جامعة الملك عبدالله
للعلوم والتقنية
King Abdullah University of
Science and Technology

أكاديمية كاوست
KAUST ACADEMY

Mapping Surface dynamics in solar cell materials using Ultrafast SEM

Khawlah K. Alqurashi
khawla811@outlook.com

Afnan S. Alsulami
afnansalehj@gmail.com

Mentor: Razan O. Nughays
razan.nughays@kaust.edu.sa

August 26, 2025

Contents

1 Introduction **2**

2 Methodology **2**

3 Results Discussion **4**

4 Challenges and Obstacles **6**

5 Resources and Tools Used **6**

6 Conclusion and Future Work **7**

1 Introduction

The growing demand for renewable and sustainable energy has accelerated research into advanced photovoltaic (PV) technologies. Among these, solar cells stand out as one of the most promising solutions to meet future energy needs and reduce dependence on fossil fuels. Improving solar cell efficiency requires a deeper understanding of the fundamental processes that govern device performance. In particular, the ultrafast dynamics of photoexcited charge carriers including generation, sepration, trapping, and recombination critically determine how effectively a material converts absorbed photons into usable electrical power. Comparing these dynamics across different semiconductors is essential, as variations in charge carrier dynamics directly impact photovoltaic performance. To study these processes, advanced characterization techniques capable of probing carrier dynamics on femtosecond timescales and nanometer spatial resolution are required. Gallium arsenide (GaAs) and cadmium telluride (CdTe) are two leading semiconductor materials for photovoltaic applications due to their suitable direct band gaps (1.42 eV and 1.5 eV, respectively) and strong absorption properties. However, differences in their carrier dynamics play a crucial role in determining their relative performance.While pump–probe techniques have provided valuable insights into carrier behavior, they often lack either the spatial or temporal resolution needed to probe surface and interface processes. Ultrafast scanning electron microscopy (USEM) overcomes this limitation by combining femtosecond temporal with nanometer spatial resolution, enabling direct visualization of ultrafast carrier dynamics at the surface. In this study, we employ USEM to investigate and compare the ultrafast charge carrier dynamics in GaAs and CdTe. Given the technological significance of both materials, such a comparison is essential to provide insight into material selection and design for future devices.

2 Methodology

The Ultrafast Scanning Electron Microscopy (USEM) setup as illustrated in Figure 1.integrates a ClarkMXR femtosecond fiber laser with a modified Quanta FEI-650 SEM . The laser emits infrared (IR) pulses centered at 1030 nm, with a pulse width of 270 fs. These pulses are directed through mirrors onto a beam splitter, enabling the generation of green (515 nm) and ultraviolet (343 nm) beams through second and third harmonic generators,at a variable repetition rate that can be controlled depending on the experimental requirements .in this project the laser system operates at a repetition rate of 8.33 MHz, corresponding to a 120 ns interval between pulses This delay is sufficient for the system to return to its ground state before the next excitation pulse. In this configuration, the ultraviolet beam is used to trigger the SEM's electron gun via photoemission, generating pulsed electron beams instead of relying on conventional continuous thermal emission. At the same time, the green beam is focused onto the sample inside the SEM, resulting surface excitation. Temporal control of the experiment is achieved using an optical delay line, which adjusts the relative arrival times of the optical and electron pulses to

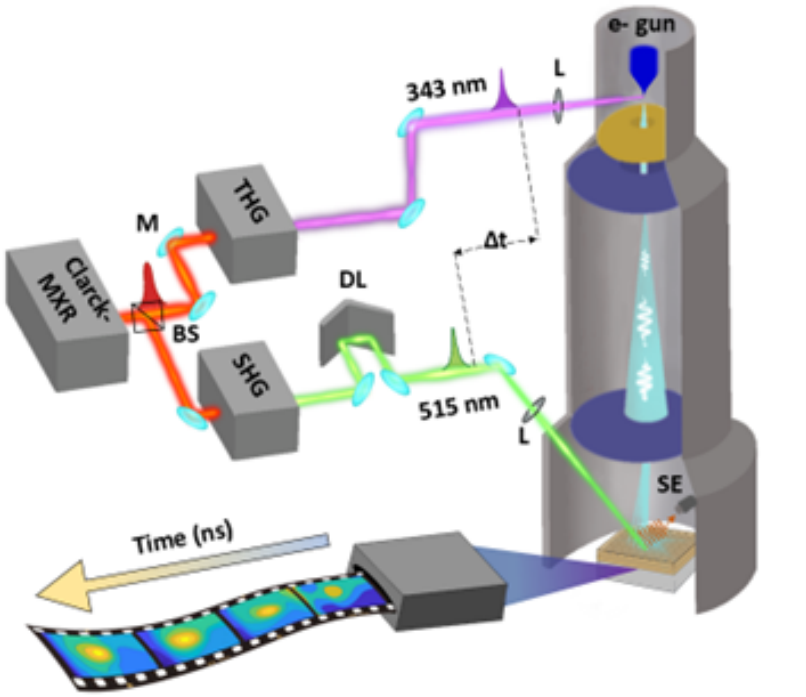


Figure 1: Schematic diagram of the USEM experimental setup used in this work. The electron pulse is scanned over the surface that is illuminated with the photon pulse. The SE emitted from the sample surface are collected to construct time-resolved images at various time delays between the photon and electron pulses.

define the time axis of the time-resolved images recorded. The working distance between the pole piece and the sample is fixed at 10 nm . As the pulsed electrons interact with the optically excited sample, they generate secondary electrons from the surface regions. These emitted electrons are collected by a positively biased Everhart–Thornley detector. To reduce noise and enhance image clarity, the final image is constructed by averaging 64 individual frames, each captured with a 100 ns exposure. During the experiment in this work,the green beam power is maintained at 1.7 mW for both GaAs and CdTe and the electron beam operates at an acceleration voltage of 30 keV . by using USEM, we acquired time-resolved images before and after excitation. Subtracting the pre-excitation (baseline) frames from the post-excitation frames in MATLAB produced difference images that isolate pump-induced changes, highlight contrast in the illuminated region, and enable investigation of charge carrier dynamics in GaAs and CdTe. The GaAs and CdTe samples in this project were used as received without further treatment. We cut the samples to expose clean,fresh edges for characterization[1] [2].

3 Results Discussion

To examine the ultrafast charge carrier dynamics in GaAs and CdTe, USEM measurements were conducted under two probing regimes. The first is the photon–electron regime (positive time), where the optical pulse reaches the surface before the electron pulse. The second is the electron–photon regime (negative time), where the electron pulse arrives before the optical pulse. In the two probing regimes, the resulting SE signals appear in the time-resolved images either as bright contrast (corresponding to SE energy gain) or as dark contrast (corresponding to SE energy loss). The observed contrast depends primarily on the number of secondary electrons emitted from the surface and detected by the detector. The surface response observed in GaAs, as shown in Figure 2a, further

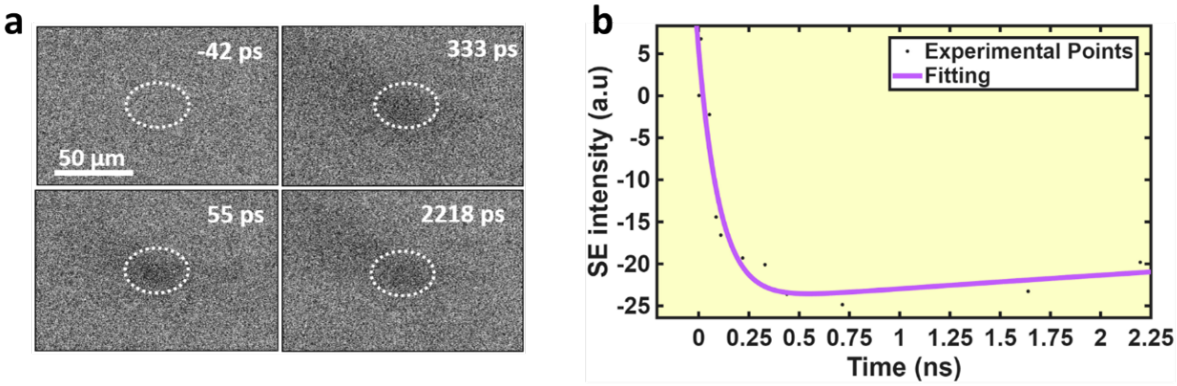


Figure 2: (a) Time-resolved SE images of GaAs at different time delays (b) Extracted dynamics of the time-resolved SE, where the x-axis represents the delay between the optical and electron beams, and the y-axis represents SE intensity.

illustrates the differences between the two probing regimes. At early negative time delays, when the electron pulse arrives before the optical pulse, no significant response is detected on the GaAs surface. However, at positive time delays , when the optical pulse excites the surface then the electron pulse probe it , a dark contrast gradually appears within the elliptical region that marks the laser-irradiated area. This contrast intensifies over time, then begins to fade, indicating that the observed contrast in the positive time regime is related to photon-induced carrier dynamics, as previously observed in earlier studies . In this regime, electron-impact effects are excluded, The reduction in secondary electron emission is mainly attributed to scattering between photoexcited carriers traveling toward the surface. The observed dynamics Figure 2b exhibit an initial decrease in intensity followed by a recovery process, with the characteristic lifetime estimated to be on the order of 500 ps.

For CdTe, there are 3 key observations: (i) dark contrast at negative time, (ii) a flip in signal at early positive time from dark contrast to bright contrast, and (iii) the SE intensity decreases rapidly, indicating fast recovery. The initial dark contrast represents a response due to scattering, related to electron–matter interactions that cause energy loss. Then the change in contrast occurs when the optical pulse arrives first, promoting

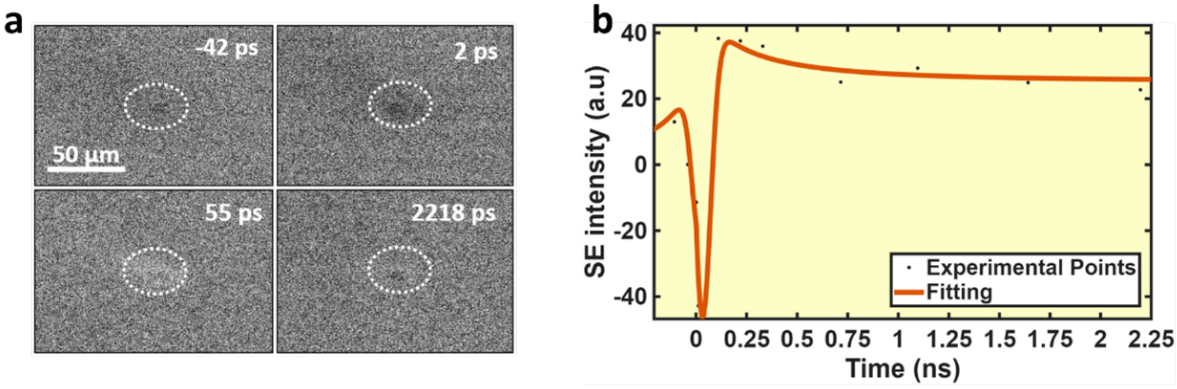


Figure 3: (a) Time-resolved SE images of CdTe at different time delays (b) Extracted dynamics of the time-resolved SE, where the x-axis represents the delay between the optical and electron beams, and the y-axis represents SE intensity.

electrons to the conduction band, and when the electron pulse arrives later, it provides an energy-gain mechanism for the photoexcited electrons. Figure 3a illustrates all these changes in CdTe. Dynamically, Figure 3b shows this flipping of contrast as a rapid fall and rise (spike-like feature), with a recovery time of approximately 250 ps.

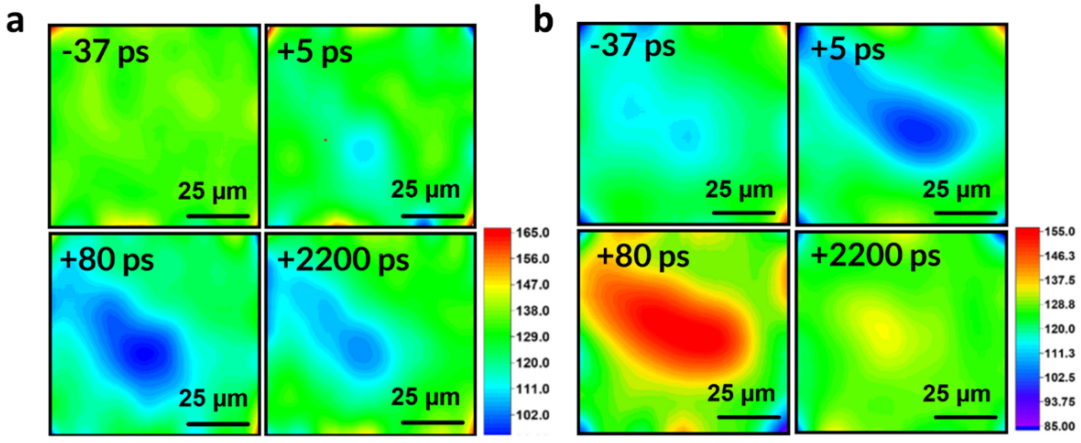


Figure 4: False-colored USEM images of (a) GaAs and (b) CdTe

We used Origin to convert the USEM images into false-colored maps in order to visualize the contrast differences and recovery more clearly. In these maps, the red regions represent higher SE intensity (energy-gain mechanism), while the blue regions correspond to lower SE intensity (energy-loss mechanism). As shown in Figure 4, the charges gradually spread over time, indicating diffusion occurring on both GaAs and CdTe surfaces.

In conclusion, GaAs exhibits a longer lifetime than CdTe, which reflects better charge carrier behavior and makes it more suitable for achieving higher efficiency in solar cells, depending on charge carrier dynamics. This agrees with previous studies that have demonstrated the superior efficiency of GaAs compared to CdTe[3] [4].

4 Challenges and Obstacles

The primary challenge in this project was mastering data analysis and find the perfect fitting of time-resolved USEM datasets. While the laboratory setup and instrumentation operated flawlessly, processing and interpreting the multidimensional data required proficiency with tools such as MATLAB and Origin, as extracting meaningful parameters like carrier lifetimes depends on careful analysis. Although initially demanding, this challenge provided a valuable opportunity to strengthen analytical and computational skills, improve data interpretation abilities. Overcoming these obstacles contributed significantly to our development as a researchers and enhanced our abilities to conduct scientific investigations.

5 Resources and Tools Used

In this project, the primary tool utilized was the Ultrafast Scanning Electron Microscope (USEM), which provides femtosecond temporal resolution combined with nanometer scale spatial resolution. This setup is a combination of an ultrafast laser system (Clark-MXR) synchronized with a modified Quanta FEI-650 SEM, enabling direct visualization of charge carrier dynamics at semiconductor surfaces and interfaces. The study also relied on semiconductor samples (GaAs and CdTe) prepared with clean and controlled surfaces to ensure accurate measurements. For data processing and analysis, software tools such as MATLAB and Origin (for color mapping, curve fitting, and plotting) were used. Supporting resources included relevant literature databases and scientific articles, which provided theoretical background and benchmarks for comparison.

6 Conclusion and Future Work

by using Ultrafast Scanning Electron Microscopy (USEM), this project revealed time-resolved carrier dynamics in GaAs and CdTe By directly visualizing surface photogenerated charge behavior in real space and time, we were able to highlight the distinct lifetimes and contrast behaviors of the two materials. These insights provide a deeper understanding of how intrinsic material properties influence ultrafast carrier processes, which is essential for optimizing their performance in photovoltaics applications. Future work could extend this approach to explore other semiconductor materials, such as perovskites, which have shown great potential in photovoltaic technologies. Furthermore, the study could be expanded to investigate the influence of crystal orientation as well as the effects of surface passivation treatments on enhancing carrier dynamics. These directions would broaden the scope of the research and provide a more comprehensive understanding of ultrafast carrier dynamics in various material systems.

References

[1] Jingya Sun et al. "Real-space imaging of carrier dynamics of materials surfaces by second-generation four-dimensional scanning ultrafast electron microscopy". In: *The Journal of Physical Chemistry Letters* 6.19 (2015), pp. 3884–3890.

[2] Jianfeng Zhao et al. "Access to ultrafast surface and interface carrier dynamics simultaneously in space and time". In: *The Journal of Physical Chemistry C* 125.27 (2021), pp. 14495–14516.

[3] Jongweon Cho, Taek Yong Hwang, and Ahmed H Zewail. "Visualization of carrier dynamics in p (n)-type GaAs by scanning ultrafast electron microscopy". In: *Proceedings of the National Academy of Sciences* 111.6 (2014), pp. 2094–2099.

[4] Ahmed M El-Zohry et al. "Extraordinary carrier diffusion on CdTe surfaces uncovered by 4D electron microscopy". In: *Chem* 5.3 (2019), pp. 706–718.