion, since the dielectric layers do not seem to provide the DMD any extra carriers, it must be assumed that the major part of the lateral conductivity measured on each stack (i.e. Sheet Resistance), must be due to the conduction in the metallic layer.

As one may see in **Fig(6) for the VAV structures**, there is a step-wise transition of several orders of magnitude from $10^5$ Ohms square to $10^2$ Ohms Square, which is significantly lower than TCOs. This step change in sheet resistance is also reported by other groups in Molybdenum oxide and Silver DMDs (MAM).

![Sheet resistance](image)

**Fig(6) Sheet resistance of VAV and VauAgV electrodes as a function of metal thickness.**
This threshold thickness where the stack drops in sheet resistance can be associated with the coalescence limit of a Volmer-Webber growing material. As material keeps depositing onto the substrate the islands converge and form a homogeneous film, according to Fig(6) this seems to happen at thickness near to 9 nm. Now in this homogeneous film electrons can freely flow through the metallic layer and the stepwise drop in resistivity is justified. Furthermore, as the wave vector can’t now match the condition for surface plasmon excitation there is a justified increase of average optical transmission of the VAuAgV samples with respect to VAuAgV.

As a final step of the characterization process of the multilayer, we implemented the presented V2O5/Au/Ag/V2O5 alternative in a complete solar cell as both the Hole Transport Layer and Conductive Antireflection Coating in an Indium Free solar cell. In order to maximize the efficiency of the device, a simulation of the effect of both top and bottom dielectric thickness has been performed using TMM.

From the Transmitted and reflected coefficients obtained by TMM for each thickness of the vanadium layer, we can get an estimation of the absorbed light inside the silicon wafer using the absorbance coefficient of Silicon and the Beer-Lambert Law as a first approximation. Multiple reflections in the rear and front electrodes will not be taken into account in this simulation. Finally, assuming AM1.5 illumination conditions one can calculate the photo-generated current in 1 sun conditions using the following equation:

\[ J_{ph} = \int_0^{hc/E_g} A(\lambda) \frac{q\lambda}{hc} AM1.5(\lambda) \, d\lambda \]

If a 2D map is done plotting photo-generated current as a function of thickness of the top and bottom dielectric layers, a maximum can be identified for low thickness of the bottom dielectric layer and a larger thickness of the top dielectric.

Therefore for the devices we arranged the thickness of the multi layer to 20 nm of V2O5 in the bottom electrode to provide good hole selectivity, and 50-60 nm in the top electrode thickness to provide the stack with matching optical properties to AM1.5 illumination and Silicon absorption. Finally, the simulation shown was run for a 10 nm homogeneous Ag layer, however the improved optical domains were not affected when a simulation was run including a 1 nm Au layer and a 7 nm Ag layer.

The final fabricated device showed a good performance when measured in light conditions. As one can see in Fig(9) the device is obtaining a 13.3% Power Conversion Efficiency (PCE). Open circuit Voltage (Voc) of 618mV indicates that the multilayer structure is properly working as a Hole Transport layer and providing better surface passivation than other solutions such as MAM DMDs without seed layer [20] and other alternatives to DMD such as selective conducting polymers, PEDOT:PSS for instance[21], that slightly underperforms this VAAV structure. A suprisingly high short circuit current indicates that the strategies followed to decrease optical absorption by the stack are working when compared with aforementioned of the art DMD structures, however a good selective transparent top contact should normally provide a Jsc of 32-33 mA/cm2 in flat substrates, which indicates that there are close to 6 mA/cm2 lost in the front contact.

[Fig(7) Simulated dielectric Thickness dependence of the photo generated current inside the cell.]

[Fig(8) Pseudo-JV vs JV measured by QSSPC.]
Finally, and the most notably result is the very large FF of the fabricated cell. The FF is a characteristic parameter of the solar cell and it strongly relates to the maximum power a solar cell can achieve with respect to its open circuit voltage and short circuit current. For Silicon solar cells a the typical FF range from 50% to 82%. The FF is strongly reduced by series parasitic resistances, therefore the 79% FF achieved in this structure indicates how the electronic transport of the stack is very good and very close to the top values one can for Si.

Fig(9) Light J/V curve of the finished device.

The low sheet resistance achieved with the Au/Ag stacks could be the main factor that contributes to this good result. In this regard, the QSSVoc of the device was measured as a function of the illumination intensity. These data was used to calculate a pseudo-JV curve in which the effect of the series resistance is eliminated Fig(8).

The corresponding pseudo-FF (pFF) increases to 81.6%, which points to a good-quality diode. Actually, the exponential region of the pseudo-JV curve could be fitted by considering a single-diode model as follows:

\[ J = J_0 \left( e^{\frac{qV}{nkT}} - 1 \right) \]

With a low saturation current density \( J_0 = 4.8 \text{ pA/cm}^2 \) and a rather good (close to one) ideality factor \( n = 1.1 \). The value of the total series resistance \( R_s \) can be obtained from the pFF and the parameters of the JV curve under illumination [22] as follows:

\[ R_s = \frac{V_{oc}}{J_{sc}} \left( 1 - \frac{\text{FF}}{\text{pFF}} \right) \]

This calculation results in an \( R_s \) value as low as 0.6 \( \Omega \text{ cm}^2 \), which proves the good electrical quality of optimized VAuAgV electrodes. The moderate \( J_{sc} \) value is the main factor that limits the efficiency of this solar cell structure. Fig(9) shows the EQE curve of the solar cell together with its front reflectance spectra. In the inset, charge-carrier generation and different loss mechanisms are balanced for an AM1.5 irradiance. The incident photons with energy higher than the Si bandgap could generate a maximum photocurrent of 42.3 mA/cm2. Reflection on the front surface causes a 16.7% loss, which limits the photogenerated current to approximately 35.2 mA/cm2. The measured EQE curve implies a 23% internal loss, which results in a final \( J_{sc} \) value of 27.1 mA/cm2. This reduction can be explained by considering the optical absorption of the VAuAgV structure, mainly at its metallic stack. The internal charge-carrier recombination also reduces the \( J_{sc} \) value but less significantly because of the good quality c-Si absorber and the use of a passivated rear contact. All the samples and solar cells studied in this paper were fabricated on flat substrates.

Assuming that internal losses should remain similar, the use of textured substrates could lead to \( J_{sc} \) values of about 30 mA/cm2. Furthermore, according to the electrical characterization Fig(6), the Au/Ag stack can be thinned below 6 nm and \( R_{sh} \) values maintained in the range of 102 \( \Omega \text{ sq} \). In combination with an optimized metallization scheme, this change would increase the \( J_{sc} \) value by 3–4 mA/cm2 without a significant FF degradation.

Fig(10) EQE, IQE, Reflectivity of the fabricated device.
3.2 Effect of Aluminium doping in Ag layers using co-Sputtering

It’s been reported by AFM measurements that the use of doping agents, mainly aluminium, in thin film silver layers that can decrease the amount of clustering due to silver aggregation and smooth the layer roughness.[23]

Therefore, using this idea we tested the optical and electrical properties of Al doped Ag films using a co-sputtering process. It is necessary to remember that sputtering technique offer a series of advantages with respect to thermal evaporation, mainly better film adhesion to the substrate, the possibility of easily co-sputtering different materials and easy scalability to large area devices. Nevertheless, there are some drawbacks to using Sputtering. And this are a larger damage to the substrate surface due to the bombardment of Argon ions and the target clusters as well as light induced degradation from the UV generated in the Argon plasma.

Table 1. Sheet resistance effect of Aluminum co-Sputtering in Ag thin films.

<table>
<thead>
<tr>
<th>Thickness (nm)</th>
<th>Sheet resistance (Ω/sq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>10^6</td>
</tr>
<tr>
<td>5</td>
<td>10^6</td>
</tr>
<tr>
<td>10</td>
<td>50k</td>
</tr>
<tr>
<td>Al doping Ag</td>
<td></td>
</tr>
<tr>
<td>Sputtering power (W)</td>
<td>Sheet resistance (Ω/sq)</td>
</tr>
<tr>
<td>100</td>
<td>500</td>
</tr>
<tr>
<td>125</td>
<td>154</td>
</tr>
<tr>
<td>138</td>
<td>60</td>
</tr>
<tr>
<td>150</td>
<td>110</td>
</tr>
<tr>
<td>175</td>
<td>140</td>
</tr>
</tbody>
</table>

Sputtering has been studied also to deposit TMOs as a more industrial alternative to thermal evaporation. Nevertheless, it is a nontrivial problem and selectivity issues that have been reported seem to be fundamentally intrinsic to the deposition method used. Therefore, as a more fundamental study we have decided to sputter ultra-thin metallic layers on top of borosilicate glass and study its optical properties when Al was used as a doping agent, and avoid its use in a DMD structure, which would be the next step.

Results of electrical conductivities are summarized in table(1) while optical measurements can be seen in Fig(10) and Fig(11).

It is clear that a low power co-sputtering of aluminum instantly reduces the absorption in high visible frequencies (green and blue), this can be attributed to the decrease of LSP absorption and therefore it could be an evidence of the layer smothering due to the presence of Aluminium.

Finally, the stepwise electrical properties of the isolated silver layer is maintained, however it is evident from the 4 point prove measurements that the use of aluminium as a dopant instantly decreases the sheet resistance by 3 to 5 orders of magnitude. This drop in sheet resistance is very consistent with the previously introduced Volmer-Webber growth silver experience, and it looks like Aluminium doping during the process of silver deposition would be a cheaper alternative to the use of an expensive material like gold as a seed layer.
Some improved results on the line. (27.1 mA/cm²). In this sense, technological transfer to the also novel rear contact that has been implemented here. Contacts prove of the passivation of the silicon surface by VAV transparent electrode. The open resistance that has been achieved with this alternative remarkably high fill has yielded a conversion efficiency of 13.3%. The selective character of V₂O₅ layers on silicon, the fabrication of optical transmittance by more than 15%. Given the hole the thickness of the intermediate metallic layer increases the nm already coalesce into a continuous film. The reduct ultra achieve low sheet resistance in this sense, a minimum Ag thickness of 10 nm is required to achieve low sheet resistance values. However, the use of an ultra-thin Au seed (1 nm) favors that Ag layers as thin as 6 nm already coalesce into a continuous film. The reduction in the thickness of the intermediate metallic layer increases the optical transmittance by more than 15%. Given the hole-selective character of V₂O₅ layers on silicon, the fabrication of dopant-free heterojunction solar cells is straightforward. In this paper, an optimized V₄Au₄V structure on n-type c-Si has yielded a conversion efficiency of 13.3%. The remarkably high fill-factor (79.5%) points out the low sheet resistance that has been achieved with this alternative transparent electrode. The open-circuit voltage (618 mV) is a prove of the passivation of the silicon surface by VAV contacts, more so when considering that it is likely limited by the also novel rear contact that has been implemented here. There is definitely room for improvement in the Jsc value (27.1 mA/cm²). In this sense, technological transfer to textured substrates could be the next step for this research line.

On the other hand, co sputtering of Aluminum showed some improved results on the optical and electrical properties of sputtered Ag thin films, the improvement was consistent with the coalescence of the thin metallic film.

Further investigation on the integration of this technique with sputtered DMDs is the next step for this research line.

Acknowledgements

Thanks to Prof. Voz and Prof. Puigdollers for help and support during research. Thanks to Fellow researchers and of the MNT group. Thanks to Family and friends.

References

[6] A highly flexible transparent conductive electrode based on nanomaterials, Chang-Lae Kim, 10.1038/am.2017.177

**Fig(12).** Transmittance of Al doped Ag films for several Aluminum co-sputtering power.


[19] Toward indium-free optoelectronic devices: Dielectric/metal/dielectric alternative transparent conductive electrode in organic photovoltaic cells, Jean Christian Bernede et al 0.1002/pssa.201228089

[20] Multilayer MoO$_x$/Ag/MoO$_x$ emitters in dopant-free silicon solar cells, Weiliang Wu et al, 2017 J.matlet.2016.11.059

[21] Junction formation and current transport mechanisms in hybrid n-Si/PEDOT:PSS solar cells, Sara Jäckle et al, 10.1038/srep13008


[23] An Ultrathin, Smooth, and Low-Loss Al-Doped Ag Film and Its Application as a Transparent Electrode in Organic Photovoltaics, Cheng Zhang et al, 10.1002/adma.201306091