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LETID in legacy and modern PV modules: accelerated testing and field deployment

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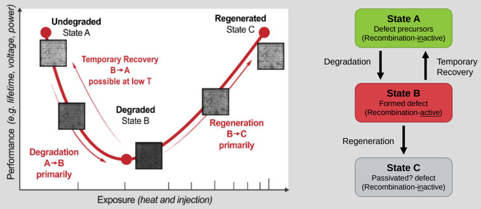
The kinetics of light- and elevated temperature-induced degradation (LETID) in silicon solar cells depend on the precise operating excess carrier density (*Δn*) of the device. This dependency causes differences in the way LETID manifests in modern, higher-efficiency devices compared to lower-efficiency, legacy devices that might have been deployed in the field in previous years. In this work we model how different vintages of devices are expected to behave in both accelerated laboratory testing, as well as field deployment. The differing excess carrier densities encountered in various module vintages has implications both for interpreting accelerated test data, as well as identifying, diagnosing, and potentially treating LETID in the field.

Motivation

- ~**10 years** between the discovery of LETID and codification of a formal test for it:
  - Early reports of LETID showed >10% power loss [1]
  - Today's products likely have little LETID susceptibility
  - Future products can be tested according to forthcoming IEC TS 63342 [2]
- This 10-year period also coincides with transition of industry from primarily **BSF** to primarily modern Cz-Si **PERC** cells. During this time, many GW of LETID-sensitive modules (both BSF ***and*** PERC) may have been deployed. (BSF cells can be LETID-sensitive too!) [3]
- Modern cells have **higher** bulk and effective **lifetime** (τ), therefore operate at a point of **greater excess carrier density** (Δn)
- LETID defect transitions are known to be **accelerated by *Δn***
  - ➢ **To predict LETID rates, one must be able to estimate *Δn* in the device!**

Characteristics of LETID



Schematic of LETID-related performance loss and recovery in c-Si wafers, cells, or modules, and the primary defect states and transitions associated with performance changes. Note that more defect states and transitions are known to exist, but the degradation → regeneration cycle depicted here are the most relevant for field conditions and accelerated testing. Temporary recovery of defects from State B→A may play an important role with injection at low-to-moderate temperatures. Luminescence images of a LETID-affected cell show the loss and recovery of minority charge carrier lifetime and performance as LETID progresses.

$$\frac{dN_A}{dt} = k_{BA}\cdot N_B + k_{AB}\cdot N_A$$

$$\frac{dN_B}{dt} = k_{AB}\cdot N_A + k_{CB}\cdot N_C - (k_{BA}+k_{BC})\,N_B$$

$$\frac{dN_C}{dt} = k_{BC}\cdot N_B - k_{CB}\cdot N_C$$

$$k_{ij} = \nu_{ij}\cdot e^{\frac{E_{a,ij}}{kT}}$$

$$\nu_{ij} = \nu'_{ij}\cdot \Delta n^{x_{ij}}$$

Transition ($i \rightarrow j$)	$x_{i,j}$	E_a (eV)	ν'_{ij}
Degradation A → B	1.0	0.827	4.67×10^{7}
Regeneration B → C	1.2	0.871	1.99×10^{7}
Temporary Recovery [4] B → A	1.7	-1.15	4.70×10^{-25}

LETID kinetic parameters used in this work. See references [4-5].

Lifetime loss results in power loss

Minority carrier lifetime is proportional to the # of defects in state B: N_B

$$\tau(t) \propto 1/N_B(t)$$

Minority carrier lifetime loss results in

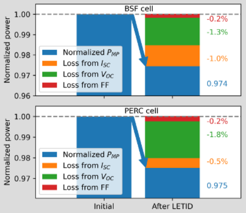
- **Voltage loss**

$$\tau \propto \frac{1}{J_0} \qquad V = \frac{kT}{q}\ln\left(\frac{J}{J_0}\right)$$

- **Fill factor (FF) loss**

$$FF = \frac{v_{oc} - \ln(v_{oc}+0.72)}{v_{oc}+1} \quad [6]$$

- **Current loss**
  - Especially if minority carrier diffusion length is < wafer thickness
  - Experiments have shown **roughly equal % V and I loss** from LETID [7]
  - **More work to do** to understand LETID-related current losses in different devices

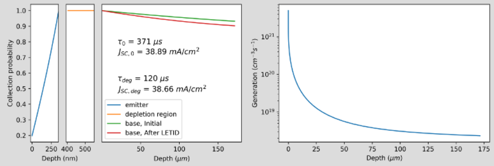


Modeled power, current (I_{SC}), voltage (V_{OC}), and fill factor (FF) loss from LETID for a BSF cell (top) and PERC-like cell (bottom).

How to model current loss?

- **Minority carrier lifetime can be related to a collection probability** profile by making **reasonable assumptions** about the cell front & junction, minority carrier diffusivity in the base, and rear surface recombination [8-9]
- Optical generation profile for a c-Si cell using reasonable assumptions

$$J_{SC} = q\int_0^W CP(z)G(z)dz$$



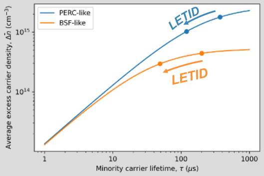
(Left) Collection probability calculated for a modeled PERC-like cell before and after modeled LETID lifetime loss. (Right) Generation profile calculated by OPAL2 [10] for a 180-μm-thick, SiN_x-coated, textured wafer under AM1.5G illumination. Integrating through the wafer depth provides an estimate of J_{SC}.

Δn in PERC vs. BSF devices

- Reasonable assumptions suggest ***Δn* will be ~4× higher in PERC devices**, both before and after LETID-related lifetime loss [11]
- Therefore, each transition $i \rightarrow j$ **will proceed faster by a factor of** $\sim 4^{x_{ij}}$ in PERC vs. BSF devices

BSF-like module		
τ_0 (μs)	τ_{deg} (μs)	S_{rear} (cm/s)
200	49	500
PERC-like module		
τ_0 (μs)	τ_{deg} (μs)	S_{rear} (cm/s)
371	120	90 (effective)

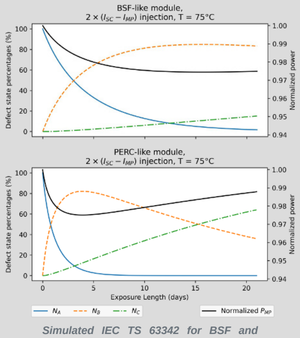
Assumptions for BSF-like and PERC-like devices modeled in this work. See references [5, 12] for justification for τ_0 and S_{rear}. τ_{deg} chosen such that maximum modeled LETID susceptibility is ~2.5% for each cell type.



Excess carrier density Δn modeled for BSF-like and PERC-like devices before and after LETID degradation.

Modeling the IEC TS 63342 test procedure

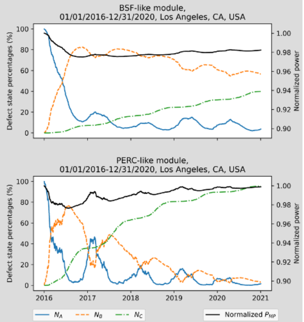
- IEC TS 63342 expected to be published in 2022
- Prescribes up to 3 weeks of dark current injection equal to $2\times(I_{SC} - I_{MP})$ at 75°C
- Stop criteria: anytime after 1 week if module has begun to improve
- BSF-like module at right would be tested for 3 weeks, PERC-like module test could be stopped after ~1 week
  - These modules have roughly equal maximum LETID susceptibility, but ~4× difference in time to maximum degradation



Simulated IEC TS 63342 for BSF and PERC-like modules with roughly equal maximum LETID susceptibility (~2.5%).

Modeling outdoor systems

- 5 years simulated outdoor deployment in Los Angeles using NSRDB data and pvlib-python
- For both modules, the degradation reaches its maximum (~2% power loss) within the first year.
- **BSF** module **regenerates very slowly**: after 5 years, power has barely recovered
- **PERC** module **regenerates more quickly**, also exhibits more **seasonality** due to **temporary recovery in winter**
- LETID-related **energy yield loss is substantially different** in BSF vs. PERC modules, even though modeled **LETID susceptibility is roughly the same**



Five years simulated outdoor deployment in Los Angeles, CA, USA for BSF and PERC-like modules with roughly equal LETID susceptibility.

Conclusions

- **LETID will progress faster in modern PERC-like** devices than in **legacy, BSF**-like devices because of **higher *Δn***.
- Indoor accelerated testing (e.g., IEC TS 63342):
  - **Modern**, higher injection devices will reach degradation saturation **more quickly** than older, lower injection devices
  - Tests may be stopped sooner
- Outdoors:
  - **Modern devices will regenerate more quickly**. Legacy devices **may never regenerate** completely.
  - ➢ **Energy yield losses** in **legacy devices could be substantial**.
  - **Climate** plays an **important** role: hotter ambient T prevents temporary recovery, speeds up regeneration

➢ Accurately estimating LETID rates **requires careful characterization** to reasonably accurately estimate Δn, τ_0, & τ_{deg}

- Open-source **LETID modeling tools** are **in development**, **expected late 2022**.
- Future modelling improvements:
  - Robust LETID-related current loss modeling
  - Robust defect electronic model (injection-dependence of LETID defect)
  - Validation against controlled experiments
- Future studies:
  - Explore the effects of climate & device details on LETID energy yield loss
  - Explore the potential of in-field accelerated regeneration of LETID-degraded modules (increase T, increase injection)

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