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A Review of Minority Carrier Recombination Lifetime Measurements

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Abstract: The recombination lifetime of minority carriers is a critical parameter in semiconductor devices such as photovoltaic cells since it controls the efficiency of such devices. Many techniques have been developed to accomplish recombination measurements and thereby test semiconductor devices' efficiencies. Recombination lifetime average values differ according to semiconductor device type; thus, choosing an appropriate technique is important. This paper studies the concept of excess minority carrier lifetime and its calculations. It also investigates the advantages, limitations, and capabilities of the most common recombination lifetime measurement techniques. A chart was drawn with all known measurement methods to make it easier to understand the relation between these techniques.
Keywords: Efficiency, minority carriers, measurement techniques, recombination lifetime, Excess Minority Carrier Lifetime

I. INTRODUCTION

Minority carrier recombination is a phenomenon that occurs in semiconductors. Semiconductors are materials that have electrical conductivity between conductors and insulators. The conductivity of semiconductors can be increased by introducing impurities into the material, which creates excess electrons or holes. These excess carriers are called minority carriers because they are present in smaller numbers than the majority carriers (electrons or holes) [1]. In a semiconductor, when an electron and hole meet, they can recombine and release energy in the form of light or heat. This process is called minority carrier recombination. The rate at which minority carrier recombination occurs depends on several factors such as temperature, doping concentration, and the presence of defects. Minority carrier recombination plays an important role in electronic devices such as solar cells and transistors. In solar cells, it is desirable to minimize minority carrier recombination to increase efficiency [1]. The lifetime of photo-generated excess minority carriers is a significant property of semiconductors, especially in photonics and photovoltaic fields. This property is mainly employed to estimate the performance of many devices such as photovoltaic cells [2]. There is always a need for effective techniques to measure this fundamental property and estimate the efficiency of photovoltaic devices [1]. It is imperative to understand the mechanism of the recombination process of minority carriers to comprehend the practical measurements of the lifetime. Recombination typically occurs on both surfaces as well as in the bulk region of a solar cell. Thus, the effective lifetime of minority carriers in photovoltaic cells mainly depends on the minority carrier lifetime at surfaces and in the bulk region. Many techniques and methods have been developed to measure the lifetime. These techniques can be generally classified as direct and indirect measurement techniques depending on their methods to measure recombination lifetime. Direct techniques are typically directly applied to give the exact measurements of the effective minority carrier lifetime by changing conductivity or reversing the characteristics of the semiconductor. Indirect techniques measure other properties of solar cells, which can be used to estimate the lifetime [1–3]. This paper investigates the concept of minority carrier effective lifetime in photovoltaic operations. In addition, it presents a review of the most common experimental methods that are implemented in recombination lifetime measurements.

II. CONCEPT OF EXCESS MINORITY CARRIER LIFETIME (EMCL)

Excess Minority Carrier Lifetime (EMCL) refers to the duration of time in which minority carriers, such as electrons or holes, remain in a semiconductor material before recombining with majority carriers. The longer the EMCL, the greater the efficiency of electronic devices such as solar cells and transistors [4]. The EMCL is affected by several factors including the quality of the semiconductor material, doping levels, and temperature. Higher-quality materials with fewer defects tend to have longer EMCLs. Doping can also play a role in increasing or decreasing EMCLs depending on whether it introduces impurities that trap minority carriers. Temperature can affect EMCLs by increasing or decreasing carrier mobility and recombination rates. In solar cells specifically, a longer EMCL means that more photons can be absorbed and converted into electrical energy before recombination occurs [4].

Recombination mechanisms are critical parameters in solar cells since they refer to the processes by which electron–hole pairs lose their energies to stabilize in lower energy positions. The recombination rate, which affects the efficiency of the solar cell, mainly depends on the number of excess carriers in a semiconductor [5].

A. Bulk Recombination Mechanisms

Bulk recombination mechanisms refer to the various processes that contribute to the recombination of electron-hole pairs in a semiconductor material. These mechanisms are crucial in determining the efficiency of solar cells and other electronic devices that rely on semiconductors. Understanding and controlling bulk recombination mechanisms is essential for improving device performance. By reducing defects in materials and optimizing device design, we can minimize these losses and improve overall efficiency. There are typically three mechanisms of recombination that can occur in a single-crystal semiconductor. These mechanisms are:

1) *Radiative Recombination:* It is a process that occurs when an ion and an electron combine to create a neutral atom, emitting radiation in the form of photons. It is also known as band-to-band recombination. The electron, which is located in the conduction band, recombines with a hole in the valence band. The emitted energy is given off as a photon [4, 6]. This phenomenon is observed in various natural and artificial systems, including stars, plasmas, and semiconductors. In semiconductors, radiative recombination is responsible for producing light emissions from LEDs or laser diodes. By applying an electric field across a semiconductor material, electrons and holes are injected into the device [6].
2) *Auger Recombination:* It is a process in which the energy released during the recombination of an electron and a hole in a semiconductor material is transferred to another electron instead of being emitted as a photon. This nonradiative process can result in the loss of energy and efficiency in devices such as solar cells and light-emitting diodes [5]. The Auger effect occurs when an electron fills a hole created by the removal of another electron, releasing energy. In traditional radiative recombination, this energy is emitted as light, but in Auger recombination, it is transferred to another free electron within the material. The excess energy can cause this second electron to be ejected from its original position or promote it to a higher energy level [7, 8]. This mechanism involves three particles, i.e. two electrons and a hole, to occur. One electron recombines with a hole in the valance band giving its energy to another electron in the conduction band. This second electron is pushed up to a higher energy level due to the received energy. It progressively releases its energy thermally to calm on the conduction band edge [7, 8]. This process can lead to significant losses in device performance, particularly for high-energy applications where Auger recombination rates are increased. Researchers are exploring ways to reduce these losses through materials engineering and other techniques.
3) *Shockley-Read-Hall Recombination:* It is also known as trap-assisted recombination. This recombination mechanism requires extra energy levels, i.e. traps, to occur. Shockley-Read-Hall recombination is a type of non-radiative recombination that occurs in semiconductors. This process involves the trapping of minority carriers by defects or impurities in the material, which then leads to their annihilation with majority carriers. The recombination rate is determined by the concentration and properties of these traps [5, 9]. This phenomenon has important implications for the performance of semiconductor devices, as it can limit their efficiency and speed. For example, in solar cells, Shockley-Read-Hall recombination can reduce the amount of energy that is converted into electricity, while in photodetectors, it can increase noise and reduce sensitivity [9]. In this mechanism, an electron moves to a trap, extra energy level, in the band-gap region emitting energy as a photon. It moves again to the valance band recombining with a hole and releasing energy as a photon or multiple photons [9, 10]. Fig. 1 illustrates the concept of these mechanisms. To overcome this issue, various strategies have been developed to reduce trap densities or passivate them with suitable materials.

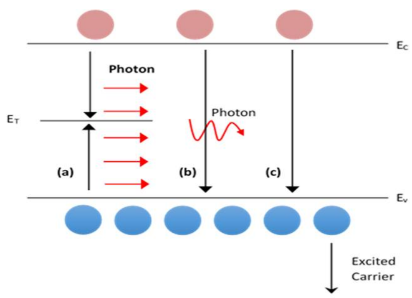

Fig. 1. (Color Online) Schematic diagram of recombination mechanisms (a) SRH (b) Radiative (c) Auger.

Minority carrier lifetime and diffusion length are the most significant parameters that are integral to the recombination rate. The lifetime is related to the recombination in low-level injection materials [11]. This relation in a p-type semiconductor is given by [11]:

$$\tau = \frac{\Delta n}{R},$$

Where τ is the minority carrier lifetime, Δn represents the concentration of the excess minority carriers, and R represents the recombination rate. The minority carrier lifetime in a bulk semiconductor is given by [11]:

$$\frac{1}{\tau_{bulk}} = \frac{1}{\tau_{rad}} + \frac{1}{\tau_{Auger}} + \frac{1}{\tau_{SRH}},$$

Where τ_{bulk} is the minority carrier lifetime in a semiconductor, τ_{rad}, τ_{Auger} and τ_{SRH} are the radiative recombination lifetime, auger lifetime, and Shockley-Read-Hall (SRH) recombination lifetime, respectively [11]. TABLE. I presents the minority carrier calculations for each recombination mechanism in both low and high injection levels. These formulas represent the general minority carrier calculations in a p-type silicon sample

TABLE. I- MINORITY CARRIER LIFETIME ACCORDING TO RECOMBINATION MECHANISM [5]

R \ Injection	Low-Level	High-Level
Radiative	$\tau_{rad,li} = \frac{1}{BN_{dop}}$	$\tau_{rad,hi} = \frac{1}{B\Delta n}$
Auger	$\tau_{Auger,li} = \frac{1}{Cp\ N_A^2}$	$\tau_{Auger,hi} = \frac{1}{(Cn + Cp)\Delta n^2}$
SRH	$\tau_{SRH} = \frac{\tau_{no}(p0 + p1 + \Delta n) + \tau_{po}(n0 + n1 + \Delta p)}{n0 + p0 + \Delta n}$	

where, B represents the radiative recombination coefficient, N_{dop} is the doping value, and Δn is the excess minority carriers, which are the electrons, and concentration. In the Auger recombination, Cn and Cp are Auger coefficients, and they are typically $2.8\times10^{-31}cm^6s^{-1}$ and $0.99\times10^{-31}cm^6s^{-1}$, respectively, for silicon [12]. The SRH lifetime is the same for both low and high injection levels. n_0 and p_0 are the concentration values of electrons and holes at equilibrium, n_1 and p_1 represent the electrons and holes concentrations after doping, and Δn and Δp are the excess carriers concentrations for electrons and holes, respectively [5]. For n-type samples, holes represent the minority carriers, and the calculations are the same for all recombination mechanisms.

B. Surface Recombination Mechanism

The surface recombination mechanism is a process that occurs at the interface between a semiconductor and an external medium. In this process, electrons and holes that are generated within the semiconductor are recombined at the surface before they can contribute to the current flow in a device. This leads to a reduction in the carrier lifetime and, consequently, lowers the efficiency of the device. The surface recombination rate depends on various factors including surface states, doping concentration, temperature, and illumination intensity. Surface passivation techniques such as thermal oxidation or deposition of thin films have been used to reduce surface recombination rates. Surface recombination can be modeled using mathematical equations such as Shockley-Read-Hall (SRH) equation or the Auger recombination equation. These models provide insights into how different parameters affect surface recombination rates and help in optimizing device performance [13, 14].

Surface recombination can be a significant issue in photovoltaic cells since semiconductors' surfaces naturally have an enormous number of recombination centers, i.e. active states. Therefore, surface recombination is promoted by any defects at the surface of the semiconductor. Surface recombination is typically defined by a parameter called "surface recombination velocity", which is measured in units of $cm.s^{-1}$. It is essential to decrease the surface recombination rate in a solar cell to obtain an accurate minority carrier lifetime, thereby improving cell efficiency. The surface recombination rate for a single defect is given by [5]:

$$U_s = \frac{n_s p_s - n_i^2}{\frac{n_s + n_1}{S_{po}} + \frac{p_s + p_1}{S_{no}}},$$

where n_s and p_s are the surface concentrations of electrons and holes, respectively. S_{p0} and S_{n0} are related to the density of surface states, which is expressed per unit area, of holes and electron carriers. These surface states are given by [5]:

$$S_{p0} = \sigma_n V_{th} N_{ts},$$
$$S_{n0} = \sigma_p V_{th} N_{ts},$$

where, σ_n and σ_p are capture cross-sections of defects, and N_{ts} is the density of surface states. The surface recombination velocity in n-type and p-type semiconductors can be mathematically expressed as [5]:

$$S_{n-type} = \frac{U_s}{\Delta n_s}$$

$$S_{p-type} = \frac{U_s}{\Delta p_s}$$

Surface recombination velocity is typically used to appraise and calibrate the surface recombination mechanism. The minority carrier lifetime at the surface is expressed as [5]:

$$\tau_{surface,p-type} = \left(\frac{2S}{W} + \frac{1}{Dn}\left(\frac{W^2}{\pi}\right)\right)^{-1}$$

$$\tau_{surface,n-type} = \left(\frac{2S}{W} + \frac{1}{Dn}\left(\frac{W^2}{\pi}\right)\right)^{-1}$$

where, W is the cell thickness. The surface recombination process has a crucial impact on the effective lifetime calculations in photovoltaic cells. Thus, it has an essential role in estimating solar cells' efficiency.

C. Effective Lifetime

Minority carriers' effective lifetime refers to the duration of time that minority carriers remain in a semiconductor material before they recombine. Minority carriers are electrons or holes that are present in a material where they are not the majority carrier. The effective lifetime of minority carriers is an important factor in determining the performance of semiconductor devices, such as solar cells and transistors [15].

The effective lifetime of minority carriers can be influenced by various factors such as temperature, impurities, radiation, and defects in the material. Higher temperatures increase the rate of recombination while impurities can act as trapping centers for minority carriers leading to a decrease in their effective lifetime. Radiation and defects also have similar effects on the lifetime of minority carriers. A longer effective lifetime for minority carriers leads to better device performance due to higher efficiency and faster response times. Therefore, it is crucial to optimize the conditions under which semiconductor materials are produced so that they have long minority carrier lifetimes [16].

The effective lifetime is accomplished by combining the effects of the bulk region and surface within a sample. The effective lifetime is given as [17]:

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_{bulk}} + \frac{1}{\tau_{surface}}$$
$$\frac{1}{\tau_{eff}} = \left(\frac{1}{\tau_{rad}} + \frac{1}{\tau_{Auger}} + \frac{1}{\tau_{SRH}}\right) + \frac{1}{\tau_{surface}}$$

Surface recombination can be practically reduced to be very low, and thereby the bulk lifetime will be much larger than the effective lifetime. Otherwise, if the bulk lifetime is adequately high, the effective lifetime measurement is totally influenced by the surfaces.

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III. RECOMBINATION LIFETIME MEASUREMENTS TECHNIQUES

Recombination lifetime measurement techniques are critical in understanding the electrical properties of semiconductors. The recombination process is a fundamental aspect of semiconductor materials, and it occurs when an electron and hole combine to form a neutral atom. The recombination lifetime refers to the time taken for the majority carriers (electrons or holes) to recombine with their minority counterpart. Various techniques have been developed to measure the recombination lifetime, including photoconductance decay, time-resolved photoluminescence, and open-circuit voltage decay. These methods rely on measuring changes in electrical signals or luminescence over time after exciting the sample with light pulses. Accurate measurement of recombination lifetime is crucial for characterizing the quality of semiconductor materials used in semiconductor devices such as solar cells, LEDs, and transistors [18, 19].

Since recombination lifetime is an imperative parameter in deciding the efficiency of semiconductor devices, there was an urgent need for different methods to measure the effective recombination lifetime of minority carriers. Many techniques have been developed depending on measurement methods, which can be classified as direct and indirect measurement methods [20].

Some many parameters and properties are related to the minority carrier's lifetime. Measurement techniques have been developed depending on these parameters, such as the conductivity change method, the steady-state photoconductivity method, and the diffusion method. Fig. 2 and Fig. 3 show the most common techniques that are usually applied to directly and indirectly measure the minority carrier lifetime of a semiconductor sample.

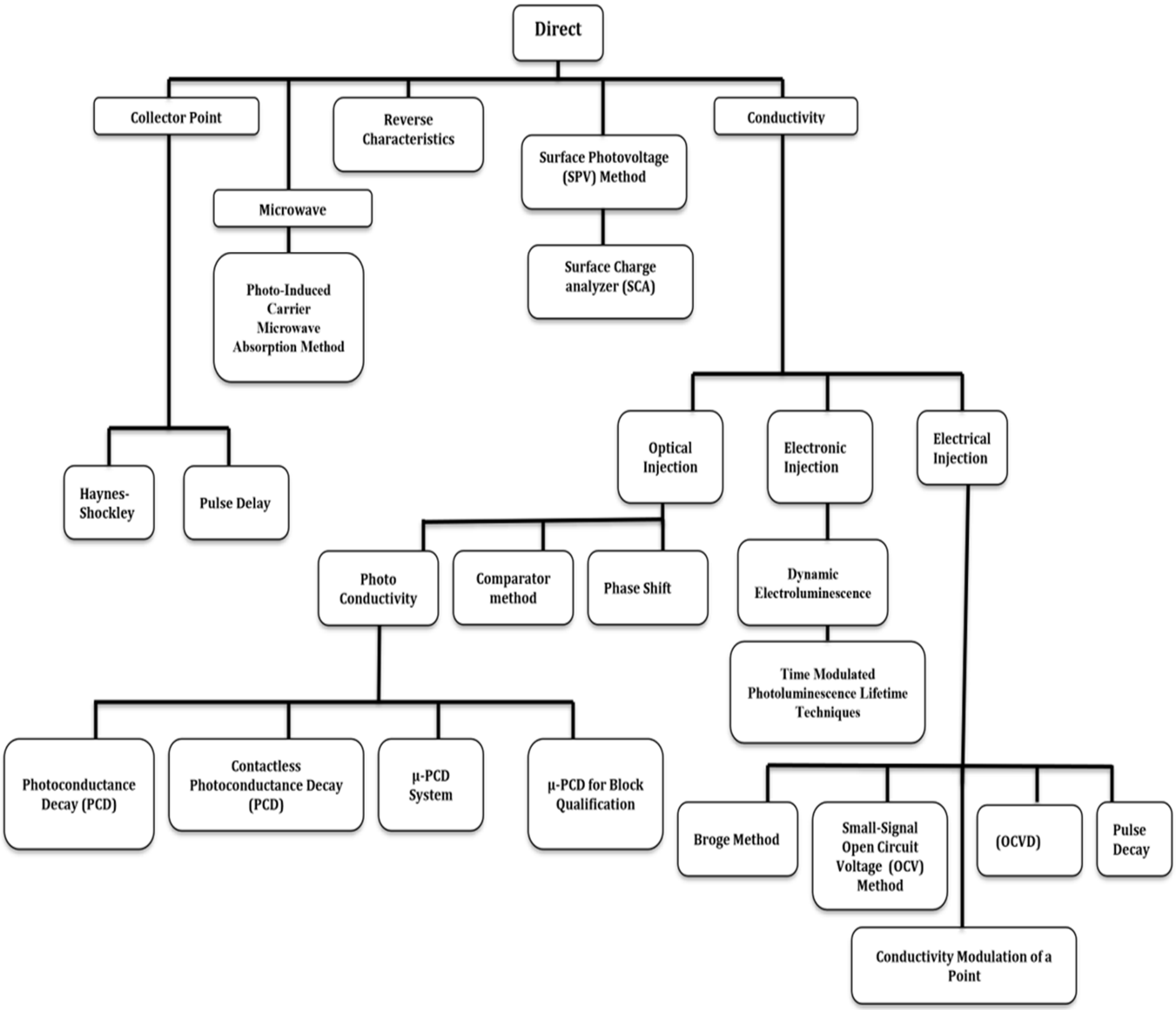

FIG. 2. Direct measurements of excess minority carrier lifetime [11, 21–28].

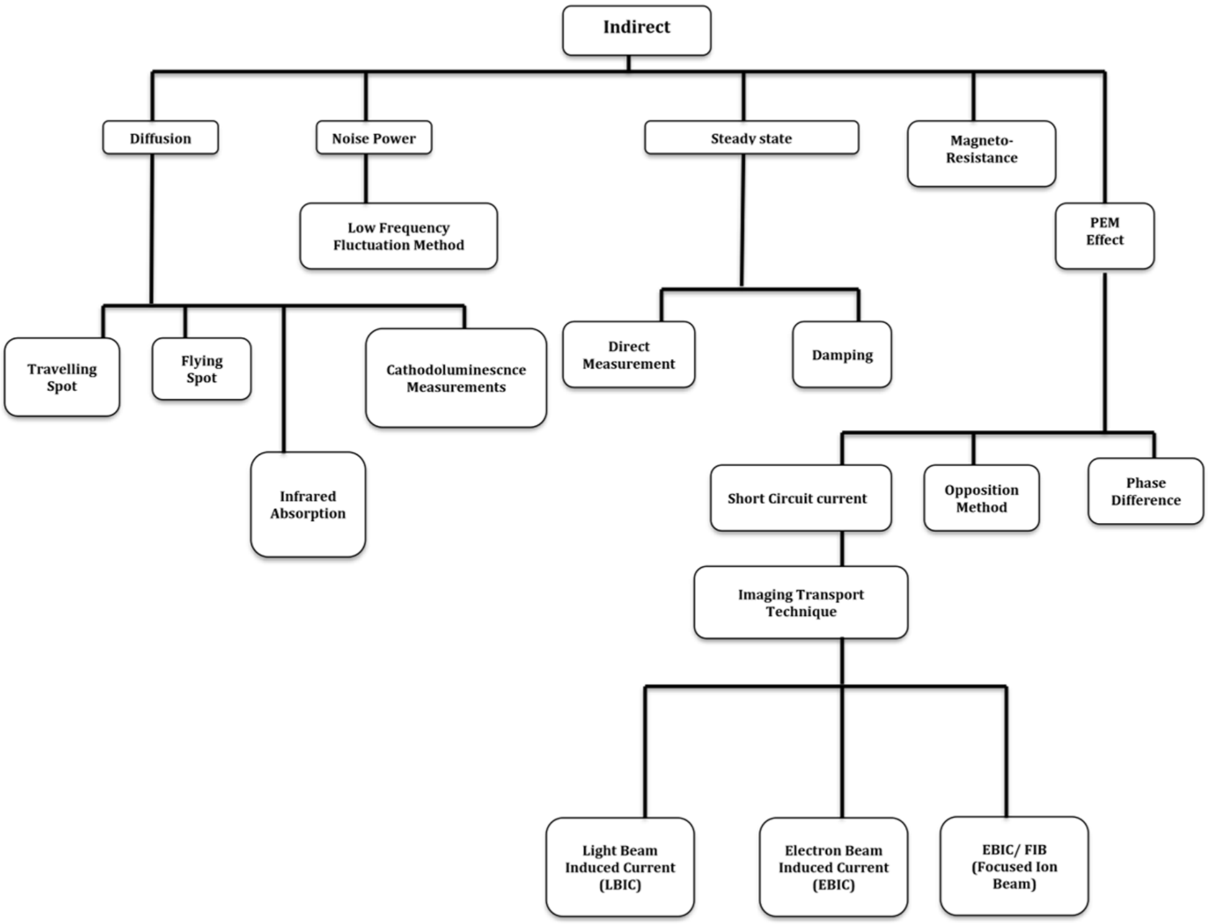

FIG. 3. Indirect measurements of excess minority carrier lifetime [29–36].

These techniques mainly depend on the optical and electrical properties of semiconductor devices. Thus, the most used techniques can be classified according to these properties to be [11]:

1) Optical measurements techniques: The most common techniques that depend on the optical properties are Photo-conductance Decay, Photo-luminescence Decay, Quasi-Steady-State Photo-conductance, Steady-State Short-Circuit Current, Surface Photo-voltage, Electron Beam Induced Current, Light Beam Induced Current, and Free Carrier Absorption.
2) Electrical measurements techniques: The most common techniques that depend on the electrical properties are Pulsed MOS Capacitor, Open-Circuit Voltage Decay, Diode Current-Voltage, and Reverse Recovery.

A. Advantages and Limitations of the Most Widespread Measurements Techniques

Recombination lifetime measurement techniques are essential in determining the quality of semiconductor materials and devices. The two most widespread techniques used for this purpose are photoconductance decay (PCD) and time-resolved photoluminescence (TRPL). Both methods have their advantages and limitations [37].

The PCD method is a non-destructive, fast, and straightforward technique that provides accurate measurements. It is especially useful for measuring recombination lifetimes in heavily doped semiconductors. However, PCD requires high-quality contacts in the sample, which can be challenging to achieve in some cases [38].

On the other hand, TRPL is a highly sensitive method capable of measuring low-level minority carrier lifetimes with high accuracy. It also allows for spatially resolved measurements. However, it requires expensive equipment and is more time-consuming than PCD [39, 40].

Each technique has some unique advantages that make it the best choice in specific fields. The following points show the most interesting advantages and disadvantages of the most common techniques.

1) *Photo-conductance Decay (PCD):* This technique, which is a direct measurement method, typically depends on a laser beam, which is focused on a fixed point on the front surface of the solar cell, to generate electron-hole pairs [27]. Fig. 4 shows a schematic diagram for contact PCD measurements.

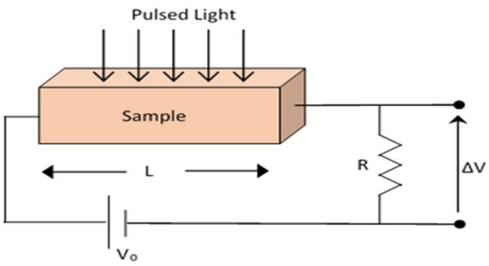

FIG. 4. (Color Online) Schematic diagram for contact PCD.

Significant improvements have been accomplished such as µ-Wave PCD. These new improvements provide contactless and fast measurements. High-resolution Mapping of measurements can be achieved by using the µ-Wave PCD technique. Fig. 5 shows a schematic diagram for contactless PCD measurements.
Using the µ-Wave PCD measurements method is not accurate with samples that have either too high or too low surface recombination velocities.

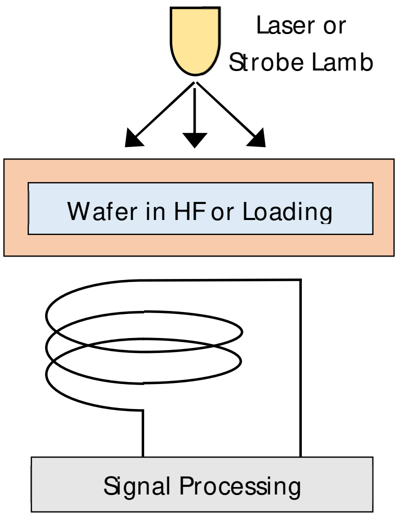

FIG. 5. (Color Online) The schematic diagram for contactless PCD (Rf bridge)

2) *Open-Circuit Voltage Decay (OCVD):* The effective recombination lifetime can be directly estimated by using this technique. OCVD measurements technique depends on the voltage decay across a forward-biased diode, p-n junction when bias is precisely terminated [41]. Fig. 6 shows the fundamental concept of this technique.

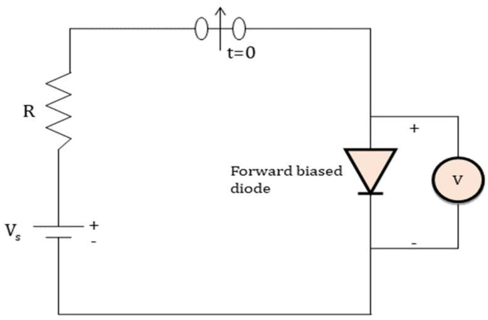

FIG. 6. (Color Online) The fundamental concept of OCVD technique with voltage waveform.

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The main advantages of this technique are that it is easy to implement, it has an accurate interaction with real electrical parameters, and it has a good analysis of experimental data [41]. In addition, the OCVD technique can achieve effective measurements of recombination lifetime at high and low-level injections [25]. The essential issue with using this technique is that it is not able to give accurate measurements when it is applied to structures with non-uniform carrier lifetime distribution since it depends on the position of the contacts [26].

"Small signal" open-circuit voltage decay (SSOCVD) has been developed from the main method, which is the open-circuit voltage decay method. "Small signal" open-circuit voltage decay allows controlling the injected carriers. In detail, additional carriers can be injected with pulse "on", and carriers start recombining with pulse "off". The main issue with this method is that some factors like surface recombination are neglected [42].

3) *Light Beam Induced Current (LBIC):* This technique is an indirect method, and it is typically used to achieve localized characterization on solar cells. LBIC technique uses a scanning laser beam to create electron-hole pairs in tested samples [43]. Fig. 7 shows the main schematic diagram of this technique.

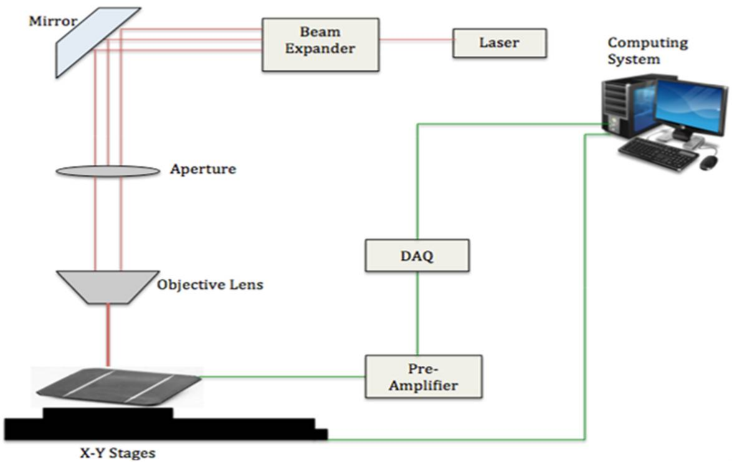

FIG. 7. (Color Online) Schematic diagram of the LBIC measurements technique.

LBIC technique can provide effective imaging of large area samples like photovoltaic cells, and it provides a large penetration of depth. These significant advantages make the LBIC technique a good method in actual solar cell operations; nevertheless, this technique has poor resolution.

4) *Electron Beam Induced Current (EBIC):* EBIC technique, which is an indirect method, uses a high-energy electron beam to create electron-hole pairs in tested samples [33]. Fig. 8 shows the main structure of the EBIC system.

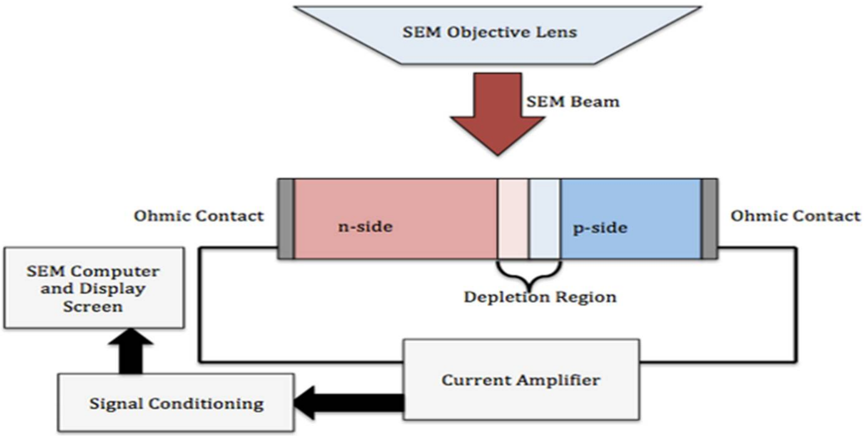

FIG. 8. (Color Online) Schematic diagram of the EBIC system.

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The advantage of the EBIC technique against the LBIC technique is that it has an accurate resolution. Moreover, it can give I-V characteristics of tested samples as well as current time dependency measurements [34]. However, the EBIC technique is not able to provide imaging of large-area samples like solar cells, and it has a small penetration of depth compared with the LBIC technique.

5) *Photoluminescence Decay (PLD):* This technique provides direct measurements of recombination lifetime. It uses a band-gap light emission to create electron-hole pairs in tested samples. It is significant to consider the drifting of carriers across the depletion region when using this technique for solar cell analysis [35]. Fig. 9 shows the main concept of this method.

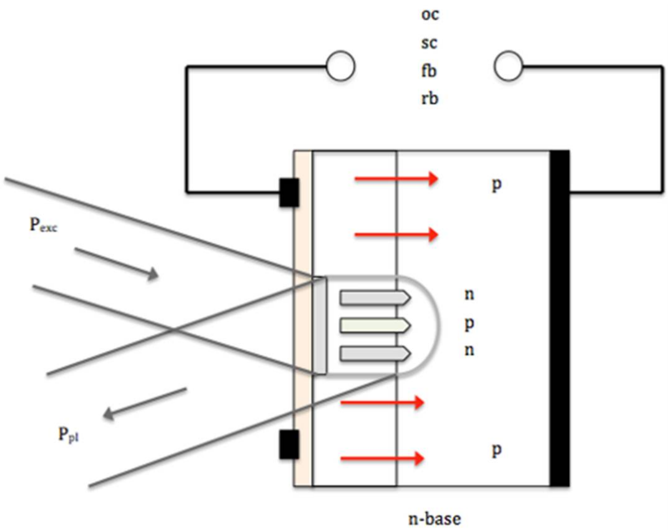

FIG. 9. (Color Online) Main concept of the PLD measurements method.

The main advantage of the Photo-luminescence Decay (PLD) technique is that even below the intrinsic carrier density, artifact-free data can be achieved. This technique can be implemented in both high-resolution imaging and non-imaging applications. However, it strongly depends on the doping levels, wafer thickness, and surface texturing [44].

6) *Quasi-Steady-State-Photo-conductance (QSSPC):* QSSPC uses a slowly tuned down light to make sure that the tested sample is always in a quasi-steady state mode. This technique is typically applied to detect the changes in the permeability of the tested sample, thereby estimating the recombination lifetime [45]. Fig. 10 shows the main principle of this method.

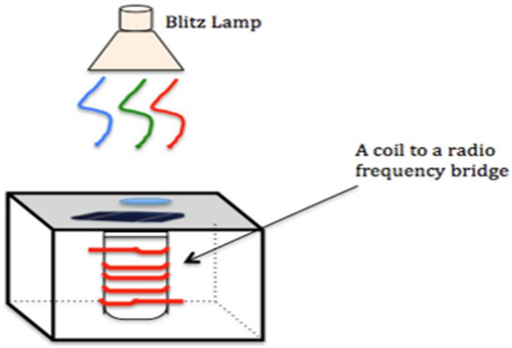

FIG. 10. (Color Online) Principle of QSSPC measurements method.

In the QSSPC technique, the effective recombination lifetime is typically accomplished at every light intensity. The very low recombination lifetimes can be easily determined by using this technique. Moreover, short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) data are inherently included in the QSSPC measurements. QSSPC technique can be effectively implemented for a wide range of materials [46]. However, there are significant issues with using the QSSPC technique such as the incapability of providing mapping for tested samples, and the need for mobility and photogeneration measurements.

7) *Surface Photovoltage (SPV):* The surface photovoltage (SPV) measurement technique primarily depends on chopped light to generate electron-hole pairs. It is typically implemented to determine minority carrier diffusion length and thereby estimate the recombination lifetime in semiconductors [47]. Fig. 11 shows a schematic diagram of the main principle of this technique.

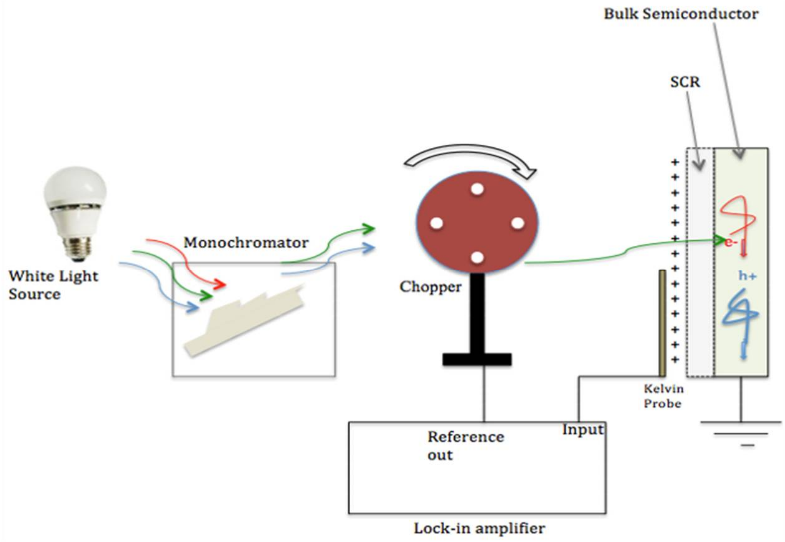

FIG. 11. (Color Online) Schematic diagram of the SPV method.

The main issue with this technique is that it requires considerably thick samples, i.e. h is higher than 4L, to give accurate measurements [47]. Fig. 12 shows the concept of this issue.

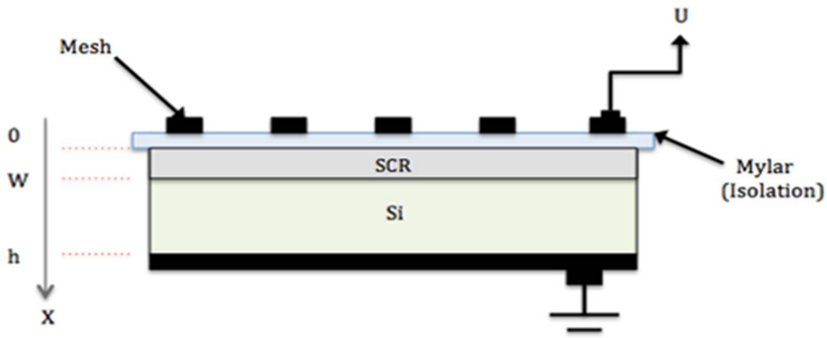

FIG. 12. (Color Online) SPV considerations.

A more accurate method, which is the contactless photovoltaic (CPV) method, has been developed to give more accurate measurements with less thick semiconductor devices. This improved method is typically applied to passivated emitter solar cells [36, 47]. It depends on creating two depletion regions as seen in Fig. 13.

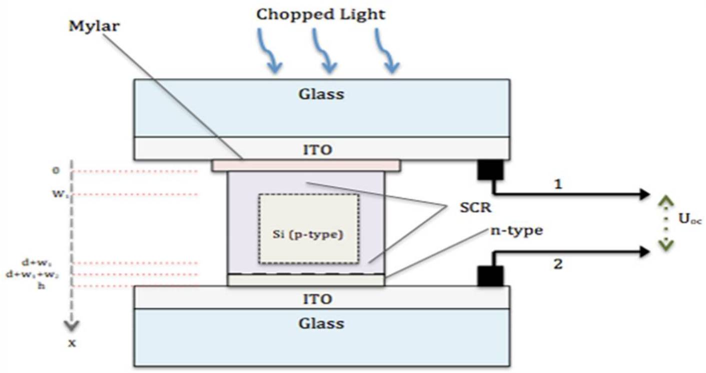

FIG. 13. (Color Online) The main concept of the CPV method.

B. Range of Capability of the Most Widespread Measurements Techniques

Recombination lifetime is an important parameter to measure in semiconductor materials as it determines the efficiency of charge carrier generation and recombination. There are various techniques available for measuring the recombination lifetime of semiconductors, each with its range of capabilities. The most widespread measurement techniques include time-resolved photoluminescence (TRPL), time-resolved microwave conductivity (TRMC), and photoconductance decay (PCD). TRPL can measure lifetimes ranging from nanoseconds to milliseconds and is suitable for materials with high radiative recombination rates. TRMC measures lifetimes ranging from microseconds to milliseconds and is best suited for materials with low radiative rates but high mobility. PCD measures lifetimes ranging from microseconds to seconds and is ideal for materials with low mobility. Overall, the choice of technique depends on the material being tested and the desired accuracy of the measurement. It's important to understand the range of capability of each technique before selecting one for a specific application. [48, 49].

In solar cells, for example, the recombination lifetime is typically larger than that in transistors. Thus, implementing an appropriate technique is the key to achieving accurate results. TABLE II shows the ranges of measurements for the most common techniques.

TABLE II. RANGE OF MEASUREMENTS

Method	Typical Range of Measurements	Image Mapping
OCVD	40 µs to 180 µs (high-level injection) 190µs to 215 µs (low-level injection)	No
µ-wave	10 µs to 1 ms	Yes
PLD	30ns (for mid-wavelength) 100ns (for long wavelength)	Yes
QSSPC	Four orders of magnitude from 10ns to 60 µs	No
Photo-induced carrier microwave absorption method	m-seconds	Yes
Low-frequency fluctuation method	µ-seconds to m-seconds	No
Reverse-Recovery Transient (RRT)	200 ns to ~ 16 µs	No

IV. CONCLUSIONS

Many direct and indirect measurement methods can be applied to achieve accurate recombination lifetime measurements. These techniques mainly deal with the optical and electrical characteristics of semiconductor devices. The key to choosing an appropriate method is to know its capability and its limitations. In solar cell measurements, it is desired to have methods that can measure large lifetimes for different solar cell thicknesses.

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