A new universal metric called the relative defect concentration, *β* in c-Si solar cells

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The normalised defect density (*NDD)* metric has been widely used to quantify the two common types of light-induced degradation (LID): boron-oxygen-related LID (BO-LID) [1,2] and light- and elevated temperature-induced degradation (LeTID) [3–6]. *NDD* is calculated as the difference in inverse effective lifetime (τ_{eff}) before and after degradation, where *NDD* is equivalent to the inverse of the Shockley-Read-Hall lifetime ($1/\tau_{SRH}$) equation [7] as follows:

$$NDD = \frac{1}{\tau_{eff}(t)} - \frac{1}{\tau_{eff}(t=0)} = \left(\frac{1}{\tau_{BG}} + \frac{1}{\tau_{SRH}}\right) - \frac{1}{\tau_{BG}} = \frac{1}{\tau_{SRH}} = N_t \sigma_n \frac{N_{dop} + \Delta n}{\frac{k}{v_{th,p}}(n_1 + \Delta n) + \frac{1}{v_{th,n}}(N_{dop} + p_1 + \Delta n)}, \quad 1)$$

where they are determined by the concentration of the defect (N_t), capture cross-section of holes (σ_p) and electrons (σ_n), the thermal velocity of electrons ($v_{th,n}$ = 2.05 × 10^7 cm·s^{-1}) and holes ($v_{th,p}$ = 1.69 × 10^7 cm·s^{-1}) at 300 K [8], background doping density (N_{dop}), and capture cross-section ratios, $k = \sigma_n/\sigma_p$. When σ_n and σ_p of the specific defect of interest are known, the *NDD* or $1/\tau_{SRH}$ value can be used to identify N_t directly with different N_{dop}. However, when σ_n and σ_p are unknown, despite the known value of the ratio k (= σ_n/σ_p), the absolute value of N_t cannot be identified. Therefore, *NDD* has been widely used to represent N_t where *NDD* is linearly proportional to N_t in specific circumstances [9]. However, variations in the doping density (N_{dop}) and injection-level or excess carrier concentrations (Δn) result in significant variations in the calculated value of *NDD*. To resolve this issue, in this work, we define a new term, the relative defect concentration, *β*. This is the product of N_t and σ_n, given in the following equation:

$$\beta = N_t \sigma_n, \quad 2)$$

Since defects are often studied with unknown σ_n and σ_p values, the *NDD* (Eq. 1), *k* and Eq. 2 can be combined such that *β* can be expressed as:

$$\beta = \left(\frac{\Delta n + n_1}{N_{dop} + \Delta n}\frac{k}{v_{th,p}} + \frac{N_{dop} + \Delta n + p_1}{N_{dop} + \Delta n}\frac{1}{v_{th,n}}\right) NDD. \quad 3)$$

Thus, the *NDD* can be converted into *β*, to account for differences in the dependent values (Δn and N_{dop}.) This can be simplified using typical conditions and assumptions. Figure 1 (a) depicts a variance of over an order of magnitude in NDD simply due to differences in N_{dop} (x-axis) or Δn (y-axis), whereas for the same range of N_{dop} and Δn in (b), the differences in *β* are negligible. Thus, the conversion of *NDD* into *β* makes it possible to compare the relative N_t regardless of difference in N_{dop} or Δn with less than 5% error.

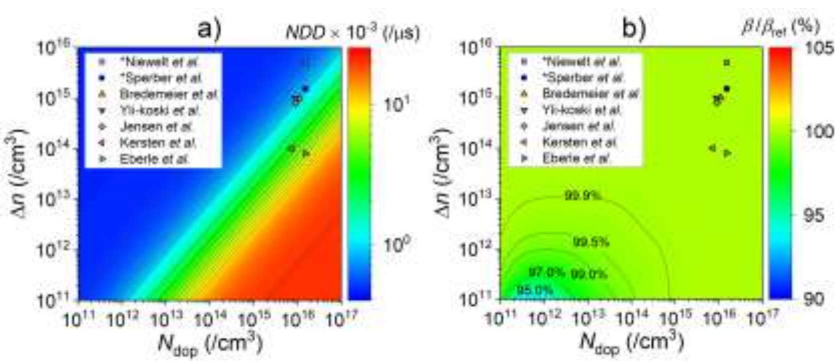

Figure 1: Plots of simulated results of a) *NDD* and b) the converted value of *β* using Equation 3 over β_{ref} (β/β_{ref}) as a function of N_{dop} in *p*-type silicon, and Δn. The symbols on the graphs show Δn where effective lifetimes (τ_{eff}) were extracted to calculated *NDD* and N_{dop} that are used in the studies of LeTID [3,6,10–14]. * indicates that the study only reported τ_{eff}.

Converting *NDD* to β can, therefore, enable the comparison of the maximum degradation extent (MDE) from different studies, where different materials and testing conditions are used. In Figure 2, the MDE in terms of *NDD* (NDD_{MDE}) from some LeTID studies [6,10,11,13–15] is converted to β (β_{MDE}), and also shown on the plots in Figure 2. Despite the values of NDD_{MDE} varying by more than one order of magnitude across the different studies, β_{MDE}, in contrast, typically lie within the range of ~ (3 - 10) × 10^{-3} /cm. This small variation indicates that the relative concentration of LeTID causing defects observed in various studies is far more similar than was previously possible to identify using the *NDD* metric.This shows an example of the advantages of β, where the value is directly comparable and convertible under different conditions.

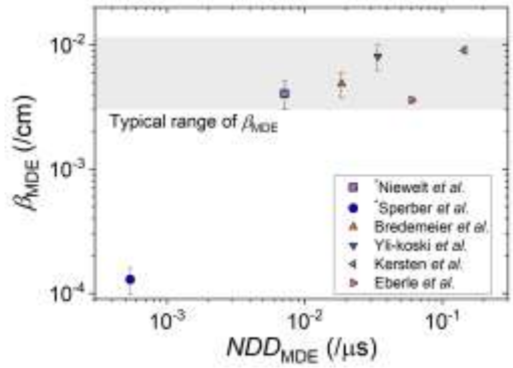

Figure 2: NDD_{MDE} from the literature [6,10,11,13–15] **versus β_{MDE}, which is calculated based on given N_{dop} and Δn with assumed k of 35 ± 10. Error is based on the error of k.**

Moreover, the formulation of β can also be used to identify the k of unknown defects. Figure 3 depicts an example of BO-LID and LeTID in Czchalski-grown mono-crystalline (Cz-Si) and multi-crystalline silicon (mc-Si) wafers, respectively. Both samples are a symmetrical lifetime structure with phosphorus emitter (sheet resistance of ~ 65 Ω/sq) and SiN_x:H dielectric layers on both sides. The mc-Si sample was fired at peak temperature of ~ 740 °C, which, is known to introduce LeTID-related defect precursors into the wafer [16]. The Cz-Si sample was degraded under a 0.2 kW/m^2 LED lamp for 48 hours at room temperature whilst the mc-Si sample was degraded under a set of halogen lamps (1 kW/m^2) for ~ 167 hours at 75 °C. Figure 3 a) and b) show the Auger corrected inverse effective lifetime, and *NDD* as a function of Δn before (BD) and after degradation (AD). Solid lines are the fit on NDD using Eq. 1 where k for BO-LID (k_{BO}) and LeTID (k_{LeTID}) were found to be 10.4 and 34.3, respectively. Using Eq. 3, β as a function of Δn with different input k (k_{in}) for Cz-Si and mc-Si are shown in Figure 3 c) and d), respectively. Note that as k_{in} converges to the k from each type of LID, β becomes flat and more independent from Δn. Therefore, based on the standard deviation, χ_β, of β over Δn with different k_{in}, optimal k-value, k_{opt} can be found, which are 10.6 ± 3.2 and 30.7 ± 4.0 for BO-LID and LeTID, respectively. The result demonstrates the approach can be used to identify k-value of unknown defects.

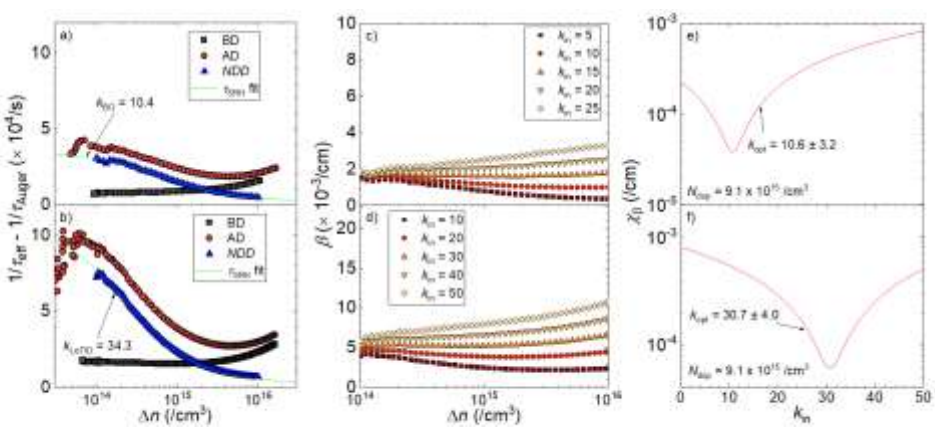

Figure 3: a) and b) $1/\tau_{eff} - 1/\tau_{Auger}$, and *NDD* as a function of Δn before (BD) and after degradation (AD). Solid line shows the best fit on *NDD* curve using τ_{SRH} Equation (Eq. 1). c) and d) β as a function of Δn with different k_{in}. e) and f) Standard deviation of β (χ_β) as a function of input capture cross-section ratio (k_{in}) with different Δn ranges. a), c), and e) are from Cz-Si and b), d), and f) are from mc-Si.

In this work, we offer a solution to the analytical incongruities between numerous LID studies as a result of variations in samples and processing conditions. We introduce and define a new metric, the relative defect concentration, β. The universality of this new metric will allow for a more direct comparison of LeTID results across different studies, which will help to accelerate our understanding of the defect in crystalline silicon solar cells. It is also a useful tool in helping to identify the *k*-value of an unknown defect.

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