Quasi-steady-state Photoluminescence Lifetime Imaging of $p$- and $n$-type Multicrystalline Silicon Wafers

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This thesis titled
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ABSTRACT

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In a silicon solar cell, there are many factors that influence the efficiency of the cell. Minority-carrier lifetime is the fundamental factor that directly relates to defect and impurity based recombination in silicon affecting the overall quality of the photovoltaic devices. Estimation of minority carrier lifetimes at every stage of the solar cell production without any electrical contacts or device structure is very useful for process development and quality control. The photoluminescence carrier lifetime characterization tool can be applied at different processing stages of solar cell device. The advantages of photoluminescence carrier lifetime imaging tool are fastness and absolute lifetime values are obtained from this method. Unlike, the industry standard characterization tools like Sinton’s lifetime tester and Semilab’s microwave-photoconductive decay method, the photoluminescence lifetimes are absolutely trap free values even at very low injection levels.

In this thesis, we demonstrated the applicability of the calibration method developed to solar-grade (SoG) p-type and n-type multicrystalline silicon wafers which have plasma-enhanced chemical vapor deposited (PECVD) silicon nitride (SiN) passivation layers on both sides of the wafer. We have also demonstrated that photoluminescence lifetime imaging technique is a fast, absolute and trap free carrier
lifetime characterization method. Also, the obtained results are compared with industry standard carrier lifetime tools like Sinton’s lifetime tester and Semilab’s microwave-photoconductive decay method. Furthermore, we suggest some improvements in the calibration method and we also discuss the applicability of this characterization method to other silicon morphologies.

The thesis also presents the preliminary work on the light-induced carrier lifetime degradation in Al doped multicrystalline silicon wafers. The lifetime degradation upon illumination of light is seen in Al doped multicrystalline p-Si wafers. After annealing the wafers at 200°C for 1 hour the initial lifetime is recovered. Furthermore, Fourier Transform Infrared (FTIR) spectroscopy is performed to check the oxygen content present in the wafers. Based on these results we conclude that the degradation effect is due to interstitial oxygen present in the wafers.

The work was carried out at Energy research Center of Netherlands under the supervision of Dr. Gianluca Coletti.

Approved: Wojciech M. Jadwisienczak

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1 INTRODUCTION

Photovoltaics is the direct conversion of sunlight into electricity by using solar cells. Solar cell converts sunlight to electricity using a basic physical process known as photovoltaic effect. In 1839, Edmund Becquerel, a French physicist observed the photovoltaic effect while experimenting with electrolytic cells [1]. When a solar cell is illuminated with sunlight, some photons are absorbed or reflected by the material or may just pass through the material. When a photon is absorbed, the photon knocks the electron to higher energy state creating a hole. If this free electron is captured, it contributes to the electric current [2].

In 1905, Albert Einstein described the theories behind photoelectric effect, for which he later won a Nobel Prize in physics [3]. In 1954, the first photovoltaic module based on crystalline Si was built by Bell Laboratories [4]. In 1960s, the space industry used this technology to provide power a spacecraft abroad. These space programs enabled to advance the technology, establish reliability, and decline the cost [5]. In 1970s, the energy crisis spurred many nations to consider renewable energies for production of electricity. So, photovoltaics gained recognition as a valuable electricity source for non-space applications. In 1980s, the photovoltaic industry began to mature with emphasis on manufacturing and cost.

Over the last few decades, photovoltaic has been gained potential in the renewable energy field and has attracted the interest of many investors and researchers around the world. Many researchers and scientists are exploring wide range of
semiconductor materials and cell architectures for application of solar cells as shown in Fig. 1.1.

Figure 1.1: Best research-solar cell efficiencies reported from 1975 to 2007 [6].

Various solar cell technologies include multi-junction solar cells, crystalline Si solar cells, thin-film solar cells and organic solar cells. The efficiencies of all solar cell technologies have improved over the last few decades as shown in Fig. 1.1. A triple junction device developed by Boeing SpectroLab has demonstrated an efficiency of 42.8% [7]. Among crystalline silicon cells, highest conversion efficiency up to 24.7% is reported with mono crystalline silicon solar cells at the University of New South Wales (UNSW) [8]. Almost 20% efficiency has been reached with thin-film technology by National Renewable Energy Laboratory (NREL) with copper indium gallium selenide
(CIGS) thin films [9]. Emerging PV technologies like organic and dye-sensitized solar cell have demonstrated a highest efficiency of 7.9% [10]. Today, more than 80% of PV modules are produced based on crystalline silicon worldwide [11]. The significant advantages of crystalline silicon for PV applications are outlined below [12]:

- In microelectronics industry, silicon is well researched and understood in terms of its device and material physics. Also, silicon is used for many other microelectronics applications.
- Silicon is non-toxic, abundant material and mechanically robust which facilitates easy cell processing and assembling.
- Silicon can form high quality interface with silicon dioxide (SiO$_2$), which has a highly stable native oxide.
- The industrial manufacturing infrastructure already exists in the market and silicon based PV modules have low manufacturing costs.

Currently, research on crystalline silicon solar cells focuses on cost reduction, improving lifetime and efficiency and thin-film solar cells. These are also the challenging aspects of the silicon photovoltaics in the future, which will be discussed in the following section.

(a) Cost reduction:

The silicon material cost is the major cost factor of a PV module. It is estimated up to two third of the total module cost is due to the silicon material [13]. Various developments are being made to keep this cost low, by using inexpensive silicon feedstock material and by using thin-film silicon thus reducing the amount of silicon used
A new and cheaper production process like direct refinement of metallurgical silicon yields a material of low quality. A 15% efficient multicrystalline solar cells have been reported with this low purity material. In the future, producing the cost effective and good purity (efficient) silicon material will be the major challenge.

(b) Thin-film silicon cells:

A silicon thin-film solar cell uses only a few micrometers of silicon as an active layer, thus reducing the amount of silicon used and also lowers the cost. Using thin-film silicon facilitates to reduce the recombination of carriers in the bulk and thus improving the open-circuit voltage ($V_{oc}$) and fill factor (FF). These advantages also lead to several challenges like fabrication and cell design. Current and future development also includes the deposition of silicon thin-film on a cheap foreign substrate. Glass can be used a cheap substrate but requires low temperature processing. Other challenge for silicon thin-films (with thickness of 30 [µm]) in the perspective of optical absorption is the effective light trapping structures which can be incorporated to capture the light. Other challenges include reducing the recombination at grain boundaries and gettering techniques to reduce the impurities.

(c) Improving carrier lifetime:

In general the efficiency of multicrystalline solar cells is limited due to the lattice defects, which directly influence the minority carrier lifetime. Other factors like grain boundaries, dislocations, and precipitates or small clusters of atoms are mainly responsible for recombination. The process control and optimization can be achieved by studying the foreign atoms and their interaction. Especially for the silicon feedstock
material and directly purified metallurgical silicon which are cost effective methods, the impurity concentration is high and advanced process control tools are necessary [11]. To improve the processing technology involved in fabrication of silicon solar cells, it is critical to monitor the factors limiting the performance of the device in all the cell development stages. Especially, contactless characterization tools are useful for step-by-step monitoring, process development and optimization of the silicon solar cells. These tools can be applied at any step of the cell development and doesn’t require a device structure. Various tools like *Sinton’s* lifetime tester (WCT-120 model) and *Semilab’s* microwave photoconductive decay (µW-PCD, WT-2000PV model) tools developed by *Sinton Instruments* [18] and *Semilab co. ltd* [19] respectively are commercially available lifetime characterization tools for silicon wafers. These tools are widely used for contactless determination of carrier lifetimes in silicon wafers.

In this thesis, we developed a quasi-steady-state photoluminescence lifetime imaging tool, which is a very fast, trap free, contactless spatially resolved lifetime mapping technique for silicon wafers [20]. This characterization method can be applied at any step of the solar cell development. The PL images are calibrated with QSS-PC measurement setup at same illumination intensity. The application of this calibration procedure has been successfully studied with various solar-grade (SoG) *p*- and *n*- type multicrystalline silicon wafers. We have demonstrated that photoluminescence lifetime values are not affected by experimental artifacts even at very low injection levels unlike the techniques discussed earlier and absolute lifetime values are obtained using this method [21,22]. The accuracy of the PL carrier lifetimes is verified with commercially
available lifetime characterization tools like *Sinton’s* lifetime tester (WCT-120 model) and *Semilab’s* microwave photoconductive decay (µW-PCD, WT-2000PV model) with good agreement.

All the experiments, result analysis and software development were performed under the guidance of Dr. Gianluca Coletti at Energy research Center of Netherlands. This work created a launching platform for designing an experimental setup capable of contact-less life time measurements on different photovoltaic materials at Ohio University in the future.
2 THEORY

2.1 Fundamentals of Silicon

Crystal structure:

Silicon is the eight most abundant element in the universe but doesn’t exist in the purest form [23]. The atoms in the crystalline silicon are arranged in a periodic pattern. Silicon crystallizes in the diamond cubic lattice structure and bonds with four nearest neighbors as shown in Fig. 2.1. This lattice structure can be interpreted as two interpenetrating face centered cubic lattice [4].

![Crystal lattice structure of silicon](image)

Figure 2.1: Crystal lattice structure of silicon [23].

Different types of defects can occur in silicon crystal during and after growth. For example defects due to vacancies, atomic impurities, dopant impurities, dislocations, stacking faults and precipitates.
The defects in silicon crystal lattice can be viewed as dimensional damages. These type of defects are point defects if they are 0-dimensional, linear if 1-dimensional, surface if 2-dimesional and spatial defects if 3-dimensional. Complicated defects may occur if these defects interact with each other. The point defects which lie interstitially in the lattice of the silicon crystal are referred to as vacancies which involves foreign impurity atoms in the form of null nodes in the matrix as shown in Fig.2.2 [24] [25]. Planar defects are especially the grain boundaries in twin crystals and the crystal boundaries themselves. Spatial defects include microcracks and foreign phase inclusions which are microscopic damages. The defects due to impurity atoms comprise of substituting or implanting solutions which depends on the difference in electrical negativity of impurity and matrix atoms and also covalent radii mismatch of impurity atoms also depending on the [24] [25].

Figure 2.2: (a) Ideal crystalline lattice, (b) Lattice with an impurity atom, (c) Lattice with a vacancy [25].
The mechanical defects involve the defects due to plastic–elastic deformation, mechanical polishing, chemical polishing and also during processes like slicing, grinding [25]. The Fig. 2.3 is the cycle showing various manufacturing steps and concludes that practically all technological processes result in defects in the material [26].

Figure 2.3: Basic technological processes and defects involved in manufacturing silicon based device [25].
Defects induced during to various thermal cycle of crystals are thermal defects. Various chemical defects during ionic implantation, diffusion and epitaxy are due to the impurity atoms introduced at the growth stage of the crystal. The current technology involving semiconducting material manufacturing are practically free of defects but mistreatment of such materials will induce significant point defects [25]. The performance of semiconducting material is worsen in the form of structural defects during thermal cycles and degradation caused by point defects and their clusters. Structural defects in particular with impurities influence the devices thus declining the yield [25].

Band structure:

Silicon is an indirect band gap semiconductor. The absorption and emission process are different than direct band gap semiconductors. Band structures relate the energy of electrons with the wave vector (k) and are quantum mechanical in nature [27]. The band structure estimations are carried in k-space with coordinates k= (k_x,k_y,k_z). The Fig. 2.4 shows the band diagram of silicon.
Figure 2.4: Band structure of silicon [27].

The k-space region where \(k=(0,0,0)\) is known as first Brillouin zone. The middle of Brillouin zone corresponding to \(k=(0,0,0)\) is referred to as \(\Gamma\) point. The one edge of Brillouin zone refers to \(X\) point corresponding to \(k=(\pi/2)(1,0,0)\). Similarly, the \(L\) point refers to \(k=(\pi/2)(1,1,1)\). The center points of \(\Gamma\) point and \(X\) point or \(L\) point are \(\Delta\) points. The band structure of a silicon material consists of a valance band and conduction band. The energy difference between the highest point of valance band and lowest point of conduction band is known as band gap. If the k-vector of the lowest point in the conduction band corresponds to k-vector of the highest point in the valance band then the
materials is called the direct band gap semiconductor. In the other case it is an indirect band gap semiconductor like silicon [27] [28] [29].

In silicon, one critical point exists near Γ point called the $E_0$ which is the direct bandgap of Si ~ 3.4 eV. For photon energy less than 3.4 eV, there are no direct transitions from the top of valance band to the lowest point of the conduction band. In the visible region and near-infrared i.e. ~1.1-3.4 eV absorption in silicon is indirect ($E_{\text{indirect}}$).

The lowest point of conduction band in silicon is at ~ $k=(\pi/2)(1,0,0)$ i.e. close to X-point.

![Figure 2.5: Band structure of silicon [30].](image)

The energy difference between the conduction band minima and the valance band edge is the intrinsic gap ($E_g$).
2.2 Carrier Lifetime in Crystalline Silicon

Over the past few decades the energy conversion efficiency of crystalline silicon solar cells has been improving; however there are remaining many factors limiting the efficiency. The material quality is strongly related to cell efficiency and thus affect the cost of the solar cell. The defects introduced during the crystal growth process or during the solar cell production will impact the quality of material [31]. Occurrence of such defects allows the carriers to recombine in different regimes of the solar cell i.e. in the bulk, surface and emitter regions. These defects directly limit the solar cell efficiency and can be studied in terms of an important microscopic parameter, carrier recombination lifetime [32].

In semiconductors, the term generation refers to the process of electron-hole pair creation [31]. The transition of an electron from valence band to the conduction band can be due to thermal processes, electrical excitation or optical excitation. The transition of an electron to conduction band across the energy gap results in spontaneous generation of hole in the valance band, and the generated carriers are described as electron-hole pair. After a subsequent motion through the lattice, the electron in the conduction band recombines with a hole and undergoes a recombination transition. The term recombination is the inverse process of generation, where electron-hole pair recombines due to the spontaneous transition of an excited electron from conduction band to the valance band. During the transition of electron from conduction band to valance band, the excess energy is released as a photon or phonon or both. The generation and recombination is a continuous process, and the average time between the carrier
generation and recombination is called the \textit{carrier lifetime}, often referred as \textit{recombination lifetime} \cite{33}. The recombination lifetime ($\tau$), can be determined from the recombination rate ($U$),

$$\tau = \frac{\Delta n}{U}$$  \hspace{1cm} (2.1)

where, $\Delta n$ is the excess minority carrier density, $U$ is the recombination rate.

The recombination lifetime is an average of all the carriers, whose behavior depend on various factors like bulk defects, carrier density and surfaces. As different recombination mechanisms occur in the semiconductor, the total recombination rate ($U_{eff}$) is sum of the individual recombination rates ($U_i$) as shown in Eq. (2.2).

$$U_{eff} = \sum_i U_i \rightarrow \frac{1}{\tau_{eff}} = \sum_i \frac{1}{\tau_i}$$  \hspace{1cm} (2.2)

Thus here the recombination lifetime can be referred as \textit{effective lifetime}. In order to minimize the recombination processes, there is a need to understand various bulk and surface recombination mechanisms that occur in semiconductors.

In silicon, the fundamental recombination mechanisms are \cite{31}:

(a) radiative recombination.

(b) Auger recombination.

(c) bulk recombination through defects (Shockley-Read-Hall recombination).

(d) surface recombination.

The four recombination processes are represented in the Eq. 2.3 as

$$U_{bulk} = \frac{\Delta n}{\tau_{bulk}} = U_{rad} + U_{aug} + U_{SRH} = \frac{\Delta n}{\tau_{rad}} + \frac{\Delta n}{\tau_{aug}} + \frac{\Delta n}{\tau_{SRH}}$$  \hspace{1cm} (2.3)

(a) Radiative recombination:
Radiative recombination is the direct band-band recombination of an electron-hole pair, which involves the emission of a photon with an energy approximately same as band gap as depicted in Fig. 2.5.

![Band diagram illustrating radiative recombination.](image)

As the electron from conduction band falls into a vacant valence band state to recombine with hole, the radiative recombination rate \( B \) depends on the density of free electrons \( n \) and free holes \( p \) [31]. The radiative lifetime for low level injection i.e. at low generation rates \( \Delta n << n_0 + p_0 \) and for high-level injection \( \Delta n >> n_0 + p_0 \) is simplified and is given by Eq. (2.4). The detailed derivation of Eq. (2.4) is given in Appendix A.

\[ \tau_{rad,low} = \frac{1}{BN_{DA}} \quad \text{and} \quad \tau_{rad,high} = \frac{1}{B\Delta n} \quad (2.4) \]

where \( N_{DA} \) is the doping density of donor \( (N_D) \) or acceptor \( (N_A) \) atoms. So, from Eq. (2.4) it is clear that the radiative lifetime depends on the inverse of carrier density. For low level injection conditions the \( \tau_{rad} \) is constant and under high injection level conditions \( \tau_{rad} \) decreases as the injection level increases.

(b) Auger recombination:

In Auger recombination process, the excess energy released by the recombination of an electron-hole pair is transferred to a third free electron or hole, which releases its
excess energy as phonons [34]. Thus, the Auger recombination is a three-particle interaction. This process is shown in the Fig. 2.6.

![Band diagram illustrating Auger recombination process.](image)

As seen in the Fig. 2.2, the third particle can be either a valence band hole or conduction band electron. The Auger recombination rate in eeh process is proportional to $n^2p$, for ehh process where the excess energy is transferred to another hole, the Auger recombination rate is proportional to $np^2$ respectively [35].

The Auger recombination lifetime $\tau_{Aug}$ can be determined from Eq. (2.5). Thus the injection level dependent Auger recombination lifetimes can be given for $p$-type silicon as

$$
\tau_{Aug,low} = \frac{1}{C_pN_A^2} \quad \text{and} \quad \tau_{Aug,high} = \frac{1}{(C_n + C_p)\Delta p^2}
$$  

(2.5)

The Auger coefficients determined by Dziewior and Schmid for silicon with doping concentration greater than $5\times10^{18} \, [\text{cm}^{-3}]$ are $C_n=2.8\times10^{-31} \, [\text{cm}^6 \, \text{s}^{-1}]$ and $C_p=0.99\times10^{-31} \, [\text{cm}^6 \, \text{s}^{-1}]$ [36]. So, the Auger lifetime depends on the inverse square of the
carrier density. At high injection levels the Auger recombination is dominant recombination mechanism in silicon.

Though a simple Auger process is discussed here more complicated Auger processes are possible also like trap-assisted Auger recombination, phonon assisted Auger recombination.

![Trap assisted Auger process diagram](image)

**Figure 2.8: Trap assisted Auger process.**

The trap assisted Auger process was studied by Landsburg. The four trap assisted Auger process are shown in Fig. 2.7. In process (a), the electron is captured at trap and gives its electron in conduction. In a heavily doped silicon, the process (a) is negligible as the trap level is below Fermi level. In process (b), the electron in conduction band gives it energy to hole in the valance band. The process (c) is hole capture by trap followed by giving its energy to an electron in conduction band. In process (d), the hole is captured
and energy is given to another hole [37]. As the wafers used in the thesis are high quality wafers the trap assisted Auger processes are neglected.

(c) Bulk recombination through defects:

In a semiconductor, the defects present within a semiconductor crystal can be foreign atoms, dislocations, native defects and also there complexes. [38]. The presence of such defects can form additional energy levels within the forbidden gap in the semiconductor, also known as *traps*, which can act as efficient recombination centers mainly when they are closer to the middle of the gap. These defect levels can be occupied either by an electron or by a hole followed by interaction with conduction and valance band. This process is schematically shown in the Fig. 2.8.

![Band diagram illustrating the interaction mechanisms of free carriers in presence of a defect level.](image)

The defect level can act as *recombination center* if a free electron from the conduction band (2) and a free hole from valance band (3) are simultaneously captured by the defect level. Also the recombination can be a two stage process, a free electron
from the conduction band relaxes to defect level (2) and then to the valance band (3). Also, this defect level can act as trap center, where an electron is captured at defect level and emitted back into the conduction band ((2) followed by (1)). The theory for SRH recombination was developed by Shockley and Read [39], and Hall [40]. The SRH lifetime ($\tau_{SRH}$) is given by.

$$\tau_{SRH} = \frac{\tau_p(n_0 + n_l + \Delta n) + \tau_n(p_0 + p_l + \Delta p)}{n_0 + p_0 + \Delta n}$$

(2.6)

The SRH lifetime can be simplified based on the injection level, which is shown in Eq. (2.7) and (2.8).

For $p$-type silicon

$$\tau_{SRH,low} = \tau_p \quad \text{and} \quad \tau_{SRH,high} = \tau_p + \tau_n$$

(2.7)

For $n$-type silicon

$$\tau_{SRH,low} = \tau_n \quad \text{and} \quad \tau_{SRH,high} = \tau_p + \tau_n$$

(2.8)

where $\tau_p$ and $\tau_n$ are hole and electron lifetimes which depends on capture cross sections. See Appendix A for detailed derivation.

(d) Surface recombination:

The surface of the silicon substrate has discontinuity in the crystal structure, which results in partially bonded Si atoms. This also creates interface trap density levels within the forbidden band. So the effective lifetime is also includes the surface recombination lifetime as shown in the Eq. (2.9)

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_{bulk}} + \frac{1}{\tau_{surface}}$$

(2.9)

The surface recombination rate can be reduced by applying plasma-deposited silicon nitride (SiNx) surface passivation on both sides of silicon surfaces which reduces the interface trap density [41,42]. Since all the wafers used in this work are SiNx
passivated, the surface recombination is neglected. The effective lifetime is considered only as the measure of bulk lifetime.

For the simplicity of discussion we use the continuity equation to measure the effective lifetime \( \tau_{\text{eff}} \) of excess minority carrier density \cite{43}

\[
\frac{\partial \Delta n}{\partial t} = G(t) - U + \frac{1}{q} V J
\]  

(2.10)

where, \( G(t) \) is the generation rate, \( U \) is the recombination rate, \( q \) is the charge and \( J \) is the electron current density. Since, the work is carried out in open-circuit conditions, the value of \( J=0 \). The recombination rate \( U \), is defined in Eq. (2.1). Also the effective lifetime is the bulk lifetime, by applying all these conditions, the Eq. (2.10) is modified as

\[
\tau_{\text{eff}}(\Delta n) = \frac{\Delta n(t)}{G(t) - \frac{d\Delta n(t)}{dt}}
\]  

(2.11)

This equation is the generalized analysis of effective lifetime in silicon wafer. The effective lifetime directly depends on the injection level \( \Delta n \).

The effective lifetime measurements in this work are carried under the steady-state conditions \textit{i.e.}

\[
\frac{d\Delta n(t)}{dt} = 0
\]  

(2.12)

which simplifies the equation to

\[
\tau_{\text{eff}} = \Delta n G
\]  

(2.13)
This equation describes the effective minority carrier lifetime in silicon under steady-state conditions. The lifetime is dependent on excess carrier concentration ($\Delta n$) and generation rate ($G$).

2.3 Photoluminescence Lifetime Imaging Technique

Photoluminescence (PL) is the emission of light from a semiconductor upon the light excitation. The photoluminescence from a silicon wafer can be used to characterize the minority carrier lifetime [20,44]. To extract the minority carrier lifetime, the photoluminescence analyzed in this technique is not in the form of spectral distribution, rather it uses the relation between band-band radiation and the separation of quasi-Fermi energy levels [45]. When illuminated, the rate of spontaneous emission $R_{sp}$ inside a silicon wafer is proportional to the product of minority and majority carrier densities.

$$R_{sp} = B(T) n_e n_h = B(T) n_i^2 e^{\Delta \eta}$$

(2.14)

where $n_e$ and $n_h$ are the electron and hole densities. $B(T)$ is the radiative recombination rate. $\Delta \eta$ is the separation of quasi-Fermi levels.

The luminescence intensity from the silicon is assumed to be linear with rate of spontaneous emission due to the constant quasi-Fermi levels separation throughout the thickness and also the optical properties do not change under the illumination [44]

$$I_{pl} = A_i R_{sp} = A_i B(T) n_e n_h$$

(2.15)

The advantage of the photoluminescence imaging method is that the product of the electron ($n$) and hole ($p$) density is measured. The main advantage of this method is that the trapping effects are negligible [44]. Unlike other methods, for example
photoconductance method, where the sum of excess electrons and holes are measured, the effective lifetime values are affected by the trapping effects which causes the over estimation of minority carrier lifetime [46]. For more details on the influence of trapping effects on photoconductance and photoluminescence method see Appendix B.

For a $p$-type silicon wafer,

$$I_{pl} = A_i B(T) (\Delta n + N_a) \Delta n$$  \hspace{1cm} (2.16)

Where $I_{pl}$ is the PL signal, $\Delta n$ is the minority carrier concentration, $N_a$ is the doping concentration. The $B(T)$ is assumed to be constant for $\Delta n < 10^{15}$ [cm$^{-3}$] and $N_a > 10^{15}$ [cm$^{-3}$]. By determining the calibration factor ($A_i$), the photoluminescence signal can be calibrated to absolute minority carrier lifetimes. The $A_i$ is calculated by measuring PL signal and the corresponding absolute value of excess carrier concentration ($\Delta n$) for one injection level at same illumination as given in Eq. (2.17).

$$A_i = \frac{I_{pl}}{(\Delta n + N_{D/A}) \Delta n}$$  \hspace{1cm} (2.17)

The same calibration factor can be used to correlate the photoluminescence signal with other injection levels as shown in Eq. (2.18).

$$\Delta n = -\frac{N_a}{2} + \sqrt{\left(\frac{N_a}{2}\right)^2 + \frac{I_{pl}}{A_i B(T)}}$$  \hspace{1cm} (2.18)

and the effective minority carrier lifetime can be calculated using relation.

$$\tau_{eff} = \frac{\Delta n}{G}$$  \hspace{1cm} (2.19)

Thus by calculating the calibration factor ($A_i$), the photoluminescence response can be correlated to minority carrier lifetime.
2.4 Light-Induced Lifetime Degradation in Crystalline Silicon

The carrier lifetime degradation due to the light illumination is also one of the vital factors that influence the efficiency of the device. In the past, light-induced lifetime degradation was observed in boron-doped silicon wafers [47]. It was investigated that the degradation is due to the formation of $\text{B}_2\text{O}_i$ defect pairs which are very effective recombination center. Upon a low-temperature annealing step $\text{B}_2\text{O}_i$ pairs dissociate and the recombination sites are deactivated leading to the recovery of the degraded lifetime [48,49,50]. This degradation can be suppressed either by dropping the concentration of B and O or by substituting boron with gallium or phosphorus. It has already been studied that the reduction of B doping results in high efficiency up to 22%. The drawback of that approach was that it requires a complex ohmic back contact [51]. In the past Ga was studied as a substitute for B, interestingly light-induced degradation effect was not seen in Ga doped Si and this approach seemed to be very promising [52]. However, the low segregation coefficient of Ga in Si results in resistivity variations in the crystal length [53]. Usage of $n$-type Si can also be an alternative but it requires different solar cell technology for e.g. it requires a $p^+$ emitter. In this context we have studied the feasibility of degradation in Al-doped (1-1.35 $\Omega$-cm) multicrystalline Si wafers. In this work we demonstrated that the Al doped silicon wafers also degrade upon the light illumination. To investigate the degradation process, lifetimes are measured using quasi-steady-state photoconductance method.
3 EXPERIMENTAL METHODS

3.1 Sinton’s Lifetime Tester (WCT-120)

The Sinton’s lifetime tester developed by Sinton Instruments is widely used commercial tool for minority carrier lifetime measurements on multicrystalline silicon wafers. The measurement technique is based on Eddy-current method. A radio frequency (rf) coil is built into the WCT-120 bench and the silicon wafer is placed on the top of this coil which sends electromagnetic waves to the wafer [18].

![Sinton’s lifetime tester (Model: WCT120) [18].](image)

After the light is pulsed onto the wafer creating excess carriers, the coil senses the change in the conductance of the wafer and based on this data the minority carrier lifetime is reported. The change in the conductance under steady-state conditions is given by Eq. (3.1) [54].
\[ \Delta \sigma = q(\Delta n \mu_n + \Delta p \mu_p)W = q\Delta n(\mu_n + \mu_p)W \quad (3.1) \]

where, \( \Delta n = \Delta p \) is the photogenerated excess carrier density, \( W \) is the width of the wafer, \( \mu_n, \mu_p \) are mobility of electron and hole respectively.

Under steady state conditions, the rate of generation of electron-hole pairs is in balance with recombination rate.

\[ U = G \quad (3.2) \]

The total recombination rate can be expressed in terms of effective carrier lifetime (\( \tau_{eff} \)) as,

\[ U = \frac{\Delta n}{\tau_{eff}} \quad (3.3) \]

The Eq. (3.3) can be written as,

\[ \tau_{eff} = \frac{\Delta \sigma}{q(\mu_n + \mu_p)W \times G} \quad (3.4) \]

where \( W \) is the thickness of the wafer, which is given as input in the measurement sheet. \( (\mu_n + \mu_p) \) is assumed to be constant over the range of injection level. The conductivity increase (\( \Delta \sigma \)) and generation rate (\( G \)) are calculated from the calibrated rf coil and generation rate (\( G \)) is calculated from a calibrated solar cell as shown below in Fig. 3.2.
In general this method is called *quasi-steady-state photoconductance* (QSS-PC) method. This method is a non-imaging technique, so it can only measure lifetime at a given spot on the wafer [54].

The measured effective minority carrier lifetime with QSS-PC is the average lifetime over the area of the wafer which is directly on the top of the RF coil which has diameter of 3.8 cm. The measured minority carrier lifetime with Sinton’s lifetime tester is the effective lifetime which is the measure of different components of bulk lifetimes discussed in *Section 2.1*. The excess carrier density ($\Delta n$), generation rate ($G$) and effective carrier lifetime ($\tau_{eff}$) are obtained from the measurement sheet. An example of measurement on a $p$-type multicrystalline silicon wafer is shown below.
All the sensors shown in the Fig. 3.2 are calibrated before the measurement is conducted. For QSS-PC measurement, the exponential decaying curve (shown in blue, Fig. 3.3) after a rapid rise is the light intensity is measured by the calibrated solar cell. The exponential decaying curve (shown in red, Fig. 3.3) is the photoconductance curve measured by the rf coil. The excess carrier density and effective lifetime are calculated using the Eq. (3.1) and (3.4) and are outlined in the measurement sheet. The Fig. 3.4 shows the injection-level dependent minority carrier lifetime obtained from this measurement.
The excess carrier concentration and minority carrier lifetime can be obtained from measurement sheet at a given illumination intensity in the range (0-10 [suns]).

3.2 Photoluminescence Setup

An *Enfis Quattro Red* 630 nm Light Emitting Diode (LED) array is used to illuminate the entire wafer at a constant intensity (up to 300 [mW-cm$^{-2}$]). A cooled Si charge-coupled device (CCD) camera is used to capture the image of the PL emission at 1392x1040 resolution with variable integration time. An infrared (IR) filter is used in front of the CCD camera to block the visible light from the background. The LED array is built inside an illumination case which has highly reflective mirror coating on the walls of the case. The wafer is illuminated from the back (see Fig. 3.5), so that the signal captured by the Si-CCD camera is only the photoluminescence signal and doesn’t constitute the component of reflected illumination light, which is the case in front side illumination method.

![Minority-carrier lifetime vs excess carrier density](image-url)
Since, both the QSS-PC and PL measurements are at same illumination conditions, it is important to determine the illumination intensity (suns) from the LED array. The illumination intensity from LED array is determined using a calibrated solar cell which has a short circuit current ($I_{sc}$) of 110.1 [mA] at 1 [sun]. The short circuit current of reference solar cell varies linearly with the illumination (suns).

The CCD camera has an offset (45-55 counts) at integration time of 0 [sec] which is removed using a Matlab program during the calibration. This offset occurs at all the integration times greater than 1 [sec] and is removed to obtain precise PL data. Also, the CCD camera responds linearly with integration time. This is clearly illustrated in Fig. 3.6.

Figure 3.5: Photoluminescence setup (left) and LED array spectrum (right, [55]).
Figure 3.6: Si CCD camera response at different exposure times.

The photoluminescence data marked in blue (dots) are the precise values after removing the offset.

3.3 Semilab’s Microwave-Photoconductive Decay Method

In Semilab’s μW-PCD tool, the wafer is placed under a microwave antenna which can direct microwaves to the surface of the wafer. Some portion of microwave signal penetrates the wafer and some part reflects. The reflected wave decays exponentially with time as conductivity of the wafer changes. Based on the reflected microwave signal, the time constant is determined, which is the carrier recombination lifetime [19,56,57]. Since the carrier lifetime is calculated from the time constant, this method is called Photo Conductive Decay (PCD) method. With this tool, high spatially resolved lifetime maps can be obtained. The Semilab’s μW-PCD tool measures differential lifetime and scanning
the whole wafer takes long time [58]. However, for both the techniques, at low injection levels ($<10^{14}$ [cm$^{-3}$]) the lifetime values are affected with experimental artifacts like trapping or depletion region modulation (DRM) [59,60] which leads to overestimation of lifetime. In this thesis, we use Semilab’s µW-PCD method for comparison only and the carrier lifetime maps are not analyzed explicitly.
4 CALIBRATION METHODS

4.1 Single point calibration method

The flow chart shown in Fig. 4.1 explains the step-by-step calibration procedure:

Figure 4.1: Flow chart illustrating the photoluminescence image calibration procedure for obtaining minority carrier lifetime maps of silicon wafers.
Step 1: As mentioned in the theory of photoluminescence lifetime imaging, for determining the calibration factor \((A_i)\) absolute value of excess carrier density for at least one injection level is needed. The same calibration factor can be extended for all the injection levels. In this thesis we use Sinton’s lifetime tester (QSS-PC method) for measuring the absolute value of excess carrier density and thus determining the calibration factor \((A_i)\). For QSS-PC, the measured lifetime is the average lifetime over the area of the wafer which is directly on the top of the \(rf\) coil. The Fig. 4.2 illustrates the case. If a measurement is performed with a wafer placed on the test bench, the effective minority carrier lifetime obtained is the average lifetime over the area marked in white in Fig. 4.2.

Figure 4.2: Overview of the measurement method with Sinton’s lifetime tester.
Once, the measurement is performed the excess carrier concentration ($\Delta n$) and generation rate ($G$) can be obtained from the measurement sheet. Since, the QSS-PC and photoluminescence data are correlated to determine the calibration factor ($A_i$). $\Delta n$ and $G$ are extracted at same illumination intensity where the photoluminescence will be carried out. The doping density ($N_{D/A}$) is also available in the measurement sheet.

Step 2: The illumination intensity (suns) of the LED array is measured using a calibrated solar cell. The photoluminescence image of the whole wafer is captured at a given [suns].

Step 3: The area averaged pixel value ($I_{pl}$) is calculated from the PL image using a Matlab code. $I_{pl}$ is calculated over the same area as where the QSS-PC measurement is performed i.e. over the area shown in white in Fig. 4.2.

Step 4: $I_{pl}$, $\Delta n$, $N_{D/A}$ and $G$ are obtained from steps 1, 2 and 3. The calibration factor ($A_i$) is calculated.

Step 5: The same calibration factor ($A_i$) is used to estimate the excess carrier densities for the whole wafer.

Step 6: Once, the excess carrier density is known, the carrier lifetime map of the entire wafer can be obtained.

Validating the calibration procedure:

Once the minority carrier lifetime map of the entire wafer is obtained, the calibration is validated. This step is to verify if the determined calibration factor ($A_i$) is a valid factor. The QSS-PC measurements are performed at various locations on the wafer
and the photoluminescence carrier lifetime values are calculated at same locations. The effective carrier lifetimes obtained from QSS-PC and from the PL imaging are compared.

4.2 Fit calibration method

In the single point calibration method, only one injection level is used for the calibration. Here, in the fit calibration method a range of injection levels are used to determine the calibration factor ($A_i$).

QSS-PC measurement is performed at a given location on the wafer. Various photoluminescence images are captured at various illumination intensities say ($S_1$, $S_2$, $S_3$, ..., $S_j$). The area averaged pixel values ($I_{pl1}$, $I_{pl2}$, $I_{pl3}$, ..., $I_{plj}$) are determined at the same location where the QSS-PC measurement is performed. At illumination intensities ($S_1$, $S_2$, $S_3$, ..., $S_j$), the absolute values of excess carrier densities ($\Delta n_1$, $\Delta n_2$, $\Delta n_3$, ..., $\Delta n_j$) are extracted from the QSS-PC measurement sheet. The area averaged pixel values ($I_{pl1}$, $I_{pl2}$, $I_{pl3}$, ..., $I_{plj}$) and excess carrier densities ($\Delta n_1$, $\Delta n_2$, $\Delta n_3$, ..., $\Delta n_j$) are fitted into Eq. (4.1) and by fixing the doping density ($N_{D/A}$), the calibration factor $A_i$ is determined using the fit equation.

$$I_{plj} = \sum_{j=1}^{j} A_i (\Delta n_j + N_{D/A}) \Delta n_j$$  \hspace{1cm} (4.1)$$

Once, the calibration factor ($A_i$) is determined, the PL lifetime map is obtained using the same procedure (Steps 5, 6) as single point calibration method followed by validating the calibration procedure.
5 RESULTS AND DISCUSSIONS

5.1 P-type multicrystalline silicon wafers

5.1.1 Calibration on wafer#PVPC1

The single point calibration method discussed in Section 4.1 is demonstrated on a $p$-type multicrystalline silicon wafer with thickness of 210 [µm]. The wafer is well passivated on both sides with silicon nitride (SiN). The wafer parameters are outlined below.

- $p$-type, Multicrystalline Silicon, 210 [µm]
- SiN passivated, Doping: 7.3×10$^{15}$ [cm$^{-3}$]
- Optical constant: 0.85

The optical constant is measure of the amount of incident light that is absorbed by the sample. Optical constant is assumed as 0.85 for determining the generation rate. As a decaying flash light is used for the QSS-PC measurement, the injection-level dependent carrier lifetime is obtained as shown in Fig. 5.1. Generalized QSS-PC measurements are performed at various locations on the wafer. The calibration factor ($A_i$) is calculated at (5 [cm], 5 [cm]) location on the wafer. At 0.6 [suns] the excess carrier density ($\Delta n$), Generation rate ($G$), and doping concentration ($N_a$) are extracted from the QSS-PC data sheet. The injection-level considered for the calibration at 0.6 [suns] is marked with red dot in Fig. 5.1. At this point, the excess carrier density ($\Delta n$) = 8.45×10$^{13}$ [cm$^{-3}$], generation rate ($G$) = 9.84×10$^{16}$ [cm$^{-3}$ sec$^{-1}$] and the doping ($N_a$) = 7.3×10$^{15}$ [cm$^{-3}$].
Figure 5.1: QSS-PC measurement on wafer#PVPC1 at (5 [cm], 5 [cm]) location, red dot is the calibration point at 0.6 [suns].

The photoluminescence image of the wafer is captured at 0.6 [suns] with a Si-CCD camera for an exposure time of 10 [sec], shown in Fig. 5.2.

Figure 5.2: Photoluminescence image of wafer#PVPC1 captured at 0.6 [suns] for an integration time of 10 [sec] (scale in counts).
The effective lifetime ($\tau_{\text{eff}}$) and excess carrier concentration ($\Delta n$) measurement shown in Fig. 5.1 corresponds to average lifetime over the area of circle shown in the Fig. 5.2. The photoluminescence intensity is averaged over this area using the Matlab code. Which is $I_{pl}=253.19$ [counts].

Using Eq. (2.17), $A_i$ is determined as $8.514 \times 10^{-28}$ [counts cm$^6$] and this calibration factor is used to calculate excess carrier densities and minority carrier lifetime at other locations on the wafer.

Table 5-1: Comparison of calibrated photoluminescence and measured QSS-PC lifetime values at various locations on wafer#PVPC1

<table>
<thead>
<tr>
<th>Position in [cm] (Wafer)</th>
<th>Averaged Pixel Value</th>
<th>Minority Carrier Lifetime in [$\mu$s]</th>
<th>Excess Carrier Density in [cm$^{-3}$]</th>
<th>$\Delta$Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X$ $Y$ $I_{pl}$ $QSSPC$ $PL(A)$ $QSS-PC$ $PL(A)$ $(\tau_{pc} - \tau_{pl})/\tau_{pc}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 5 206.44 12.6 13.9 6.26$\times 10^{13}$ 6.91$\times 10^{13}$</td>
<td>-10.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 10 217.22 15.4 14.9 7.66$\times 10^{13}$ 7.07$\times 10^{13}$</td>
<td>7.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5* 5* 253.19 17.1 17.1 8.45$\times 10^{13}$ 8.45$\times 10^{13}$</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.8 7.8 338.81 17.7 23.2 8.84$\times 10^{13}$ 1.16$\times 10^{14}$</td>
<td>-31.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 10 350.02 16.4 24.2 8.14$\times 10^{13}$ 1.20$\times 10^{14}$</td>
<td>-47.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 13 516.06 26.5 36 1.35$\times 10^{14}$ 1.76$\times 10^{14}$</td>
<td>-30.4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Calibration point location and corresponding data.
For comparison, QSS-PC measurements are taken at various locations on the wafer and compared with calibrated photoluminescence lifetime values at corresponding locations to check the applicability of the calibration as outlined below in Table 5-1. QSS-PC measurements are taken at various locations \((X, Y)\) on the wafer and corresponding photoluminescence signal \((I_{pl})\) is calculated at same location. By using the calibration factor \((A_i = 8.514 \times 10^{-28} \text{ counts cm}^6)\), excess carrier densities and carrier lifetimes are calculated. There is a vast deviation in the PL lifetimes and QSS-PC values. The error is partly due to the influence of the following factors, which occurs during the experiments and data analysis.

a) Background light

b) Trapping effects

c) Uneven suns distribution

In order to alleviate these factors various measures are taken during the experimentation and data analysis. The following methods are implemented step-by-step to improve the accuracy of the measurements and analysis.

a) Background light correction:

The LED illumination case has dimensions of 16 cm×16 cm where the wafer is mounted. But the \(p\)-type mc-Si wafer has dimensions of 15.6 cm×15.6 cm allowing light to escape from the edges which can undergo reflections and also some light can be re-absorbed by the wafer. This causes some offset in the photoluminescence signal. In order to avoid this offset in the PL signal, a frame is used to reduce the background light (see Fig. 5.3).
The PL image is captured again using the frame and calibration is performed again with precise photoluminescence data. For calibration and comparison the same QSS-PC measurements are used, as only the photoluminescence data is corrected in this step. Fig. 5.4 shows the PL image with and without using the frame and later the image is cropped to extract the \( I_{pl} \).

The calibration is performed with the photoluminescence signal measured without any background light. An improvement in the calibration which is carried out without any background light is observed (see Table 5-2).
Table 5-2: Improvement in the calibration parameters after removing the offset signal from photoluminescence data.

<table>
<thead>
<tr>
<th>Position in cm (Wafer)</th>
<th>Avg. Pixel Value</th>
<th>Minority Carrier Lifetime in [µs]</th>
<th>Excess Carrier Density in [cm(^{-3})]</th>
<th>ΔError % (Without frame)</th>
<th>ΔError % (With frame)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>QSS-PC</td>
<td>PL(A)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>Y</td>
<td>(I_{pl})</td>
<td>QSS-PC PL(A)</td>
<td>(\frac{\tau_{pc} - \tau_{pl}}{\tau_{pc}})</td>
<td>(\frac{\tau_{pc} - \tau_{pl}}{\tau_{pc}})</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>174.51</td>
<td>12.6</td>
<td>6.26×10(^{13})</td>
<td>6.78×10(^{13})</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>13.7</td>
<td>6.78×10(^{13})</td>
<td>-10.4</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>205.03</td>
<td>15.4</td>
<td>7.66×10(^{13})</td>
<td>7.14×10(^{13})</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>14.4</td>
<td>7.14×10(^{13})</td>
<td>7.7</td>
</tr>
<tr>
<td>5*</td>
<td>5*</td>
<td>243.18</td>
<td>17.1</td>
<td>8.45×10(^{13})</td>
<td>8.45×10(^{13})</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>17.1</td>
<td>8.45×10(^{13})</td>
<td>0.0</td>
</tr>
<tr>
<td>7.8</td>
<td>7.8</td>
<td>327.8</td>
<td>17.7</td>
<td>8.84×10(^{13})</td>
<td>1.13×10(^{14})</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>22.9</td>
<td>1.13×10(^{14})</td>
<td>-31.7</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>338.51</td>
<td>16.4</td>
<td>8.14×10(^{13})</td>
<td>1.17×10(^{14})</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>23.6</td>
<td>1.17×10(^{14})</td>
<td>-47.4</td>
</tr>
<tr>
<td>5</td>
<td>13</td>
<td>515.97</td>
<td>26.5</td>
<td>1.35×10(^{14})</td>
<td>1.75×10(^{14})</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>34.2</td>
<td>1.75×10(^{14})</td>
<td>-30.4</td>
</tr>
</tbody>
</table>

*Calibration point location and corresponding data.

It is clearly seen from the error that the reduced offset in photoluminescence signal has improved the accuracy of the calibration. With the reduced background light, approximately 4\% reduction in the error is achieved at (5 [cm], 10 [cm]) location. The error reduction of ~8\% is obtained for the other wafers (not shown here). This signifies that the background light is one of the factors contributing for significant error reduction.

b) Trapping effects correction:
As mentioned in the theory of Sinton lifetime tester, the QSS-PC measures excess photoconductance ($\Delta \sigma$) by means of an inductive coupled coil. The photoconductance is then related to excess carrier concentration ($\Delta n$) using the mobility model. During the analysis it is assumed that the electrons and hole contribute equally to the change in the photoconductance. When minority carrier traps are present in the silicon wafer this assumption fails. The trapped minority carriers cannot recombine, thus breaking the balance between the generation and recombination. In order to attain a new equilibrium between generation and recombination the majority carrier concentration increases and contributes to the excess photoconductance [46]. This result in overestimation of excess photoconductance at low carrier densities, thus the excess carrier concentrations and carrier lifetimes are also over estimated.

The Fig. 5.5 clearly shows this trapping effect in this wafer and the QSS-PC measurements are affected by trapping at low injection levels for $\Delta n < 10^{14}$ [cm$^{-3}$]. The over estimation of minority carrier lifetime at low injection levels is clearly seen in the Fig. 5.5 (left). It is possible to correct the QSS-PC data for trapping to a certain extent by introducing a bias light term in the QSS-PC data sheet as described in reference [46]. By introducing the bias light correction the excess photoconductance induced by the traps are subtracted. Thus the trap free excess photoconductance ($\Delta \sigma - \sigma_{traps}$) is calculated and the actual carrier densities and minority carrier lifetime are obtained as shown in Fig. 5.5 (right).
After removing traps, the calibration is carried out with trap free QSS-PC data and the values are compared in Table 5-3. In this step, only the QSS-PC data is corrected for trapping. For calibration, the background light corrected photoluminescence data is considered. Calibration is carried out with the background light corrected PL data. Significant error reduction (up to 30%) is seen with the trap correction.

Table 5-3: Improvement in the calibration parameters after removing the trapping effects from QSS-PC measurements

<table>
<thead>
<tr>
<th>Position in [cm] (Wafer)</th>
<th>Averaged Pixel Value</th>
<th>Minority Carrier Lifetime in [µs]</th>
<th>Excess Carrier Density in [cm⁻³]</th>
<th>ΔError % (With Traps)</th>
<th>ΔError % (Trap free)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X Y Iₚl QSSPC PL(A) QSS-PC PL(A) (τₚc − τₚl)/τₚc (τₚc − τₚl)/τₚc</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 5 174.51 10.1 10.5 4.60×10¹³ 4.81×10¹³</td>
<td>-8.3</td>
<td>-4.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 10 205.03 10.9 11.1 4.99×10¹³ 5.07×10¹³</td>
<td>6.7</td>
<td>-1.6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 5-3: Improvement in the calibration parameters after removing the trapping effects from QSS-PC measurements (Continued)

<table>
<thead>
<tr>
<th>Position in [cm] (Wafer)</th>
<th>Averaged Pixel Value</th>
<th>Minority Carrier Lifetime in [µs]</th>
<th>Excess Carrier Density in [cm⁻³]</th>
<th>ΔError % (With Traps)</th>
<th>ΔError % (Trap free)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X Y Iₚₚ QSSPC PL(A) QSS-PC PL(A) (τₚₑ – τₚₚ) / τₚₑ</td>
<td>X Y Iₚₚ QSSPC PL(A) QSS-PC PL(A) (τₚₑ – τₚₚ) / τₚₑ</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5* 5* 243.18 13.1 13.1 6.00×10¹³ 6.00×10¹³ 0.0 0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.8 7.8 327.8 16.2 17.6 7.45×10¹³ 8.05×10¹³ -28.1 -8.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 10 338.51 16 18.1 7.33×10¹³ 8.31×10¹³ -43.5 -13.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 13 515.97 29.4 31.8 1.35×10¹⁴ 1.46×10¹⁴ -29.6 -8.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Calibration point location and corresponding data.

Also, this signifies that the photoluminescence image calibrated lifetime values have no trapping effects even at low injection levels.

c) Uneven suns correction:

The photoluminescence measurement is carried out at 0.6 [suns] and it is important that the whole wafer is uniformly illuminated. The light from the LED array is not homogenous and has a variation of approximately 0.03 [suns] (5%) over the surface area of the LED illumination case. This results in non-homogenous illumination over the entire area of the wafer which changes the injection level across the wafer. The non-homogeneity is checked with a calibrated solar cell and this non-homogeneity is checked
periodically and it is always approximately constant. The Fig. 5.6 shows the top view of the LED illumination case. When the wafer is mounted on the top of the illumination case all the locations on the wafer are not illuminated uniformly.

![Figure 5.6: Variation in the illumination from LED array: Top view of the LED case.](image)

Table 5.4 illustrates the effect of uneven [suns] distribution on the comparison of the PL lifetimes with QSS-PC. Since, the uneven illumination from the LED arrays cannot be made uniform; the QSS-PC values are corrected accordingly with the actual [suns].

The value of injection-level from QSS-PC at 0.6 (or 0.62) [suns] should be interpolated considering the real illumination from the LED array in that location of the wafer. For example at (5 [cm], 10 [cm]), the excess carrier density at 0.6 [suns] is $7.33 \times 10^{13} \text{ cm}^{-3}$, on the other hand at this location the photoluminescence value is averaged at 0.62 [suns]. For the comparison it is wise to consider the QSS-PC excess carrier density at ~0.62 [suns] which is $8.08 \times 10^{13} \text{ cm}^{-3}$. The corrected values are
compared which minimize the error by ~11%. Similarly, at other locations the correction for suns distribution is made and significant error reduction was achieved.

Table 5-4: Improvement in the calibration parameters after suns correction

<table>
<thead>
<tr>
<th>Position in [cm] (Wafer)</th>
<th>Averaged Pixel Value</th>
<th>Minority Carrier Lifetime in [µs]</th>
<th>Excess Carrier Density in [cm⁻³]</th>
<th>ΔError % (Corrected)</th>
<th>ΔError % (Corrected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X  Y  Ipl  QSSPC  PL(A)  QSS-PC  PL(A)  (τpc-τp)/τpc  (τpc-τpl)/τpc</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10  5  174.51  11.3  10.5  4.71×10¹³  4.81×10¹³  3.8  3.8  3.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10  10  205.03  11.1  11.1  5.11×10¹³  5.07×10¹³  -1.6  0.8  0.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5*  5*  243.18  13.1  13.1  6.00×10¹³  6.00×10¹³  0.0  0.0  0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.8  7.8  327.8  16.2  17.6  7.45×10¹³  8.05×10¹³  -8.1  -8.1  -8.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5  10  338.51  17.6  18.1  8.08×10¹³  8.31×10¹³  -13.4  -2.8  -2.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5  13  515.97  30.3  31.8  1.39×10¹⁴  1.46×10¹⁴  -8.1  -5.0  -5.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Calibration point location and corresponding data.

Comparison of the calibrations carried out with different error corrections are outlined below in Table 5-5. The final calibration results are without background light which eliminates the offset light in the photoluminescence image, without any experimental artifacts like trapping and also corrected illumination [suns] over the entire
wafer. The final PL carrier lifetime values are in good agreement with the QSS-PC lifetimes.

Table 5-5: Step-by-step illustration of improvement in the calibration

<table>
<thead>
<tr>
<th>Position in [cm] (Wafer)</th>
<th>Error %*</th>
<th>Error %**</th>
<th>Error %***</th>
<th>Error %****</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 5</td>
<td>-10.4</td>
<td>-8.3</td>
<td>-4.6</td>
<td>-2.1</td>
</tr>
<tr>
<td>10 10</td>
<td>7.7</td>
<td>6.7</td>
<td>-1.6</td>
<td>0.8</td>
</tr>
<tr>
<td>5 5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>7.8 7.8</td>
<td>-31.7</td>
<td>-28.1</td>
<td>-8.1</td>
<td>-8.1</td>
</tr>
<tr>
<td>5 10</td>
<td>-47.4</td>
<td>-43.5</td>
<td>-13.4</td>
<td>-2.8</td>
</tr>
<tr>
<td>5 13</td>
<td>-30.4</td>
<td>-29.6</td>
<td>-8.1</td>
<td>-5.0</td>
</tr>
</tbody>
</table>

* Error with background light, with trapping, without [suns] correction  
** Error without background light, with trapping, without [suns] correction  
*** Error without background light, without trapping, without [suns] correction  
**** Error without background light, without trapping, with [suns] correction

Once the accurate calibration has been reached the photoluminescence lifetime map of the entire wafer is calculated as shown in Fig. 5.7.
Figure 5.7: Photoluminescence Lifetime map of wafer#PCPV1 (scale in [µs]).

The entire process of calibration and then error correction takes long time to reach the accurate photoluminescence lifetimes which affect the fastness of the photoluminescence lifetime imaging characterization technique. In order to avoid all these experimental artifacts, the Engineering and Services Department of Energy Research Center of Netherlands (ECN) [61] has developed a new photoluminescence setup which has the following properties.

a) Illumination of ~3 [suns] can be reached at 100% illumination level which allows to work with the injection levels above the trapping level or density (>10^{14} [cm^{-3}]).

b) With the new photoluminescence setup, the background light is almost reduced to 0%.

c) PL setup has homogenous light illumination.

The calibration performed with the new photoluminescence setup does not require trap correction in most of the wafers, background light and [suns] correction. The trap
density is wafer dependent and the trapping effect should always be checked at the given injection level. The wafers can be easily calibrated and calibrations performed on various wafers with new PL setup are discussed below.

5.1.2 Calibration on wafer#PVDA196

With the new photoluminescence measurement setup, maximum of 3.0 [suns] can be reached at 100% illumination. The calibration methods discussed in Sections 4.1 and 4.2 are demonstrated on a different $p$-type multicrystalline silicon wafer from a different ingot. The thickness of the wafer is 250 [$\mu$m] measured with a thickness meter and optical constant is assumed to be constant value of 0.85. The wafer is SiN passivated on both sides. The wafer parameters are outlined below.

- $p$-type, Multicrystalline Silicon, 250 [$\mu$m]
- SiN passivated, Doping: $9.5 \times 10^{15}$ [cm$^{-3}$]
- Optical constant: 0.85

QSS-PC measurements are performed on various locations on the wafer. The doping density is also measured with Sinton lifetime tester if not specified. For the calibration, both single point and fit calibration methods are demonstrated on this wafer. Single point calibration:

For, single point calibration, a single injection level is considered for determining the calibration factor. Fig. 5.8 shows the injection level dependent carrier lifetimes at (5cm, 5cm) location on the wafer#PVDA196. It is evident from the Fig. 5.8 that the trapping level has been overcome at 2.42 [suns] (red dot). At 2.42 [suns], the excess
carrier density ($\Delta n$) = $7.67 \times 10^{14}$ [cm$^{-3}$], generation rate ($G$) = $4.9 \times 10^{17}$ [cm$^{-3}$ [sec$^{-1}$]] and doping ($N_a$) = $9.5 \times 10^{15}$ [cm$^{-3}$].

Figure 5.8: QSS-PC measurement on wafer#PVDA196 at (5 [cm], 5 [cm]) location, red dot is the calibration point at 2.42 [suns].

Next photoluminescence image of the entire wafer is captured at 2.42 [suns] at 1392×1040 resolution with an integration time of 1 [sec] (see Fig. 5.9).
Similarly, QSS-PC lifetime measurements are taken at various positions on the wafer for future comparisons. The regions indicated in blue in Fig. 5.9 represent low PL intensity and regions indicated in red represent high PL intensity.

The \( \tau_{\text{eff}} \) and \( \Delta n \) measurement shown in Fig. 5.8 corresponds to the average lifetime over the area of circle shown in Fig. 5.9. The photoluminescence intensity is averaged over this area using Matlab code. Which is \( I_{pl} = 1192.8 \) [counts].

Using Eq. (2.17), \( A_i \) is determined as \( 1.516 \times 10^{-28} \) [counts cm\(^6\)] and this calibration factor is used to calculate excess carrier densities and minority carrier lifetime at other locations on the wafer and for the whole wafer. For validation, the calibrated QSS-PL lifetime values are compared with the measured QSS-PC lifetime values at same locations and are outlined in Table 5-6.

The percentage error is calculated with the measured QSS-PC lifetimes and calibrated photoluminescence lifetimes. The PL lifetime values are direct calibrated.
values without any need for error correction steps discussed earlier. The PL lifetime values are in good agreement with QSS-PC lifetimes with a maximum error of 12.5% i.e. with difference of 3.6 [µs] in the lifetimes.

Table 5-6: Comparison of calibrated photoluminescence and measured QSS-PC lifetime values at various locations on wafer#PVDA196

<table>
<thead>
<tr>
<th>Position in [cm] (Wafer)</th>
<th>Pixel Value</th>
<th>Minority Carrier Lifetime in [µs]</th>
<th>Excess Carrier Density in [cm(^{-3})]</th>
<th>ΔError %</th>
</tr>
</thead>
<tbody>
<tr>
<td>X 6.25 8 608.36 20.5 19.8 4.04×10(^{14}) 4.05×10(^{14}) -0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.25 7.5 622.92 22.0 20.6 4.28×10(^{14}) 4.15×10(^{14}) 3.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.5 6.25 658.36 23.1 22.3 4.53×10(^{14}) 4.37×10(^{14}) 3.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.25 6.25 710.27 27.4 23.8 5.37×10(^{14}) 4.70×10(^{14}) 12.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 6.25 842.02 28.5 28.1 5.57×10(^{14}) 5.53×10(^{14}) 0.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.25 5 985.14 33.8 32.9 6.60×10(^{14}) 6.41×10(^{14}) 2.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5* 5* 1192.8 39.2 39.2 7.67×10(^{14}) 7.67×10(^{14}) 0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Calibration point location and corresponding data.

Apart from overcoming all the error correction factors, small deviation from the QSS-PC and PL lifetimes is still present. The error can be due to the measured QSS-PC
values or also due to the PL signal. The following discussion can be considered to alleviate the error.

a) Since, the wafer has inhomogeneous lifetime distribution and PL lifetime values are area averaged values in this comparison, the small deviation between the PL and QSS-PC values is always expected. Apart from the actual radius (1.8 [cm]) of the Sinton rf coil, for averaging, the coil radius is assumed to be 1.1 [cm] where vast majority of the sensitivity (98%) of the coil lies inside this radius (1.1 [cm]). The rest 2% of the sensitivity falls between the concentric circles of radii 1.1 [cm] and 1.8 [cm]. Therefore, QSS-PC lifetime values also contain this 2% sensitivity region and this region is ignored for area averaged photoluminescence signal. Although for the entire lifetime map of the wafer, where each pixel is calibrated individually, the lifetime values are estimated to be more accurate.

b) Also, the measured wafers are not assured to have uniform thickness over the entire wafer. Thus, also changing the calculated doping concentration from conductance measurements (QSS-PC). In addition the doping concentration can vary within the wafer as well. The measured doping concentration at various locations is varying over the range of \((7.4 - 7.6) \times 10^{15} \text{ [cm}^{-3}]\). For the calibration, the doping is assumed to be an averaged value of \(7.5 \times 10^{15} \text{ [cm}^{-3}]\).

c) Two different light excitation sources are used \(i.e.\) for QSS-PC a flash lamp is used to illuminate the wafers and for PL measurements a LED array with single wavelength light is used.
The fit calibration method discussed in Section 4.2 is also demonstrated on this wafer.

Fit calibration method:

In the fit calibration various injection levels (Δn) and corresponding area averaged pixel values (I_{pl}) at a given location are considered for the estimation of calibration factor (A_i). Once, the calibration factor is known the same procedure discussed in for the single point calibration is followed. QSS-PC measurement is performed at (5cm, 5cm) location on the wafer. Various photoluminescence images are captured at various illumination intensities (0, 0.3, 0.5, 1, 1.2, 1.5, 2, 2.42, 2.7, and 3). The area averaged pixel values (0, 92.521, 126.53, 292.51, 378.34, 530.23, 834.65, 1192.8, 1316.7 and 1574) are determined at (5cm, 5cm) location on the wafer. At illumination intensities (0, 0.3, 0.5, 1, 1.2, 1.5, 2, 2.42, 2.7, and 3), the absolute values of excess carrier densities (Δn_1, Δn_2, Δn_3,..... Δn_j) are extracted from the QSS-PC measurement sheet. The area averaged pixel values and excess carrier densities (Δn_1, Δn_2, Δn_3,..... Δn_j) shown in Table 5-7 are fitted into Eq. (4.1).

<table>
<thead>
<tr>
<th>Illumination in [suns]</th>
<th>Area Averaged Pixel Value (I_{pl})</th>
<th>Excess Carrier Density (Δn) in [cm^{-3}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.3</td>
<td>92.521</td>
<td>1.02×10^{14}</td>
</tr>
<tr>
<td>0.5</td>
<td>126.53</td>
<td>1.5×10^{14}</td>
</tr>
<tr>
<td>1</td>
<td>292.51</td>
<td>2.92×10^{14}</td>
</tr>
</tbody>
</table>
Table 5-7: $I_{pl}$ vs $\Delta n$ data used for fitting (Continued)

<table>
<thead>
<tr>
<th>Illumination in [suns]</th>
<th>Area Averaged pixel value ($I_{pl}$)</th>
<th>Excess Carrier Density ($\Delta n$) in [cm$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>378.34</td>
<td>$3.5 \times 10^{14}$</td>
</tr>
<tr>
<td>1.5</td>
<td>530.23</td>
<td>$4.42 \times 10^{14}$</td>
</tr>
<tr>
<td>2</td>
<td>834.65</td>
<td>$6.12 \times 10^{14}$</td>
</tr>
<tr>
<td>2.42*</td>
<td>1192.8</td>
<td>$7.67 \times 10^{14}$</td>
</tr>
<tr>
<td>2.7</td>
<td>1316.7</td>
<td>$8.63 \times 10^{14}$</td>
</tr>
<tr>
<td>3</td>
<td>1574</td>
<td>$9.73 \times 10^{14}$</td>
</tr>
</tbody>
</table>

*Calibration point

Figure 5.10: $I_{pl}$ and $\Delta n$ fit at (5cm, 5cm) location on wafer#PVDA196.
Table 5-8: Comparison of fit calibrated photoluminescence and measured QSS-PC lifetime values at various locations on wafer#PVDA196

<table>
<thead>
<tr>
<th>Position in [cm] (Wafer)</th>
<th>Pixel Value</th>
<th>Minority Carrier Lifetime in [µs]</th>
<th>Excess Carrier Density in [cm(^{-3})]</th>
<th>ΔError %</th>
</tr>
</thead>
<tbody>
<tr>
<td>X 6.25 8 Y 608.36</td>
<td>I(_{pl})  20.5</td>
<td>21.6</td>
<td>4.04E+14 4.23E+14</td>
<td>-4.7</td>
</tr>
<tr>
<td>X 6.25 7.5 Y 622.92</td>
<td>I(_{pl})  22.0</td>
<td>22.0</td>
<td>4.28E+14 4.32E+14</td>
<td>-0.8</td>
</tr>
<tr>
<td>X 7.5 6.25 Y 658.36</td>
<td>I(_{pl})  23.1</td>
<td>23.3</td>
<td>4.53E+14 4.56E+14</td>
<td>-0.7</td>
</tr>
<tr>
<td>X 6.25 6.25 Y 710.27</td>
<td>I(_{pl})  27.4</td>
<td>24.9</td>
<td>5.37E+14 4.88E+14</td>
<td>9.1</td>
</tr>
<tr>
<td>X 5 6.25 Y 842.02</td>
<td>I(_{pl})  28.5</td>
<td>29.4</td>
<td>5.57E+14 5.77E+14</td>
<td>-3.5</td>
</tr>
<tr>
<td>X 6.25 5 Y 985.14</td>
<td>I(_{pl})  33.8</td>
<td>34.1</td>
<td>6.60E+14 6.69E+14</td>
<td>-1.4</td>
</tr>
<tr>
<td>X 5 5 Y 1192.8</td>
<td>I(_{pl})  39.2</td>
<td>41.1</td>
<td>7.67E+14 8.06E+14</td>
<td>-5.1</td>
</tr>
</tbody>
</table>

Here, instead of using only single injection level (2.42 [suns]) a range of injection levels are used for determining \(A_i\). Using fit equation, \(N_a\) is fixed at 9.5×10\(^{15}\) [cm\(^{-3}\)] and \(A_i\) is determined as 1.443×10\(^{-28}\) [counts cm\(^6\)] and the fit is shown in Fig. 5.10. The calculation procedure is repeated at 2.42 [suns] with the new calibration factor.
For both the calibration methods it can be clearly seen that at (6.25 cm, 6.25 cm) highest error is seen with difference in the PL and QSS-PC lifetimes of 3 [µs]. The reason for that is studied by plotting the area averaged pixel values and carrier densities at multiple locations on the wafer which is shown in Fig. 5.11. According to the Eq. (2.16), when illuminated, the photoluminescence intensity from the silicon wafer should vary linearly (with a small quadratic term) with the excess carrier densities.

![Image of a graph showing area averaged pixel value vs excess carrier density]

Figure 5.11: $I_{pl}$ vs Δn at various locations on the wafer#PVDA196.

But from Fig. 5.11 the QSS-PC values (solid black line) are varying linearly (with a small quadratic term) except for the point at $5.37\times10^{14}$ [cm$^{-3}$]. This is the reason for the difference in the lifetime of 3 [µs] at this point. Two cases are considered here. Firstly, this point has been checked by performing QSS-PC measurements multiple times to
reduce the experimental error but the same value is repeated. Secondly, multiple PL images are taken and checked for the $I_{pl}$ at the same location, also with repeatable PL values.

Thus this can be considered as an uncertainty due to thickness variation or doping density or surface texturization of the wafer or effect of the different spectrum used in the two experimental conditions. PL and QSS-PC values at other spots on the wafers are in good agreement with an error in the range (1-0.9) [µs].

To check the applicability of the calibration procedure with new photoluminescence setup other multicrystalline silicon wafers are calibrated and are discussed in the following sections.

5.1.3 Calibration on wafer#PVFJ174

The calibration method discussed in Sections 4.1 is demonstrated on a different $p$-type multicrystalline silicon wafer from a different ingot. The thickness of the wafer is 185 [µm] measured with a thickness meter and optical constant is assumed to be constant value of 0.85. The wafer is SiN passivated on both sides. The wafer parameters are outlined below.

- $p$-type, Multicrystalline Silicon, 250 [µm]
- SiN passivated, Doping: $9.5 \times 10^{15}$ [cm$^{-3}$]
- Optical constant: 0.85

The single point calibration procedure outlined in the previous section is applied to this $p$-type multicrystalline silicon wafer. The Fig. 5.12 shows the QSS-PC
measurement at (7.8 cm, 7.8 cm) location on the wafer. This is a trap free wafer even at low injection levels. At 2.42 [suns], the excess carrier density ($\Delta n = 2.37 \times 10^{15}$ [cm$^{-3}$]), generation rate ($G = 4.9 \times 10^{17}$ [cm$^{-3}$ sec$^{-1}$]), doping ($N_a = 1.24 \times 10^{16}$ [cm$^{-3}$]). Similarly, QSS-PC measurements are taken at various locations on the wafer for validation.

The PL image is captured at 2.42 [suns] with an integration time of 2 [sec] (See Fig. 5.13).
The measurement shown in the Fig. 5.12 corresponds to the average lifetime over the area shown in Fig. 5.13. So now, the area averaged photoluminescence signal over this area is $I_{pl}=1453.74$ [counts] and the calibration factor is calculated as $A_i=4.153\times10^{-29}$ [counts cm$^6$]. To assess the accuracy of the single point calibration, the measured QSS-PC values are compared with the calibrated PL values and outlined in Table 5-9.
Table 5-9: Comparison of calibrated photoluminescence and measured QSS-PC lifetime values at various locations on wafer#PVFJ174

<table>
<thead>
<tr>
<th>Position in [cm] (Wafer)</th>
<th>Pixel Value</th>
<th>Minority Carrier Lifetime in [µs]</th>
<th>Excess Carrier Density in [cm^-3]</th>
<th>ΔError %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
<td>$I_{pl}$</td>
<td>$QSSPC$</td>
</tr>
<tr>
<td>7.8</td>
<td>6</td>
<td></td>
<td>886.496</td>
<td>58.5</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td></td>
<td>1036.74</td>
<td>64.9</td>
</tr>
<tr>
<td>7.8</td>
<td>9</td>
<td></td>
<td>1130.91</td>
<td>78.1</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td></td>
<td>1272.56</td>
<td>80.4</td>
</tr>
<tr>
<td>6</td>
<td>7.8</td>
<td></td>
<td>1313.7</td>
<td>80.8</td>
</tr>
<tr>
<td>9</td>
<td>7.8</td>
<td></td>
<td>1385.42</td>
<td>87.6</td>
</tr>
<tr>
<td>7.8</td>
<td>7.8</td>
<td></td>
<td>1453.74</td>
<td>89.6</td>
</tr>
</tbody>
</table>

The maximum error in the measured QSS-PC and calibrated PL lifetime is 6.4 [µs] at (7.8 cm, 9 cm) location on the wafer. But on the other locations the error is about (2-0.4) [µs]. The error is explained using Fig. 5.14. According to the Eq. (2.17), when illuminated, the photoluminescence intensity from the silicon wafer should vary linearly (with a small quadratic term) with the excess carrier densities. But from Fig. 5.14 the QSS-PC values (solid black line) are varying linearly (with a small quadratic term)
except for the point at $1.90 \times 10^{15} \text{ [cm}^{-3}\text{]}$. This is the reason for the difference in the lifetime of 6.4 [$\mu$s] at this point.

Figure 5.14: $I_{pl}$ vs $\Delta n$ at various locations on the wafer#PVFJ174.

Same discussion as in previous section applies for the deviation in the linearity when $I_{pl}$ VS $\Delta n_{qsspc}$ are plotted (shown in Fig. 5.14). The deviation is more at (7.8 cm, 9 cm) where maximum error of 8.1% occurs.

For more verification and to compare the fastness of the PL lifetime technique, the photoluminescence lifetime map (shown in Fig. 5.15, left) is compared with the $Semilab's$ $\mu w$-PCD lifetime map (shown in Fig. 5.15, right) scanned at a bias light of 2.42 [suns].
Table 5-10 illustrates the comparisons and advantages of photoluminescence lifetime imaging method over *Semilab’s* µw-PCD method.

**Figure 5.15**: Photoluminescence lifetime map (left) and Semilab’s µw-PCD map (right) of wafer#PVFJ194.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Photoluminescence imaging</th>
<th>Semilab’s µw-PCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>suns</td>
<td>2.42</td>
<td>2.42</td>
</tr>
<tr>
<td>Analysis</td>
<td>Steady state</td>
<td>Transient</td>
</tr>
<tr>
<td>Lifetime values</td>
<td>Absolute</td>
<td>Differential</td>
</tr>
<tr>
<td>Scanning time</td>
<td>2 [sec]</td>
<td>2 [hours]</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>~150 [µm]</td>
<td>250 [µm]</td>
</tr>
<tr>
<td>Average lifetime</td>
<td>82.3 [µs]</td>
<td>88.2 [µs]</td>
</tr>
<tr>
<td>Minimum lifetime</td>
<td>1.7 [µs]</td>
<td>3.7 [µs]</td>
</tr>
<tr>
<td>Maximum lifetime</td>
<td>274 [µs]</td>
<td>310 [µs]</td>
</tr>
</tbody>
</table>
The average lifetime of the entire wafer obtained by PL and PCD methods is in good agreement. However, the µw-PCD lifetime is in transient mode while the PL lifetime is in steady state mode, therefore the lifetime cannot be directly correlated. The measurement time clearly indicates that the PL imaging method can be potentially a fast lifetime characterization tool with good spatial resolution.

5.2 *N*-type multicrystalline silicon wafers

So far photoluminescence lifetime calibration was demonstrated with the *p*-type multicrystalline silicon wafers. In this section we demonstrate that the photoluminescence lifetime imaging technique is also applicable to *n*-type multicrystalline silicon wafers.

5.2.1 Calibration on wafer#1-B1-62

The single point calibration method discussed in Section 4.1 is demonstrated on an *n*-type multicrystalline silicon wafer with thickness of 285 [µm]. The wafer is well passivated on both sides with silicon nitride (SiN). The wafer parameters are outlined below.

- *n*-type, Multicrystalline Silicon, 285 [µm]
- SiN passivated, Doping: $1.47 \times 10^{15}$ [cm$^{-3}$]
- Optical constant: 0.85

As a decaying flash light is used for the QSS-PC measurement, the injection-level dependent carrier lifetime is obtained as shown in Fig. 5.16. Generalized QSS-PC measurements are performed at various locations on the wafer. The calibration factor ($A_i$)
is calculated at (5 [cm], 5 [cm]) location on the wafer. At 3.0 [suns], the excess carrier density ($\Delta n = 8.99 \times 10^{14}$ [cm$^{-3}$]), generation rate ($G = 6.1 \times 10^{17}$ [cm$^{-3}$ sec$^{-1}$]), doping ($N_d = 1.47 \times 10^{15}$ [cm$^{-3}$]). Similarly, QSS-PC measurements are taken at various locations on the wafer for calibration validation.

![Figure 5.16: QSS-PC measurement on wafer 1-B1-62 at (5 [cm], 5 [cm]) (red dot) as excess carrier density corresponding to 3 [suns]](image)

The PL image is captured at 3.0 [suns] with an exposure time of 5 [sec] (see Fig. 5.17)

![Figure 5.17: Photoluminescence image of wafer#1-B1-62 captured at 3 [suns] for an integration time of 5 [sec].](image)
The measurement shown in the Fig. 5.16 corresponds to the average lifetime over the area shown in Fig. 5.17. The area averaged photoluminescence signal over this area is $I_{pl} = 511.73$ [counts]. The calibration factor is determined as $A_i = 2.4028 \times 10^{-28}$ [counts cm$^6$] followed by calibration of the entire wafer and comparison with QSS-PC lifetime values (outlined in Table 5-11).

Table 5-11: Comparison of calibrated photoluminescence and measured QSS-PC lifetime values at various locations on wafer#1-B1-62

<table>
<thead>
<tr>
<th>Position in [cm] (Wafer)</th>
<th>Pixel Value</th>
<th>Minority Carrier Lifetime in [µs]</th>
<th>Excess Carrier Density in [cm$^{-3}$]</th>
<th>$\Delta$Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 4</td>
<td>475.005</td>
<td>39.2</td>
<td>8.39×10$^{14}$</td>
<td>-1.6</td>
</tr>
<tr>
<td>5 6</td>
<td>489.937</td>
<td>40.9</td>
<td>8.75×10$^{15}$</td>
<td>0.5</td>
</tr>
<tr>
<td>5 4</td>
<td>501.632</td>
<td>40.8</td>
<td>8.72×10$^{15}$</td>
<td>-1.6</td>
</tr>
<tr>
<td>4 5</td>
<td>502.524</td>
<td>40.9</td>
<td>8.75×10$^{15}$</td>
<td>-1.4</td>
</tr>
<tr>
<td>5* 5*</td>
<td>511.735</td>
<td>42.1</td>
<td>8.99×10$^{15}$</td>
<td>0.0</td>
</tr>
<tr>
<td>6 5</td>
<td>532.382</td>
<td>43.4</td>
<td>9.28×10$^{15}$</td>
<td>0.3</td>
</tr>
<tr>
<td>7 7</td>
<td>536.817</td>
<td>43.1</td>
<td>9.20×10$^{15}$</td>
<td>-1.2</td>
</tr>
<tr>
<td>7 5</td>
<td>543.624</td>
<td>46.2</td>
<td>9.87×10$^{15}$</td>
<td>4.9</td>
</tr>
</tbody>
</table>
The minority carrier lifetime values obtained from the photoluminescence image calibration are in good comparison with QSS-PC measurement method with a maximum error of 2.3 [µs] in the PL and QSS-PC lifetimes. For the other locations, the error is within (0.7-0.1) [µs].

For further comparison, the photoluminescence lifetime map is also compared with Semilab’s µw-PCD map. Fig. 5.18 shows the comparison of the lifetime map obtained from the photoluminescence (left) and from Semilab’s µW-PCD method (right). The PL image is captured at ~ 150 [µm] resolutions and the Semilab’s µW-PCD map is scanned at 250 [µm] resolution.

Table 5-12 illustrates the comparison and advantages of photoluminescence lifetime imaging method over Semilab’s µw-PCD method.
Table 5-12: Comparison between PL and µW-PCD method for lifetime characterization

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Photoluminescence imaging</th>
<th>Semilab’s µw-PCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>suns</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Analysis</td>
<td>Steady state</td>
<td>Transient</td>
</tr>
<tr>
<td>Lifetime values</td>
<td>Absolute</td>
<td>Differential</td>
</tr>
<tr>
<td>Scanning time</td>
<td>5 [sec]</td>
<td>1.5 [hours]</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>~150 [µm]</td>
<td>250 [µm]</td>
</tr>
<tr>
<td>Average lifetime</td>
<td>62.2 [µs]</td>
<td>58.4 [µs]</td>
</tr>
</tbody>
</table>

The average lifetime of the entire wafer obtained by PL and PCD methods is compared. The average PL lifetime of entire wafer is in good agreement with *Semilab’s* µw-PCD, as the µw-PCD lifetime is in transient mode while the PL is in steady state mode, therefore the lifetime cannot be directly correlated. The scanning time of entire wafer clearly indicates that the PL imaging method can be potentially a fast lifetime characterization tool with good spatial resolution.

5.2.2 Calibration on wafer#1-B1-176

The calibration method discussed in *Section 4.1* is demonstrated on a different *n*-type multicrystalline silicon wafer from different position in the same ingot (1-B1). The
thickness of the wafer is 285 [µm] measured with a thickness meter and optical constant is assumed to be constant value of 0.85. The wafer is SiN passivated on both sides. The wafer parameters are outlined below.

- *n*-type, Multicrystalline Silicon, 285 [µm]
- SiN passivated, Doping: $1.00 \times 10^{15}$ cm$^{-3}$
- Optical constant: 0.85

The single point calibration procedure outlined in the previous section is applied to this *n*-type multicrystalline silicon wafer. Fig. 5.19 shows the QSS-PC measurement at (5 cm, 5 cm) location on the wafer. At 3.0 [suns], the excess carrier density ($\Delta n$) = $1.18 \times 10^{15}$ [cm$^3$], generation rate ($G$) = $6.1 \times 10^{17}$ [cm$^3$ [sec]$^{-1}$] and doping ($N_a$) = $1.0 \times 10^{16}$ [cm$^{-3}$]. Similarly, QSS-PC measurements are taken at various locations on the wafer for validation.

Figure 5.19: QSS-PC measurement on wafer#1-B1-176 at (5cm, 5cm) location, red dot is the calibration point at 3 [suns].
The PL image is also captured at 3.0 [suns] with an exposure time of 5 [sec] (see Fig. 5.20),

![Image]

Figure 5.20: Photoluminescence image of wafer#1-B1-176 captured at 3.0 [suns] for an integration time of 5 [sec]

The measurement shown in the Fig. 5.19 corresponds to the average lifetime over the area shown in Fig. 5.20. The area averaged photoluminescence signal over this area is $I_{pl} = 714.53$ [counts]. The calibration factor is calculated as $A_i = 5.416 \times 10^{-29}$ [counts cm$^6$]. The results and comparisons of the calibration are discussed in the Table 5-13. The values obtained from the PL calibration are in good comparison with measured QSSPC values with a maximum error of 2.3 [$\mu$s]. For the other locations, the error is within (1.5-0.3) [$\mu$s].
Table 5-13: Comparison of calibrated photoluminescence and measured QSS-PC lifetime values at various locations on wafer#1-B1-176.

<table>
<thead>
<tr>
<th>Position in [cm] (Wafer)</th>
<th>Pixel Value</th>
<th>Minority Carrier Lifetime in [µs]</th>
<th>Excess Carrier Density in [cm$^{-3}$]</th>
<th>ΔError %</th>
</tr>
</thead>
<tbody>
<tr>
<td>X Y QSSPC PL(A) QSS-PC PL(A) ($\tau_{pc} - \tau_{pl}$)/$\tau_{pc}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 4 694.45 51.6 53.9 1.1E×10$^{15}$ 1.15×10$^{15}$ -4.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5* 5* 714.53 55.3 55.3 1.18×10$^{15}$ 1.18×10$^{15}$ 0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 5 739.89 57.7 57.1 1.23×10$^{15}$ 1.22×10$^{15}$ 0.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 5 740.68 57.7 57.1 1.23×10$^{15}$ 1.22×10$^{15}$ 0.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 5 749.94 58.1 57.8 1.24×10$^{15}$ 1.23×10$^{15}$ 0.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 5 759.71 60.0 58.5 1.28×10$^{15}$ 1.25×10$^{15}$ 2.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Calibration point location and corresponding data.

For further clarification, the PL lifetime map is also compared with Semilab’s µW-PCD map (see Fig. 5.21). Fig 5.21 shows the comparison of the lifetime map obtained from the photoluminescence (left) and from Semilab’s µW-PCD method (right). The PL image is captured at ~ 150 [µm] resolutions and the Semilab’s µW-PCD map is scanned at 250 [µm] resolution.
Figure 5.21: PL lifetime map (left) and Semilab’s µW-PCD lifetime map (right) of wafer 1-B1-176.

Table 5-14 illustrates the comparison and advantages of photoluminescence lifetime imaging method over Semilab’s µw-PCD method. The average lifetime of the entire wafer obtained by PL and PCD methods is compared. The PL average lifetime of entire wafer is in good agreement with Semilab’s µw-PCD lifetime, as the µw-PCD lifetime is in transient mode while the PL uses is in steady state mode, therefore the lifetime cannot be directly correlated.
The scanning time of entire wafer with *Semilab’s* µW-PCD is 1.5 hours and with PL imaging method is 5 [sec]. Thus it can be concluded that the PL imaging method can be potentially a fast lifetime characterization tool with good spatial resolution.
6 CONCLUSIONS

In this project we successfully developed a photoconductance-calibrated photoluminescence lifetime imaging tool at Energy Research Center of Netherlands (ECN Solar Energy). The following conclusions are drawn from the work described in this thesis:

- We demonstrated the applicability of the minority carrier lifetime characterization tool for both $p$- and $n$- type multicrystalline silicon wafers. The calibration was successfully performed on different multicrystalline silicon wafers from different ingots. To verify the precision of photoluminescence lifetime calibration procedure, the minority carrier lifetimes were compared with industry standard lifetime tools like *Sinton’s QSS-PC* lifetime tester and *Semilab’s μw-PCD* with good agreement.

- The tool was optimized to characterize minority carrier lifetimes in silicon wafers with the following advantages and capabilities:
  - Absolute values of the minority carrier lifetimes are measured with this technique. Step-by-step experimental and data analysis was carried out to study, identify and eliminate the experimental artifacts like trapping, uneven [suns] distribution and noise in photoluminescence signal.
  - Unlike *QSS-PC* lifetime tester, the photoluminescence lifetimes are trap free values even at low injection levels ($<10^{14}$ [cm$^{-3}$]). With the new photoluminescence setup, calibration can be carried out with a trap free QSS-PC measurement.
Photoluminescence lifetime tool is a fast characterization tool with measurement times down to 1 [sec] with a good spatial resolution of approximately 150[µm] when compared with *Semilab’s µw-PCD* which takes more than 1 hour for scanning the whole wafer at 250 [µm] resolution.

Two different calibration algorithms (single point and fit calibration method) were developed using same experimental data for validation. Good lifetime agreement has been obtained from these methods. The fit calibration method is mainly used in this project to verify the accuracy of the experimental data and the calibration.

For the calibration and data analysis, a Matlab program was developed which implements the algorithm discussed here. Various tools like image processing tool, data and statistics tools were used for implementing the algorithm. All the photoluminescence and lifetime maps, comparison tables and theoretical values were obtained from this program. Also, the simulation time for implementing the algorithm on a 32-bit machine is very low making the calibration and data analysis faster.
7 FUTURE WORK

7.1 Photoluminescence Lifetime imaging on crystalline silicon:

The calibrations performed on $p$- and $n$- type multicrystalline silicon wafers were in good comparison with other lifetime characterization tools. Apart from these comparisons, there are small uncertainties (error) found in the photoluminescence lifetime values when compared with measured QSS-PC values. As discussed earlier, firstly, this error can be due to the photoluminescence signal. Secondly it can be due to the uncertainty in QSS-PC. For future development, the following suggestions can be implemented.

a) Correction of uncertainties in QSS-PC and PL:

As discussed earlier, the Sinton RF coil has a radius of 1.8 [cm], but the vast majority (98%) of the sensitivity lies inside the coil of radius 1.1 [cm]. The rest 2% of the sensitivity falls between the concentric coils of radii 1.1 [cm] and 1.8 [cm].

Figure 7.1: PL image of PVDA196 (left) and area considered for QSS-PC and PL measurements at (6.25 cm, 6.25cm) (right).
For the calibration, area averaged pixel value \((I_{pl})\) has to be calculated from PL image over area of coil with appropriate radius which is assumed as 1.1 [cm] (area inside circle with white boundary in Fig. 7.1) for the calibrations in this project. The photoluminescence outside the circle with white boundary is neglected as it constitutes only 2% (See Fig. 7.1).

Now, all the pixels between concentric coils of radii 1.1 [cm] and 1.8 [cm] are neglected for the calculation of \(I_{pl}\) but this region is considered by Sinton RF coil in the QSS-PC measurements. This induces some error in the measured QSS-PC and calibrated PL lifetimes. The possible approach here is to study the variation in the \(I_{pl} vs \Delta n_{QSS-PC}\) with different the coil radii (0.9 cm-1.8 cm) by fitting \(I_{pl}\) and QSS-PC data into a linear fit. At certain coil radius an appropriate linear relation between \(I_{pl}\) and \(\Delta n_{QSS-PC}\) can be obtained \(i.e.\) an R-squared value closer to 1.0 from the fit, and this radius can be considered as an optimal radius. Also, this has to be verified with other wafers with repeatable results.

b) Calibration factor \(A_i\):

In this project calibration factor \(A_i\) is determined for each wafer, but in some cases the calibration factor obtained from a wafer can be extended to other wafers. This can be applicable for wafers from same ingot or for wafers with identical properties like surface properties etc. For example, in this project, the \(n\)-type multicrystalline wafers (1-B1-62, 1-B1-176) discussed in the Sections 5.2.1 and 5.2.2 are from same ingot but with different doping densities. In this project, we determined calibration factors for each of these wafers individually. Since the calibration factor depends on the doping and surface
properties of the wafer, in this case there is no need of determining the calibration factor for both wafers individually. Once, a calibration factor is determined for wafer#1-B1-62, the same $A_i$ can be extended to the any wafer in the ingot. The new calibration factor for each wafer can be calculated with the following equation.

$$A_{new} = \frac{A_{ref} \times (N_{DA(new)} + \Delta n_{ref})}{(N_{DA(ref)} + \Delta n_{ref})}$$  \hspace{1cm} (7.1)$$

Once the calibration factor for reference wafer is calculated, the same calibration factor can be used to calculate new calibration factor without any additional measurements. 

For the reference wafer#1-B1-62, $\Delta n_{ref} = 8.99 \times 10^{14}$ [cm$^{-3}$], $N_{a(ref)} = 1.47 \times 10^{15}$ [cm$^{-3}$], $A_{ref} = 2.4028 \times 10^{-28}$ [counts cm$^6$]. To calibrate the wafer#1-B1-176 it is not necessary to perform QSS-PC measurements. The calibration factor can be calculated by knowing the doping and using the Eq. 7.1. The doping density of wafer#1-B1-62 is $N_{a(new)} = 1.0 \times 10^{16}$ [cm$^{-3}$].

The new calibration factor is determined, $A_{new} = 5.227 \times 10^{-29}$ [counts cm$^6$] and the results are outlined in Table 7.1.
Table 7-1: Calibrations performed on wafer#1-B1-176 using reference wafer ($A_{ref}$)

<table>
<thead>
<tr>
<th>Position in cm (Wafer)</th>
<th>Pixel Value</th>
<th>Minority Carrier Lifetime in [µs]</th>
<th>Excess Carrier Density in cm$^{-3}$</th>
<th>ΔError</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X$ $Y$</td>
<td>QSS-PC</td>
<td>PL(A)</td>
<td>QSS-PC (A)</td>
<td></td>
</tr>
<tr>
<td>5 4</td>
<td>694.45</td>
<td>51.4 55.1</td>
<td>$1.1\times10^{15}$</td>
<td>$1.18\times10^{15}$</td>
</tr>
<tr>
<td>5 5</td>
<td>714.53</td>
<td>55.1 56.5</td>
<td>$1.18\times10^{15}$</td>
<td>$1.21\times10^{15}$</td>
</tr>
<tr>
<td>6 5</td>
<td>739.89</td>
<td>57.5 58.4</td>
<td>$1.23\times10^{15}$</td>
<td>$1.25\times10^{15}$</td>
</tr>
<tr>
<td>4 5</td>
<td>740.68</td>
<td>57.5 58.5</td>
<td>$1.23\times10^{15}$</td>
<td>$1.25\times10^{15}$</td>
</tr>
<tr>
<td>7 5</td>
<td>749.94</td>
<td>57.9 59.5</td>
<td>$1.24\times10^{15}$</td>
<td>$1.27\times10^{15}$</td>
</tr>
<tr>
<td>3 5</td>
<td>759.71</td>
<td>59.8 60.2</td>
<td>$1.28\times10^{15}$</td>
<td>$1.29\times10^{15}$</td>
</tr>
</tbody>
</table>

It is seen that the PL lifetimes are in good agreement with measured QSS-PC values. So, with this suggested calibration procedure the fastness of the photoluminescence lifetime imaging tool can be improved.

This suggested calibration procedure has to be verified with other wafers from same ingot. Also, this has to be verified with other ingots.

c) Photoluminescence lifetime imaging on other Si morphologies:

For standard silicon wafer there exists many lifetime characterization methods which include photoconductance method [54], microwave photoconductance decay [56] [57] and photoluminescence method [20]. But similar characterization methods for thin-film silicon are still deficient. The quasi-steady-state photoluminescence method
described in this thesis cannot be directly applied to the crystalline and amorphous silicon thin-films. The following discussion is considered:

A silicon thin-film solar cell uses only a few micrometers of silicon as an active layer, which is typically deposited on top of a crystalline substrate. The back side illuminated PL setup cannot be applied for this kind of device structure. While performing the photoluminescence using front side illumination, the total detected photoluminescence signal contains PL intensity from active layer and also a fraction of PL signal from the substrate. Also, the recombination at the interface between the active layer and substrate is another factor to be considered which results in the loss of excess carriers. The recombination may be due to the crystal defects or impurities at boundary surface between active layer and substrate [62]. For active layer with low lifetime, the recombination is dominated in the volume of the layer than at the surface or at layer/substrate interface. For active layer with high lifetime, in addition to the volume recombination, the recombination processes also include surface recombination and diffusion of carriers from layer to substrate [63]. So, the lifetime determination in the active layer of the thin-film silicon cell needs additional information about the carrier densities profiles and corrected photoluminescence intensity which contains the PL from substrate is needed. Recently, based on carrier densities profiles obtained using PC1D simulation and corrected photoluminescence intensities, Fraunhofer Institute for Solar Energy Systems (ISE) in Germany has demonstrated a new method to determine the lifetime in active layer of the crystalline silicon thin-films [63].
7.2 Light-Induced Lifetime Degradation in Al Doped Silicon Wafers

The lifetime degradation in the silicon wafers due to the light illumination is studied in this section. The carrier lifetimes in Al doped multicrystalline grown silicon wafers are studied upon soaking the light over interval of time. The QSS-PC method is used here to measure the carrier lifetimes in the wafers. The wafers are illuminated with a halogen lamp at ~8.0 [suns] for a certain time followed by the lifetime measurement. Again the wafer is illuminated and minority carrier lifetime is measured. This process is repeated until the lifetime saturates as shown in the Fig. 7.2. The degradation is due to the Al\textsubscript{i}O\textsubscript{i} defect pairs formed upon light illumination, where these Al\textsubscript{i}O\textsubscript{i} defect pairs act as active recombination centers and hence reduces the carrier lifetime. Immediately upon annealing the wafer at 200°C for 60 [min] all the Al\textsubscript{i}O\textsubscript{i} pairs are dissociated and the initial lifetime is recovered. Complete lifetime recovery is seen in some wafers. For the other wafers, approximately 95% of the initial lifetime is recovered. This is clearly illustrated in Fig. 7.2 (a), (b), (c), (d). The 5% loss in the lifetime is due to damage caused by the light on the surface passivation of the wafer.
(a) Lifetime degradation effect in wafer E10-006. 10.2% degradation in lifetime has been observed in this wafer. 95% of lifetime has been recovered after an annealing step at 200°C for 60 min.

(b) Lifetime degradation effect in wafer E10-007. 6.2% degradation in lifetime has been observed in this wafer. 95% of lifetime has been recovered after an annealing step at 200°C for 60 min.
(c) Lifetime degradation effect in wafer E10-070. 16.8% degradation in lifetime has been observed in this wafer. 95% of lifetime has been recovered after an annealing step at 200°C for 60 min.

(d) Lifetime degradation effect in wafer E10-071. 6% degradation in lifetime has been observed in this wafer. 95% of lifetime has been recovered after an annealing step at 200°C for 60 min.

Figure 7.2: Carrier lifetime vs illumination time on Al doped Si wafers from various positions in the ingot.
For further investigation of lifetime degradation the interstitial oxygen content present in the ingot is measured by performing FTIR (Fourier Transform Infrared) spectroscopy on the wafers. The interstitial oxygen content present in the whole ingot is plotted below in the Fig. 7.3 (marked in pink). The oxygen content present in the wafers investigated at various positions is also marked in the Fig. 7.3 (marked in blue). Due to the presence of oxygen content the lifetime decay is always expected.

![Figure 7.3: Oxygen content variation in the ingot.](image)

The summary of the experiment and measurements are presented in Table 7-2.
A fundamental study on the effect of light illumination on Al doped multicrystalline $p$-Si wafers were carried out. Similarly like boron doped mc $p$-Si wafers, carrier lifetime degradation were seen in Al doped mc $p$-Si wafers upon light illumination. Upon light illumination, minority carrier lifetime degraded exponentially with time until a saturation point was reached. After annealing step at 200°C for 1 hour, initial lifetime was recovered which indicates that all the $Al_{i}O_{i}$ defect pairs are broken. This activity clearly confirmed the presence of $Al_{i}O_{i}$ defect pair formations in the wafers. More silicon wafers doped with Al need to be investigated and more advanced properties like defect concentration, open circuit voltage decay, decay constant etc have to be studied. The wafers studied in this thesis have very slight variation in the oxygen content.
which did not facilitate to correlate the % degradation with oxygen content. So, more wafers with highly varying oxygen content need to be studied.

7.3 Home-built Photoluminescence lifetime imaging setup

The photoluminescence lifetime imaging technique discussed in this thesis work can be realized using an rf bridge circuit and a CCD camera capable of detecting emission wavelengths from silicon wafers or other test material. As discussed in the theory the Sinton test beach system has a built in rf coil which senses the change in current in the silicon wafer. This technique uses an inductive coupling between the coil and the wafer. The schematic of the RF bridge circuit is shown below.

![RF bridge circuit](image)

*Figure 7.4: RF bridge circuit for measuring the carrier lifetime in semiconductors.*
The oscillator generates a high frequency electric voltage ($V_{in}$) with peak amplitude of voltage signal approximately 10 V and constant frequency typically in the range 400 MHz-500 MHz. Thus the oscillator generates current in the coil which is connected to the bridge. The bridge circuit has resistors typically 50 Ω and preferably same resistance and a capacitor. The coil has to be protected by placing it in a case and also for proper positioning in relative to the semiconductor material. The signal processor eliminates the unnecessary part of the amplified signal ($V_{out}$) from the amplifier and the computer stores the signal from the signal processor.

The wafer is directly placed on the top of the rf coil. When the wafer is illuminated excess carriers are generated changing the photoconductance of the wafer and thus changing the electrical characteristics of the circuit which is measured as $V_{out}$ [64] [65]. The voltage is calibrated to photoconductance which is in turn converted to excess carrier concentration using the mobility model discussed in the experimental methods.
REFERENCES


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APPENDIX A: CARRIER LIFETIME DERIVATIONS

Derivation of radiative lifetime:

The radiative recombination rate, $U_{rad}$, is given by

$$U_{rad} = B(np - n_i^2) \quad (A.1)$$

In crystalline silicon, the radiative constant $B$ has been calculated to be $2 \times 10^{15}$ [cm$^3$ s$^{-1}$] [66], which leads to negligible radiative recombination rate i.e. a high lifetime.

The total carrier concentration after the absorption of light is the sum of equilibrium and excess carrier concentrations, i.e.

$$n = n_0 + \Delta n \quad , \quad p = p_0 + \Delta p \quad and \quad n_i^2 = n_0 p_0 \quad (A.2)$$

From Eqs. (A.1) and (A.2), assuming charge neutrality ($\Delta n = \Delta p$), the general expression for radiative recombination lifetime ($\tau_{rad}$) in silicon can be derived and shown in Eq. (A.4).

$$U_{rad} = B(n_0 + p_0)\Delta n + B\Delta n^2 \quad and \quad \tau_{rad} = \frac{\Delta n}{U_{rad}} \quad (A.3)$$

$$\tau_{rad} = \frac{1}{B(n_0 + p_0) + B\Delta n} \quad (A.4)$$

The radiative lifetime (Eq. (A.4)) for low level injection ($\Delta n \ll n_0 + p_0$) and high-level injection ($\Delta n \gg n_0 + p_0$) is simplified and is given by Eq. (A.5).

$$\tau_{rad,low} = \frac{1}{BN_{DA}} \quad and \quad \tau_{rad,high} = \frac{1}{B\Delta n} \quad (A.5)$$

From Eq. (A.5) the radiative lifetime depends on the inverse of carrier density. For low level injection conditions the $\tau_{rad}$ is constant and under high injection level conditions $\tau_{rad}$ decreases as the injection level increases.
Derivation of Auger lifetime:

The Auger recombination rate in $e e h$ process is proportional to $n^2p$, for $e h h$ process where the excess energy is transferred to another hole, the Auger recombination rate is proportional to $n p^2$ [35].

The net Auger recombination rate is given by

$$U_{Aug} = C_n (n^2 p - n_0^2 p_o) + C_p (n p^2 - n_0 p_0^2)$$  \hspace{1cm} (A.6)

Where $C_n$ and $C_p$ are the Auger coefficients of $e e h$- and $e h h$-process.

The total carrier concentration after the absorption of light is the sum of equilibrium and excess carrier concentrations, given by Eq. (A.2)

$$n = n_o + \Delta n \quad \text{and} \quad p = p_o + \Delta p$$

The Auger recombination lifetime $\tau_{Aug}$ can be determined from Eq. (2.8) and injection level dependent Auger recombination lifetimes are given below for $p$-type silicon.

$$\tau_{Aug,low} = \frac{1}{C_p N_A} \quad \text{and} \quad \tau_{Aug,high} = \frac{1}{(C_n + C_p) \Delta p^2}$$  \hspace{1cm} (A.7)

From Eq. (A.7) the Auger lifetime depends on the inverse square of the carrier density. At high injection levels the Auger recombination is dominant recombination mechanism in silicon.
Derivation of SRH lifetime [67]:

![Band diagram illustrating the interaction mechanisms of free carriers in presence of a defect level.](image)

From Fig. A.1, the rate of change of $n$ and $p$ due to recombination and generation is

$$\frac{dn}{dt} = (1) - (2) = U_n$$

$$\frac{dp}{dt} = (4) - (3) = U_p$$

At steady state conditions,

$$U_n = U_p$$

$$U_{n1} - U_{n2} = U_{p4} - U_{p3}$$

$U_{n1}$ is the thermal generation rate due to the process where an electron can jump from recombination center to the conduction band. Let $N_r$ be the density of recombination centers and $n_r$ is the concentration of electrons occupying the recombination centers and $f(E_i)$ is the probability of the electron to occupy the defect center with energy $E_i$ and $e_n$ is the emission rate of electron.

Then $U_{n1}$ can be written as
\[ U_{n1} = e_n N_t f(E_t) \text{ and } e_n = v_{th} \sigma_n n_t e^{(E_t - E_i)/kT} \]

\( U_{n2} \) is the recombination rate due to the recombination centers. \( U_{n2} \) is proportional to the electron density in the conduction band \((n)\) and concentration of empty recombination centers \((N_t - n_t)\). Then \( U_{n2} \) can be written as,

\[
U_{n2} = v_{th} \sigma_n n (N_t - n_t) = v_{th} \sigma_n n N_t \left(1 - \frac{n_t}{N_t}\right)
\]

\[
= v_{th} \sigma_n n N_t (1 - f(E_t))
\]

where \( v_{th} \) is the thermal velocity and \( \sigma_n \) is the electron capture cross section.

Similarly, \( U_{p3} \) is the recombination rate of holes,

\[
U_{p3} = v_{th} \sigma_p p N_t f(E_t)
\]

\( U_{p4} \) is the thermal generation rate where a hole can jump to the valance band from the recombination center,

\[
U_{p4} = e_p N_t \left(1 - f(E_t)\right) \text{ and } e_p = v_{th} \sigma_p n_t e^{(E_i - E_t)/kT}
\]

\( e_p \) is the probability of hole emission by the recombination or generation centers.

When the steady state conditions are reached,

\[
U_{n1} - U_{n2} = U_{p4} - U_{p3}
\]

\[
e_n N_t f(E_t) - v_{th} \sigma_n n N_t (1 - f(E_t)) = e_p N_t \left(1 - f(E_t)\right) - v_{th} \sigma_p p N_t f(E_t)
\]

Solving above equation for \( f(E_t) \) gives,

\[
f(E_t) = \frac{\sigma_n n + \sigma_p n_t e^{(E_i - E_t)/kT}}{\sigma_n \left(n + n_t e^{(E_i - E_t)/kT}\right) + \sigma_p \left(p + n_t e^{(E_i - E_t)/kT}\right)}
\]

The SRH recombination rate is given by,
\[ U = U_n = U_p = U_{n1} - U_{n2} \]

\[ e_n N_t f(E_t) - \nu_{th} \sigma_n n N_t (1 - f(E_t)) \]

Substituting \( f(E_t) \) in the above equation gives,

\[ U = \frac{\sigma_n \sigma_p \nu_{th} N_t (pn - n_i^2)}{\sigma_n \left( n + n_i e^{(E_t - E_i)/kT} \right) + \sigma_p \left( p + n_i e^{(E_i - E_t)/kT} \right)} \]

This can be rewritten as,

\[ U = \frac{(pn - n_i^2)}{\tau_p \left( n + n_i e^{(E_t - E_i)/kT} \right) + \tau_n \left( p + n_i e^{(E_i - E_t)/kT} \right)} \]

where

\[ \tau_p = \frac{1}{\sigma_p \nu_{th} N_t} \quad \text{and} \quad \tau_n = \frac{1}{\sigma_n \nu_{th} N_t} \]

For the recombination centers where the recombination rate is highest i.e. \( E_t \approx E_i \) and

\[ n = n_0 + \Delta n \quad , \quad p = p_0 + \Delta p \quad \text{and} \quad n_i^2 = n_0 p_0 \]

By applying these conditions Eq. (\ref{eq:2.16}) can be written as

\[ U = \frac{(p_0 \Delta n + n_0 \Delta p + \Delta n \Delta p)}{\tau_p (n_0 + \Delta n + n_i) + \tau_n (p_0 + \Delta p + n_i)} \]

Assuming charge neutrality (\( \Delta n = \Delta p \)), the SRH recombination lifetime can be written as.

\[ \tau_{SRH} = \frac{\tau_p (n_0 + n_i + \Delta n) + \tau_n (p_0 + p_i + \Delta p)}{n_0 + p_0 + \Delta n} \quad (2.16) \]
APPENDIX B: TRAPPING EFFECTS

*Trapping effects in photoconductance method* [68]:

When minority carrier traps are present in the silicon wafer, the trapped minority carrier cannot recombine which breaks the balance between the generation and recombination. In order to attain a new equilibrium between generation and recombination the majority carrier concentration increases and contributes to the excess photoconductance.

For *p*-type silicon, without any traps:

\[
\Delta \sigma = q(\Delta n \mu_n + \Delta p \mu_p)W = q\Delta n(\mu_n + \mu_p)W \quad (B.1)
\]

With the presence of traps:

\[
\Delta \sigma_t = q(\Delta n \mu_n + \Delta p \mu_p)W \quad \text{and} \quad \Delta p = \Delta n + n_t \quad (B.2)
\]

Where, \(n_t\) is the trap density. Eq. (B.2) can be written as

\[
\Delta \sigma_t = q(\Delta n \mu_n + (\Delta n + n_t)\mu_p)W \quad (B.3)
\]

\[
\Delta \sigma_t = q\Delta n \left(\mu_n + \mu_p + \frac{\mu_p n_t}{\Delta n}\right)W \quad (B.4)
\]

\[
\Delta \sigma_t = q\Delta n(\mu_n + \mu_p) \left(1 + \frac{n_t}{\Delta n} \frac{\mu_p}{\mu_n + \mu_p}\right)W \quad (B.5)
\]

Using Eqs. (B.1) and (B.5)

\[
\Delta \sigma_t = \Delta \sigma \left(1 + \frac{n_t}{\Delta n} \frac{\mu_p}{\mu_n + \mu_p}\right) \quad (B.6)
\]

Assuming \(n_t=10^{14} \text{ [cm}^{-3}\text{]}\) and \(\Delta n = 10^{12} \text{ [cm}^{-3}\text{]}\) and \((\mu_n + \mu_p) = 1700 \text{ [cm}^2 \text{ V}^{-1} \text{ s}^{-1}\text{]}\) and \(\mu_p = 300 \text{ [cm}^2 \text{ V}^{-1} \text{ s}^{-1}\text{]}.\)
\[
\Delta \sigma_t = \Delta \sigma \left(1 + 100 \times \frac{300}{1700}\right) \approx 18.64 \Delta \sigma \tag{B.7}
\]

Therefore, the minority carrier lifetime is given by

\[
\tau_{eff,t} \approx 18.64 \tau_{eff} \tag{B.8}
\]

Thus, the effective minority carrier lifetime is overestimated (approximate 18 times higher) in the presence of trapping at low injection levels.

**Trapping effects in photoluminescence method [68]:**

The photoluminescence emission is directly proportional to the product of electron and hole density

\[
I_{pl} = A_i \cdot R_{sp} = A_i \cdot B(T) \cdot n_e \cdot n_h \tag{B.9}
\]

For \(p\)-type silicon, without any traps:

\[
I_{pl} \propto (\Delta n + N_a)\Delta n \tag{B.10}
\]

Assuming same conditions,

\[
n_i = 10^{14} \text{ [cm}^{-3}] \text{ and } \Delta n = 10^{12} \text{ [cm}^{-3}] \text{ and } N_a = 1 \times 10^{16} \text{ [cm}^{-3}]
\]

So, \(\Delta n << N_a\) and Eq. (B.10) can be rewritten as,

\[
I_{pl} \propto N_a \Delta n \tag{B.11}
\]

For \(p\)-type Si wafer, in the presence of trapping

\[
I_{pl} \propto (\Delta p + N_a)\Delta n
\]

\[
\propto (\Delta n + n_t + N_a)\Delta n \tag{B.12}
\]

So, \(\Delta n << N_a\) and Eq. (B.12) can be written as,

\[
I_{pl} \propto (n_t + N_a)\Delta n \tag{B.13}
\]

Considering the ratio of \(I_{pl}\) with and without trapping,
\[
\frac{I_{pl,t}}{I_{pl}} = \frac{(n_t + N_a)}{N_a} = 1.01 \quad \text{(B.14)}
\]

Therefore, the minority carrier lifetime is given by

\[\tau_{eff,t} \approx 1.01\tau_{eff} \quad \text{(B.15)}\]

From Eq. (B.15) using the photoluminescence lifetime characterization, the minority carrier lifetime values are very less affected by trapping effects. From Eq. (B.8) using the photoconductance method, the minority carrier lifetime values are approximately 18 times higher in the presence of trapping at low injection levels.
APPENDIX C: MATLAB CODE

MATLAB code for calibration and analyzing experimental data:

```matlab
%% Program for calibrating and analyzing the PL images and Sinton data
clear all;

%% WAFER PARAMETERS
% Enter the wafer parameters
W_wafer=12.5; %Width of the wafer in cm
H_wafer=12.5; %Height of the wafer in cm
T=0.0250; %Thickness of the wafer in cm
r=1.1; %Radius of the Coil
o=0.85; %optical constant
Nda=9.5e+15; %doping density in cm^-3
G=4.9e+17; %Generation rate
s=3.0; %illumination
W_PL=input('Enter the PL image width in cm:');
H_PL=input('Enter the PL image height in cm:');

%% IMAGE PROCESSING
% This section uses image processing tool box to crop the image
Tint=input('Enter exposure time in sec');
cr=0;
while cr<20
    clear pl;
    if Tint<10
        [File,path] = uigetfile('*.tif','select the PL image in .tif format');
        pl=imread([path,File]);
        plcrop=imtool(pl);
    else
        [File_back,path_back] = uigetfile('*.tif','select the background image in .tif format');
        pl_back=imread([path_back,File_back]);
        [File_PL,path_PL] = uigetfile('*.tif','select the PL image in .tif format');
        pl_PL=imread([path_PL,File_PL]);
        pl=pl_PL-pl_back;%removes background pixels for exposure time greater than 10 sec
        plcrop=imtool(pl);
    end
    char=input('Do you want to recrop? y/n: '),cond=strcmp(char, 'n');
    if cond==1
        break;
    end
```
cr=cr+1;
end
cor=input('Press Ctrl+V');
cord=round(cor);
[File_crop,path_crop] = uigetfile("*.tif','select the cropped PL image in .tif format");
pl_data=imread([path_crop,File_crop])/16;
if Tint<10
pl_data=pl_data-50;  %removes background pixels for exposure time less than 1 sec
end
a=min(min(pl_data));
b=max(max(pl_data));
imshow(pl_data,[a b]);
colorbar;
colormap(jet);
saveas(gcf,'Pl image.jpg');
cali=input('Enter the calibration method (s for single point, f for fit)', 's');
cond=strcmp(cali, 'f');

%% Determination of Ipl (Area averaged pixel value)
% This section calculates the area averaged pixel value over the radius of
% 1.1 cm by taking the center (x1,y1) as inputs. The logic here is to check
% if a given pixel is inside the circle. All the pixel values inside the
% circle are retained in the matrix and averaged. Also the first point for
% analysis is always the calibration point.
if cond==1
% Fit calibration
image=input('Enter no .of PL images:');
count=1;
X1=input('Enter the calibration point X-distance in cm:');  %x-Center value of the coil
Y1=input('Enter the calibration point Y-distance in cm:');  %y-Center value of the coil
while (count<=image)
[File,path]=uigetfile("*.tif','select the PL image in .tif format");
pl_sun=imread([path,File]);
pl_sun=pl_sun/16;
pl_crop=imcrop(pl_sun,[cord]);
[row,col]=size(pl_crop);  %Assigns the number of rows to row and columns to col
i=1;
j=1;
N=0;
while (i<=(row+1))  %Allows to work with all the rows
j=1;
while j<=(col+1) \%Allows to work with all the columns in a specific row
    Y=i*H_PL/row; \%Converts row number to centimeter scale
    X=j*W_PL/col; \%Converts column number to centimeter scale
    K=(X-(X1-(W_wafer-W_PL)/2))^2+(Y-(Y1-(H_wafer-H_PL)/2))^2; \%Circle equation
    if K<=r^2 \%Checks if the given point lies on or inside the circle
        Mat(i,j)=pl_crop(i,j); \%If TRUE: Then the pixel value is retained in the matrix
    end
    N=N+1; \%Gives the total points in the circle
    j=j+1;
end
i=i+1;
end
Tot=(sum(sum(Mat))); \%Gives sum of all the pixels inside the circle
Ipl(count)=(Tot/N) \%Final Averaged value
Mat=0;
pl_crop=0;
pl_sun=0;
count=count+1;
Nfit(count)=input(‘Enter trap free DeltaN from sinton(QSS) at this sun: ’); \%Minority carrier density from sinton
end;
else
    \%Single point calibration
    [row,col]=size(pl_data); \%Assigns the number of rows to row and columns to col
    i=1;
    N=0;
    X1=input(‘Enter the calibration point X-distance in cm:’); \%x-Center value of the coil
    Y1=input(‘Enter the calibration point Y-distance in cm:’); \%y-Center value of the coil
    while (i<=(row+1)) \%Allows to work with all the rows
        j=1;
        while j<=(col+1) \%Allows to work with all the columns in a specific row
            Y=i*H_PL/row; \%Converts row number to centimeter scale
            X=j*W_PL/col; \%Converts column number to centimeter scale
            K=(X-(X1-(W_wafer-W_PL)/2))^2+(Y-(Y1-(H_wafer-H_PL)/2))^2; \%Circle equation
            if K<=r^2 \%Checks if the given point lies on or inside the circle
                Mat(i,j)=pl_data(i,j); \%If TRUE: Then the pixel value is retained in the matrix
            end
            N=N+1; \%Gives the total points in the circle
            j=j+1;
        end
        i=i+1;
    end
end
end;
j=j+1;
end
i=i+1;
end;
Tot=(sum(sum(Mat))); %Gives sum of all the pixels inside the circle
Ipl=(Tot/N); %Final Averaged value
Nqss=input('Enter trap free DeltaN from sinton(QSS): '); %Minority carrier density from sinton
Tqss=Nqss*T/G; %carrier lifetime from sinton
A=Ipl/((Nda+Nqss)*Nqss); %Calibration factor
Npl=(-Nda+sqrt((Nda)^2+(4*Ipl/A)))/2;
Tpl=Npl*T/G;
Error=(Nqss-Npl)*100/Nqss
Mat=0;
end

if cond==1
    Ipl=sort(Ipl);
    Nfit=sort(Nfit);
    dlmwrite('Ipl and deltan.dat',Ipl', ',',0,0);
    dlmwrite('Ipl and deltan.dat',Nfit','-append');
    disp('Fit the data saved in Ipl and deltan.dat file in origin');
    A=input('Enter the value of A obtained from the fit:');
end; % Data comparision(PL and sinton)
points=input('Number of points to compare with sinton:');
count=1;
while count<=points
    [row,col]=size(pl_data); %Assigns the number of rows to row and columns to col
    i=1;
    N=0;
    X1_cmp(count)=input('Enter the X-distance in cm:'); %x-Coordinate value of the coil
    Y1_cmp(count)=input('Enter the Y-distance in cm:'); %y-Coordinate value of the coil
    while (i<=(row+1)) %Allows to work with all the rows
        j=1;
        while j<=(col+1) %Allows to work with all the columns in a specific row
            Y=i*H_PL/row; %Converts row number to centimeter scale
            X=j*W_PL/col; %Converts column number to centimeter scale
            K=(X-(X1_cmp(count)-(W_wafer-W_PL)/2))^2+(Y-(Y1_cmp(count)-(H_wafer-H_PL)/2))^2; %Circle equation
            if K<=r^2 %Checks if the given point lies on or inside the cirle
                Mat_cmp(i,j)=pl_data(i,j); %If TRUE: Then the pixel value is retained in the matrix
            end
        end
    end
end
N=N+1;  \%Gives the total points in the circle
end;
    j=j+1;
end
i=i+1;
end;

Tot_cmp=(sum(sum(Mat_cmp)));  \%Gives sum of all the pixels inside the circle
Ipl_cmp(count)=(Tot_cmp/N);  \%Final Averaged value
Nqss_cmp(count)=input('Enter trap free DeltaN from sinton(QSS): ');  \%Minority carrier density from sinton
Tqss_cmp(count)=Nqss_cmp(count)*T/G;  \%carrier lifetime from sinton
Npl_cmp(count)=(-Nda+sqrt((Nda)^2+(4*Ipl_cmp(count)/A)))/2;
Tpl_cmp(count)=Npl_cmp(count)*T/G;

Error(count)=(Nqss_cmp(count)-Npl_cmp(count))*100/Nqss_cmp(count)
count=count+1;
Mat_cmp=0;
end;

%%
% Exports all the data to excel file
[File,path] = uiputfile('*.xls','select the location to save the data');
Wafer=[s;Nda;o;G;A];
xlswrite(File, Wafer, 'Data sheet', 'H8');
xlswrite(File,[X1_cmp' Y1_cmp' Ipl_cmp' Tqss_cmp' Tpl_cmp' Nqss_cmp' Npl_cmp'
Error'], 'Data sheet', 'D19');

%% Lifetime Map
dlmwrite('PL map.dat', pl_data, ',', 0, 0);
pl_data_dat=dlmread('PL map.dat');
count=0;
[row,col]=size(pl_data_dat);
i1=1;
while (i1<=row)  \%Allows to work with all the rows
    j1=1;
    while (j1<=col)  \%Allows to work with all the columns in a specific row
        Tpl(i1,j1)=pl_data_dat(i1,j1)*T/(Nda*A*G);
        j1=j1+1;
        count=count+1;
    end;
    i1=i1+1;
end;
dlmwrite('Lifetime map.dat', Tpl, ',', 0, 0);  \%Writes the matrix into a .dat file
a=min(min(Tpl*10^6));
b=max(max(Tpl*10^6));
imshow(Tpl*10^6,[a b]);
colorbar;
colormap(jet);
saveas(gcf,'Lifetime map.jpg');
Tavg=sum(sum(Tpl))/count;