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# Harmonically Modulated Luminescence: Bridging Gaps in Carrier Lifetime Metrology Across the PV Processing Chain

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Abstract—Carrier lifetime measurements via harmonically modulated luminescence have considerably evolved recently, giving rise to numerous relevant advances and applications in materials science. An essential asset of this technique lies in its unified applicability across the photovoltaic processing chain-from ingots to solar cells. This paper shows how present gaps in carrier lifetime metrology are overcome via harmonically modulated luminescence by focusing on the complete theoretical understanding of harmonically modulated lifetime, on its unmatched bulk lifetime contrast for silicon ingots, and on the capability to monitor the metalization process. Practical considerations for a straightforward (and spatially resolved) ingot bulk lifetime extraction via harmonically modulated luminescence are detailed and validated. Example lifetime investigations demonstrate this technique's capability of bridging the addressed conceptual and instrumental gaps.

*Index Terms*—Carrier lifetime, ingot, luminescence, metalization, silicon, solar cell, wafer.

#### I. INTRODUCTION

ARMONICALLY modulated lifetime embraces both, self-consistent, as well as explicitly phase-sensitive (e.g., lock-in) techniques, with a common ground of harmonic (sinusoidal) modulation of excess carrier generation rate and an explicitly time-dependent (dynamic) determination of relaxation time (see Fig. 1).

The harmonically modulated approach to carrier lifetime features a long and widely ramified interdisciplinary history, likely to trace back to attempts by Tolstoi and Feofilov to access carrier lifetimes via self-consistent hysteresis elimination in 1949 [1]. Investigations of semiconductor recombination properties via harmonically modulated light-induced or electron beam-induced short-circuit currents in the 1970s were followed by implementations of modulated photoluminescence (PL) by Guidotti *et al.* [2] and of modulated free carrier absorption by Sanii *et al.* [3] in the 1980s. Within the past decade, modulated photoluminescence was refined, extended, and readopted for photovoltaic applications by Mandelis *et al.* [4], by Brüggemann and Reynolds [5], and, particularly, by Trupke *et al.* [6].

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Fig. 1. Basic scheme of a harmonically modulated lifetime measurement. Injection-dependent carrier lifetime is extracted from the phase shift between modulated generation rate and excess carrier density.

The essential advantage of harmonically modulated luminescence lies in the combination of highly sensitive luminescence metrology, immediate access to carrier lifetime virtually free of required a priori assumptions about electronic material properties, and a negligible impact of artifacts imposed on measured signal amplitudes. Such concentration of advantages has given rise to our ongoing development of a harmonically modulated luminescence instrument for versatile silicon material analyses-built upon theoretical, experimental, and conceptual advances [7]. Theoretical advances comprise the understanding of harmonically modulated lifetime as a differential lifetime technique and the recovery of actual lifetime thereof [8]-[10], as well as the complete understanding and interpretability of the measured quantity, even in the presence of highly nonuniform recombination rates (e.g., high surface recombination) [11]. Experimental advances involve a carrier lifetime sensitivity down to the range of 1  $\mu$ s [12] and down to excess carrier densities below  $10^8 \text{ cm}^{-3}$  [13], lifetime measurements on metalized substrates [14], and a prototype study of modulated electroluminescence [15]. Conceptual advances include an effective carrier lifetime calibration of luminescence images [16], the most accurate determination of bulk lifetime and surface recombination velocities of silicon ingots [17], as well as accurate access to net dopant concentration [18] and both majority [18] and minority carrier mobilities [19].

The present contribution provides a review of the aforementioned recent advances of harmonically modulated luminescence lifetime metrology in the light of its capability of bridging today's major conceptual and instrumental gaps in carrier lifetime metrology—henceforth denoted as the so-called gaps of *wafering* and *metallization*—to be described in Sections II and III, respectively. This paper also presents a novel and much

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simplified approach to access bulk lifetimes in bare ingots via harmonically modulated luminescence, which is thoroughly validated experimentally. It delineates the generalization of our photoluminescence image carrier lifetime calibration algorithm [16], enabling accurate bulk lifetime extraction from photoluminescence images of bare ingots. Illustrative experimental examples of the benefits of bridging today's major gaps in carrier lifetime metrology are provided, and details about the stateof-the-art experimental setup for accurate metalization process control are revealed.

## II. BRIDGING THE GAP OF WAFERING

The *gap of wafering* shall denote the conceptual and instrumental break between carrier lifetime measurements on silicon ingots and wafers. A conceptual break may open up either because different quantities are measured (e.g., diffusion length [20] as opposed to carrier lifetime) or because the recombination properties of interest have a fundamentally different relation to the measured effective carrier lifetime in wafers or bare ingots [21], [22]. An instrumental break simply denotes different instruments for carrier lifetime measurements on ingots and wafers, respectively.

## A. Steady-State Versus Dynamic Lifetime Measurements

It is noted that effective carrier lifetime measurements on commonly bare (i.e., unpassivated) ingots are much dominated by surface recombination. Therefore, the recovery of bulk lifetime from such measurements is usually complicated by a relatively low contrast with the measured effective lifetime with respect to bulk lifetime [21], [23], [24], making measurements very prone to both scattering of data and systematic errors. Such signal contrast is substantially enhanced, if dynamic lifetime techniques are applied (cf., Fig. 2). However, their interpretation in terms of recombination properties is more complex than for steady-state techniques. As previously stressed by Sinton and Trupke [25], dynamically obtained effective carrier lifetimes may largely exceed steady-state effective carrier lifetimes for excess carrier generation rates confined to highly recombinative substrate interfaces of thick substrates (e.g., ingots). Thus, dynamically obtained effective carrier lifetimes are practically useless in cases of high-surface recombination [25] if their interpretation in terms of, e.g., bulk lifetime, has no sound theoretical foundation.

## B. Interpretation of Harmonically Modulated Lifetime

We managed to establish such theoretical foundation for harmonically modulated lifetime, which is a dynamic decay time technique (cf., Fig. 1), and to thereby exploit its much enhanced bulk lifetime contrast, as illustrated in Fig. 2. A Green's function solution of the heat equation [11], [26] allows excess carrier density to be described as a series of decay modes with different decay times [11]. Based on this formalism, the essential distinction between steady-state effective lifetime (i.e., the ratio of cumulative excess carrier density and generation rate [25]) and quasi-steady-state harmonically modulated life-



Fig. 2. Comparison of steady-state effective lifetimes  $\tau_S$  (squares) and harmonically modulated lifetimes  $\tau_H$  (solid lines) calculated as functions of bulk lifetime  $\tau$  of a bare silicon ingot according to (1) and (2) [11], respectively. For most relevant irradiation wavelengths  $\lambda$  between 800 and 1000 nm (absorption coefficients  $\alpha$  shown) harmonically modulated bulk lifetime contrast (the derivative of harmonically modulated lifetime with respect to bulk lifetime) typically exceeds steady-state bulk lifetime contrast by 1–2 orders of magnitude. At identical double-logarithmic curve slopes, bulk lifetime contrast of  $\tau_H$  would exceed bulk lifetimes of  $\tau_S$  by the ratio  $\tau_H(\tau)/\tau_S(\tau)$ . However (particularly for high bulk lifetimes), the double-logarithmic slope of  $\tau_H$  is even higher than that of  $\tau_S$ . Parameters: Diffusion coefficient  $D = 27 \,\mathrm{cm}^2 \, s^{-1}$ , and surface recombination velocity  $S = 3 \times 10^5 \,\mathrm{cm} \,\mathrm{s}^{-1}$ .



Fig. 3. Depiction of weights  $\beta_n$  of the modes *n* of excess carrier decay for different ingot surface recombination velocities *S*. The higher the *S*, the broader the distribution of mode weights. If only the first mode is significant, steady-state and harmonically modulated effective lifetime expressions according to (1) and (2) must coincide. Significant weights of higher order modes give rise to substantially enhanced modulated lifetime and cause the favorable signal contrast of the latter with respect to bulk lifetime. Parameters as of Fig. 2, irradiation at  $\lambda = 791$  nm, and bulk lifetime  $\tau = 10^{-3} s$ .

time can be shown to be caused by their different decay mode weighting. With relative mode weights  $\beta_n$  (with a sum over all modes  $n = 1, \ldots, \infty$  of unity, cf., Fig. 3) and their corresponding quasi-periodic inverse decay times  $\kappa_n$ , steady-state effective lifetime is found to be

$$\tau_S = \sum_{i=1}^{\infty} \frac{\beta_n}{\kappa_n} \tag{1}$$

whereas harmonically modulated lifetime reads

$$\tau_H = \tau_S^{-1} \sum_{i=1}^{\infty} \frac{\beta_n}{\kappa_n^2}.$$
 (2)

The *ab initio* derivation of mode weights  $\beta_n$  and inverse mode decay times  $\kappa_n$  is to be found in [11].

## C. Origin of Differences Between Measured Lifetimes

The quadratic superposition of decay times in (2) [as opposed to their linear superposition in (1)] eventually gives rise to deviations between steady-state effective lifetime and harmonically modulated lifetime. While this is a purely mathematical explanation of the often large difference between steady-state and harmonically modulated lifetime expressions in the case of broad distributions of mode weights  $\beta_n$  (cf., Fig. 3), the actual physical origin of this phenomenon is to be attributed to the fact that harmonically modulated lifetime is of dynamic nature, whereas steady-state effective lifetime is sensitive to the total magnitude of excess carrier density. If, as in the case of bare ingots at shallow optical excess carrier generation, dominant surface recombination velocity gives rise to a weak contrast of cumulative excess carrier density (and thereby of steady-state effective lifetime) with respect to bulk lifetime, this is very different for harmonically modulated lifetime. The latter yields the aggregated decay time of only the excess carriers alive, rather than rigorously relating the number of excess carriers to the number of excess carriers generated within a certain time interval, as steady-state effective lifetime does. For bare ingots, steady-state effective lifetime is therefore highly affected by rapidly decaying higher order modes of excess carrier decay, whereas harmonically modulated lifetime is only weakly affected by such higher order modes. The significance of higher order modes in the case of enhanced surface recombination is illustrated in Fig. 3 by the distribution of mode weights at different surface recombination velocities.

#### D. Real Bulk Lifetime Measurements

The aforementioned superior contrast of harmonically modulated lifetime with respect to bulk lifetime of bare ingots enables a most accurate and precise determination of ingot bulk lifetimes via this technique. This is because the higher bulk lifetime contrast becomes, i.e., the higher the derivative of the measured lifetime with respect to bulk lifetime is, the lower is the impact of both statistic and systematic measurement errors on the resulting bulk lifetimes. As illustrated in Fig. 2, harmonically modulated lifetime features a substantially higher bulk lifetime contrast than steady-state effective lifetime throughout the range of relevant optical irradiation wavelengths for silicon at room temperature. For typical irradiation wavelengths of optical characterization techniques near 800-nm, harmonically modulated bulk lifetime contrast may easily exceed steady-state bulk lifetime contrast by two orders of magnitude.

In a recent publication, we proposed the determination of ingot bulk lifetime via harmonically modulated luminescence pursuing a Green's function approach to the continuity equation [17]. By applying the mode weighting rule given in (2), such bulk lifetime analysis is substantially simplified, as it overcomes the requirement of numerical integration over time [17]. Equation (2) allows the calculation of bulk likfetime  $\tau(\tau_H)$ , as a function of harmonically modulated lifetime, such that bulk lifetime can be directly assigned to a harmonically modulated lifetime measurement. However, it must be noted that (2), as opposed to our previous approach [17], does not take into ac-



Fig. 4. Comparison between measurements of harmonically modulated lifetime  $\tau_H$  in *transmissive* and *reflective* luminescence detection geometries, respectively. The upper plot shows two injection-dependent self-consistent lifetime analyses [6] for each detection configuration (plotted over electron-holepair generating photon current density  $j_{\gamma}$ ). In the lower plot, resulting 1 sun equivalent lifetimes  $\tau_H$  (symbols) are converted into bulk lifetimes via curves (solid lines) calculated according to (2). Consideration of depth-dependent luminescence detection probability in transmissive (green) and reflective (red) curves yields consistent bulk lifetime results, whereas a considerable mismatch is encountered for the general treatment (black curve), which does not take detection probability into account.

count the characteristics of our experimental setup. It is solely based on the continuity equation, while the experimental setup features a pronounced depth-dependent luminescence detection probability (cf., [17]). However, it can be shown that such experimental effects can be easily accounted for in the calculation of  $\tau(\tau_H)$ : As can be concluded from the full derivation given in [11], the depth profile of excess carrier density only affects the calculation of mode weights  $\beta_n$ , whereas it does not affect inverse decay times  $\kappa_n$ . Assuming low-level injection conditions, the impact of depth-dependent luminescence detection probability can be taken into account by simply weighting (i.e., multiplying) excess carrier density depth profiles by the relative depth-dependent detection probability in the calculation of  $\beta_n$ . It is noted that the resulting mode weights  $\beta_n$  then lack normalization. However, such normalization is irrelevant for (2), as any constant real normalization factor would cancel out due to the division by steady-state effective lifetime.

We validated this approach by comparing harmonically modulated luminescence lifetime measurements on a 2.4 mm thick as-cut silicon slice carried out in both *transmissive* and *reflective* luminescence detection geometries (with respect to laser irradiation), respectively. As can be seen in Fig. 4, the two measurement configurations would precisely yield bulk lifetimes deviating more than 13.1%, if depth-dependent luminescence detection effects were not taken into account. In contrast, taking them into account via modified mode weights (as proposed above) yields nearly coinciding bulk lifetime results. The remaining very minor deviation between bulk lifetime results of



Fig. 5. Bulk lifetime calibration of PL images of a bare ingot (left, 1 sun) and of a silicon wafer (right, 0.02 suns), featuring an aluminum oxide surface passivation (with no further high temperature step except the aluminum oxide's 25 min 440 °C activation anneal). Slightly higher ingot bulk lifetimes are measured at identical excess carrier density (cf., discussion in text). Note the different scales.

transmissive and reflective luminescence detection geometries could be due to two effects: First, bulk lifetime was not homogeneous within the active harmonically modulated luminescence measurement area. This could have given rise to very minor bulk lifetime differences due to a slightly different weighting of laterally inhomogeneous lifetime distributions. Second, the roughness of substrate interfaces is likely to give rise to a slight deviation between the assumed and the true relative depthdependent luminescence detection probabilities. However, the reduction of the deviation between bulk lifetime results from more than 13.1% without accounting for depth-dependent luminescence detection probability to less than 2.4% clearly indicates that it is possible to take experimental setup characteristics into account within this approach, as the data given in Fig. 4 support our assumptions fairly accurately.

## E. Example Investigation: Accurate Ingot Bulk Lifetimes

Harmonically modulated luminescence lifetime measurements on bare ingots can be used for a bulk lifetime calibration of PL images. In [16], we proposed an effective lifetime calibration of luminescence images on (passivated) silicon wafers via harmonically modulated luminescence. As the averaging algorithm required for a bulk lifetime calibration on bare (unpassivated) ingots requires a generalization of the concept delineated in [16], the derivation of such a generalized averaging algorithm is given in the appendix of this paper.

Fig. 5 shows two *bulk* lifetime images of multicrystalline *p*-type silicon feedstock material: one image of an as-cut silicon brick interface and another image of a neighboring wafer from a brick position 8 mm up along the crystallization direction from the investigated brick interface. The wafer features

a 10-nm thick Al<sub>2</sub>O<sub>3</sub> surface passivation (annealed at 440 °C for 25 min) coated via a 70-nm thick SiN capping. The aluminum oxide passivation has been demonstrated by many (e.g., [27]) to yield injection-independent surface recombination velocities below 10 cm·s<sup>-1</sup> on 1- $\Omega$ ·cm *p*-type material; therefore, (for  $\tau < 100 \,\mu s$ ) the measured effective lifetime images could be expected to yield similar bulk lifetime distributions. Notably, the investigated wafer was explicitly not subjected to any treatment that could potentially affect bulk lifetime. It should also be noted that all measurements were conducted at an irradiation wavelength of 791 nm. Irradiances were an equivalent of 1 sun (here  $2.5 \times 10^{17}$  photons cm<sup>-2</sup> s<sup>-1</sup>) in the ingot case and an equivalent of 0.02 suns in the wafer case. The ratio of irradiances was adapted such that excess carrier density in the ingot [21] would most closely match maximal excess carrier density in the passivated wafer ( $4 \times 10^{12}$  cm<sup>-3</sup>). Thereby, deviations due to an injection-dependent bulk lifetime evaluation at different excess carrier densities could be minimized. As for metastable defects, it should be noted that the ingot contained a considerable concentration of interstitial iron from the crucible. Iron imaging [28] revealed an interstitial iron concentration of  $1 \times 10^{11}$  cm<sup>-3</sup> in the less-contaminated right part of the image, and, even  $1 \times 10^{12}$  cm<sup>-3</sup> in its more contaminated very left part. As it was not possible to reliably prepare all iron atoms in their interstitial state in the ingot due to very low excess carrier densities in the unpassivated thick substrate, all images and calibrations were conducted in the state of all iron atoms bound in a compound with boron. This so-called pure iron-boron state was ensured in both ingot and wafer via a 15 min 81 °C exposure (in the dark) before the lifetime measurement, and verified by a degradation test image immediately after the actual lifetime image was acquired.

Disregarding the cautious preparation of both substrates and the careful choice of measurement conditions such that bulk lifetimes could be expected to be comparable, interestingly, Fig. 5 still reveals systematic differences between the two bulk lifetime images (notice the different scale). One likely reason for this observation could be inhibited lateral carrier diffusion in the ingot compared with the passivated wafer because of the highly recombinative interfaces, many excess carriers would not reach highly localized sites of bulk recombination, whereas, in the wafer case, they would. The much higher level of localization of bulk recombination centers can actually be well seen when comparing the images. However, there must be an additional cause to the observed discrepancy, as highest lifetimes are approximately 15% lower in the wafer even in regions unaffected by localized recombination centers. Such experimental evidence is well supported by simulations of the segregation of metal impurities during crystallization. As for interstitial iron concentration, a 20% increase between the brick surface and the wafer position (8 mm away) is found. Other relevant metal impurities behave very similarly; therefore, the observed lower lifetime is likely to be attributed to this impurity segregation effect. However, a low-level injection breakdown of aluminum oxide surface passivation due to a high-surface defect concentration (multicrystalline material) cannot be rigorously ruled out.

Regardless of the exact cause of the observed deviation, what is most important with regard to the subject of this paper is that it reveals benefits brought about by the capability of bridging the metrological *gap of wafering*. Thus, a direct comparison of bulk lifetimes obtained via one instrument and one methodology is enabled.

## III. BRIDGING THE GAP OF METALIZATION

The term gap of metalization is intended to address the problem of different conceptions and instruments for recombination measurements before and after metalization. While on the wafer level, photoconductive effective carrier lifetime measurements are a commonly accepted and widespread choice, any such techniques suffer from a lack of resolution or dynamic range needed for accurate carrier lifetime measurements on metalized substrates. Therefore, effective minority carrier diffusion lengths or open-circuit voltages are commonly preferred over carrier lifetime, even though the mathematical relation between these different quantities is rarely straightforward, and their conversion is thus often based on simplified assumptions (e.g., about intrinsic carrier density or about the depth distribution of excess carrier density). Moreover, metalized cell precursors or wafers without electrical contacts require contactless measurement techniques. Thus, reliable metalization process control requires broadly applicable contactless carrier lifetime measurements. Harmonically modulated luminescence represents a powerful tool to bridge this gap of metallization, as demonstrated in [14]. Promising applications involve investigations of surface passivation quality after the metalization process, as well as detailed investigations of bulk material quality changes brought about by metalization.

#### A. Effective Lifetimes of Metalized Wafers and Solar Cells

Fig. 6 shows effective carrier lifetime calibrations (via harmonically modulated luminescence) of PL images of both, a multicrystalline wafer and two differently processed solar cells of nearly the same brick position as the samples shown in Fig. 5. Lifetime images of a standard solar cell (featuring an aluminum  $p^+$  back surface region) and a PERC solar cell are compared, while the bulk lifetime reference wafer featured the exact same temperature treatment as the PERC cell. As can be seen from the inset in Fig. 6, such lifetime mapping allows us to compare effective lifetimes before and after the metalization process at a defined injection level. We note that the reference wafer had no emitter during lifetime measurements. Thus, in this particular case, the differences in effective lifetime account for both enhanced Auger and space charge region recombination, as well as recombination caused by metalization. However, process control of the immediate metalization process is possible likewise.

#### B. On Lateral Balancing Currents in Solar Cells

The PL images of solar cells under open-circuit conditions shown in Fig. 6 are known to be potentially affected by a lateral redistribution of excess carrier concentration because of lateral carrier transport through emitter and metal grid [29]–[31]. In



Fig. 6. Effective carrier lifetime calibrations of (1 sun) PL images of a (PERC process) lifetime reference wafer, a PERC cell, and a standard Al  $p^+$  cell via harmonically modulated luminescence (note the different scales). Cells (made from the same ingot as depicted in Fig. 5) were homogeneously illuminated on a  $156 \times 156 \text{ mm}^2$  area for harmonically modulated lifetime measurements. The bottom plot shows effective lifetimes at the highlighted image points.

a most recent contribution by Shen *et al.* [32], the extent of such lateral carrier transport was quantified, revealing excess carrier densities up to 20% above (at low lifetimes) or below (at high lifetimes) their expected value according to local effective lifetime. Further, Shen *et al.* provided accurate experimental evidence in support of previous approaches unaffected by such lateral currents [30]–[34], and they proposed an effective lifetime calibration of such *virtual static* open-circuit PL images via terminal voltage.

Our harmonically modulated luminescence approach to solar cell effective lifetimes is largely unaffected by lateral balancing currents. This is because it is sensitive to decay time, rather than to a signal amplitude related to excess carrier density. Lateral balancing currents then only affect harmonically modulated lifetime in that decay time is measured at a somewhat higher or lower excess carrier density than to be expected if they were null. Therefore, only the injection dependence of carrier lifetime may give rise to very minor systematic errors. However, using the harmonically modulated luminescence approach for an effective lifetime calibration of PL images [14], [16], resulting local effective lifetimes may be affected by lateral balancing currents to the very extent discussed by Shen et al. [32]. However, by making use of what Shen et al. denote as a virtual static open-circuit PL image (to be obtained from Glatthaar's [30], [33] or Shen's [34] approaches), harmonically modulated lifetime calibrations of PL images become virtually unaffected by lateral balancing currents.

Harmonically modulated luminescence features several advantages over an effective lifetime calibration of PL images via terminal voltage measurements [32], [34]: First, it is also applicable to devices without junction and electrical contacts. Second, its dynamic nature provides lifetime access independent of *a priori* assumptions of any sort. Most critically, inferring effective lifetimes from voltage measurements requires assumptions about intrinsic carrier density. Such assumptions are controversial in view of bandgap narrowing [35], and they require most accurate temperature control.

# APPENDIX

# PL BULK LIFETIME IMAGES OF BARE INGOTS

In [16], an averaging algorithm to recover (possibly laterally inhomogeneous) carrier lifetimes of passivated wafers from steady-state PL images via harmonically modulated luminescence was derived. Under low-level injection conditions, to which the following generalization shall be restricted (justified for almost any bare ingot), measured harmonically modulated lifetime  $\tau_H$  was shown to yield local (bulk) lifetimes  $\tau_i$  at PL image pixels of intensity  $\varphi_i$  via

$$\tau_H = \frac{\sum \varphi_i s_i \tau_i}{\sum \varphi_i s_i} \tag{3}$$

with the local harmonically modulated luminescence detector sensitivity  $s_i$ . For uniform  $s_i$ , this expression would much simplify to  $\varphi(\tau_H) = \sum \varphi_i^2 / \varphi_i$  for passivated wafers. For bare ingots, this does not hold for two reasons: First, luminescence intensity is not proportional to (bulk) lifetime anymore. Rather, the relation  $\varphi \sim \sqrt{\tau}$  [which directly follows from the steadystate solution of the continuity equation, cf., (5)] approximately holds, even though higher order setup specific characteristics, such as depth-dependent luminescence detection probability are to be additionally taken into account. Second, harmonically modulated lifetime may substantially differ from bulk lifetime  $\tau$ , albeit modeling of  $\tau_H(\tau)$  suggests proportionality of these two quantities (cf., Fig. 2) in almost any relevant case. Exploiting this very proportionality, we may therefore express the bulk lifetime corresponding to measured harmonically modulated lifetime [according to (2)] as

$$\tau(\tau_H) = \frac{\sum \varphi_i s_i \tau_i(\varphi_i)}{\sum \varphi_i s_i} \tag{4}$$

with a general injective function  $\tau(\varphi)$  (not necessarily proportional). Its inverse—PL image intensity as a function of bulk lifetime—is modeled via

$$\varphi(\tau) = c_{\varphi} \int dz \; p_{\varphi}(z) \Delta n(z)|_{\tau} \tag{5}$$

with excess carrier density  $\Delta n(z)|_{\tau}$  according to the continuity equation, with depth-dependent luminescence detection probability  $p_{\varphi}(z)$  [17], and with a free parameter  $c_{\varphi} \in \mathbb{R}^+$ , which is fitted to satisfy (4). The obtained curve  $\varphi(\tau)$  thereby allows for an accurate bulk lifetime assignment  $\varphi_i \to \tau_i$ .

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