

Spectrally Resolved OCVD Investigation of Surface and Bulk Recombination in Silicon Photovoltaic Materials [†]

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Abstract

The developed spectrally selective open-circuit voltage decay (OCVD) system uses pulsed LEDs to probe carrier recombination at varying depths in monocrystalline and multicrystalline silicon solar cells. Full-size c-Si cells exhibit a 15 ms voltage decay under broad-spectrum illumination, while $2 \times 2 \text{ cm}^2$ mini-cells with a 5 mm LED spot reveal localized decays around 300 μs . Low-temperature annealing at 115 °C for 3 min enhances surface passivation, shown by increased decay times under blue (458 nm) excitation. In contrast, infrared (864 nm) excitation indicates minimal improvement in bulk carrier lifetime. This technique effectively differentiates surface from bulk recombination, providing valuable insights for optimizing passivation strategies in silicon solar cells.

Keywords: silicon solar cells; carrier lifetime; recombination; OCVD technique; surface passivation

1. Introduction

Crystalline silicon remains the dominant material in photovoltaic technologies due to its favorable electronic properties and scalability [1–4]. However, performance limitations arising from recombination losses, particularly at interfaces and in defect-rich regions, continue to challenge the efficiency potential of both monocrystalline (c-Si) and multicrystalline silicon (mc-Si) solar cells [5,6]. In fact, the efficiency of solar cells is fundamentally governed by the dynamics of charge carriers within the semiconductor material. A critical figure of merit in this regard is the minority carrier effective lifetime (τ_{eff}), which quantifies how long carriers exist before recombining. A longer lifetime indicates superior material quality and lower defect density, directly correlating with higher open-circuit voltages (V_{oc}) and overall device efficiency [7]. Therefore, precise characterization of τ_{eff} is indispensable for optimizing manufacturing processes and evaluating material quality. While traditional lifetime measurement techniques such as quasi-steady-state photoconductance (QSSPC) and microwave-detected photoconductance decay (μPCD) provide valuable bulk and surface insights [8–10], they often lack temporal resolution. The open-circuit voltage decay (OCVD) technique offers a dynamic probing of recombination kinetics under transient excitation [11–13], making it sensitive to material quality and processing variations [14].



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Initially developed in the 1950s for germanium diodes, this method was quickly applied to silicon (Si) devices. Since then, it has evolved from a traditional technique for determining minority carrier lifetime in crystalline Si p-n junctions to a versatile tool for analyzing complex recombination kinetics in new solar cell technologies, including amorphous silicon [15], organic [16] and perovskite solar cells [17,18]. It involves analyzing the decay kinetics of the voltage after the cessation of forward bias or illumination. In general, the OCVD response can be divided into three distinct phases. The first phase shows a sharp decline in voltage, primarily caused by the influence of the series resistance. This is followed by a second phase, governed by the diffusion and recombination of minority carriers as they move through the quasi-neutral regions. The final phase reflects the behavior of the space-charge region, where its capacitance slows the rate of voltage decay. The second phase is the one typically analyzed for determining carrier lifetime, as it displays an approximately linear voltage decrease whose slope is inversely related to the lifetime τ_{eff} .

$$\tau_{eff} = -\frac{\eta k_B T}{q} \frac{1}{dV/dt} \quad (1)$$

Here, η denotes the ideality factor of the p-n junction, k_B represents the Boltzmann constant ($J \cdot K^{-1}$), T is the absolute temperature expressed in kelvin, q is the elementary charge measured in coulombs, and dV/dt corresponds to the rate at which the voltage decreases ($V \cdot s^{-1}$).

The linear slope of the voltage decay curve allows us to determine the bulk lifetime of the material, separating it from surface recombination effects.

Here, we implement a custom OCVD system with spectral-selective illumination to comprehensively evaluate recombination dynamics across device architectures and treatment conditions. This study validates the OCVD technique as a powerful, spatially resolved, non-destructive diagnostic tool for silicon-based photovoltaic applications.

2. Material and Methods

P-type silicon wafers ($10 \times 10 \text{ cm}^2$) were used, including monocrystalline ($380 \mu\text{m}$, $2.5 \Omega\text{cm}$) and multicrystalline ($280 \mu\text{m}$, $1.0 \Omega\text{cm}$) types. Phosphorus diffusion formed the n-type emitter, and wafers were passivated with hydrogenated silicon nitride ($\text{SiN}_x\text{:H}$) via PECVD. Aluminum back surface field (Al-BSF) solar cells were fabricated by standard industrial processes [19]. A subset was cut into $2 \times 2 \text{ cm}^2$ mini-cells for localized OCVD analysis before and after thermal annealing (115°C , 3 min). The overall experimental methodology, including wafer processing and characterization workflow, is summarized in Figure 1.

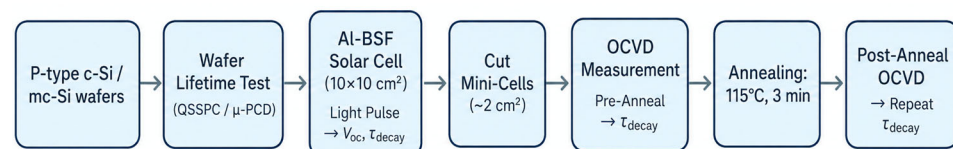


Figure 1. Methodology flowchart for the fabrication and characterization of c-Si and mc-Si solar cells.

The OCVD technique measures voltage decay after pulsed excitation to extract the injection-dependent decay time (τ_{decay}), which is sensitive to the interface and bulk recombination [13,20–22]. Figure 2 shows the OCVD measurement system developed to characterize silicon solar cells. The system was specifically designed to investigate carrier recombination dynamics under pulsed illumination with high temporal resolution. The custom OCVD system utilizes transparent color LEDs with a spot size of approximately 5 mm in diameter for mini-cell excitation, and a high-power 10 W white lamp providing a broad excitation area exceeding 10 cm diameter for full-size cells. The pulse generation and

synchronization were managed using an Arduino microcontroller interfaced with MATLAB/Simulink (MATLAB R2016a), enabling precise control of pulse timing. Pulse durations were configured at 500 μs for mini-cells and extended to 100 ms for full-size cells, in accordance with their respective optoelectronic requirements. A second Arduino microcontroller was employed for V_{oc} acquisition, allowing high-resolution, time-resolved measurements.

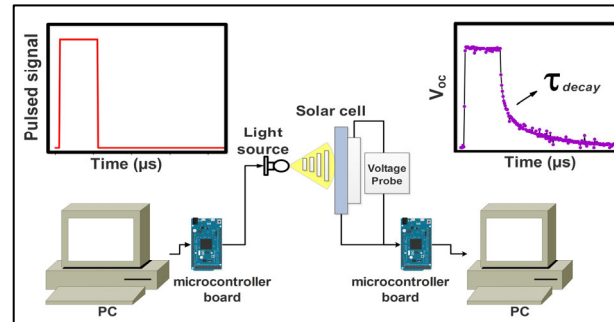


Figure 2. Schematic illustration of the OCVD measurement custom system.

The decay time (τ_{decay}) is extracted by fitting the open-circuit voltage (V_{oc}) decay curve to a single exponential function [20]:

$$V_{oc} = V_0 e^{-\frac{t}{\tau_{decay}}} \quad (2)$$

where V_0 corresponds to the open circuit-voltage at steady state. At low light injection levels, minority carrier behavior dominates the recombination dynamics. This approach aligns with the small-signal OCVD method, where the exponential decay regime is well-established for low-injection conditions [23,24].

The spectral intensity profiles of the employed light sources were analyzed, as illustrated in Figure 3. These profiles are critical for assessing depth-selective carrier generation and associated recombination behavior. Measurements obtained using a UV-VIS-NIR spectrometer show distinct emission characteristics for each light source. These LEDs feature a round, transparent head with a 3 mm diameter and 18 mm pin length. Their forward voltages are from 2.0 to 3.2 V with a maximum current of 20 mA.

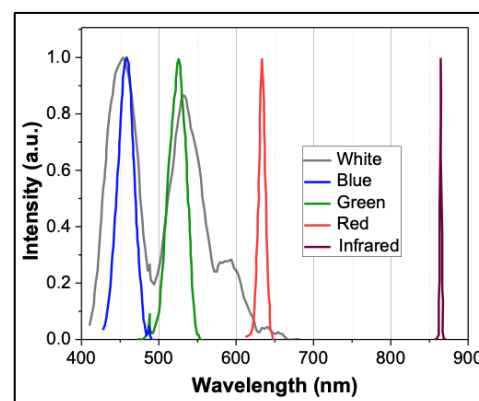


Figure 3. Spectral intensity distribution of the employed light sources. The emission profiles were measured using UV-VIS-NIR spectrometry.

3. Results and Discussions

A comparative analysis of QSSPC (Sinton WCT-120) and μPCD (Semilab WT-2000) measurements reveals that c-Si wafers exhibit significantly higher minority carrier lifetimes (τ) than mc-Si wafers, owing to their superior crystalline quality and lower defect density.

QSSPC results indicate lifetimes of 50 μs for c-Si and 20 μs for mc-Si, while μPCD minority carrier lifetime maps shown in Figure 4 reveal even higher values of 63 μs for c-Si and 25 μs for mc-Si highlighting the impact of grain boundary-induced defects in mc-Si that enhance the recombination rate, thereby reducing carrier lifetime [25]. The higher τ values observed with μPCD are attributed to its localized sensitivity to surface passivation quality [14,26].

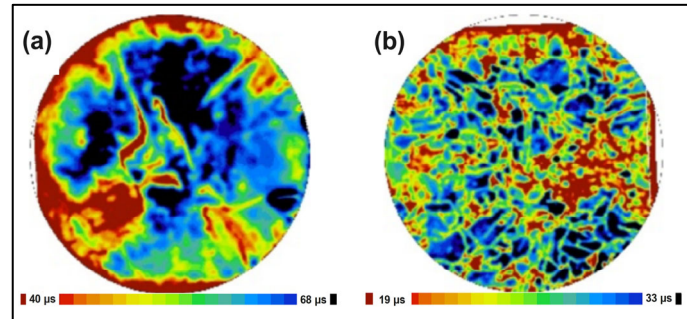


Figure 4. μPCD lifetime mapping comparison of: (a) c-Si and (b) mc-Si wafers.

The markedly long open-circuit voltage decay observed in the monocrystalline silicon (c-Si) solar cell extending beyond 15,000 μs (15 ms) under high-power white-lamp excitation (Figure 5a), is attributed to both the superior crystal quality of the c-Si material and the large active volume of the full-size $10 \times 10 \text{ cm}^2$ device [27]. The extended 100 ms illumination pulse and the broad excitation area exceeding 10 cm generate a substantial excess carrier population, leading to a slow voltage decay as recombination dominates [28]. In contrast, the localized response of the $2 \times 2 \text{ cm}^2$ mini-cells exhibits a small-signal decay ($\tau_{\text{decay}} \approx 300 \mu\text{s}$), characteristic of the microsecond regime (Figure 5b). This pronounced difference mainly arises from the distinct measurement approaches: the white-lamp excitation probes the voltage collapse over the entire device under high-injection steady-state conditions, whereas the 5 mm LED spot combined with a short 0.5 ms pulse isolates the intrinsic electronic lifetime by fitting the late-stage exponential decay [20]. Furthermore, the confined LED illumination allows spectrally selective excitation, enabling spatial localization of recombination centers. This capability distinctly separates surface and bulk recombination effects, which would otherwise be averaged under broad-area illumination from the white lamp [24].

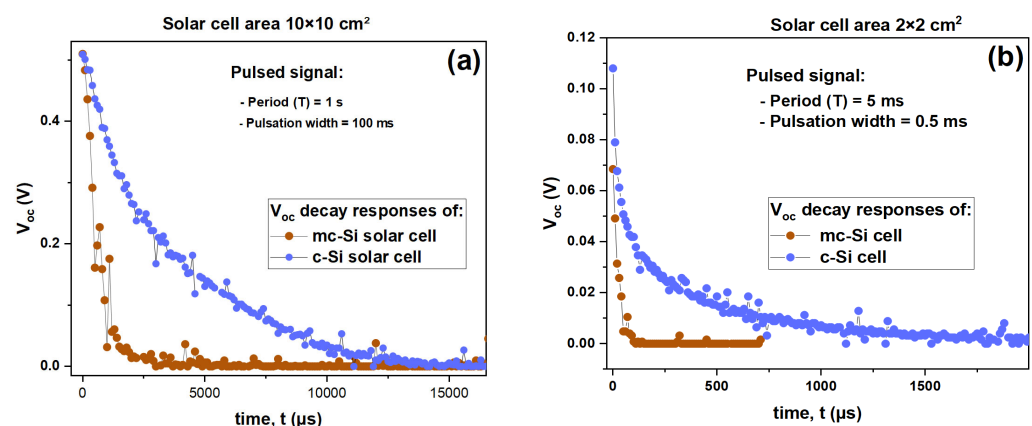


Figure 5. Open-circuit voltage (V_{oc}) decay responses of c-Si and mc-Si solar cells under: (a) high-power white-lamp excitation, and (b) 633 nm wavelength LED excitation.

The spectral-dependent OCVD measurements presented in Figure 6 utilize the varying photon penetration depths of different LED sources to spatially resolve the effects of thermal annealing on carrier recombination. Blue light at short wavelengths (458 nm) is absorbed

close to the surface, producing most of its excess carriers in the n-type emitter and near the Si/SiN_x:H interface [29]. The marked relative improvement in open-circuit voltage (V_{oc}) under this excitation for both c-Si and mc-Si following annealing at 115 °C confirms that the treatment mainly enhances surface passivation through hydrogen redistribution and passivation of interface dangling bonds [30]. Conversely, infrared light (864 nm), with the lowest photon energy, penetrates deeply into the silicon bulk, generating carriers essentially within the p-type base region. The consistently high baseline V_{oc} values under 864 nm excitation for both cell types indicate good intrinsic bulk quality, while the limited relative improvement after annealing, especially in the mc-Si sample, suggests that the low-temperature annealing has minimal effect on bulk-related defect states [31]. Intermediate wavelengths, including green (524 nm) and red (633 nm), probe the transition region between surface and bulk, and their corresponding V_{oc} responses reflect a combined influence from interface and near-surface bulk recombination [32].

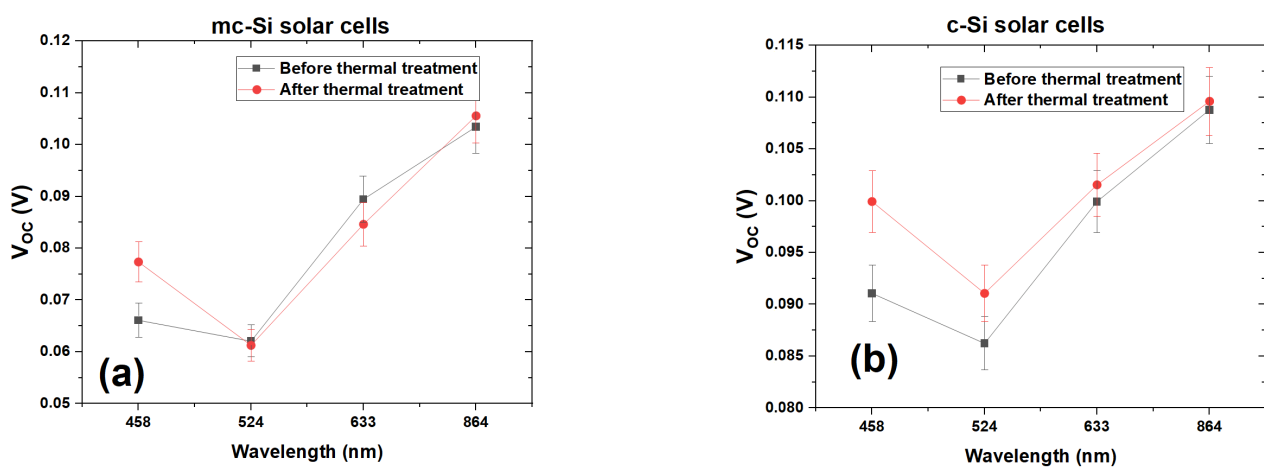


Figure 6. Open-circuit voltage (V_{oc}) values extracted from OCVD curves for (a) mc-Si and (b) c-Si solar cells under pulsed illumination from different LED sources, before and after annealing at 115 °C for 3 min.

The decay time (τ_{decay}) evolution shown in Figure 7 under spectrally selective excitation correlates directly with variations in carrier recombination lifetime at specific depths probed by each LED wavelength. Blue light (458 nm) generates carriers predominantly at the Si/SiN_x:H interface and within the shallow emitter region. The significant, uniform increase in τ_{decay} across blue, green (524 nm) and red (633 nm) wavelengths for the c-Si cell confirms that the 115 °C annealing effectively enhances surface quality through improved hydrogenation-induced passivation. In contrast, infrared excitation (864 nm), which penetrates deeply into the p-type bulk region, shows a moderate lifetime improvement in the c-Si device but minimal change in the mc-Si cell, which displays a much lower τ_{decay} baseline. This limited response to the infrared excitation indicates that the low-temperature anneal is largely ineffective against bulk defects such as grain boundaries and dislocations dominating recombination in mc-Si cells [33]. Thus, the distinct spectral dependencies observed in τ_{decay} highlight differing dominant recombination mechanisms governing each silicon material type.

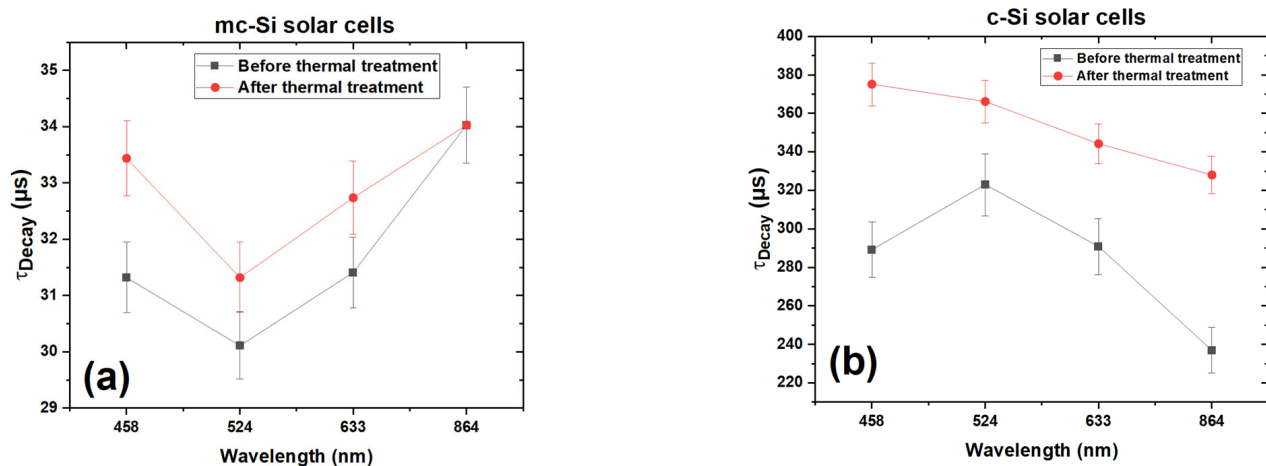


Figure 7. Time decay evolution for (a) mc-Si and (b) c-Si silicon solar cell under pulsed illumination from different LED sources, before and after 115 °C thermal treatment.

4. Conclusions

A novel, spectrally selective OCVD system has been developed and applied to study carrier recombination dynamics in monocrystalline and multicrystalline silicon solar cells. This technique overcomes the limitations of conventional methods by combining spatial localization with wavelength-dependent excitation, enabling precise differentiation of surface and bulk recombination phenomena. Thermal annealing at 115 °C was shown to substantially improve surface passivation, particularly in c-Si devices, while bulk-related recombination remained largely unchanged, especially in mc-Si devices. The approach offers a powerful, non-destructive diagnostic tool with significant potential to guide optimization of passivation and fabrication processes in silicon photovoltaic manufacturing.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/engproc2026147008/s1>, Presentation slides delivered at the 3rd International Online Conference on Energies (IOCEN 2026), 12–15 May 2026.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Al-BSF	Aluminum Back Surface Field
c-Si	Monocrystalline Silicon
LED	Light Emitting Diode
mc-Si	Multicrystalline Silicon
OCVD	Open-Circuit Voltage Decay
PECVD	Plasma Enhanced Chemical Vapor Deposition
PV	Photovoltaic
QSSPC	Quasi-Steady-State Photoconductance
SiN _x :H	Hydrogenated Silicon Nitride
UV-VIS-NIR	Ultraviolet–Visible–Near-Infrared
Voc	Open-Circuit Voltage
μPCD	Microwave Photoconductance Decay
τ_{eff}	Effective Minority Carrier Lifetime
τ_{decay}	Decay Time

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