# Evaluation of Effective Carrier Lifetime of CdTe Solar Cells Using Transient Photovoltage Decay Measurements

Vincent Tsai*, George Koutsourakis, Martin Bliss, Thomas R. Betts, Ralph Gottschalg
Centre for Renewable Energy Systems Technology (CREST), Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK
* Corresponding Author v.tsai@lboro.ac.uk

## Abstract
A transient photovoltage decay (TPVD) measurement system is currently being developed at CREST and measurements were conducted on several CdTe solar cells. The extracted effective carrier lifetimes were around 100ns. The effect of external illumination biasing was investigated and was found to reduce the effect of junction capacitance and saturate trap states in the devices. This resulted in shorter extracted effective carrier lifetimes. Increasing the illumination of the pulsed-laser intensity also increased the effective carrier lifetime.

## Introduction
The carrier lifetime of solar cells is an important parameter as it is influenced by material quality and subsequently affects overall efficiency of photovoltaic (PV) devices. Therefore, measurement methods to extract its value are necessary for developing high efficiency PV devices. Usually time resolved photoluminescence systems are used for such measurements [1]. One alternative and not so well established characterisation technique for this purpose is transient photovoltage decay (TPVD).
During TPVD measurements, the PV device is contacted and connected directly to an oscilloscope. Excess minority carriers are created in the junction of the PV device using pulsed optical excitation, usually using a laser source. Each pulse creates excess carriers and thus generates a photovoltage. The subsequent voltage decay is measured as a function of time and the effective minority carrier lifetime can be extracted [2].
TPVD carrier lifetime values are affected by different physical processes in solar cells. They are mainly influenced by the recombination processes (radiative, non-radiative Shockley-Read-Hall (SRH) and Auger) but they are also affected by other factors, such as device junction capacitance, recombination current in the space-charge region, series and shunt resistances, or capacitance of the measurement system [3][4]. Furthermore, TPVD is strongly affected by the injection levels set by the measurement conditions [5].
In this work, TPVD measurements are conducted on several CdTe solar cell samples. The effect on the variability in measurements by averaging will be examined. Furthermore, the effect on the carrier lifetime by applying external biasing and different laser intensities are investigated. It is demonstrated that TPVD measurements are straightforward to implement and have the potential to provide a cost effective way to measure the effective carrier lifetime of solar cells.

## System Setup and Methodology
A TPVD measurement system is being developed at CREST and is currently being tested. Figure 1 shows the experimental setup schematic. The transient photovoltage is stimulated by a 640nm picosecond pulsed laser head. The laser intensity and pulse frequency are controlled by a laser driver. For frequencies <2.5MHz, the laser driver is triggered by a function generator. The size of the collimated output beam was 1.5 × 3.5mm$^2$ and was linearly polarised by collimation optics in the laser head. The sample is contacted by Kelvin probes which are connected to the sampling channel of an 11GHz digital sampling oscilloscope with a 50Ω input impedance via a matching SMA coaxial cable. The output synchronisation signal of the laser driver is connected to the trigger channel of the oscilloscope and is used as the external trigger for TPVD measurements. A tungsten halogen lamp was used to provide external biasing to the sample when required.
The oscilloscope was controlled by LabVIEW to automatically conduct multiple measurements and extract the decay time of the photovoltage decay. The resulting decay curves were fitted by the following single exponential decay function from which the effective carrier lifetime can be obtained [6]:

$$V(t) = A \times \exp(-t/\tau) + V$$

Where $A$ is the initial peak value, $\tau$ is the extracted effective carrier lifetime and $V$ is the voltage offset.

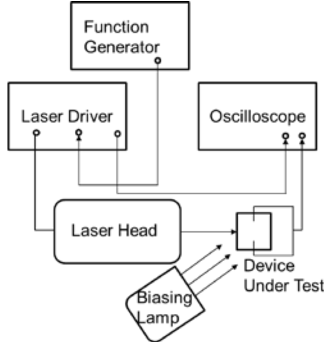


*Figure 1 Experimental setup schematic*

## Measurement Variability

Initial TPVD measurements were conducted on a Cadmium Telluride (CdTe) sample. The laser repetition rate was set to 1MHz and the maximum laser power was ~0.3mW.

Figure 2 shows the resulting TPVD curves of the CdTe cell from a single measurement and for an average of 100 measurements at both maximum intensity (denoted as I10) and half intensity (denoted as I5). The decay curves follow a similar trend; there is an initial rapid charging-up of voltage followed by a slower exponentially decay process. The exponential decay indicates the low-injection condition where the excess minority concentration is less than the equilibrium value [5]. From Figure 2, it can be observed that increasing the number of readings for each point increases the signal-to-noise ratio (SNR) of the measured decay curves, which is particularly useful at lower laser intensities (I5) where the measured decay curves are noisier.

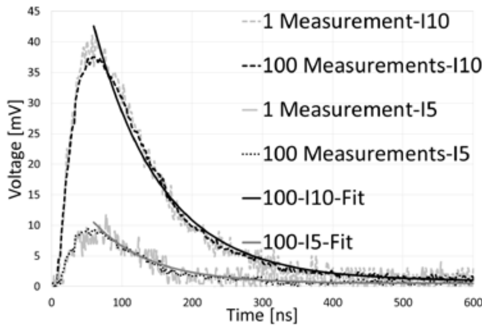


*Figure 2 TPVD curves of the CdTe cell measured under 640nm wavelength, 1MHz frequency, laser at maximum (I10) and half intensity (I5), unbiased and at room temperature.*

For this particular cell, the fitted values for $\tau$ were found to be in the range of 96-110ns which is within the expected ns regime for CdTe carrier lifetime [1][7]. The values of $\tau$ from a single reading can fluctuate by ~15% due to the low SNR of the decay curve. Averaging multiple measurements increased the SNR significantly and reduced the fluctuation of the results as shown in Figure 3.

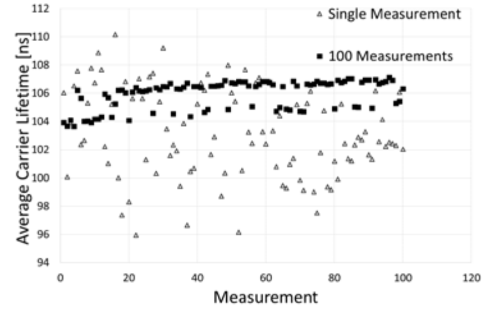


*Figure 3 Fluctuation of carrier lifetime for single measurements versus an average of 100 measurements*

## Further Measurements

Further TPVD measurements were conducted on two CdTe cells (denoted as C2 and D2) fabricated at CREST. CdS was deposited on 50×50mm$^2$ substrates using a sono-chemical bath resulting in ~200nm thick films. CdTe was deposited by a close-space sublimation resulting in 4-6μm thick films. Devices were finished by depositing ~80nm of gold to act as the back contact.

The laser setting was the same as the previous test. The aim of the measurements was to connect different device parameters with effective carrier lifetime values. Furthermore, the effects of applying external DC biasing as well as altering the laser intensity were studied. The cells' parameters, extracted carrier lifetimes at maximum laser intensity and IV curves are shown in Table 1 and Figure 4, respectively.

The effect of using external DC biasing was investigated by illuminating the entire device with a tungsten halogen lamp. For both cells, biased and unbiased measurements were conducted at the same laser excitation spot. It was found that under bias lighting, a shorter effective carrier lifetime is extracted than when no bias is applied. This is because without the bias illumination, the decay curves are dominated by junction capacitance effects and trap energy level capture effects [6]. This will result in longer measured photovoltage decay times and thus overestimate the extracted effective carrier lifetime [8]. The bias light saturates trap states and minimises the effects of junction capacitance, resulting in shorter measured lifetimes.

| CELL | C2 | D2 |
|---|---|---|
| $V_{oc}$ (V) | 0.58 | 0.54 |
| $I_{sc}$ (mA) | 3.37 | 5.56 |
| $R_s$ (Ω) | 0.025 | 0.041 |
| $R_{sh}$ (kΩ) | 12.94 | 4.87 |
| FF | 0.566 | 0.546 |
| η (%) | 4.42 | 6.5 |
| $\tau_{bias}$ (ns) | 73.1 | 88.19 |
| $\tau_{nobias}$ (ns) | 110.59 | 136.92 |

*Table 1 Device parameters and extracted carrier lifetime of CdTe C2 and D2 cells*

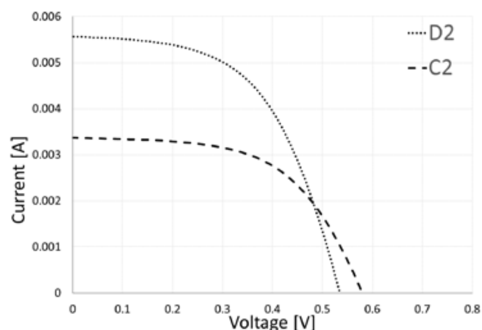

*Figure 4 IV curves of CdTe C2 and D2 cells*

It was observed for both biased and unbiased measurements that the higher efficiency cell D2 had a longer effective carrier lifetime than the less efficient cell C2 in both cases, with and without bias light application. Although C2 has a higher open circuit voltage ($V_{OC}$) than D2, it has a lower short circuit current ($I_{SC}$) as shown in the IV curves in Figure 4. This effect is also observed in the TPVD curves in Figure 5 where C2 is excited to a higher peak voltage than D2, but it decays faster. This is because the $I_{SC}$ is affected by the charge collection efficiency of the device which also depends on the minority carrier lifetime. The lifetime determines if electrons which travel across the CdTe device are able to reach the p-n junction [9].
It should also be noted that due to the 50Ω input impedance of the oscilloscope, the cell is operating nearer to short circuit conditions. This can be seen from the peak voltages from the TPVD curves in Figure 5 and the corresponding current in the IV curves in Figure 4. The extracted carrier lifetime nearer short circuit conditions tend to occur at a faster timescale than nearer to open circuit conditions. This is because charge collection effects are more dominant in the decay curves which is a faster process than recombination [10].

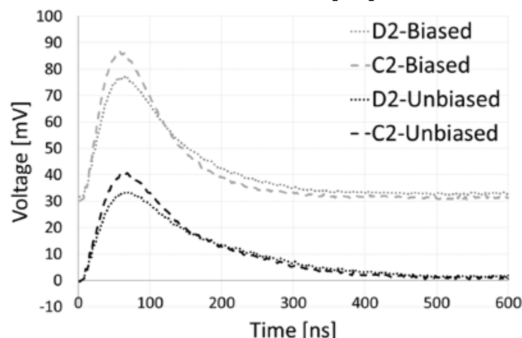

*Figure 5 TPVD curves of CdTe samples under bias and no bias at maximum laser intensity*

For both cells, different laser intensities were used to examine the relationship between extracted carrier lifetime and excitation laser intensity. The results are presented in Figure 6. The relative intensity of the figure is represented as 10 being the highest and 4 being the lowest. For each intensity level, an average of 1000 measurements were acquired.
Figure 6 shows that the measured effective carrier lifetime increases with the laser intensity. At the lowest laser intensity (4) the extracted carrier lifetime value is similar for both cells when biased or unbiased. The curves are noisier and junction capacitance effects are more dominant than recombination and charge collection. However as the intensity increases, the extracted value begins to reflect the underlying recombination and collection effect in the cells.

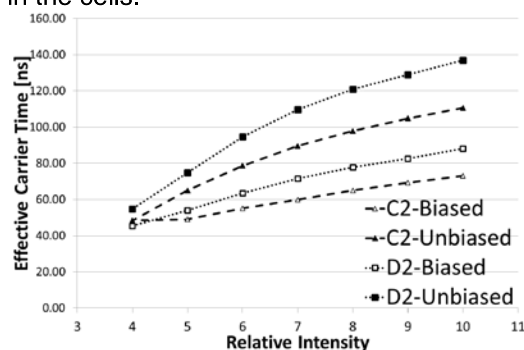

*Figure 6 Comparison between cells C2 and D2 changing laser intensity and effect of external biasing*

## Design Considerations

As TPVD measurements are conducted under very fast time scales (pico to nanoseconds), it is important to ensure that the acquired signal is as accurate as possible. Factors such as cable lengths and low frequency response of components can introduce delays and distort the acquired measurement signal.
As the pulse width of the laser is ~92ps, one would expect an almost instantaneous charge up in the voltage of the cell after a single laser excitation pulse. However, Figures 2 and 5 show that the peak voltage was reached after ~50ns. It was identified that the Kelvin probes introduced delays into the signal. As a result, TPVD measurements were conducted on another CdTe cell (denoted as D1) by altering the probes for each measurement.
The original coupling consisted of a component which connected the probes to a BNC to free end Pomona test lead. The two probes had two pins each and one was lifted up so only two pins contacted the sample rather than four (denoted Is and Vs Probes Single and 2 Single Probes no coupling). BNC to free end only used the test lead to contact the sample directly with no Kelvin probes. The results are presented in Figure 7. The measurement conditions were the same as the previous measurements.
It was observed that there was a delay in reaching the peak voltage of around 10-20ns

between the original coupling and BNC to free end only. The extracted carrier lifetimes for Original Coupling and BNC to Free End only were 101ns and 128ns, respectively. The extracted carrier lifetimes for the other probe settings were all ~117ns. Therefore, the probes only had a minor influence on the extracted charge carrier lifetimes. Further investigation is required to identify major sources of delay such as cable length, and improve the response time of the sample signal pick-up.

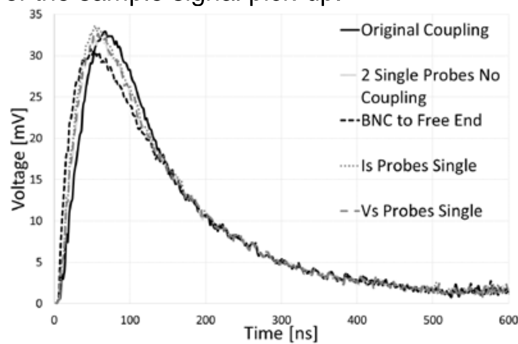


*Figure 7 TPVD measurements on CdTe cell D1 using different probe setups*

## Summary and Future Work

This TPVD measurement system has demonstrated the relatively straightforward and cost-effective setup to measure the effective carrier lifetime of CdTe solar cells. It was found that the extracted carrier lifetimes were in the expected timescales of nanoseconds which demonstrated the feasibility of this method. The use of external biasing reduced the effect of junction capacitance and saturated trap states resulting in shorter carrier lifetimes. Furthermore, certain components in the measurement system limited the response time of the measurements. Future work will involve finalising the measurement setup and improving the response time of the sample signal pick-up.

## References


[1] W. Metzger, R. Ahrenkiel, and P. Dippo, “Time-resolved photoluminescence and photovoltaics,” in *Department of Energy Solar Energy Technologies Program Review Meeting*, 2004, vol. 1, no. January, pp. 1–2.

[2] U. Stutenbaeumer and E. Lewetegn, “Comparison of minority carrier diffusion length measurements in silicon solar cells by the photo-induced open-circuit voltage decay (OCVD) with different excitation sources,” *Renew. Energy*, vol. 20, no. 1, pp. 65–74, 2000.

[3] M. A. Green, “Solar Cell Minority Carrier Lifetime Using OCVD,” *Sol. Cells*, vol. 11, pp. 147–161, 1984.

[4] K. Price, C. Lacy, and D. P. Hunley, “Photovoltage Decay in Cdte / Cds Solar Cells,” in *Photovoltaic Energy Conversion, Conference Record of the 2006 IEEE 4th World Conference*, 2006, pp. 436–437.

[5] J. E. Mahan, T. W. Ekstedt, R. I. Frank, and R. Kaplow, “Measurement of minority carrier lifetime in solar cells from photo-induced open-circuit voltage decay,” *IEEE Trans. Electron Devices*, vol. 26, no. 5, 1979.

[6] H. Cui, J. Wang, C. Wang, C. Liu, K. Pi, X. Li, Y. Xu, and Z. Tang, “Experimental Determination of Effective Minority Carrier Lifetime in HgCdTe Photovoltaic Detectors Using Optical and Electrical Methods,” *Adv. Condens. Matter Phys.*, vol. 2015, pp. 1–6, 2015.

[7] V. Buschmann, H. Hempel, A. Knigge, C. Kraft, M. Roczen, M. Weyers, T. Siebert, and F. Koberling, “Characterization of semiconductor devices and wafer materials via sub-nanosecond time-correlated single-photon counting,” *J. Appl. Spectrosc.*, vol. 80, no. 3, pp. 449–457, 2013.

[8] T. Pisarkiewicz, T. Stapiñski, and P. Wójcik, “Influence of junction parameters on the open circuit voltage decay in solar cells,” *Sci. Technol.*, vol. 12, no. 1, pp. 79–83, 2004.

[9] A. Cuevas and D. Macdonald, “Measuring and interpreting the lifetime of silicon wafers,” *Sol. Energy*, vol. 76, no. 1–3, pp. 255–262, 2004.

[10] S. Wood, D. O. Connor, C. W. Jones, J. D. Claverley, J. C. Blakesley, C. Giusca, and F. A. Castro, “Solar Energy Materials & Solar Cells Transient photocurrent and photovoltage mapping for characterisation of defects in organic photovoltaics,” *Sol. Energy Mater. Sol. Cells*, vol. 161, no. November 2016, pp. 89–95, 2017.