TCAD Parameters for 4H-SiC: A Review

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In this paper we review the models and their parameters to describe the relative permittivity, bandgap, impact ionization, mobility, charge carrier recombination/effective masses and incomplete dopant ionization of 4H silicon carbide in computer simulations. We aim to lower the entrance barrier for newcomers and provide a critical evaluation of the status quo to identify shortcomings and guide future research. The review reveals a rich set of often diverging values in literature based on a variety of calculation and measurement methods. Although research for all the selected parameters is still active, we show that sometimes old values or those determined for other kinds of silicon carbide are commonly used.

Keywords: 4H-SiC, TCAD simulations, simulation parameters, silicon carbide

CONTENTS

I. CHARGE CARRIER RECOMBINATION

In a semiconductor electron-hole pairs are continuously created, for example due to thermal processes, adding additional charge carriers. Their concentration is denoted as excess carrier Δ_N, non-equilibrium, generated[1,2] or solely carrier concentration[3]. Simultaneously to the generation, electron-hole pairs also recombine, such that the rate of change can be described as shown in Eq. (1)[4–6].

$$\frac{\mathrm{d}\Delta_N}{\mathrm{d}t} = D\frac{\mathrm{d}^2\Delta_N}{\mathrm{d}\mathbf{x}^2} - R + G \tag{1}$$

The first term denotes the diffusion of charge carriers (D equals the ambipolar diffusion coefficient), R the recombination and G the generation rate. One of the effects accounting to the latter is impact ionization, which we already investigated in **??**, or optical generation. In equilibrium, all the contributions compensate and the net change is zero.

In TCAD simulations it is essential to correctly model the localized change in charge carrier concentration, as it influences, among others, the conductivity and the internal electric fields. In this section we are, thus, going to review the relevant charge carrier recombination mechanisms in 4H-SiC. The time between two recombination events depends on several parameters that have to be clearly distinguished. Partially, the values are very sample depend and thus a wide range of values were found in the literature.

A. Theory

The decay of excess charge carriers towards the equilibrium value is described by the recombination rate R[7]. It can be written as shown in Eq. (2)[5,8–11] where R_{SRH} denotes the trap-assisted Shockley-Read-Hall, R_{bim} the bimolecular and R_{Auger} the Auger recombination rate[12].

$$\begin{aligned} R &= R_{\mathrm{SRH}} + R_{\mathrm{bim}} + R_{\mathrm{Auger}} \\ &= \frac{\Delta_N}{\tau_{\mathrm{SRH}}} + \frac{\Delta_N}{\tau_{\mathrm{bim}}} + \frac{\Delta_N}{\tau_{\mathrm{Auger}}} = \frac{\Delta_N}{\tau_{\mathrm{r}}} \end{aligned} \tag{2}$$

In the second line an alternative representation using lifetimes τ_{x} is shown[13], which denote the average time between two recombination events. The single contributions to the recombination will be shortly investigated in the sequel. For a more comprehensive description the interested reader is referred to the dedicated literature[8,14–16].

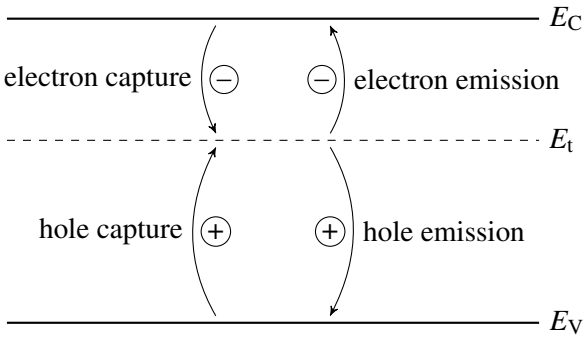

FIG. 1. Capture and emission of charge carriers described by R_{SRH}. E_t denotes the trap level energy.

1. Shockley-Read-Hall Recombination

The term R_{SRH} denotes the successive capturing of a hole and an electron in a trap level with energy E_t inside the band gap[8,17], sometimes also called monomolecular recombination[12]. Due to the lower energy difference between trap and energy bands compared to the overall band gap, the transition of a charge carrier to a trap is much more likely than a band-to-band transition. To describe this process in detail specific terms have been proposed in literature (see also Fig. 1)[18–20]: *electron capture* denotes the transition of an electron from the conduction band into the trap while *electron emission* describes the reverse process. Similarly, during *hole capture* a hole rises from the valence band to the trap level, i.e., an electron drops from the trap into the valence band. *Hole emission* denotes the reverse case. Overall, during any capture process the electron looses energy, while during emission it gains some. In this context the electron/hole *capture cross sections* are used to quantify the possibility for an electron/hole capture.

The excessive energy released/consumed during these transitions is exchanged with lattice vibrations[8], whereat different phonon interactions are distinguished, e.g., multi- or cascade-phonon interaction[14,21]. Among these the capture cross section and their respective temperature dependencies differ[19].

The recombination rate R heavily depends on the material quality[8]. Certain defects, e.g., impurities or damages in the lattice, are very effective "lifetime killers"[22], meaning that they increase the recombination rate significantly. Lots of effort is undertaken to refine growth conditions to achieve cleaner samples and, thus, higher lifetimes[11,23–41]. The recombination rate even varies across a single wafer. Typically it is smallest in the middle where the best growth conditions are available[25,38,40,42–52], but also in thick 4H-SiC layers variations were reported[53]. In fact, the

recombination rate decreases at structural defect positions[54] but increases inversely linear with temperature[55–57].

For an accurate description of R_{SRH} detailed information, i.e., energy level, type (acceptor or donor) and cross section of the defects in the device are required. Many investigations in regard to these parameters have been published[13,28–30,35,52,58–212], making a comprehensive analysis within this review infeasible. Instead, we refer the interested reader to an analysis by Gaggl *et al.* [213], who investigated defects in 4H-SiC. In regard to recombination, the most important ones are called $\mathrm{Z}_{1/2}$ and $\mathrm{EH}_{6/7}$[196,209,214,215] and, presumably, denote different charge states of a carbon vacancy[74].

The trap-assisted recombination can be split into the recombination in the bulk ($R^{\mathrm{b}}_{\mathrm{SRH}}$) and on the surface ($R^{\mathrm{s}}_{\mathrm{SRH}}$). Both occur simultaneously and are therefore often hard to separate[8,216]. In the sequel we are going to investigate these in more detail.

a. Bulk Recombination Rate The Shockley-Read-Hall recombination of the bulk was mathematically first described by Shockley and Read [18], Hall [217] as shown in Eq. (3)[16,18,20,62,153,217,218].

$$R^{\mathrm{b}}_{\mathrm{SRH}} = \frac{np - n_{\mathrm{i}}^2}{\tau_{\mathrm{p}}(n+n_1)+\tau_{\mathrm{n}}(p+p_1)} \tag{3}$$

$$n_1 = \frac{1}{g_{\mathrm{t}}} N_{\mathrm{C}} \exp\left(-\frac{E_{\mathrm{C}}-E_{\mathrm{t}}}{k_{\mathrm{B}}T}\right) \tag{4}$$

$$p_1 = g_{\mathrm{t}} N_{\mathrm{V}} \exp\left(-\frac{E_{\mathrm{t}}-E_{\mathrm{V}}}{k_{\mathrm{B}}T}\right) \tag{5}$$

$$n_{\mathrm{i}} = \sqrt{n_1 p_1} = \sqrt{N_{\mathrm{C}}N_{\mathrm{V}}} \exp\left(-\frac{E_{\mathrm{C}}-E_{\mathrm{V}}}{2k_{\mathrm{B}}T}\right) = \sqrt{N_{\mathrm{C}}N_{\mathrm{V}}} \exp\left(-\frac{E_{\mathrm{g}}}{2k_{\mathrm{B}}T}\right) \tag{6}$$

$$\tau_{\mathrm{n,p}} = \left(\sigma_{\mathrm{n,p}} v_{\mathrm{th}} N_{\mathrm{t}}\right)^{-1} \tag{7}$$

Here, n_{i} denotes the intrinsic carrier concentration, $\tau_{\mathrm{n,p}}$ the electron resp. hole lifetime, $\sigma_{\mathrm{n,p}}$ the electron resp. hole cross section, N_{t} the trap concentration, $v_{\mathrm{th}} = \sqrt{3k_{\mathrm{B}}T/m^*_{\mathrm{d}}}$[20,219] the thermal velocity and g_{t} the trap degeneracy factor, which is often neglected as they are usually one[76]. E_{t} denotes the trap energy level, whereat Shockley and Read [18] stated that this is actually an effective energy level that is derived from the actual one by considering the degeneracies of the empty (w_{p}) and full (w) trap, i.e., $E_{\mathrm{t}} = E_{\mathrm{t}}(\mathrm{true}) + k_{\mathrm{B}}T\ln(w_{\mathrm{p}}/w)$. In TCAD tools either the lifetimes $\tau_{\mathrm{n,p}}$ or the cross sections $\sigma_{\mathrm{n,p}}$ can be provided as input, however, none of the investigated tools allows to specify the degeneracy factor at the moment.

It is also possible to define p_1 and n_1 as shown in Eq. (8)[13,21,220], i.e., by using the intrinsic carrier concentration and an effective Fermi level E_{i}, which must not be confused with the intrinsic Fermi level E_{F} used to calculate the actual carrier concentration $n = N_{\mathrm{C}}\exp[(E_{\mathrm{F}}-E_{\mathrm{C}})/k_{\mathrm{B}}T]$ and

$p = N_V \exp[(E_V - E_F)/k_B T]$. Care has to be taken in this case as the intrinsic carrier concentration n_i changes with the doping concentration due to band gap narrowing effects (see **??**).

$$\begin{aligned} n_1 &= \frac{1}{g_t} n_i \exp\left(-\frac{E_t - E_i}{k_B T}\right) \\ p_1 &= g_t n_i \exp\left(-\frac{E_i - E_t}{k_B T}\right) \end{aligned} \tag{8}$$

The SRH carrier lifetime is not constant but depends on the temperature and doping concentration $N_{A,D}$[221]. The latter describes the increase of lattice defects, i.e., recombination centers, that accompany the doping process[218] and has to be clearly distinguished from the excess carrier concentration Δ_N. The reduction of the lifetime can be described for each charge carrier separately using the empirical Scharfetter relation[21,62,71,218,222–227] shown in Eq. (9). A more detailed analysis on the change of the lifetime for various relations of donor and acceptor concentrations was recently provided by Shao *et al.*[228]. We want to highlight that dopants (see **??**) themselves are a special form of defects, i.e., recombination centers, whose impact on the recombination can be described also with Eq. (3)[179].

$$\tau = \frac{\tau_{max}}{1 + \left(\frac{N_A + N_D}{N_{ref}}\right)^{\gamma}} \tag{9}$$

It also common practice to determine the reduced lifetime in a more simplistic fashion from the defect concentration, e.g., $\tau(\mu s) = 1.5 \times 10^{13}/N_{VC}$[214,229] and $\tau(\mu s) = 1.8 \times 10^{13}/N_{VC}$[128] for carbon vacancies, and $\tau(\mu s) = 1.6 \times 10^{13}/N_{Z1/2}$[130] and $\tau(\mu s) = 2 \times 10^{13}/N_{Z1/2}$[31] for the $Z_{1/2}$ defect, instead of using Eq. (7)[230].

At high temperatures the energetic charge carrier has to approach the center of the defect more closely to be captured[225]. This implies that the lifetime increases with increasing temperature[34,37,50,231], which was extensively analyzed by Udal and Velmre[232]. The cross section changes in the order of T^{-x}[233], which leads, in conjunction with the change of the thermal velocity according to $\sqrt{T}$, to a power law description[229]. In TCAD tools the model shown in Eq. (10)[234–236] is used, whereat τ_{T0} denotes the lifetime at some reference temperature T_0.

$$\tau_{max} = \tau_{T0} \left(\frac{T}{T_0}\right)^{\alpha} \tag{10}$$

Because the lifetime approaches zero for $T \to 0$ in this approximation a slightly modified version[179] shown in Eq. (11) was proposed. By comparison we find $\tau_0 = \tau_{T0}/2$ that is achieved for $T = 0\,\mathrm{K}$.

$$\tau_{max} = \tau_0 \left(1 + \left(\frac{T}{T_0}\right)^{\alpha}\right) \tag{11}$$

We also found an exponential description using an activation energy E_{act} shown in Eq. (12)[232], where τ_∞ denotes the lifetime for $T \to \infty$.

$$\tau_{\max} = \tau_\infty \exp\left(\frac{-E_{\mathrm{act}}}{k_{\mathrm{B}} T}\right) \tag{12}$$

Since the meaning of τ_∞ is hard to grasp, it can be replaced by $\tau_{T0}\exp(E_{\mathrm{act}}/k_{\mathrm{B}}T_0)$[130,237], with τ_{T0} the lifetime at $T = T_0$. For $E_{\mathrm{act}} = 0.105\,\mathrm{eV}$ and $T_0 = 300\,\mathrm{K}$ we get $\exp(E_{\mathrm{act}}/k_{\mathrm{B}}T_0) = 57.9$[130,237]. A very similar approach show in Eq. (13)[4] approaches a value of $51\tau_0$ for $T \to \infty$.

$$\tau_{\max} = \tau_0 \left(1 + \frac{100}{1 + \exp\left(E_{\mathrm{act}}/k_{\mathrm{B}}T\right)}\right) \tag{13}$$

The models in Eq. (12) and Eq. (13) have the disadvantage that the lifetime stalls for high temperatures. Consequently these are only suitable for moderate temperatures between 300–500 K[232], which circumvented by the model shown in Eq. (14)[238,239].

$$\tau_{\max} = \tau_{T0} \exp^{C\left(\frac{T}{T_0} - 1\right)} \tag{14}$$

A recent investigation by Lechner[238] identified an initial increase in the lifetime followed by a decrease at high temperatures. Based on the research by Schenk[236] the fitting shown in Eq. (15)[238] was proposed.

$$\tau_{\max} = \tau_{T_0} \left(\frac{T}{T_0}\right)^{T_{\mathrm{coeff}}} \exp\left[-\alpha_\tau \left(\frac{T}{T_0} - 1\right)^{\beta_\tau}\right] \tag{15}$$

Be aware that in state-of-the-art simulation tools only Eq. (10) and Eq. (14) are included.

b. Surface Recombination Rate Surface recombination includes mechanisms that occur on surfaces or interfaces due to imperfections or impurities at the transition between two materials. It includes many different surface types and thus also effects, such as semiconductor-oxide, semiconductor-semiconductor or oxides across the latter. Naturally, these can be heavily influenced by the chosen materials and growth conditions. The share of surfaces recombination on the overall recombination rate decreases with the thickness of the samples, because the ratio of surface to bulk volume decreases[230].

In general, the surface recombination is written as the boundary condition of the diffusion term[240–243] as shown in Eq. (16). A fantastic review on the causes, characterization methods and possible countermeasures of surface recombination is presented by Mao *et al.*[6] and a theoretical analysis by Gulbinas *et al.*[240].

$$D\frac{\mathrm{d}\Delta_N(\mathbf{x},t)}{\mathrm{d}\mathbf{x}} = S_0\Delta_N(\mathbf{x},t) \tag{16}$$

Despite the tight correlation to the diffusion the surface recombination is described in TCAD tools by the SRH formalism, with the sole difference that instead of a lifetimes the *surface recombination velocities* $s_{n,p}$ (see Eq. (17))[8,16,76,218] that depend on the interface trap density N_{it} are used.

$$R^{\mathrm{s}}_{\mathrm{SRH}} = \frac{(n_{\mathrm{s}} p_{\mathrm{s}} - n_{\mathrm{i}}^2)}{(n_{\mathrm{s}} + n_1)/s_{\mathrm{p}} + (p_{\mathrm{s}} + p_1)/s_{\mathrm{n}}} \tag{17}$$

$$s_{\mathrm{n}} = \sigma_{\mathrm{ns}} v_{\mathrm{th}} N_{\mathrm{it}} \tag{18}$$

$$s_{\mathrm{p}} = \sigma_{\mathrm{ps}} v_{\mathrm{th}} N_{\mathrm{it}} \tag{19}$$

As inputs, the TCAD tools expect s_{n} and s_{p}. Their dependency on the crystal faces[48,216,241–243] is not included in state-of-the-art simulation tools yet. Some, however, provide the possibility to model a doping dependency but we found no reliable data for 4H-SiC in literature.

The surface recombination velocity again depends on the surface quality and the neighboring material. Therefore, there have been studies to improve the material quality[1,216,240,244–250] by differing growth mechanisms or by irradiation[106]. Even a more elaborate model using trap regions inside the band gap was developed[251–253].

The temperature dependency of the surface recombination velocity was described by Klein *et al.* [230], Kato *et al.* [242] and can be modeled by Eq. (20)[254,255]. $-E_{\mathrm{bb}}$ denotes the band bending near the surface, which leads to accumulation of charge carriers of one type at the surface and effectively repelling the other type[30,255].

$$s_{\mathrm{eff}}(T) = s_{\infty} \exp\left(\frac{-E_{\mathrm{bb}}}{k_{\mathrm{B}} T}\right) \tag{20}$$

2. *Bimolecular Recombination*

The term R_{bim} denotes the recombination rate due to the interaction of two particles, which can be described by Eq. (21)[153,218] with B the bimolecular recombination coefficient[5,13].

$$R_{\mathrm{bim}} = B(np - n_{\mathrm{i}}^2) \tag{21}$$

We want to highlight that in literature this type of recombination is sometimes reduced to the radiative band-to-band recombination process emitting a photon[9]. Since 4H-SiC is an indirect semiconductor (see **??**) and this process, thus, always requires a phonon to absorb the momentum, radiative recombination is less important[4,5,13,19,49]. In addition to the radiative band-to-band recombinations R_{bim} includes (i) recombinations between donor-acceptor pairs (DAP)[11,256] (ii) the

recombination of a charge carrier from the conduction/valence band and an unionized dopant (e.g. e-A)[256,257] and (iii) the recombination of excitons (see **??**)[9].

Trap-assisted Auger recombination (TAA)[258] is also a bimolecular process but it is handled in differing fashions in the literature. TAA denotes the process when an electron (hole) interacts with a trap (capture resp. emission) and the additional/missing energy is exchanged with a particle of the same kind. Since two particles are involved many authors include this process in the bimolecular recombination coefficient[9,12,259,260], some in the Auger process[181,261], whereat others add it to SRH[14,258,262]. The latter is also the only option to model TAA in existing TCAD tools, however, for 4H-SiC no suitable values have been found. TAA is also used to explain the rather high values of the bimolecular recombination coefficient[9]. We want to highlight that in the literature a lot of additional trap-assisted Auger processes are mentioned, which have to be handled with care. For example, the excitonic Auger capture process described by Hangleiter[17] is denoted as "markedly different" from TAA and should be regarded as an alternative explanation for multi-phonon/SRH recombination[259]. Booker *et al.*[74] describe a trap-Auger mechanism, where the energy of a hole captured in a neutral $EH_{6,7}$ trap, which contains two electrons, is transferred to the other electron in the trap, ejecting it to the conduction band.

Little data about the temperature dependency of B is available. Tawara *et al.*[37] present measurements for six different temperatures and state, that the value stays constant. If one would assume, however, the first data point as flawed, a clear decrease would be visible. Ščajev *et al.*[263] state that the radiative recombination coefficient doubles in the range of 10–1000 K, which could also lead to an increase of B. For more definite statements, however, further investigations would be necessary.

3. Auger Recombination

At last, the term R_{Auger}, also called Auger recombination "(first discovered in atomic systems by Pierre Auger; soft g, please, the gentleman is French not German!)"[14], denotes a three particle interaction where the excessive resp. missing energy and momentum is taken from/transferred to a third particle (either hole or electron). This process is an intrinsic property of the material[8] and dominates for high excessive charge carrier densities. It is described by Eq. (22)[62,153,218,264] where C_{n} denotes the energy transfer to an electron and C_{p} the transfer to a hole[12].

$$R_{\text{Auger}} = (C_{\text{n}} n + C_{\text{p}} p)(np - n_{\text{i}}^2) \tag{22}$$

The Auger recombination coefficients are also temperature dependent[37,265]. Galeckas *et al.* [12] describes this effect by Eq. (23).

$$C_\mathrm{n} + C_\mathrm{p} = \gamma_{30} \exp\left(-\frac{\alpha(T - 300\,\mathrm{K})}{k_\mathrm{B} T}\right) \tag{23}$$

Ščajev and Jarašiūnas[4] received quite different results, as they argue that Galeckas *et al.* [12] did not consider the in-depth profile. Instead the authors propose the model in Eq. (24), with $B_\mathrm{CE}(T) \propto T^{-1.5}$ the Coulomb enhancement coefficient and a_SC the screening parameter.

$$C(T, \Delta_N) = \left(C_0 + \frac{B_\mathrm{CE}(T)}{\Delta_N}\right) / \left(1 + \frac{\Delta_N}{a_\mathrm{SC} \times T}\right)^2 \tag{24}$$

Ščajev *et al.* [9] mentioned a dependency of C with $\Delta_N^{-0.3}$ due to the screening of the Coulomb enhancement coefficient and Tanaka, Nagaya, and Kato[261] derived a dependency of $\Delta_N^{-0.68}$. The differences can be explained due to a deviating fitting.

Also the model used to describe the temperature induced changes of the Auger recombination coefficients in Silicon (shown in Eq. (25)) is used[151,266].

$$C_\mathrm{n,p} = \left(A_\mathrm{n,p} + B_\mathrm{n,p}\left(\frac{T}{T_0}\right) + D_\mathrm{n,p}\left(\frac{T}{T_0}\right)^2\right)\left[1 + H_\mathrm{n,p} \exp\left(-\frac{n, p}{N_\mathrm{0n,p}}\right)\right] \tag{25}$$

4. *Analysis*

In the sequel we want to analyze the presented equations and extract further useful information. Some reader might have already noticed that all recombination rates contain the multiplicative factor shown in Eq. (26) with n_0, p_0 the intrinsic- and Δ_n, Δ_p the excessive carrier concentrations for electrons resp. holes.

$$(np - n_\mathrm{i}^2) = (n_0 + \Delta_n)(p_0 + \Delta_p) - n_0 p_0 = n_0 \Delta_p + p_0 \Delta_n + \Delta_n \Delta_p \tag{26}$$

For a device without traps, i.e., $\Delta_p = \Delta_n = \Delta$, and for low-level (ll, $\Delta \ll n_0, p_0$) resp. high-level (hl, $\Delta \gg n_0, p_0$) injections the models can be significantly simplified[8,15,16,153,259], which is also important to correctly interpret the measurements results[8]. After a short calculation we get, due to $R = \Delta_N / \tau_\mathrm{r}$ (see Eq. (2)), for low-level injections the results shown in Eq. (27) and high-level in

Eq. (28).

$$\tau_{\mathrm{SRH}}^{\mathrm{ll}} = \frac{\tau_{\mathrm{p}}(n_0+n_1)+\tau_{\mathrm{n}}(p_0+p_1)}{n_0+p_0} \tag{27a}$$

$$\tau_{\mathrm{bim}}^{\mathrm{ll}} = \frac{1}{B(n_0+p_0)} \tag{27b}$$

$$\tau_{\mathrm{Auger}}^{\mathrm{ll}} = \frac{1}{(C_{\mathrm{n}}n_0+C_{\mathrm{p}}p_0)(n_0+p_0)} \tag{27c}$$

$$\tau_{\mathrm{SRH}}^{\mathrm{hl}} = \tau_{\mathrm{p}}+\tau_{\mathrm{n}} \tag{28a}$$

$$\tau_{\mathrm{bim}}^{\mathrm{hl}} = \frac{1}{B\Delta} \tag{28b}$$

$$\tau_{\mathrm{Auger}}^{\mathrm{hl}} = \frac{1}{(C_{\mathrm{n}}+C_{\mathrm{p}})\Delta^2} \tag{28c}$$

The results show that for SRH and Auger at high-injection levels always the sum of electron and hole parameters is achieved, whereat $\tau_{\mathrm{p}}+\tau_{\mathrm{n}}$ in Eq. (28) is also denoted as ambipolar lifetime[130,267]. Separate measurements are only possible at low-injection level and with doped semiconductors, i.e., either $n_0 \gg p_0, p_1, n_1$ or $p_0 \gg n_0, n_1, p_1$. In that case one of the summands gets significantly smaller and can be ignored.

For doped semiconductors we can rewrite the high-level injection results from Eq. (28) as shown in Eq. (29)[5,8–10,12–14,88,153,259], which highlights that the introduced recombination terms actually represent a polynomial approximation of the recombination rate up to degree three in respect to the excess carrier concentration.

$$\begin{aligned} R = \Delta\tau^{-1} &= \Delta(\tau_{\mathrm{SRH}}^{-1}+\tau_{\mathrm{bim}}^{-1}+\tau_{\mathrm{Auger}}^{-1}) \\ &= A\Delta+B\Delta^2+C\Delta^3 \end{aligned} \tag{29}$$

Note that for no excess charge carriers, i.e., $\Delta = 0$, also $R = 0$. For relatively low excess charge carrier densities the SRH term dominates while for high densities the Auger process is most important.

All these simplifications are only valid for $\Delta \geq 0$. If $(np - n_{\mathrm{i}}^2) < 0$ the recombination rate becomes negative, meaning that according to Eq. (1) charge carriers are generated. The corresponding rate of change can be described by using the so-called generation lifetime τ_{g}[7,16,153,215,268].

However, a simple inversion is only meaningful for the SRH and Auger descriptions, because for bimolecular generation incoming photons are mandatory[7]. We want to highlight that often impact ionization (see **??**) is stated as the inverse of Auger recombination[15,21,269]. However, Selberherr[218] states that there is a difference, namely the source of the energy. While impact ionization

requires high current densities the inverse process of the Auger recombination only requires high charge carrier concentrations with negligible current flow. Due to these facts the recombination rates in TCAD tools, specifically bimolecular and Auger, often get deactivated when they drop below zero. For the Auger process some simulation tools allow to explicitly enable generation while the optical generation of charge carriers (inverse of bimolecular recombination) is implemented separately in the tools.

B. Results & Discussion

In the sequel the results of our analyses are presented. We did not include values when solely the effective lifetime was proposed[47,268,270] or if it was not possible to clearly distinguish τ_n and τ_p[9,271,272]. We also do not show values for different faces inside the crystal[36,242].

1. SRH Lifetime

The recombination lifetime can be measured either optically or electrically. Commonly used optical techniques include photoluminescence decay (PLD)[50,114,221], (transient) (time-resolved) free carrier absorption ((T)(TR-)FCA)[4,9,10,12,24,49,259,263,273,274], electron beam induced current (EBIC)[23], time-resolved photoinduced absorption (TRPA)[12], time-resolved photoluminescence (TRPL)[6,25,32,35–37,49,52,196,209,230,275], time-resolved transient absorption (TRTA), transient absorption spectroscopy (TAS)[5], four wave mixing (FWM)[3], low-temperature photoluminescence (LTPL)[221,226], capacitance transient (C-t)[245], differential transmittivity (DT)[226] and (microwave) photoconductance decay ((μ)-PCD)[1,2,6,26–31,33,34,40–42,44,49,88,128,216,242,249,271,272,276–279]. For electrical measurements possible techniques are reverse recovery (RR)[232,280–282], thyristor turned off gate current (TTOGC)[55], short-circuit current/open-circuit voltage decay (SCCVD/ OCVD)[13,56,181,229,283–2 diode current density (DCD)[287–289], bipolar transistor emitter current (BTEC)[290] and diode forward voltage degradation (DFVD)[291]. Also utilized is fitting to measurement results in literature (FT)[292–294] or simulations (SIM)[57].

The achieved lifetime values depend on the utilized method[181]. Overall it has to be assured that the same quantity is measured, and that injection level and temperature are taken into account[181]. For example, Kato, Mori, and Ichimura[295] claim that μ-PCD tends to overestimate the carrier lifetimes in high injection conditions and, similarly,Tawara *et al.*[196] experienced that μ-PCD to

TABLE I. Electron lifetime results. Column *inj.* denotes the carrier injection level, i.e., low (ll) resp. high (hl), and column *excess* the exact amount. A *y* in column *impr.* highlights that the shown value is the highest lifetime achieved in an optimization process.

ref.	τ_n [s]	dop	conc. [$1/cm^3$]	T [K]	inj.	excess [$1/cm^3$]	impr.	method
[Agar01][55]	6×10^{-7}	p	7×10^{14}	293	hl	-	-	TTOGC
[Ivan06a][57]	6.6×10^{-8}	p	2×10^{17}	300	-	-	-	SIM
[Alba10][13]	8×10^{-9}	-	2.04×10^{17}	300	-	-	-	OCVD
[Haya11][1]	1.3×10^{-6}	Al	9×10^{14}	-	ll	1.5×10^{14}	y	uPCD
[Haya11a][2]	1.6×10^{-6}	p	9×10^{14}	300–525	ll	1.5×10^{14}	y	uPCD
[Haya12][26]	1.7×10^{-6}	p	5.6×10^{14}	-	ll	1×10^{15}	y	uPCD
[Okud13a][33]	3.1×10^{-7}	Al	1×10^{18}	300	-	9.1×10^{15}	-	uPCD
[Dibe14][287]	1×10^{-9}	-	-	-	hl	-	-	DCD
[Okud14][34]	1×10^{-5}	Al	2×10^{14}	300	-	3.6×10^{16}	y	uPCD
[Liau15][226]	2×10^{-8}	Al	1×10^{17}	300	hl	-	-	DT
[Okud16][278]	1.2×10^{-5}	Al	1×10^{15}	300	-	3.6×10^{14}	y	uPCD
[Hase17][288]	4×10^{-7}	p	8×10^{14}	-	-	-	-	DCD
[Kato20][242]	1.2×10^{-6}	Al	6×10^{14}	300	ll	-	y	uPCD
[Koya20][291]	1.3×10^{-7}	p	1×10^{19}	-	-	-	-	DFVD
[Maxi23][293] [a]	6×10^{-6}	-	-	-	-	-	-	FT
[Zhan23a][40]	3.14×10^{-6}	Al	2×10^{14}	300	-	-	y	uPCD

[a] value fitted to measurements by Kimoto *et al.* [128]

achieves longer lifetimes than the ones by TRPL. Deviations might also results from improper measurement setups, because, e.g., OCVD is limited to low and high injection regions only[13]. For more detailed information, e.g., which carrier lifetime is extracted from the decay time for high and low injection by each measurement technique, the interested reader is referred to the dedicated literature[49,130].

A wide range of values for τ_n (see Table I) and τ_p (see Table II) are available in literature, whereat much more results for holes are available. In early days, Bakowski, Gustafsson, and Lindefelt[67] still had to use Silicon values due to a lack of data but since then many investigations have been conducted. Despite the wide range of values, the relation $\tau_n = 5\tau_p$, which was originally

used for Si, is still utilized[124,146,227,296–302]. Recently, $\tau_n = \tau_p$ was observed as well[178,239,303–307].

TABLE II: Hole lifetime results. Column *inj.* denotes the carrier injection level, i.e., low (ll) resp. high (hl), and column *excess* the exact amount. A *y* in column *impr.* highlights that the shown value is the highest lifetime achieved in an optimization process.

ref.	τ_p [s]	dop	conc. [1/cm^3]	T [K]	inj.	excess [1/cm^3]	impr.	method
[Kord96][50]	2.1×10^{-6}	n	-	300	-	-	-	PLD
[Gale97][12]	2.6×10^{-7}	N	5×10^{15}	-	hl	-	-	TRPA
[Neud98][281]	7×10^{-7}	N	$(2–4) \times 10^{16}$	-	-	-	-	RR
[Gale99a][46]	5×10^{-7}	N	<1e16	-	-	-	-	FCA
[Ivan99][56]	6×10^{-7}	n	6×10^{14}	293	hl	-	-	OCVD
	3.8×10^{-6}	n	6×10^{14}	550	hl	-	-	OCVD
[Kimo99][280]	3.3×10^{-7}	N	5×10^{14}	-	-	-	-	RR
[Udal00][282]	5.2×10^{-8}	n	$(0.9–2.6) \times 10^{15}$	-	-	-	-	RR
[Cheo03][245]	1×10^{-6}	N	$(1–1.8) \times 10^{16}$	300	-	-	-	Ct
[Dome03][290]	3.5×10^{-9}	n	8.6×10^{15}	-	hl	-	-	BTEC
[Zhan03][209]	3×10^{-7}	n	$(1–200) \times 10^{14}$	-	-	-	-	TRPL
[Levi04][285]	1.55×10^{-6}	n	3×10^{14}	293	hl	-	-	OCVD
[Tawa04][196]	$(0.26–6.8) \times 10^{-6}$	n	$(1.8–34) \times 10^{14}$	300–500	-	$(1.1–4.2) \times 10^{15}$	-	TRPL
[Resh05][181]	1×10^{-6}	n	7×10^{15}	-	-	-	-	OCVD
[Huh06][114]	5×10^{-7}	n	1×10^{14}	-	ll	1×10^{13}	-	PLD
[Ivan06b][284]	3.7×10^{-6}	n	2×10^{14}	300	hl	-	-	OCVD
[Jenn06][23]	1.55×10^{-5}	N	5×10^{15}	-	-	-	-	EBIC
[Neim06][3]	1.2×10^{-8}	N	1×10^{16}	-	-	-	-	FWM
[Dann07][88]	2.5×10^{-6}	N	1.5×10^{15}	300	hl	$(2–20) \times 10^{16}$	y	uPCD
[Stor07][35]	2.18×10^{-7}	N	5×10^{15}	300	-	-	y	TRPL
[Udal07][232]	4.4×10^{-9}	n	7×10^{15}	297	-	-	-	RR
[Kimo08][30]	8.6×10^{-6}	n	$(1–2) \times 10^{15}$	-	ll	5×10^{12}	-	uPCD
[Stor08][36]	9.9×10^{-7}	n	1×10^{14}	300	-	-	y	TRPL
[Hiyo09][41]	1.62×10^{-6}	N	$(1–5) \times 10^{15}$	-	hl	$(2–20) \times 10^{16}$	y	uPCD
[Resh09][283]	2.13×10^{-6}	n	$(1–1.2) \times 10^{15}$	-	hl	-	-	OCVD
[Alba10][13]	1.5×10^{-11}	-	2.21×10^{17}	300	-	-	-	OCVD
[Kimo10][31]	9.5×10^{-6}	n	$(0.9–1) \times 10^{15}$	-	hl	$(5–50) \times 10^{15}$	y	uPCD
[Kimo10a][249]	1.31×10^{-5}	N	7×10^{14}	-	hl	$(5–50) \times 10^{15}$	y	uPCD
[Klei10][230]	>100e-6	N	<1e16	222	ll	2×10^{14}	-	TRPL
[Miya10][277]	1.85×10^{-5}	N	7×10^{13}	-	ll	3×10^{12}	-	uPCD
[Haya11a][2]	4.6×10^{-6}	n	1.2×10^{15}	300–525	ll	1.5×10^{14}	y	uPCD
[Donn12][292] [308]	2.4×10^{-7}	N	1×10^{16}	-	-	-	-	FT
[Ichi12][27]	3.32×10^{-5}	N	$(3–8) \times 10^{14}$	-	-	$(1–10) \times 10^{15}$	y	uPCD
[Kawa12][29]	6.5×10^{-6}	n	1×10^{16}	300	-	1×10^{16}	y	uPCD
[Lilj13][25]	1.6×10^{-6}	N	3×10^{15}	300	ll	-	y	TRPL
[Miya13][32]	1.3×10^{-5}	N	$(2–3) \times 10^{14}$	300	-	-	y	TRPL
[Scaj13][4]	5.5×10^{-7}	n	4×10^{14}	-	ll	-	-	FCA
[Dibe14][287]	1×10^{-8}	-	-	-	hl	-	-	DCD
[Usma14][294] [309]	1.3×10^{-6}	n	2×10^{14}	-	-	-	-	FT

[Chow15][276]	2.5×10^{-6}	n	2.5×10^{14}	300	hl	-	-	uPCD
[Kaji15][28]	2.16×10^{-5}	N	2×10^{14}	-	-	1×10^{14}	y	uPCD
[Suva15][273]	3.5×10^{-7}	N	8×10^{15}	-	hl	6×10^{17}	-	FCA
[Puzz16][289]	1×10^{-6}	n	3×10^{15}	400	-	-	-	DCD
[Sait16][279]	2.6×10^{-5}	n	1×10^{14}	300	-	1.8×10^{17}	-	uPCD
[Tawa16][37]	3×10^{-7}	N	7.7×10^{17}	300	ll	-	-	TRPL
[Tsuc16][275]	2.6×10^{-6}	n	1.4×10^{14}	-	-	-	-	TRPL
[Ayed17][22]	2×10^{-5}	N	1×10^{15}	-	-	-	y	-
[Lilj17][221]	3.5×10^{-6}	N	1.3×10^{15}	300	ll	-	-	PLD
[Fang18][5]	$(11\pm3)\times10^{-9}$	N	9.1×10^{18}	300	-	-	-	TAS
[Kimo18][128]	0.000 11	n	1×10^{14}	-	-	$(1–10)\times10^{14}$	y	uPCD
[Cui19][42]	1.05×10^{-6}	N	2×10^{13}	300	-	4×10^{16}	-	uPCD
[Mura19][52]	9.9×10^{-6}	N	1×10^{15}	293	ll	-	-	TRPL
[Kato20][242]	7×10^{-7}	N	$(1–10)\times10^{15}$	300	ll	-	y	uPCD
[Naga20][10]	1×10^{-5}	N	1×10^{18}	293	hl	1.5×10^{18}	-	TR-FCA
[Sapi20][229]	1.9×10^{-5}	n	1×10^{16}	300	hl	-	-	OCVD
[Erle21][44]	5×10^{-6}	N	$(5–10)\times10^{14}$	-	ll	-	-	uPCD
[Mura21][256]	1.4×10^{-7}	N	2×10^{17}	293	ll	7×10^{14}	-	TRPL
[Maxi23][293] [310]	2×10^{-6}	-	-	-	-	-	-	FT
[Kato24][216]	4.5×10^{-6}	n	1×10^{15}	300	-	$(5–50)\times10^{15}$	-	uPCD
[Sozz24][286]	6.09×10^{-6}	n	1.5×10^{14}	298	hl	4×10^{17}	-	OCVD

This overview is already a simplification, as many publications present values for multiple operating conditions, i.e., temperature, doping concentration or excess carrier concentration. Only the best achieved values are shown here. For example Hayashi *et al.*[2] provides measurements over injection level for two temperatures (300 K and 525 K). Grivickas *et al.*[24] show measurements with different intensities but no actual values. The lifetime depends on all the mentioned parameters simultaneously, which makes a proper presentation very challenging. Therefore, we highlight each single dependency separately. For example, we depict the measured lifetimes with the respective doping densities if specified in the paper (see Fig. 2). A decreasing lifetime with increasing doping density can be observed, but no actual difference between electron and hole lifetime. However, all these values were most probably measured with differing excess carrier concentrations and at deviating temperatures.

Note that we explicitly show the injection level during the measurements, because for a high level only the sum $\tau_n + \tau_p$ is achieved[114,273] (cp. Eq. (28)). Consequently, it can be expected that the lifetime increases when going from low to high injection level, until it eventually starts to decrease when the bimolecular or Auger recombination become dominant. This effect was explicitly shown in literature[1,2,26,216]. Despite that, Kimoto *et al.*[311] stated in 2016 that the injection-level

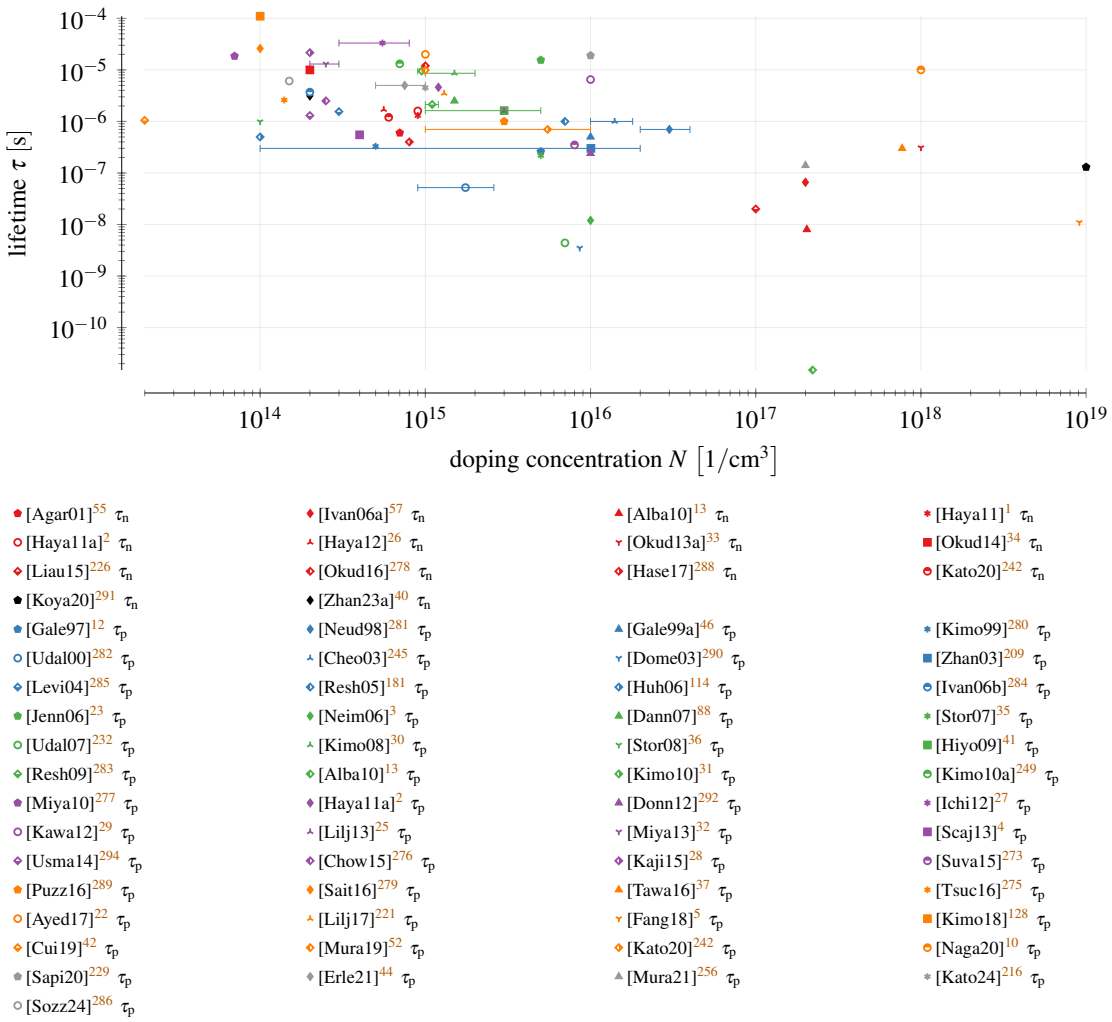

FIG. 2. Measurements of the minority charge carrier lifetime for the respective doping densities.

dependence of SRH lifetimes is not known in SiC, calling for further research. In contrast, Ščajev and Jarašiūnas[4] stated that the lifetime is almost injection level independent. Very different results were reported by Tawara *et al.*[37], who saw a lifetime decrease, eventually approaching a constant value.

For thin samples the achieved recombination rate has diminishing resemblance to the bulk contribution $R^{\mathrm{b}}_{\mathrm{SRH}}$[8], since the surface recombination $R^{\mathrm{s}}_{\mathrm{SRH}}$ dominates. In any case it is always important to consider the impact of the surface during measurements[49]. Optimally the surface contribution is measured separately[230,277,280,281], which is, however, not always practical[49]. For sufficiently thick samples $R^{\mathrm{b}}_{\mathrm{SRH}}$ can be determined directly, however, this demands extraordinarily thick ones[8]: Depending on the surface recombination velocity, thicknesses in the range of mm or even cm would be required[16].

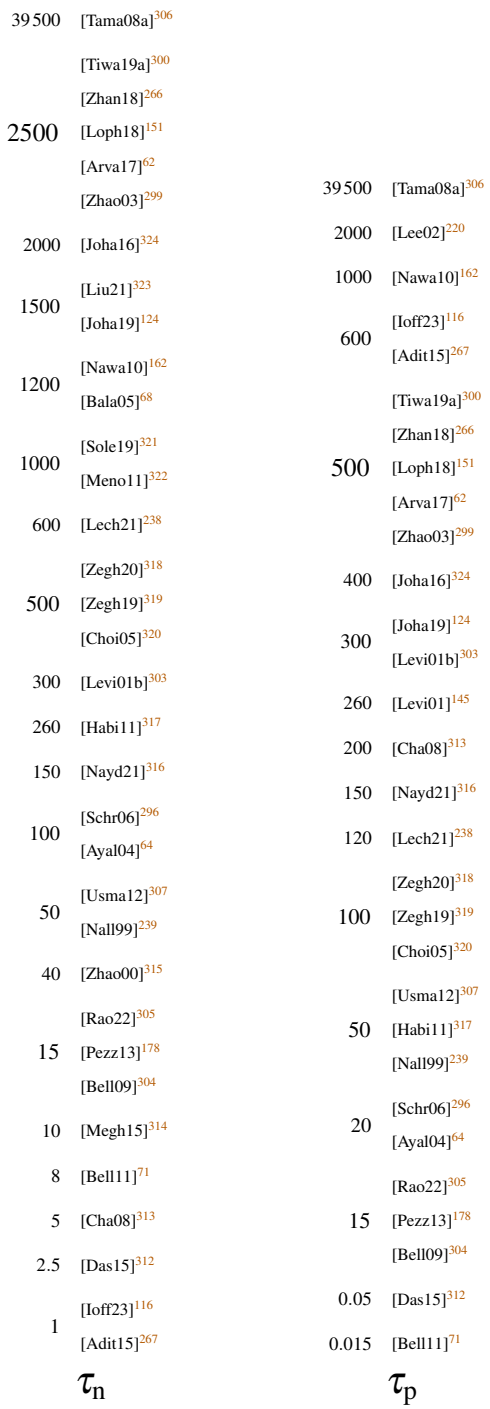

FIG. 3. Lifetime values referenced in literature.

Finally, we also investigated the values that are referenced in literature (see Fig. 3). Overall, there are only very few references compared to the amount of fundamental investigations. This shows that the lifetime depends on many parameters and may differ considerably among samples. As mentioned before, very similar values for τ_n and τ_p are encountered.

TABLE III. Parameters for doping dependency according to the Scharfetter relation in Eq. (9). are fittings to suitable measurements and fittings to the excessive carrier concentrations.

	electrons		holes	
ref.	N_{ref}	γ	N_{ref}	γ
	$[1/\text{cm}^3]$	[1]	$[1/\text{cm}^3]$	[1]
[Ruff94][227] [a]	3×10^{17}	0.3	3×10^{17}	0.3
[Nall99][239] [c]	1×10^{16}	1	1×10^{16}	1
[Levi01b][303]	7×10^{17}	1	-	-
[Choi05][320] [b]	5×10^{16}	1	5×10^{16}	1
[Donn12][292] [b] [f]	2×10^{18}	1.9	2×10^{18}	1.9
[g]	4×10^{18}	1.4	4×10^{18}	1.4
[Liau15][226] [e]	5×10^{18}	1.2	-	-
[Lech21][238]	7×10^{16}	1	7×10^{16}	1
[Maxi23][293] [d]	5×10^{15}	0.55	5×10^{15}	0.67

[a] Silicon data from multiple sources combined
[b] References Harris and Inspec [104] but no data found there. According to Albanese [13] based on Silicon data.
[c] fit to lifetime over excessive charge carrier densities[12]
[d] fit to measurements for changing doping concentration by Kimoto *et al.* [128]
[e] fit to own measurements for changing doping concentration
[f] fit to lifetime over excessive charge carrier densities[325]
[g] fit to lifetime over excessive charge carrier densities[3]

2. *Doping Dependency of SRH Lifetime*

The decrease of the minority carrier lifetimes with doping concentration (cp. Fig. 2) is described by additional recombination centers (Scharfetter relation, Eq. (9)). We acquired multiple parameter sets (see Table III) for the latter. In the 1990s no values for 4H-SiC values were available, so Ruff, Mitlehner, and Helbig [227] settled for a combination of Silicon based values gathered from various sources. Surprisingly, these parameters are still the most commonly ones used in literature (see Fig. 5). While some publications are well aware that Silicon data are used[64,76,251] this information seems to was lost over the years.

The only fittings we could actually trace back to measurements of τ_{SRH} with varying doping concentration are the investigations by Liaugaudas *et al.* [226], who did their own differential transmittivity measurements, and Maximenko [293], who fitted to the results of the μ-PCD measure-

ments by Kimoto *et al.* [128]. We also found dedicated measurements by Lilja *et al.* [221] and Murata *et al.* [256], which, seemingly, were not yet used in any fitting. For other publications[238,303,320] we were simply unable to retrace the origin of the values, although often explicit references were provided.

There are often confusions between the doping and the excess charge carrier concentration. While both lead to a decrease in lifetime with increasing concentration the physical process causing that are fundamentally different. While more doping causes more recombination centers, more excess charge carrier lead to a higher contribution of bimolecular and Auger recombination. For example, Kimoto *et al.* [128] adds bimolecular and Auger coefficients to a plot over the doping concentration. In addition, fittings of the Scharfetter relation versus an increasing excess charge carrier concentration were proposed[239,292]. Although we believe that such a fitting is not reasonable we included the respective results in the table but highlighted them accordingly.

In a double logarithmic plot (see Fig. 4) the differences are well observable. There are differences in the onset of lifetime degradation, i.e., the value N_{ref}. For a specific reduction of the lifetime the respective doping can vary by up to three orders of magnitude. Also the rate of change deviates, whereat for the Silicon based model proposed by Ruff, Mitlehner, and Helbig [227] a significantly lower transition rate is observable. Interestingly also the models based on the measurements differ quite significantly. We also added some measurement result, which show significant variations and thus also lead to deviating fitting results.

In the literature the values by Ruff, Mitlehner, and Helbig [227] are still heavily utilized to describe the doping dependency (see Fig. 5), although these are not based on 4H. The dedicated fittings to 4H measurements have not been referenced so far.

3. Temperature Dependency of SRH Lifetime

There are various fantastic investigations on the changes of the lifetime with temperature[216,242] some even distinguishing between surface and bulk lifetime[230]. Even various excess charge carriers in the range $(1\text{–}1000) \times 10^{16}\,1/\mathrm{cm}^3$ were investigated[257], whereat the behavior varies.

In the literature predominantly the power law descriptions of Eq. (10) and Eq. (11) are used (see Table IV). The values for the exponent α thereby commonly vary between 1 and 2. Udal and Velmre [232] stated a fitting in two regions, as the lifetime started to increase faster above 700 K. Sapienza *et al.* [229] achieved $\alpha = 1.5$ which is exactly the value expected for Coulomb-attractive

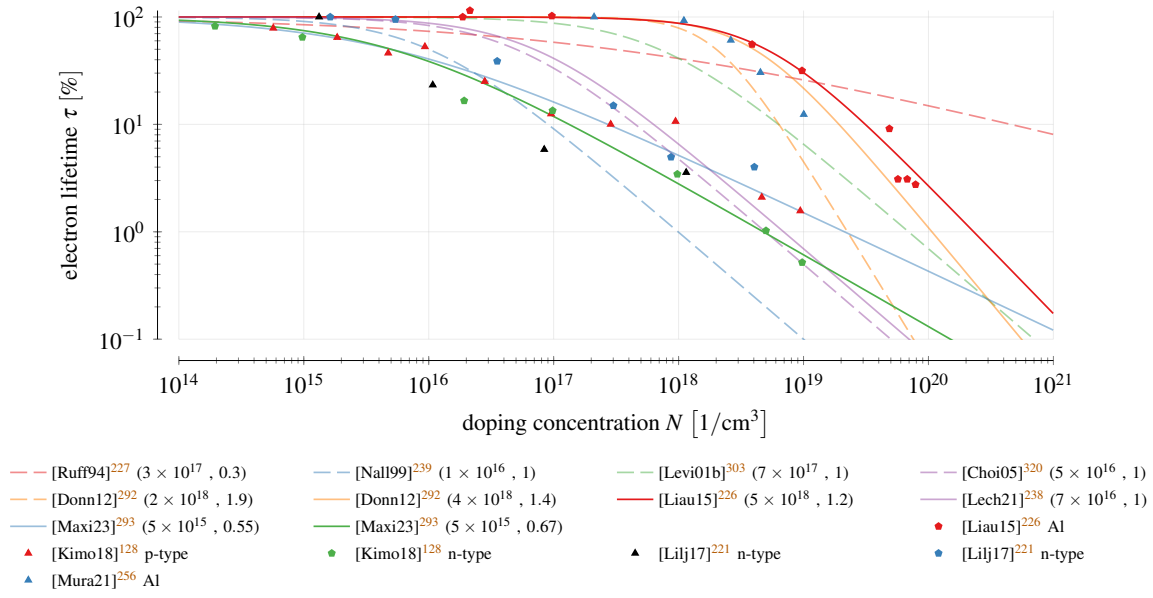

FIG. 4. Doping dependency according to the Scharfetter relation in Eq. (9). In brackets are the values for (N_{ref}, γ). Only one graph is shown if electron and hole parameters are equal (see Table III). Solid non-opaque lines represent fitting to 4H-SiC measurement data.

charge recombination centers[232].

More complex is the situation for the value $\alpha_{\mathrm{n,p}} = 5$[68,162,294]. Although we stated Balachandran, Chow, and Agarwal[68] as the origin here we were actually not able to determine the origin of this parameter. We suspect that it might have been the default value of a TCAD tool but we could not even confirm that. In the same sense we were not able to pinpoint the origin of the value $C = 2.55$[239] for Eq. (14). Although Lechner[238] provided a reference[333] we were not able to find anything in there either.

For the exponential based approaches the value of E_{act} is between 110–125 meV. Please note that for Eq. (15) a lot of parameters have been presented[238]. We calculated the average from the single sets and achieved the values shown in Eq. (30), where an initial increase followed by a decrease in the lifetime is visible.

$$T_{\mathrm{coeff}} = 0.666, \quad \alpha_\tau = 0.06385, \quad \beta_\tau = 5.716 \tag{30}$$

A comparison of the single models (see Fig. 6) shows that for all the lifetime increases with increasing temperature. We also added some temperature measurements and scaled them such that the room temperature values are around 1 µs, which we fixed. Please be aware that we had to dismiss the values by Lophitis *et al.*[151] as only the parameters but not the according equations

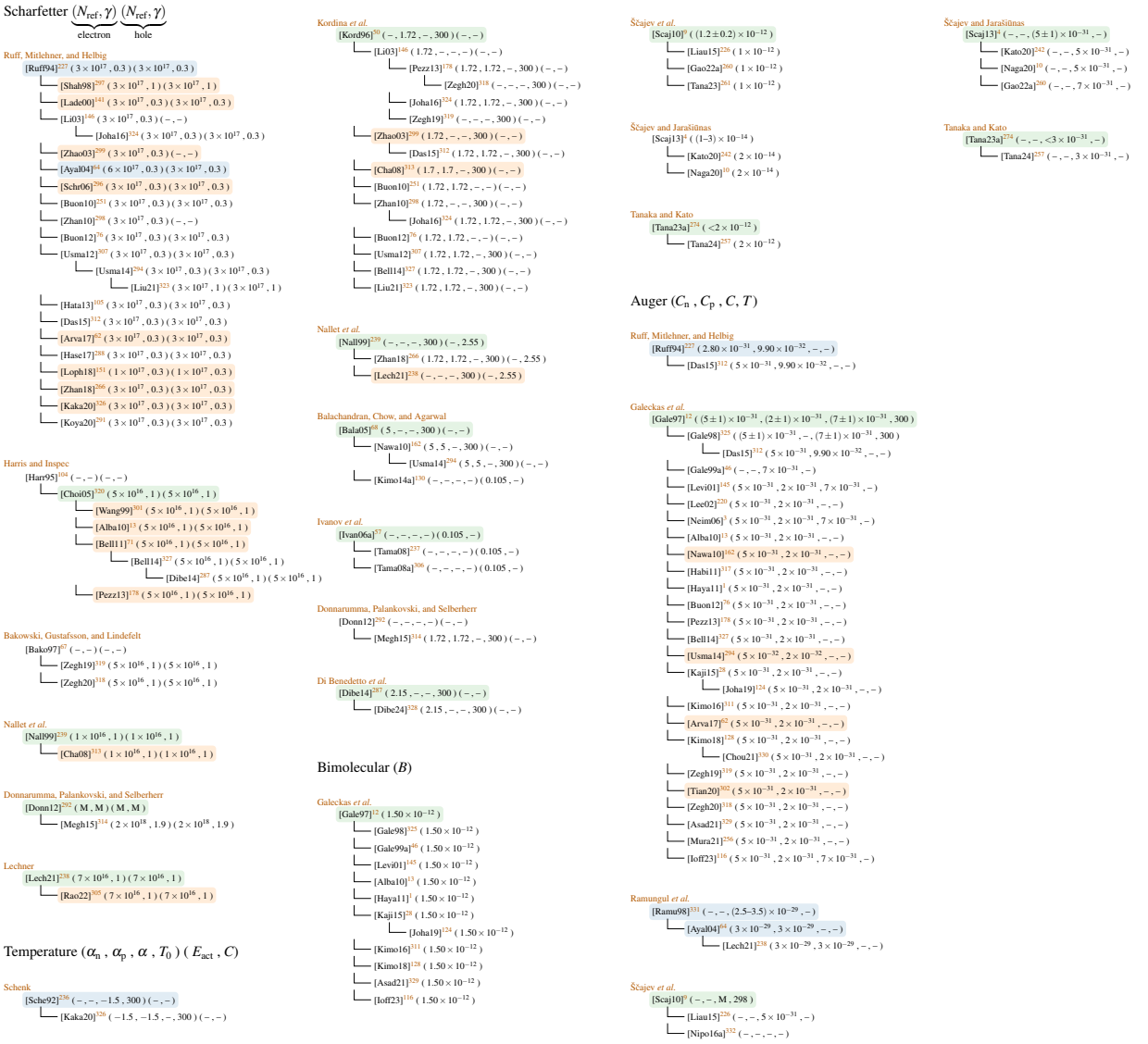

FIG. 5. Reference chain for charge carrier recombination. are fundamental investigations, research not focused on 4H and connections predicted from the used values.

were defined. We also do not show the results by Puzzanghera and Nipoti[289] as only minor deviations around the value at room temperature were achieved. Again we want to highlight that the plots have to be considered with a grain of salt as temperature changes depend on doping[256]. For high-level injection the sum of hole and electron lifetime is measured[276], which, again, can have a differing temperature dependency. Sapienza *et al.*[229] compares various sources in this respect[50,232,330].

The most prominent model in literature is the one proposed by Kordina *et al.*[50] (see Fig. 5), which, was, however, only characterized up to 200 K.

TABLE IV. temperature dependency parameters in literature. If only one value for $\alpha_{n,p}$ is stated no charge carrier specification was made in the publication.

ref.	α_n [1]	α_p [1]	T_0 [K]	E_{act} [eV]	C [1]	conf. [K]	equ.	method
[Kord96][50] [a]	-	1.72	300	-	-	0–200	(10)	PLD
[Ivan99][56] [d]	-	-	-	0.11	-	300–500	(12)	OCVD
[Nall99][239] [b]	-	-	300	-	2.55	-	(14)	-
[Udal00][282]	-	2.2	300	-	-	200–450	(10)	RR
[Agar01][55] [d]	-	-	-	0.12	-	300–500	(12)	TTOGC
[Bala05][68]	5	-	300	-	-	-	(10)	-
[Levi05][231] [d]	-	-	-	0.08	-	300–500	(12)	-
[Ivan06a][57] [e]	-	-	-	0.105	-	300–500	(12)	SIM
[Udal07][232]	-	1.9	300	-	-	300–700	(10)	RR
	-	4.4	300	-	-	700–1000	(10)	RR
[Scaj13][4]	-	-	-	0.125	-	70–1000	(13)	FCA
[Dibe14][287]	2.15	-	300	-	-	250–500	(10)	DCD
[Chow15][276] [c]	1.2		300	-	-	300–525	(10)	uPCD
[Rakh20][179]	-	8	450	-	-	100–700	(11)	-
	-	14	530	-	-	100–700	(11)	-
[Sapi20][229]	1.5		300	-	-	300–450	(10)	OCVD
[Tian20][302]	1.84	1.84	300	-	-	300–573	(10)	-
[Maxi23][293]	1.72	1.72	300	-	-	-	(10)	FT
[Sozz24][286]	1.7		298	-	-	300–450	(10)	OCVD

[a] fitting provided in citing articles (see Fig. 5), Sapienza *et al.* [229] fitted $\alpha = 1.9$

[b] default value of many simulation tools, according to Lechner [238] based on the research from Grasser *et al.* [333]

[c] fitting done by Sapienza *et al.* [229]

[d] fitting done by Udal and Velmre [232]

[e] fitting done by Tamaki *et al.* [237]

4. *Surface Recombination Velocity*

The surface recombination velocity is, as the name indicates, not a bulk property but depends on many parameters such as crystal faces, i.e., Si-, C-, a- or m-face[242,243], and interface treat-

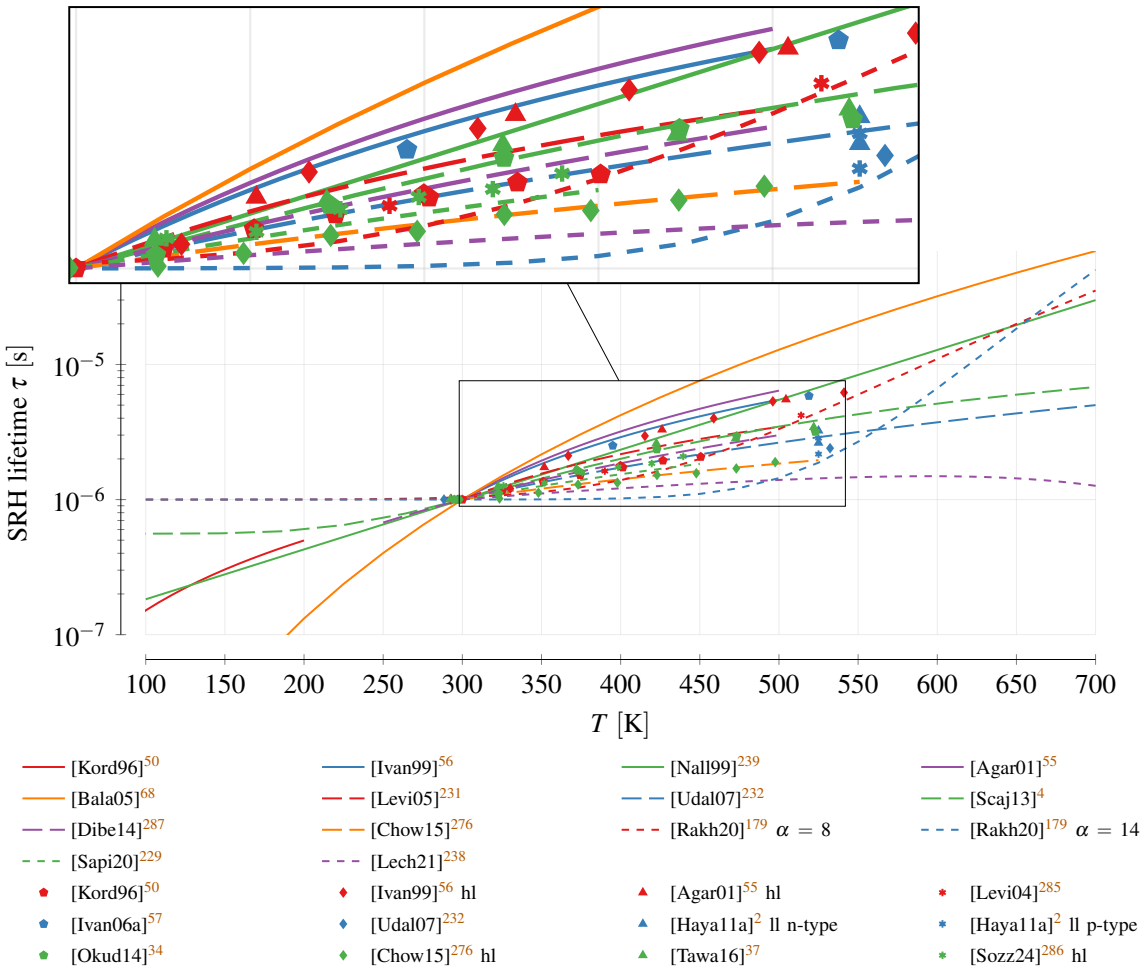

FIG. 6. Temperature Dependency of the SRH lifetime. Models are calibrated to hit 1 µs at 300 K. Measurement results are scaled such that 1 µs at (296 ± 4) K is achieved.

ment. For these reasons we will only roughly cover this topic. Interesting analyses of the surface recombination velocity were published by Ščajev *et al.*[9], Gulbinas *et al.*[240], Mori, Kato, and Ichimura[243].

In general, the surface recombination velocity has to be determined for each sample separately, due to the dependency on so many factors. It was pointed out that the injection level during measurements has an impact[9,16,216], which was possibly explained by a band banding near the interface[30]. Furthermore the surface recombination velocity is temperature dependent and increases with increasing temperature[230,242]. Overall, suitable values in literature are mainly based on dedicated investigations (see Table V) or are simply assumed, e.g., $s = 2.2 \times 10^5\,\mathrm{cm/s}$[250], $s = 1 \times 10^3\,\mathrm{cm/s}$[27].

For the surface recombination velocity additional measurement methods to the earlier explained

TABLE V. Surface recombination velocity. A *y* in column *impr.* indicates that the velocities were achieved at the end of an optimization process.

ref.	s [cm/s]	s_n [cm/s]	s_p [cm/s]	type[a]	impr.	method
[Gale97][12]	-	-	$4\times10^4/1\times10^4$	S/I	-	FCA
[Neud98][281]	-	-	5×10^4	M	-	RR
[Gale99a][46]	-	-	$(5–8)\times10^3$	S	y	FCA
[Kimo99][280]	-	-	5×10^4	M	-	CD
[Gale01][47]	$(5–500)\times10^3$	-	-	S	y	TA
[Cheo03][245]	-	-	1–1000	S	y	Ct
[Huh06][114]	-	-	2.50×10^3	S	-	TRPL
[Ivan06a][57]	4200	-	-	M	-	CD
[Neim06][3]	-	-	$(4\pm1)\times10^4$	S	-	FWM
[Griv07][265]	1×10^4	-	-	S	-	NFCD
[Klei08][49]	-	-	$(5–500)\times10^3$	S	y	TFCA
[Klei10][230]	-	-	400–6940	S	-	TRPL
[Scaj10][9]	$(2–13)\times10^3$	-	-	S	-	FCA
[Gulb11][240]	-	$(1.5–3)\times10^4$	$(1–100)\times10^4$	S	y	CPP
[Pour11][334]	-	1.07×10^3	$(1.07–57)\times10^3$	S	y	FCA
[Kato12][241]	-	-	$(1–2)\times10^3$	S	y	uPCD
[Mori14][243]	-	-	1500–7500	S	y	uPCD
[Suva15][273]	-	-	$(3.5–200)\times10^4$	S/I	y	FCA
[Asad18][246]	$(6–120)\times10^5$	-	-	M	y	CD
[Ichi18][248]	-	300–6000	200–2500	S	y	uPCD
[Kato20][242]	-	400–1950	150–750	S	y	uPCD
[Xian21][335]	$((6\pm7)–58\pm5)\times10^5$	-	-	M	y	CD
[Kato24][216]	-	-	100–2500	S	y	uPCD

[a] mesa structure (M), surface (S) or interface (I)

ones were used, for example colinear pump probe (CPP)[240], non-equilibrium free-carrier density (NFCD)[265], via the exponential prefactor in the current density (CD)[246,335] or reverse recovery (RR)[280]. By changing the thickness of the devices the impact of the surfaces and their recombination velocities was extracted[240] and sometimes even eliminated[277,281]. An effective bulk lifetime of more than 1 µs can, however, only directly measured within epitaxial layers thicker than 100 µm[130]. Due to the numerous growth parameters[334] a wide range of growth optimizations and surface treatments were proposed. Nevertheless, it seems that mechanically polishing surfaces, which leads to a significant roughness, delivers bad results (high velocities)[49]. The most recent values of $< 200\,\mathrm{cm/s}$ indicate high surface qualities. The amount of publications in the recent years also shows that this is an active field of research.

Publications referencing other publications often combine multiple values to achieve reasonable values, e.g., $s = (1\text{–}100) \times 10^3\,\mathrm{cm/s}$[116,145], $s = 2 \times 10^3\,\mathrm{cm/s}$[124], $s = 1 \times 10^4\,\mathrm{cm/s}$[226], $s = 1 \times 10^3\,\mathrm{cm/s}$[10,261], $s = 4 \times 10^4\,\mathrm{cm/s}$[4] and $s_\mathrm{n} = s_\mathrm{p} = 1 \times 10^5\,\mathrm{cm/s}$[290]. Finally, we want to highlight that the values for 4H and 6H are fairly similar[46].

5. *Bimolecular Recombination*

The bimolecular coefficient B was determined in several investigations (see Table VI). The most influential is the one of Galeckas *et al.* [12] (cp. Fig. 5), whereat Institute [116] states that the bimolecular factor is just an estimation. All the studies achieve a value of $(1.5 \pm 0.5) \times 10^{-12}\,\mathrm{cm^3/s}$. Exceptions were the investigation by Neimontas *et al.* [3], whose value is one order of magnitude bigger, and Murata *et al.* [256], who achieved 3-4 times higher values. In some investigations[4,10,242] deliberately only the radiative component with a value of $(1\text{–}3) \times 10^{-14}\,\mathrm{cm^3/s}$[263] was used for the bimolecular parameter B. The rather high values of B compared to the radiative part is explained by the additionally included trap-assisted Auger recombination[12] and electron-acceptor (e-A) recombination[256].

6. *Auger Recombination*

The most fundamental research on Auger coefficients in 4H-SiC was conducted by Galeckas *et al.* [12], who provided separate values for electrons (C_n) and holes (C_p). This is, so far, the only publications that did that. Following publications achieved, in general, similar combined coef-

TABLE VI. Fundamental investigations of the bimolecular recombination parameter.

ref.	B [cm^3/s]	T [K]	interval [$1/cm^3$]	method
[Gale97][12]	1.50×10^{-12}	300	$(1–1000) \times 10^{16}$	FCA
[Neim06][3]	$(3 \pm 1) \times 10^{-11}$	-	$(1–2000) \times 10^{16}$	FWM
[Scaj10][9]	$(1.2 \pm 0.2) \times 10^{-12}$	298	-	FCA
[Tawa16][37]	1.3×10^{-12}	300	$(3–70) \times 10^{17}$	TRPL
	0.94×10^{-12}	523	$(3–70) \times 10^{17}$	TRPL
[Mura21][256]	5.6×10^{-12}	293	$(1–100) \times 10^{17}$	TRPL
	4.5×10^{-12}	523	$(1–100) \times 10^{17}$	TRPL
[Tana23a][274]	$<2 \times 10^{-12}$	-	$(2–10) \times 10^{18}$	FCA

ficients (see Table VII) and thus confirmed the results. Solely Grivickas *et al.*[265] and Tawara *et al.*[37] derived parameters that are one order of magnitude smaller. Interesting are also the results by Tanaka, Nagaya, and Kato[261], who identified a dependency of the Auger parameter on the excess carrier concentration Δ_N. In the investigations by Murata *et al.*[256] Auger recombination turned out to be not important for an Aluminum doping concentration of $1 \times 10^{19}/\mathrm{cm}^3$ but considerable for a Nitrogen doping in mid $1 \times 10^{18}/\mathrm{cm}^3$ range.

We want to highlight that there were also some values based on 6H[331] used for 4H[64,238] and even some based on Silicon[227,297] for 4H[312]. Zhao *et al.*[315] simply assumed $C_\mathrm{n} = C_\mathrm{n} = 1 \times 10^{-28}\,\mathrm{cm}^6/\mathrm{s}$. For the results presented by Tawara *et al.*[37] we concluded from the description of samples and measurement (low injection and highly n-doped material) that C_n was measured and added it appropriately to the table.

For a comparison of the temperature dependency models in Eq. (23) and Eq. (24) we use the parameters shown in Eq. (31), Eq. (32) and Eq. (33).

$$\alpha = 0.45\,\mathrm{meV/K} \tag{31}$$

$$B_\mathrm{CE}(T) = 3.5 \times 10^{-9} T^{-3/2}\mathrm{cm}^3/\mathrm{s} \tag{32}$$

$$a_\mathrm{SC} = 7.8 \times 10^{16}\,\mathrm{K/cm}^3 \tag{33}$$

In a graphical representation (see Fig. 7) a contradiction among the models can be observed. Dedicated 4H-SiC models and measurements predict a decrease of C with increasing temperature, which confirms the prediction that Auger recombination is not significant for power devices op-

TABLE VII. Auger recombination parameters.

ref.	C_n [cm^6/s]	C_p [cm^6/s]	T [K]	method	Δ_N [1/cm^3]
[Gale97][12]	$(5\pm1)\times10^{-31}$	$(2\pm1)\times10^{-31}$	300	FCA	-
[Griv07][265]	2×10^{-30}	-	75	FCA	-
[Scaj10][9]	$(7\pm4)\times10^{-31}$		298	FCA	$(1–3)\times10^{18}$
	$(0.8\pm0.2)\times10^{-31}$		298	FCA	$(1–10)\times10^{19}$
[Scaj13][4]	$(5\pm1)\times10^{-31}$		-	FCA	-
[Tawa16][37]	1.6×10^{-30}	-	300	TRPL	-
	0.44×10^{-30}	-	523	TRPL	-
[Zhan18][266]	7.25×10^{-31}	1.21×10^{-31}	-	-	-
[Tana23][261] [a]	$7.4\times10^{-19}\ \Delta_N^{-0.68}$		-	FT	-
[Tana23a][274]	$<3\times10^{-31}$		-	FCA	-

[a] fitting to measurements by Ščajev *et al.* [9]

TABLE VIII. Parameters for Auger model shown in Eq. (25)

ref	type	A [cm^6/s]	B [cm^6/s]	D [cm^6/s]	H	N_0 [1/cm^3]	T_0 [K]
[Loph18][151]	electron	6.7×10^{-32}	2.45×10^{-31}	-2.2×10^{-32}	3.47	10^{18}	300
	hole	7.2×10^{-32}	4.5×10^{-33}	2.63×10^{-32}	8.26	10^{18}	300
[Zhan18][266]	electron	5×10^{-31}	2.45×10^{-31}	-2.2×10^{-32}	0	-	-
	hole	9.9×10^{-32}	4.5×10^{-33}	2.63×10^{-32}	0	-	-

erated at high temperatures Bellone *et al.* [71]. In contrast, the models used for Silicon predict an increase of C.

Finally, Lophitis *et al.* [151] present parameters for the model shown in Eq. (25) (see Table VIII). We found these values also as default in some TCAD simulation suites, which, in general, correspond to Silicon. Thus, these values have to be handled with care.

For Auger recombination there is one main reference in literature, namely Galeckas *et al.* [12] (see Fig. 5).

Finally, we combine all contributions to the lifetime into one plot, showing the lifetime over the

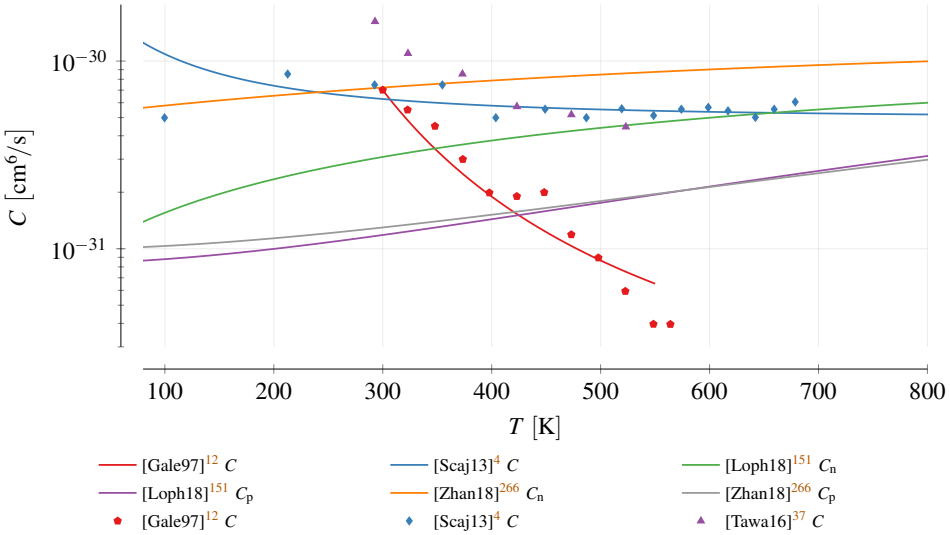

FIG. 7. Temperature dependency of the Auger recombination coefficients C_n and C_p for $\Delta_N = 2.5 \times 10^{18}/\mathrm{cm}^3$

excess carrier concentration (see Fig. 8). For the SRH lifetimes we added all measurements that clearly specified the excess carrier concentrations. In this log-log representation the bimolecular and Auger coefficients only cause a horizontal shift while the derivative (-1 for bimolecular, -2 for Auger) stays constant. Overall, it can be noted that the higher the value of τ_{SRH} the earlier and more pronounced the impact of the bimolecular recombination. A decrease due to Auger recombination only gets significant for $\Delta_N > 10^{18}/\mathrm{cm}^3$. Interestingly, there seem to be measurements that extract SRH values in regions where bimolecular resp. Auger recombination should be already very pronounced.

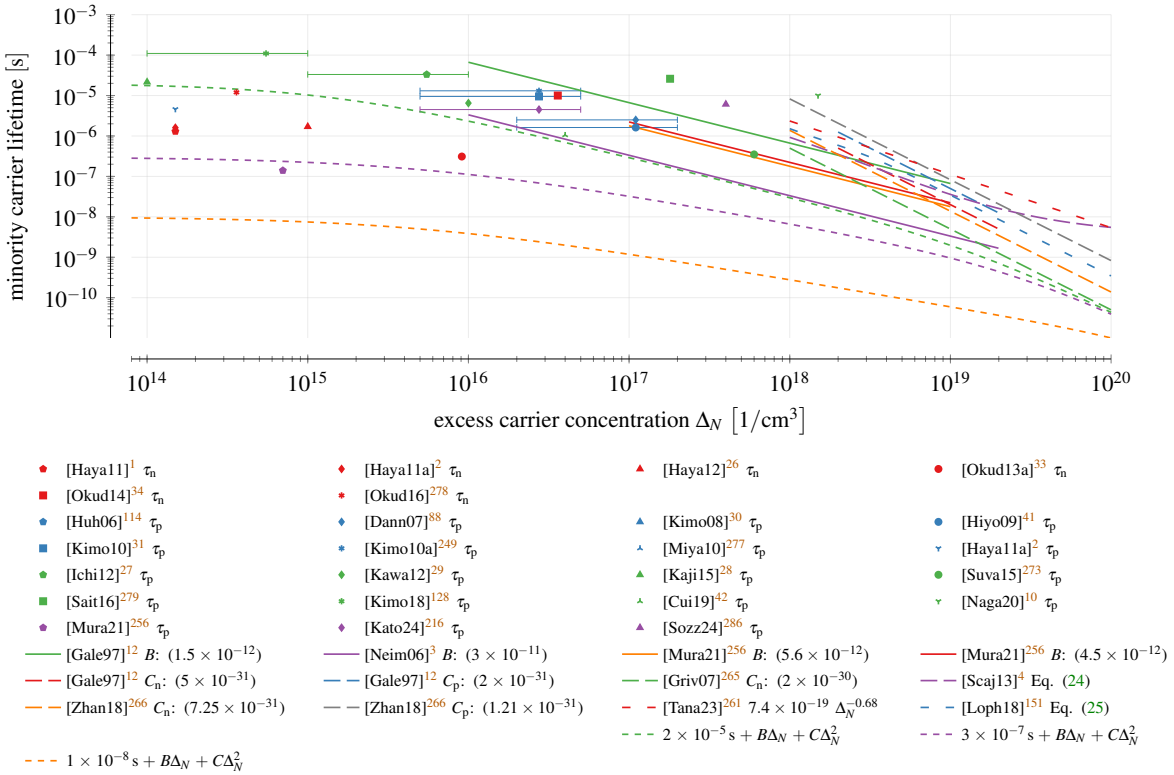

FIG. 8. Charge carrier lifetime considering the contributions of SRH, bimolecular (solid lines) and Auger (dashed lines). The overall recombination lifetime τ_r (dotted line) is shown for different values of τ_{SRH}, $\tau_{\mathrm{bim}} = 3 \times 10^{-11}\,\mathrm{s}^3$ and $\tau_{\mathrm{Auger}} = 2 \times 10^{-30}\,\mathrm{s}$.

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