

Measuring and interpreting the lifetime of silicon wafers

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Abstract

The carrier lifetime is the most important electronic property of semiconductor materials for solar cells. In this paper we discuss traditional and novel methods for its experimental determination. Among the latter, the Quasi-steady-state photoconductance is particularly powerful since it permits measuring the injection level dependence of the lifetime. The analysis and interpretation of this dependence yields a wealth of information on the physical mechanisms that limit the performance of silicon solar cells. The effect of the surfaces of the silicon wafers, the emitter saturation current density and the Shockley–Read–Hall and Auger recombination mechanisms are explained and their possible determination from lifetime measurements discussed.

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1. Introduction

The concepts of carrier lifetime in semiconductor materials and *average life expectancy* in demography are similar. Like common mortals, electrons (and holes) die after some time and the average of this time is called the *minority carrier lifetime*. The rate at which they disappear, or *recombine*, is given, in *p*-type material, by $\Delta n/\tau$, where τ is the electron lifetime, and Δn is the excess electron concentration, which is essentially equal to the total electron population in most practical cases. When a typical 300 μm thick silicon wafer is illuminated by strong sunlight (having a power density, or irradiance, of 100 mW/cm^2 and the standard spectral distribution AM1.5G), electrons and holes are generated at a rate of $G_L = 9 \times 10^{18} \text{ cm}^{-3} \text{ s}^{-1}$. In a steady-state situation the generation and recombination rates are perfectly balanced:

$$G_L = \frac{\Delta n}{\tau} \quad (1)$$

In a solar cell it is important to determine the electron population. This is possible if their average lifetime is

known. For example, using a relatively common value of $\tau = 80 \mu\text{s}$ we obtain $\Delta n = 7.2 \times 10^{14} \text{ cm}^{-3}$. The significance of being able to calculate the excess carrier density is that the voltage of a solar cell is directly related to it; in this example the voltage would be 660 mV, for a 1 Ωcm *p*-type wafer. The relationship is logarithmic, and it is necessary to increase the lifetime (and, therefore, the electron density) by a factor of 10 to obtain a 60 mV higher voltage, which approximately represents a 10% relative improvement in device performance. In addition, the cell's output current is also related to the lifetime. This is because electrons take some time to travel across the silicon wafer and they reach the pn junction only if their life expectancy (or lifetime) is long enough to complete the journey.

The lifetime is quite unpredictable and difficult to control. It can vary by several orders of magnitude, from approximately 1 μs to 1 ms in common silicon solar cell materials. The highest value ever measured is 32 ms, for undoped silicon, and the lowest 10^{-9} s, for heavily doped silicon. In the same way that the life expectancy is an indicator of the quality of life in a country, the lifetime epitomises the quality of the silicon material. This quality depends, primarily, on the methods used to purify and grow crystalline silicon. The float zone (FZ) technique produces the best silicon, while Czochralski-grown (CZ) and multicrystalline silicon usually have lower lifetimes. In addition, the lifetime can change

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when the wafers are processed at high temperatures or subjected to certain treatments. It is, therefore, essential to measure the lifetime experimentally.

2. Measuring the lifetime

There are two basic approaches to measure the lifetime depending on the way that an excess of carriers (electrons and holes) is created in the semiconductor. The intention is to replicate in real practice the conditions that underlie the concept of lifetime as the life expectancy of the carrier population. One possibility is to maintain a steady-state generation rate of known value, and use the expression given above for the balance between generation and recombination to calculate the lifetime. This constitutes the steady-state method. A second possibility is to terminate the generation abruptly and measure the rate at which carriers disappear as time passes by, which can be expressed as dn/dt . Since the photogeneration is zero the only reason for the electron concentration to change is recombination and we can then write the following equality between the rates of change and recombination:

$$\frac{dn}{dt} = -\frac{\Delta n}{\tau} \quad (2)$$

This second approach is the transient decay method. In both methods we need to measure the excess electron concentration, Δn . There are several techniques to do this based on different properties of semiconductor materials. The simplest and most common of them is to measure the conductance of the wafer and the way it changes with either illumination or time. This can be easily implemented by inserting the piece of silicon in a circuit that measures its resistance by forcing a flow of current through it and measuring the resulting voltage drop. More conveniently, the wafer can be placed over an inductor that forms part of a radio-frequency circuit, which also produces a voltage that is proportional to the conductivity of the wafer. When light is shone on the wafer, the electron concentration increases by Δn , and so does the hole concentration. Note that every photon generates one electron-hole pair, so that $\Delta n = \Delta p$ (an exception to this equality is produced by the phenomenon of *trapping*, as discussed by Hornbeck and Haynes, 1955, and Macdonald and Cuevas, 1999). As a result, the conductivity increases and the excess photoconductance is given by

$$\Delta\sigma_L = qW(\mu_n + \mu_p)\Delta n \quad (3)$$

where W is the wafer thickness. Typical mobility values are $\mu_n = 1100 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ for electrons and $\mu_p = 400 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ for holes in silicon. It is important to remember, however, that the mobilities are a function

themselves of carrier density (both via doping and excitation) and temperature (Arora et al., 1982). Because of this, Eq. (3) needs to be iterated a few times to obtain self-consistent values of Δn and $\mu_n + \mu_p$. Once Δn is found, the lifetime can be determined from Eqs. (1) or (2), as appropriate:

$$\tau_{\text{SSPC}} = \frac{\Delta n}{G_L} \quad \tau_{\text{PCD}} = -\frac{1}{\Delta n} \frac{dn}{dt} \quad (4)$$

Note that in the second method the determination of the lifetime is quite robust, since it only relies on the measurement of the relative change of the carrier density with time. This is why it has classically been the preferred method to measure lifetimes, the well-known *photoconductance decay* method, or *PCD*. It has, nevertheless, disadvantages, particularly if one ignores the fact that the lifetime is, in general, strongly dependent on the experimental conditions, that is, on the electron concentration itself. Therefore, the absolute value of the conductance should always be measured in order to determine the specific excess carrier density at which the measurement has taken place, even if the *PCD* method does not strictly require this. As mentioned above, it is also important to break down the photoconductance into carrier density and carrier mobilities before calculating the derivative indicated in Eq. (4).

An absolute measurement of the excess carrier density is clearly required to determine the lifetime in the *steady-state photoconductance* method, or *SSPC*. In addition, the generation rate needs to be determined accurately as well. We can do the latter by using a photodetector, which can for example be a calibrated solar cell. The detector measures the total photon flux incident on the surface of the wafer per unit area. For the standard solar spectrum this flux is $N_{\text{ph}} = 2.7 \times 10^{17} \text{ cm}^{-2} \text{ s}^{-1}$ (this is the number of photons per second and cm^2 with energy greater than the bandgap of silicon, 1.12 eV). We commonly refer to this flux as *one sun* intensity. Because of their finite thickness and reflectivity, silicon wafers absorb only a fraction of these photons. The value of the absorption fraction for a polished, bare silicon wafer is $f_{\text{abs}} \approx 0.6$. If the wafer has an optimised antireflection coating, such as a 70 nm thick silicon nitride or titanium oxide layer, then $f_{\text{abs}} \approx 0.9$. A textured wafer with antireflection coating can approach $f_{\text{abs}} \approx 1$. The generation rate per unit volume G_L can be evaluated from the incident photon flux and the wafer thickness:

$$G_L = \frac{N_{\text{ph}} f_{\text{abs}}}{W} \quad (5)$$

The steady-state method requires, therefore, determining the photoconductance, the photon flux and the fraction of absorbed photons, which is itself affected by the reflectivity of the front and back surfaces, the pos-

sible faceting of those surfaces, and the thickness of the wafer. In addition, the electron and hole mobilities must also be known. Although this may seem daunting, in practice it is quite acceptable to use published values for the mobilities and tables or graphs for the absorption fraction, which can be calculated accurately using optical models. The uncertainties associated with the determination of f_{abs} can be kept very small, less than 5%. In the end, the only magnitudes that need to be measured are the photoconductance and the light intensity. The overall error in determining the lifetime by the QSSPC method using Eq. (7) is usually less than 10%.

Each method has some advantages and some disadvantages. One advantage of the inductively-coupled PCD method (some PCD methods are based on small-signal excitation and do not have this advantage) that has been frequently overlooked is that it automatically scans the possible variability of the lifetime over a broad range of different carrier injection levels, since Δn gradually decreases with time. To achieve the same with a pure steady-state method would be cumbersome, because it would require many well-stabilised light intensities and it would risk heating the sample excessively. Fortunately, it is possible to combine the best of both methods in what has been called the *quasi-steady-state photoconductance* method, or *QSSPC* (Sinton and Cuevas, 1966). The experimental conditions used in the latter method are such that the intensity of the illumination varies with time in a gradual fashion. Appropriate light sources are photographic flashes that, in combination with attenuating filters, can produce irradiance levels from nearly 1000 suns to 10^{-5} suns. A single flash typically spans a factor of 100 in light intensity levels over a time of just 10 ms, thus avoiding sample heating. The accompanying conceptual advance in the understanding of the lifetime is based on the realisation that in the QSS condition there are three concurrent physical mechanisms: generation, recombination, and carrier density change (Nagel et al., 1999). The simplest way of incorporating them in a mathematical formulation is to define a net photogeneration rate:

$$N_{\text{ph}}f_{\text{abs}}|_{\text{net}} = N_{\text{ph}}f_{\text{abs}} - W \frac{d\Delta n}{dt} \quad (6)$$

Introducing this net photogeneration in the steady-state lifetime expression, we obtain a generalised *QSSPC* expression for the lifetime that encompasses the previous two traditional definitions:

$$\tau_{\text{QSSPC}} = \frac{\Delta n W}{N_{\text{ph}}f_{\text{abs}} - W \frac{d\Delta n}{dt}} \quad (7)$$

In writing the previous equations, we have assumed that the excess carrier density Δn is uniform within the wafer. The product $\Delta n W$ therefore represents the integrated

carrier density. This is a good approximation if proper care is taken in performing the measurements, for example using infrared illumination. It is also a good approximation if the thickness of the wafer is lower than the carrier diffusion length, even if short-wavelength illumination is used. In the transient, PCD method, the carrier density tends to become uniform very quickly. In the quasi-steady-state method Eq. (7) is still valid, because it only requires the integrated excess carrier density, with Δn representing its average value (Cuevas and Sinton, 1997).

The generalised *QSSPC* method is very powerful and can give a complete picture of recombination processes within the semiconductor. These processes are intrinsically very complex, and several of them frequently co-exist in a given wafer. To recognise this fact we refer to the measured lifetime as an *effective* lifetime, τ_{eff} . Its de-convolution into the different surface and volume recombination mechanisms is not trivial but not impossible either. We discuss below different practical situations and physical effects that can affect the measured effective lifetime.

3. The effect of the surfaces of the wafer

In order to understand practical measurements of the lifetime it is, first of all, essential to realise that usually we measure relatively thin slices of material and, therefore, should expect that the surfaces of the wafer may play an important role in the global recombination processes that we are measuring. Electrons and holes can recombine at the surfaces of a silicon wafer, and the speed at which they do is characterised traditionally by a parameter called the *surface recombination velocity*, S . The corresponding recombination rate is directly proportional to this parameter and, just like any recombination mechanism, to the excess carrier concentration, Δn . The concepts of S and τ_{eff} are interchangeable, but have opposite meanings: a high lifetime means a low recombination rate, whereas a high S implies a high recombination rate. What has been said about the lifetime can be extended to the surface recombination velocity: it can be determined via photoconductance measurements by either transient, steady-state or QSS methods. Also, the surface recombination velocity itself is usually strongly dependent on the carrier density at which it is measured.

In a general case, surface and volume recombination mechanisms coexist, and it is important to remember the presence of both. Let us consider a common case where the two surfaces of the wafer are identical and characterised by a certain surface recombination velocity S . All we have to do is write again the equation that balances the generation (the net generation, defined by Eq. (6))

and recombination rates, adding all the recombination mechanisms that are present in the wafer.

$$N_{\text{ph}}f_{\text{abs}}|_{\text{net}} = \frac{\Delta n W}{\tau_{\text{bulk}}} + 2S\Delta n \quad (8)$$

Comparing this expression to the definition of effective lifetime we can write the following expression for the latter:

$$\frac{1}{\tau_{\text{eff}}} = \frac{1}{\tau_{\text{bulk}}} + \frac{2S}{W} \quad (9)$$

Sometimes one can neglect the effect of the surfaces, for example if they are well passivated with a thermal oxide or with SiN, and use the measurement to determine the bulk recombination properties of the wafer. At other times we may actually be more interested in determining the surface recombination velocity, in which case we would use wafers with a very high bulk lifetime, so that its effect on the previous expression can be neglected. A more complex way of discriminating bulk from surface recombination is to prepare wafers with different thicknesses and identical bulk and surface properties (Kampwerth et al., 2003).

According to the last expression, the effective lifetime would be zero when the surface recombination velocity is very high. In reality there is a limit on how low the effective lifetime can be because electrons and holes have to travel towards the surfaces by the relatively slow diffusion mechanism in order to recombine. It can be calculated that for uniform photogeneration (produced by infrared light), the minimum effective lifetime is:

$$\tau_{\text{eff}(S=\infty)} = \frac{W^2}{12D_n} \quad (10)$$

Eq. (10) is valid for a steady-state measurement, in the case of a transient PCD measurement, the 12 in the denominator should be replaced with π^2 (Luke and Cheng, 1987). For a typical *p*-type 0.03 cm thick wafer, and a diffusion coefficient for electrons $D_n = 27 \text{ cm}^2 \text{ s}^{-1}$, the lifetime that can be expected for a non-passivated surface is $\tau_{\text{eff}} = 2.8 \text{ } \mu\text{s}$. Nevertheless, the surface-limited lifetime can be even lower if the source of light is predominantly of short wavelength, because electrons that are photogenerated by visible or blue light (such as a white flash lamp) are very close to the surface and can diffuse to it almost instantaneously (Cuevas and Sinton, 2003).

4. The effect of diffused emitters

It is frequent that wafers have dopant diffusions on their surfaces. The best way to consider the effect of these diffused, or *emitter* regions is by means of the parameter called the *saturation current density*, J_{oe} . This

parameter gives, when multiplied by the product of electron and hole concentrations normalised to n_i^2 , the total recombination rate in the emitter. Note that this includes the recombination within the bulk of the thin diffused region as well as the recombination at the heavily doped surface. If both sides of the wafer are diffused we have:

$$N_{\text{ph}}f_{\text{abs}}|_{\text{net}} = \frac{\Delta n W}{\tau_{\text{bulk}}} + 2J_{\text{oe}} \frac{\Delta n [N_A + \Delta n]}{qn_i^2} \quad (11)$$

where we have assumed a *p*-type silicon wafer and calculated the hole concentration from the dopant density as $p = \Delta n + N_A$. It is important to note that the emitter recombination term has a different dependence on the carrier injection level than the bulk recombination term. This allows us to determine the *emitter saturation current density*, J_{oe} , by examining the injection level dependence of the lifetime, particularly in the high injection regime (Kane and Swanson, 1985). At sufficiently high injection levels, that is, $\Delta n \gg N_A$, the emitter contribution becomes much larger than the bulk recombination term and the effective lifetime essentially measures emitter recombination:

$$\frac{1}{\tau_{\text{eff}}}|_{\text{high injection}} \approx \frac{2J_{\text{oe}}}{qn_i^2 W} \Delta n \quad (12)$$

Fig. 1 illustrates the effect of different emitter saturation current densities on the effective lifetime of a lowly doped *p*-type ($N_A = 10^{15} \text{ cm}^{-3}$) silicon wafer, with all other physical recombination mechanisms neglected. In the high injection regime, the inverse of the effective lifetime varies linearly with the excess carrier density, and different J_{oe} values result in different slopes of the

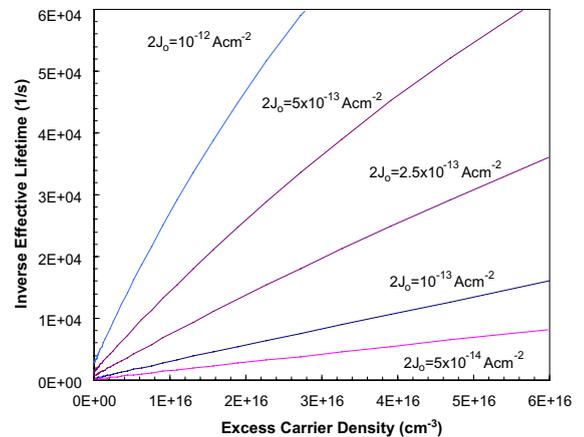


Fig. 1. Effect of different emitter saturation current densities on the effective lifetime of a lowly doped *p*-type ($N_A = 10^{15} \text{ cm}^{-3}$) silicon wafer.

straight lines. All the lines intercept the horizontal axis at $\Delta n = -N_A$, which is 10^{15} cm^{-3} in this case, as predicted by Eq. (11).

It is important to realise that at very low injections the emitter may still have an effect on the lifetime, while being indistinguishable from the bulk lifetime (Cuevas, 1999). This limitation on the measurable lifetime is particularly serious if the doping of the wafer is high and the emitter is itself not passivated, which usually results in a high J_{oe} . For $\Delta n \ll N_A$, we have

$$\frac{1}{\tau_{\text{eff}}} \Big|_{\text{low injection}} \approx \frac{1}{\tau_{\text{bulk}}} + \frac{2J_{oe}}{qn_i^2 W} N_A \quad (13)$$

On the other hand, well-designed emitters with a good surface passivation can provide an excellent suppression of possible surface effects and are frequently used to investigate the bulk lifetime of silicon wafers (essentially, the previous expression reduces to $\tau_{\text{eff}} = \tau_{\text{bulk}}$ for very low J_{oe}). Fig. 2 shows the limitation on the measurable lifetime due to an emitter saturation current density of $J_{oe} = 10^{-13} \text{ A cm}^{-2}$, a value typical of laboratory quality solar cells, as a function of the dopant density of the silicon wafer. Note that to determine the value of J_{oe} it is advantageous to use very lowly doped wafers, for example $N_A = 10^{14} \text{ cm}^{-3}$, to maximise the range where the lifetime shows a linear dependence on carrier density. The slope of the straight part of the curves is, in these logarithmic plots, equal to -1 , consistent with the above expression. Fig. 3 shows the limitation imposed by different values of J_{oe} on the measurable lifetime of a p -type $1 \Omega \text{ cm}$ ($N_A = 1.5 \times 10^{16} \text{ cm}^{-3}$) silicon wafer.

If one side of the wafer is diffused and the other passivated we can write the following expression for the effective lifetime, τ_{eff} , that is inclusive of the volume, rear

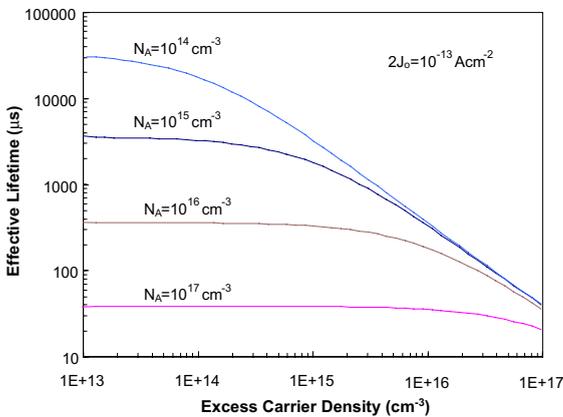


Fig. 2. Limitation on the measurable lifetime of wafers with different dopant concentrations due to an emitter saturation current density of $J_{oe} = 10^{-13} \text{ A cm}^{-2}$, a value typical of laboratory quality solar cells.

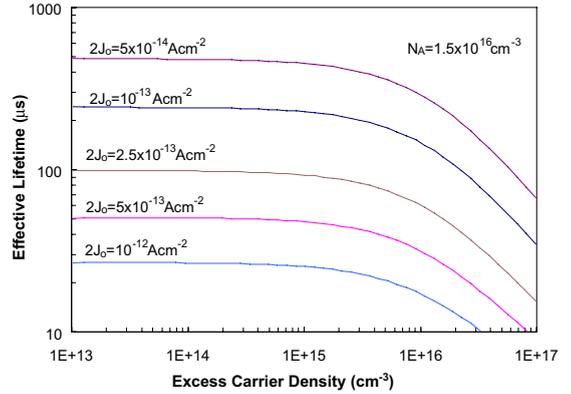


Fig. 3. Limitation on the measurable lifetime of a p -type $1 \Omega \text{ cm}$ ($N_A = 1.5 \times 10^{16} \text{ cm}^{-3}$) silicon wafer due to different possible values of the emitter saturation current density J_{oe} .

surface and emitter recombination mechanisms occurring in the sample (space charge recombination may also be explicitly added):

$$\frac{1}{\tau_{\text{eff}}} = \frac{1}{\tau_{\text{bulk}}} + \frac{S}{W} + J_{oe} \frac{[N_A + \Delta n]}{qn_i^2 W} \quad (14)$$

At $25 \text{ }^\circ\text{C}$, $qn_i^2 = 12 \text{ C cm}^{-6}$. In low injection, surface recombination velocity and emitter saturation current can be established to be equivalent: $S_{\text{eff}} \approx J_{oe} N_A / qn_i^2$.

5. Variability of the lifetime with carrier injection level

In addition to the effect of emitter regions discussed above, there are other reasons why the effective lifetime τ_{eff} can vary with the excess carrier density. In practical silicon wafers, the most important recombination losses occur through crystallographic defects and impurities that create energy levels within the band gap. The effect of such recombination centres can be adequately described with the Shockley-Read-Hall model (Hall, 1952; Shockley and Read, 1952). This model predicts that the lifetime is a function of the excess carrier density Δn , the dopant density, N_A (considering a p -type semiconductor), the density of recombination centres, the defect energy level E_T , and the electron and hole time constants τ_{n0} and τ_{p0} (which are related to the respective capture cross-sections). For the common case that the recombination centre is located near the middle of the energy gap, it is possible to simplify the SRH expression for the minority carrier lifetime to show more clearly its dependence on carrier injection level:

$$\tau_{\text{(SRH)}} = \tau_{n0} + \tau_{p0} \frac{\Delta n}{\Delta n + N_A} \quad (15)$$

Eq. (15), which assumes that the densities of excess carriers, dopant atoms and recombination centres are approximately constant across the wafer, predicts an increased lifetime between low and high injection levels from τ_{n0} to $\tau_{n0} + \tau_{p0}$. Fig. 4 shows an example with $\tau_{p0} = 6 \times 10^{-4}$ s and $\tau_{n0} = 2 \times 10^{-5}$ s. Nevertheless, every recombination centre is characterised by a distinctive set of parameters E_T , τ_{n0} and τ_{p0} , which leads to different injection and temperature dependences of the lifetime, as reviewed by Rein et al. (2002). For example, when the energy level is not near the middle of the gap, the lifetime can be found to decrease with injection level, rather than increase.

The determination of the fundamental parameters E_T , τ_{n0} and τ_{p0} of recombination centers based on the injection level or temperature dependence of the lifetime is a growing field of semiconductor physics. The application of the injection-level-dependent lifetime spectroscopy method (IDLs) to a specific defect level has been illustrated, for example, by Schmidt and Cuevas (1999). Although it is not obvious in the simplified form of Eq. (15), the lifetime is also strongly dependent on temperature, as shown by Hall (1952) in an early example of temperature-dependent lifetime spectroscopy, TDLS, a method that has been comprehensively discussed by Rein et al. (2002). Recently Schmidt (2004) has shown that the combination of both the temperature and injection level dependences of the lifetime (TIDLs) is a powerful tool for physical investigations of defects in semiconductors. When applying these spectroscopy methods to practical silicon wafers it is rarely found that a single defect centre can explain the full range of

measurements. It is common that one centre is dominant in a certain range of carrier injection levels, while a second centre (or more) is necessary to model the full range.

It should be noted that the SRH recombination mechanism also applies to the surfaces of the wafer, and similar injection level dependences can be due to either surface or bulk recombination. Controlled experiments and careful analysis are usually required to be able to attribute the measured lifetimes to one or the other. In most cases it is convenient to apply a dielectric layer to passivate the surfaces and thus render them practically inactive in comparison to bulk recombination. This can be difficult to achieve when exploring fundamental recombination limits, because the level of surface recombination is not negligible, even if the best passivation methods are used. The latter include thermally grown silicon oxide and plasma-deposited silicon nitride, as shown by Kerr and Cuevas (2002a,b).

Fig. 4 shows additional mechanisms that produce a variability of the effective lifetime with injection level. At high carrier densities the effective lifetime is affected by recombination at the dopant diffusions frequently present at the surfaces of the wafer. In addition, Auger and band-to-band recombination also come into effect (Kerr and Cuevas, 2002c). As can be noted, Auger recombination needs to be subtracted out from the measured effective lifetime before analysing the data to extract the emitter saturation current density, particularly for very low values of J_{oe} . The range of very low carrier densities is frequently obscured by trapping effects (not shown in Fig. 4). For a more detailed description of lifetime measurement methods and their limitations see Cuevas and Sinton (2004). Despite these difficulties, lifetime measurements are one of the most useful tools at the disposal of the semiconductor researcher.

6. Discussion

In this paper we have presented a simplified view of carrier recombination, sacrificing mathematical complexity in order to emphasise the physics and permit an easy interpretation of experimental measurements. It is worth reflecting once more on the concept of effective lifetime, defined by Eq. (1). This definition is essentially the same proposed by Shockley and Read (1952) and by the majority of the early researchers in the field. While recognizing that the problem is fundamentally more complex and that using a single lifetime constant may be an oversimplification, the concept of lifetime has served semiconductor physicists very well over the years. Although they focused the application of their model to the simplest, most important cases, Shockley and Read only assumed non-degeneracy and steady-state condi-

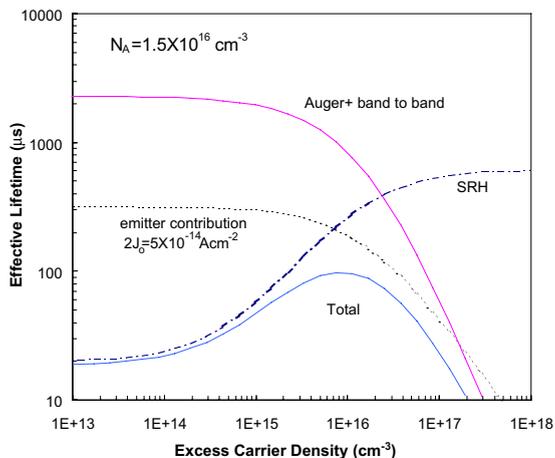


Fig. 4. Typical curve of lifetime as a function of carrier injection level due to a combination of physical mechanisms: Shockley–Read–Hall, Auger and emitter recombination. The limitations due to an emitter saturation current density of $J_{oe} = 2.5 \times 10^{-14}$ A cm⁻², and the intrinsic Auger and band-to-band recombination are also shown.

tions to describe the statistics of carrier transitions between defect levels in the gap and the conduction and valence bands. Their model is, in fact, applicable to any injection level. In its classical, simplified form the SRH model assumes a low concentration of defect centers and, because of this, it does not account for carrier trapping effects. Nevertheless, Blakemore (1962) has shown that general solutions of the continuity equations can be found for arbitrary excess carrier and recombination center densities, making the assumptions in the simplified SRH model largely unnecessary. Macdonald and Cuevas (2004) have recently revisited these solutions to discuss the limits of applicability of the simple SRH model, showing that they are not very restrictive in most cases.

Built into its simple, physically intuitive definition, the effective lifetime contains all the complexities of the global recombination mechanisms that may be present in a silicon wafer. To start with, it is important to list all the contributions from the various parts that compose the wafer: the quasi-neutral bulk region, the surfaces, any emitter (or highly doped) regions, and the associated space-charge regions. Each of those regions may follow different recombination statistics and become important in a certain operation range. For example, space-charge regions are important only at very low carrier densities, while emitter regions usually become dominant at high injection levels. Next, it is necessary to remember that, even within the bulk region of the wafer, there are several fundamental physical mechanisms, the most important of which are SRH, three-particle Auger, and band-to-band radiative recombination. Again, the relative importance of these mechanisms varies with carrier density, but it is usually the case that indirect SRH recombination is the most restrictive mechanism, except at very high injection or dopant levels. Finally, it is important to keep in mind that, although the common form of the SRH model applies to just one defect level, the observed effective lifetime frequently is the result of the parallel action of several recombination centres. Frequently, each of those defect levels is dominant in a certain carrier density or temperature range, and this allows their discrimination.

In summary, the familiar concept of carrier lifetime is still adequate to visualise recombination in semiconductors. The effective lifetime is the measurable parameter that links the observable reality to the underlying physics. In the real world the carrier lifetime rarely has a single, constant value. On the contrary, it varies strongly with the experimental conditions used to measure it. The detailed physical and mathematical description of such variability can be quite complex, but it is a rich resource of fundamental physics. Its measurement has been greatly facilitated by the introduction of quasi-steady-state methods. This is enabling rapid progress in the understanding of silicon materials for photovoltaic ap-

plications and the identification of limiting factors for improved performance.

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