An open-source python library for modeling LETID and LID in silicon solar cells and wafers

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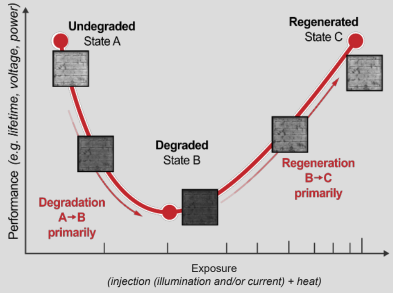
This poster demonstrates an (*in development*) open-source software library, written in python, to aid in modeling and understanding light- and elevated temperature-induced degradation (LETID) and boron-oxygen light-induced degradation (B-O LID) in silicon solar cells and wafers. We discuss the underlying equations and necessary input parameters for constructing realistic models. We demonstrate several use cases for the library, including modeling LETID progression in scenarios like indoor, accelerated tests and outdoor field deployment. We also demonstrate using the library to model B-O LID, and we demonstrate using the library to model degradation in passivated wafers, rather than solar cells.

Review of LETID and B-O LID



J. Karas *et al.*, *Progress in Photovoltaics: Research and Applications*, 2022, doi: 10.1002/pip.3573.
I. L. Repins *et al.*, *MRS Bulletin*, 2023, doi: 10.1557/s43577-022-00438-8.

- Light- and elevated temperature-induced degradation (LETID)
  - Relatively recently-discovered degradation mode in silicon
  - Some early cases showed ~10% degradation; more typically 0-3%
  - Losses will eventually "regenerate", but this may take decades, depending on climate and technology
- Boron-oxygen light-induced degradation (B-O LID)
  - More well-known and better understood defect in mono c-Si
  - Motivated the industry transition to Ga-doped wafers
  - Compared to LETID: faster and less severe. Often accounted for by "First Year" losses in warranties and financial models.
- Both LETID and B-O LID can be described by a 3-state model
  - Degradation (A → B) followed by regeneration (B → C)
  - Kinetics and time constants are different in LETID and B-O LID, but they can be modeled similarly.
- Progression between states depends on time, carrier injection (either illumination or electrical current), and temperature.

LETID and B-O LID Modeling

Performance loss is a function of the number of defects in state B.

$$Degradation \propto N_B$$

Defect state transitions depend on simultaneous, competing reaction rates

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

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

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

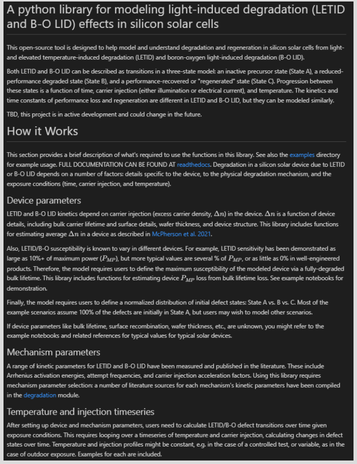
Reaction rates (k_{ij}) have Arrhenius behavior, with modification for injection (excess electronic carrier density in the device)

Kinetic parameters taken from literature: $E_{a,ij} \mid v'_{ij} \mid x_{ij}$

$$k_{ij} = v_{ij} \cdot \exp\left(\frac{E_{a,ij}}{kT}\right)$$

$$v_{ij} = v'_{ij} \cdot \Delta n^{x_{ij}}$$

Library in development



A python library for modeling light-induced degradation (LETID and B-O LID) effects in silicon solar cells

This open-source tool is designed to help model and understand degradation and regeneration in silicon solar cells from light- and elevated temperature-induced degradation (LETID) and boron-oxygen light-induced degradation (B-O LID).

Both LETID and B-O LID can be described as transitions in a three-state model: an inactive precursor state (State A), a reduced-performance degraded state (State B), and a performance-recovered or "regenerated" state (State C). Progression between these states is a function of time, carrier injection (either illumination or electrical current), and temperature. The kinetics and time constants of performance loss and regeneration are different in LETID and B-O LID, but they can be modeled similarly.

TBD, this project is in active development and could change in the future.

How it Works

This section provides a brief description of what's required to use the functions in this library. See also the examples directory for example usage. FULL DOCUMENTATION CAN BE FOUND AT readthedocs. Degradation in a silicon solar device due to LETID or B-O LID depends on a number of factors: details specific to the device, to the physical degradation mechanism, and the exposure conditions (time, carrier injection, and temperature).

Device parameters

LETID and B-O LID kinetics depend on carrier injection (excess carrier density, Δn) in the device. Δn is a function of device details, including bulk carrier lifetime and surface details, wafer thickness, and device structure. This library includes functions for estimating average Δn in a device as described in McPherson et al. 2021.

Also, LETID/B-O susceptibility is known to vary in different devices. For example, LETID sensitivity has been demonstrated as large as 10%+ of maximum power (P_{MP}), but more typical values are several % of P_{MP}, or as little as 0% in well-engineered products. Therefore, the model requires users to define the maximum susceptibility of the modeled device via a fully-degraded bulk lifetime. This library includes functions for estimating device P_{MP} loss from bulk lifetime loss. See example notebooks for demonstration.

Finally, the model requires users to define a normalized distribution of initial defect states: State A vs. B vs. C. Most of the example scenarios assume 100% of the defects are initially in State A, but users may wish to model other scenarios.

If device parameters like bulk lifetime, surface recombination, wafer thickness, etc., are unknown, you might refer to the example notebooks and related references for typical values for typical solar devices.

Mechanism parameters

A range of kinetic parameters for LETID and B-O LID have been measured and published in the literature. These include Arrhenius activation energies, attempt frequencies, and carrier injection acceleration factors. Using this library requires mechanism parameter selection: a number of literature sources for each mechanism's kinetic parameters have been compiled in the degradation module.

Temperature and injection timeseries

After setting up device and mechanism parameters, users need to calculate LETID/B-O defect transitions over time given exposure conditions. This requires looping over a timeseries of temperature and carrier injection, calculating changes in defect states over time. Temperature and injection profiles might be constant, e.g. in the case of a controlled test, or variable, as in the case of outdoor exposure. Examples for each are included.

Required inputs:
- **Device parameters**
  - **Bulk lifetime (initial | degraded), surface recombination, wafer thickness, device structure (cell | passivated wafer)**
  - **Suggested example values included**
- **Mechanism parameters**
  - **LETID or B-O LID kinetic parameters taken from literature sources (included)**
- **Temperature and injection timeseries**
  - **Time, temperature, injection (irradiance or applied current, operating point)**

Example: LETID progression in accelerated tests

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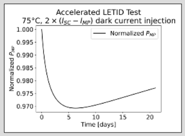
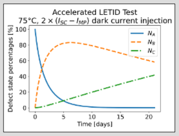
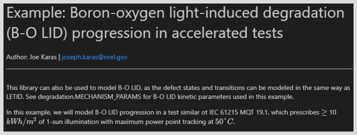
Several standardized accelerated tests have been developed for LETID. These include IEC TS 63342 for c-Si photovoltaic modules, and IEC TS 63202-4 for c-Si photovoltaic cells. Both procedures essentially prescribe exposure to constant light or current injection at constant elevated temperature for a prescribed duration of time. This notebook demonstrates how to use this library to model device behavior in such a procedure.

What happens in an accelerated LETID test?
- **IEC TS 63342**
- **3 weeks, 2 × (I_{SC}-I_{MP}), 75° C**





Use cases:
- Compare model to real test results
- Differentiate between LETID and B-O LID in tests



Example: Boron-oxygen light-induced degradation (B-O LID) progression in accelerated tests

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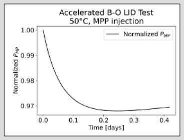
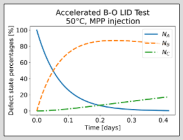
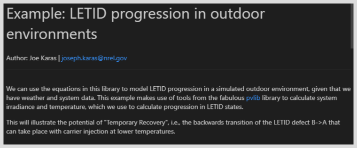
This library can also be used to model B-O LID, as the defect states and transitions can be modeled in the same way as LETID. See degradation.MECHANISM_PARAMS for B-O LID kinetic parameters used in this example.

In this example, we will model B-O LID progression in a test similar ot IEC 61215 MQT 19.1, which prescribes ≥ 10 kWh/m^2 of 1-sun illumination with maximum power point tracking at $50^\circ C$.

What happens in an accelerated B-O LID test?
- **(IEC 61215 MQT 19.1)**
- **10h, MPP, 50° C**







Example: LETID progression in outdoor environments

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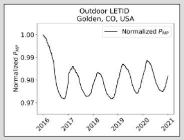
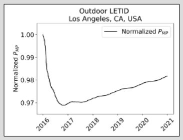
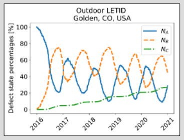
We can use the equations in this library to model LETID progression in a simulated outdoor environment, given that we have weather and system data. This example makes use of tools from the fabulous pvlib library to calculate system irradiance and temperature, which we use to calculate progression in LETID states.

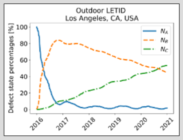
This will illustrate the potential of "Temporary Recovery", i.e., the backwards transition of the LETID defect B->A that can take place with carrier injection at lower temperatures.

What does LETID look like in different climates?
5 years in Golden CO vs. Los Angeles CA
weather data and injection (POA irradiance assuming continuous MPP tracking) via NSRDB & pvlib



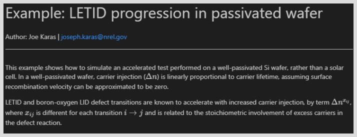






Temporary Recovery (B→A transition, which can dominate with injection at low temperature), results in substantial seasonal "recovery" during winter in cooler climates, but slows regeneration overall.

Use cases:
- Model LETID risk across climates and technology types (e.g., export degradation profiles to SAM/PVSyst)
- Compare modeled degradation to real outdoor data to aid in diagnosing LETID



Example: LETID progression in passivated wafer

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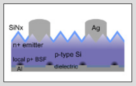
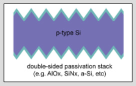
This example shows how to simulate an accelerated test performed on a well-passivated Si wafer, rather than a solar cell. In a well-passivated wafer, carrier injection (Δn) is linearly proportional to carrier lifetime, assuming surface recombination velocity can be approximated to be zero.

LETID and boron-oxygen LID defect transitions are known to accelerate with increased carrier injection, by term $\Delta n^{x_{ij}}$, where x_{ij} is different for each transition $i \rightarrow j$ and is related to the stoichiometric involvement of excess carriers in the defect reaction.

Can we model experiments performed on passivated Si wafers (instead of cells)?
- **Academic experiments are often performed on wafers, rather than finished solar cell structures.**



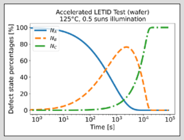
Typical PERC cell structure

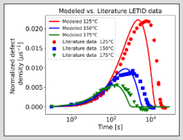


Typical passivated wafer structure

Example device parameters

	PERC cell	Passivated wafer
Undegraded bulk lifetime (States A & C), τ_0 (μs)	115	350
Degraded bulk lifetime (State B), τ_{deg} (μs)	55	40
Surface recombination velocity, s_{rear} (cm/s)	45	N/A
Wafer thickness (μm)	180	180





Use cases:
- Compare model to real experimental data
- Cross-compare literature results taken under different conditions
- Evaluate kinetic parameters published in literature

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