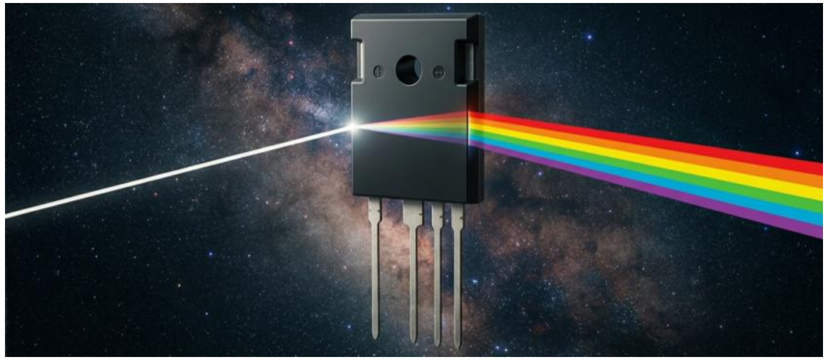
Federatie van technologiebranches

TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

When Power Devices Glow: Electroluminescence for In-Situ Junction Temperature Sensing

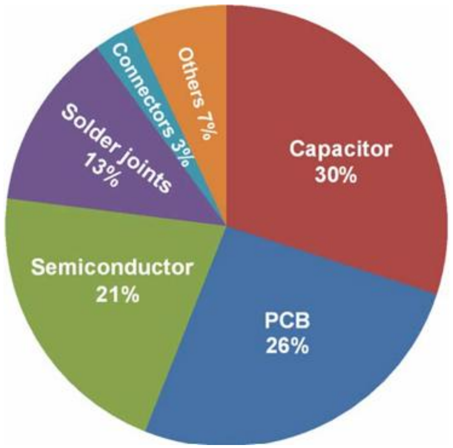
Antonis Stathatos
Eindhoven University of Technology



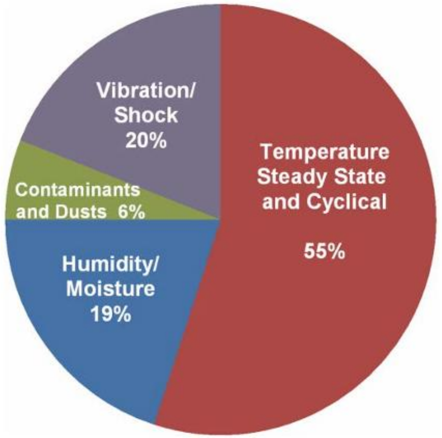
Design of Power Electronic Converters

Trade-off between performance goals & temperature as limiting factor

- Power density
  - Sets minimum cooling/volume
- Efficiency
  - Increases losses with temperature
- Cost
  - Drives cooling, package and device cost
- Reliability
  - Accelerates thermal aging and fatigue



Failure distribution in power electronic components



Failure sources distribution of electronic equipment

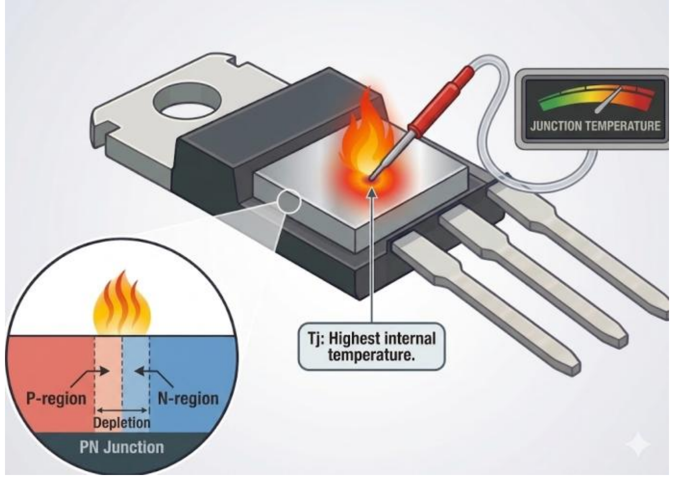
➢ Temperature defines practical design boundaries

➢ Real-time temperature monitoring enables reliable operation at maximum power point

Why Junction Temperature Sensing Is Needed

Semiconductor junction – where losses are generated

- Affects electrical parameters
- Causes device aging
- Sets device limits
- Drives thermal runaway risk



➢ Junction temperature is true stress indicator of semiconductor

Existing methods

- Acoustic
- Temperature-sensitive electrical parameters (TSEPs)
- Physical methods

Limited by invasiveness, calibration drift and aging sensitivity

➢ Investigate fundamental semiconductor properties for reliable junction temperature estimation

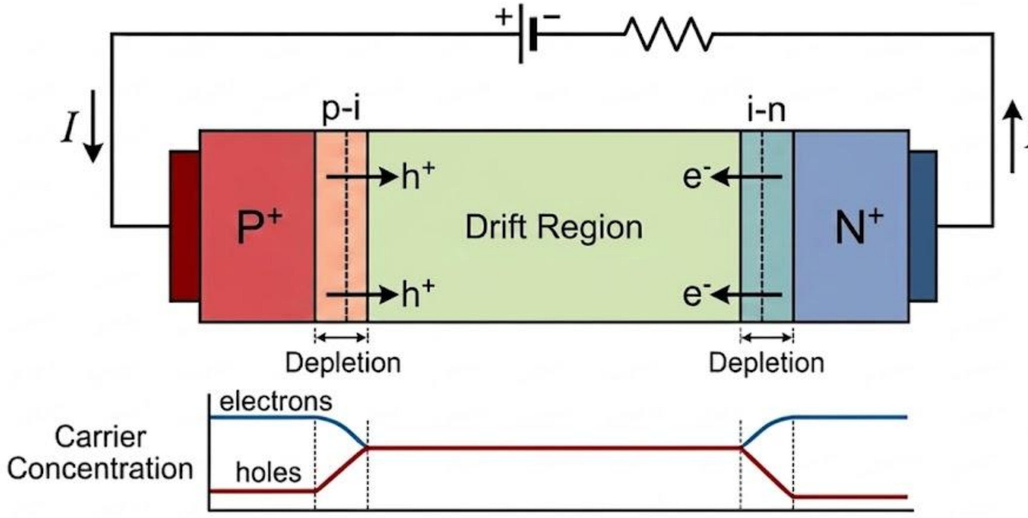
Back To The Basics: The P-i-N Junction

Fundamental structure in many power semiconductor devices

- P-i-N junction with lightly N-doped drift region

Under forward bias

- Depletion regions narrow
- Electrons and holes injected in drift region
- Carrier recombination restores equilibrium



Forward biased P-i-N junction found in

- Diodes
- Thyristors
- IGBTs
- MOSFETs body diode during reverse conduction

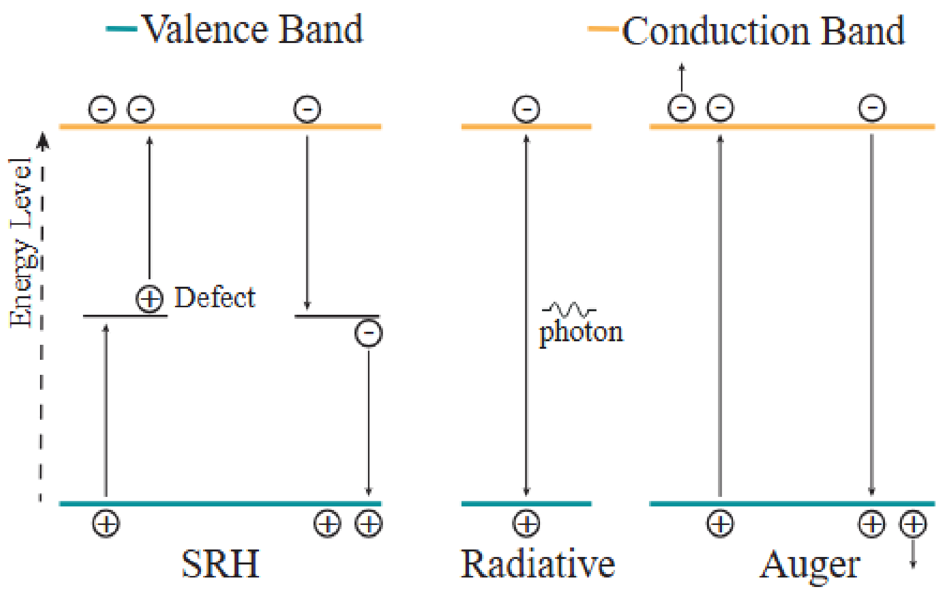
Recombination Phenomena

Non-radiative recombination

- Shockley-Reed-Hall (SRH) and Auger
- Typically, dominant in power semiconductors
- Result: energy released as heat through lattice vibration

Radiative recombination

- Result: energy released as photon emission
- Emission intensity depend on temperature & current
- Occurs through
  - Band-to-band transition
  - Impurity/defect levels within bandgap



➢ Radiative recombination serves as: Temperature-sensitive optical parameter (TSOP)

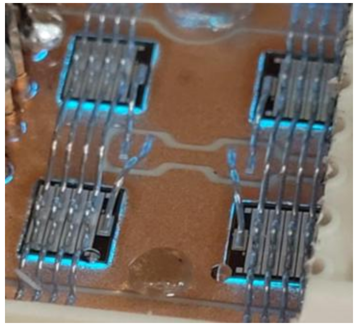
Let There Be Light

Peak wavelength from Planck-Einstein relation

$$\lambda = \frac{h \cdot c}{E_g} \quad \text{or} \quad \lambda = \frac{1240}{E_g}$$

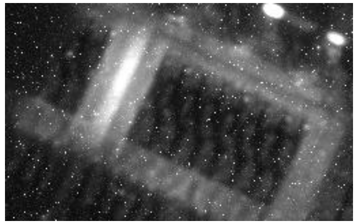
At room temperature

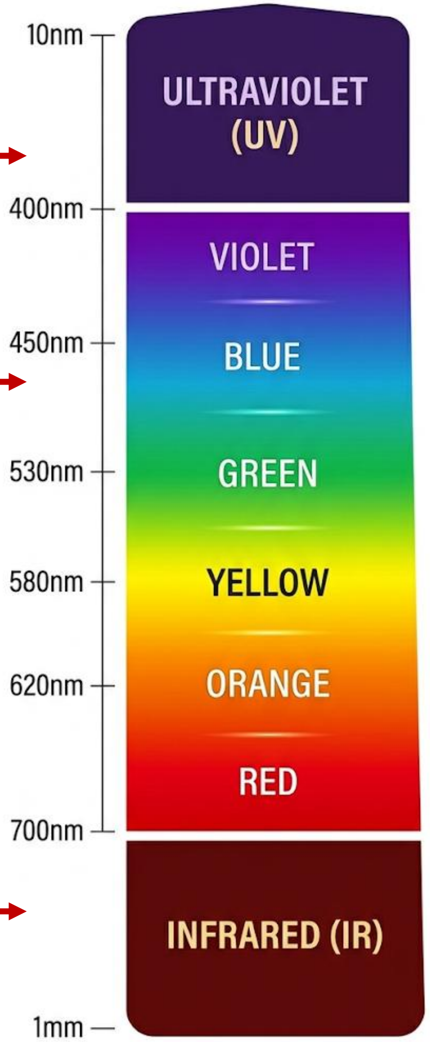
- Si
  - Bandgap energy: $E_g \approx 1.12\mathrm{eV}$
  - Band-to-band emission: $\lambda \approx 1107\mathrm{nm}$
- SiC
  - Bandgap energy: $E_g \approx 3.24\mathrm{eV}$
  - Band-to-band emission: $\lambda \approx 382\mathrm{nm}$
  - Defect levels: lower recombination energy E_g → visible emission: $\lambda \approx 485\mathrm{nm}$



SiC MOSFET

Si Diode





Main Challenges

1. Acquiring the emitted electroluminescence from the chip
2. Calibrating the collected electroluminescence with junction temperature
3. Investigating electroluminescence-based junction temperature sensing under pulsed current condition

Main Challenges

1. Acquiring the emitted electroluminescence from the chip

2. Calibrating the collected electroluminescence with junction temperature

3. Investigating electroluminescence-based junction temperature sensing under pulsed current condition

FHI Federatie van technologiebranches

TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

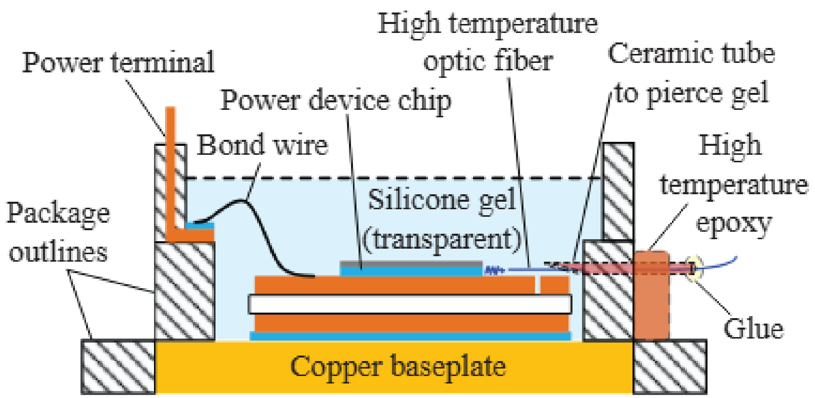
Electroluminescence Capture

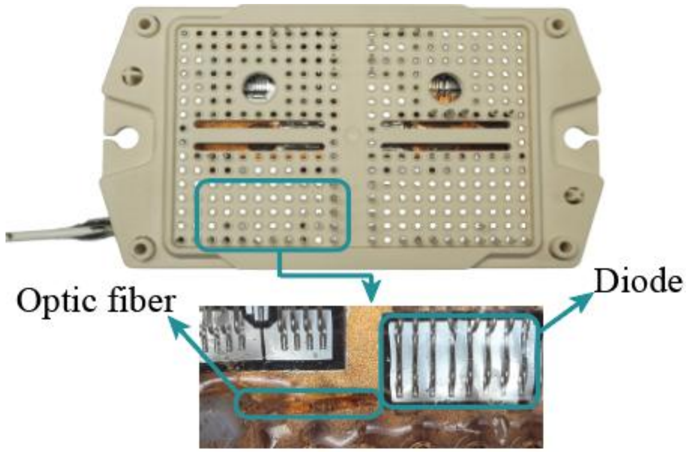
- Optical access to chip limited to sides

- Package-side optic fiber insertion
  - High-temperature optic fiber
  - Ceramic tube guides fiber through package
  - Optic fiber piercing silicone gel
  - Fiber tip positioned near chip edge

- Low-impact modification
  - Avoids critical structures (bond-wires, pins, etc.)
  - Preserves electrical, mechanical & thermal behavior

- Detection
  - Fiber-coupled InGaAs photodetector
  - High-gain amplification





Main Challenges

1. Acquiring the emitted electroluminescence from the chip

2. Calibrating the collected electroluminescence with junction temperature

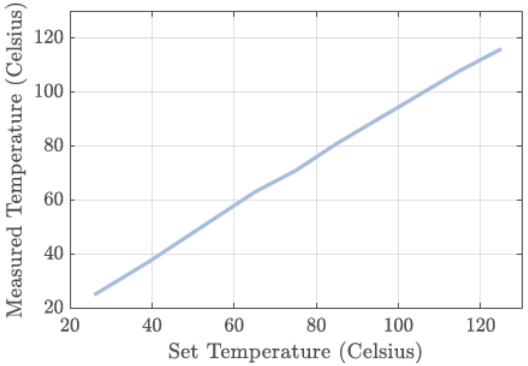
3. Investigating electroluminescence-based junction temperature sensing under pulsed current condition

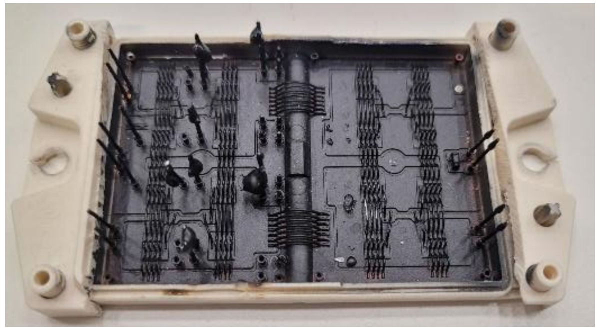
Junction Temperature Calibration

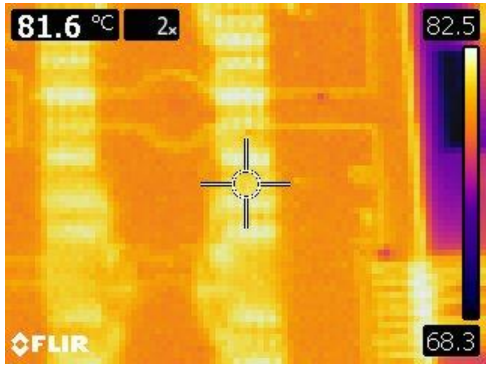
Junction temperature set by controllable heating plate

Reference:

- Remove silicone gel & black-coat module surface
- Measure chip surface temperature with thermal camera
- Build setpoint-to-chip temperature calibration curve
- Use calibrated setpoint as reference for mapping







Main Challenges

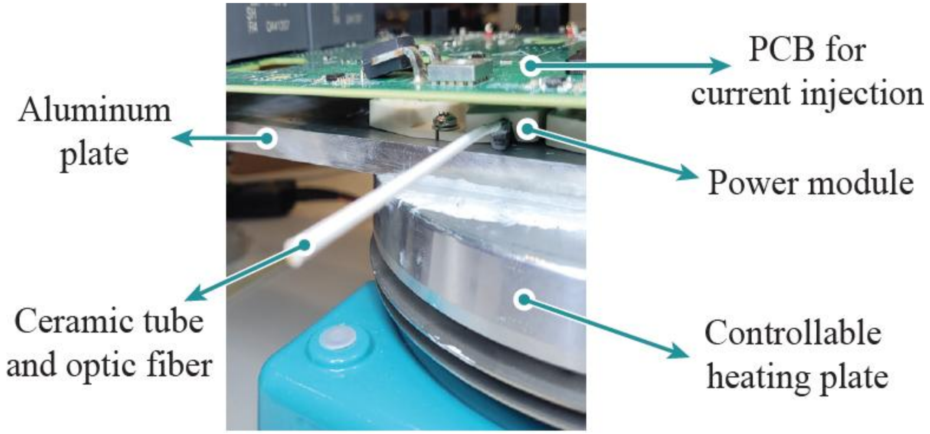
1. Acquiring the emitted electroluminescence from the chip

2. Calibrating the collected electroluminescence with junction temperature

3. Investigating electroluminescence-based junction temperature sensing under pulsed current condition

Electroluminescence Experiment

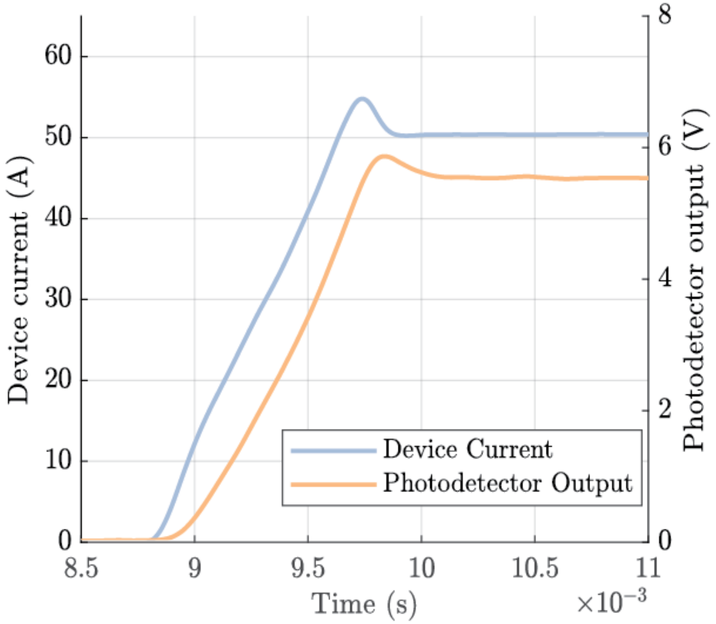
- Device under test: silicon diode anti-parallel to IGBT
- Set reference junction temperature using calibrated heating setup
- Inject controlled current in power device
- Capture electroluminescence response
- Extract photo-electro-thermal model



Experimental Results (1/2)

Measured electroluminescence response during current injection

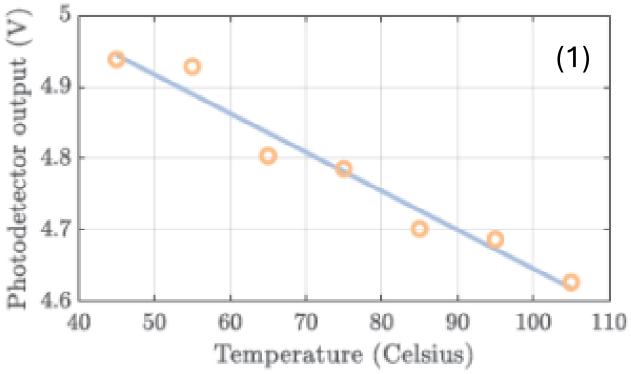
- Current injection generates electroluminescence
- Fiber collects light from chip side
- InGaAs photodetector converts light into voltage
- Optical response follows current transient in < 1ms



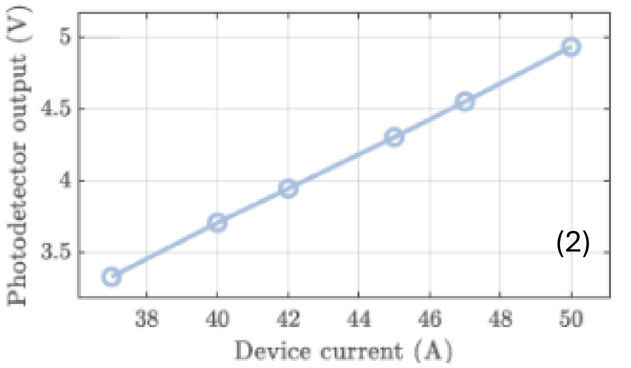
➢ Detection bandwidth sufficient for real-time junction temperature sensing

Experimental Results (2/2)

- At constant current with increasing temperature (Fig. 1)
  - Non-radiative recombination becomes more dominant
  - Electroluminescence intensity decreases
  - Linear dependence: photodetector output vs. temperature



- At constant temperature with increasing current (Fig. 2)
  - Radiative & non-radiative recombination rates increase
  - Electroluminescence intensity increases
  - Linear dependence: photodetector output vs. current



➢ Electroluminescence shows separable linear dependence on temperature & current

Electroluminescence Model (1/2)

- Experimental observations show that

$$V_{EL} = \mathrm{f}(\mathrm{I}, \mathrm{T_j})$$

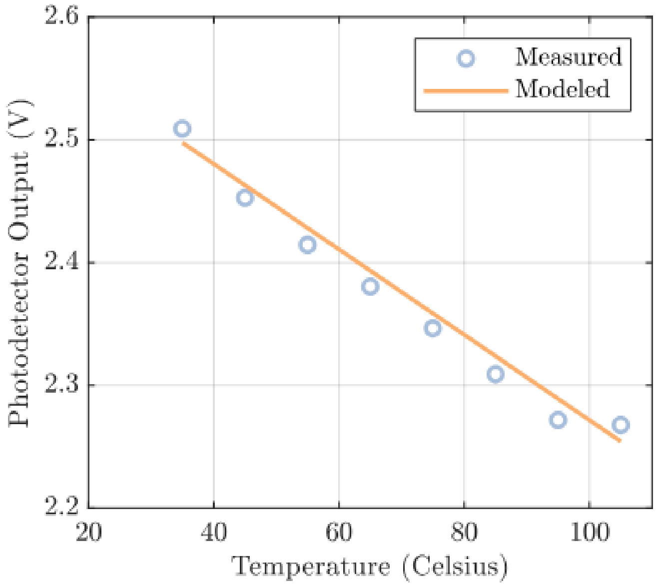
- V_{EL}: photodetector output
- I: device current
- $\mathrm{T_j}$: junction temperature
- Model $\mathrm{f}(\mathrm{I}, \mathrm{T_j})$ fitted using polynomial regression

- During converter operation
  - Measure V_{EL}
  - Measure (directly/indirectly) I
  - Solve for $\mathrm{T_j}$

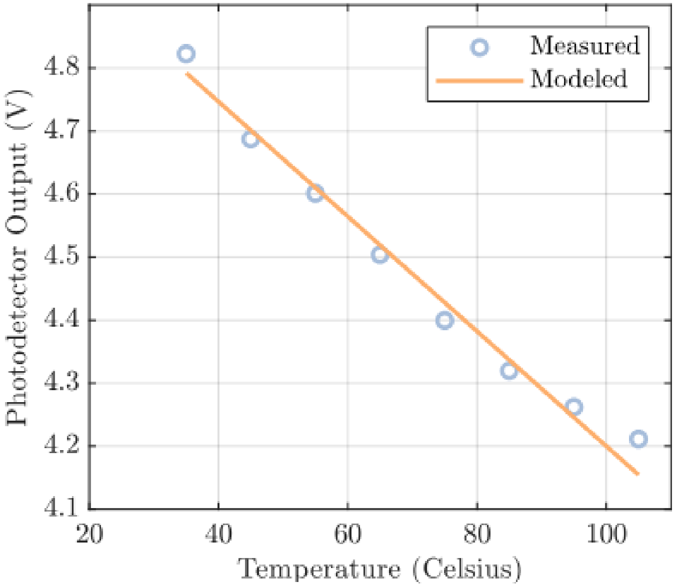
➢ Photodetector signal + current → junction temperature estimation

Electroluminescence Model (2/2)

- Photo-electro-thermal model validation
  - Maximum error 4°C
  - $R^2 > 0.95$



Photodetector output vs. temperature at 30A device current



Photodetector output vs. temperature at 40A device current

Overview & Conclusion

- Electroluminescence-based junction temperature sensing
  - Information transmitted optically
    - No induced EMI
    - Galvanic isolation
    - Fast data acquisition
  - Optical signal from junction reduces dependence on package degradation

- Proposed
  - Electroluminescence acquisition with minimal package modification
  - Detection with < 1ms response time
  - Regression model for real-time junction temperature estimation

Thank you for your attention!
Questions?

(a.stathatos@tue.nl)