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Constant voltage I–V curve flash tester for solar cells

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Abstract

Flash testers are commonly used for measuring solar cells and modules but in their usual implementation are complex, expensive, and susceptible to transient errors. This work presents a new tester design that is simple, low cost, and reduces transient errors by use of a constant-voltage cell-bias circuit. A novel feature of the system is that it extracts a family of $I-V$ curves over a decade range of light intensity, which provides comprehensive information on cell performance. The new design has been tested and used extensively.

Keywords: Concentrator cell characterisation; Flash tester; I–V curve; Transient error

1. Introduction

Flash testers have been used for solar cell measurement for at least 30 years. Their primary advantages over continuous illumination testers are that they can provide high light intensity with good uniformity over large areas, and that the brief pulse of light causes little heating of the cell, which is essential when testing concentrator cells that have not been bonded to a heatsink.

A variety of flash tester designs have been tried in the past, both for 1-sun and concentrator cell testing. Some have been documented in the literature [1–6] and several commercial systems are available for 1-sun testing, but none are made specifically for concentrator cells.

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Flash testers can be categorised as single flash or multi-flash. The majority of commercial systems are single flash. These systems produce a light pulse that has a plateau of constant light intensity lasting a few milliseconds and the entire $I-V$ curve is traced out in this time. This is expensive to implement, as the flashes used typically have peak power outputs of tens of kilowatts or more, and building circuitry to regulate power flows of this magnitude is not easy. Single flash testers also require a high-speed electronic load for the cell, to sweep out the $I-V$ curve in a few milliseconds. Finally, the high-speed sweep of the $I-V$ curve can lead to transient errors, particularly with high-efficiency cells. Multi-flash systems, as the name implies, use many flashes to build up the $I-V$ curve, taking only a single $I-V$ point with each flash. They have the potential to be simpler and cheaper than the single flash systems, as neither the regulated flash nor the high-speed load is required. They also have the potential to reduce transient errors. In addition to these issues, all commercial flash testers are expensive—a recent survey of commercial solar simulators [7] quotes prices of US\$60 000 to US\$270 000.

In view of the issues described above, we decided to build an alternative flash tester for concentrator cells as part of the PV/Trough concentrator project (http://solar.anu.edu.au) at the ANU Centre for Sustainable Energy Systems. The resulting design, described in this paper, is a low-cost tester suitable for medium concentration (up to 100 suns). To minimise transient errors, the cell bias circuitry maintains the cell at constant voltage during each flash. To reduce the complexity of the flash, the system is a multi-flash design. This allows the use of a low-cost commercial flash (a powerful disco strobe). The multi-flash design also allows a new feature—the gradual change of light intensity during each flash can be used to extract a family of $I-V$ curves, each one measured at a different light intensity.

In operation, a bias voltage is applied to the cell and sufficient time is allowed for the device to stabilise. The flash is then triggered and the light intensity, cell current, and cell voltage are measured repeatedly for the duration of the flash. Then, one $I-V$ point is extracted for each light intensity at which an $I-V$ curve is being generated. This process is repeated for different bias voltages, during subsequent flashes, to measure the entire set of $I-V$ curves. The process is illustrated in Fig. 1.

The family of $I-V$ curves can be used to examine how cell behaviour varies with light intensity. This is very useful, both for concentrator and 1-sun cells. For the system described in this work, $I-V$ curves can be obtained over a decade range of light intensity. Compared with a conventional tester that measures a single $I-V$ curve, this system provides more comprehensive information about cell behaviour, allowing more accurate modelling of the cell. For example:

- At high light intensity series resistance has a large effect on the $I-V$ curve and shunt resistance has little effect. At low light intensity, the reverse is true. Having data at high and low light intensities allows both series and shunt resistance to be estimated more accurately.
- The dominant recombination mechanism in a solar cell varies with illumination level, and is reflected in the ideality factor, n. Having measurements of n over a

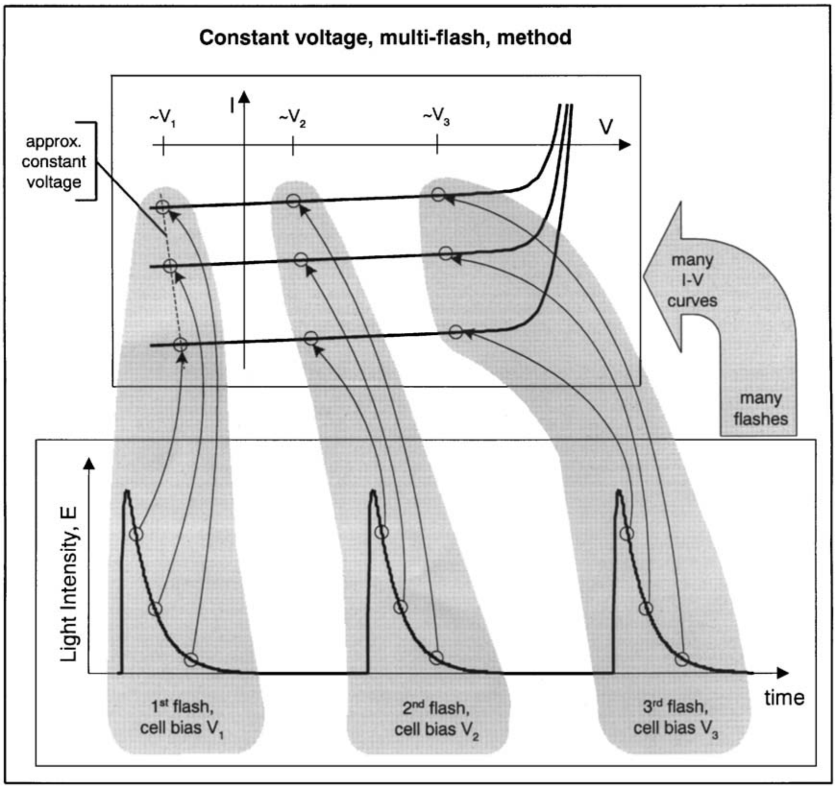

Fig. 1. Operating principle of the constant-voltage, multi-flash design.

range of light intensities therefore allows recombination processes to be characterised better.

- In cell design, the thickness of front surface metallisation is a trade-off between shading the cell and maintaining sufficiently low series resistance. By observing the light intensity at which maximum FF occurs it is possible to optimise front surface metallisation.
- In real-world applications, cells operate under varying light intensity (usually lower than the light intensity under standard testing conditions). Having data for the cell over its full operating range allows performance in the field to be predicted more accurately.

2. Analysis of transient errors during flash testing

To get accurate measurements of a cell's $I-V$ curve it is essential for the cell to be in quasi-steady state. With flash testers this is difficult to guarantee, so measurement errors often occur due to transient effects. Similar problems can also occur with continuous illumination testers if the $I-V$ curve is swept out too rapidly.

Transient errors are caused by rapid changes of the charge distribution in the cell. Minority carrier concentrations are much higher in forward bias than at short circuit, so large amounts of charge have to be moved when changing bias condition. Under illumination, there are two current sources that can rearrange charge—current generated by the light source and current from the external circuit. If the bias voltage is rapidly increased (sweeping from I_{sc} towards V_{oc}), carrier concentrations have to be raised. Excess electrons are added to the p region, and holes to the n region. This charge rearrangement will consume some of the photocurrent, reducing the measured external current. Consequently, FF and V_{oc} will be underestimated. Alternatively, if the bias voltage is rapidly decreased (sweeping from V_{oc} towards I_{sc}) carrier concentrations have to be lowered. This charge rearrangement will add to the photocurrent, giving an exaggerated FF and V_{oc}. The two effects give the well-known curve-splitting phenomenon [9].

The magnitude of transient errors depends on the amount of excess charge stored in the cell. The amount of excess charge is largest for high bias voltages, in lightly doped material, and with low recombination (in cells with diffusion lengths longer than the wafer thickness, thickness becomes a limiting factor rather than lifetime). All of these factors suggest that the largest transient errors will occur when measuring excellent cells made on high resistivity wafers and at high bias voltage. Experimental observations confirm that these cells are indeed problematic.

Transient errors due to rapid bias changes have been well studied. King [9] found that FF errors became noticeable ($>1\%$) when bias rate exceeded 100 V/s for low resistivity cells ($1\,\Omega\,$cm) and 20V/s for high resistivity cells ($200\,\Omega\,$cm). Given that sweeping the full $I-V$ curve of a typical cell requires a voltage change of about 1 V, it is clear that as much as 50 ms may be required to avoid transient errors. This is much longer than the few millisecond pulse lengths of most flashes.

What can be done about transient errors? For single-flash testers, the only solution is to make the flash pulse last longer. But this option may be limited by the maximum pulse energy the flash tube can handle. Alternatively, it is possible to correct for the errors, either through estimating the capacitance of the cell and recalculating the curve without it [6], or through dark $I-V$ measurements [10]. It is preferable though to measure the true curve directly. For multi-flash systems, the situation is potentially much better. Since the major cause of transient error is rapid change in the bias voltage, it should be possible to greatly reduce the error by holding the voltage constant during each flash and changing it slowly between flashes. This is the approach taken in this work. Not all multi-flash systems use constant voltage though—one of the commercial multi-flash systems [4] maintains constant *current*, causing a full sweep from I_{sc} to V_{oc}, in <1 ms, with every flash. As might be expected, this system suffers from serious transient problems.

Even for constant-voltage systems, there will always be some voltage change in practice due to internal series resistance in the cell. The change will be tolerable provided the cell is operating in the region of, or below, its design concentration. Under these conditions the internal voltage drops will be tens of mV or less. For typical flash rise/fall times in the range of milliseconds, this will give a rate of change of cell voltage of less than 10 V/s, which should not cause transient errors.

Maintaining a cell at constant voltage reduces transient errors, but does not eliminate them entirely. There is still the question of how rapidly the cell current responds to changes in light intensity. This issue has not been examined in detail in the literature, but a paper by Metzdorf [10] states that when bias voltage was held constant cell current tracked light intensity with no observable distortion, for a flash with a rise/fall time of approximately 1 ms.

The question of how quickly cell current responds to changes in light intensity was explored in this work by simulating, with PC1D [11], some typical real world cells and some projected worst-case possibilities. PC1D was used to estimate the time for cell current to reach steady state in response to an abrupt change in light intensity, while at constant voltage. Two light intensities were used, 1-sun, and 100-sun, and both dark-to-light and light-to-dark transitions were investigated. Cell voltages near short circuit, maximum power, and open circuit were used. The cells simulated are shown in Table 1. These five cells cover the range of important factors affecting the amount of excess charge stored in the cell—cell thickness, minority carrier lifetime in the bulk, background doping levels, and surface recombination rates. The cell response time was taken to be t_{99}, the time for cell current to reach 99% of the steady-state value.

The results shown in the right-hand column of Table 1 are the maximum t_{99} values for each cell. These results show that, for realistic cells, the response time is always less than a few hundred microseconds. Provided the flash rise/fall time is greater than this, there will be no transient errors in the current measurement. Most flashes have rise/fall times of milliseconds, so easily satisfy this requirement. In addition, the light-to-dark and dark-to-light times for each cell were similar (within a factor of 2) so measurements on the rising and the falling edges of a flash pulse should be equivalent. The measurements at 1-sun vs 100-sun for each cell were also roughly similar (within a factor of 5), so no distinction needs to be drawn between 1-sun and concentrator measurements.

In conclusion, these simulation results show that for typical flash rise/fall times of several milliseconds, a cell maintained at constant voltage will be in quasi-steady state and no significant error will appear in the current measurement. This shows that a constant voltage bias circuit can eliminate transient errors when flash testing.

Table 1
Construction parameters for the cells used to estimate current response time and a summary of simulation results, shown in the last column

Cell type	S_R, S_F (cm/s)	τ (ms)	ρ (Ω cm)	Thick (μm)	t_{99} (μs)
Typical commercial 1 sun	10^5	0.1	1	500	<90
Excellent low resistivity (e.g. ANU concentrator cell)	1000	1	1	500	<50
Excellent high resistivity (e.g. SunPower cell)	1000	1	200	200	<160
Worst-case low resistivity	100	10	1	1000	<700
Worst-case high resistivity	100	10	2000	1000	<1000

3. System components

The components of the flash tester system are shown in Fig. 2. The hardware required to implement the design is cheap and simple since most of the complexity is in a commercial data acquisition card. The components of the system are described in detail in the following sections. Further information is available in the first author's Ph.D. Thesis [8], which can be obtained on the web.

3.1. Constant voltage cell bias circuit

The majority of modern flash testers use active circuitry to bias the cell, allowing precise control of the tracing of the $I-V$ curve. However, the design of an active load to control solar cells is not trivial. It has to control large currents (tens of amps at least) with many kHz bandwidth, and remain stable for any cell under any bias condition. Not all commercial systems succeed—Mantingh [12] reports that the bias circuits for the JPL-LAPSS and Pasan flash testers have stability problems with some cells.

In view of potential design problems with active loads, it was decided in this work to use a semi-passive load. The resulting design, shown in Fig. 2, consists of a large capacitor ($\sim 1\,\mathrm{F}$), which is connected directly across the cell, and a low speed four-quadrant power amplifier. During the flash, the capacitor operates as a passive load, maintaining a nearly constant voltage across the cell. The capacitor is sufficiently large that charging from the cell current is minimal. Between flashes, the amplifier

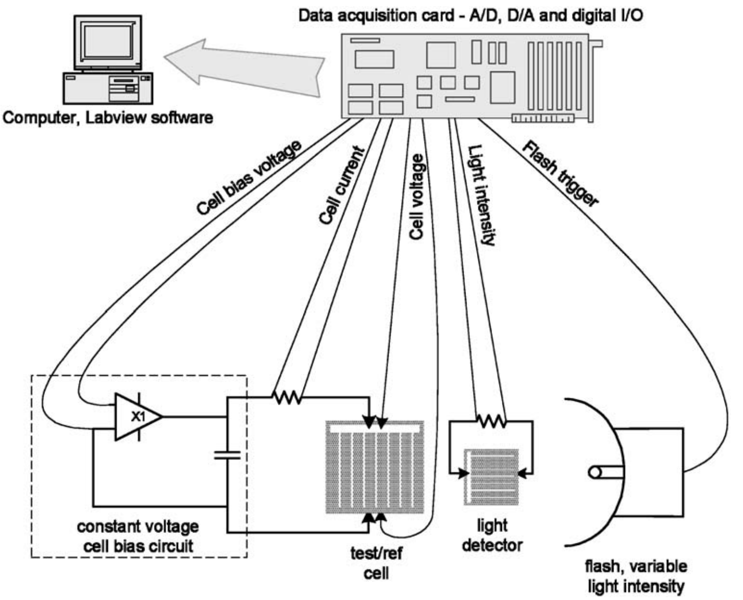

Fig. 2. Block diagram of the constant voltage flash tester.

changes the bias voltage on the cell and capacitor. Since the capacitor handles the high-speed transients, the amplifier can be relatively low speed. This makes the amplifier cheaper, and makes it easier to guarantee stability. The amplifier consists of an LM12 power op-amp operating as a unity-gain buffer.

The capacitive load has proved to be stable and works well, but has one limitation—series resistance in the circuit prevents it from regulating the voltage perfectly. Series resistance comes from internal resistance in the capacitor, the current sensing resistor, wiring resistance, and the contacts to the cell. Owing to this series resistance, the cell voltage changes with varying cell current (due to changing light intensity) and this may lead to transient errors. Higher currents and more rapid changes of light intensity cause larger $\mathrm{d}V/\mathrm{d}t$. Analysis of the circuit shows that, on the rising edge of the flash pulse (light getting brighter), cell voltage is moving from I_{sc} towards V_{oc}. If $I-V$ points are taken in this period, FF and V_{oc} will be underestimated. Conversely, if $I-V$ points are taken on the falling slope of the flash pulse, cell voltage will be moving from V_{oc} towards I_{sc}, and FF and V_{oc} will be overestimated.

Some transient errors were observed during the development of the system. Investigation of these errors suggested that they were due to the bias circuit allowing the voltage to change excessively. To confirm this, measurements from the rising and falling edges of a symmetrical flash pulse were compared. As predicted above, the FF was under-estimated on the rising slope and exaggerated on the falling slope. The difference was about 5% at worst. Then the cell was masked down to $\frac{1}{10\text{th}}$ area, reducing the current and hence the rate of change of voltage to $\frac{1}{10\text{th}}$, but leaving the rate of change of light intensity unchanged. This eliminated the FF error, confirming that the FF error was indeed due to the rate of change of voltage, not the rate of change of light intensity.

There are two potential ways to resolve the problem of these transient errors: reduce the rate of change of light intensity, or improve the load's ability to hold the voltage constant. We chose the former option, by building a capacitor bank to drive the flash. This provided variable flash decay times of up to 50 ms, assisting the investigation of the transient errors. Analysis of the transient error problem, described in the previous section, demonstrates that the capacitor bank is actually not necessary providing cell voltage is held constant. Under these conditions the internal flash pulse is slow enough to avoid transient errors. For future systems, improving the load circuitry may be less costly than building a capacitor bank.

An estimate of the maximum tolerable $\mathrm{d}V/\mathrm{d}t$ is needed to improve the load circuitry. This was determined by measuring the error in FF as a function of $\mathrm{d}V/\mathrm{d}t$, which was varied by changing the flash decay time and adding resistance to the load circuit. The measurement showed that for an excellent ANU concentrator cell (at 30-suns, $V_{oc} = 755\,\mathrm{mV}$, $J_{sc} = 1.06\,\mathrm{A/cm^2}$, $\eta = 21\%$) made on a $1\,\Omega\,\mathrm{cm}$ wafer FF error became noticeable ($>1\%$) when $\mathrm{d}V/\mathrm{d}t$ exceeded 100 V/s, similar to the result found by King [9].

The rise/fall time of the flash when running from its internal supply (no external capacitor bank) is about 1 ms. With a limit of 100 V/s on $\mathrm{d}V/\mathrm{d}t$, this means that $\mathrm{d}V$ must be $<0.1\,\mathrm{V}$. The capacitive load, as it exists, has a series resistance of about

$20\,\mathrm{m}\,\Omega$, so the maximum cell current that can be measured without risk of transient errors is about 5 A. To increase the current that can be measured, the series resistance in the load circuit should be reduced. This could be done by using a bank of capacitors rather than one and connecting them with much shorter, thicker wires. A series resistance of a few milliohms should be achievable, allowing cell currents of tens of amps. However, it could become a mechanical design challenge and it may be better to invest the effort building an active load that pins the voltage precisely via feedback control.

3.2. Flash

The flash used in this system is a commercial disco strobe (Geni Megastrobe), costing about US$300. It uses a Phillips XOP linear xenon discharge tube. The spectrum of the flash is only known approximately from information in the manufacturers data sheet as it is very difficult to measure the spectrum of a transient light source like a flash. The spectrum shown in the data sheet meets ASTM Class C requirements [13] for a solar simulator. In general terms it is deficient in the blue and has too much IR. The spectrum will therefore be closest to the AM1.5 G standard at the peak of the flash, when the xenon plasma is hottest. Experiments have shown that the spectrum is quite adequate for routine measurement of silicon cells—measurements on the full range of ANU concentrator cells showed that spectral mismatch is less than 1.7% for any of these cells.

A major feature of the new flash tester design presented here is its ability to easily extract $I-V$ curves for a range of light intensities as the flash turns off. The spectrum of the lamp does not remain constant—as it dims it becomes slightly redder. This complicates the measurement as it introduces a changing spectral mismatch at the same time as a changing light intensity. The most obvious consequence is an apparent non-linearity of short circuit current with light intensity (for the ANU concentrator cells a few per cent at worst over a decade range of light intensity). The light detector calibration, described later, compensates for this spectral change, but requires that the change in the spectrum be repeatable from flash to flash. To test the repeatability, an experiment was performed to measure the effect of spectrum changes as the flash heated up. The change was insignificant—even when the flash was run so hard that it smelled bad and was too hot to touch, the measured cell current changed by $<0.2\%$. The varying spectrum does mean that the family of $I-V$ curves cannot be used to determine I_{sc} linearity as it is impossible to distinguish true non-linearity from apparent non-linearity caused by spectral mismatch.

The flash used in this work has good uniformity of illumination over the test area—at 30 suns, $\pm 5\%$ (ASTM class B) over an area of $\sim 15 \times 15\,\mathrm{cm}$, and $\pm 2\%$ over $10 \times 10\,\mathrm{cm}$. A peak light intensity of up to 100 suns can be achieved. It can also be used for 1-sun measurements by inserting a neutral density filter or placing the flash approximately 2m away from the cell. Flash uniformity, as supplied, was poor ($\pm 15\%$) but was improved by placing a diffuse white surface over the polished metal reflector behind the lamp. The uniformity of the flash was measured by moving a

1.5 cm square cell around the test area while firing the flash. A second, stationary, cell was used to correct for flash-to-flash variations.

The shape of the flash pulse, when running on its internal supply, is a $\frac{1}{2}$ sine wave with total duration of 10 ms. The symmetry of the rising and falling edges allows measurements to be taken on both slopes, which is useful for detecting transient errors. When running on the external supply, the shape of the flash pulse is an exponential decay (the shape shown in Fig. 1).

The heating effect of the flash at 30 suns peak intensity and maximum repetition rate is equivalent to approximately 0.5 suns continuous. The bias circuit limits the flash rate to well below this, so cell heating due to the flash will be minimal.

3.3. Cell testing block

The cell-testing block performs several functions. It makes electrical contact to the cell, controls the temperature of the cell, and ensures that its physical position is repeatable. The block consists of a temperature controlled aluminium plate with electrical contacts along the edge. To simulate the final tabbing arrangement of the cell as closely as possible, flexible metal contact finger-strips are used along the whole busbar. Contacts are made to the top and bottom of the cell (the block is not used as a contact). A 4-point contact scheme is used, with the voltage sense fingers in the middle of the current contact fingers to minimise FF exaggeration. The cell is held onto the plate by vacuum.

The temperature of the plate is controlled by a thermoelectric cooler (Peltier device) and an auto-tuning PID process controller. This is smaller, lighter, and cheaper than commonly used water chiller/heaters. The temperature can be changed quickly to any value in the range 0–70°C. Temperature regulation, including controller error and heating due to the flash, is ± 3°C.

3.4. Light detector

The light detector is used to measure the light intensity during each flash. It does not need to be particularly well matched to the test cell, or in the uniformly illuminated area, because it is calibrated before the measurement against a reference cell. The reference cell is then swapped for the test cell, and the test cell is measured. Provided the reference cell is similar to the test cell in size and spectral response, the calibration procedure will cancel both spatial non-uniformity in the light and spectral mismatch between the light detector and the reference cell.

The light detector calibration is effectively a mapping between the voltage measured on the light detector and the light intensity seen by the reference cell. To determine the calibration, the 'true' I_{sc} vs. light intensity characteristic for the reference cell must be known in advance. This can be determined either by measuring it with another more accurate technique or by assuming that I_{sc} is proportional to light intensity and scaling from an accurate 1-sun measurement. To calibrate the light detector, the reference cell is measured on the flash tester using a first estimate of the light detector calibration. $I-V$ curves are obtained for about 100 different light intensities. This provides, for each apparent light intensity (i.e. each $I-V$ curve), a light detector voltage corresponding to the apparent light intensity, and I_{sc} for the reference cell at the apparent light intensity. The true characteristic of the reference cell can then be used to find the true light intensity corresponding to the apparent light intensity. The new point in the calibration then maps the light detector voltage to the true light intensity. Once all $I-V$ curves are processed, the light detector calibration is complete.

As described earlier, the spectrum of the flash varies with intensity. The light detector calibration process will cancel the effect of this change if the test and reference cells have similar spectral responses. If the test and reference cells have significantly different spectral responses, then the spectrum change will not be calibrated out and will lead to a spectral mismatch that varies with light intensity. This will manifest as an apparent non-linearity of I_{sc} with light intensity for the test cell. For ANU concentrator cells, the greatest non-linearity observed is a few percent. So, the appearance of non-linearity in the test results is probably a warning that the reference cell and test cells are not well matched.

It is advisable for the light detector to have a roughly similar spectral response to the test and reference cells. This will make the light detector calibration less sensitive to slight variations in the lamp spectrum. For the system used at ANU, the light detector is a SunPower concentrator cell (http://www.sunpowercorp.com). This is a high efficiency cell with performance similar to the cells produced at ANU.

The reference cells used at ANU are normal production cells that have been calibrated outdoors, using natural sunlight. They are measured at 1-sun illumination and the 30-sun current is then calculated assuming 1% superlinearity of I_{sc} with light intensity. The 1% figure was chosen based on papers [14–16] reporting the linearity of I_{sc} for various types of silicon cell.

3.5. Data acquisition circuitry

The main components of the data acquisition circuitry in the flash tester are a commercial data acquisition card and current sensing resistors.

The data acquisition card, a 12 bit 1.25 MSa/s multipurpose card (National Instruments MIO16E1), performs several functions:

- It measures the cell current, cell voltage and light intensity: 12 bit analog inputs (adequate to measure $I-V$ curves over a decade range of light intensity).
- It generates the bias voltage to be applied to the cell: 12 bit analogue output.
- It triggers the flash: digital output.

The data acquisition card does not measure each input simultaneously. It has only one A/D converter, so the inputs are measured sequentially. At low sampling rates this signal interleaving can introduce some error. During prototyping of the system, using an 80 kSa/s card, interleaving was found to be a problem. It was initially resolved by interpolating the signals (in software) to determine the truly simultaneous values. Later, the 1.25 MSa/s card was purchased, eliminating the need for the interpolation. Comparison of the measurements showed that the interpolation worked adequately and the high-speed card was unnecessary. Data is acquired at the maximum rate possible and digitally low-pass filtered to eliminate noise above 10 kHz.

The data acquisition card only measures voltages, so sense resistors are used to convert the cell and light detector currents to voltages. To minimise temperature errors, the chosen resistors have a low temperature coefficient and are rated such that their peak power dissipation during the brief flash is less than their continuous rating. Inductive voltage on the sense resistors is a significant concern at the high currents and low voltages used in this system, so non-inductive resistors are used. Their inductance was measured and the inductive voltage at peak dI/dt then calculated. It was found to be $<0.1\%$ of the measured voltage, which is insignificant. The resistors are mounted in easily swapped DB25 connectors, to allow a range of different cells to be tested. To eliminate contact resistance 4-point connections are used in the sense resistors.

The signal wiring in the system uses shielded-twisted-pair cable, and the inputs on the data acquisition card are used in their differential mode to minimise noise pickup. The light detector and cellblock are isolated from earth and each other to avoid ground loops.

3.6. Software

The software for the flash tester was programmed using National Instruments LabVIEW, a high-level instrumentation programming language that provides excellent support for data acquisition, processing, and display. At the start of a test a set-up screen allows the user to specify the light intensities at which $I-V$ curves are desired and the bias voltage range. The flash can also be fired to check the peak light intensity and to check that the cell connections are good.

The measurement then starts. For each flash, the bias voltage is set, the flash is fired, and the cell current, cell voltage, and light detector voltage are measured rapidly for the duration of the flash. The data is then digitally filtered to get rid of high-frequency noise, and the light detector calibration is used to convert light detector voltage to light intensity. Finally, the $I-V$ point extraction occurs. For each $I-V$ curve to be generated the software determines the time at which the light intensity was the desired value, and then looks up I and V at that time.

Once all the flashes are complete, the family of $I-V$ curves are processed to extract the cell parameters, using standard algorithms. The following parameters are determined as a function of light intensity: I_{sc} (short circuit current), V_{oc} (open circuit voltage), FF (fill-factor), η (efficiency), n (ideality factor), I_0 (saturation current), R_{sh} (shunt resistance) and R_s (series resistance). The $I-V$ curves and parameters are then displayed on the front panel, where notes can be added and the data saved.

4. Experimental verification

The performance of the flash tester was verified by comparison with measurements made using an accurate outdoors technique.

The cells used in the comparison experiment were chosen from ANU concentrator cells produced in the year 2000. The experimental set included a selection of the best cells, the worst cells, some typical cells and some randomly chosen cells. It was not a well-matched group (efficiency values varied between 15% and 22% at 30 suns) so the results for the group should give a useful estimate of measurement accuracy for normal production.

No facility was available to measure the cells independently at 30 suns. Instead, the cells were measured at 1-sun under natural sunlight. The natural sunlight calibration technique paid careful attention to weather conditions to ensure a good match to the AM1.5D standard spectrum [17]. The $I-V$ curves were measured with a capacitive curve tracer, which took ~ 0.5 s to trace from short circuit to open circuit. This was slow enough to be certain that there were no transient errors (a bias rate of a ~ 1 V/s), but at the same time fast enough to ensure that variations in sunlight intensity did not upset the measurement. The same cellblock was used outdoors and under the flash tester, to minimise problems due to contacting differences.

To test the quality of the spectrum, the 30-sun current for each cell was calculated from the 1-sun current, assuming linear scaling. One of the cells (c156oo) was used as the reference to calibrate the light detector, followed by measurement of the rest of the cells. The results are shown in Table 2. The worst case measurement error for I_{sc} was 1.7%. This shows that the quality of the Geni Megastrobe spectrum is reasonable.

To test the accuracy of FF and V_{oc} measurement, the flash tester was used to make 1-sun measurements that could be directly compared to the outdoors measurements.

Table 2
Results of experimental verification of flash tester

Cell	30X I_{sc} (A)			1X V_{oc} (mV)			1X FF ()		
	outd.	FT	Err (%)	outd.	FT	Err (%)	outd.	FT	Err (%)
c156oo	20.73	Ref cell	Exact	646	649	0.5	0.762	0.764	0.3
c149l	19.21	19.08	−0.7	633	636	0.5	0.790	0.790	0.0
c149ll	19.32	19.12	−1.0	633	637	0.6	0.784	0.784	0.0
c149m	19.27	19.10	−0.9	638	637	−0.2	0.790	0.788	−0.3
c149mm	19.23	19.08	−0.8	635	637	0.3	0.786	0.785	−0.1
c149nn	19.13	19.00	−0.7	634	637	0.5	0.794	0.796	0.3
c154s	19.49	19.50	0.1	549	551	0.4	0.541	0.541	0.0
c155rr	18.95	19.28	1.7	613	624	1.8	0.792	0.793	0.1
c156p	20.25	20.46	1.0	640	647	1.1	0.760	0.763	0.4
c162o	19.77	20.03	1.3	624	635	1.8	0.775	0.777	0.3
c175o	16.73	16.50	−1.4	597	609	2.0	0.784	0.789	0.6
c194ff	18.59	18.55	−0.2	623	631	1.3	0.804	0.805	0.1

The columns labelled 'outd.' are the accurate outdoors measurements, and the columns labelled 'FT' are the flash tester measurements.

To reduce the light intensity from the flash a simple neutral density filter was made by laser printing a fine array of black dots on an overhead transparency. Such a filter should be reasonably neutral since laser printer toner is mostly carbon black. An $I-V$ curve was then taken with the flash tester that had the same I_{sc} as the cell produced outdoors. The FF and V_{oc} of this curve were then compared to the values measured outdoors. The results are shown in Table 2.

FF's measured outdoors and with the flashtester were all within 0.6%, which confirms the accuracy of FF measurement. The $\mathrm{d}V/\mathrm{d}t$ values, due to bias circuit resistance, were <10V/s at the low currents produced by the cells at 1-sun. The accuracy of FF measurement confirms the analysis in the transient error section, which showed that measurements should be free of transient error for $\mathrm{d}V/\mathrm{d}t < 10$ V/s.

The V_{oc} measurements were less accurate then the FF measurements. The largest difference between outdoor and flash tester measurements was 12 mV (2%). Although greater than expected, this result is still acceptable. The temperature control outdoors was not ideal (up to 4°C high) and the V_{oc}'s measured outdoors are lower than the flashtester measurements, so temperature probably accounts for some of the V_{oc} error.

5. Conclusions

This paper describes a constant-voltage flash tester system and demonstrates its successful implementation. The system is less sensitive to transient errors than other flash tester designs since it maintains a nearly constant bias voltage during each flash. The capacitive bias circuit used to implement the constant-voltage concept works well at low currents, below a few amps. However, it is not as effective for higher currents, due to series resistances. The cost of the system is minimised by using a commercial xenon flash instead of an expensive custom-engineered design. This is possible because of the multi-flash, constant voltage design approach. A powerful feature of the system is that it extracts a family of $I-V$ curves over a decade range of light intensity. This provides important additional data on cell performance.

Experimental verification shows that the tester measures I_{sc}, FF, and V_{oc} with sufficient accuracy for routine production testing.

The constant voltage flash tester design has been used extensively. One of these systems is in operation at the Centre for Sustainable Energy Systems, ANU, and has tested tens of thousands of concentrator cells. Another of these systems has been sold to a major solar cell manufacturer.

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