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Mode Notes

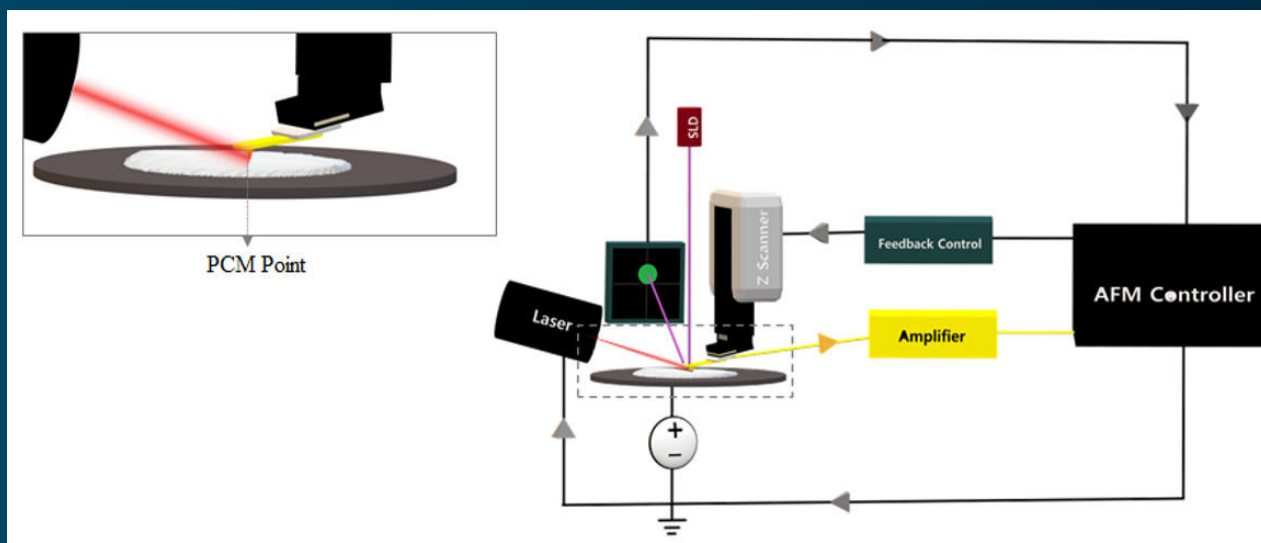
Photo-Current Mapping

Photo-induced electrical properties describe a large class of phenomena where the interaction of light and matter can be used to harness electricity. The outer photoelectric effect was first described in 1887 and has been intensively studied ever since. Nowadays, this research and the related inner photoelectric effect gave rise to a huge branch of technologies, ranging from semiconductors in everyday electronic devices to photovoltaic applications.

To advance the miniaturization of modern optoelectronics devices, the conductivity of photoactive semiconductors needs

to be studied down to the nanoscale. For photoactive semiconductors used in optoelectronic applications like solar cells, the local conductivity strongly depends on illumination. Such semiconductors will absorb light, if the photon energy is larger than the bandgap of the absorber. In that case, an electron is promoted from its bound state in the valence band into the conduction band, where it acts as a free charge carrier and thus increases the material's conductivity. Therefore, the absorption properties of a photoactive semiconductor can be measured with the change in conductivity.

Figure 1. Schematic diagram of the experimental set-up for PCM with a close-up of the external PCM laser projected to a tip-sample contact position. The feedback controller ensures a stable tip-sample contact force, while the amplifier measures the current flow between tip and sample at the given sample bias and optical excitation.



Park Systems augmented conductive atomic force microscopy with an adjustable laser that enables focused optical excitation while measuring local currents under the tip with a nano-scale resolution as well as a time resolution down to tens of microseconds.

This photo-current mapping (PCM) mode images the photo-induced current in a point-by-point approach and can capture the current decay length or other time-dependent optoelectric properties of a given sample. To fully customize the experiment for a large range of samples, the PCM mode can be conducted with three different monochrome lasers with wavelengths of 785 nm, 635 nm, and 450 nm. Moreover, Park Systems SmartScan™ software enables easy control of laser exposure parameters and mapping conditions and allows for measuring a so-called “dark C-AFM” with a switched-off feedback SLD.

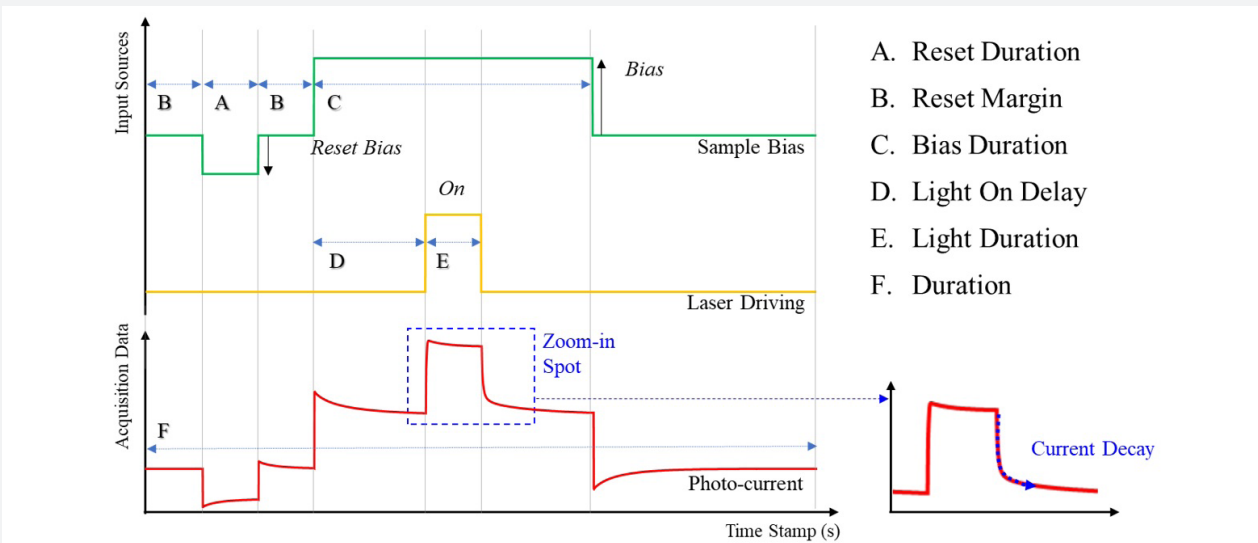
Figure 1 shows a schematic diagram of the PCM setup. Here, the external PCM laser is focused onto the contact area between tip and sample. The laser module is tilted with respect to the surface to avoid any hardware

interference or a shadowing effect from the cantilever and thus ensuring an unobstructed beam path.

Figure 2 depicts a typical data set when conducting a single photo-current measurement at a given pixel. Each measurement can be tailored to fit the respective requirements with a possibility to apply a short negative bias pulse to purge all residual charges (A) prior to the measurement, customizable duration for bias application (C) and illumination (E), as well as flexible periods between bias application (B) and illumination (D). The green curve displays the applied sample bias and the yellow line represents the illumination over time. The time-resolved current is depicted by the red curve.

While applying the negative bias pulse (A), a negative current flows between tip and sample. Accordingly, a positive current is recorded, when applying a positive bias (C). During the laser pulse (E), the sample absorbs photons and electrons are promoted into the conduction band, creating more free charge carriers and thus increase the conductivity. Hence, an increased current is measured with

Figure 2. Displays a typical photo-current measurement at one pixel. The green curve displays the applied sample bias, the yellow curve displays the laser illumination, and the red curve depicts the corresponding measured current over time. A zoomed-in graph displays the change of current with illumination and the decaying current after.



illumination. After the laser is turned off, the number of photo-excited charge carriers decreases over time, which is reflected in a time-dependent photo-current decay until the current reaches its initial level before the laser pulse.

Figure 3 (next page) shows a set of measurements on a lead halide perovskite, which is used as a photon-absorbing material for thin-film solar cells. Initial, large-scale topography and C-AFM images in Figure 3 (a) and (b) were recorded simultaneously with an applied sample bias of 2 V to identify areas of interest for the subsequent PCM measurement. PCM was conducted within the highlighted area with an image size of $0.5 \times 0.5 \mu\text{m}^2$ and at 16×16 pixels. Figure 3 (c) is a juxtaposition of the current volume image without photo-excitation and the photo-current volume image with photo-excitation. Here, the voltage bias, laser illumination, and current are measured over time for each pixel of a topographic 2D image. When displaying both volume images in identical coloring scale range, it becomes apparent that illumination with the PCM laser leads to a distinct increase

in the detected current level compared to the current volume image without illumination. The set of spectroscopy data presented in Figure 3 (d) reveals a current increase of ~ 70 nA upon PCM laser exposure at the pixel indicated in green.

Figure 4 (next page) shows another example of a photo-current measurement on a photoactive perovskite material. Here, instead of using the PCM mode, the photo-current was probed by varying the intensities of the LED illumination from the optical CCD camera without an external laser. At a sample bias of 1 V, the current image measured without LED illumination resulted in a mean current of ~ 0.3 nA (Figure 4 (b)). For the subsequent measurement, the LED illumination was gradually increased in 20 % steps from 0 up to 80 % of maximum light intensity. At 80% intensity the maximum current was ~ 1.2 nA at 1 V sample bias giving an overall increase of around 0.9 V (Figure 4 (c)).

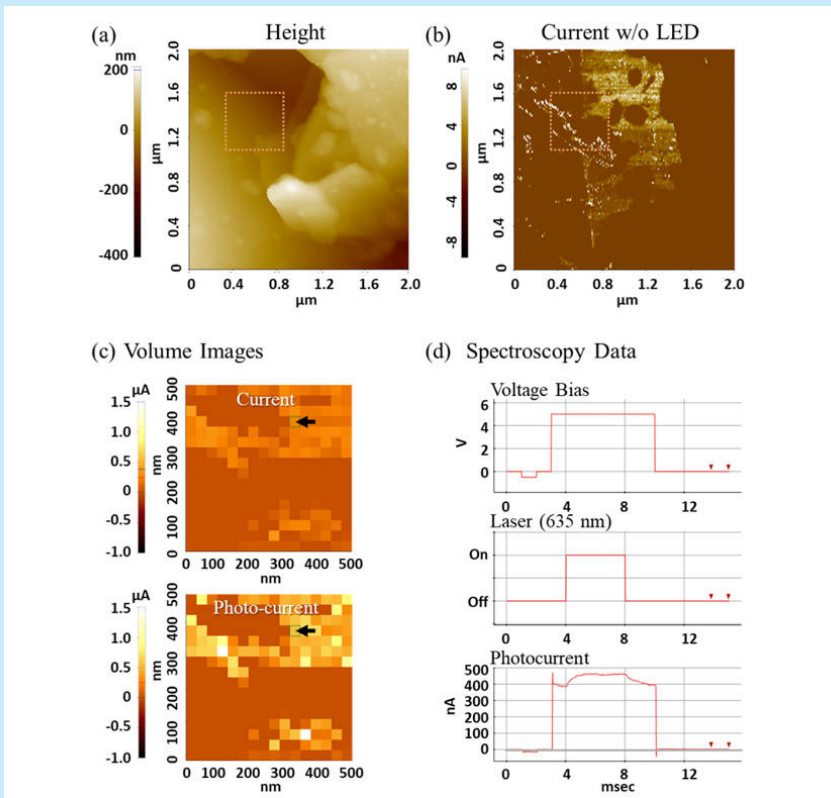


Figure 3. (a) Height and (b) current images of a C-AFM measurement on a perovskite material with an organic coating layer at 2 V sample bias. PCM was conducted in the highlighted area. (c) Current volume images without and photo-current image with illumination, (d) voltage bias, laser intensity, and photocurrent over time, measured at the indicated pixel.

Figure 4. Photocurrent measurement under different LED illumination intensities conducted on a photoactive perovskite material. (a) Height and (b) current image under 1 V of sample bias without LED light. (c) The current image at the same area with 0 ~ 80 % LED illumination intensity.

