Analysis of failure modes in Kesterite solar cells

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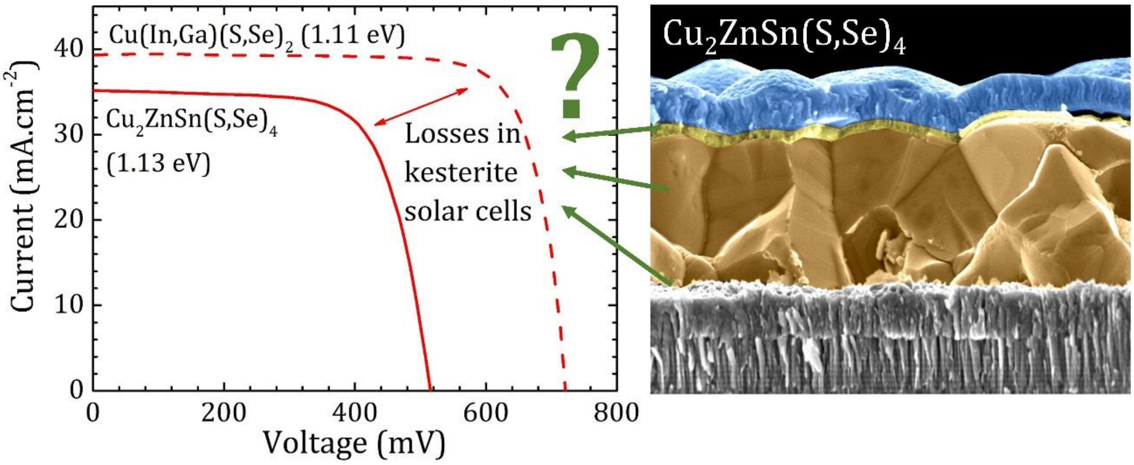
Abstract

An intense research activity has been carried out in the past few years to improve efficiencies and understand limitations in kesterite based solar cells. Despite notable efforts to determine and list the different failure modes affecting the photovoltaic properties of these devices, very few works try to quantify and classify the effect of these failure modes. In this study, an exhaustive literature review has first been conducted to determine the different causes leading to limited efficiencies in kesterite devices with an additional focus on cadmium free and critical raw material free devices. Second, an original approach has been employed to quantify the impact of these failure modes on solar cells with the evaluation of feedbacks from 18 scientific experts working on kesterite technology. The result of this survey is analyzed, which allow to determine what should be the research priority for the community to improve efficiencies and drive kesterite technology to the market.



1. Introduction

1.1 Kesterite solar cells

Thin film solar cell technologies Cu(In,Ga)(S,Se)$_2$ (CIGS) and CdTe have already demonstrated power conversion efficiencies above 22% at laboratory scale and above 15% for large modules[1]. Industrialization of these technologies is already ongoing with cumulative production over 4 GWp in 2016[2]. However, both of these technologies contain elements that have been listed by the European Commission as Critical Raw Materials (CRM) for the energy sector[3,4], namely gallium, indium and tellurium because of their scarcity in the earth crust[5] and their use in other markets. Additionally, progressive implementation worldwide of regulations similar to Restriction on the use of Hazardous Substances (RoHS) will limit or prevent the use of cadmium in these technologies[6], both in the absorber layer (CdTe) or in the buffer layer (CdS).

Kesterite semiconductors Cu$_2$ZnSn(S,Se)$_4$ (CZTSSe) have been identified as a promising candidate for thin film photovoltaic (PV) applications due to their similarities to CIGS materials without containing CRM. To date, a record efficiency of 12.7% has been obtained for a CZTSSe solar cell with a CdS/In_2S_3 buffer layer[7] and 9.0% for a Cd&CRM-free (i.e. without Cd, In or any CRM) kesterite solar cell[8].

Due to these limited efficiencies and the gap generally observed between laboratory scale efficiencies and commercial modules efficiencies[1], it is felt premature to envisage up-scalling and industrialization of kesterite solar cells. However, evaluating these technologies with an industrial proven result-driven methodology such as Failure Mode and Effect Analysis (FMEA)[9] is of prime importance to correctly assess the challenges relative to the design of the targeted structure and its scalability. Preliminary works on the FMEA of the kesterite absorber have been published in Reference[10].

1.2 Scope of the study

This study focuses on the active part of the CRM free and Cd&CRM-free kesterite solar cell which consists in a back electrode (Mo), an absorber material ($Cu_2ZnSn(S,Se)_4$), a buffer layer (without Cd nor CRM) and a window layer (without In). The choice of the substrate, the encapsulant as well as the interconnection of the different solar cells are out of the scope of this study. Although several methods exist for synthesizing the different layers and particularly the absorber layer (precursors deposition via chemical or physical routes, selenization and/or sulfurization, co-evaporation), but also the buffer layer (chemical bath deposition, atomic layer deposition, sputtering), only the final design of the solar cell is considered and not the way to produce it. This focus on a final product is called design FMEA (D-FMEA). The influence of processes to achieve the desired design is out of the scope of the study.

As kesterite based solar cells and particularly Cd&CRM-free kesterite solar cells are still far from the market, no “standard” device does exist. Particularly, no unique buffer layer is commonly chosen. Therefore different options are considered in this study.

Inventory of the different failure modes occurring in kesterite devices have been gathered in different literature review[11-14] and are generally as exhaustive as possible. However little effort is generally made to quantify and classify these data. This study precisely aims at providing this classification.

1.3 D-FMEA analysis

D-FMEA is both a qualitative and quantitative technique to determine how an existing or an under development product might fail and what are the likely effects of these particular mode of failure[9]. It is based on three figures of merit (FOM) related to the severity, the occurrence and the non-detection of all failure modes. Each indicator is rated on a 1-10 scale defined in table 1 and are multiplied together to give a *risk priority number* (RPN):

(1) RPN = (severity of effect) x (likelihood of occurrence) x (likelihood of non-detection)

This global value allows to compare the different failure modes and prioritize the ameliorations or modifications that have to be brought to improve the final product. First, actions must address the failure mode with the highest RPN to reduce its value until a second failure mode becomes predominant and so on.

Table 1: Values chosen for the indicators Severity, Occurence and Non detectability. The reference technology for a CZTSSe device is as a state-of-the-art CIGSSe device with a similar bandgap.

Severity	
PCE<20% of the reference technology PCE can be expected for this technology if only this failure without prior notice	10
PCE<20% of the reference technology PCE can be expected for this technology if only this failure without prior notice	9
20%<PCE<50% of the reference technology PCE can be expected for this technology if only this failure without prior notice	8
	7
	6
50%<PCE<80% of the reference technology PCE can be expected for this technology if only this failure without prior notice	5
	4
	3
80%<PCE<90% of the reference technology PCE can be expected for this technology if only this failure without prior notice	2
90%<PCE<100% of the reference technology PCE can be expected for this technology if only this failure without prior notice	1

Occurrence	
Very high. Almost 100% sure, according to the experience/knowledge of the evaluator, the type/cause of the failure will happen very frequently. Failure almost unavoidable.	10
	9
High. The type/cause of failure happens repeatedly. Problematic, non-perfect design.	8
	7
Moderate. The type/cause of the failure happens moderately. Advanced design.	6
	5
	4
Low. The probability of the type/cause of failure to happen is low. Proven design.	3
	2
Remote. The type/cause of the failure is highly unlikely to happen.	1

Non-detection	
Cannot be detected and/or controlled	10
Can only be detected indirectly - even if detected, the solution is unknown	9
Can be detected directly with exotic techniques or a combination of exotic techniques only - if detected, requires thorough study to be overcome	8
	7
Can be detected with a combination of standard techniques - If detected, requires non trivial layout or process adjustment to be overcome	6
	5
Can be detected with standard techniques and corrected with trivial adjustments	4
	3
	2
Totally under control, always detected automatically corrected-	1

D-FMEA is most often used to analyze an existing product and is thus based on historical data recorded from monitoring system directly on the production line. Particularly, severity and occurrence of failure can be assessed with statistical tools on existing products. In the case of development of new products such as kesterite solar cells, the analysis is more qualitative: a literature review is conducted to determine the different failure modes and to tentatively quantify their FOM. As insufficient data are gathered with this approach, feedbacks from experts in the domain has been recorded and is summarized in section 2.3.

2. *Results*

2.1 Mapping of fundamental failures in Cd-free kesterite solar cells

$Cu_2ZnSn(S,Se)_4$ (CZTSSe) materials are similar to well established $Cu(In,Ga)(S,Se)_2$ materials and integrated in devices with similar structures[15]. Both materials have tunable bandgaps in the range 1.0 eV – 1.5 eV by changing the sulfur on selenium ratio or the indium on gallium ratio in CIGSSe solar cells. Similar bandgap variation with cationic substitution can be achieved by replacing tin by germanium in CZTSSe (CZTGSSe). Thus, kesterite as well as chalcopyrite solar cells are theoretically optimum to work as a single junction and to reach the maximum of Shockley-Queisser (SQ) limit[12]. To illustrate the main limitations of these technologies, the fraction of the SQ limit achieved by all photovoltaic properties (Power conversion efficiency PCE, Fill Factor FF, Open Circuit Voltage V_{OC} and Short Circuit Current J_{SC}) of the most efficient solar cells as function of their bandgaps is depicted in Figure 1.

This figure highlights the gap between kesterite and chalcopyrite solar cells. The latter can reach up to 70% of the SQ efficiency limit at intermediate bandgap (1.05 – 1.2 eV) and 50% for the small ($CuInSe_2$: 0.96 eV) and wide ($Cu(In,Ga)S_2$: 1.57 eV) bandgaps while $CuInS_2$ and $CuGaSe_2$ are notably underperforming (~ 40% of SQ limit). The analysis of the most efficient CIGSSe solar cells (PCE > 22%) shows that these devices can exceed 90% of the SQ limit for FF and J_{SC} while V_{OC} stands in the 80%-85% range of this limit.

The picture for kesterite solar cell is totally different. The efficiency of the best devices can only reach 40% of the SQ limit and this value is further decrease to 30% at wider bandgaps (1.5 eV). The origin of these low efficiencies can be mainly attributed to a limited V_{OC}, which never surpasses 65% of SQ limit whereas FF and J_{SC} can reach up to 80% of this limit. Introduction of Ge in CZTGSe absorbers has been claimed to improve devices properties and particularly V_{OC}[22-26] but Ge containing devices currently do not outperform their Ge-free counterparts in literature. At low Ge content, FF and V_{OC} are similar to Ge-free CZTSSe solar cells but with lower J_{SC} while at higher content, an additional drop in FF is noticed. As Ge is listed in the CRM[3], CZTGSe solar cells will be discarded from the further analysis.

As far as Cd&CRM-free CZTSSe solar cells are concerned, the picture is even gloomier and replacement of the traditional CdS buffer layer systematically lowers V_{OC} and FF while J_{SC} seems to be less affected. Only two candidates emerge as possible candidate to be integrated in kesterite solar cells: ZnS(O,OH)[27,28] and ZnSnO[8,29]. Other possibilities such as ZnMgO already used in chalcopyrite solar cells have not been successfully tested so far. CZTSSe/ZnS(O,OH) materials reveals very poor performances (< 25% SQ limit) mainly limited by V_{OC} (< 50% of SQ limit) and FF (< 70% of SQ limit). ZnSnO buffer layers seems to be the most promising candidate with V_{OC} > 50% of SQ limit while FF and J_{SC} can surpass 70% of SQ limit. Particularly for pure sulfide CZTS absorbers (1.5 eV), solar cells with ZnSnO buffer layers outperform those with the CdS reference one[8] and exhibit similar performances as the state-of-the-art devices.

Different review articles have been published to tentatively explain the efficiency limitation of kesterite solar cells[11-14]. All of them notice first the large V_{OC} deficit (expressed as $E_G/q-V_{OC}$ where E_G is absorber bandgap and q the elemental charge) of kesterite devices followed by low FF and J_{SC} to a lesser extent similarly as the observation made in Figure 1. Starting from these review papers and updated with the most recent literature, a mapping of the fundamental failures in keserite solar cells has been drawn in Figure 2. The list of failure modes depicted in this mapping is summarized in table 2. A particular attention has been paid to the influence of Cd&CRM free buffer layer on device performances since to the best of our knowledge, no review publication does exist on this subject.

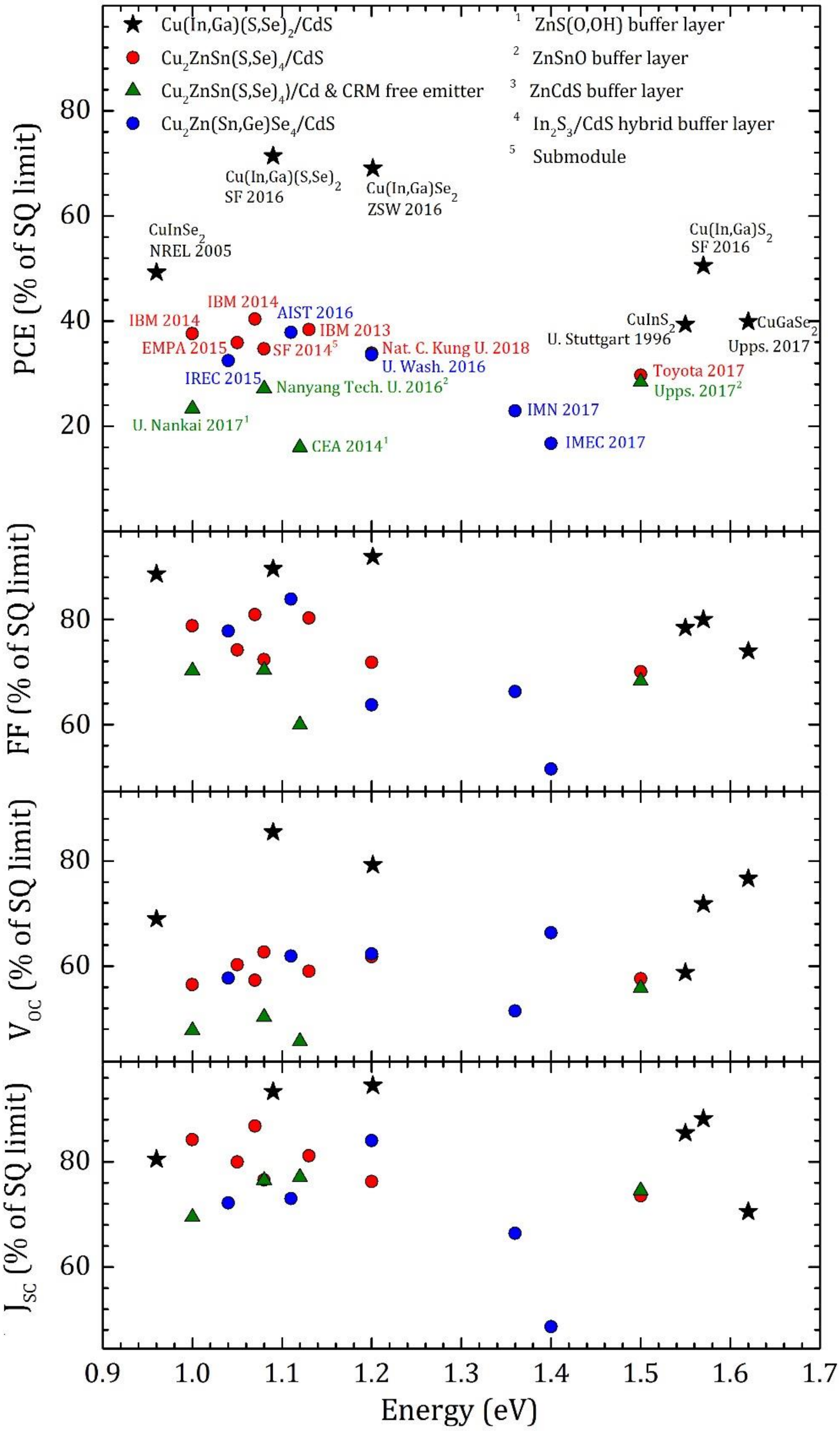


***Figure 1**: Fraction of the Schockley-Queisser limit (% of SQ limit) achieved by the PV properties of the record CIGSSe, CZTSSe, CZTGSSe Cd&CRM-free CZTSSe solar cells as function of their bandgap. Tabulated values of the SQ limit for all parameters from Reference[12]. PV data and related bandgaps from References[17-35]. Bandgaps are extracted from EQE spectra.*

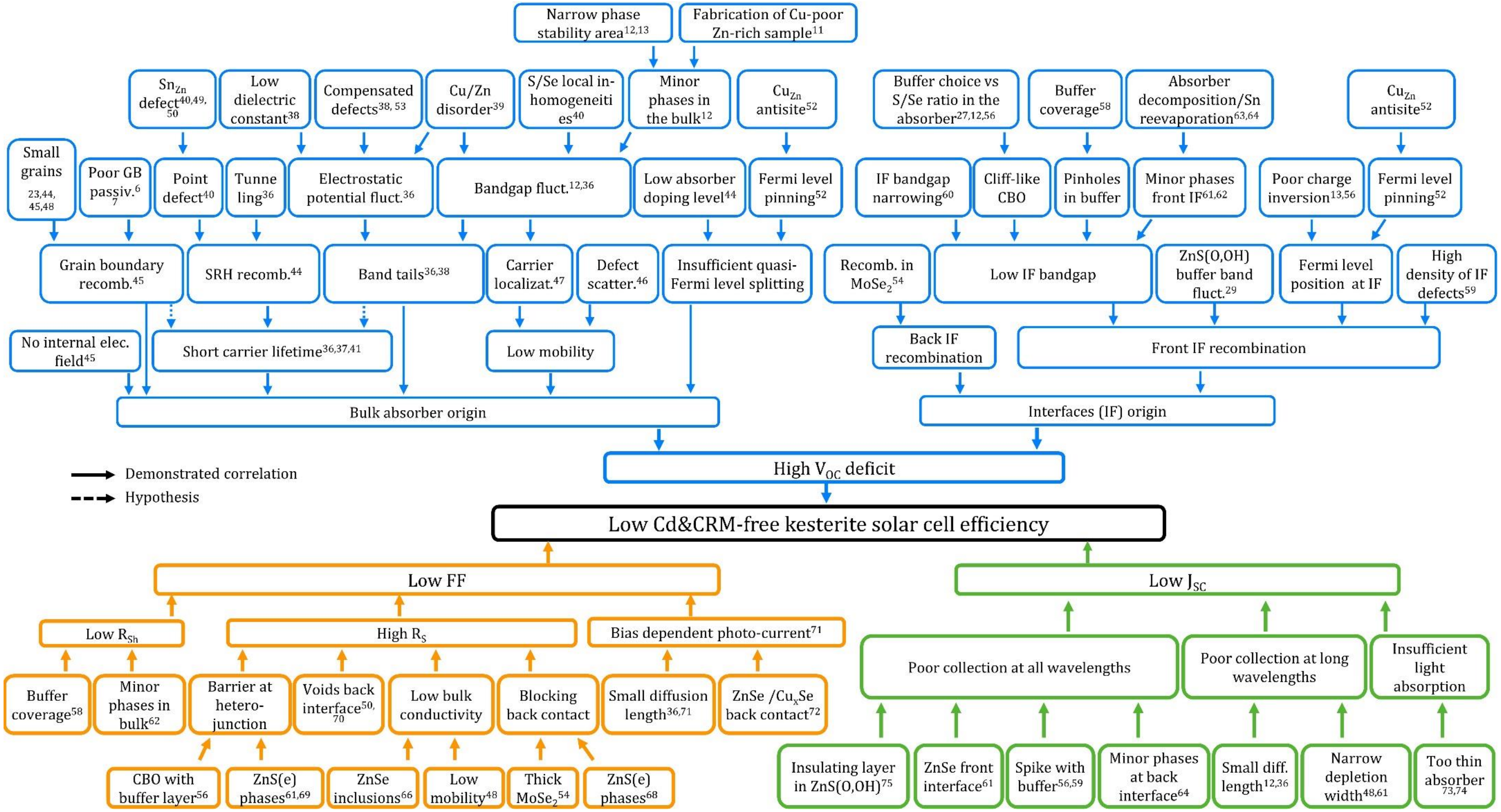


***Figure 2**: Mapping of the fundamental failures of Cd&CRM free kesterite solar cells*

***Table 2**: List of the failure modes identified in Figure 2*

#	Item/Function	Potential Failure Mode	Potential Effects of Failure	Potential Cause/ Mechanism of Failure
1	Back electrode	Carrier recombination in $MoSe_2$	V_{OC} deficit	Too thick $MoSe_2$
2	Back electrode	Resistive back contact	Low FF	Too thick $MoSe_2$
3	Absorber (back interface)	High R_S	Low FF	Voids at the back interface
4	Absorber (back interface)	High R_S	Low FF	ZnS(e) segregation close to the back contact
5	Absorber (back interface)	Bias dependent photo-current	Low FF	ZnS(e) and Cu_xS(e) close to the back contact due to decomposition on Mo
6	Absorber (bulk)	Low mobility	V_{OC} deficit	Defect scattering
7	Absorber (bulk)	Low mobility	V_{OC} deficit	Carrier localization due to bandgap fluctuations
8	Absorber (bulk)	Short carrier lifetime	V_{OC} deficit	SRH recombination on deep defect in the gap
9	Absorber (bulk)	Short carrier lifetime	V_{OC} deficit	Tunneling assisted recombination
10	Absorber (bulk)	Short carrier lifetime	V_{OC} deficit	Non-radiative carrier recombination through bi-molecular recombination
11	Absorber (bulk)	Grain boundary recombination	V_{OC} deficit	Grains too small & poor grain boundary passivation
12	Absorber (bulk)	Electrostatic potential fluctuations	V_{OC} deficit	Cu/Zn disorder
13	Absorber (bulk)	Electrostatic potential fluctuations	V_{OC} deficit	Very high concentration of compensated defect clusters + low dielectric constant
14	Absorber (bulk)	Bandgap fluctuations	V_{OC} deficit	Presence of secondary phases in the bulk
15	Absorber (bulk)	Bandgap fluctuations	V_{OC} deficit	Cu/Zn disorder
16	Absorber (bulk)	Bandgap fluctuations	V_{OC} deficit	S/Se local inhomogeneities
17	Absorber (bulk)	Absence of internal electric field	V_{OC} deficit	No bandgap gradient
18	Absorber (bulk)	Insufficient quasi fermi-level splitting	V_{OC} deficit	Quasi-fermi level pinning due to high defect (Cu_{Zn}) density
19	Absorber (bulk)	Insufficient quasi fermi-level splitting	V_{OC} deficit	Low doping level in absorber
20	Absorber (bulk)	Short carrier lifetime	Low FF	Non-radiative carrier recombination through bi-molecular recombination
21	Absorber (bulk)	Low R_{Sh}	Low FF	Secondary phases in the bulk ($SnSe_2$)
22	Absorber (bulk)	High R_S	Low FF	Low bulk absorber conductivity
23	Absorber (bulk)	High R_S	Low FF	Presence of ZnSe nano-inclusions

24	Absorber (bulk)	Bias dependent photo-current	Low FF	Small diffusion length in absorber
25	Absorber (bulk)	Poor collection at long wavelengths	Low J_{SC}	Small diffusion length in absorber/absence of bandgap gradient
26	Absorber (bulk)	Poor collection at long wavelengths	Low J_{SC}	Narrow depletion width (too high carrier concentration)
27	Absorber (bulk)	Insufficient light absorption	Low J_{SC}	Sulfur-based absorber too thin
28	Absorber (front interface)	Front interface recombination	V_{OC} deficit	Low interfacial bandgap due to bandgap narrowing (CZTS)
29	Absorber (front interface)	Front interface recombination	V_{OC} deficit	Presence of minor phases at front interface due to absorber decomposition (Sn-loss)
30	Absorber (front interface)	Front interface recombination	V_{OC} deficit	Fermi level position at the middle of hetero-interface (Fermi level pinning)
31	Absorber (front interface)	Front interface recombination	V_{OC} deficit	Poor / no charge inversion in kesterite absorber
32	Absorber (front interface)	Front interface recombination	V_{OC} deficit	High density of non-passivated surface defects
33	Absorber (front interface)	High R_S	Low FF	ZnS(e) secondary phase at the absorber surface
34	Absorber (front interface)	Poor collection at all wavelengths	Low J_{SC}	ZnS(e) secondary phase at the absorber surface
35	Buffer layer - ZnO	Front interface recombination	V_{OC} deficit	Cliff-band alignment with absorber
36	Buffer layer - ZnS(O,OH)	Recombination in buffer layer	V_{OC} deficit	Band fluctuation in buffer layer
37	Buffer layer by sputtering	Front interface recombination	V_{OC} deficit	Insufficient buffer coverage
38	Buffer layer by sputtered	Low R_{Sh}	Low FF	Insufficient buffer coverage
39	Buffer layer - ZnS(O,OH)	High R_S	Low FF	Spike too high at high S content in buffer layer
40	Buffer layer - ZnS(O,OH)	Poor light collection at all wavelengths	Low J_{SC}	Insulating layer formation close to the interface during buffer deposition
41	Buffer layer - ZnS(O,OH)	Poor light collection at all wavelengths	Low J_{SC}	Spike too high at high S content in buffer layer

V_{OC} deficit in kesterite solar cells can originate either from the bulk material or from its interfaces with supporting layers (buffer layer and Mo back electrode). The two main reasons generally invoked to explain this high V_{OC} deficit are a short minority carrier lifetime and the presence of band tails in the bulk of the absorber material[36-38]. It is worth noticing that both causes cannot be considered at the same level. While band tails (due to electrostatic potential fluctuations or bandgap fluctuations) are directly linked to structural defects in the material (presence of secondary phases in the bulk of the material[12], Cu/Zn disorder[39], locally inhomogeneous distribution of the anion[40], high level of compensated defects[38]), short minority carrier lifetime might be considered as a potential consequence of similar defects. Shockley-Read-Hall (SRH) recombination on point defects in the bulk of the absorber is generally said to be responsible for this short lifetime[42] but the influence of band tails, grain boundaries or even interfaces on lifetime is rarely discussed[13]. SRH recombination and tunneling-enhanced recombination[38], grain boundary recombination[43], low carrier mobility due to defect scattering[46] or carrier localization[50] and insufficient quasi-Fermi level splitting because of too low carrier density[51] or Fermi level pinning[52] are mentioned as well as responsible for this V_{OC} deficit. Moreover, the absence of internal electric field cannot counterbalance these poor electronic properties[43].

V_{OC} deficit of kesterite devices does not only arise from the bulk absorber but also from its interfaces with buffer layer and back electrode. A too thick $MoSe_2$ layer can impact device performance[54]. Although decomposition of the absorber in secondary phases on the back electrode has been observed[55], it has not be claimed to decrease V_{OC}. Front interface is said to be responsible for part of the V_{OC} deficit. Most of the papers discuss the conduction band offset (CBO) between absorber and buffer to form a “spike” at the interface (i.e. conduction band maximum (CBM) of the buffer layer slightly higher (< 0.5 eV) than CBM of the absorber layer). For instance CdS is not suitable at high S content in the absorber because of a negative CBO (“cliff” alignment)[12,27]. As far as Cd&CRM-free buffer layers are concerned: CBO with ZnO (- 0.1 eV) can lead to low V_{OC}[56], ZnSnO has a suitable CBO with CZTSSe for various S content in absorber[27-28] and if CBO with ZnS(O,OH) can be correctly adjusted[57], inhomogeneity in this buffer layer can drastically reduce V_{OC}[29]. Insufficient buffer coverage can also lead to decreased V_{OC}[58]. The position of Fermi level close to the middle of hetero-interface due to Fermi level pinning[52], the absence of charge inversion at hetero-interface[13,59], the high density of interface defects[59] and the presence of secondary phases at the interface[61,62] are mentioned as well to explain the V_{OC} deficit compared to CIGSSe solar cells. Concerning pure sulfide CZTS absorber, it has been demonstrated that bandgap narrowing at the front interface reduces V_{OC}[60].

As shown in Figure 1, kesterite solar cells and particularly Cd&CRM-free devices suffer as well from reduced FF compared to chalcopyrite ones[12,14]. This lower FF is mainly due to a higher series resistance (R_S)[64]: state-of-the-art CZTSSe devices exhibit R_S~0.7 Ω.cm^2 [17] compared to R_S~0.3 Ω.cm^2 for CIGSSe devices[31] and a slightly lower shunt resistance (R_{Sh}). This high R_S has been attributed partly to an insufficient bulk absorber conductivity[65]. The explanation can be found in a too low mobility[48] or in the presence of nano-inclusions of ZnSe secondary phases[69]. The influence of a blocking back contact[67] has been revised[65] but the presence of a thick $MoSe_2$ layer at the back interface[54] or the segregation of ZnSe close to the back interface[68] can anyway imply an additional R_S. Part of this high R_S can also be linked to a barrier at heterojunction due to the presence of a ZnS(e) phase at the surface of the absorber[61,69] or to the CBO with the buffer layer[56]. However, state-of-the-art solar cells with ZnS(O,OH) and ZnSnO buffer layers show similar FF as cells with reference CdS buffer layers[28-29]. It is still not clear whether the presence of voids at the back interface can impact the R_S or not[50,70].

Another source of FF loss in kesterite devices is linked to low R_{Sh} which can be due to the presence of secondary phases ($SnSe_2$) in the absorber[62] or to direct contact with the window layer because of insufficient buffer coverage[58]. Interestingly, devices with reasonable R_S and R_{Sh} in the dark can still suffer from low FF under AM1.5 illumination because of bias dependent current collection[71]. This effect can be related to small minority carrier diffusion length in the absorber[38,74] or to the presence of ZnSe and Cu_xSe close to the back contact[72].

Last, CZTSSe-based devices suffer from lower J_{SC} than CIGSSe-based ones with similar bandgaps (Figure 1). For pure sulfur CZTS, an insufficient light absorption because of too thin absorbers is noticed[73,74]. The presence of a potential barrier for photocurrent decrease current collection at all wavelengths of the external quantum efficiency (EQE) spectrum[61]. It can be caused by the presence of an insulating ZnSe layer at the top of the absorber[61], a too high spike at the buffer/absorber interface[56,57] or, in the case of ZnS(O,OH) buffer layers, the formation of a thin ZnS layer at the interface that impedes current collection[75]. The same effect is caused by the presence of secondary phases at the back contact[64] due to absorber decomposition on Mo[55]. Poor photocurrent collection at long wavelengths, which results from small diffusion length in the absorber[12,38] or a too narrow depletion width[48,61] can be responsible as well for the low J_{SC}.

2.2 Analysis of the figures of merit

The classification of the different failures modes with their respective RPN requires to quantify the figures of merit defined in section 1.3. As no production line for kesterite solar cells can provide reliable historical data to assess *severity*, *occurrence* and *non-detectability* of the different failure modes determined in section 2.1, an attempt to quantify these FOM has been made from literature. It should be noticed that the values obtained within section 2.2 are only estimations based on the data extracted from literature. A precise quantification of the failure mode on photovoltaic properties is sometimes provided (analysis of V_{OC} losses in References [38,40,41,78] for instance) but most of the time, lack of information leads to a rough estimation in Tables 3, 4 and 5. Moreover, contradictory studies can lead to controversial values for part of the FOM and the impact of some failure modes is still subject to debate.

2.2.1 Severity quantification in literature

Potential fluctuations (bandgap or electrostatic fluctuations) due to cationic disorder in kesterite solar cells are one of the main reasons evoked to explain their V_{OC} deficit in literature. Bourdais & al.[40] show that this disorder can account for a maximum deficit of 47 meV (< 10% of the V_{OC} deficit) and is not responsible for the majority of the loss. Similarly, S/(S+Se) inhomogeneities at macroscopic and microscopic scales are responsible for less than 30 meV of the V_{OC} deficit. Severity of these failures are relatively low. Additionally, the relative contributions of bandgap and electrostatic potential fluctuations (which originates from Cu/Zn disorder) to band tails is determined to be 70% and 30% respectively in Reference[76]. According to the authors, it explains the absence of correlation between V_{OC} deficit and Cu/Zn disorder as observed elsewhere[77].

In Reference[38], Hages & al. discuss quantitatively the impact of different parameters on voltage limitation at room temperature. While the increase in lifetime from 10 ns to 100 ns results in a ~150 mV higher V_{OC} (~ 25% relative gain), a 50% increase in the standard deviation for potential fluctuation would lead to a ~100 mV V_{OC} reduction (~15% relative loss). However, potential fluctuations in this study account for both bandgap and electrostatic fluctuations and regardless from their origin. Thus, this quantification cannot be attributed unambiguously to a defined failure mode. Suppression of tunneling assisted recombination can only improve V_{OC} by ~7% relative[38]. Hempel & al.[50] discuss the relative influence of low mobility and minority carrier lifetime on device performance. By comparison with chalcopyrite material, they attribute most of the losses to insufficient carrier lifetime while Gokmen & al.[77] draw an opposite conclusion and incriminate the low mobility. Other studies[41] quantify losses due to low carrier lifetime ("30-50 mV in V_{OC} and 2-4% absolute in efficiciency"). Another debated point in literature concerns the responsibility of interface recombination in V_{OC} deficit. While it has been argued to be a major contributor in some studies[79,80], this point has been questioned in Reference[81] and attributed to misinterpretation from data due to non-ideal device behavior.

A rough estimation of the severity of these failure modes from the available data found in literature is given in table 3.

***Table 3**: Estimation of the severity FOM from literature review*

Failure mode	**Severity**		
	Analysis	**Val.**	**Ref.**
#6-#7	*μ_e is considerably lower for CZTSSe compared to CIGSSe samples whereas τ, as determined by TRPL, is not much different*	6	[78]
#7	*the minority carrier mobility is not a real fundamental limit to photocurrent collection and thus device efficiency*	2	[50]
#8	*Significant improvements in the V_{OC} are expected […] from improvements in the minority carrier lifetime.*	6	[38]
	increasing lifetimes from 2 to 3 ns […] to>100 ns [would gain]30–50mV in V_{OC} and 2–4% absolute in efficiency	5	[41]
	μ_e is considerably lower for CZTSSe compared to CIGSSe samples whereas τ, as determined by TRPL, is not much different	2	[78]
#9	*an improvement in V_{OC} by only ~7% is estimated for CZTSSe as $E_{00} \rightarrow 0$*	3	[38]
#12	*The maximum potential V_{OC} deficit induced by the Cu/Zn disorder is only of 47 meV*	3	[40]
	The open circuit voltage deficit was not affected by the ordering degree.	1	[77]
#16	*a very negligible fraction (less than 2.5%) of the Voc deficit can be attributed to spatial bandgap fluctuation stemming from anion non-uniformity at the small scale*	2	[40]

2.2.2 Occurrence quantification in literature

Among the FOM used to classify the failure modes identified in kesterite technology, occurrence is probably the least documented in literature and if repeatability issues are of prime importance particularly in view of future industrialization, it is not often discussed at this early stage of development. Thus, assessing occurrence of each failure mode only with literature review is not possible and consequently another strategy has been used (see section 2.3).

A very interesting example of process variability is given in Reference[72] in which efficiencies of more than 100 devices over almost 3 years are presented. Variation in the results is attributed to ZnSe phase at the back interface leading to bias dependent photocurrent (failure mode # 5 in table 2). As most of the cells do not reach the maximum efficiency value, one can argue that occurrence is very high for this particular failure mode. However, among the tens of solar cells presented in this work, analysis of failure mode is based on the comparison of only 2 cells and it is thus not possible to know for certain that it is responsible for all low efficiency cells. This example reveals the difficulty for quantifying this FOM, particularly when no production line and in-line characterization tools are available.

In few cases however, quantification of occurrence is still possible without producing hundreds of samples. Bourdais & al.[40] have shown that CZTSSe samples can have a Cu/Zn disorder ranging from 20% to 100% at room temperature. They demonstrate as well that Cu/Zn disorder does not have an impact on solar cell efficiency in this range of values. However, samples with 0% disorder may exhibit higher efficiencies but are theoretically possible only at 0 K. Thus, an occurrence of 10 can be attributed to failure mode #12 in table 2 but it is impossible to evaluate simultaneously its severity.

Table 4: *Estimation of the occurence FOM from literature review*

Failure mode	**Occurence**		
	Analysis	**Val.**	**Ref.**
#5	- *[Comparison of] power conversion efficiency of more than 100 devices* - *we have analyzed the electrical and physical differences between two devices* - *The reason for the lower efficiency turned out to be a strong bias dependent photocurrent, likely caused by ZnSe secondary phases present at the back contact*	?	[72]
#12	*it is not practically possible to reach a degree of Cu-Zn order near S = 1*	10	[76]

2.2.3 Non-detectability quantification in literature

Short minority carrier lifetime are frequently evoked among the main culprit for V_{OC} deficit in kesterite solar cell[38,37,41]. Time-resolved photoluminescence (TRPL) is mostly used for determining these lifetimes and values of few nanoseconds are generally determined. However, Hages & al.[37] have demonstrated that extracting this crucial parameter from decay rate in TRPL signal is not straightforward and thus, non-detectability FOM related to failure modes #8 to #10 in table 2 are very high (estimated value > 8).

The presence of secondary phases in the bulk CZTSSe absorber is also mentioned as a limiting factor for device performances[12,82]. However, detection of part of these minor phases is not straightforward: due to signal overlapping, simple X-Ray Diffraction (XRD) cannot be used[82]. More sophisticated methods need thus to be employed, such as multi-wavelength Raman spectroscopy[84], X-ray absorption near edge structure analyses (XANES)[83], scanning transmission electron microscopy (STEM) in combination with energy dispersive X-ray spectroscopy[85] or atom probe tomography[66].

Moreover, detection level of secondary phases can be problematic as well. It has been demonstrated that, even with XRD refinement using Rietveld analysis, amounts of ZnS and Cu_2SnS_3 smaller than 10% and 50% respectively are not detectable in CZTS and that Raman spectroscopy using a green laser is unable to detect low level (30%) of Cu_2SnS_3[86]. Better accuracy for ZnS detection (3%) is obtained using XANES but requires the use of a synchrotron source and is better working for S samples than for Se samples[83].

Based on this literature review, values for the non-detectability indicator have been estimated and summarized in table 5.

Table 5*: Estimation of the non detectability FOM from literature review*

Failure mode	**Non-detectability**		
	Analysis	**Val.**	**Ref.**
#8-#10	*various nonideal absorber properties can dominate the TRPL signal making reliable extraction of the minority carrier lifetime not possible*	8	[37]
#4-#5-#23	*Zn-rich phases such as Zn(S,Se) or* $Cu_2Sn(S,Se)_3$ *X-ray reflections are difficult to separate from kesterite CZTSSe*	5	[82]
	GIXRD investigations[...] cannot be used to identify sufficiently small amounts of ZnS (<10%) or Cu_2SnS_3 *(<50%) phases in a mixed,* Cu_2ZnSnS_4 *containing sample*	5	[86]
	- *X-ray absorption near edge structures (XANES) at the sulfur K-edge* - *quantify the ZnS fraction with an absolute accuracy of ±3%* - *The investigation of the sulfurabsorption spectra is preferable*	8	[83]

2.2.4 RPN quantification from literature

An attempt to calculate RPN for the different failure modes defined in table 2 has been made from a literature review (Severity, Occurrence and Non-Detectability FOM are reported in table 3, 4 and 5 respectively). If the calculation of RPN for some failure modes seems to be possible (for instance, RPN related to low minority carrier lifetime #8 would be very high), two difficulties are encountered in most cases. First, an obvious lack of information does exist, which may be partially but not totally completed by a more exhaustive literature review to the best of our knowledge. Particularly, data concerning occurrence are not available for all failure modes. Second, table 3 shows that contradictory assessment for a single failure mode can be found in literature. For instance, opposite conclusions are drawn to evaluate severity for short minority carrier lifetime and low mobility in Reference[77] and Reference[38,41,50]. This contradiction can either be linked to different analyses of experimental results or more fundamentally can originate from differences in samples behavior that have been prepared by various techniques. Hence, it is not possible with literature review to determine the proportion of devices suffering from the different failure modes and consequently, drawing universal conclusions to determine the origin of efficiency limitations in kesterite devices would be problematic.

Another approach has been developed in the next section to circumvent this difficulty.

2.3 Risk priority number

When statistical data from production lines are not available to quantify the RPN for each failure mode, they need to be subjectively determined from knowledge and experience of the experts[9]. As this study has been carried out within the framework of the H2020 STARCELL project, it has been asked to all members of the consortium to evaluate the 3 FOM (Severity, Occurrence and Non-Detectability) for the failure modes listed in table 2 through the participation to a survey. This evaluation has been based on their own samples or on their own observations and is not extracted from literature review.

Figure 3 shows all answers to the survey. Part of the partners answered individually the survey (small points) while other groups sent joint answers (from 2 to 5 people, the data point size represents the number of participants). A total of 18 experienced scientists have evaluated the losses in kesterite devices.

First, it is noticeable that each failure mode has not been evaluated by all participants. Particularly failure modes related to the to the Cd&CRM-free buffer layers did not receive many notations which can be explained by the limited number of groups working on alternative buffer layers. As far as kesterite absorber or back contact are concerned, the following identified failure modes have been evaluated by less than 30% of participants: low mobility in kesterite absorber, complex recombination scheme (tunneling assisted recombination or bi-molecular recombination), insufficient quasi-Fermi level splitting, high concentration of compensated defects along with a low dielectric constant and heterointerface issues (position of the Fermi level at heterointerface and charge inversion in the absorber). On the contrary, the following failure modes have been evaluated by most of the groups (> 75 % participation): impact of the $MoSe_2$ thickness, short minority carrier lifetime due to SRH recombination and the presence of secondary phases ($SnSe_2$ in the bulk and ZnSe at the front interface).

Particularly, some failure modes have received a very high RPN only by a small minority of the experts (low mobility issues, quasi-Fermi level pinning, impact of low dielectric constant and tunneling assisted recombination). These evaluations are of course questionable due to the few replies, but a huge effort from the community is requested first and foremost to better understand the related limitations.

Variability in the answers from the participants needs as well to be analyzed. Weighted mean values over the failure modes for each FOM are similar (5.6, 5.4 and 5.3 for severity, occurrence and non-detectability respectively), but standard deviation for severity is noticeably higher (2.1) than those for occurrence and non-detectability (1.7 and 1.5 respectively). Thus, it seems that getting a consensus in the community to determine the impact of the most detrimental failure mode will be more challenging than determining their occurrence or detectability.

The variability in the answers can also be studied for each failure mode: the standard deviation divided by the weighted mean value of the RPN (Relative Standard Deviation RSD) given by all participants has been calculated for each failure mode. Highest values (5.3 and 1.2) have been obtained for failure modes #3 and #2 relative to the impact of back contact (presence of voids and too thick $MoSe_2$) on device series resistance. These high uncertainty has been obtained despite the fact that these failure modes have been evaluated by a majority of participants (11 and 14 respectively). Thus, impact of back contact on series resistance is clearly under debate, but is not considered as highly problematic (RPN < 50). Among the most open question (RSD > 1), one can find the origin of parasitic resistances (R_S and R_{Sh} due to minor phases in the bulk: #21 and #22) as well as detrimental behavior at the front interface (presence of secondary phase #29, insulating layer #40 or unfavorable band alignment #35). Impact of S/Se local inhomogeneity (#16) is also subject to debate.

On the other hand, it is agreed (RSD < 0.3, 90% of voters) that low minority carrier lifetime due to SRH recombination in the bulk is one of the most detrimental issues in kesterite devices (RPN = 491).

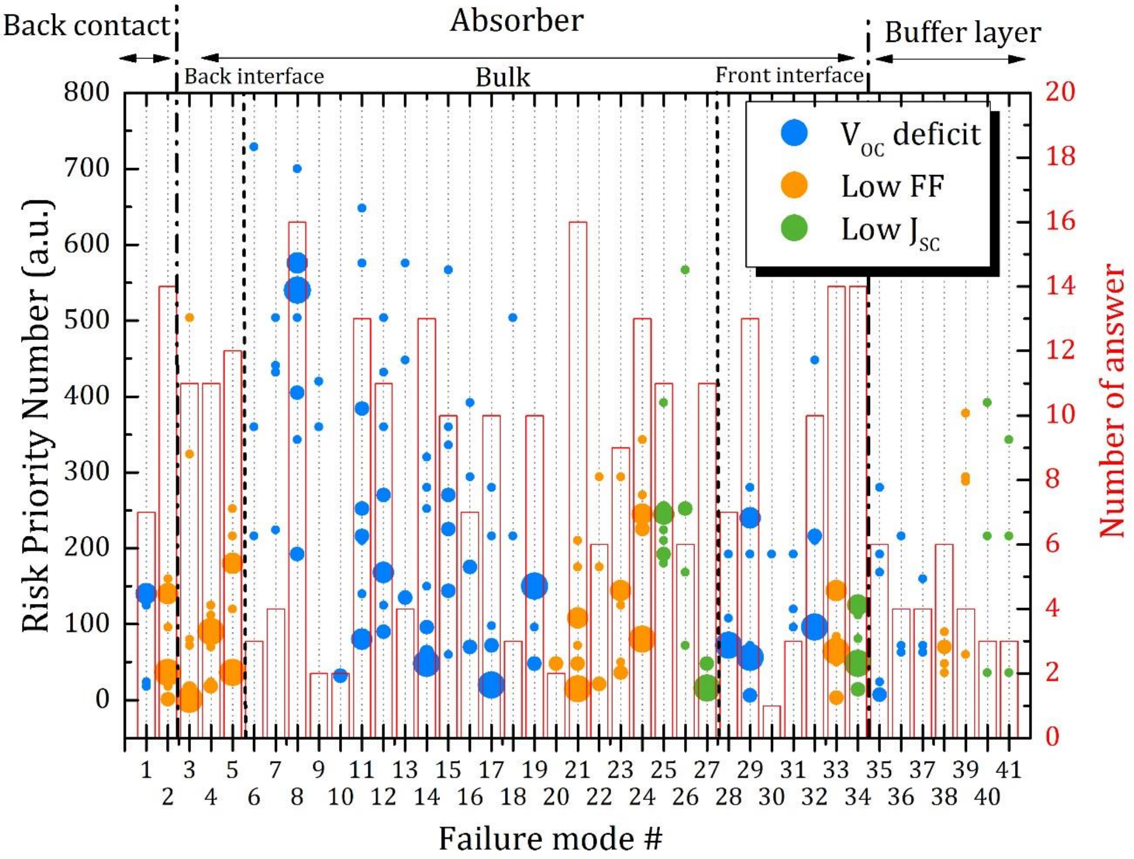


***Figure 3**: Detailed analysis of the answers to the survey. List of failure modes is given in Table 2. Each point correspond to an answer: its RPN value is given on the left scale, its size corresponds to the number of people answering and its colors indicate the effect on PV properties. Red data bars (scale on the right) indicates the number of answers received per failure mode.*

Figure 4 summarizes the data obtained from the survey. Weighted mean values for each FOM (Severity, Occurrence and Non-detectability) of all failure modes are shown (grey level, scale on the left) while related RPN are reported on the right. Similarly to Figure 3, the color indicates the effect of the failure mode on the PV properties of the device.

Unsurprisingly, failure modes leading to high V_{OC} deficit obtain the highest RPN. Particularly, values of 491 and 370 are found for short minority carrier lifetime (due to SRH recombination, #8) and electrostatic potential fluctuations (due to high concentration compensated defect cluster and low dielectric constant, #13). Solutions to tackle these issues in kesterite solar cells are crucially needed. Impact of grain boundary (#11, RPN = 269) and electrostatic potential fluctuation due to Cu/Zn disorder (#12, RPN = 225) are regarded by a majority of experts as other important causes for the V_{OC} deficit issue.

It must be noted as well that the RPN related to low mobility (due to defect scattering #6 or due to carrier localization in potential fluctuation #7) are extremely high (values of 420 and 422 respectively). Similarly, insufficient quasi-Fermi level splitting (#18, RPN = 504) and tunneling assisted recombination (#9, RPN = 398) are said to be major contributor to the V_{OC} deficit. However, the low participation (< 25%) to evaluate these 4 latter cases implies that first efforts should be devoted to correctly understand these issues before trying to care them.

As far as interfaces are concerned, front interface recombination (due to non-passivated surface defects #32) is identified as well as a major contribution to V_{OC} limitation (RPN = 209) whereas maximum RPN for failure modes related to back contact (#1 to #5) does not exceed 100. Thus, at the present stage of technological development, CZTSSe front interface is more problematic than its back interface.

Another point to be highlighted lies in the higher RPN for low J_{SC} than for low FF despite low FF is generally said to be the second reason for limited efficiencies in kesterite devices[12]. Particularly, low J_{SC} resulting from poor collection at long wavelengths (#26 and #25) have been identified as major issues. RPN of 253 and 219 have been attributed to these failures caused by narrow depletion width (too high carrier concentration) and by small diffusion length in absorber (along with the absence of bandgap gradient). The small diffusion length in absorber is also responsible for bias dependent photo-current, leading to limited FF (RPN = 165). Main limitation in FF (RPN = 231) is attributed to unfavorable band alignment for S-rich samples (#39) which is consistent with Figure 1: wide bandgap kesterite devices suffer from low FF compared to Se-based samples.

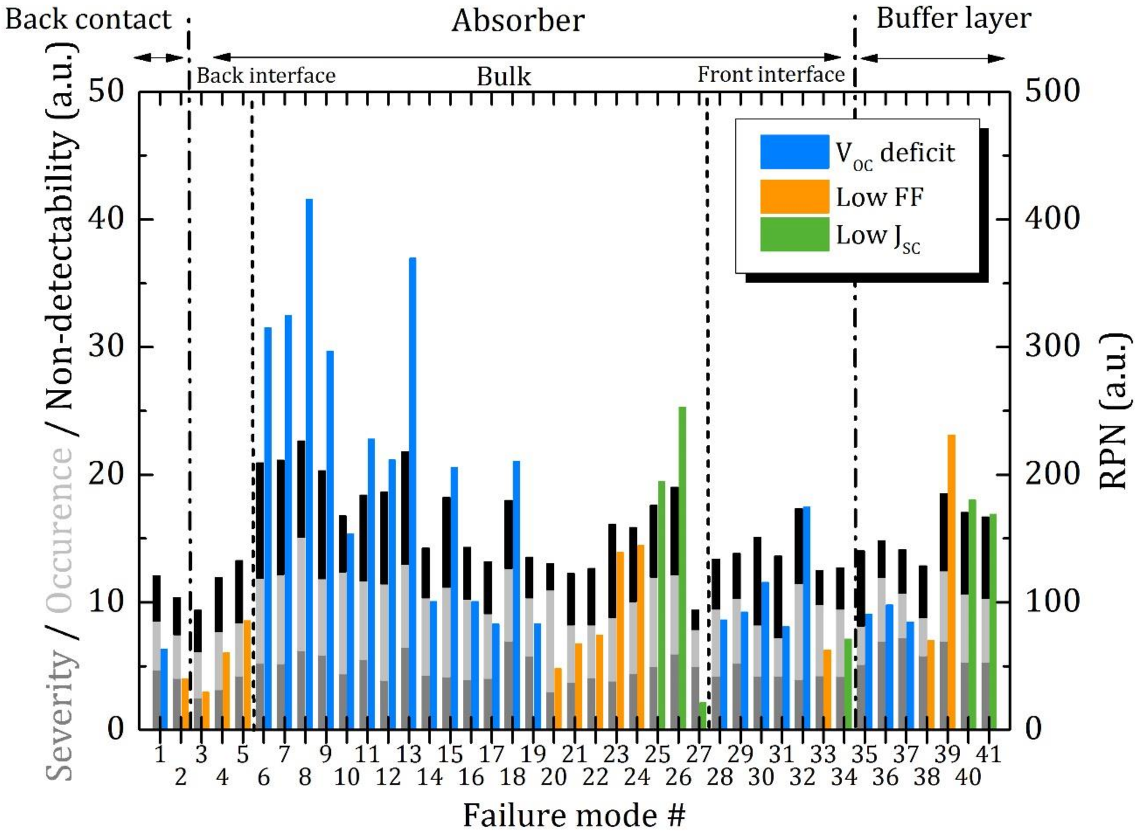


***Figure 4**: Summary of the answers. List of failure modes is given in Table 2. Mean values obtained for each FOM is shown in grey color (scale on the left). Mean value of the RPN is shown in color bars (same colors as in Figure 3, scale on the right).*

The 10 most critical failure modes (i.e. with the highest RPN) have been gathered and classified in a descending order in table 6. It is worth noticing that all of them are contributing to the V_{OC} deficit of the kesterite solar cells and are related to the bulk absorber itself except the failure mode #32 dealing with the front interface. It is important to understand that the values given in table 6 have not been scientifically demonstrated but have been assessed from the experience of 18 confirmed scientists and reflect the most up-to-date knowledge on kesterite technology. Thus, they need to be considered with care and can be subject to debate, particularly when they are estimated from a low number of responses. However, they give very clear indications where research efforts have to be devoted in order to improve efficiency of CZTSSe solar cells.

***Table 6**: List of the 10 failure modes with the highest RPN identified in the kesterite technology. All these failure modes are impacting the V_{OC} deficit of the solar cells.*

#	Potential Failure Mode	Potential Cause/ Mechanism of Failure	Number of answers	Severity	Occurrence	Non-detectability	RPN
8	Short carrier lifetime	SRH recombination on deep defect in the gap	14	7.3	8.4	7.9	478
18	Insufficient quasi Fermi level splitting	Quasi-fermi level pinning due to high defect (Cu_{Zn}) density	3	8.6	5.7	9.3	455
6	Low mobility	Defect scattering	3	7.0	6.7	9.0	420
13	Electrostatic potential fluctuations	Very high concentration of compensated defect clusters + low dielectric constant	4	6.8	7.0	8.7	410

7	Low mobility	Carrier localization due to bandgap fluctuations	4	6.6	7.0	8.8	407
9	Short carrier lifetime	Tunneling assisted recombination	2	7.8	6.0	8.3	384
11	Grain boundary recombination	Grains too small & poor grain boundary passivation	13	6.6	6.4	7.1	297
32	Front interface recombination	High density of non-passivated surface defects	8	5.8	7.0	7.2	291
12	Electrostatic potential fluctuations	Cu/Zn disorder	11	5.3	7.7	6.8	273
15	Bandgap fluctuations	Cu/Zn disorder	10	5.3	7.3	6.6	253

3. Conclusions

This study describes an FMEA study of kesterite solar cells with an additional focus on Cd&CRM free devices. A systematic and exhaustive literature review has been conducted to determine the origin of the photovoltaic limitations in kesterite devices including those with alternative buffer layer. A particular attention has been paid to the demonstration of the causes of each failure mode. However, the physical origin of short minority carrier lifetime which is said to be responsible for a significant part of the V_{OC} deficit is barely discussed.

As this literature review does not allow to quantify the FOM related to these failure modes and thus does not allow to classify them, an alternative solution has been chosen. A survey has been distributed within the consortium of the STARCELL project; an evaluation of the kesterite devices failure modes has been brought by 18 scientific experts. This original feedback on concrete experience allows to quantify and classify the limitations in CZTSSe solar cells.

Short minority carrier lifetime and presence of band tails are mostly identified as culprits for the V_{OC} deficit, which is the main limitation for device efficiency. However, few contributions have noticed as well the possible very detrimental impact of insufficient quasi Fermi level splitting and low carrier mobility, which must be subject of high attention. Last, a consensus emerges on the fact that limitations in kesterite technologies arise from the bulk absorber itself rather than from its interfaces.

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