Summary of Laser Stepping Apparatus

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Overview

The laser stepping apparatus was constructed to measure the spatial uniformity of solar cell photo-response with very high resolution. The initial goals were (1) to achieve a diffraction-limited spot size (~1 μm), (2) measure photocurrent at low enough levels so that when using the most sharply focused beam, photon densities are as close as possible to "real-world conditions" i.e. 100 mW/cm^2, and (3) to be able to map a solar cell, remove it from the apparatus to perform heat, light, or environmental stress, and subsequently replace it in the apparatus and find the same position to ± 1 μm.

The apparatus consists of three basic sub-systems: optical system, positioning equipment, and electronics. The optical system consists of laser diodes coupled into single-mode fibers, a collimating lens, a mechanical chopper, a beam sampler, a neutral density filter wheel, beam steering mirrors, and a high quality microscope objective with compensation for focusing through glass. The positioning equipment is made up of three identical high resolution computer controlled translation stages. The electronics setup incorporates a current-to-voltage amplifier and a lock-in amplifier. In addition, extensive LabView™ software control has been developed, integrating positioning and electronics. The setup allows full control of experimental parameters from a single screen on the monitor.

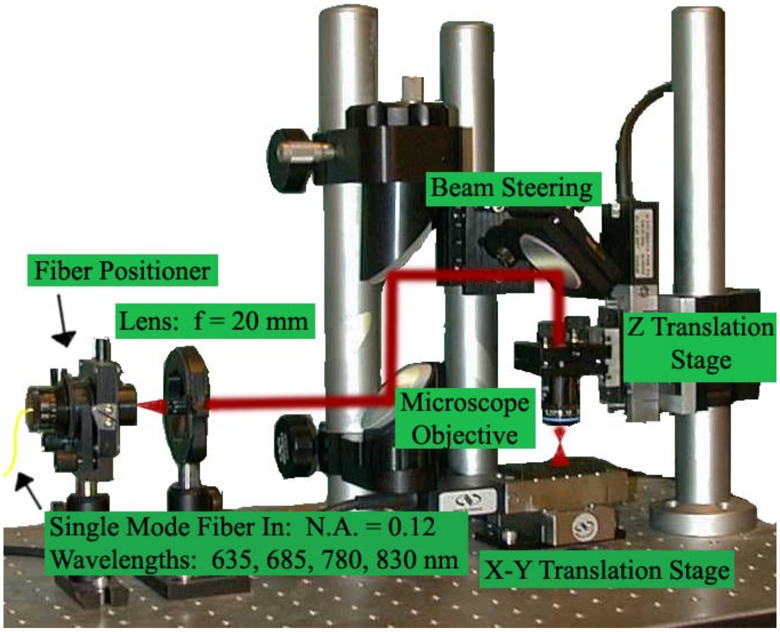


Figure 1. Schematic of Apparatus.

Optics

Laser Diode Controller

The Thor Labs LDC500 laser diode controller was selected for the stability of its current supply and its easy operability. Specifications on the LDC500 met or exceeded those of a more expensive controller from Newport which also had a GPIB interface and internal intensity modulation control. Since only the diode current needs to be set on the controller, a GPIB interface was not a priority, and modulation could be provided from the SR810 lock-in to a BNC-connector on the back panel of the LDC500. The laser can be modulated in constant current or power mode. The output current or power is controlled to given by:

$$I_{LD} = I_{LDset} + I_{LIM} \cdot \frac{V_{MOD}}{10 \cdot volts} \quad ; \quad I_{PD} = I_{PDset} + 0.2 \cdot mA \cdot V_{MOD}$$

where I_{LD} is the current output in constant current mode, I_{LDset} is the laser diode current setting in constant current mode, I_{LIM} is the current limit, I_{PD} is the photodiode current (monitors the laser diode output), I_{PDset} is the current setting in constant power mode, and V_{MOD} is the modulation voltage at the BNC-connector. See Figure 2 for the output of one laser as I_{LDset} is varied. Initial observations indicate that the controller provides output stable on the 1-3% level. The controller electronics appear to follow the modulation voltage extremely well.

Fiber-Coupled Laser Diodes

Laser diodes were chosen over a HeNe laser partly because of the relatively low cost of having multiple wavelengths (only one controller for many lasers need be purchased) but primarily because of the superior beam characteristics obtained from a single-mode fiber. The small fiber core excludes all but the nearly Gaussian TEM 00 spatial mode, ideal for focusing a beam down to a minimum spot size. 630, 680, 780 and 830 nm lasers were chosen both because of availability (none are readily available below 630 nm at a reasonable price) and to match the response of the solar cells under study. Additional lasers can be added to the system as needed. The laser diodes are "pigtailed" at Thor Labs, and have typical output powers of 3-10 mW from the fiber. Such power is more than sufficient, which allows extra flexibility in monitoring the laser and coupling all lasers into a common fiber. See Figure 2 for the output characteristics of the 680 nm laser.

Another significant advantage of solid state lasers is the ability to modulate the output current on the controller with an external signal, in this case provided by the SR810 Lock-in Amplifier's high-quality sine wave output. With intensity modulation, the light need not be chopped, which leads to less noise at the detection frequency, and results in a better signal-to-noise ratio. The practice of modulating laser intensity is one best approached with an oscilloscope in hand, since the waveform quality can depend on many factors. One must also monitor the background (not modulated) light signal, which can affect the device significantly, as well as lead to DC offset currents which may overload the electronics.

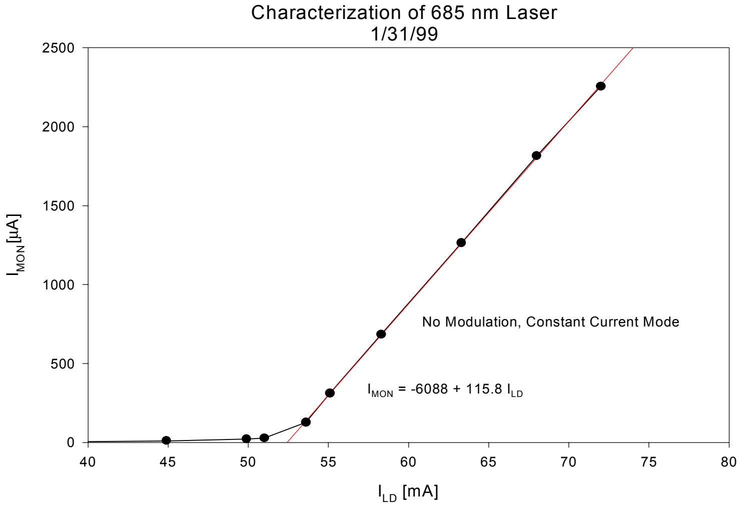


Figure 2. Fiber Pigtailed Laser Diode Output.

The laser diodes can either be exchanged at the holder on the breadboard, or, if coupling losses are not too great, with a coupler between the laser diode and a patchcord, which terminates at the holder on the breadboard. This latter option has the advantage of minimal adjustment of the mount on the breadboard when lasers are switched. One should in principle only need to compensate for the very small shift in focal length of the collimating lens at different wavelengths. This has to be evaluated, as do the coupling losses. The issue of coupling losses is complicated by the fact that a patchcord must be selected which will keep all wavelengths single-mode.

One designed for a 630 nm laser is currently being used, but power coupling efficiency is reduced at higher wavelengths.

A tunable laser diode system would be a useful addition to the current capability, especially if the output ranged over the bandgap of a particular material. The cost of these systems, however, is high. The same versatility of changing wavelengths smoothly could be provided by a grating monochrometer, but high resolution would most likely be unattainable due to the problems inherent in focusing an incoherent beam of light. Also, it is likely that noise would be dramatically increased due to fluctuations in the DC light source. However, incorporating a monochrometer appears to be an inexpensive way to measure spatial variations in bandgap.

Temperature Control of the Laser Diodes

Temperature controlled mounts for laser diodes are available commercially, using thermoelectric cooling. Temperature control reduces 'mode-hopping' in laser diodes, essentially improving stability. Since the lasers used operate at relatively low power and thus produce little heat, mounts with good heat-sink characteristics were used instead. Since laser diode lifetime decreases with operating temperature, care should be taken to monitor the temperature at the mounts.

Fiber Holder

The pigtailed laser diodes come with FC style connectors. FC/APC is also available, and reduces back-reflections. Since this application is not very sensitive to back reflections, and FC/APC is not compatible with coupling into an FC patchcord, the standard FC style is used. The FC connector was initially held by a Newport FPR-C1 Fiber holder, which features x-y-z-θ–ϕ adjustments in an inexpensive package. The mount, however, was found to be very difficult to adjust in small increments, and was not sufficiently stable over time. To provide a more stable, dependable mount, the New Focus Model 9091 was purchased.

Collimating Lens

The lens used to collimate the output of the fiber (essentially a point source of light) is a key component. A Gradium™ lens was chosen for its well corrected (for spherical aberration), achromatic (focal length changes minimally for wavelengths from 630 - 1000 nm) behavior. The focal length (20 mm) was chosen to produce a beam large enough to fill the microscope objective clear aperture. The collimated beam radius, w, is calculated from the numerical aperture (N.A.) of the lens (0.12) and the focal length (20 mm) as:

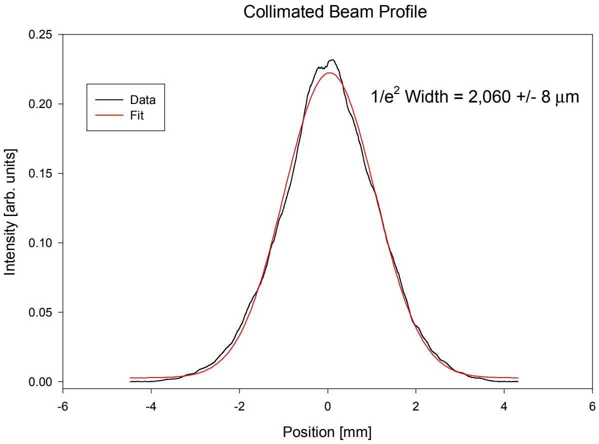


Figure 3. Example of collimated beam: 680 nm laser.

$$N.A. = \frac{w}{f} \quad \therefore w = 2.4 \cdot mm$$

A larger focal length lens of similar material could be selected to overfill the objective and thus get a smaller spot size (see section on objective). Figure 3 shows a profile of the collimated beam. Other scans after better collimation have produced slightly better Gaussian profiles very close to 2.4 mm. The lens is quite sensitive to angular alignment, and a New Focus 9885 mount provides stable adjustment. Note that the collimating lens is plano-convex. Care should be taken to orient the lens with the plane side toward the fiber output to reduce aberrations.

Mechanical Chopper

The Stanford Research Systems (SRS) model SR540 was selected. It is a standard model used by many labs. The chopper is needed for several reasons. Firstly, if a light source (such as a monochrometer) which cannot be modulated electrically is used, one must chop the light to use phase sensitive detection. Secondly, electronically modulated light results in an AC wiggle on top of a DC light - the light does not go to zero at any time. Disadvantages of a chopper include poorer noise performance (due to vibration and jitter at the reference frequency) and that high frequency components inherent in a square wave may result in complications in the solar cell response. Whether to use the optical chopper or electrical modulation should be evaluated for each type of measurement.

Beam Sampler

The beam sampler reflects <10% of the incident light and allows one to monitor the output power of the beam. This feature was added because of observed fluctuations in beam power (due to temperature fluctuations or other phenomena in the laser diode) on the order of 2-3 % even after a generous warm-up time.

Neutral Density Filter Wheel

The intensity of the beam needs to be varied by several orders of magnitude. A filter wheel was purchased from New Focus containing one wheel of six filters varying from 0.04 to 2.5 in 0.5 optical density (O.D.) increments in series with another of six filters varying from 0.04 to 0.5 in 0.1 O.D. increments. The attenuation is given by $10^{-O.D.}$, with the O.D. being the sum of the two filter settings. One issue with the neutral density filters is that the surface quality is not as good as preferred. Any scratches or distortion in the flatness results in distortion of the wavefront which can result in a larger than optimal spot size. The filters should be placed at a slight angle to the incoming beam to eliminate multiple reflections.

One solution would be to purchase a digital attenuator (OZ Optics is one manufacturer). This option has the advantage that the attenuation could be set with high resolution and repeatability without introducing wavefront distortion, but one would still need to couple all lasers into a common patchcord, with unknown coupling losses.

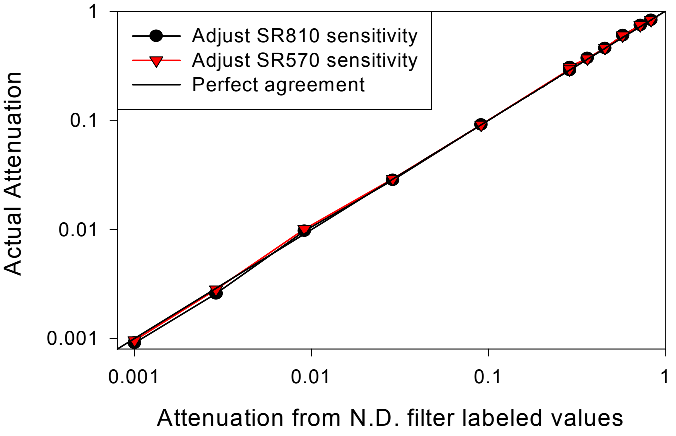


Figure 4. Attenuation by Neutral Density Filters.

Measured attenuation (Figure 4) shows that the labeled optical densities are quite accurate. In this figure, since the signal varied by three orders of magnitude, issues of changing instrumentation sensitivity arise. To address this possibility, the attenuation was measured by changing the sensitivities of first the lock-in (second stage electronics) to get a full-scale reading and then the front-end current-to-voltage amplifier. While deviation from labeled optical densities is greater than disagreement between these two methods, it is believed that leaving the front-end electronics at a constant sensitivity is preferred, due to effective input impedance changes (see section on electronics for details).

Mirrors / Beam Steering

MAXBRite/003 Mirrors were selected from Melles Griot for good surface quality (60-40 scratch-dig, λ/10 flatness) and excellent reflection (>98%) over the wavelength range 630-850 nm. The mirrors are the limiting factor in the wavelength range accessible to this apparatus. Since they do not reflect significantly below 630 nm, no blue or green lasers may be incorporated into the system without replacing the mirrors. Beam steering is provided by Newport components (670-RCT and 670-RCB), which feature excellent stability and adjustability. Damped rods are used to reduce vibrations in the system.

Alignment of the beam to be collinear with the translation axis of the z translation stage is crucial to ensure that changing the spot size (by moving the objective in the vertical, or z-direction) does not affect the intensity delivered to the sample. Four degrees of freedom are required (x,y,θ,ϕ) and are provided by the two mirrors mounted above the sample. The Thor Labs mount holding the second mirror could be replaced by a more precise one, making alignment easier. Alignment is accomplished in the following way:

1) A position-sensitive-detector (PSD - see the section below for details) is mounted to the objective holder. Care should be taken that the center of the quadrant PSD is aligned to the center of the objective holder. The vision system in the CSU High Energy Lab (see Dave Warner) can be used.
2) The beam must be roughly aligned in both position and angle.
3) The translation stage is then moved up maximally and the beam is centered on the PSD using the first (in beam line) adjustable mirror.
4) The translation stage is moved down maximally and the beam is again centered, but this time with the second adjustable mirror (directly above the objective).
5) The stage is moved up and the beam position is over-corrected with the first mirror and moved to the center of the PSD with the second mirror.
6) The stage is moved down and the beam is centered on the PSD with second mirror only.
7) Steps 5 and 6 are repeated until beam is centered on the PSD at all z positions. To avoid confusion, the direction all four knobs must be turned (cw or ccw) is identified and only turned in one direction. Relatively small over-corrections are used in step 5.

The beam should also be aligned to the optical axis of the microscope objective. In practice this is very difficult, since a mount for the objective should be designed to be goniometric - the center of the objective should not move when it is tilted. When the optical axis is not aligned, the beam emerges at some unknown angle to the z translation axis, resulting in the x-y beam center position changing with spot size. This can in principle be compensated with software, and may not be an issue if the angle is small enough. The minimum spot size, however, will be compromised if the beam is not nearly parallel to the optical axis.

PSD / Quadrant Detector

A UDT quadrant detector (Spot-9DMI), a silicon photodiode segmented into four quadrants, each isolated electrically, was purchased, and an op-amp circuit (simple current-to-voltage) was designed and built. The four outputs are connected to the A/D inputs of the SR810 lock-in. The position of the center of the beam is given by:

$$X = \frac{(A+D)-(B+C)}{A+B+C+D}; Y = \frac{(A+B)-(C+D)}{A+B+C+D}$$

where A, B, C, D are the voltage outputs of the four quadrants (labeling clockwise). The device works remarkably well for positioning. Resolution has not been evaluated in detail, but it is less than 5 μm.

Other Detectors

To quantify beam intensity power, two UDT sensors (PIN-DPI and PIN-DP) were purchased and calibrated at NREL (NIST-traceable external quantum efficiency). Data files are available containing the quantum efficiency at 5 nm intervals. The power is then calculated from the output current as:

$$P = \frac{I}{QE} \cdot \frac{h \cdot c}{e \cdot \lambda} = \frac{I}{QE} \cdot \frac{6.625 \cdot 10^{-34} (J \cdot s) \cdot 3 \cdot 10^{8}\ {}^{m}\!/\!_{s}}{1.602 \cdot 10^{-19} C \cdot 680 \cdot nm} = \frac{I}{QE} \cdot 1.825\,\frac{watts}{amp}$$

where I is the current and QE is the quantum efficiency at the lasing wavelength (0<QE<1).

Microscope Objective

The Olympus 1-UB367 SL C PLAN FLUORIDE 40x/0.55 N.A. objective, equipped with a correction collar for focusing through 0 - 2.5 mm of glass, appears to be the ideal objective for this type of work. Its large working distance of 8.8 mm allows room for cell contacts. Spot size measurements indicate that its performance is near-diffraction-limited. Its clear aperture is 4.59 mm, which should be filled for best performance. Note that if the objective is filled with light with a gaussian intensity profile, the output will also be gaussian. However, if the objective is filled with a uniform intensity, an Airy disc intensity distribution will be produced. The transmission specification ranges from 93% at 630 nm to 30% at 850 nm.

The beam can be characterized using a razor blade, a slit, or a pinhole. The razor blade is the easiest (it can be taped above the sample) but one must differentiate the scan to get the beam profile. Also, the razor blade is good for all ranges of spot size, though edge structure at the micron level can lead to measurement errors at the smallest spot sizes. A precision ground steel edge has been made which has less micron-scale structure and is preferred for measurements of the smallest spot sizes. A slit is a good option if a direct profile is desired, and one is interested in spot sizes large compared to the slit width. A pinhole is used when two-dimensional imaging is needed. The beam output depends strongly on the alignment, so great care must be taken to get the best alignment possible. Figure 5 shows a typical beam output.

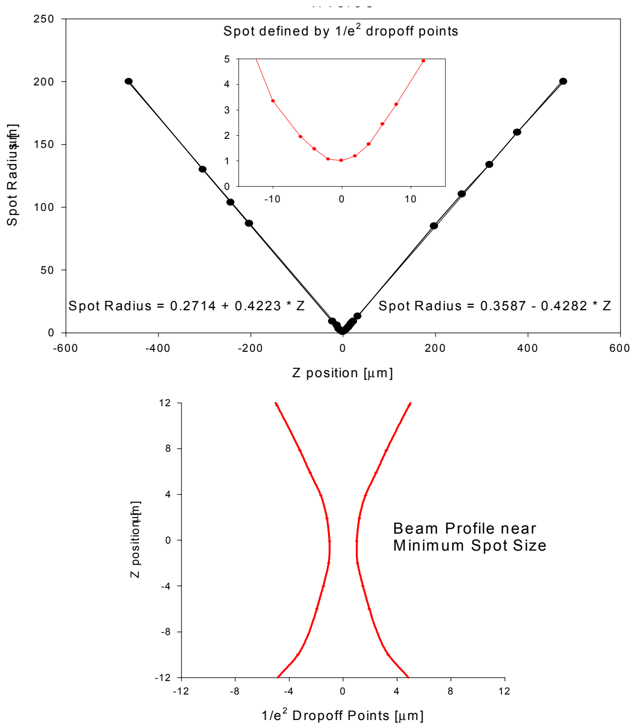


Figure 5. Example of Beam Profile.

The minimum spot size observed with zero correction has been 0.71 µm. With the correction collar, a 1 µm spot has been achieved at λ = 680 nm after going through 1.4 mm of glass. It is clear that the lens is near-diffraction-limited. The minimum spot size is given by:

$$w_{\min} = \frac{\lambda}{2 \cdot \pi \cdot N.A.} \cdot \frac{\phi}{w_o} = \frac{630 \cdot nm}{2 \cdot \pi \cdot 0.55} \cdot \frac{4.59 \cdot mm}{2.4 \cdot mm} = 0.35 \cdot \mu m$$

where ϕ is the clear aperture of the objective and w_o is the radius of the incoming beam. See the Melles Griot Optics Guide or other optics reference for detail.

General Comments

Care must be taken with the optics components, especially the mirrors, objective, and lasers. Mirrors should never be touched, and must be cleaned properly using the drop-and-drag or similar technique. When not in use, place a lens tissue over mirrors and objective so that dust does not collect. The fibers must not be coiled too tightly, and the current limit for each laser must never be exceeded. The lasers are also prone to electrostatic discharge damage; to avoid this, short all leads together when not in use.

Positioning Equipment

Translation Stages

Three Newport MFN-25CC translation stages and a board-level MM2000 controller make up the computer controlled positioning system. Specifications and a tutorial can be found in the Motion Control catalog from Newport. The stages must be tuned for optimal performance, accomplished using LabView™ software. Instructions for tuning can be found in the stage documentation. The stages are entry-level models from Newport, and feature 1 μm repeatability and board level correction of backlash. Two of the stages were aligned at Newport to be orthogonal to 50 μrad.

The minimum step size at the present time is 0.4 μm. It is possible that smaller steps could be accomplished with better tuning of the PID parameters. Since the tuning parameters are dependent on the exact loading configuration of the stages, stages should be independently tuned after any changes.

Ground Edges

The goal of removing a sample and replacing it with the ability to find the same spot to within a micron has proven, so far, to be one of the biggest challenges. At the micron level, even a razor blade (see Figure 6) has structure which presents problems. It is evident that not only is the edge not well defined, but also the structure includes somewhat large features which make it difficult to define a straight line. Figure 7 shows a similar scan on a precision ground steel edge. It is evident that the edge is much sharper, though some structure remains. The height of the objective was adjusted to keep the spot size constant at less than one micron in both cases.

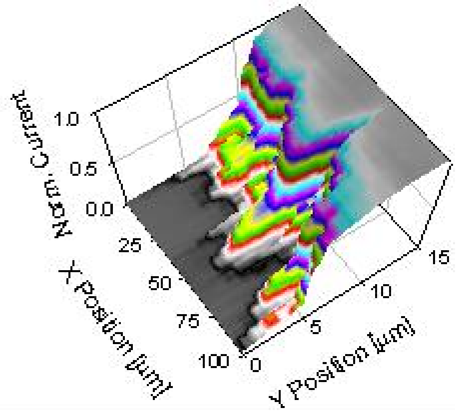


Figure 6. 2D Scan of Razor

To repeatedly find the same position to within a micron, two edges are placed perpendicular to one another (see Figure 8). By stepping the beam across an edge at many points, a line can be generated (in practice, the maximum of the first derivative of the scan defines the edge). With both lines, an origin and angle with respect to the translation directions is calculated and saved. With this information for both placements of the sample, a coordinate transformation can translate and rotate one scan into the frame of the other. The two lines should be measured as precisely as possible.

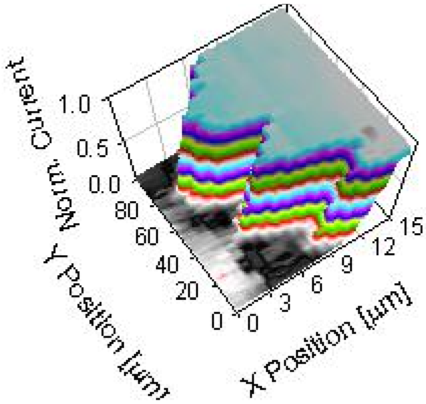


Figure 7. 2D Scan of Ground Steel Edge.

Another issue is that the sample cannot be mechanically placed so that its plane is precisely perpendicular to the incoming beam, and hence the spot size will change with horizontal position. Since deviation from perpendicularity cannot easily be measured with the solar cell alone, the plane of the ground edge must be the same as the plane of the solar cell. Because it is not possible to use two razor blades to do this, the ground steel edges were machined from a single piece of high-carbon steel (which rusts quickly - store appropriately) in an L-shape.

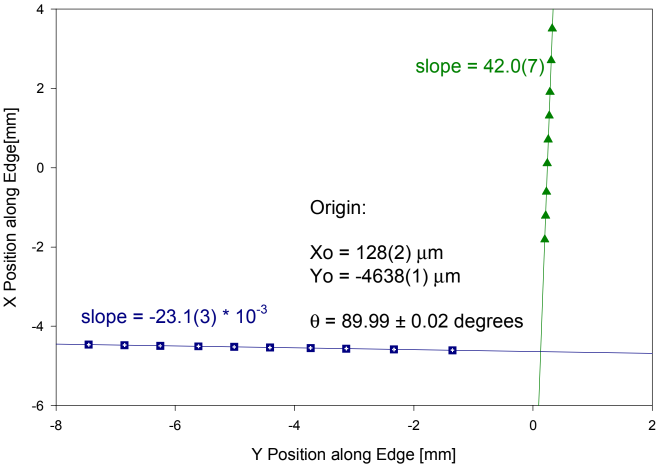


Figure 8. Lines Defined by Ground Straight Edges.

Electronics

Contacting

A four probe technique is used to contact the solar cell. Two contacts are used for voltage sense and two for current read and biasing. In the case of glass-on-top device structures (CdTe), a conductive epoxy is used to attach leads to the sample. This has the advantage of a low-profile / low-resistance contacting configuration. The leads are attached to BNC connectors as close to the sample as possible to reduce noise pickup. Good quality cables should be used at all times.

Current Amplifier

Since the characteristics of the devices under study can vary, it is important to have good control over the input impedance of the current detection electronics to avoid changes in measured current because of loading errors (see Figure 9). A Stanford Research Systems SR570 current-to-voltage amplifier allows device output to a virtual null (~2 ohm input impedance) or to a user-selectable bias from -5 to +5 volts. This allows J-V data to be automatically acquired in low-noise mode. In addition, an input current offset is available to avoid overloading the amplifier with a DC offset current. Two RC filters with adjustable frequency cutoffs are also available. Specifications are included in the manual.

The sensitivity of the SR570 should be adjusted to produce ~1 volt RMS when the maximum expected signal is present on the input. Note, however, that the frequency response and input impedance depend on the sensitivity setting. Attenuation of the signal by a poor choice of sensitivity and/or filtering at a particular frequency is to be avoided. The high bandwidth mode can be used to decrease the attenuation at higher frequencies, but increased noise at the output will result when measuring low level signals. Also, the sensitivity setting should not be changed once data taking has begun. Having the output voltage present on an oscilloscope facilitates choosing the best set of parameters.

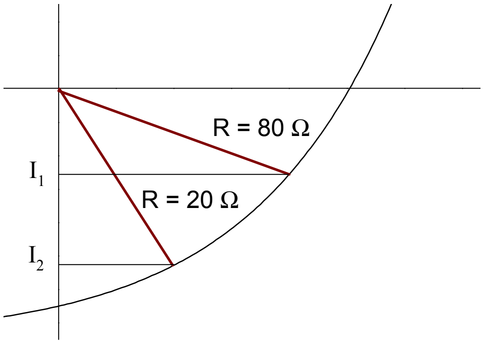


Figure 9. Effect of loading on photocurrent for a poor quality solar cell.

For best low-noise operation, the SR570 should be located close to the device and unplugged from the wall outlet. The instrument can operate on battery power for up to six hours. It is extremely important to recharge the batteries to full capacity on a daily basis; if the instrument is placed in storage, the batteries must be recharged at three month intervals.

Lock-In Amplifier

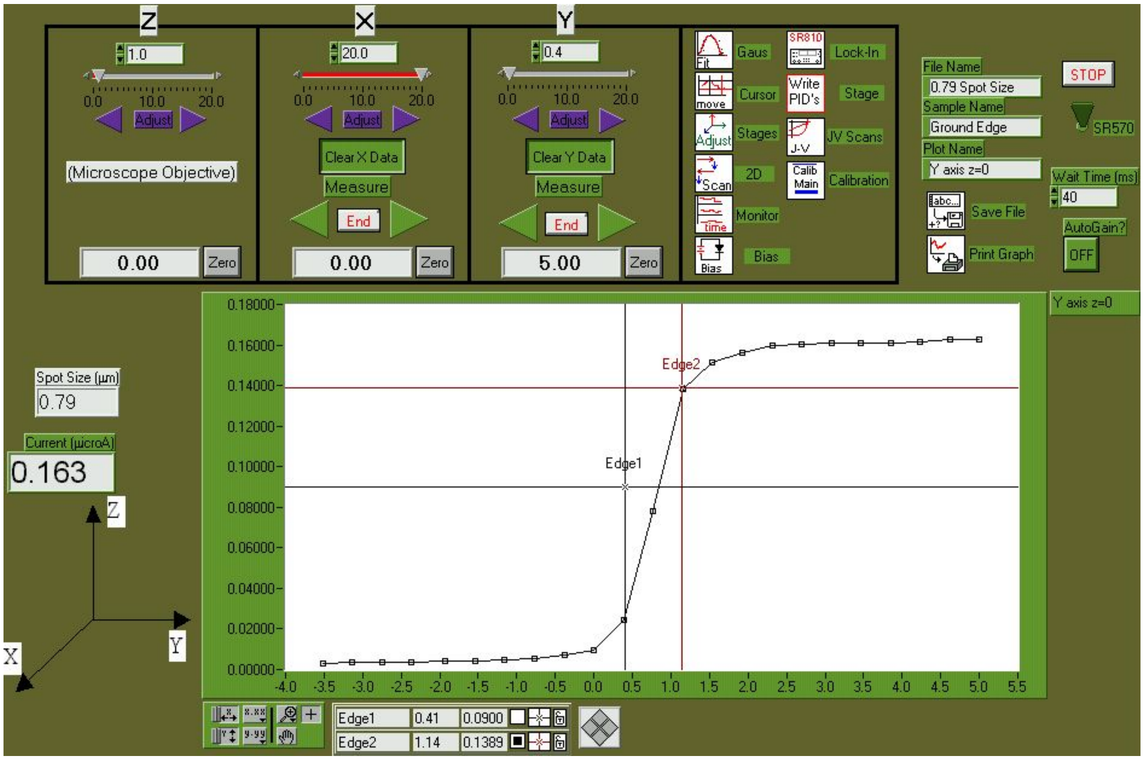
The output of the SR570 goes to the Stanford Research Systems SR810 Lock-in Amplifier. It multiplies the signal by a sine wave at the reference frequency, decreasing the effective bandwidth to a fraction of a hertz. Since the SR810 is a dual-phase lock-in, both X and Y (and thus R and ϕ) are available. Details on the theory of operation are available in the manual. The SR810 features digital signal processing; this and its ease of use make it the best lock-in on the market.

To ensure the best signal detection, the time constant (τ), sensitivity, and input parameters should all be optimized. The time constant minimum is determined by the signal frequency: τ is essentially how long the lock-in is looking at the signal, it is best to average over at least three cycles of the waveform. Therefore, for a 1 kHz signal, the time constant should be greater than 3 ms. The time between readings should exceed 3τ for independent measurements. The sensitivity is easily set by sending an auto-scale command. The signal input should be set to AC - FLOAT, to eliminate coupling to ground. The parameter R should be read to eliminate phase shift errors as the sample is translated. The phase has to date not been carefully monitored.

LabView™ Software

Overview

Software to control all experiment parameters from a single screen (Figure 10) has been developed. The main window shows a one dimensional stepping scan of the measured photocurrent as a function of position (in this case as the ground straight edge is translated through the beam at the focal point, resulting in a 0.79 µm measured spot size from a fit of the first derivative to a gaussian). Control of step sizes and



Z: 1.0 — 0.00
X: 20.0 — 0.00
Y: 0.4 — 5.00

File Name: 0.79 Spot Size
Sample Name: Ground Edge
Plot Name: Y axis z=0
Wait Time (ms): 40
AutoGain?: OFF
Y axis z=0

Spot Size (µm): 0.79
Current (µcroA): 0.163

Edge1	0.41	0.0900
Edge2	1.14	0.1389

Figure 10. Experiment control software.

other basic parameters are available on this window, others are accessed via clicking on various icons (labeled 'Gaus', 'Lock-In', etc.). In addition, other icons call sub-programs which allow the user to do two-dimensional scans, photocurrent vs. voltage measurements, etc. The software has been designed to generate immediate feedback, so that it is as easy as possible to keep track of where the beam is on the sample. 1D and 2D photocurrent versus position, current versus voltage, current versus time, as well as calibration data can be saved to data files. Comparisons can easily be done using graphing software such as SigmaPlot™.

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