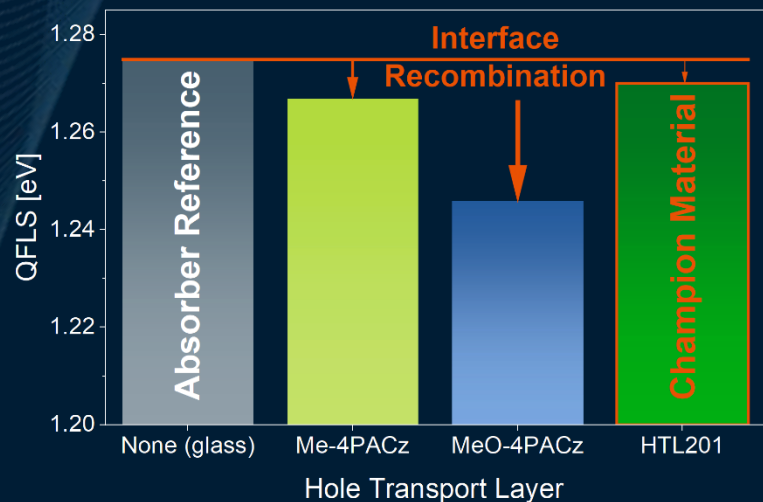
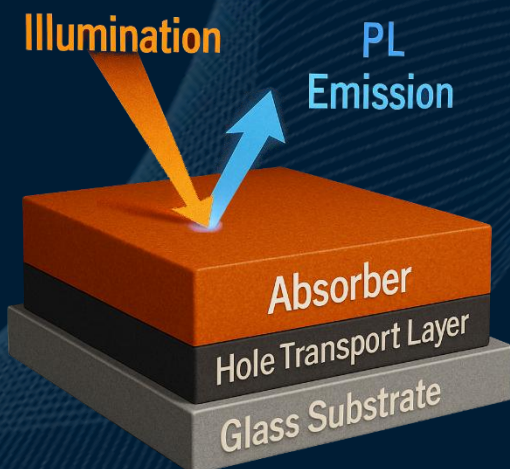
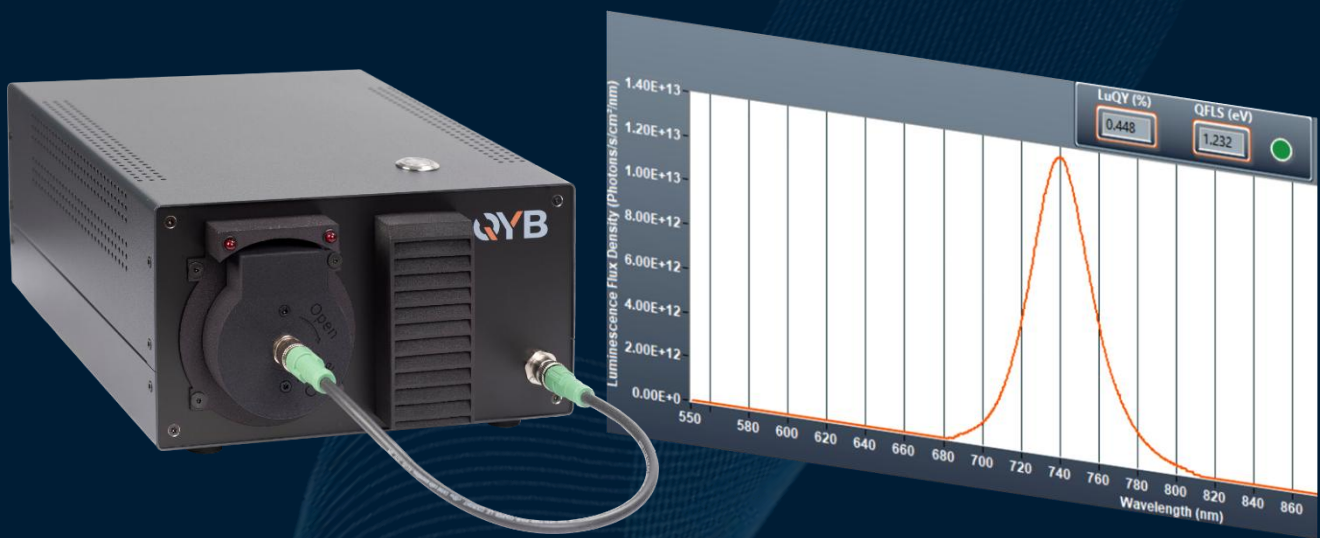


Application Note:

Characterizing Semiconductor Quality with PLQY & QFLS Using the LuQY Pro



Executive Summary

This report introduces the **LuQY Pro**, a metrology system for characterizing and optimizing semiconductor layers and devices. This application note highlights two key metrics: **photoluminescence quantum yield (PLQY)** and the **quasi-Fermi level splitting (QFLS)**.

- **PLQY** represents a semiconductor's radiative efficiency which correlates with the material quality.
- **High PLQY values** indicate **excellent material quality**, with fewer material defects and impurities, good passivation at surfaces and interfaces, and low trap-assisted Shockley-Read-Hall (SRH) recombination
- **QFLS** is the energy separation between electron and hole quasi-Fermi levels under illumination. It represents the maximum theoretical voltage a device can produce (iV_{oc}), revealing potential losses before full device fabrication.
- Both metrics are **crucial in the development of high-performance semiconductors** for LEDs and solar cells, providing **deep insights into material quality and device potential long before full device fabrication**

The note details how these metrics are used for applications like interface engineering and process optimization.

The LuQY Pro system offers a precise method for R&D on high-performance LEDs and solar cells.

- The LuQY Pro is a fully integrated instrument for swiftly and accurately measuring **PLQY** and **QFLS**.
- Working within a spectral range of 550-1050 nm, with laser intensity control from 0.001 to 10 suns. This allows for non-destructive and rapid material testing at specific operating conditions.
- **LuQY-Control software** allows to calculate **QFLS**, offering both a **direct mode** for quick estimates and a **detailed mode** that uses EQE data for enhanced accuracy.
- Its compact, plug-and-play design is ideal for lab environments, compatible with gloveboxes, and it boasts high sensitivity for materials with very low PLQY

1. Introduction

In the development of high-performance thin-film semiconductors—particularly for LEDs and solar cells—understanding non-radiative recombination losses is critical. Two key photophysical parameters in this context are **Photoluminescence Quantum Yield (PLQY)** and **Quasi-Fermi Level Splitting (QFLS)**. These parameters offer deep insights into material quality and device potential well before full device fabrication. The **LuQY Pro** is a versatile measurement system that enables swift, accurate, and non-destructive evaluation of these parameters. It offers a **non-contact and pre-fabrication assessment** of a device's performance potential which dramatically accelerates your research.

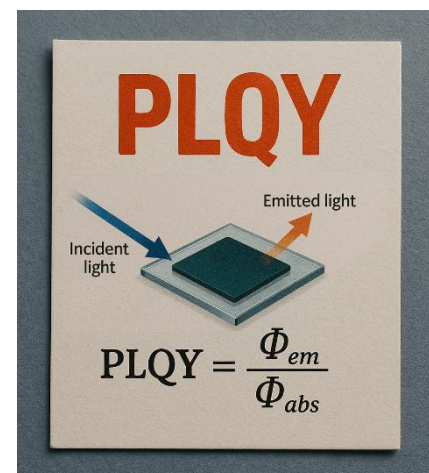
2. What Is PLQY and QFLS?

Photoluminescence Quantum Yield (PLQY)

When a photon is absorbed in a semiconductor and excites an electron from the valence band to the conduction band:

- Excited electrons and holes can recombine **radiatively**, emitting a photon (good!).
- Or they can recombine **non-radiatively**, transferring their energy typically to vibrational modes (phonons) into the lattice, heating the material (bad!).

PLQY is the ratio of radiatively emitted (good!) to totally absorbed photons in a semiconductor excited by light.



$$PLQY = \frac{\text{Number of emitted photons}}{\text{Number of absorbed photons}} \quad (1)$$

It is a direct indicator of the **radiative efficiency**, revealing how much of the absorbed energy is lost as heat through non-radiative recombination. High PLQY values typically correspond to:

- Fewer material defects and impurities
- Good passivation at surfaces and interfaces
- Low trap-assisted Shockley–Read–Hall (SRH) recombination

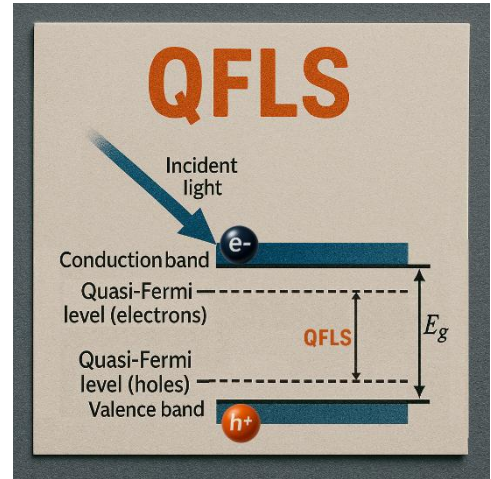
Interpretation of PLQY Values

PLQY Value	Interpretation
10-100%	Nearly all recombination is radiative → Excellent material quality (like GaAs).
0.1-10%	Increased amount of non-radiative losses; still allowing for highly efficient solar cells (e.g. world record cells in perovskites).
0.01 – 0.1%	Significant non-radiative losses; material still usable but improvements recommended.
< 0.01%	Dominant non-radiative recombination; poor optoelectronic quality.

Quasi-Fermi Level Splitting (QFLS)

Quasi-Fermi Level Splitting (QFLS) refers to the energy separation between electron and hole quasi-Fermi levels under illumination. It represents the **maximum achievable open-circuit voltage (Voc)** if there were no potential losses between the bulk of the absorber and the external contacts (i.e., ideal contacts).

In thermodynamic equilibrium (dark conditions), the Fermi level is flat. But under illumination, electrons and holes accumulate in conduction and valence bands, respectively. This **separates the quasi-Fermi levels** for electrons (E_{Fn}) and holes (E_{Fp}).



QFLS is thus defined as the energy difference between these quasi-Fermi levels:

$$QFLS = E_{Fn} - E_{Fp}. \quad (2)$$

Further, it is directly linked to the **implied open-circuit voltage (iV_{oc})**:

$$iV_{oc} = e \cdot QFLS, \quad (3)$$

where e is the elementary charge.

Thus, the QFLS represents the **maximum possible voltage** the device could output under illumination if there were **no energy losses between the bulk of the absorber and the external contacts** – e.g. from misaligned work functions at electrodes or mobile ions accumulating at interfaces. For more details, please refer to Warby et al. 2023 [1].

[1] Warby et al., Mismatch of Quasi-Fermi Level Splitting and Voc in Perovskite Solar Cells. *Adv. Energy Mater.* Vol. 13, Issue 48, **2023**, 2303135.

3. Applications of PLQY and QFLS

In summary, what do we learn from PLQY and QFLS?

Metric	Reflects	Use Case
PLQY	Radiative vs. non-radiative recombination balance	Evaluate material quality, effect of surface treatments
QFLS	Maximum achievable voltage	Predict open circuit voltage, diagnose and quantify performance loss origins

These metrics are crucial in:

- **Interface engineering:** Evaluating passivation layers or contact materials.
- **Material screening:** Identifying high-performance absorber compositions.
- **Process optimization:** Monitoring deposition quality, post-treatments, and screening process parameter variations.

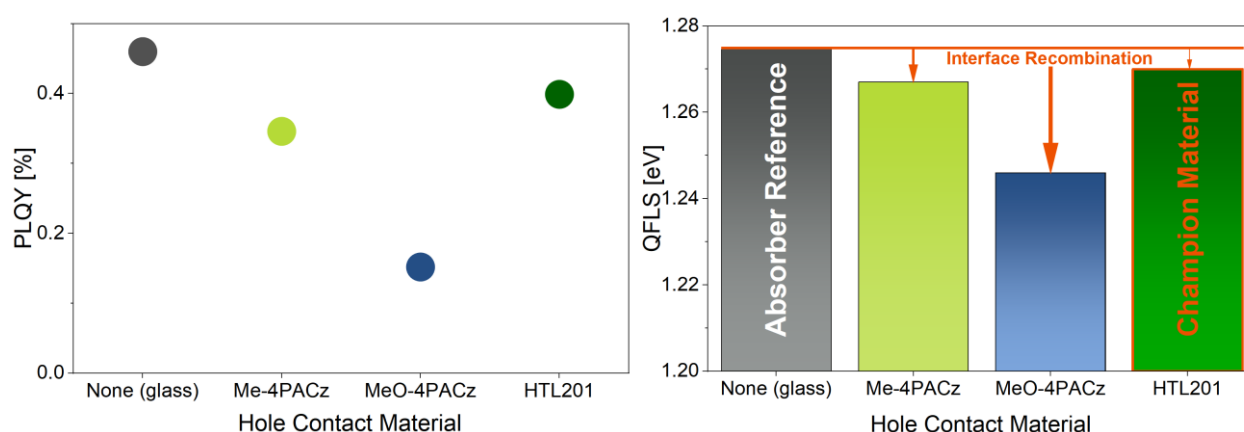


Fig. 1. PLQY (left) and QFLS (right) values of perovskite absorbers measured on glass (absorber reference) and on different hole contact materials. The results, as published by Jia et al. in *Nature* [2], clearly highlight how the LuQY Pro can identify loss mechanisms e.g., by different contact materials and performance bottlenecks in opto-electronic devices even without fabricating the full device. Graphs adapted according to [2].

As an example, a recent study by Jia et al. was published in *Nature Journal* [2]. Jia et al. use the LuQY Pro measurement system to **resolve interface recombination losses** at the hole contact/absorber interface. First, they fabricate half stacks of glass/perovskite absorber and measure PLQY and QFLS on this stack. This yields the maximum quality of the absorber without any contact layer at the interfaces. Next, they built glass/ITO/hole contact/perovskite stacks and varied the hole contact material. By measuring PLQY and QFLS on those samples, they clearly resolve the champion contact material of their study and quantify the QFLS and implied voltage. This allowed them to realize an at this time **world record perovskite/silicon tandem solar cell efficiency**.

[2] Jia, L., Xia, S., Li, J. et al. Efficient perovskite/silicon tandem with asymmetric self-assembly molecule. *Nature* (2025). <https://doi.org/10.1038/s41586-025-09333-z>

4. Measuring PLQY & QFLS with the LuQY Pro

The **LuQY Pro** is a fully integrated platform that measures absolute **photoluminescence fluxes**, while automatically computing PLQY and QFLS.

Key Capabilities:

- Spectral range: 550–1050 nm with detection of absolute photon numbers
- Laser intensity control: 0.001–10 suns
- QFLS calculation from PL spectra using built-in analysis algorithms

Quick-start for PLQY & QFLS Measurement:

0. **Sample Mounting:** Thin films, layer stacks, or full devices can be tested. Mount the sample into the sample holder and attach it to the LuQY Pro sample port.
1. **Activate the spectrometer live view** if not already active → "Live View" button must light up orange, by default active upon software start
2. **Activate the Laser and open the shutter**
3. **Select the 1 cm² laser spot size if not yet selected;** we recommend to always use the 1 cm² spot if possible as this will allow higher PLQY resolution and better signal-to-noise ratio of the PL detection. 0.1 cm² spot is useful for high excitation or to probe local spots on the sample.
4. **Move laser spot to your region of interest**
5. **Click the "Auto-Integration" time button**
6. **Perform dark measurement**
7. **Record the spectrum**
8. **PLQY and QFLS values will be displayed directly after the measurement.**

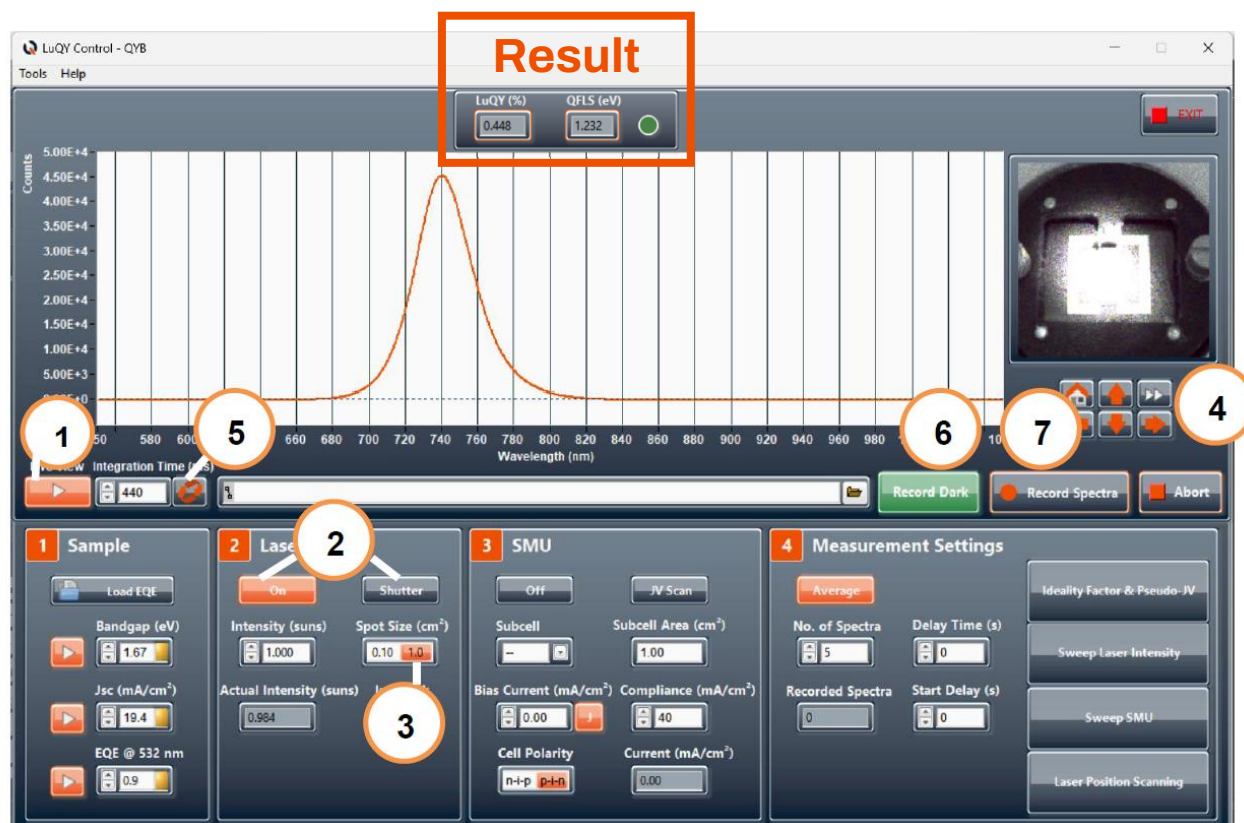


Fig. 2. LuQY-Control GUI after a PLQY & QFLS measurement.

For more accurate QFLS prediction, you can also load an EQE or absorption spectrum of your sample. For this, first click the “Load EQE” button in section 1 – sample. This will open the following sub-window:

Load your EQE or absorptance data. Bandgap, J_{SC} and EQE@532nm will be directly calculated.

Close this window with the close button, the values will be transferred into the main program.



Advanced functions are for having fun with the data. Calculate radiative V_{OC} limits and losses, radiative dark saturation currents for different substrate temperatures and LuQYs.

Fig. 3. ‘Load EQE’ window with possibility to have external quantum efficiencies or absorption data of your sample analyzed to extract band gap, J_{SC} and EQE at the laser wavelength.

‘Load Data’ allows to import your EQE or absorptance data. Your input file must be ASCII with two columns, **first column with Wavelength (nm) or Energy (eV) and second column with EQE/absorptance (% or absolute values)**. There must be no units behind the values and numbers must use a decimal point. Examples are:

Wavelength vs. EQE in %		Wavelength vs. EQE in % - Scientific		Wavelength vs. EQE in abs. values		Energy vs. EQE in absolute values	
300	4.76	3.00E+2	4.76E+0	300	0.0476	4.13	0.040
310	16.9	3.10E+2	1.69E+1	310	0.169	4	0.10
320	39.4	3.19E+2	3.94E+1	320	0.394	3.875	0.237
...		...		...		...	

The bandgap energy is calculated from the inflection point of the absorption onset, J_{SC} by convolution of the data with the AM1.5G spectrum and the EQE @ 532 nm is interpolated from the given data.

With this data, the laser excitation can be set more precisely to the target value, e.g. 1-sun equivalent excitation, and the band gap can be derived which both allows for more accurate QFLS prediction.

QFLS Determination:

The LuQY-Control software which is part of the LuQY Pro system can calculate **QFLS** directly from the absolute emission spectrum in two ways:

- **Direct mode (high-energy tail fit):** no sample data needed (± 10 mV accuracy for many perovskites).
- **Detailed mode (PLQY based method):** Enhanced accuracy with user-supplied data (EQE, absorption, optical bandgap, etc.).

The high energy tail fit method transforms the recorded absolute photon fluxes to the following equation:

$$\ln\left(\frac{\phi_{lum}(E)h^3c^2}{2\pi E^2\alpha(E)}\right) = -\left(\frac{E - QFLS}{kT}\right), \quad (4)$$

where ϕ_{lum} = absolute luminescence flux density, E = photon energy, h = Planck constant, c = speed of light, α = absorptance of sample, q = electric charge, k = Boltzmann constant, T = Temperature of electron gas.

A fit of the high energy PL emission tail and extrapolation of this fit to 0 eV energy allows to extract the QFLS.

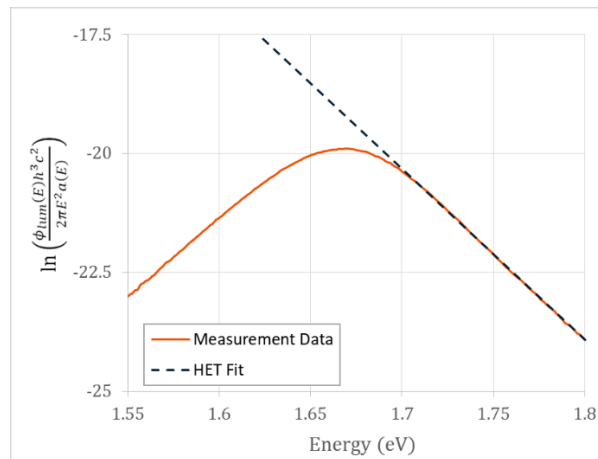


Fig. 4. Exemplary luminescence emission data and high energy tail fit. The intersection of the fitted line with the ordinate at 0 eV yields QFLS /k/T.

[3] Unold, T.; Güta, L. Photoluminescence Analysis of Thin-Film Solar Cells. In *Advanced Characterization Techniques for Thin Film Solar Cells*; Wiley-VCH Verlag GmbH & Co. KGaA, 2011; pp 151–175.

[4] Kirchartz, T.; Márquez, J. A.; Stolterfoht, M.; Unold, T. Photoluminescence-Based Characterization of Halide Perovskites for Photovoltaics. *Adv. Energy Mater.* **2020**, 1904134.

5. Advantages of the LuQY Pro System

- **Plug-and-play usability**
- **Compact design to fit in constrained spaces such as gloveboxes**
- **High sensitivity** (down to PLQY of 10^{-6})
- **Non-destructive** and rapid testing
- **Contactless QFLS prediction**

6. Conclusion

The combination of **PLQY** and **QFLS** provides a powerful, contactless toolkit to assess and optimize semiconductor materials early in the solar cell development pipeline. The **LuQY Pro** systems make this analysis easy-to-use with precision and flexibility, accelerating your research to optimize opto-electronic devices such as LEDs and solar cells.

If you're working at the forefront of semiconductor luminescence, quantum yield analysis, or next-generation optoelectronic devices, **LuQY Pro is your system of choice**. It transforms complex characterization into clear, reliable results, giving your research a competitive edge.

Backed by authoritative studies of our team such as Unold et al. (*Wiley*, 2011, ISBN: 9783527410033) or Al-Ashouri et al. (*Science*, 2020) and trusted by renowned users around the world, for example:

[5] Z. Jia *et al.*, "Efficient near-infrared harvesting in perovskite-organic tandem solar cells," **Nature**, vol. 643, no. 8070, pp. 104–110, Jul. 2025, doi: 10.1038/s41586-025-09181-x.

[6] H. Chen *et al.*, "Improved charge extraction in inverted perovskite solar cells with dual-site-binding ligands," **Science**, vol. 384, no. 6692, pp. 189–193, Apr. 2024, doi: 10.1126/science.adm9474.

[7] J. Li *et al.*, "Enhancing the efficiency and longevity of inverted perovskite solar cells with antimony-doped tin oxides," **Nature Energy**, vol. 9, no. 3, pp. 308–315, Mar. 2024, doi: 10.1038/s41560-023-01442-1

[8] Z. Wei *et al.*, "Surpassing 90% Shockley-Queisser V_{oc} limit in 1.79 eV wide-bandgap perovskite solar cells using bromine-substituted self-assembled monolayers," **Energy Environ. Sci.**, vol. 18, no. 4, pp. 1847–1855, 2025, doi: 10.1039/d4ee04029e.

[9] Y. Yuan, G. Yan, C. Dreessen, and T. Kirchartz, "Understanding Power- Law Photoluminescence Decays and Bimolecular Recombination in Lead- Halide Perovskites," **Advanced Energy Materials**, vol. 15, no. 6, Feb. 2025, doi: 10.1002/aenm.202403279.

[10] O. Er-raji *et al.*, "Tailoring perovskite crystallization and interfacial passivation in efficient, fully textured perovskite silicon tandem solar cells," **Joule**, vol. 0, no. 0, Jul. 2024, doi: 10.1016/j.joule.2024.06.018.

In short: if your goal is innovation, LuQY Pro is your partner.



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