# TRANSIENT PRECONDITIONING IN CIGS SOLAR CELLS AND MODULES

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ABSTRACT: Transient preconditioning refers to a light induced performance change in CIGS which occurs and relaxes on a millisecond to seconds timescale. This effect appears to be distinct from the better known and more persistent preconditioning which typically takes several hours or days to relax. In this paper some properties of this phenomenon are explored including the variation of if the effect with voltage and temperature. The consequences for repeatable and accurate device measurement are explored. In particular the transient rise in photocurrent during measurements using a pulsed simulator can be successfully eradicated using voltage preconditioning when there is no gap between the preconditioning voltage being applied and the start of the illumination pulse.
Keywords: CIGS, performance rating, defects

## 1 INTORDUCTION

The term transient preconditioning refers to an effect which has been observed for a variety of CIGS devices. There is a very rapid light induced performance improvement which both occurs and relaxes on a timescale which is faster than that of the better known light soaking effect [1]. The *transient* effect appears to arise from a distinctly separate cause than the better known light soaking / preconditioning, which is referred to in this paper as *persistent* preconditioning. Both effects have been observed to occur in most CIGS modules. The timescales involved for the transient preconditioning present a challenge for measurements made using pulsed solar simulators and for this reason long pulse simulators are generally recommended for performance measurements of CIGS modules. The effect of too short a pulse is an underestimation of the fill factor and for some modules the open circuit voltage. The size of the measurement error depends on the measurement setup and the type of module but can be quite large, errors of over 5% in measured power have been reported from using a 5ms flash [2].

The time taken to stabilise and the rate of relaxation of the transient preconditioning is an important factor because it will have an impact on the selection of viable preconditioning strategies to enable repeatable measurements. In addition to this, the rate may also be affected by the illumination intensity, temperature and voltage load set point and the state of the cell/module with regard to the persistent preconditioning. This can cause further problems for energy rating measurements at a variety of temperature and irradiance values, since measurement procedures that work effectively at STC may no longer be valid. Thus it is important to understand the physical origins of this effect to develop reliable pre- and intra-test conditioning methods. This work presents a progressive step towards this goal.

There are a variety of possible strategies for measuring CIGS modules. The first is to use a steady state simulator. This is a guaranteed solution to the preconditioning problem but poses significant problems in terms of cost and temperature control of the module. A second option is to use a long pulse flash simulator. This can be a good option but the required pulse duration may vary for different module types and measurement conditions, also again there is a cost issue. So it would be advantageous if there were a preconditioning method that could be used with existing pulse simulators with flash length 10ms. Possible preconditioning methods include voltage preconditioning which would be applied right up to the point of measurement or a lower intensity light source that could be applied until immediately before the measurement or even left on during the measurement. In this work the voltage preconditioning method was tried and found to significantly reduce or eliminate any rise in current during the illumination pulse.

## 2 METHODS

### 2.1 Transient impact voltage dependence

The transient rise in photocurrent during a 10ms solar simulator pulse was measured at a number of different voltages for 4 modules. Each module was from a different commercial manufacturer. A PASAN IIIB simulator was used for the illumination. The electrical voltage was supplied by KEPCO BOPs. The current and voltage measurement were made using resistor networks with resistors connected in series and parallel to the PV module. The voltages were recorded using a simultaneous data acquisition card, which also simultaneously recorded the illumination intensity from a monitor cell.

### 2.2 Effect of voltage preconditioning

The transient rise in photocurrent was measured before and after voltage preconditioning at 90% of the Voc for the modules. The same power supply was used to supply the preconditioning voltage and the voltage required for the measurement. Because of this it was possible to have no delay between the removal the preconditioning voltage and application of the measurement voltage when the illumination pulse begins. In many cases the Voc of the module depends on the preconditioning state and is therefore a slightly ambiguous term. The Voc was defined as the one measured directly from dark storage with no preconditioning. The measurements were made using the same setup as in 2.1.

### 2.3 Small scale measurements

Since the pulse simulator flash was shorter than the time taken for the current to stabilize, an LED simulator was used to measure the transient rise and relaxation rate in CIGS cells. Using this simulator, the whole transient could be observed but the setup is limited in area to cells. The relaxation rate was measured for a CIGS cell by measuring the current at a fixed voltage and illumination and then turning the illumination off for different periods of time and measuring the difference in current between just before and just after the dark period. During the dark period the cell is kept at 0V. The CREST prototype LED simulator was used for the measurements [3]. After correction for spectral mismatch to AM1.5 the intensity was approximately 350Wm$^{-2}$. It should also be noted that the spectral mismatch was quite large due to a lack of power in the infrared range. The photocurrent was measured for 10 seconds after the illumination was turned on. As the LEDs heated up during after the start of illumination they gradually reduced in power output, this was compensated for by increasing the power input to them in stepwise manner. Corrections were made for variations in intensity of the light source and the temperature of the cell as it heated up under the light. The temperature correction was approximated as a linear reduction in current with time, the gradient of which was extracted from the final portion of the measurement once the transient had stabilized. The illumination intensity correction consisted of a linear and a logarithmic term. The size of the logarithmic term was determined as the value which eliminated discontinuities in the measured current at the points where the LED power was increased. The final result was a very smooth curve showing the increase in current against time since the illumination was applied.

The measured transients were fitted to double exponentials. A double exponential was used since it has been observed that there seem to be two different timescales for the preconditioning but that there is some overlap. This model provided a generally good fit to the data, an example of which is shown in Figure 1.

This experiment was repeated at a number of temperatures between 15ºC and 55ºC at the same load voltages. The rate constants of the exponential fits were plotted so as to extract apparent activation energy for the preconditioning process.

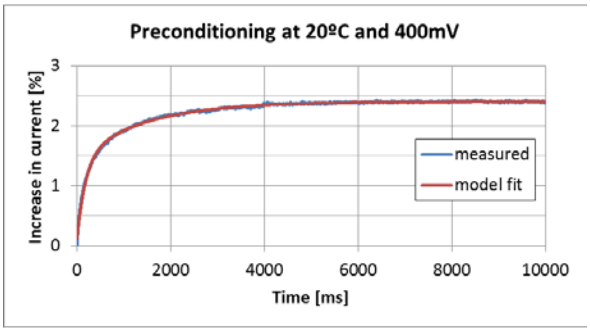


**Figure 1: Transient rise in photocurrent for a CIGS cell, along with double exponential fit**

## 3 RESULTS

### 3.1 Transient impact voltage dependence

The size of the rise in photocurrent was generally seen to be higher when the measurement voltage is set between the maximum power point and open circuit voltage. No rise in photocurrent was observed at short circuit or low voltages. This is a generally similar trend to what is observed from the persistent preconditioning, however in some cases the change in shape of the IV curve due to the persistent preconditioning is different from what is observed from the transient preconditioning. Figure 2 shows an example of a module where the change in shape of the IV curve caused by the transient and persistent preconditioning is different. In this case the persistent preconditioning significantly reduces the Voc while increasing the fill factor, whereas the transient preconditioning increases the Voc. The curves for the transient preconditioning have been created by taking current at the beginning and the end of the pulse for the transient measurements at each voltage. It should be noted that the photocurrent did not have time to stabilise before the end of the flash, so that if a longer flash had been used a larger separation between the two curves would be expected.

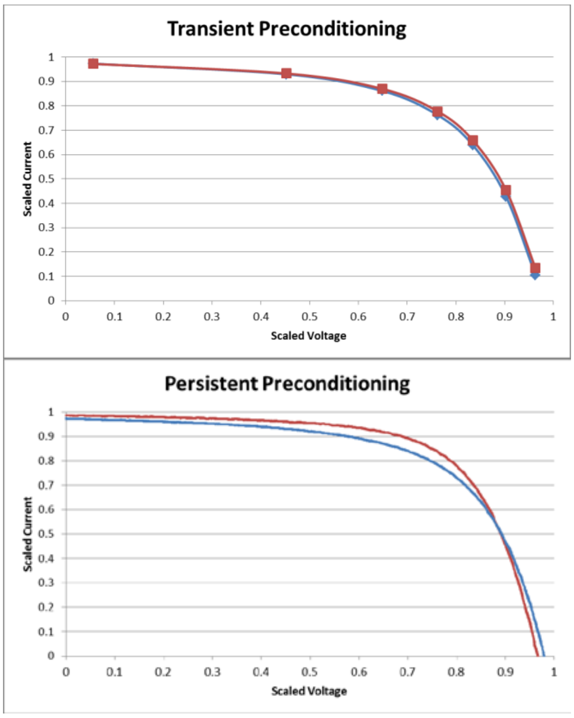


**Figure 2: Top: IV curves created from the current at the beginning (blue) and the end (red) of the illumination pulse. Bottom: IV curves before (blue) and after (red) 6.8 hours of forward bias preconditioning at 90% of Voc.**

### 3.2 Effect of voltage preconditioning

When there was no gap between voltage precondition and measurement the voltage preconditioning reduced the size of the transient rise in photocurrent until the point where it was either impossible to observe or negligibly small. Figure 3 shows the transient rises in photocurrent for 4 different modules measured at a voltage close to maximum power point both before and after preconditioning.

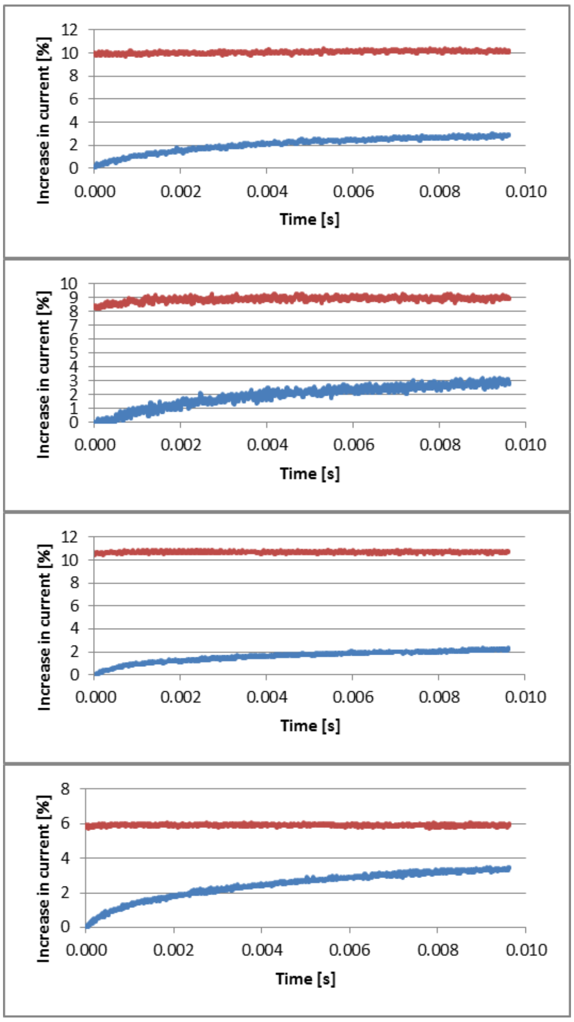


**Figure 3: Current measured during the flash before (blue) and after (red) preconditioning.**

3.3 Small scale measurements

As mentioned in section 2.3 the transient rise in photocurrent measured in the LED simulator was fit very well by a double exponential curve as seen in Figure 1. This suggests that there is an overlap in timescales between the transient and persistent preconditioning. The transient rise is slower than the rise observed in the pulse simulator measurements which could be a result of lower illumination or spectral differences, or because of differences in the cell construction.

Figure 4 shows the measured relaxation rate for the device which is seen to be occurring on the timescale of a few seconds. The logarithmic fit shown in the figure is purely phenomenological.

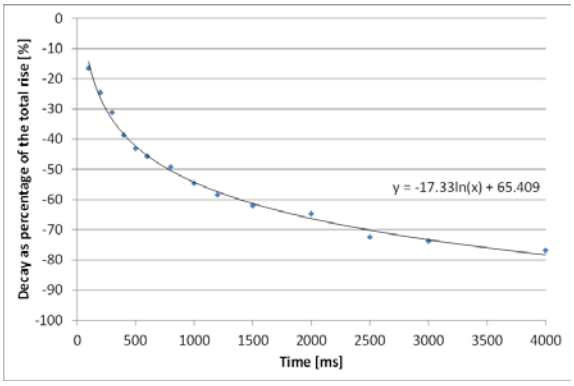


**Figure 4: Rate of relaxation in the dark for transient preconditioning with phenomenological logarithmic fit. The measurements were made by plotting the fall in output current when illumination and voltage bias were removed for different time intervals.**

The activation energy for the preconditioning can be extracted by plotting the logarithm of rate constant from the faster component of the fit against q/kT, where q is the electronic charge, k is Boltzmann's constant and T is the temperature in kelvin as shown in Figure 5. The gradient of this plot gives the apparent activation energy for the preconditioning voltage, which is 0.16eV. If the preconditioning effect is caused by metastable defect transitions then this activation energy is related to the activation energy for the atomic reconfiguration. However the temperature dependence of the carrier concentrations could also contribute to the measured value, if the preconditioning process involves the capture of electrons or holes.

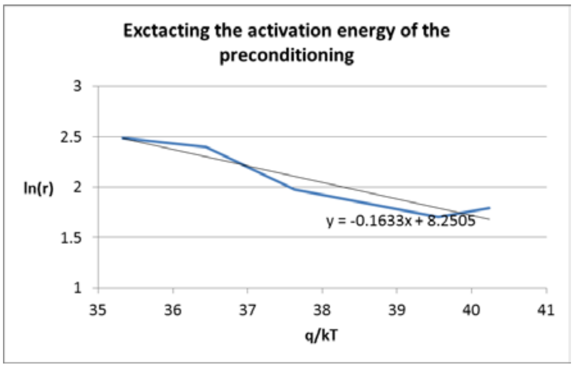


**Figure 5: plot of the logarithm of the fitted exponential rate constant against q/kT. The gradient of the plot gives the activation energy for the preconditioning in eV.**

## 4 DISCUSSION

The fact that the voltage preconditioning removes the transient preconditioning means that it may be possible to accurately measure these devices in short pulsed simulators. In order to validate this it is still required to check if the preconditioning level makes a difference to the stabilized photocurrent.

The success of the double exponential fit indicates two different effects rather than one effect occurring over a variety of timescales. This is further supported by the differences seen in Figure 2 between the effects on the IV curve of the persistent and transient preconditioning.

The persistent preconditioning is generally attributed to the $V_{Cu}$-$V_{Se}$ point defect [4], which is predicted from numerical modelling to be a metastable defect. A very plausible candidate for the transient preconditioning is another point defect $In_{Cu}$ or its complexes with the $V_{Cu}$ which have also been predicted to be metastable. This defect has already been implicated in the "red on bias" metastability [5] which is a particular metastable change in device capacitance induced by simultaneous application of reverse bias and red light illumination. The defect can also explain the difference between IV curve measurements under red light and white light [6]. If this defect were the cause it would take a deep defect level near the junction when the cell is stored in the dark, then after illumination the defect would take an acceptor state. This process is predicted to require the capture of one hole, but not to have an activation energy in itself. So that the measured activation energy should be completely due to the variation with temperature of hole concentration near the junction. The measured value of 0.16eV seems consistent with this theory but a complete device simulation would be required to confidently say this was the case.

## 5 CONCLUSIONS

This work has shown that it is possible to reduce the transient rise seen during a pulse simulator flash using voltage preconditioning provided that there is no gap between application of the voltage biasing and the illumination pulse. This is extremely encouraging for the prospect of measuring CIGS devices using short pulse simulators, however the task remains to check whether measurements made in this way agree with measurements made outdoors or under a steady state simulator.

The transient rise in photocurrent is not observed at short circuit current but becomes stronger at higher voltages and is usually significant at voltages between maximum power point and open circuit. In many cases the change in shape of the IV curve induced by the transient preconditioning is similar to that induced by the persistent preconditioning. However in some cases this is not true which is a strong indication that there are different underlying mechanisms for the persistent and transient preconditioning.

The transient preconditioning appears to be fit well by a double exponential curve where the slower component of the curve is likely to be the initial portion of the persistent preconditioning.

An apparent activation energy of 0.16eV has been measured for the transient preconditioning for one particular CIGS cell. At present this information is not sufficient to make good inference about the mechanism of the preconditioning, but combined with device simulations and similar measurements of different cell types this approach could yield valuable information.

## 5 REFERENCES

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