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# Mapping Shockley-Read-Hall (SRH) lifetimes with differential photoconductance in Gallium Arsenide solar cells: effect of absorber thickness and electron hole lifetime asymmetry

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**Abstract**

Recombination degrades a solar cell. Shockley-Read-Hall (SRH) recombination occurs in a solar cell due to the presence of defects. Defect controls the lifetime of electrons and holes, and in a good solar cell, these lifetimes should be as high as possible. Thus, it is a priority to know the SRH lifetimes in a working solar cell with good precision. Only if the lifetimes are measured properly, a protocol on how to increase them by minimizing the defects can be followed. Standard methods are available that extract SRH lifetimes from solar cell test structures. In this work, we use a method that is less costly and complex and applies to solar cells directly, rather than test structures. In a GaAs PIN solar cell, we study how a varying absorber thickness and electron-hole lifetime asymmetry affect this method, and we suggest a way to read the SRH lifetimes from graphs of simply processed experimental data. A method to find the SRH lifetime for any absorber thickness between 1–100 μm is proposed.

**Keywords:** Solar cells, SRH lifetime, photoconductance, photocurrent

## Introduction

A lot of research has gone into solar cells in the past years [1-3]. Crystalline solar cells, heterojunction solar cells, perovskite solar cells and several other variants have been reported to increase power conversion efficiencies with time, and have been researched on in many laboratories across the world.

Solar cells are semiconductor devices that convert light energy into usable electricity. In a PN solar cell, a P-type and an N-type semiconductor form a junction [4]. The junction is illuminated with light, often with sunlight.

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Light is absorbed in the junction, leading to the creation of photogenerated electron-hole pairs. These charge carriers feel the built-in electric field [4] and are dragged to the ends of the device. This is how a solar cell creates a current at zero applied voltage, called the short-circuit current of the solar cell. The built-in electric field arises due to the presence of immobile acceptor and donor ions in the P and N layers [4].

Sometimes an undoped semiconductor layer is sandwiched between the two extreme layers. This is called the PIN geometry of the solar cell. In these PIN solar cells [5,6], light is absorbed in the I layer for which the I layer is called the absorber. The built-in electric field extends deep into the I layer. Photogenerated carriers have to cross this absorber to be collected efficiently by the P and N contacts. The thicker the absorber, the more time the charge carriers spend in it before reaching the contacts.

Charge carrier recombination decreases carrier collection in solar cells [7-13]. Recombination in the absorber, mainly, decreases the efficiency of the solar cell. Shockley-Read-Hall (SRH) recombination [8,10,11] is a type of recombination that occurs due to the presence of defects or traps inside the absorber. These traps capture electrons and holes, and the captured carriers recombine and are lost. Thus, after photogeneration, recombination leads to the disappearance of electrons and holes and this reduces the efficiency of the solar cell.

SRH recombination is characterized by the time an electron or hole spends as a free entity before getting recombined. This is called the lifetime of an electron or a hole. The lower the lifetimes more the recombination. In thick absorbers, recombination happens even if lifetimes are large. Solar cells often require high lifetimes for smoother operation.

Lifetimes can be increased by minimizing the trap concentrations inside the absorber, for which a defect-free absorber must be fabricated by the material engineers. To gain control of the fabrication process, one must know the SRH lifetimes of electrons and holes inside a working solar cell. Only if the lifetimes are known with good precision can one try to maximize them.

## Method Comparison and Summary

Quasi-steady-state photoconductance (QSSPC) [14-17], Time-resolved photoluminescence (TRPL) [18-20], and Microwave photoconductive decay (μ-PCD) [21,22] are established techniques that can measure the SRH lifetimes in a solar cell. But these methods use sophisticated instruments and thus are both complex and costly. Also, the carrier lifetimes in a working solar cell cannot be measured directly using these methods. These techniques are rather used on solar cell test structures that have no built-in electric fields. Built-in fields sweep electrons and holes fast to the contacts, giving less chance of recombination, and this complicates the analysis of these established methods.

In this work, we use a method to detect the SRH lifetime, which is at the same time less complex and costly, and which also uses full solar cell structures instead of test structures. This method was introduced in Ref. [23], and uses experimentally measured photocurrents of solar cells. The photocurrent's slope (first-order derivative), with respect to voltage, shows a peak near the built-in potential ($V_{bi}$) of the solar cell. This peak scales linearly with the SRH lifetime in a semilogarithmic plot [23]. Thus, by measuring the peak value of this differential photoconductance (per unit area) SRH lifetimes can be directly known.

This peak occurs in a regime where built-in electric fields are very low. Near $V_{bi}$ the solar cell almost reaches flat-band conditions. This lets us measure the SRH lifetime in minimum electric fields.

In this work, a GaAs PIN solar cell [23-27] is investigated. We vary the absorber thickness between 1 – 100 μm and map the differential photoconductance peak with SRH lifetimes in the absorber. $\tau_n$, the electron SRH lifetime, is the average time an electron spends in the absorber before getting recombined. $\tau_p$, similarly, is the hole lifetime in the absorber. We also study the photoconductance peak with 2 distinct electron-hole lifetime ratios ($\tau_n/\tau_p$) 1 and 10. The absorber in GaAs solar cells often has minimal N-type doping. This reduces $\tau_p$ compared to $\tau_n$.

Photocurrents in solar cells can be easily measured experimentally using AC or pulsed techniques [28-30]. This requires a simple AC current measurement setup, often needing a lock-in amplifier and a chopper. This setup is less complex and costly compared to QSSPC, TRPL or μ-PCD.

Photocurrents get affected by recombination present in solar cells [31-34]. Photocurrents measured in solar cells are often flat near zero bias [23]. As the voltage is increased the drift component of the current decreases (because the built-in electric field decreases as the applied voltage compensates for the built-in field). But the diffusion current makes up this decrease, and the total current remains flat. Only when the applied bias reaches close to $V_{bi}$ the photocurrent starts decreasing and goes to zero at $V_{bi}$. This steep decrease gives a peak in the differential photoconductance. This photoconductance peak decreases with decreasing SRH lifetime. This can be explained in simple terms. As the SRH lifetime decreases, more and more electron-hole pairs recombine in the absorber of the solar cell. This decreases the carrier concentrations in the absorber, leading, eventually, to a decrease in conductance.

In Ref. [23], the case of a fixed absorber thickness was shown (for an absorber thickness of 10 μm).

## Simulation Results

In this work, a GaAs PIN solar cell is simulated in ADEPT 2.1 [35], a software that solves the Poisson equations, the Continuity equations and the Drift-diffusion equations [4] simultaneously using a discrete mesh and a generalized Newton iteration method. The GaAs parameters used in the simulations are given in Ref. [23]. The SRH lifetime in the absorber is varied over 2 orders of magnitude, often from 1 ns to 100 ns, or from 100 ns to 10 μs. The absorber is illuminated by the AM 1.5G radiation (1 Sun intensity). The temperature of the solar cell is fixed at room temperature (300 K).

The differential photoconductance peak for various SRH electron lifetimes is shown in Fig. 1. Hole lifetime is kept equal to electron lifetime ($\tau_n/\tau_p = 1$). Plots for absorber thickness of 1 μm, 10 μm, 30 μm and 100 μm are shown.

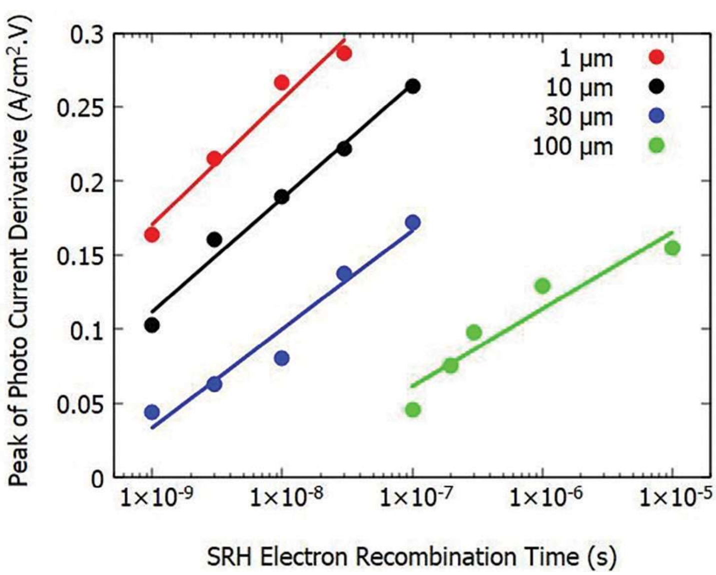


**Fig. 1:** The differential photoconductance peak vs SRH electron lifetime (including linear fits) for 4 absorber thicknesses in the solar cell

We see, as the absorber thickness is increased, the photoconductance decreases. This corresponds to a flatter photocurrent curve, near $V_{bi}$, instead of a steep one. For thicker absorbers, electrons and holes recombine more because often their diffusion lengths are smaller compared to the absorber thickness. So they cannot reach the end contacts easily as they have to travel longer distances. This reduces the effective carrier concentrations in the absorber, as mentioned before, for thicker absorbers, which reduces the conductance.

Fig. 2 shows the same plot for $\tau_n/\tau_p$ = 10. Here, in the simulations, the hole lifetime is always kept 10 times smaller than the electron lifetime. Thus, considering 2 distinct values of $\tau_n/\tau_p$, we finally have a range of conductance values. We can expect the experimental conductance from a GaAs PIN solar cell to lie within these 2 extremes.

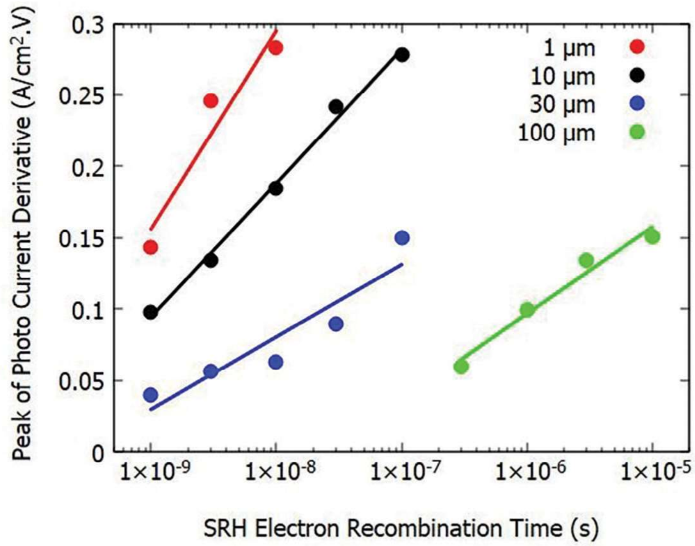


**Fig. 2:** The differential photo conductance vs the SRH electron lifetime (along with their linear fits) for 4 absorber thicknesses. $\tau_n/\tau_p$ = 10.

Fig. 3 plots the ranges of the conductance for each absorber thickness considered. Thus, as mentioned before, for any experimentally obtained differential conductance, whose value lies within the shown range, can be mapped to a unique SRH electron lifetime.

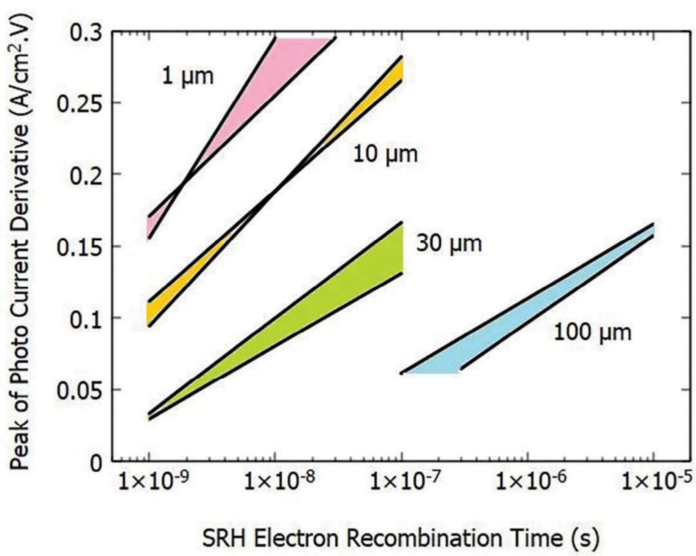


**Fig. 3:** Ranges of the photoconductance, constructed from the linear fits, for each absorber thickness in the GaAs PIN solar cell.

Fig. 4 and 5 give the slope and intercept of the linear fits (of differential conductance vs SRH electron lifetime) with a varying absorber thickness. Thus, for any absorber thickness between 1 to 100 μm, the slope and intercept can be found from the linear fits in Fig. 4 and 5 and by drawing that straight line in a graph and simultaneously comparing the differential photoconductance value the SRH electron lifetime can be found. The hole lifetime, according to this method, will fall between $\tau_n$ and $0.1\tau_n$.

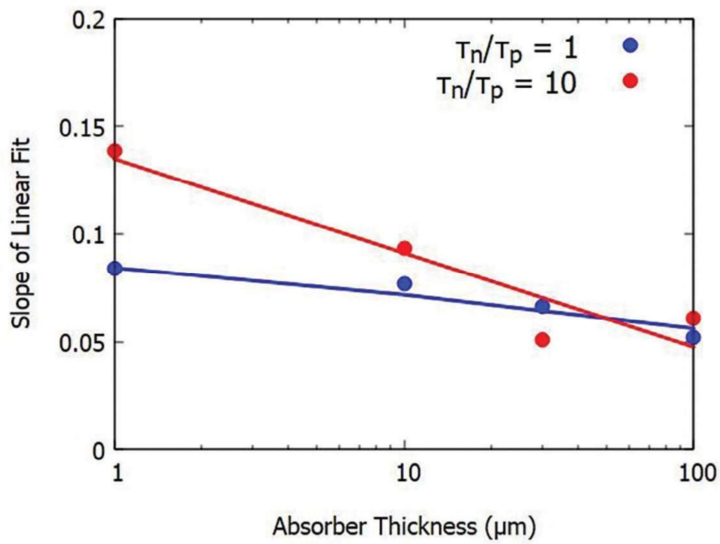


**Fig. 4:** The slope of the linear fits vs absorber thickness for 2-electron hole lifetime asymmetries.

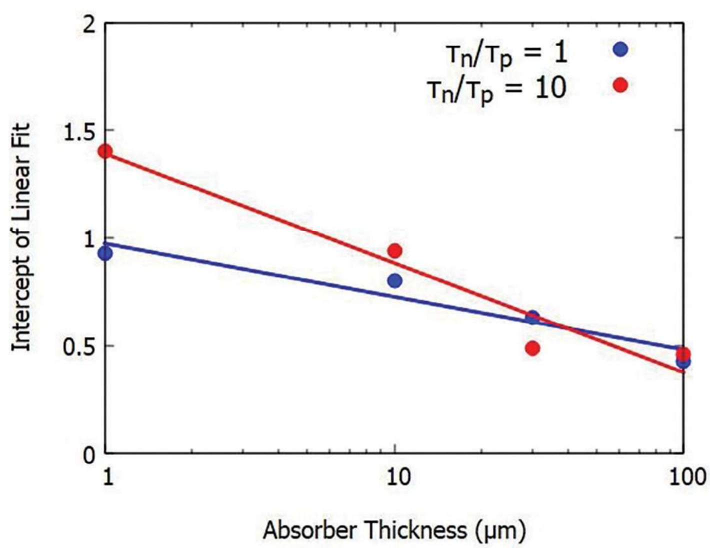


**Fig. 5:** Intercepts of linear fits vs absorber thickness for the 2 electron hole lifetime asymmetries.

We see that the slope and intercept decrease with increasing absorber thickness. As the logarithm of SRH lifetimes is negative, a higher slope of the linear fit of photoconductance vs SRH lifetime leads to a higher intercept.

The linear fit of photoconductance shows a higher slope for a lower thickness. This means the photoconductance varies more sharply with the SRH lifetime for a thinner absorber. This is understandable because, as mentioned earlier, for thicker absorbers electrons and holes recombine more often, leading to low conductance values even for a high SRH lifetime. Thus, in thicker absorbers, the change in photoconductance with SRH lifetime is smaller.

## Conclusion

The peak differential photoconductance of a Gallium Arsenide solar cell is mapped to Shockley-Read-Hall recombination lifetimes in the bulk absorber. To extract the SRH lifetime, first, the experimentally measured photocurrent of the GaAs solar cell must be obtained. From the photocurrent, by differentiating it with respect to applied voltage, the differential photoconductance can be found, which shows a peak near the built-in potential. This peak value can be compared in a graph of peak values vs the recombination lifetime, and the lifetime can be read. As the absorber thickness increases, the charge carriers have a greater chance of recombining before they reach the extreme P and N layers (contacts). This decreases the average carrier concentration inside the absorber (as more electrons and holes are lost due to recombination) for a thicker absorber and hence reduces the differential photoconductance value (as conductance is directly proportional to the carrier concentrations). Thus, for a thicker absorber, the 'calibration line' of photoconductance peak vs recombination lifetime shifts vertically downwards. The effect of electron hole lifetime asymmetry can similarly be understood as for higher asymmetry the hole lifetime is smaller, and the recombination is more. Thus, the calibration line shifts to both a higher slope and a higher intercept. This is because for a smaller recombination lifetime, the photoconductance value is lower (as the recombination is more). Such a calibration can be done for any absorber thickness by interpolating the data presented in this paper.

The method of obtaining the carrier lifetimes described in this paper has broader significance. One does not need to measure the lifetime with costly instruments; a simple measurement of the photocurrent of the solar cell suffices. Also, this method does not require multiple measurements. One measurement at 1 sun yields the lifetime values directly. This is also the advantage of this method. In contrast, when asked about the limitation, one must note that at high light intensities (e.g., 100 suns), the use of which is abundant in GaAs solar cells (concentrator photovoltaics), radiative, i.e. bimolecular recombination will also affect the photoconductivity peak. There, both SRH and bimolecular recombination will decide the photoconductance, and then to obtain the SRH lifetimes, one needs to suppress the bimolecular contribution. One more point to note is that the method described here, at 1 Sun intensity, is widely applicable to all possible PIN solar cells, including Silicon solar cells and perovskite solar cells. This method is not restricted to GaAs absorbers.

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