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LBIC Imaging of Solar Cells: An Introduction to Scanning Probe-Based Imaging Techniques

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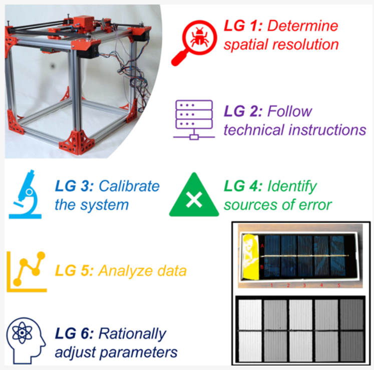
ABSTRACT: Scanning probe-based microscopes (SPMs) are widely used in biology, chemistry, materials science, and physics to image and manipulate matter on the nanoscale. Unfortunately, high school and university departments lack expensive SPM tools and materials microscopy activities to educate a large number of students in this vital SPM imaging technique. As a result, students face challenges participating in and contributing value to the nanotechnology revolution driving modern scientific innovations. Here we demonstrate an affordable scanning laser-based imaging system (approximately $400, excluding the computer) to introduce students to the point-by-point image formation process underlying SPM methods. In this laboratory activity, students learn how to construct and optimize images of a working solar panel using a laser beam-induced current (LBIC) imaging system. We envision undergraduate and graduate students should be able to use this LBIC system for independent solar energy research projects as well as apply fundamental knowledge and measurement skills to understand other SPM techniques.



KEYWORDS: *Upper-Division Undergraduate, Graduate Education/Research, Analytical Chemistry, Interdisciplinary/Multidisciplinary, Hands-On Learning/Manipulatives, Microscope Lab*

■ INTRODUCTION

Scientists routinely use scanning probe-based microscopes (SPMs) to see atoms and even manipulate matter on the nanoscale.[1] SPM techniques include atomic force microscopy (AFM), scanning tunneling microscopy (STM), and confocal Raman/photoluminescence (PL) microscopy. The common image formation principle among all SPM methods is making individual measurements in a point-by-point fashion (i.e., in x and y dimensions) and plotting the signal as a function of x,y coordinate. The probe could be a sharp tip as in AFM or STM or a focused laser spot in confocal Raman/PL microscopy.

In this laboratory activity, students learn how to construct and optimize images of a working solar panel using a laser beam-induced current (LBIC) imaging system. Imperfections in silicon can cause efficiency variations across solar panels.[2] For this reason, researchers developed LBIC to characterize the reproducibility and quality of solar panels on the assembly line.[3] In a typical LBIC imaging experiment, a focused laser spot illuminates a small spot on the solar cell while an ammeter or potentiometer measures current or voltage from the cell.[4] Early LBIC imaging systems imaged 1 cm^2 in about 15 min. The rise of the PV industry accelerated the development of high resolution and fast scanning laser-spot characterization methods.[5−12] In 2019, InfinityPV developed a scanning laser-based system that characterizes a square meter-sized solar panel in 10 s![13]

This activity introduces students to fundamental concepts in measurement science such as instrument calibration, spatial resolution, precision, and parameter optimization. After completing the activity, students should be able to use fundamental knowledge to understand other scanning probe-, light-, electron-, and X-ray-based imaging modes used in chemistry, geology, physics, and materials science.[14−21]

■ ACTIVITY OVERVIEW, LEARNING GOALS (LGs), AND IMPLEMENTATION OPTIONS

The lab has three parts. In Part 1, students perform measurements by hand to understand the point-by-point imaging principle common to SPM methods. In Part 2, students calibrate an LBIC system. In Part 3, students design and execute an imaging experiment to characterize solar panel performance. There is a Supporting Information file that describes the laboratory activity and provides representative results and solutions to assessment questions. The LBIC user

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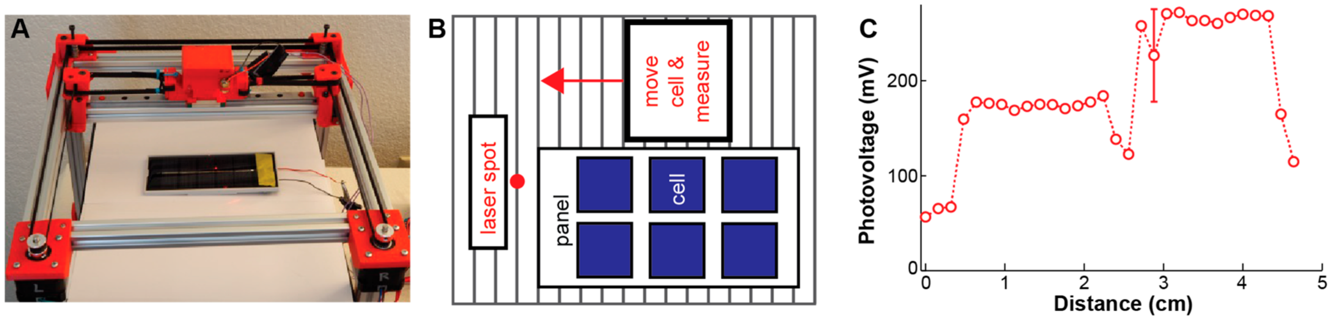

Figure 1. (A) Photograph of the LBIC imaging system with the solar panel positioned on calibrated graph paper. (B) Cartoon illustration of the manual line scan procedure. (C) Student results from a manual line profile experiment.

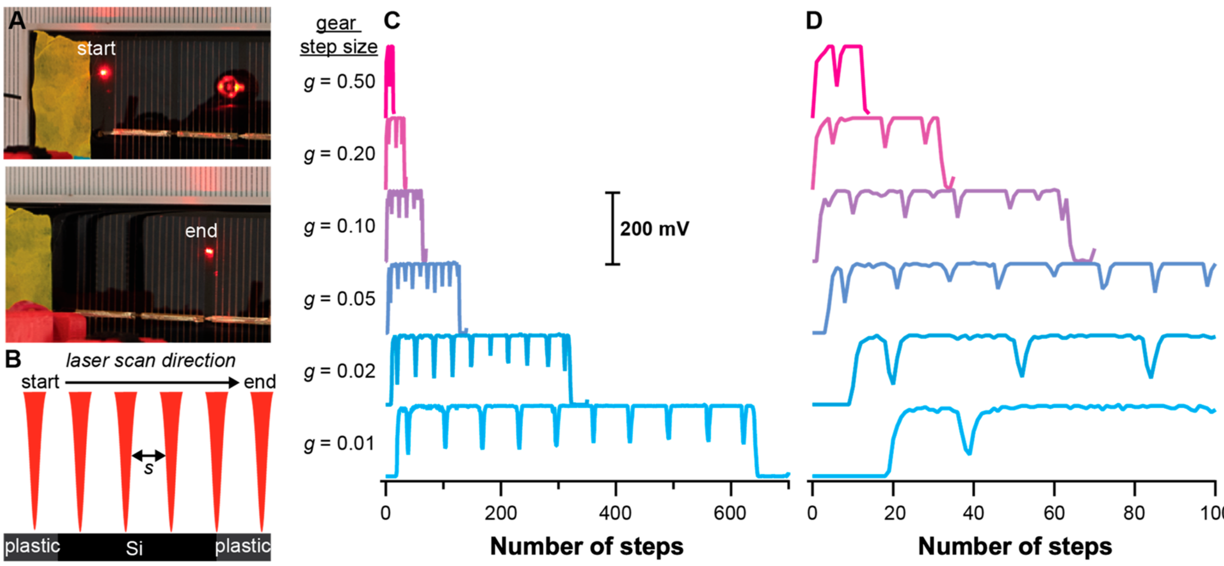

Figure 2. LBIC line scan measurements. (A) Photograph of the laser spot (top) before and (bottom) after the knife edge scan. (B) Cartoon illustration of the "knife edge" method. (C) Voltage versus distance measurements as a function of *g* (in units of mm). (D) Zoom-in view of the data in panel C for the first 100 steps.

manual Supporting Information file provides implementation options for high school, undergraduate, and graduate students.

After completing this laboratory activity, students should be able to

- LG 1: Identify essential components of an LBIC imaging system and explain what determines the spatial resolution of the method.
- LG 2: Be able to follow technical instructions to operate measurement and data acquisition systems.
- LG 3: Calibrate an LBIC imaging system.
- LG 4: Quantify how close LBIC measurements are to each other (i.e., precision) and decide whether the homemade instrument is capable of distinguishing performance variations across the solar panel.
- LG 5: Justify and use unbiased data analysis approaches to quantitatively analyze data.
- LG 6: Rationally adjust instrument parameters for desired image size, quality, and acquisition time.

■ RESULTS AND DISCUSSION

LBIC Assembly

Figure 1A shows a photograph of the assembled LBIC system. The system consists of two stepper motors (bottom of Figure 1A) connected by a pulley system. The Supporting Information provides (1) a complete parts list with prices and links to commercial vendors and (2) step-by-step written instructions and photographs for LBIC assembly. The total system cost is less than $400, making this an affordable option for high schools or undergraduate institutions. Student assembly is not required for students to operate the LBIC system. Student assembly may be appropriate for long-term independent research projects such as comparing hobby-grade solar cell performance or implementing this activity as a characterization tool for existing solar energy conversion research education activities, as described above.[22,23] The Supporting Information provides step-by-step instructions on how to operate the LBIC system.

Part 1. Fundamental Principles of LBIC Imaging

Part 1 focuses on establishing the fundamental concepts of LBIC imaging. In this part, students perform manual voltage versus distance measurements, also called single line scans, using a voltmeter. Using the experimental setup shown in Figure 1A, students measure the voltage of the solar cell as a function of laser illumination position by moving the cell on calibrated graph paper by hand (see Figure 1B; calibrated paper included in Supporting Information). Students record 3 voltage readings per position and enter the values in a spreadsheet program (e.g., Excel) according to the format

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provided in Table 1 of the Laboratory Manual (LG 2) in the Supporting Information.

In the postlab data analysis portion of the laboratory manual, students use a spreadsheet program to compute the average V ($\bar{V}$), standard deviation of the 3 measurements (s_V), and coefficient of variation (CV, in units of %) of an individual measurement with proper significant digits. In a series of assessment questions focused on LG 4, students are asked to (1) plot a line profile of the data (Figure 1C); (2) reflect on the magnitude of the signal versus noise; and (3) correlate the magnitude of the photovoltage values with solar panel features.

Part 2. LBIC Imaging System Calibration

In Part 1, students experienced point-by-point measurements by hand that are slow and tedious. In Part 2, students learn to operate and calibrate the automated LBIC system. In preparation for working with the automated LBIC system, students are asked to imagine the automated version of the Part 1 experiment. Part 2 preactivity questions (Q5 and Q6) prompt students to draw how the laser spot should move across the sample as well as write out a series of commands to execute an automated line scan. These commands must incorporate variables such as the laser spot diameter (d) and distance between measurements (s) as well as clearly articulate the timing required for laser spot and data acquisition and analysis operations. These questions assess the student's ability to achieve LGs 1, 4, and 5 which focus on fundamental principles of LBIC imaging, precision in measurement science, and being able to rationally adjust instrument parameters for desired imaging results.

The next Part 2 preactivity questions (Q7 and Q8) focus on developing an understanding of how to calibrate the LBIC instrument (LG 3) using the "knife edge" scan method.[24] This method characterizes d and s (see Figure 2B) as the stage moves the laser spot across the sample.[24] Figure 2A,B illustrates the knife edge method. In a typical measurement, the LBIC stage moves the laser spot in well-defined increments between two sharp features on the sample. The sharp feature (i.e., knife edge) shown in Figure 2A and schematically in Figure 2B is the junction between the photoactive Si and the insulating plastic. The abrupt boundary between the Si and plastic represents a knife edge because the laser will move from a photoactive area that produces a high voltage signal to a non-photo-active area that produces low voltage. The key point is the distance between the two sharp features are *known*, and the total number of steps required to traverse that known distance is used to calculate s.

We discovered students grapple with the following question: *should the distance axis be in centimeter units or arbitrary units such as "number of steps"*? This question opens an active learning opportunity for the student, which reinforces the importance of understanding how instrument settings and data collection are aligned at the start of an experimental process. This provides instructors with the opportunity to check in with students about this "x axis issue" and ask students to consider "*What is happening during the measurement?*" In the experiment, the researcher controls s by changing the stepper motor gear rotation setting (defined as parameter g, in units of mm). Once the knife edge measurement begins, the automated LBIC system acquires voltage versus position data. However, the instrument does not "know" how far the laser spot moves after each incremental step because the system is not calibrated. Instructors can emphasize that the data produced by the instrument will be voltage versus position in arbitrary units (number of steps in Figure 2) because s has not been calibrated. In summary, a series of questions in the lab manual were created to guide students through a scaffolded experience about the physical meaning of the width and peak position of the Gaussian laser profile, which are related to s, d, and the position of the knife edge, respectively (see the Student Laboratory Activity Solutions file in the Supporting Information for drawings and discussion). After completing the Part 2 preactivity questions, students should be able to explain how to execute an automated LBIC imaging experiment in terms of s and d. An additional activity to solidify student understanding could include asking students to explain their drawings and instructions to other students in the group, ensuring all students understand LBIC principles before moving to Part 2, on Calibration Measurements.

Next, students perform a series of automated line scan measurements using premade line scan .txt files provided in the Supporting Information (LG 2). All these line scan files move the laser spot across the same total distance but differ in the number of measurements per line scan. For example, one line scan file performs 10 large steps (measurements) over 2 cm whereas another file performs 500 small steps. Figure 2C,D shows student-acquired voltage versus distance data as a function of the gear step parameter g. At first, students may struggle to explain the data in Figure 2C. Small g value experiments produce larger data sets than the large g value experiments even though the laser spot travels the same total distance in all experiments. Lab activity questions encourage students to rationalize this result. A large number of measurements or total number of steps means each stage gear movement is small (i.e., small g). As a result, small g line scans take more data points per line scan and, therefore, produce higher resolution line scan data sets than large g parameter settings. The $g = 0.01$ profile shows significantly more detail than the $g = 0.50$ profile. For $g = 0.01$, the signal initially starts at 0 V and increases abruptly at 20 steps (Figure 2D, bottom trace). Then, the signal exhibits small dips (Figure 2C, bottom), likely due to the laser spot striking the bus bars. These details do not appear in the $g = 0.50$ measurement because the laser spot may or may not strike a bus bar during the large interval steps. Hence, higher resolution scans can reveal more information about solar panel performance, but they require more time. At this point in the activity, students are asked to reflect on their predictions of voltage versus distance line profiles and how or why their predictions deviated from the expected knife edge calibration results (LG 3).

Students then analyze line profile data, like that shown in Figure 2C, to determine s. To do so, students use the assumption that the laser intensity profile can be approximated as a Gaussian function, which allows them to define the laser spot diameter as the full-width-at-half-maximum (fwhm) of the Gaussian profile (Figure 2B). For each line profile experiment, students plot the derivative of the line profile data and fit the peaks with two Gaussian functions using the Supporting Information template for a two-component Gaussian fit and the Supporting Information instructional video. Questions 8–11 in the Laboratory Manual help students to recognize the physical meaning of the peak position and width of the derivative line shape. Figure 3A,B shows representative student-acquired dV/dx data and the Gaussian fit results to one knife edge as a function of g. Students calculate the real

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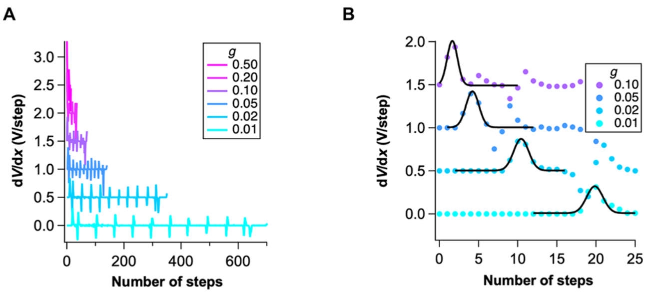

Figure 3. (A) Derivative of photovoltage versus distance data from Figure 2C. (B) Zoom-in view of selected data from (A). The solid black lines represent Gaussian fits. *g* parameter is in units of mm.

space distance of 1 step (i.e., *s* in Figure 2B) according to the following equation

$$s = \frac{\text{known total distance } (\mu\text{m})}{\text{peak separation (steps)}}$$

The key point of the Gaussian fitting is the student uses an unbiased data analysis approach instead of hand-picking data points in the derivative curve (LG 5). In addition, Gaussian fitting allows the student to determine the peak separation with substep precision, which can be used to help elucidate the importance of significant digits in measurements.

Having calculated *s* for each *g*, students can replot the data in Figure 2C,D in units of cm. Figure 4 shows calibrated voltage versus distance line scan measurements as a function of *g*. This representation of the data clearly shows each line scan spans 2 cm. However, the total number of data points per scan increases with decreasing *g*.

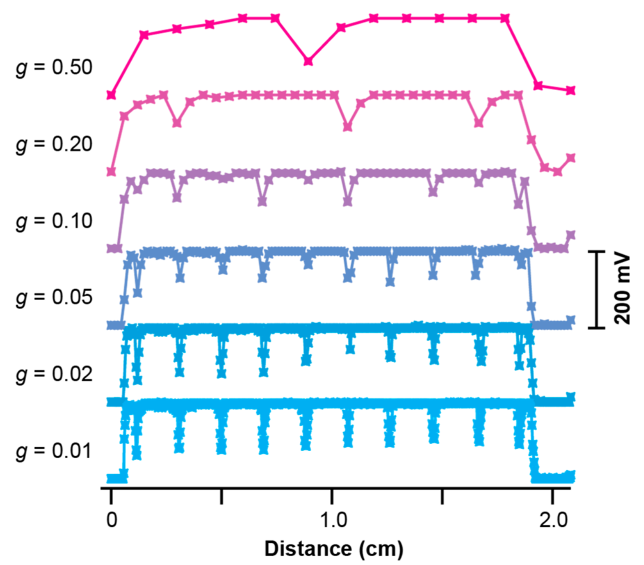

Figure 4. Voltage versus distance measurements, in units of cm, as a function of gear step size parameter *g*, in units of mm.

Next, students quantify the laser spot diameter *d* using d*V*/d*x* data. We define *d* as the fwhm of the Gaussian function, which is given by 2.355σ, where σ is the standard deviation. The peak widths for $g = 0.05$ data in Figure 3B were 1.29 and 1.02 *s* units, yielding fwhm values of ($2.355 \times 1.29s \times 0.15$ mm/step $= 4.6 \times 10^2$ μm for peak 1 and 3.6×10^2 μm for peak 2). This part of the activity and subsequent assessment questions were designed to address LG2 and LG3. The lab activity asks students to consider whether *g* should affect *d*. Students should recognize that *g* should not affect *d* by drawing the laser spot movement across the sample and explain which experimental settings likely yield accurate *d* measurements (LG 6). Students are also asked why *d* is different for the two different knife edges, which is likely related to either the angle of illumination not being perpendicular to the substrate or the knife edge not being perpendicular to the laser spot movement across the sample. Poor alignment will produce asymmetric *V* versus distance line profile results and, therefore, different *d* values for different knife edges. Following this part of the activity, students can share their results with one another or the instructor to confirm their understanding of the data collected.

The last step of Part 2 ultimately allows students to choose a desired step size for their mapping experiments in Part 3. To do so, the activity asks students to make a calibration curve of *s* versus *g*. Figure 5 shows representative student results of *s* versus *g*. The physical meaning of the linear relationship in Figure 5 is the laser spot movement along the sample is proportional to the gear step size inputted in the Arduino software. Students fit the data with a linear function to yield the proportionality constant between *g* and *s*. The proportionally constant *m* allows the student to calculate the necessary gear step size that yields a desired laser step size for any mapping experiment.

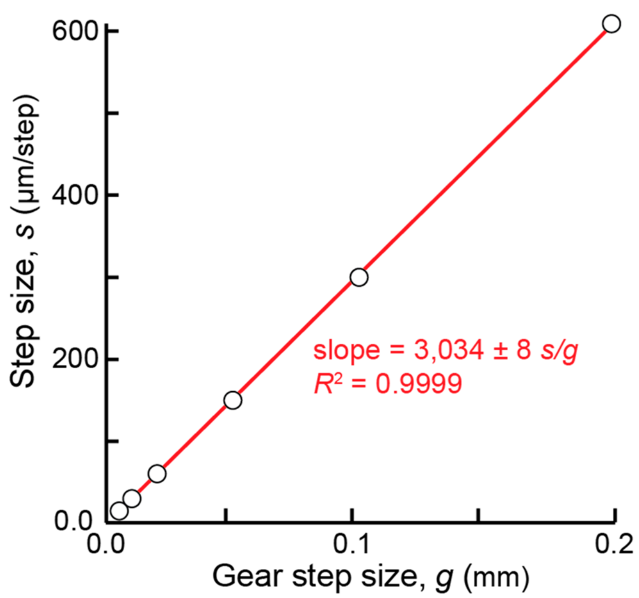

Figure 5. Student results of measured step size versus gear step size from Part 2.

Part 3. LBIC Mapping Experiments

Finally, students use the calibrated LBIC system to characterize solar panel performance across different length scales, from the single cell-level to the whole panel-level, to meet LG 6. Students are expected to choose and calculate the necessary *g* parameter that matches their desired *s* value using their calibration curve. Students are instructed to calculate the predicted experimental time and consider adjusting the image acquisition settings so they can complete the mapping experiment in a reasonable amount of time agreed upon by the lab partners and instructor. Rationally adjusting instrument parameters for desired image size, quality, and time (LG 6) demonstrates mastery of the LBIC technique and positions students to build and design their own LBIC experiments at a photovoltaic characterization facility.

Figure 6 shows representative 2D mapping results of the entire solar panel. The 351 pixel × 181 pixel LBIC voltage map

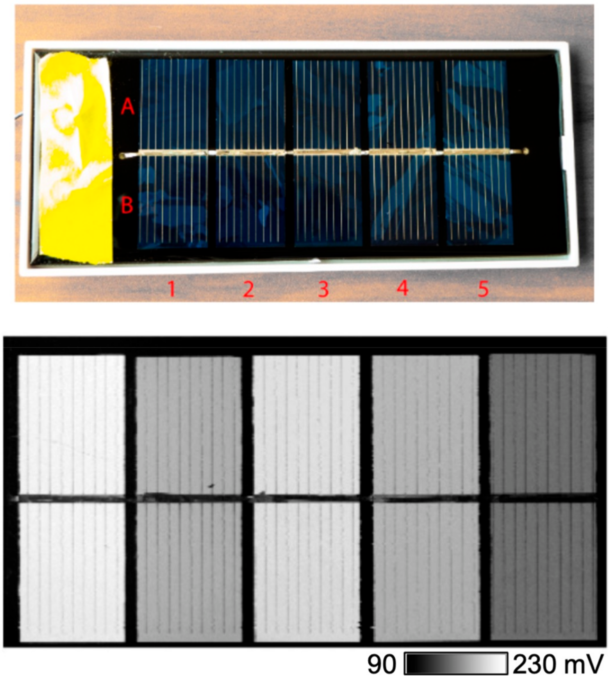

Figure 6. (top) Photograph and (bottom) 351 pixel × 181 pixel LBIC voltage map of the same panel. The LBIC image required 8 h and 1 min using a $g = 0.1$ setting. The solar panel size is 6.0 in. by 2.5 in.

required 8 h and 1 min using $g = 0.1$ mm. The "whole panel" LBIC image revealed that cells A and B in column 1 exhibited the highest photovoltage, as evidenced by the brightest contrast in the 2D map. The cell performance varied from left to right across the panel (i.e., numbered columns 1−5). However, cell performance did not vary from top to bottom (i.e., A versus B). The cell voltages decreased in the following order: 1 > 3 > 4 > 2 > 5. This result is likely due to how the cells are connected (either in series or in parallel).

Critical analysis questions in Part 3 that help address LGs 1, 4, 5, and 6 include (1) calculating the percent error between the total and predicted experimental mapping times and explaining the likely origin of the difference; (2) qualitatively describing how 2D mapping revealed performance variations across the panel; (3) explaining what system properties ultimately determine the spatial resolution of the LBIC system; and (4) explaining what changes they would make to the system to improve the resolution.

Having completed this LBIC activity, students and instructors could adapt the system for other projects. For example, the LBIC activity could be adapted to spatially resolve photoluminescence from a sample of interest. In this scenario, the experimentalist could mount a photodetector equipped with an emission filter above the sample and measure light intensity versus illumination position, being careful to reject scattered light from the sample.

■ CONCLUSION

We developed an LBIC system and complete laboratory activity for high school, undergraduate, and graduate students to spatially resolve solar cell performance. Students first perform measurements by hand to identify essential components of an LBIC imaging system. Having hopefully removed the "black box effect" of the LBIC measurement, students calibrate the instrument using a series of line scan measurements and rigorous data analyses. Finally, students use the calibrated LBIC system to design and execute an imaging experiment that characterizes solar panel performance. Scaffolded assessment questions expose students to the theory and practice behind what determines the spatial resolution of the method, how to improve the current system design while rationally adjusting the instrument parameter, and identifying the magnitude and precision in the measurements.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.2c00623.

MATLAB files to process raw data (instructions are provided in the LBIC User Manual file) (ZIP)
MATLAB files to create custom scan files (instructions are provided in the LBIC User Manual file) (ZIP)
Premade line scan map files (ZIP)
Premade 2D mapping files (ZIP)
Excel template for knife edge data analysis (XLSX)
Instructional video on Gaussian fitting in Excel (MP4)
3D printer files for parts (ZIP)
Parts list (XLSX)
Solutions for the Student Laboratory Manual (PDF, DOCX)
Described activity in the form of a Student Laboratory Manual (PDF, DOCX)
Electronic assembly instructions and parts list (PDF)
Rubric, describing how we believe students at different educational levels would respond to or "answer" the questions in the lab experiment (PDF, DOCX)
Calibration paper for handmade line scan measurements. (PDF, DOCX)
LBIC User Manual, providing complete standard operating procedures for the LBIC system (PDF)

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Notes

The authors declare no competing financial interest.

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