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Deep level defects on mono-like and polycrystalline silicon solar cells

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***Abstract*—Defects on mono-like and polycrystalline silicon solar cells are studied in depth. These defects are in the basis of the higher quantum efficiency of mono-like solar cells (∼18%) with respect to polycrystalline ones (∼16%). Using the thermal admittance spectroscopy technique we found that both of them have a deep level due to a Fe-B complex. Furthermore, the deep level in the first one (224meV) is shallower than in the second one (345meV). Shallower deep levels degrade less the efficiency on solar cells, so this characteristic of the deep level in the mono-like solar cells leads to a better results in efficiency.**

***Keywords*—Solar cell; defects; thermal admittance spectroscopy**

I. Introduction

In order to make photovoltaic solar energy an affordable option to address the energy requirements of our society, it is mandatory to achieve the fabrication of low cost, stable and high efficiency solar cells.

Currently in the photovoltaic (PV) industry more than 90% of the world production is based on Silicon in the form of mono-crystalline (c-Si), multi-crystalline (mc-Si) and thin film Si. In particular, mc-Si wafers constitute more than 60% of the Silicon PV market because of its low manufacturing cost despite its lower performance compared to c-Si wafers. Nowadays, the mc-Si PV market demands highly innovative approaches to reduce production cost increasing the energy/surface ratio. For this purpose, a new type of wafers are being introduced into the market with mono-crystalline features using common cast growth furnaces with the brand of mono-like (ML) wafers.

However, the efficiency of this solar cells is much lower than the theoretically expected (∼30%) due to several causes such as incomplete absorption of incident light, presence of intrinsic or processing induced defects, and so on. Hole traps and defects have been reported in [3]–[6] which strongly degrade the solar cell efficiency. However, despite the work done, a detailed understanding is still lacking, and thereby the characterization of these defects is necessary.

TABLE I
Samples summary

Label	Features		
	Type	*Bias (V)*	E_t *(meV)*
JJD1	ML	0.5	271
JJD3	ML	2	224
		2.5	258
		3	224
JJB3	PC	0.5	344
JJB4	PC	-3	344
		-1	345
		-0.5	339
		1	344

The present work reports some experimental results of the electrical properties of silicon substrates for solar cells. Two types of substrates have been studied: ML and polycrystalline (PC) substrates. Thermal admittance spectroscopy has been employed for characterization of the bulk levels in the silicon substrate layer. The Arrhenius plot fit indicated an emission from a deep level with an activation energy of about 224meV in the ML ones and 345meV in the PC ones, which seems correspond to iron impurities.

II. Experimental

In Table I are shown all the samples used to do our study, its type (ML or PC) and the different bias voltages applied over them.

The solar wafers, where the samples used in this work come from, were supplied by DC Wafers Investments, Spain. The grow process was performed using both Directional Solidification (DSS) and Heat Exchange Method (HEM) stations provided by GT Solar. Quartz crucibles were used to manufacture the ingots based on solar grade polysilicon. Multicrystalline growths were carried out using casting techniques on Bridgman-types furnaces. For the production of mono-

like wafers (or seed-cast growth), c-Si seeds (produced by Czochralski or Float Zone method) with different widths were placed at the bottom of the quartz crucibles. The crystal growth procedure is based on the application of a passive cooling from the bottom of the crucible to geometrically control the melting of the seed up to a defined height using a calibrating quartz rod, then applying a corresponding cooling before the seed disappear into the melt. This process allows that the crystal orientation of the seed is transferred to the ingot. Although this growth procedure is not exempt of some inconveniences, the ML wafers show interesting new features; in particular, some of the wafers are more efficient (up to 1.0-1.5%) than the usual mc-Si wafers, also depending on the wafer texturing process (alkaline-anisotropic or acid-isotropic) applied over its surface.

Otherwise, thermal admittance spectroscopy [1] is a technique which yields thermal emission rates (e_p^t) of deep levels from the variations of capacitance and conductance of junction as a function of temperature and frequency. These variations are due to the change of the time constant of charge and discharge processes of the deep levels with the change of the temperature respect to the frequency of the measuring signal around the point of the space charge region where both time constants are equal.

Experimental measurements consist on recording the conductance and capacitance when the frequency of the measuring signal is fixed and the temperature is scanned. Each deep level existing in the junction yields a maximum in conductance (G_m) at a temperature T_m and an inflection point in capacitance (C_i) at a temperature T_i. The thermal emission rate, at theses temperatures, is given by:

$$e_p^t(T_m) = \frac{\omega}{1.98} \tag{1}$$

$$e_p^t(T_i) = \frac{\omega}{1.825} \tag{2}$$

where ω is the frequency of the measuring signal. If we repeat the measurement varying the frequency value we will obtain the thermal dependency of e_p^t, from which the activation energy (E_t) can be derived according the Arrhenius law:

$$e_p^t(T) = AT^2 \cdot exp\left(-\frac{E_t}{KT}\right) \tag{3}$$

Besides, the deep-level concentration (N_t) with regard to the dopants level (N_A) can be obtained using the expression:

$$\frac{N_t}{N_A} = \frac{G_m/\omega}{0.402}\sqrt{\frac{e(U_a+U_b)}{E_t - E_F}} \tag{4}$$

where U_a and U_b are the absolute values of the bias voltage and of the built-in voltage of the junction, respectively.

In summary, thermal admittance spectroscopy is a suitable technique to obtain the activation energy and density of deep level defects in solar cells.

III. Results and Discussion

Before use the characterization technique, it is a good idea to try to find an appropriate bias value. The reason why this step is needed it is because the double schottky union of the samples does not show the ideal behavior.

We have carried out conductance and capacitance measurements vs. bias voltage for temperatures ranging from 80K to room temperature at a given frequency. The chosen bias voltage must provide a maximum on conductance as theory predict. Fig. 1 shows these curves for a ML sample where it can be seen that only positive bias values were appropriated. In contrast, in the case of PC samples both polarities were valid. The results presented in this work were obtained using V=2V and V=-1V bias value for a ML and a PC sample, respectively.

Fig. 2 and Fig. 3 show the admittance spectra for a PC and a ML sample, at frequencies ranging from 33Hz to 33KHz and 330Hz to 77KHz, respectively. In this curves we can see that both conductance peak G_m/ω and capacitance step are near independent of the frequency, so indicating that only one deep level is present in the samples. As for the defect concentration, we see that the capacitance reach near double values after emission transition, so indicating that defect concentration

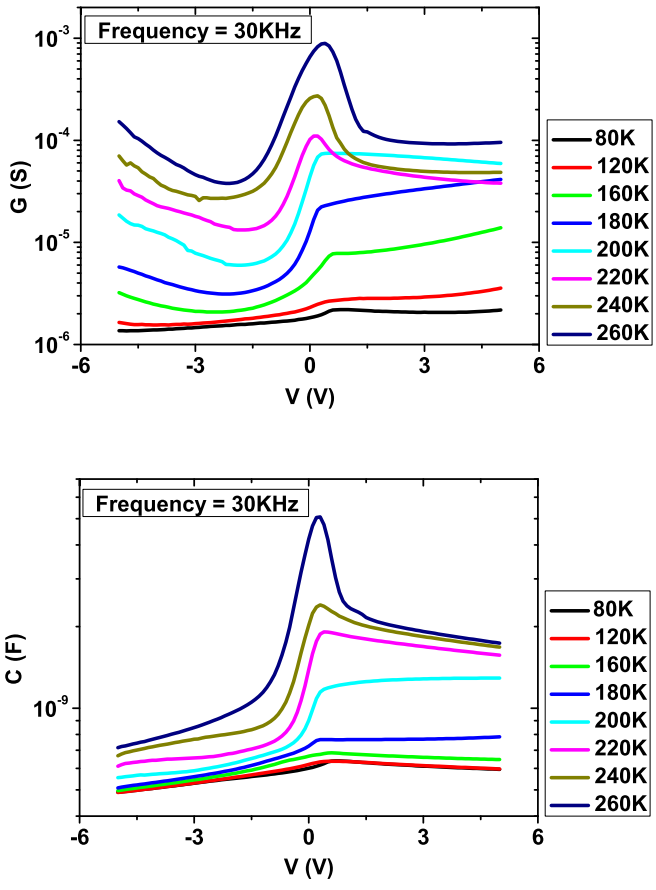

Figure 1. Conductance and capacitance vs. bias at constant frequency in a temperature sweep

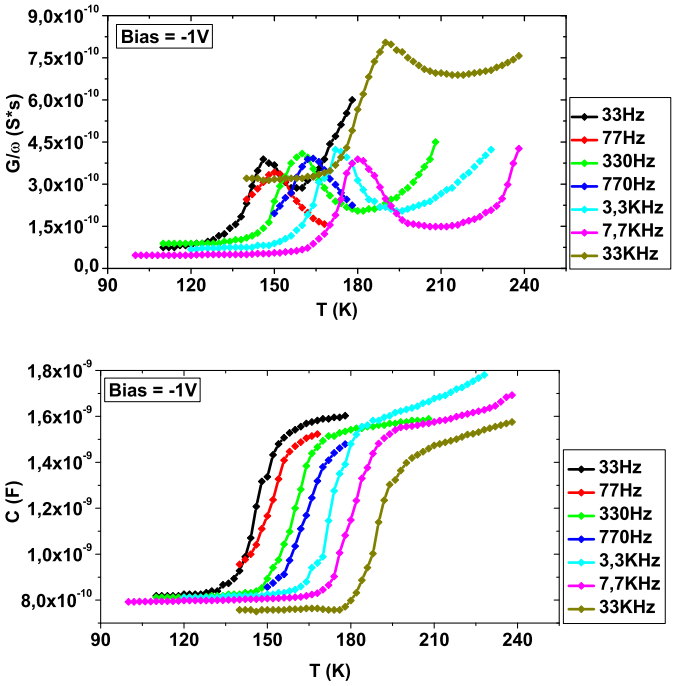

Figure 2. Conductance and capacitance curves family for PC

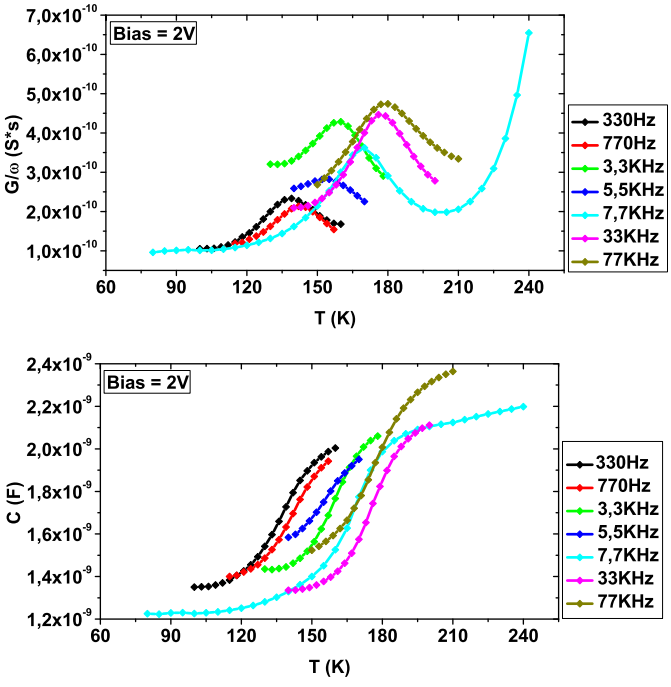

Figure 3. Conductance and capacitance curves family for ML

is in the same order of magnitude than the shallow dopant impurities.

The second parameter we will consider in the characterization of the deep level is the activation energy. Using (1) we can obtain the values of e_p^t for each frequency in each sample. If now we plot $ln(e_p^t/T^2)$ vs. $1/KT$ for each sample, according to (3), the slope of the linear fit is the activation energy mentioned. Fig. 4 and Fig. 5 show this plot for the PC and the ML sample, respectively.

The value of E_t obtained for the ML sample is 224meV. In the case of PC substrate the value obtained is 345meV. Both PC and ML are made in the same crucible, so it is so acceptable to say that both deep levels have the same nature because the source of them is essentially the same.

According to [2] interstitials of iron (Fe_i) lead a deep level in crystalline silicon which thermal activation energy is 230meV, referred to the valence band. However, other works suggested other origins as summarized in [3]. Fe-B complex, divacancies of B-O or C-V-O are proposed for this defect. As for, the 345meV deep level on PC samples, the defects proposed include Fe-B complex, B-O divacancy or instertitial iron defect. In our case, taking into account the high iron content on the crucible and the fact that the defect concentration is in the same order of magnitude as doping boron concentration, it seems like Fe-B complex is the best

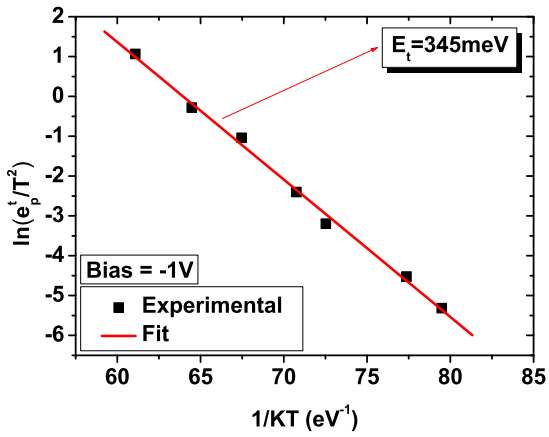

Figure 4. Arrhenius plot for the PC sample

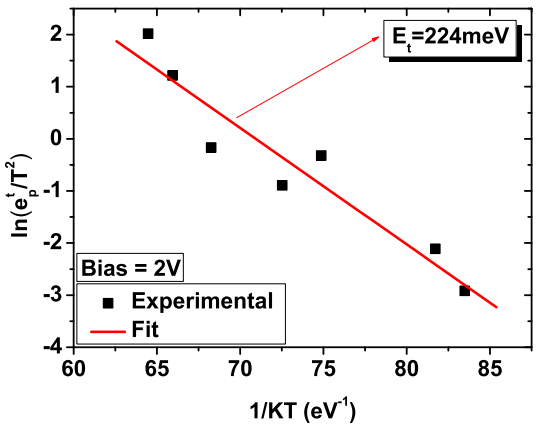

Figure 5. Arrhenius plot for the ML sample

candidate for the two kinds of samples.

The main difference between ML and PC is on the defect energy level. As it is well known, defects showing deeper energy have stronger influence on degrading the quantum efficiency of solar cells. Indeed, we have experimentally observed that polycrystalline solar cells have poorer efficiency ($\sim$16%) than mono-like ones ($\sim$18%).

IV. Conclusions

The study done over one ML and one PC sample show that there is a deep level in both of them due a Fe-B complex. In the PC sample we have an activation energy of 345meV. On the other hand we have in the ML sample an activation energy about 224meV, which are shallower than the first one. This means that the deep level on ML sample promote less non-radiative recombinations of electron-hole pairs which leads less quantum efficiency loses due to it. Which agree with the efficiency measurements.

Also, to firm up this conclusion we repeated the measurements with other bias values and other ML and PC samples. The results are summing in Table I. In PC samples the results are almost identical which ensure the accuracy of the value obtained previously for its activation energy. In ML samples the energy level values vary a little respect of the 224meV obtained. This variation is likely to be due to the influence of another unknown deep level with thermal emission rates very close to this one.

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