High Concentration (2500 suns), High Throughput, Automated Flash Tester with Calibrated Color Balance and Intensity Control

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ABSTRACT

SolFocus has designed and built a flexible and adaptable solar flash tester capable of reaching in excess of 2500x suns flux using a commercially available Xenon flash and power supply. Using calibrated isotype cells and photodetectors, the intensity and color balance of the flash are controlled through software algorithms that compensate for tube aging and thermal drift. The data acquisition system dynamically normalizes each of the 1600 I-V data pairs to the lamp intensity during each flash. Up to 32 cells can be measured simultaneously, with a flash re-cycle time of 3 seconds. The dynamic current range is 100μA to 10A over 0 to 5V. Test ranges are limited by user input through a modern GUI screen. The system is mated to a commercially available probe station tester which allows automated testing of up to 150mm diameter wafers, and is capable of testing a 4000 cell wafer in less than 8 minutes. The core software and optical components are easily adaptable to receiver and full panel testing as well. Data on the calibration and performance of the flash tester, the dynamic range achieved in test, and throughputs obtained during operation are presented.

Keywords: Solar cell, photovoltaic, concentrating photovoltaic, solar cell wafer testing, flash test

1. INTRODUCTION

High Concentration Photovoltaic (HCPV) power generation has begun to take its place alongside other photovoltaic designs, for example, flat plate silicon, as an economically viable technology [1]. Concentrating photovoltaic (CPV) cells, outgrowths of the high efficiency light weight cells used on spacecraft [2], have now reached 36 to 37% terrestrial power conversion efficiencies in volume production. Further improvements are expected to raise production efficiencies beyond 40% within one or two years [3]. Currently, CPV cells operate at 500 suns or more, at elevated temperatures, and are designed to maximize efficiency when illuminated with an AM1.5D spectrum. These conditions present special challenges to testing these cells in wafer form in a production environment.

The requirements for an accurate tester for these cells are further complicated by the construction of contemporary cells. Available CPV cells contain three sub-cells which divide the solar spectrum into segments, each sub-cell generating nearly equal currents. In particular, these designs carefully match the current in the top and middle sub-cells, with the lower sub-cell producing an excess of current. Consequently, either the top or middle cell may become the current limiting element in the series-connected stack of sub-cells. For accurate testing, the spectrum incident upon the cell under test must generate equal currents in the top and middle sub-cells, even if it does not precisely replicate the AM1.5D spectrum [4]. The cells must also be tested under high concentrations which approximate actual on-sun concentrations during use. Additionally, the tester should offer variable concentrations, a facility for maintaining accurate spectral balance, and the ability to heat the cell under test. Ideally, the tool is capable of testing at the wafer level for production control and product quality assurance and binning.

Owing to these requirements, and the extraordinary operating conditions compared to low concentration and flat plate cells, CPV cells require specialized test conditions and equipment [5]. In particular, the requisite high light fluxes preclude using continuous sources. Instead, xenon flash tubes powered from the discharge of a capacitor bank are the light source of choice. Xenon flash lamps offer brief bursts of intense light, with spectra that approximate the solar spectrum although with some notable deviations. The speed and intensity of the flash, illustrated in Fig. 1, impose several requirements on the data acquisition system.

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The system must trigger taking the data stream at or near the peak of the flash, and a complete data set must be taken before the flash intensity decays significantly (<90% of trigger-point intensity), a time of 400µS. The flash color temperature, and hence color balance, is controlled by the discharge voltage supplied to the flash tube. Similarly, the intensity of the flash is also dependent on the discharge voltage. In order to obtain independent spectral balance and intensity control, then, another means of controlling the intensity must be found. Although filters or shutters of various sorts have been employed, simply changing the flash lamp to device under test (DUT) distance is the most straightforward technique, and carries with it the advantage of retaining the lamp color spectrum unaltered by glass adsorption characteristics.

A number of CPV systems today are constructed with ~1cm sized cells and large collecting apertures (~30cm diameter). A significant variation on CPV systems, however, employs smaller cells and apertures with the goal of simplifying and economizing the system [6] as illustrated in Fig.2. These systems use ~1mm sized cells operating about 2% (absolute) higher efficiency than similar 1cm cells, and borrow from high speed automated assembly techniques used in the LED industry [7]. Typically, a 100mm diameter wafer can hold up to 4000 such cells, presenting a challenge to the test and measurement of the cell wafers. Because xenon flash tubes must cool between flashes and the capacitor bank must re-charge, there is an inherent limit on the cycle time between measurements. For example, if a lamp takes 5 seconds to cool and re-charge, then a 4000-cell wafer will take approximately 5.5 hours to test if a single cell is tested per flash. The approach to reducing such absurd test times, then, is to design a flash system that can cool and cycle faster as well as probe and test multiple cells per flash. This system employs a modestly sized dual xenon tube in a reflector housing coupled to a fast cycle power supply, both designed for commercial studio photography, which also requires fast cycle times between exposures. The system also is designed to probe 32 each of the 1mm cells simultaneously using multiple tungsten tipped probes mounted to a standard probe card. With forced air cooling, the system is capable of a 3 second cycle time when set to a discharge voltage that produces a spectrum balanced for today's high efficiency multijunction cells.

In order to achieve cost effective manufacturing of high performance multijunction cells, in very high volumes, an automated tester incorporating these features is needed. This paper presents a system that fills these requirements.

2. ARCHITECTURE

2.1 Overview

Fig. 3 shows a block diagram of the overall system. The primary components are a commercial wafer probe station, the flash lamp and its power supply, and the primary control computer and data acquisition system. The primary control computer contains the graphical user interface, and controls the probe station wafer and chuck positions, synchronizes the flash with the data acquisition hardware, controls flash intensity and spectral balance, and handles communications with the network for data storage. The wafer chuck temperature is controllable between room temperature and 150°C. Calibrations for the spectral balance and intensity are provided with software feedback loops that use NREL traceable calibrated isotype solar cells. An isotype cell is simply the full multijunction cell construct, but containing a single active subcell. There is one isotype cell that samples the top subcell spectrum and another that samples the middle subcell spectrum (the two portions of the spectrum that are of critical interest for high efficiency multijunction cells). The isotype cells are positioned close to the DUT within the 1% uniform intensity band of the lamp. The system monitors the short circuit current of each cell. The ratio of the two currents is controlled to a pre-determined factor which corresponds to the proper ratio of top subcell to middle subcell current for an AM1.5D solar spectrum. The values of the two short circuit currents are fed into another software control loop to change the lamp to DUT distance, thus achieving the desired light intensity. In operation, a table of intensity values as a function of distance is measured when first commissioning the tester, and updated periodically thereafter. The table is used to avoid lengthy seek times by providing the software approximate starting points when changing to a commanded intensity.

2.2 Flash System

The flash lamp is an off-the-shelf component utilizing two Xenon flash lamps and two power supplies with an approximate maximum energy storage of 10kJ. The lamps are contained in a single housing with a semi-specular parabolic reflector to concentrate the resultant light to a smaller focus area without imaging the flash lamps onto the test area.

The pulse characteristics of the flash lamp/power supply units are controlled by an active system that maintains a more consistent current through the lamp as well as a consistent initial discharge voltage. Because of the active feedback of lamp current, intensity is relatively stable over the duration of the discharge (Fig. 1) with a less than 10% change in irradiance over a 400µS period. By changing the target values of these quantities, the corresponding properties of the output can be modified. To increase the effective color temperature of the light, the lamp discharge voltage is increases with a commensurate increase in light output.

Fig. 4 shows a plot of the spectral balance, as measured by the short circuit current ratio of the two isotype cells, as a function of flash power. For a ratio of 1.02 (ideal for the unique pair of isotypes used in this work) the optical power available to each of the top and middle subcells is equal to the power available under AM1.5D solar illumination. For the ideal ratio of 1.02 (balance point), the power supplies take about 1 second to recycle. With modest forced air cooling, the lamps stay within their rated operating temperature range during repetitive operation.

A simple software loop is used to control the isotype current ratio by varying the power setting of the flash lamp power supply. This loop is implemented with the intensity control loop, since varying the lamp discharge power also changes the intensity. As the spectral balance shifts, and is compensated, the lamp to DUT distance is also adjusted to retain the desired intensity setting. In this fashion, drift in the lamp characteristics can be compensated for in real time, enabling a higher fidelity measurement.

Each set of full IV curves is taken during a single flash. In order to take data on a full wafer or on several large cells, the flash must be run several times successively. Due to heating of the flash tubes and re-charge time of the power supplies, the repetition rate of tests must be limited. With forced air cooling, up to 20 tests can be run in one minute. As the lamp starts to heat up, color temperature and irradiance can drift away from the target values.

To independently vary the lamp intensity without affecting color temperature, a mechanical adjustment is made to the relative position of the reflector to the lamp and of the lamp to the DUT. Moving the reflector position moves the focal point with relation to the lamp and thus the local irradiance of the lamp on the test bed. By varying both the reflector position and the distance from the lamp to the test bed, a family of curves can be created for test irradiance. The curves for each reflector position overlap and the necessary travel for the lamp can be ascertained. With two reflector positions 2cm apart and 1.3m of travel on the lamp, an effective concentration range of 200x to >2500x can be achieved.

Color temperature at the DUT is unaffected by the mechanical intensity control and is adjusted in a completely electrical manner. Using this control, a DUT can be taken from middle junction limiting to top junction limiting.

Besides acquiring data on the cell under illumination, often the dark IV curve is used to characterize cell behavior, for example, detecting leaky or shorted cells. The electronics of the tester are designed to sweep voltage between pre-set low and high limits during the 400µS window offered by the flash lamp. In the absence of a flash, the dark IV is recorded using the same biasing electronics.

2.3 Creating an IV curve

For any given set of conditions (irradiance level, color temperature, pulse duration), an IV curve can be taken on a cell or set of cells by measuring voltage across the cell(s) directly with simultaneously sampled cell current.

Because the irradiance level throughout the pulse is changing, it is important to take the measurements in the same portion of the curve each time to obtain comparable results. To achieve this goal, a trigger methodology was implemented to ensure the irradiance curve is detected correctly each flash. Two detectors are used to find the timing correctly. The first detector looks for a specific low irradiance level to determine when the flash pulse starts. The second detector looks for a zero crossing in the derivative of the irradiance pulse in order to find the peak. A variable timer is then used to start the IV curve acquisition.

At the time determined by the trigger circuitry, the ramp circuit is started. The ramp starts at 0V and ramps to a specified voltage at a specified rate. The ramp is amplified to a current sufficient to match the current generated by the DUT.

During the ramp, voltage and current from each DUT are directly sampled as well as the irradiance of the pulse by a reference triple junction cell and two isotype cells. All the data is sampled at a rate of 10 MSa/sec by a 12 bit oscilloscope. This data set is digitally filtered and down-sampled by a factor of 10 to reduce the noise during the acquisition. The digital filter is constructed from a "brick wall" filter specification and the FIR filter is calculated using the Parks-McClellan algorithm.

Within the acquisition period, the irradiance of the pulse decays. The current readings from the DUT are normalized to the irradiance at P_{mp} using the current readings acquired from the calibrated triple junction cell. For each flash, each sampled DUT current value is normalized to the synchronous reference cell current value. In this manner, the time decay of the flash intensity is normalized out of the data. Voltage is assumed constant with irradiance since the irradiance range is minimal. An independent normalization and characterization of the flash pulse is done using the isotype cells.

2.4 Electronics

The amplifier used to bias the cell during the flash is capable of four-quadrant operation and has active variable current limits to prevent damage to the DUT. Using three of the four quadrants, dark IV and reverse bias characteristics can be measured in addition to the lighted IV. The amplifier is capable of 20A, allowing for tests up to a concentration of approximately 1600x with a typical 10x10mm III-V triple junction cell. Voltage output can range from -5V to 5V during a sweep and start/end points are user defined within that range dependent upon the desired test. Sweep speed is adjustable from 1500 to 60000V/S. All parameters are user-input to the controlling software.

Simultaneous testing multiple cells presents several challenges. Several DAQ units are used to sample the desired number of channels and must be synchronized. A common trigger line to each card starts the acquisition and an accurate internal oscillator is used to synchronize the samples to much greater than the bandwidth of the measured signal. In addition to timing concerns, current from each DUT must be carried by multiple amplifiers as well as conducted through the chuck. When testing at maximum concentration and multiple cells, ground currents can exceed 60A. Ground resistances must be kept to a minimum in order to maintain measurement accuracy and repeatability.

There is also a significant amount of data to be handled and filtered. Each DUT has approximately 100,000 data points associated with it; while testing 32 cells simultaneously, filtering data can exceed the minimum flash period and prevent testing at maximum throughput. By using multithreaded applications, multi-core processors and optimized filter designs, the required number of calculations is minimized.

Several commonly used cell parameters are derived from the IV curves and stored for each DUT. These include I_{sc}, V_{oc}, P_{mp}, I_{mp}, V_{mp}, and fill factor, as well as series and shunt resistance. In addition to the parameterization of the IV curves, the filtered data from all channels and calculated IV curve for each DUT are stored for each test A Pass/Fail wafer map or a three dimensional plot for visualizing wafer performance is generated from any one of the parameters, or all combined. Cells on the wafer are also electronically binned for later use in the pick and place operation during receiver manufacturing.

Because the flash characteristics change with age and temperature, an active system is used to control the flash and seek the target values. The color balance and intensity are controlled to maintain consistent test conditions over time, both due to short-term heating and long term device aging.

2.5 User Interface

The system is coordinated by the main computer, which also contains the user interface. Fig. 5 shows screen captures of the primary interface screens. The system allows for user-selectable single shot measurements, or repetitive measurements based on a user-input wafer map. Under automated control, the probe station steps through the assigned die coordinates and stores the raw and parameterized data for each die referenced to the x-y die coordinate on the wafer, also user-defined. The IV characteristic for the cell under test, or a selected one of the 32 cells in the case of multiple cell testing, is displayed in either log or linear coordinates. The user may also view the flash intensity profile for reference. All screens report the status of the system and any out of spec system parameters such as power or spectral balance. A pass/fail wafer map is displayed, and the user may select to display a pass/fail map of any of the major parameters in real time.

3. SYSTEM PERFORMANCE

This section describes the performance achieved with the prototype system when testing single 1cm sized cells and multiple cells on wafer of the 1mm sized cells.

3.1 Intensity and uniformity as a function of lamp to DUT distance

Fig. 6 shows a plot of the light intensity as a function of the lamp to DUT distance. The intensity is determined by assuming that the short circuit current of the isotype cells, and also that of a reference multijunction cell, are linear with concentration in the range of interest. The isotype current is referenced back to NREL traceable measurements of the one sun illumination current. In addition, the concentration has been cross checked by comparing the 500 sun short circuit current generated by "gold standard" 1cm sized cells also measured at NREL under 500 AM1.5D conditions. The agreement is within 0.78%. Without varying the lamp discharge energy (and hence the spectral balance), the concentration can be varied from 250 suns to 2500 suns over 80cm of travel. The intensity fits the power law

$$C = 2x10^{8} \bullet (x^{-2.775}), \tag{1}$$

where C is concentration in suns, and x is position in cm.

Similarly, the uniformity of the illumination spot has been characterized at several intensity settings. This measurement is performed by mounting one of the 1.5mm cells onto the tester chuck and rastering it under software control over a 400 point x-y grid centered under the flash lamp. The flash intensity is measured at each point on the grid with a single flash. A second reference cell is held fixed within the illumination field to serve as a reference, and flash to flash variations are normalized out of the data using the reference cell short circuit current readings. Fig. 7 shows the resulting iso-intensity plots. Illumination intensity uniformity of ±0.95% is held over the inner 25mm diameter circle and ± 1.15% over a 50mm diameter circle from 266 to 1658 suns concentration. At 2500 suns the uniformity drops slightly to ± 1.05% and ± 1.8% for 25mm and 50mm circles, respectively, due to the proximity of the lamp to the test plane. Typical standard deviations are 0.3% and 0.4% respectively over the same range, with 0.7% at 250suns, as shown in Table 1. The 25mm circle is sufficient to cover nearly four of the 1 cm cells and all 32 of the 1.5mm cells. Fig. 8 shows a photograph of a 1cm cell with the high current probes contacting the cell. Fig. 9 shows the iso-intensity plot at 2500 suns with 32 of the 1.5mm cells superimposed schematically. With the lamp cycle times achieved, the system is capable of stepping through a 4000 cell wafer of these cells in 6 minutes.

(a) 25mm diameter	**Concentration (Suns)**						
	266	**511**	**572**	**704**	**1123**	**1658**	**2500**
	Percent of Full Power						
Average	98.6%	98.7%	98.8%	98.9%	98.7%	99.2%	98.9%
Sigma	0.4%	0.3%	0.3%	0.3%	0.3%	0.3%	0.4%
Max	99.5%	99.4%	99.4%	99.8%	99.2%	99.9%	100.0%
Min	97.7%	98.1%	98.0%	98.3%	98.0%	98.5%	97.9%
Range	1.9%	1.3%	1.5%	1.5%	1.3%	1.4%	2.1%

(b) 50mm diameter

Average	98.7%	98.8%	98.8%	98.9%	98.7%	98.9%	98.3%
Sigma	0.4%	0.4%	0.4%	0.4%	0.4%	0.5%	0.7%
Max	100.0%	100.0%	100.0%	100.0%	99.9%	100.0%	100.0%
Min	97.7%	97.7%	97.9%	97.8%	97.6%	97.7%	96.4%
Range	2.3%	2.3%	2.1%	2.2%	2.3%	2.3%	3.6%

Table 1 Summary of the uniformity of a 25mm diameter circle (a) and a 50mm diameter circle (b) centered under the flash lamp, expressed as a percentage of the maximum power point within the circle.

3.2 Intensity repeatability

Table 2 summarizes the resulting accuracy of the intensity obtained by deliberately changing the lamp to DUT distance an arbitrary amount and allowing the system to seek the commanded intensity. In order to avoid hunting behavior, a tolerance of ±2% of set-point concentration is allowed in software. The system is capable of settling to set point in less than four flash cycles, and the accuracy of the intensity value has a standard deviation of 0.8% of set-point. Full range traverse time is 30 seconds with worst case seek to settle time is 10 seconds.

Set Point (Suns)	Number of Flash Cycles to Settle	Final Settling Point (Suns)	Delta (Suns)	Delta (% of Setpoint)
250	1	253.8	3.8	1.5%
500	2	503.2	3.2	0.6%
600	3	594.6	-5.4	-0.9%
700	2	699.2	-0.8	-0.1%
1100	2	1109.4	9.4	0.8%
1600	2	1607.1	7.1	0.4%
Average			2.9	0.4%
Sigma			5.4	0.8%

Table 2 Behavior of automatic intensity seeking mechanism. Starting at an arbitrary position, the lamp positioning software moves to a pre-determined position corresponding to an approximation of the set-point intensity. Then using successive flashes, it moves to a position that is within ±2% of the commanded intensity. On average, the control system can match the set-point to within 0.4%.

4. CONCLUSIONS

A flexible, economical wafer and cell level automated test system has been assembled and characterized. The system offers a wide range of simulated concentrations, very high throughput at the wafer level, and accurate characterization of high efficiency concentrating solar cells in a production environment. Accurate, efficient testing, binning, and rejection of substandard cells at the wafer level, coupled with electronic wafer maps for operating pick and place machinery, is necessary for achieving high volume manufacturing cost reduction.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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7. FIGURES

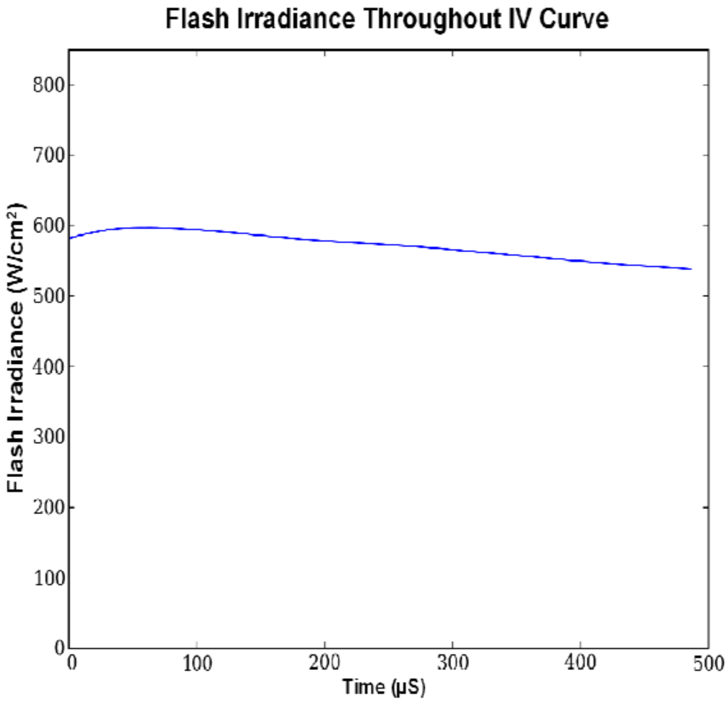


Fig. 1 Intensity of the flash lamp over time. There is a ~ 450mS window from peak intensity to 90% of peak intensity.

Fig. 2. Photograph of monolithic glass tile with array of solid concentrators. The primary lens diameter is about 25mm.

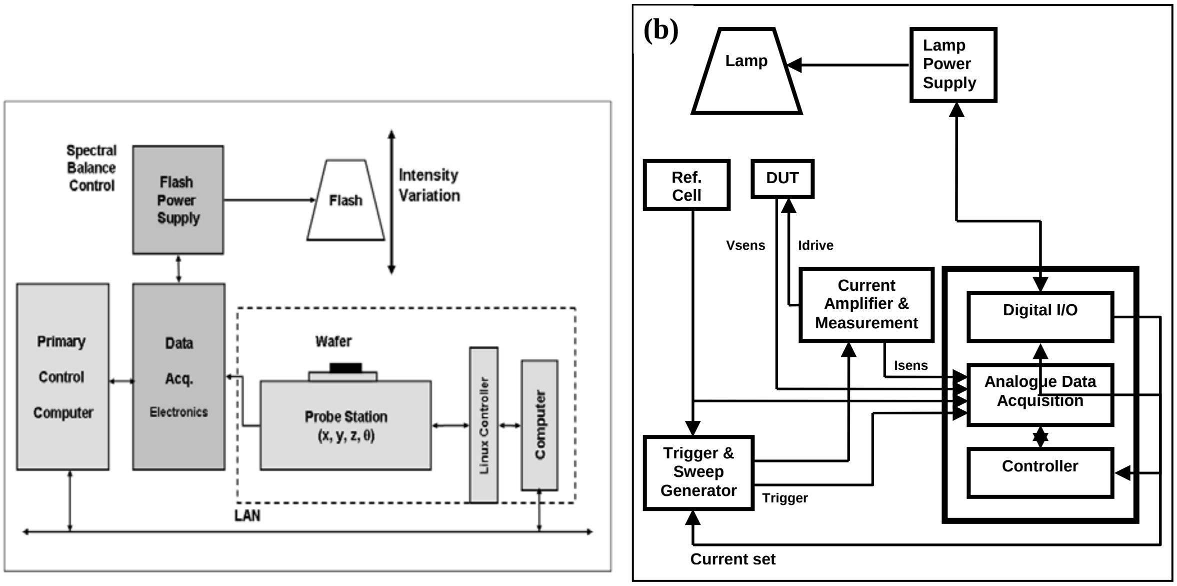


Fig. 3 (a) Block diagram of flash tester system showing wafer probe station and controls, flash lamp and power supply, and primary control computer and data acquisition system. (b) Functional block diagram of the data acquisition electronics and control system.

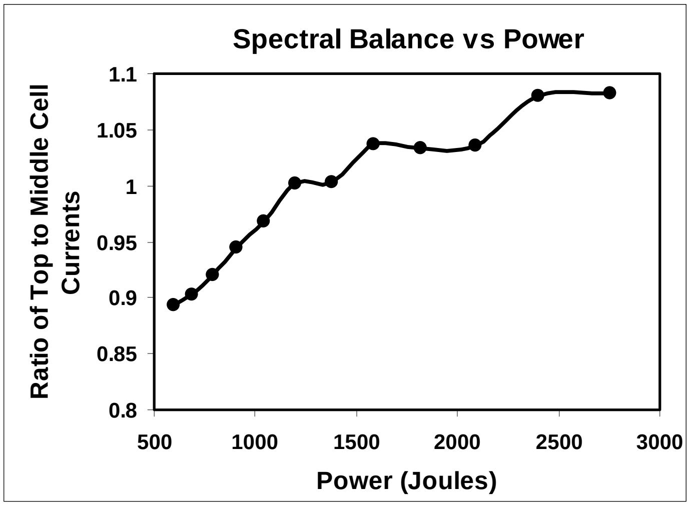
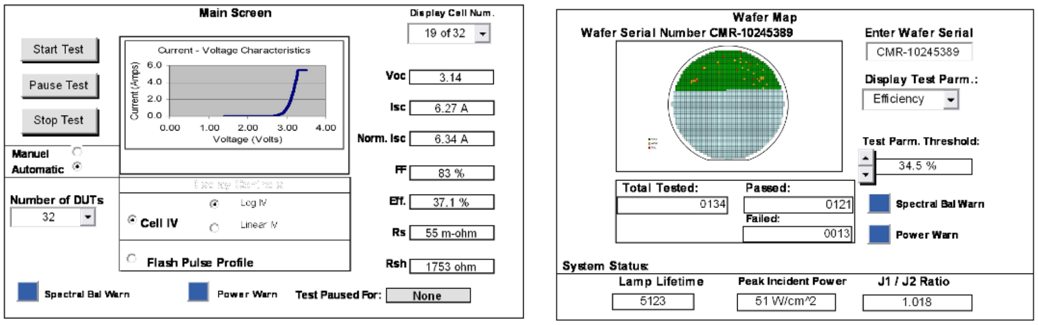


Fig. 4 Spectral balance as a function of flash power for one of the dual tubes used n the flash. The non-linearities in the curve are a result of the power supply electronics controlling the color balance for photographic purposes. The curve crosses the ideal isotype ration of 1.02 at ~1500 Joules.



Display Cell Num.: 19 of 32

○ Manuel

● Automatic

Number of DUTs: 32

● Cell IV

● Log IV

○ Linear IV

○ Flash Pulse Profile

Voc: 3.14

Isc: 6.27 A

Norm. Isc: 6.34 A

FF: 83 %

Eff.: 37.1 %

Rs: 55 m-ohm

Rsh: 1753 ohm

Test Paused For: None

Wafer Serial Number CMR-10245389

Enter Wafer Serial: CMR-10245389

Display Test Parm.: Efficiency

Test Parm. Threshold: 34.5 %

Total Tested: 0134

Passed: 0121

Failed: 0013

System Status:

Lamp Lifetime: 5123

Peak Incident Power: 51 W/cm^2

J1 / J2 Ratio: 1.018

Fig. 5 Screen layout of the GUI showing the main screen (a) and the wafer map & statistics screen. The wafer map, IV characteristics, and statistics are updated for each flash. System status and warnings are also reported in real time. The main screen offers the choice of displaying the IV characteristic (both dark and light) in linear or log coordinates, or view of the flash intensity as a function of time. The user can select any of these during the testing, as well as select which of the 32 1.5mm cells to view during any given flash. The wafer map is continuously updated, and the user may select which parameter to map, or all entered parameters "and-ed" to view overall yield.

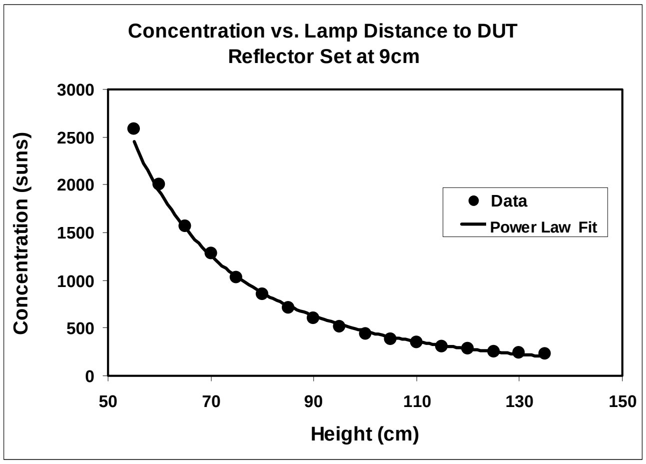


Fig. 6 Concentration intensity as a function of flash lamp to DUT distance with the reflector set at the 9cm mark. The data fits the power law $C=2x10^{8}$ $(x^{-2.775})$.

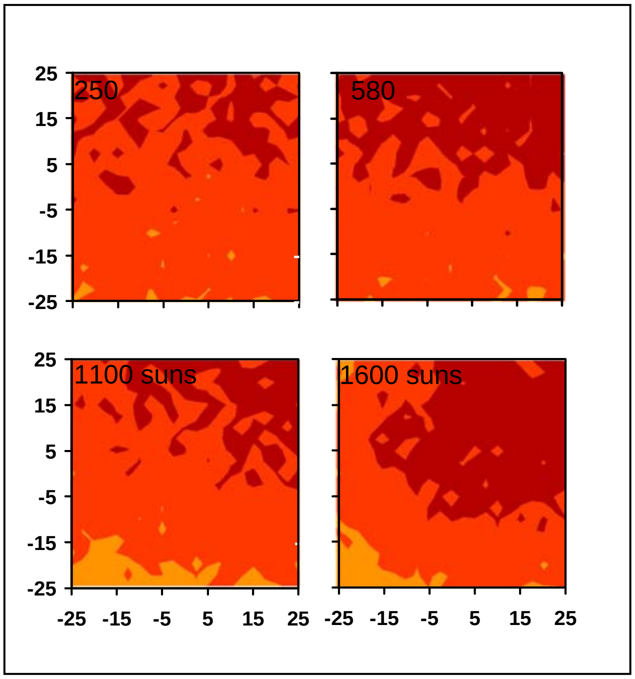


Fig. 7 Intensity contour plots if luminance at four concentrations, 250, 580, 1100 and 1600 suns. Scale is in mm. Contours are 1% changes in intensity. With some mechanical adjustment to more closely center the spot, the uniformity can be improved beyond the ±1% seen here for the inner 25mm square.

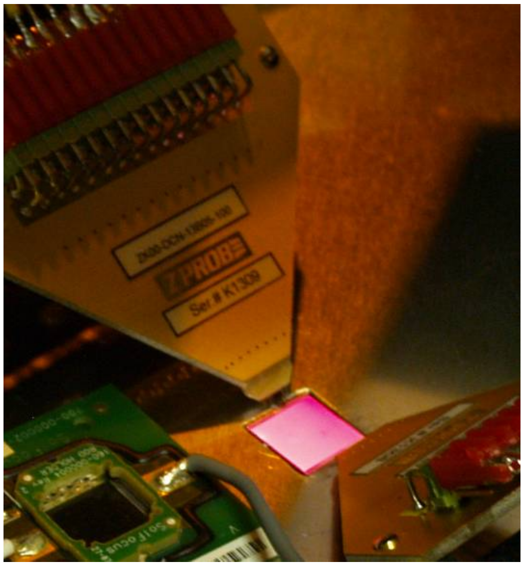


Fig. 8 High current probes forward biasing an unmounted 1 cm multijunction cell mounted on the vacuum test chuck. The top cell electroluminesces red. Second cell in the foreground is a reference cell.

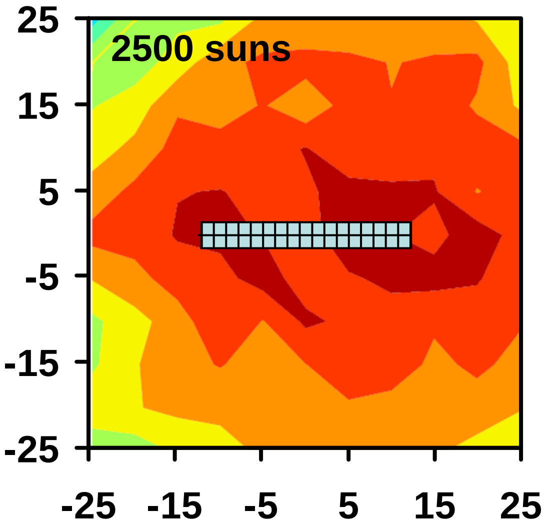


Fig. 9 Uniformity plot at 2500 suns concentration. Iso-intensity regions are in 1% steps. 32 of the 1.5mm cells are schematically superimposed for reference, and fit within the ±1% band.