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The recombination parameter J_0

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Abstract

The parameter J_0 , commonly used in solar cell modelling, has a deep physical meaning, which this paper intends to clarify. Upon examination, J_0 can be identified as the recombination current density in thermal equilibrium. In many cases the same equilibrium parameter J_0 can be used to describe carrier recombination under external illumination. Nevertheless, when carriers flow from the point where they are generated towards a high recombination site the value of J_0 that matters to solar cell operation differs from that in equilibrium. In addition, J_0 may in certain cases be dependent on the excess carrier concentration. We conclude by recommending that J_0 be referred to as a *recombination parameter*.

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1. Introduction

The purpose of this paper is to discuss the physical meaning of the parameter J_0 commonly used to characterize solar cells and propose a name for it according to the physics. We commence by showing that J_0 is just one possible conceptualisation to represent the recombination between electrons and holes, alternative to the material recombination parameter τ_{eff} , the minority carrier lifetime. We then look into the fact that the sub-index 0 commonly indicates thermo-chemical equilibrium conditions. Important magnitudes that bear such sub-index include the equilibrium electron and hole concentrations n_0 and p_0 , and the parameter J_0 . We will examine the detailed balance between generation and recombination in equilibrium and find that J_0 is indeed equal to the thermal equilibrium recombination current density.

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The question is: can an equilibrium parameter such as J_0 describe carrier recombination in a solar cell under external illumination? The answer is positive in many cases, which supports naming J_0 the *thermal recombination current*. But we also find that in the case of non-uniform generation-recombination processes there is a transport of carriers from one part of the device to another and then the J_0 under illumination differs from the J_0 based on equilibrium conditions. Let us first examine the concept of J_0 , then derive simple expressions for it in equilibrium, and finally proceed to discuss non-equilibrium conditions.

2. Two alternative ways to express carrier recombination

The rate at which electrons and holes react, that is, recombine is proportional the product of their respective concentrations. Such proportionality is clearest in the case of band to band recombination, but it approximately applies to all the other recombination mechanisms as well. Consider a silicon wafer dominated by intrinsic recombination. Experimentally, the closest implementation to such ideal wafer can be found in the measurements of the minority carrier lifetime performed by Richter et al.[1] As an example, let us take a p-type wafer with thickness $W=250\text{ }\mu\text{m}$ and doping $N_A=1.5\times 10^{16}\text{ cm}^{-3}$ and use the empirical expression proposed in that paper to plot in Fig. 1 the minority carrier lifetime as a function of the excess carrier concentration. At low carrier injection levels the empirical expression gives a lifetime τ_{eff} of 4 ms. It is straightforward to reconstruct from the lifetime curve the total recombination rate in this silicon wafer

$$R_{cum} \approx \frac{\Delta n W}{\tau_{eff}} \quad (1)$$

To see if the recombination rate is proportional to the product of the electron and hole concentrations, we plot it in Fig. 2 as a function of the pn product, normalised to its equilibrium value n_i^2 . As the straight line in Fig. 2 indicates, it is indeed possible to fit the recombination rate over a broad range of excitation levels using a simple pre-factor R_0 , according to the equation

$$R_{cum} \approx R_0 \frac{pn}{n_i^2} \quad (2)$$

In this example a good fit is obtained for $R_0=2.8\times 10^4\text{ cm}^{-2}\text{s}^{-1}$. Multiplying it by the electron charge this coefficient can be expressed as a current density, $J_0=4.5\times 10^{-15}\text{ A/cm}^2$. Therefore, the meaning of J_0 is a factor that multiplied by the normalised pn product gives the total recombination in the region under consideration expressed as a current, in this case a $250\mu\text{m}$ thick wafer.

The normalised pn product, assumed here to be constant over the whole wafer thickness, is equal to the difference between the electrochemical potentials of electrons and holes, which gives the implied, or possible voltage of this “device”,

$$qR_{cum} = J_0 \exp\left(\frac{E_{FC} - E_{FV}}{kT}\right) \approx J_0 \exp\left(\frac{V}{kT/q}\right) \quad (3)$$

Eq. 3 could be regarded as an alternative definition of the parameter J_0 , and it indicates that it could be determined from a plot of the cumulative photogeneration rate expressed as a current, equal in steady state to the recombination rate, vs. voltage. The latter can be measured directly, by contacting the device, as in the Suns- V_{oc} method, or the pn product can be determined from calibrated photoluminescence, or the excess carrier density can be determined from a photoconductance measurement. Eq. 3 is one of the terms of the widely used solar cell characteristic equation

$$J = J_{sc} - J_0 \left(\exp \frac{V}{kT/q} - 1 \right) \quad (4)$$

which expresses the intuitive idea that the operation of a solar cell can be understood as the superposition of a short-circuit current J_{sc} that is proportional to the photogeneration rate, minus a recombination loss due to the forward biased voltage that develops across the solar cell diode. The latter is no other than a manifestation of the pn product, higher now than in equilibrium, which is the physical magnitude that drives recombination. In the dark, Eq. 4 encapsulates, and frequently oversimplifies, all the material properties and all the geometrical details of device construction into a global parameter J_0 commonly called the *saturation current density*. The name comes from the expectation that in the dark and under reverse bias, the output current should “saturate” to a value equal to J_0 . Nevertheless, in practice the value of J_0 in reverse and forward bias can be quite different. Under illumination there is an additional recombination loss hidden within J_{sc} because, even when the terminal voltage is zero, an internal separation between the quasi-Fermi energies for electrons and holes must exist for a current to flow. In fact, J_{sc} is always lower than the total photogenerated current J_{ph} , which is typically in the range 40–43 mAcm⁻².

That the simple solar cell equation of Eq. 4 is not always applicable is not a secret. To stretch its validity and be able to fit experimental measurements, people have introduced an “ideality factor” in the denominator of the exponential term, or even used a second exponential term. The departure of the recombination rate from the “ideal” behaviour can be noticed in Fig. 2 at very high excitation levels. The nature of the Auger process means that there is an increased recombination rate at such levels. In other words, there is a change in the way that the recombination rate varies with the carrier concentration. As it is apparent in the graph, the J_0 extracted from a fit to the low injection range is not applicable to high injection. Appendix A examines the case of Auger recombination in detail.

Neither concept, minority carrier lifetime or recombination current parameter, is simple or general. Both can vary with the level of excitation in the wafer (i.e. with the excess carrier concentration) and with the physical mechanism that is dominant in that particular wafer. A significant difference to keep in mind is that J_0 represents the cumulative recombination in the wafer and therefore it depends on the geometrical dimensions, while τ_{eff} does not.

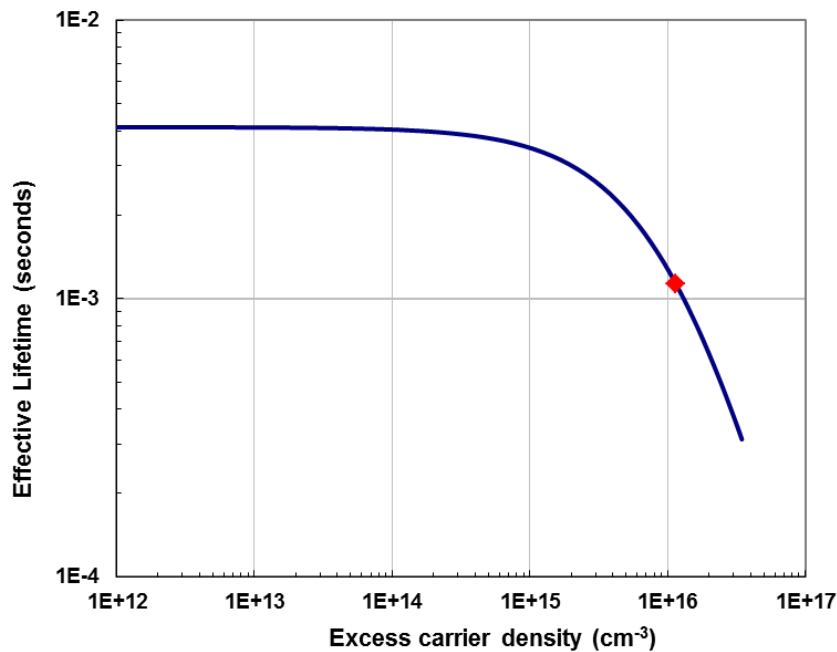


Fig. 1. Minority carrier lifetime for a p-type silicon doped with $N_A = 1.5 \times 10^{16} \text{ cm}^{-3}$, according to Richter's parameterisation.

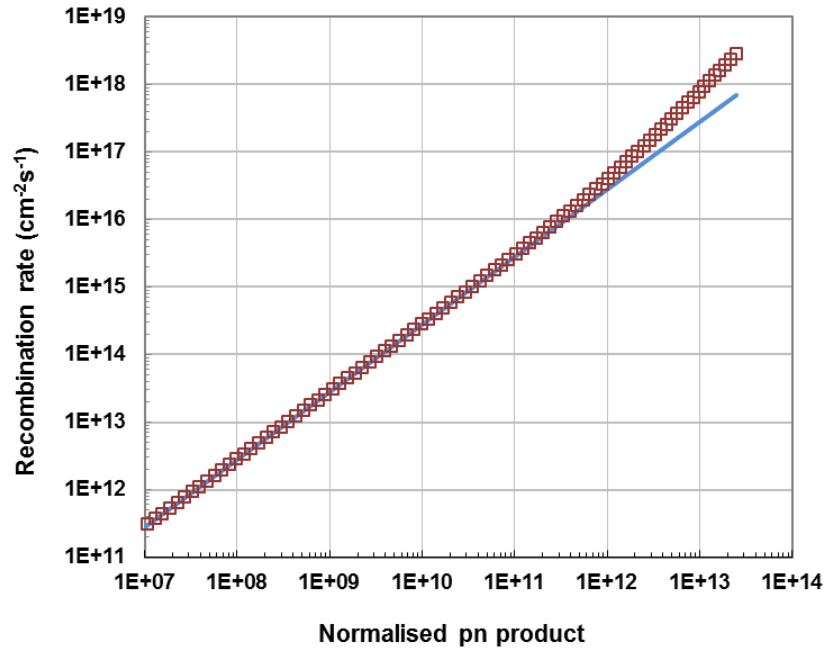


Fig. 2. Cumulative recombination rate for a $W=250\ \mu\text{m}$ thick p-type silicon wafer having the minority carrier lifetime shown in Fig. 1.

3. The thermal equilibrium J_0

In thermal and chemical equilibrium there cannot be a net flow of charge carriers, nor electric currents. It is still possible to define a recombination current $J_{0(\text{rec})}^{\text{th}}$, perfectly balanced by a thermal generation current $J_{0(\text{gen})}^{\text{th}}$. The principle of detailed balance means that in equilibrium each of the various recombination processes that exist in a semiconductor is balanced by the reverse thermal generation process. In silicon, band to band, Auger and SRH recombination co-exist, the latter usually taking place both in the volume and at the surface. Each of those processes is in perfect balance with its opposite: band to band thermal generation, thermal Auger generation (equivalent to impact ionisation), and thermal SRH generation (bulk and surface).

A particular process may be dominant; for example Auger is usually the strongest recombination mechanism in the volume of highly doped n^+ and p^+ silicon. Therefore, in equilibrium Auger generation is usually the dominant mechanism that determines the value of the thermal recombination current for a highly doped region J_{0n^+} . If we extend this reasoning to the whole device, and consider that in a contemporary silicon solar cell recombination in the n^+ and p^+ regions usually dominates device behaviour, that is, it is stronger than in the moderately doped base region, we can see that the *thermal generation* rate within a solar cell in equilibrium will be different in its various regions, being highest (Auger-dominated) in the n^+ and p^+ regions. But the greater thermal generation rate in those surface regions compared to the lowly doped base does not imply that carriers will flow from them towards the base. The consequence of the principle of detailed balance is that the various thermal generation rates are locally balanced by an identical thermal recombination rate. Indeed, in equilibrium there cannot be a net flow of carriers in a given direction. If SRH at the surface is dominant, then there will be a strong SRH thermal generation at the surface as well. Let us derive next simple expressions for J_0^{th} for each of the recombination-generation mechanisms.

3.1. Thermal J_0 due to band to band recombination

Consider the case of band to band recombination. We can determine the cumulative recombination within a region of thickness W by stating that recombination rate is proportional to the product of the concentrations of the “reacting species”, electrons and holes,

$$R_{BB(cum)} = B \cdot pn \cdot W \quad (5)$$

where $B=4.73 \times 10^{-15} \text{ cm}^3 \text{ s}^{-1}$ is the radiative recombination coefficient [2]. It is sufficient to multiply by the elementary charge and give to n and p their equilibrium values to obtain the thermal recombination current

$$J_0^{th}{}_{(BB)} = q \cdot B \cdot n_i^2 \cdot W \quad (6)$$

We can see that the value of $J_{0(BB)}$ will depend on the physical dimension W and on temperature. For example, for $W=250 \text{ } \mu\text{m}$ $J_{0(BB)}=2.4 \times 10^{-15} \text{ A/cm}^2$.

3.2. Thermal J_0 due to Auger recombination

If Auger recombination were the only mechanism, and if it followed the classical dependence on the concentrations of electrons and holes, the corresponding $J_{0(A)}$ could be shown to be

$$J_{0A_l.i.}^{th} \approx q \cdot n_i^2 N_A \cdot C_p \cdot W \quad (7)$$

For the example of $N_A=1.5 \times 10^{16} \text{ cm}^{-3}$ and $W=250 \text{ } \mu\text{m}$, if we used the Auger coefficients measured by Dzielwior and Schmid [3], $C_n=2.8 \times 10^{-31} \text{ cm}^6 \text{ s}^{-1}$ and $C_p=0.99 \times 10^{-31} \text{ cm}^6 \text{ s}^{-1}$, we would determine $J_{0(A)}=4.1 \times 10^{-16} \text{ A/cm}^2$. This is a very small value, but it should be noted that those coefficients apply only to silicon with a dopant concentration greater than $5 \times 10^{18} \text{ cm}^{-3}$. For moderately and lowly doped silicon, the full empirical expression of Richter et al.[1] should be used. That is essentially what we have done in the analysis of Section 1, which gave a total $J_{0(intrinsic)}=4.6 \text{ fA/cm}^2$, of which 2.4 fA/cm^2 correspond to band to band recombination, as determined in the previous section, and 2.2 fA/cm^2 to Auger recombination.

It is interesting to note in Eq. 7 that Auger recombination in low injection can be represented by means of a constant J_0 . Therefore, Auger recombination could be expected to have, at least in this simplified form, the same dependence on device voltage (the same ideality factor of 1) as band to band or simple SRH recombination.

3.3. Thermal J_0 due to SRH recombination

The case of Shockley-Read-Hall recombination is already expressed by Eq. 1, which is in fact the definition of minority carrier lifetime made by Shockley and Read [4]. To further show that the concepts of minority carrier lifetime τ_{eff} and J_0 are interchangeable, we can equate Eq. 1 to Eq. 2 and derive, assuming low injection,

$$J_{0(SRH)}^{th} = q \frac{n_0 \cdot W}{\tau_{eff}} = q \frac{n_i^2 \cdot W}{N_A \cdot \tau_n} \quad (8)$$

For a wafer thickness $W=250 \text{ } \mu\text{m}$ and the value $\tau_{eff}=4 \text{ ms}$ in Fig. 1, we obtain $J_0=4.6 \times 10^{-15} \text{ A/cm}^2$, in excellent agreement with the fit shown in Fig. 2. It is worth noting that the $N_A=1.5 \times 10^{16} \text{ cm}^{-3}$ sample in Richter's paper [1] presented a residual SRH defect that made the actual measured lifetime smaller in low injection, about 2 ms, than that given by the empirical expression. The result would be $J_{0(SRH)}=9.2 \text{ fA/cm}^2$.

3.4. Thermal J_0 due to surface recombination

In low injection conditions and in the absence of surface charge, SRH surface recombination can be expressed either by means of a surface recombination velocity S_n or a J_0 parameter,

$$J_{0(surf)}^{th} \approx qS_n n_0 = qS_n \frac{n_i^2}{N_A} \quad (9)$$

For example, if $N_A = 1.5 \times 10^{16} \text{ cm}^{-3}$ and $S_n = 3 \times 10^6 \text{ cm/s}$ (kinetic limit) the result would be $J_{0(surf)} = 2.2 \times 10^{-9} \text{ A/cm}^2$, an extremely high value compared to the previous mechanisms. The surface would need to be very well passivated, say $S_n = 0.1 \text{ cm/s}$ to make the resulting $J_{0(surf)} = 7.4 \times 10^{-16} \text{ A/cm}^2$, smaller than the values calculated above for intrinsic recombination. Note that the $J_{0(surf)}$ due to surface recombination does not depend on the thickness of the wafer and is directly interchangeable with the parameter S_n in low injection, although such equivalence may not apply in general, particularly if the surface is charged.

4. Applying J_0 to external photogeneration conditions

It is possible that, under excitation, the recombination mechanism itself varies with the excess carrier density. Many defects cause such variability for the SRH mechanism in silicon, even in low injection. As Eq. 8 indicates, if the effective lifetime is not constant neither will J_0 be. Given that the usefulness of J_0 relies to a large extent on it being constant, it is common to introduce a second parameter called the “ideality factor” to accommodate for the specific injection dependence of the recombination. An example of how this can be done is given in the Appendix for the case of Auger recombination.

Whereas in equilibrium the pn product and the Fermi energy are uniform, under illumination there can be an internal flow of carriers, and this demands a gradient in the quasi-Fermi energy and a pn product that varies with position. Such internal flow occurs, for example, when surface recombination is dominant.

4.1. Non-equilibrium J_0 due to surface recombination

Consider UV illumination, strongly absorbed near the front surface of the wafer, which is perfectly passivated, while the rear surface is not. Photogenerated electrons and holes will diffuse towards the rear surface region, where they will recombine. The internal flow of carriers can only occur at a velocity determined by their diffusivity (i.e. their mobility), which is finite. It is then necessary to solve the simultaneous carrier transport and recombination problem under excitation. The solution is straightforward if bulk recombination is neglected and low injection assumed, the recombination parameter J_0 of such wafer under illumination is

$$J_{0(surf)}^{illum} \approx \frac{qS_n n_0}{1 + S_n n_0 \frac{W}{n_0 D_n}} \quad (10)$$

Which for the case of a high surface recombination velocity simplifies to

$$J_{0(high_SRV)}^{illum} \approx \frac{qD_n n_0}{W} \quad (11)$$

For example, if $N_A = 1.5 \times 10^{16} \text{ cm}^{-3}$, $W = 250 \text{ } \mu\text{m}$ and $S_n = 3 \times 10^6 \text{ cm/s}$ the result would be $J_{0(surf)} = 7.9 \times 10^{-13} \text{ A/cm}^2$, quite high, but much smaller than the value calculated based on thermal equilibrium considerations.

The example of diffusivity-limited surface recombination shows that in general the concept of J_0 derived from considering the detailed balance between generation and recombination in equilibrium does not apply to non-

equilibrium, $J_0^{illum} \neq J_0^{th}$. Nevertheless, even in that case J_0^{illum} , as given by the above expressions, is still a constant, independent of the voltage (provided that the material parameters are independent of the carrier concentration). Hence, the concept of J_0 is still useful as a pre-factor to represent most recombination losses.

5. Regional J_0 parameter

The concept of J_0 can be applied to characterise the whole solar cell device or to parts of it, such as the highly doped n^+ and p^+ regions usually present at the surfaces of silicon solar cells. The requirement that J_0 remains constant, independent of the excitation level, is more easily satisfied if the domain is restricted to a region of the solar cell, rather than to the whole device. For example, it is common to characterise the recombination occurring within a highly doped n^+ diffusion by means of a J_{0n+} , and that occurring in a p^+ diffusion by means of a J_{0p+} . That recombination is determined multiplying J_{0n+} by the local difference between the quasi-Fermi potentials of electrons and holes, present at the plane that defines the boundary of the region of interest, in this case at the junction between a moderately doped “base” region and the n^+ diffusion. Hence, the recombination within the n^+ region can be expressed in units of current density as

$$qR_{n^+} = J_{0n^+} \frac{p n}{n_i^2} \quad (12)$$

where n and p are the electron and hole concentrations at the surface plane that defines the region under consideration and n_i is the intrinsic carrier concentration. Eq. 12 shows that in equilibrium, when $pn=n_i^2$ the thermal recombination current within the n^+ region is precisely equal to J_{0n+} . The reason why the concept of J_0 works well as a means of representing recombination occurring in the highly doped regions (an exception is when a charged dielectric at the surface creates depletion conditions) is because low injection conditions usually prevail within them, and all material parameters are independent of injection level. We show this through a few examples.

5.1. Bulk recombination in a highly doped region

Let us examine the case of a highly doped p^+ region near the surface of a solar cell when an excitation in the form of a separation between the quasi-Fermi potentials for electrons and holes is present at the boundary of such a region. An approximate solution for the case of negligible surface recombination and a sufficiently long diffusion length is, when the dopant density varies with position [5],

$$J_{0p+} = q \int_0^{W_{p+}} \frac{n_0}{\tau_n} dx \quad (13)$$

Eq. 13 indicates that the J_{0p+} that applies to excited conditions is the same that could be obtained by considering equilibrium and integrating the thermal recombination over the region under analysis. If the dopant density is uniform Eq. 13 reduces to Eq. 8. Considering that in highly doped silicon Auger, rather than SRH, recombination is dominant J_{0p+} can be evaluated with Eq. 9. When applying those equations to highly doped regions it is important to remember heavy doping effects, which can make the value of the effective intrinsic concentration $n_{i(eff)}^2$ up to 10 to 20 times higher than in lowly doped silicon. For dopant concentrations greater than $5 \times 10^{18} \text{ cm}^{-3}$ the Auger coefficients measured by Dziewior and Schmid are $C_n = 2.8 \times 10^{-31} \text{ cm}^6 \text{ s}^{-1}$ and $C_p = 0.99 \times 10^{-31} \text{ cm}^6 \text{ s}^{-1}$. Therefore, we can expect a lower value for $J_{0(A)}$ in a boron diffused region than in a phosphorus diffusion one, at equal doping, provided that band gap narrowing is approximately the same (there are indications that it is slightly larger in p-Si than in n-Si). As an example, for a n^+ region with $W=1 \mu\text{m}$, $N_D=1 \times 10^{19} \text{ cm}^{-3}$, the approximate result would be $J_{0n+}=5 \times 10^{-14} \text{ A/cm}^2$, whereas for a p^+ region with $N_A=1 \times 10^{19} \text{ cm}^{-3}$, the result would be $J_{0p+}=2 \times 10^{-14} \text{ A/cm}^2$.

5.2. Surface recombination in a highly doped region

In the extreme case of a very high surface recombination together with negligible bulk recombination, the analytical solution when an excitation is present is, when the dopant density varies with position [5],

$$J_{0p+} = \frac{1}{\int_0^{W_{p+}} \frac{dx}{qn_0 D_n}} \quad (14)$$

If the dopant density is constant Eq. 14 simplifies to Eq. 11, and we can calculate $J_{0p+}=5.8 \times 10^{-13}$ A/cm² for $W=1 \mu\text{m}$ and $N_A=1 \times 10^{19}$ cm⁻³. On the other hand, the *thermal recombination current* density would be given by Eq. 9, which for $S_n=3 \times 10^6$ cm/s would give $J_{0p+}^{th}=3.4 \times 10^{-11}$ A/cm², much higher than the value calculated under excitation. Hence using the *thermal* J_{0p+} would be misleading in this case, because only carriers that can travel to the surface recombine there.

5.3. Total device J_0 in equilibrium

If several regions are present in a wafer, for example a n^+pp^+ cell structure, the total J_0 in equilibrium is equal to the sum of the various J_0 that characterise each of those regions,

$$J_{0(total)}^{th} = J_{0n+} + J_{0p} + J_{0p+} \quad (15)$$

As an example, for the case of constant dopant densities,

$$J_{0(total)}^{th} \approx q \cdot C_n N_{D+} n_{i(eff)}^2 \cdot W_{n+} + q \frac{n_i^2 W_p}{N_A \tau_n} + q \cdot C_p N_{A+} n_{i(eff)}^2 \cdot W_{p+} \quad (16)$$

Under illumination adding the regional components to determine the total J_0 is approximately correct in many cases, such as high performance solar cells near the maximum power point, but not always.

6. Conclusion

We have seen that the $J_0^{(th)}$ derived from considering the detailed balance between generation and recombination in equilibrium does not always apply to non-equilibrium situations. It is also true that a single, constant value of J_0 may not be sufficient to represent the physical reality of recombination mechanisms that change with the excitation level. The latter should not come as a surprise, considering that the widely accepted parameter of minority carrier lifetime usually varies with the excess carrier concentration. Despite those limitations and exceptions, J_0 frequently signifies the generation-recombination current in equilibrium. Even if it is not always identical to J_0^{th} , and keeping that fact in mind, we could refer to J_0 as the *thermal (or equilibrium) recombination current*.

More generally, and given that J_0 is just a factor that somewhat conveniently permits to calculate the cumulative recombination by multiplying it by an “excitation factor” (the normalised pn product, or the exponential of the normalised voltage), it can always be called the *recombination factor*, or the *recombination parameter*.

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Appendix A. Auger recombination in high injection

To illustrate the problematic definition of J_0 when the recombination mechanism varies with the carrier injection level, let us take the example of Auger recombination. In a simplistic manner, it may be qualitatively described as,

$$R_{Auger} = C_n n^2 p + C_p n p^2 \quad (A1)$$

Using the ordinary definition of J_0

$$J_{0A} \equiv q R_{A(cum)} \frac{n_i^2}{pn} \quad (A2)$$

we would have, for the case of p-type doped silicon

$$J_{0(Auger)} \approx q \cdot n_i^2 \cdot W \cdot [C_n \Delta n + C_p (\Delta n + N_A)] \quad (A3)$$

It is possible to identify that this injection-dependent expression for J_0 is composed of a term that becomes prevalent in low injection and another term that is dominant in high injection

$$J_{0A_l.i.} \approx q \cdot n_i^2 \cdot W \cdot C_p N_A \quad (A4)$$

$$J_{0A_h.i.} \approx q \cdot n_i^2 \cdot W \cdot (C_n + C_p) \cdot \Delta n \quad (A5)$$

But a J_0 that is dependent on the injection level is not very useful. An alternative definition of J_0 that introduces a second parameter to describe the injection dependence called an “ideality factor” is as follows. Noting that in very high injection $pn \approx \Delta n^2$, we re-write the recombination rate for high injection

$$R_{A_h.i.} \approx (C_n + C_p) \cdot \Delta n^3 = (C_n + C_p) \cdot (pn)^{3/2} \quad (A6)$$

Which can be further transformed to

$$q \cdot R_{A(cum)_h.i.} \approx J_{0A_h.i.} \left(\frac{pn}{n_i^2} \right)^{3/2} \quad (A7)$$

Where J_0 is now constant, but depends on the cube of the intrinsic carrier density,

$$J_{0A_h.i.} = q \cdot n_i^3 \cdot W \cdot (C_n + C_p) \quad (A8)$$

A further transformation shows that the “ideality factor” of the recombination current vs. voltage characteristics is, in this case, $2/3=0.666$.

$$qR_{A(cum)} \approx J_{0A_hi} \exp \left(\frac{V}{\frac{2}{3} \frac{kT}{q}} \right) \quad (A9)$$

Experimentally, it has been found that the effective Auger recombination coefficient in high injection is not equal to the sum of the coefficients C_n and C_p measured by Dziewior and Schmid [3], but much higher. Sinton and Swanson [6] measured an ambipolar, or high injection, coefficient of $C_A = 1.66 \times 10^{-30} \text{ cm}^6 \text{ s}^{-1}$. Richter's [1] empirical expression includes a high injection trend according to a coefficient $3.0 \times 10^{-29} \text{ cm}^6 \text{ s}^{-1}$, but with an exponent for the excess carrier density of 2.92 instead of 3, eventually agreeing quite well with Sinton's measurements. The case of Auger in high injection illustrates well that the concept of "ideality factor" is not trivial. In Sinton's analysis the ideality factor coincides with the simple theoretical expectation of 0.666; the empirical expression from Kerr [7] implies an ideality factor of 0.714 in very high injection; the more recent expression by Richter et al. leads to an ideality factor of 0.685. All of them are quite similar, and fit the experimental data reasonably well, but they lead to a quite different value of the corresponding Auger coefficient, that is, of the equivalent J_0 .

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