Test Methods for Contactless Carrier Recombination Lifetime in Silicon Wafers, Blocks, and Ingots

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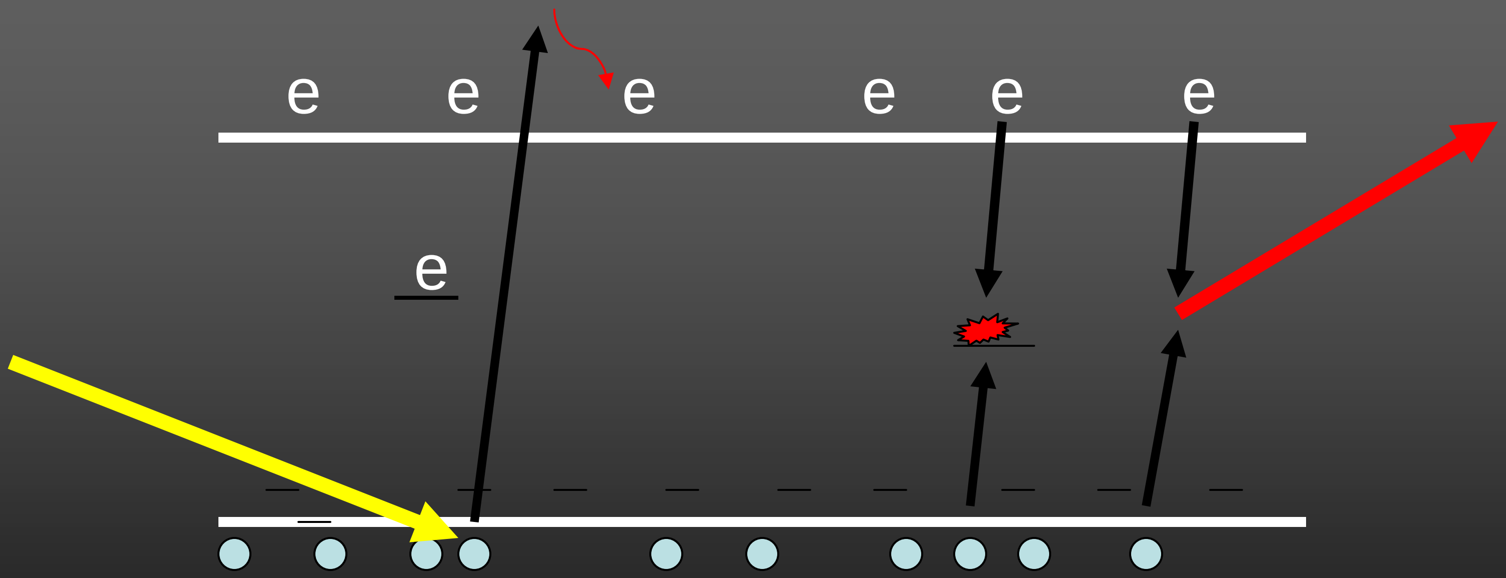
Charter of Global Photovoltaic Committee

Explore, evaluate, discuss, and create consensus-based standard measurement methods, specifications, guidelines, and practices that, through voluntary compliance, will promote mutual understanding and improved communication between users and suppliers of photovoltaic manufacturing equipment, materials and services to enhance the manufacturing efficiency and capability *so as to reduce manufacturing cost of the photovoltaic (PV) industry*. “

Carrier Recombination Lifetime



Carrier-recombination lifetime: The central parameter to the device design, production, and process control for silicon solar cells.

Why measure lifetime?

-**After crystal growth:** Process monitoring of feedstock contamination, contamination from crucible, bad growth conditions.

-**After wafering:** Qualify wafers for sale or purchase.

-**After dopant diffusion:** Monitor the quality of the dopant diffusion, check for chemical contamination, verify bulk lifetime, estimate final solar cell efficiency.

-**After nitride deposition:** Monitor nitride quality, optimize firing parameters for bulk and surface passivation quality.

-**R&D:** For use in characterizing bulk lifetimes and surface passivations. Input data for cell design and process optimization.

What determines bulk lifetime?

Metallic Impurities: Fe, Cr, Al, Au, Cu, others.

Can be from feedstock, crucible, gas contamination, chemical contamination.

Other defects: In boron CZ, B:O pairs, oxygen precipitates

Crystalline defects: dislocations, grain boundaries

What determines measured lifetime?

-Bulk lifetime

-Surface Recombination

-Wafer thickness

-Dopant-diffused region recombination

-Diffusion of excess carriers in the wafer or block

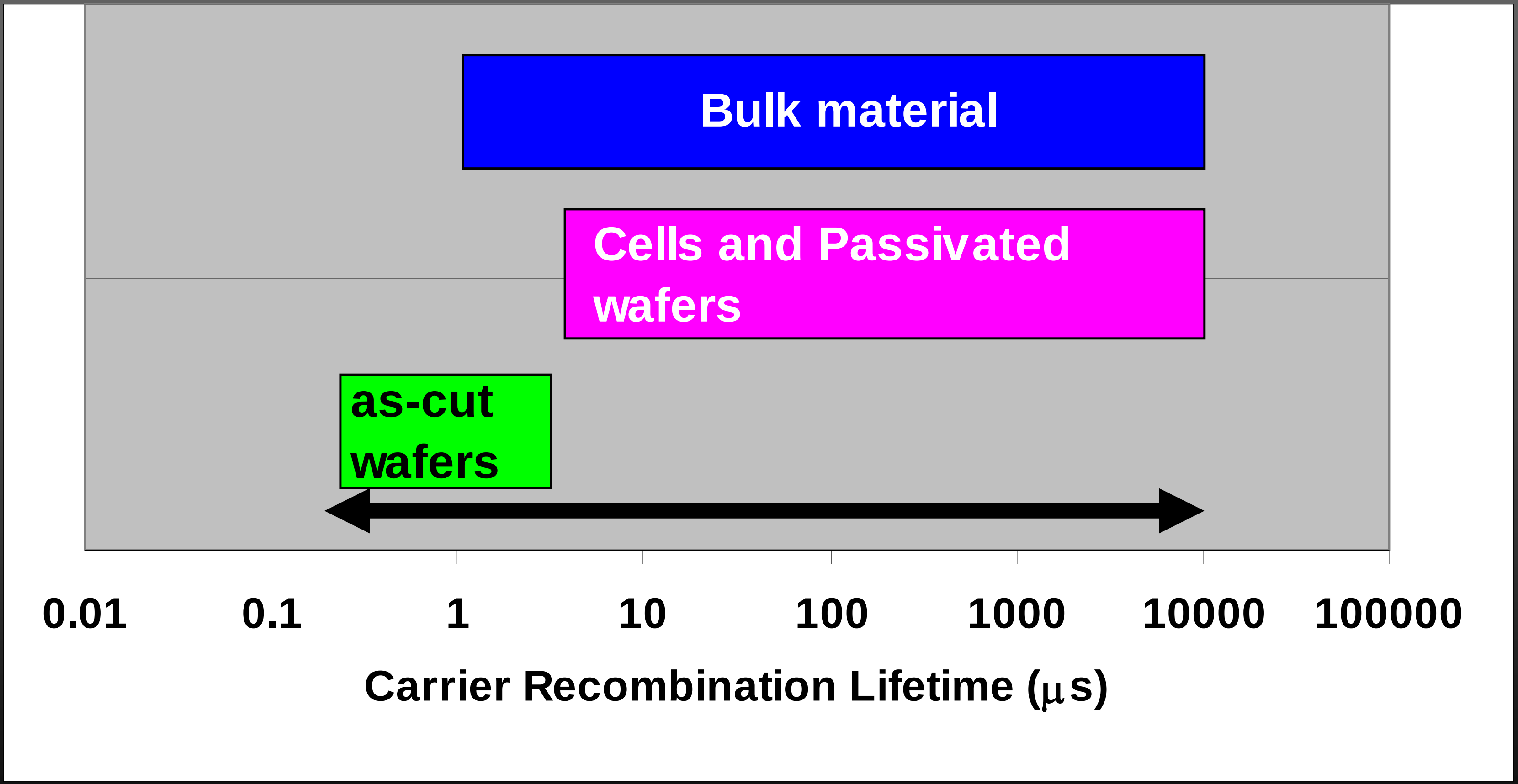
Scope of the measurement:

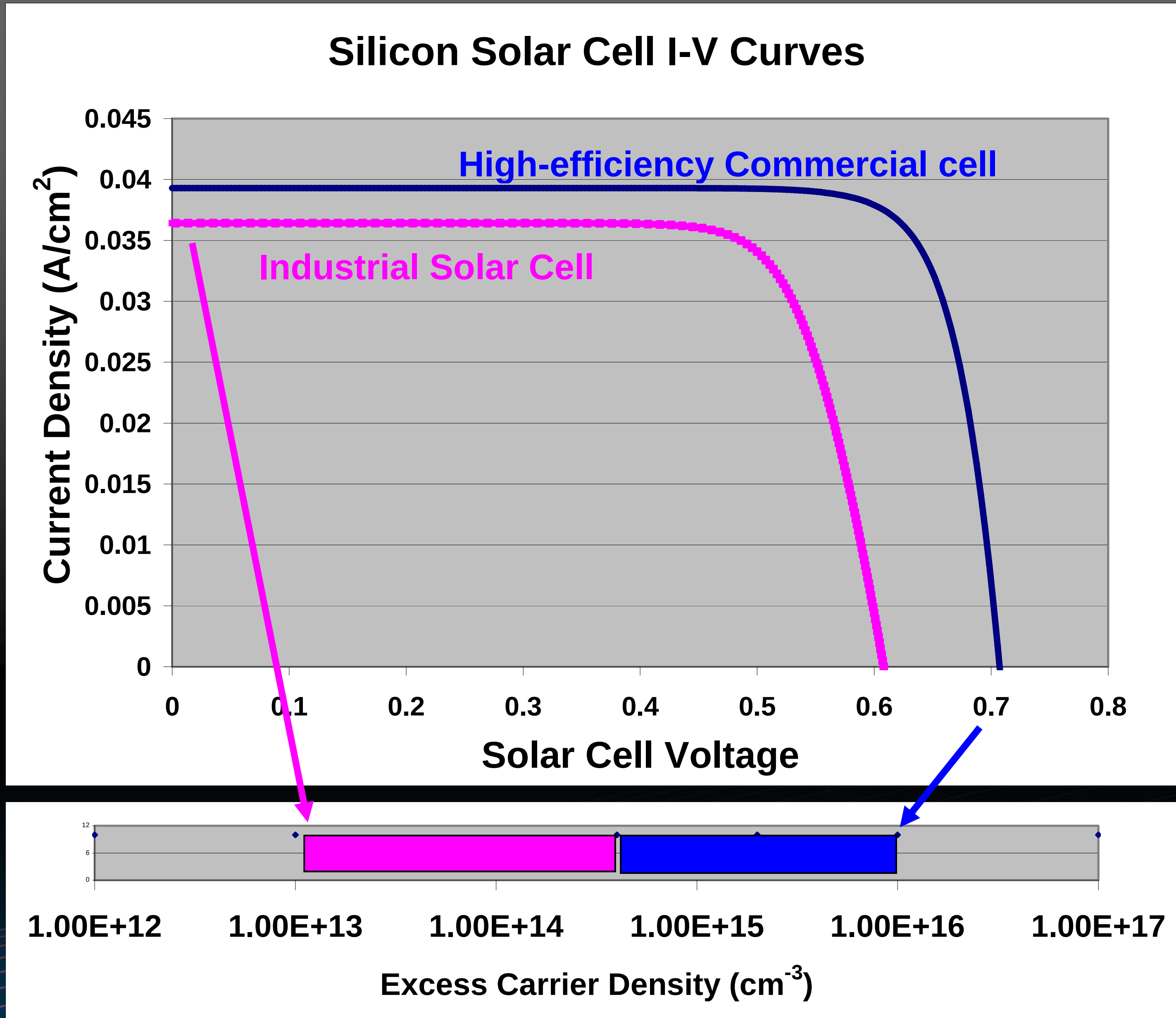
What are the excess carrier recombination lifetime and excess-carrier density ranges that are important for solar cells?

Lifetime: 0.1 to 10,000 μs

Carrier Density: 1×10^{13} to 5×10^{16} cm^{-3}

Carrier Recombination Lifetime: 0.1 to 10,000 μs




Silicon Solar Cell I-V Curves
High-efficiency Commercial cell
Industrial Solar Cell
Current Density (A/cm2)
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Solar Cell Voltage
12
6
0
1.00E+12
1.00E+13
1.00E+14
1.00E+15
1.00E+16
1.00E+17
Excess Carrier Density (cm-3)

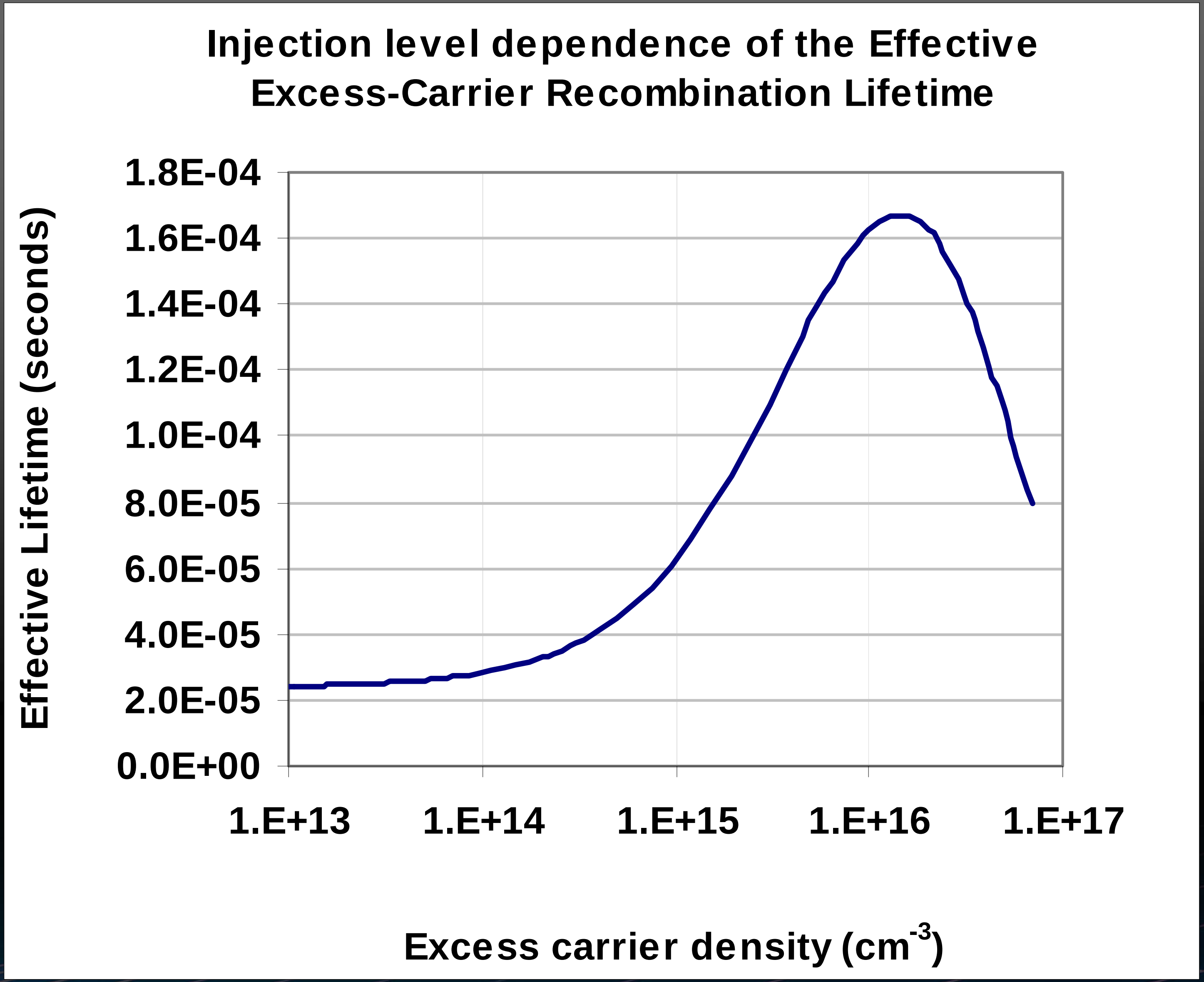


Fig. 1. The modeled recombination lifetime of a 3-ohm-cm B-doped CZ sample after degradation of the B:O defect[1]. This curve is based on recombination parameters from the studies of Bothe [1].

How To Write a "Lifetime" Test Method?

1) Develop a consensus: How should lifetime be measured so that the results are physically relevant for silicon solar cells and can be compared between laboratories, institutes, and industrial companies using different measurement methods?
2) Submit a document to become a test method.

Consensus: White Paper

1) General framework for a lifetime measurement and interpretation (sensor-type independent).

Contributors (white paper comments)

K. Bothe ISFH, Germany: μ-pcd, PhotoLuminescence, RF-pcd, RF-QSSPC, Infra-red Lifetime Mapping.

T. Roth, Fraunhofer ISE, Germany: μ-pcd, PL, RF-pcd, CDI, RF-QSSPC, QSSPL.

W. Warta: Fraunhofer ISE (same tool experience).

R. M. Swanson, SunPower Corp, USA.

R. Falster: MEMC.

S. Johnston: NREL USA: μ-pcd, RF-pcd, RF-QSSPC, PL.

K. Lauer, CiS Mikrosensorik, Germany: μ-pcd, QSSPC.

J. Nyhus, REC, Norway: μ-pcd, luminescence, QSSPC.

T. Trupke, BT Imaging, Australia: PL, QSSPC, QSSPL, Imaging PL.

L. Janssen, Solland, Netherlands: QSSPC, μ-pcd.

N. Stoddard, BP Solar

A. Cuevas, Australian National University, QSSPC.

Contactless Carrier-Lifetime Measurement in Silicon Wafers, Ingots, and Blocks

1 Introduction
2 Measurement of carrier recombination lifetime in a sample.
3 The interpretation of lifetime data on wafers
4 Interpretation of Lifetime Data Taken on Ingots or Blocks

Table 1. List of contactless sensors in relatively widespread use in 2009 for determining lifetime in silicon using the described measurement methodology.

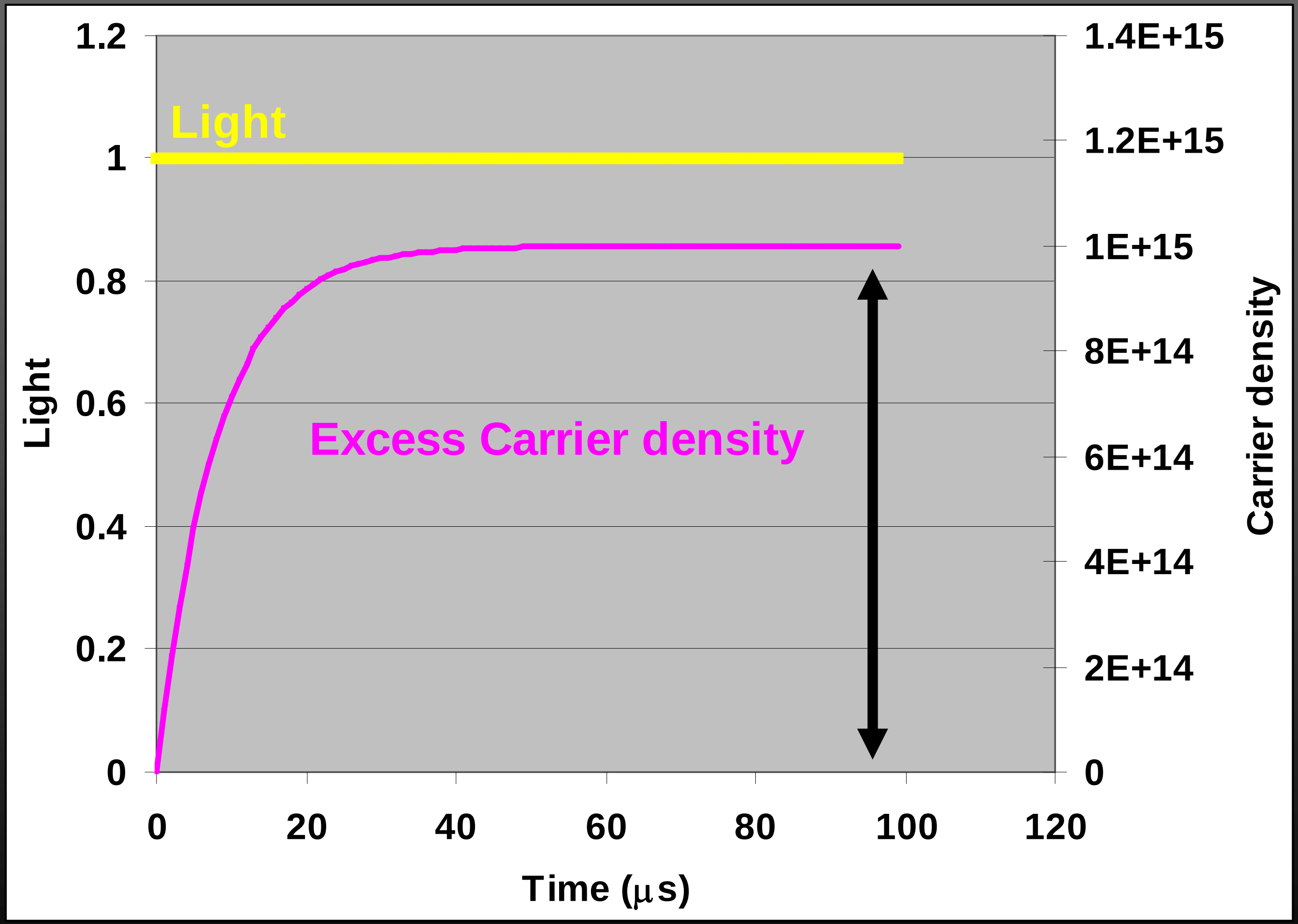
Table 2. Parameters that should be reported from a lifetime measurement to make it unique and reproducible between labs and different measurement techniques.

Contactless Carrier-Lifetime Measurement in Silicon Wafers, Ingots, and Blocks

5 Specific Example, Description of RF-photoconductance test method. (Very brief description).

6 References:

Steady-State Excess Carrier Lifetime



$$\tau_{eff}(\Delta n) = \frac{\Delta n}{G}$$

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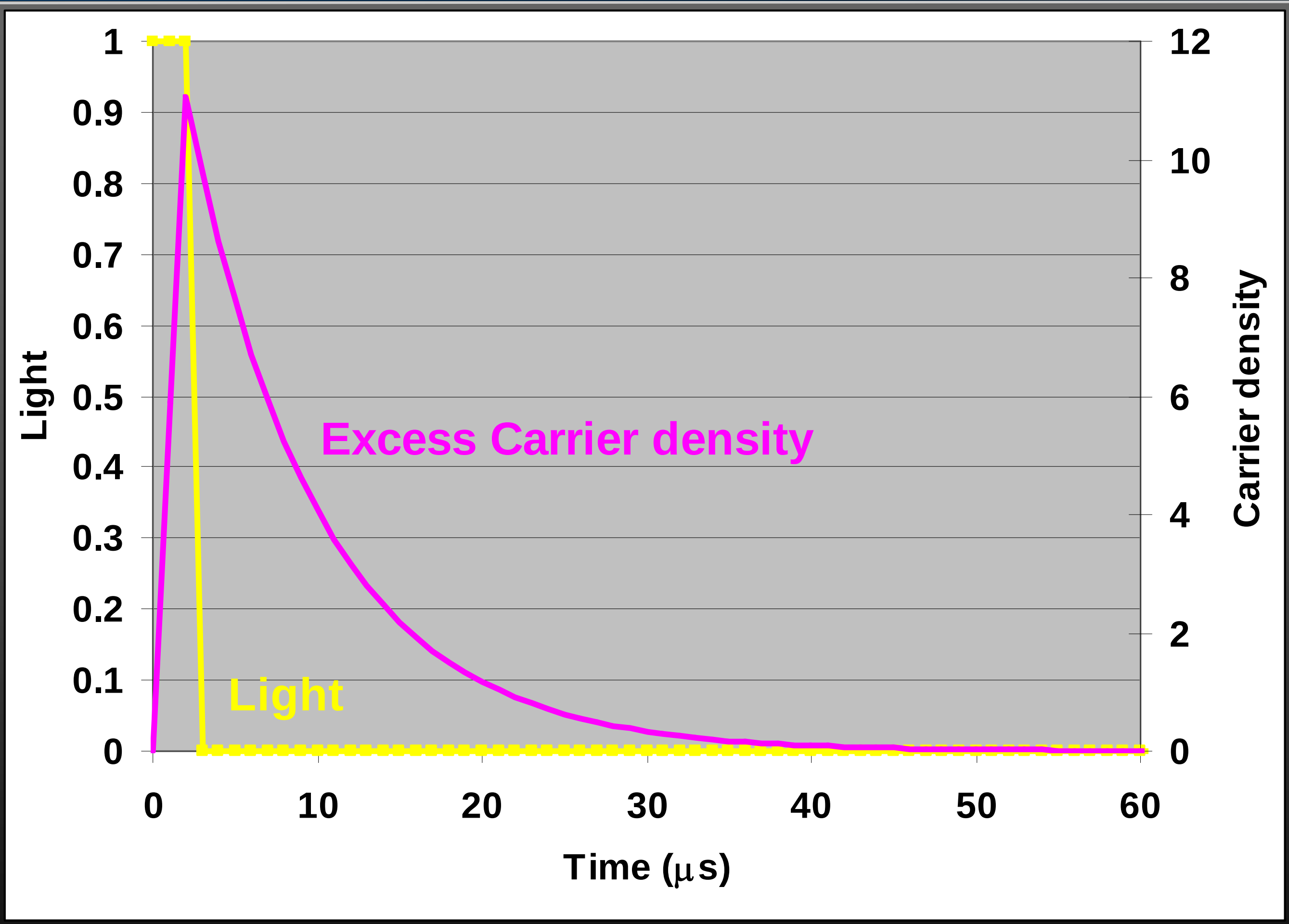
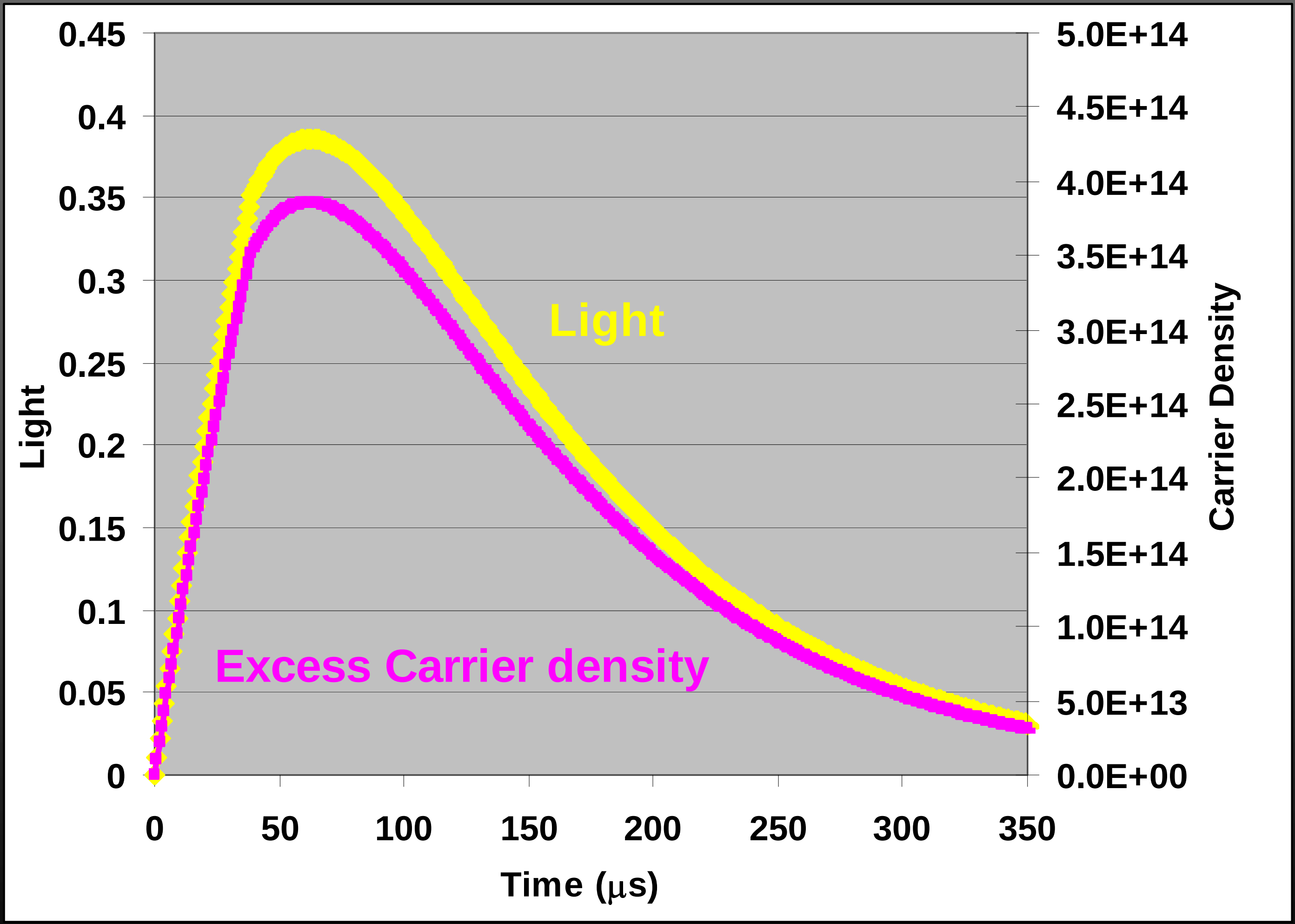
Transient Excess Carrier Lifetime



$$\tau_{eff}(\Delta n) = -\frac{\Delta n(t)}{d\Delta n(t)/dt}$$

Generalized Quasi-Steady-State Excess Carrier Lifetime



$$\tau_{eff}(\Delta n) = \frac{\Delta n(t)}{G(t) - d\Delta n(t)/dt}$$

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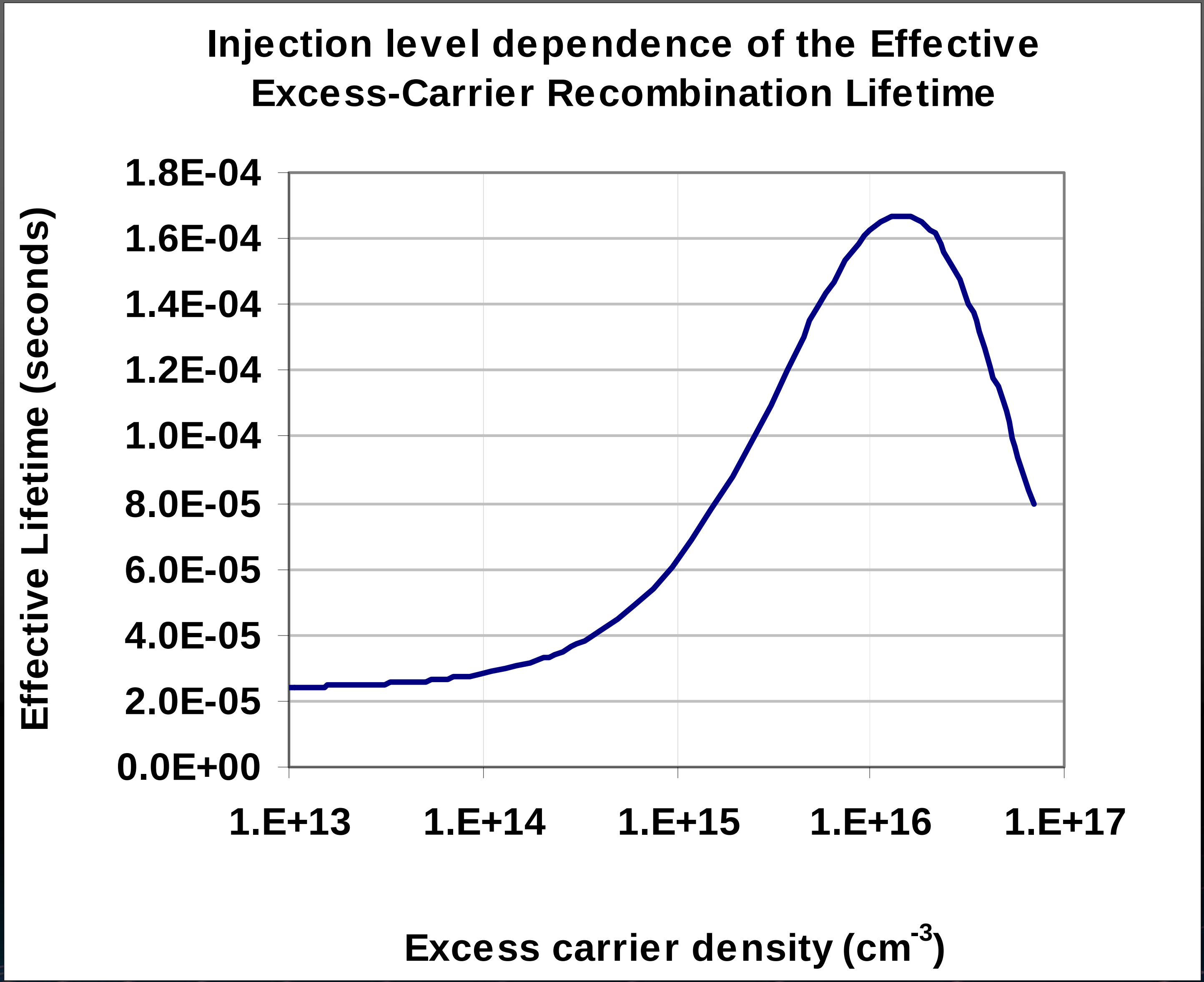


Fig. 1. The modeled recombination lifetime of a 3-ohm-cm B-doped CZ sample after degradation of the B:O defect[1]. This curve is based on recombination parameters from the studies of Bothe [1].

Table 1. List of contactless sensors in relatively widespread use in 2009 for determining lifetime in silicon

Method	How is excess carrier density sensed?	Issues: Pros / Cons
RF-QSSPC	Eddy current sensing of Photoconductance Conversion to Δn using known mobility function	Simple calibration that is valid for a wide range of samples. Requires mobility and photogeneration calculation or measurement. Non mapping or coarse mapping only. Trapping and Depletion Region Modulation artifacts at low carrier density.
RF Transient	Eddy current sensing of Photoconductance Conversion to Δn using known mobility function	Simple calibration. Can be subject to trapping and DRM artifacts at low carrier density
ILM/CDI	IR free-carrier absorption or emission.	High-resolution imaging capability. Surface texture complicates interpretation, subject to trapping and DRM artifacts
μ-PCD	Microwave reflectance sensing of photoconductance. Carrier density can be set by bias light, or by injecting known number of photons in a very short pulse.	High-resolution mapping capability. Non-linear detection of photoconductance in some injection-level or dopant ranges, skin-depth comparable to sample thickness in some cases. DRM and trapping artifacts at low carrier density.
Photoluminescence	Band-gap light emission, model for coefficient of radiative emission. Model for re-absorption.	Artifact-free data available even below the intrinsic carrier density. Used in both non-imaging and high-resolution imaging applications. Strong doping dependence, photon reabsorption depends on surface texture, detector EQE, and wafer thickness.

Interpretation of lifetime data

Wafers

Carrier Recombination Lifetime: Surface Recombination

Surface and bulk

$$\frac{1}{\tau_{eff}(\Delta n)} = \frac{1}{\tau_{bulk}(\Delta n)} + \frac{S_{front}(\Delta n) + S_{back}(\Delta n)}{W}$$

Emitter and bulk

$$\frac{1}{\tau_{eff}(\Delta n)} = \frac{1}{\tau_{bulk}(\Delta n)} + \frac{J_{oe\,front} + J_{oe\,back}}{q n_i^2 W}\left[N_A + \Delta n\right]$$

Carrier Recombination Lifetime: Surface Recombination

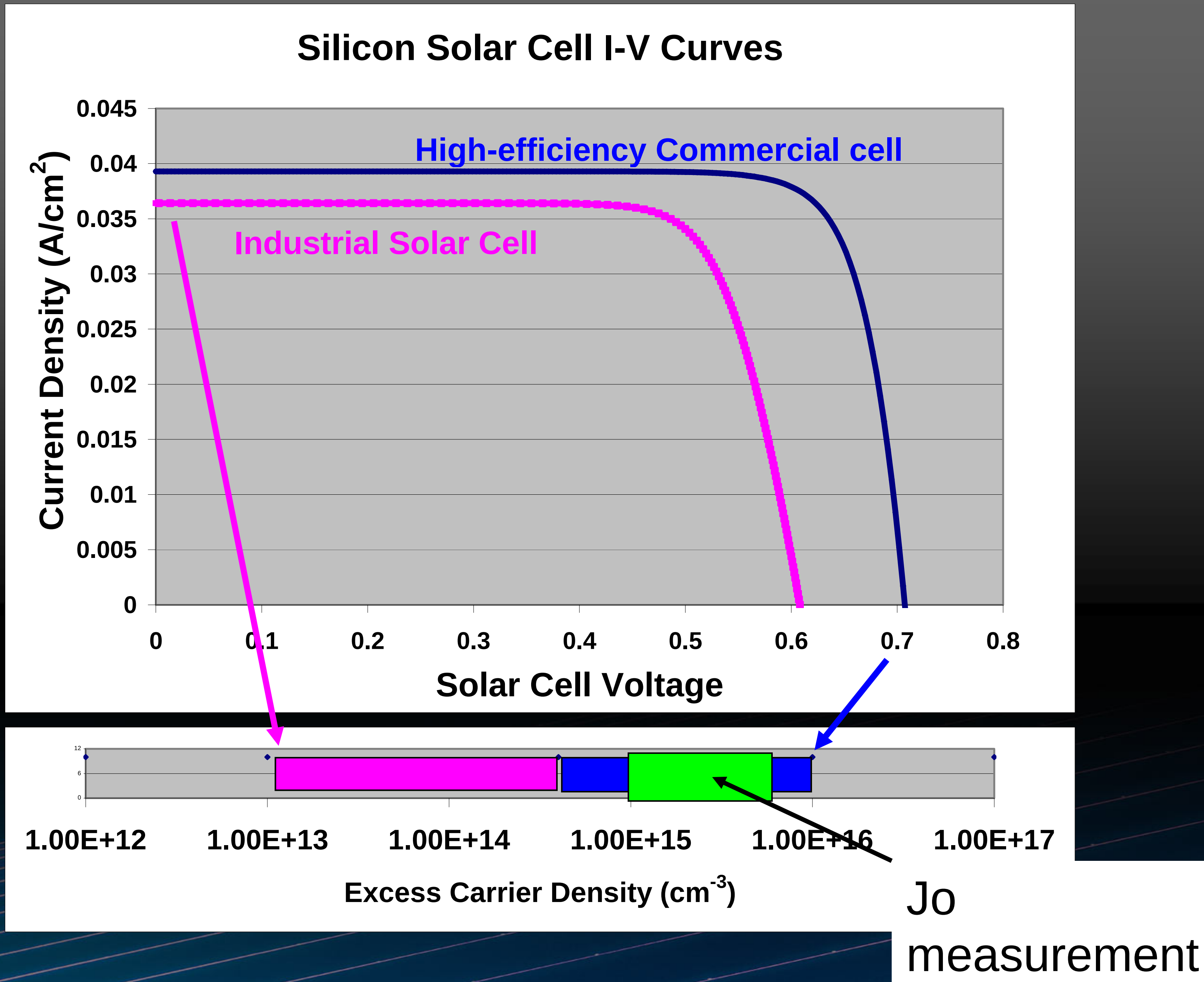
Transit time

$$\tau_{eff}(\Delta n) > \frac{W^2}{2D}$$

6 μs for 180 μm p-type
1 ohm-cm

Diffusion coefficient

$$D = \frac{(n+p)D_n D_p}{nD_n + pD_p}$$



Silicon Solar Cell I-V Curves
Current Density (A/cm^2)
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Solar Cell Voltage
High-efficiency Commercial cell
Industrial Solar Cell
12
6
0
1.00E+12
1.00E+13
1.00E+14
1.00E+15
1.00E+16
1.00E+17
Excess Carrier Density (cm^{-3})
Jo measurement

Interpretation of lifetime data

Ingots and Blocks

Wavelength dependence for QSS lifetime measurements on blocks

530 nm

Lifetime < a few μs

1000 nm

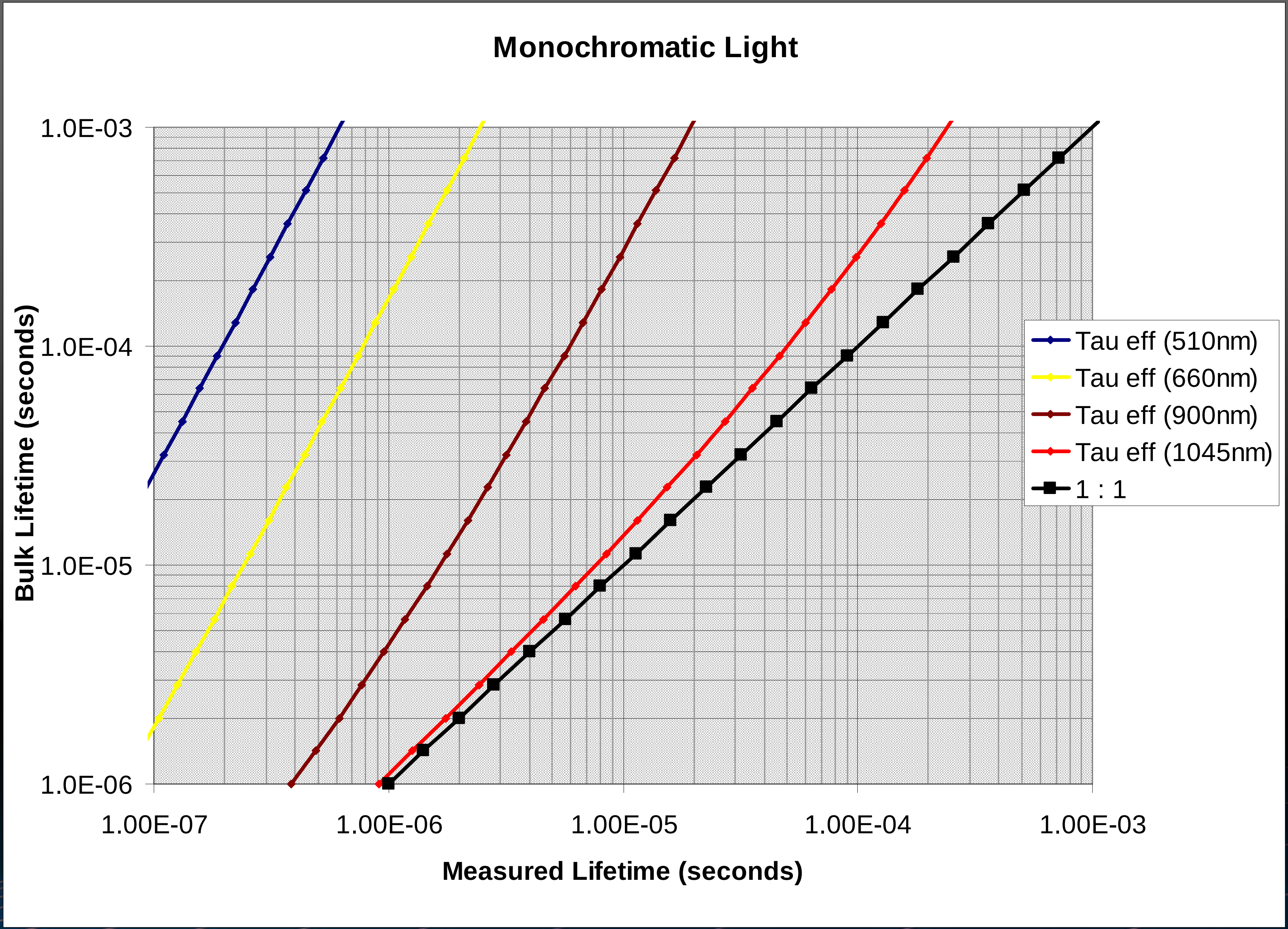
Lifetime ~ bulk lifetime if absorption depth >> L

$$\tau_{eff} = \frac{\tau_{bulk}}{\alpha L + 1}$$

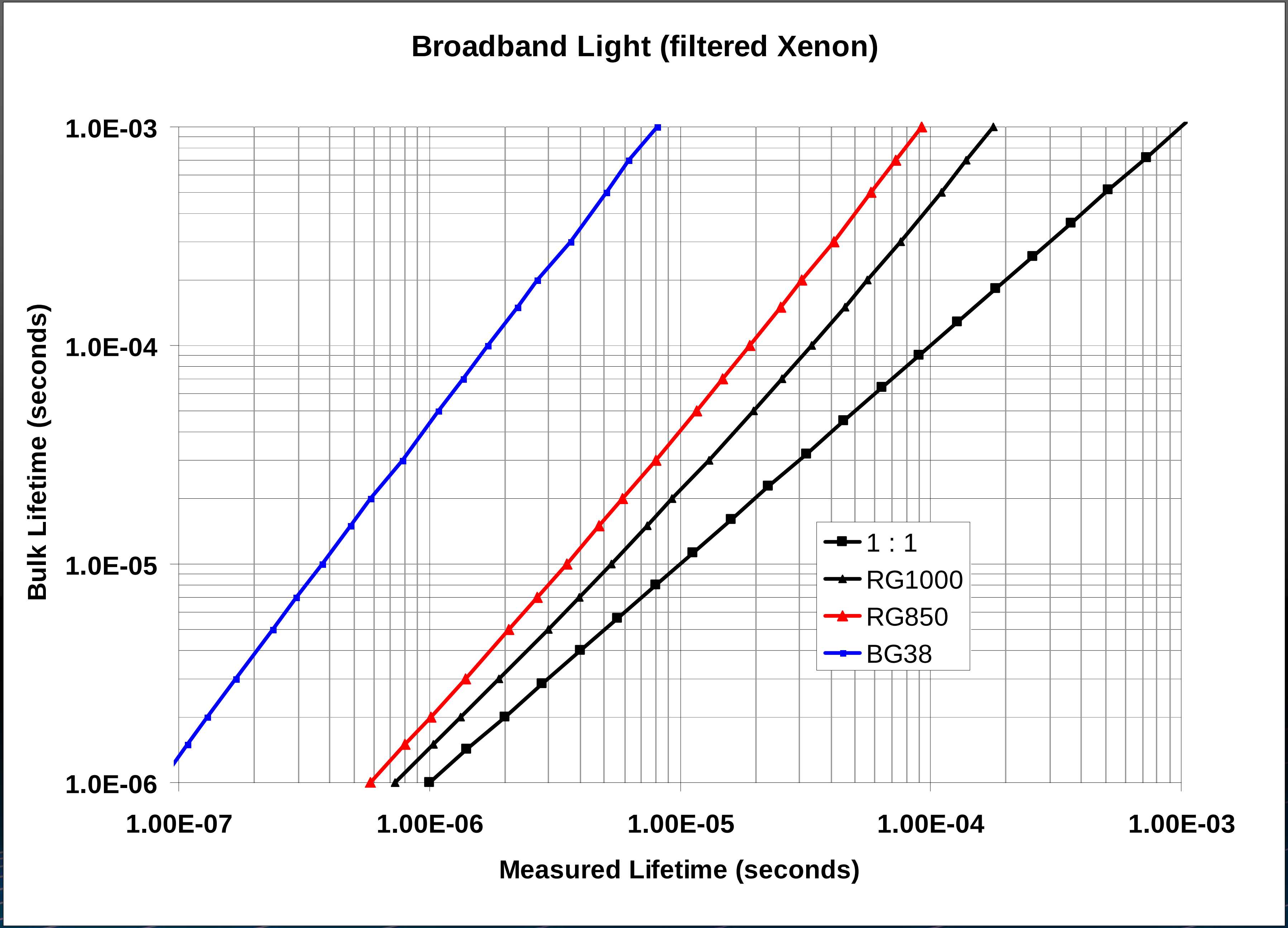
Very thick

S = ∞

Electrons photogenerated near the surface recombine instantly, electrons created deep in the silicon live longer.

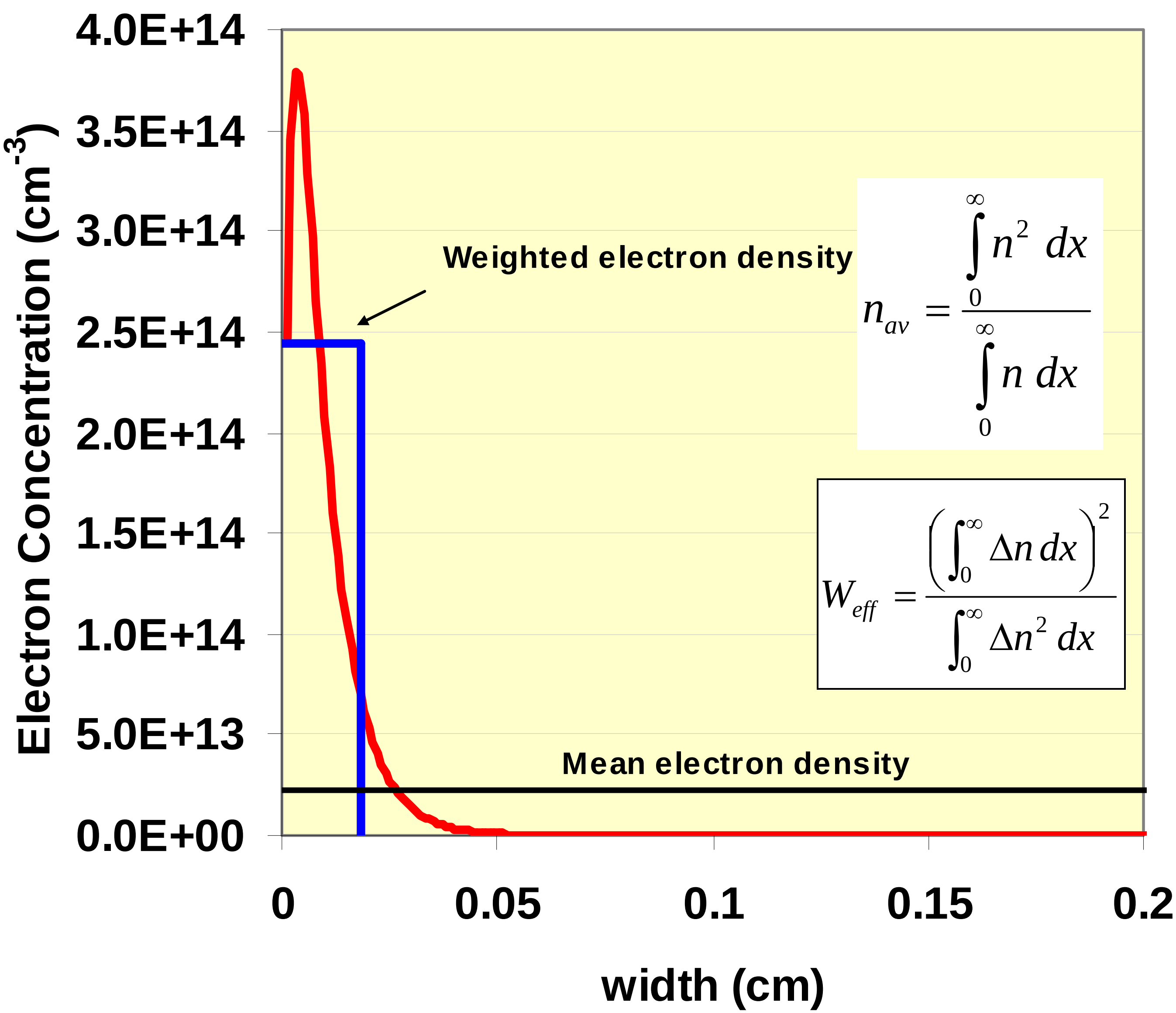


Analytical calculation



PC1D simulation

What Carrier Density to Report (QSSPC)?



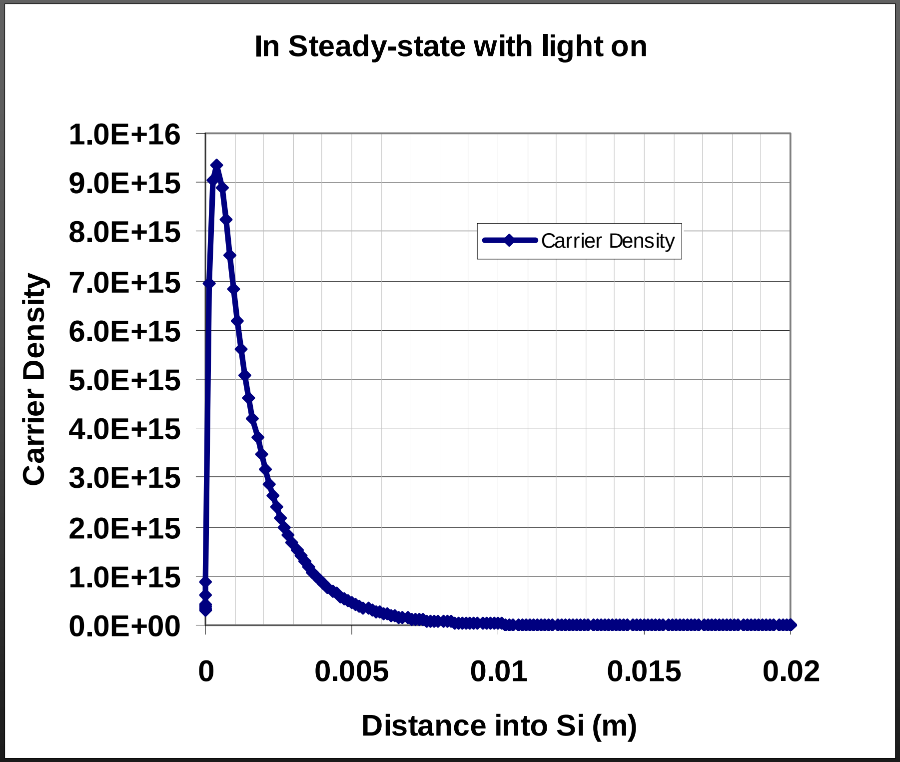
$$n_{av} = \frac{\int_0^\infty n^2 \, dx}{\int_0^\infty n \, dx}$$

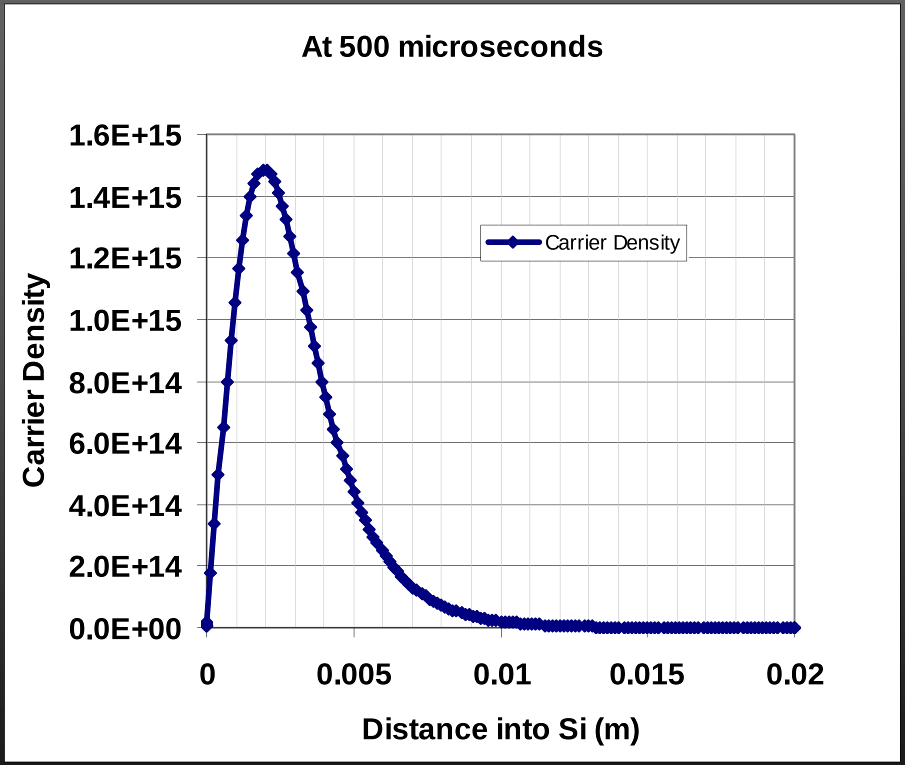
$$W_{eff} = \frac{\left(\int_0^\infty \Delta n \, dx \right)^2}{\int_0^\infty \Delta n^2 \, dx}$$

Sinton et al. ECPVSEC Paris 2004, Bowden et al. JAP 2007.

High-lifetime silicon CZ or FZ boules

Transient PCD on blocks or boules

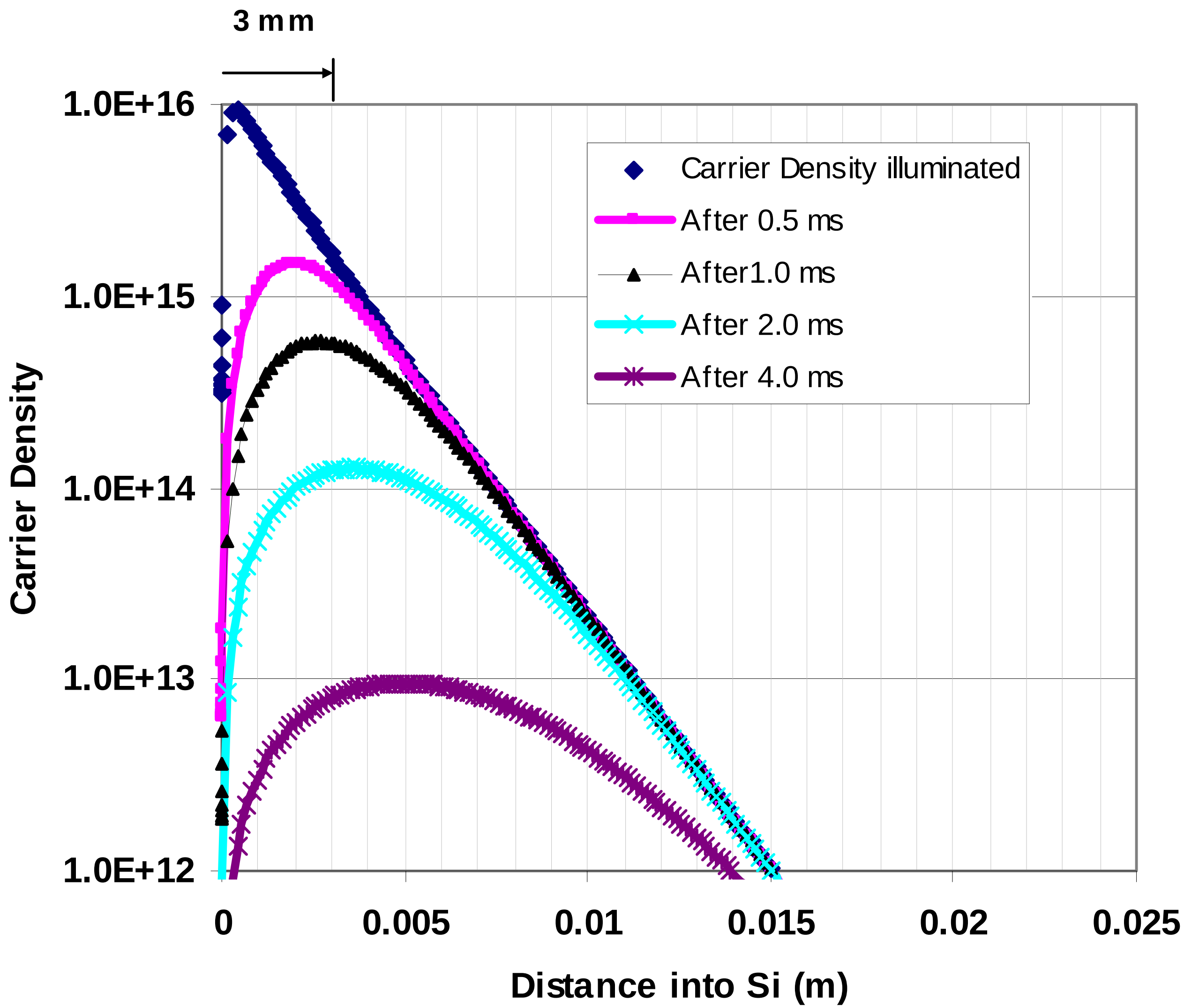




Light

PC1D simulations

Transient PCD on blocks or boules



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PC1D simulations

30 ms

Data: Taking Measurements

How to actually do a lifetime measurement: 4 steps.

1) Illuminate a sample, and measure the resulting signal with the sensor, (Raw data).
2) Use a calibration curve to convert the signal into physical units.
3) Convert the physical units into carrier density vs. time, illumination.
4) Evaluate the excess-carrier recombination lifetime by applying the equations for the transient, QSS, or steady-state case.

Table 2. Parameters to Report (sufficient for comparison between labs and methods)

Results:	Measured lifetime, τ_{eff}
	Carrier density (or range) to report lifetime
	Interpretation (if any): S, τ_{bulk}, J_{oe}
Sample parameters:	Thickness
	Doping (cm^{-3})
	p- or n-type
	Surface passivation (front and back)
Analysis type:	Transient, QSS, or Generalized
	Excitation Wavelengths
	Trapping or DRM correction (if required)
Instrument parameters:	Light time profile
	Sensor type and calibration to Δn
	Sense depth (ingot or block only unless sensitivity varies over a wafer thickness)
	Photogeneration calibration
	Detection area, number of points, method of averaging points (if any).

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Parameters to Report (sufficient for comparison between labs and methods)

Results:

Result description	Symbolic	Value	Units
Measured effective lifetime	τ_{eff}		seconds,ms,µs
Carrier density range	Δn		cm^{-3}
Interpretation parameters [if any]			
Surface recombination	S		cm^2/s
Bulk lifetime	τ_{bulk}		seconds,ms,µs
Emitter saturation current	J_{oe}		A/cm^2
Other			

Interpretation Notes:

Sample Parameters:

Parameter description	Symbolic	Value	Units
Sample thickness	w		cm,µm
Doping concentration	N_A (N_D)		cm^{-3}
Doping type	n / p		
Surface passivation, front and back	-		
Defect state [if applicable]	-		
Fe dissociation level	-		
B:O degradation level	-		
Other			

Analysis type:

- ☐ Transient
- ☐ Quasi-steady-state (QSS)
- ☐ Generalized

Excitation wavelengths/frequencies	
Transfer function τ_{eff} to τ_{bulk}	
Trapping or DRM correction [if any]	

Instrument Parameters:

Parameter description	Value	Units
Light time profile		
Calibration of photogeneration		
Sensor type		
Calibration to Δn		
Sense depth		cm,µm
Detection area		
Area		
Number of points		
Method of averaging points [if any]		

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Other			

Interpretation Notes:

Sample Parameters:

Parameter description	Symbolic	Value	Units
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Other			

Table 1. Parameters to Report (sufficient for comparison between labs and methods)

Analysis type:

- ■ Transient
- ■ Quasi-steady-state (QSS)
- ■ Generalized

Excitation wavelengths/frequencies	
Transfer function τ_{eff} to τ_{bulk}	
Trapping or DRM correction [if any]	

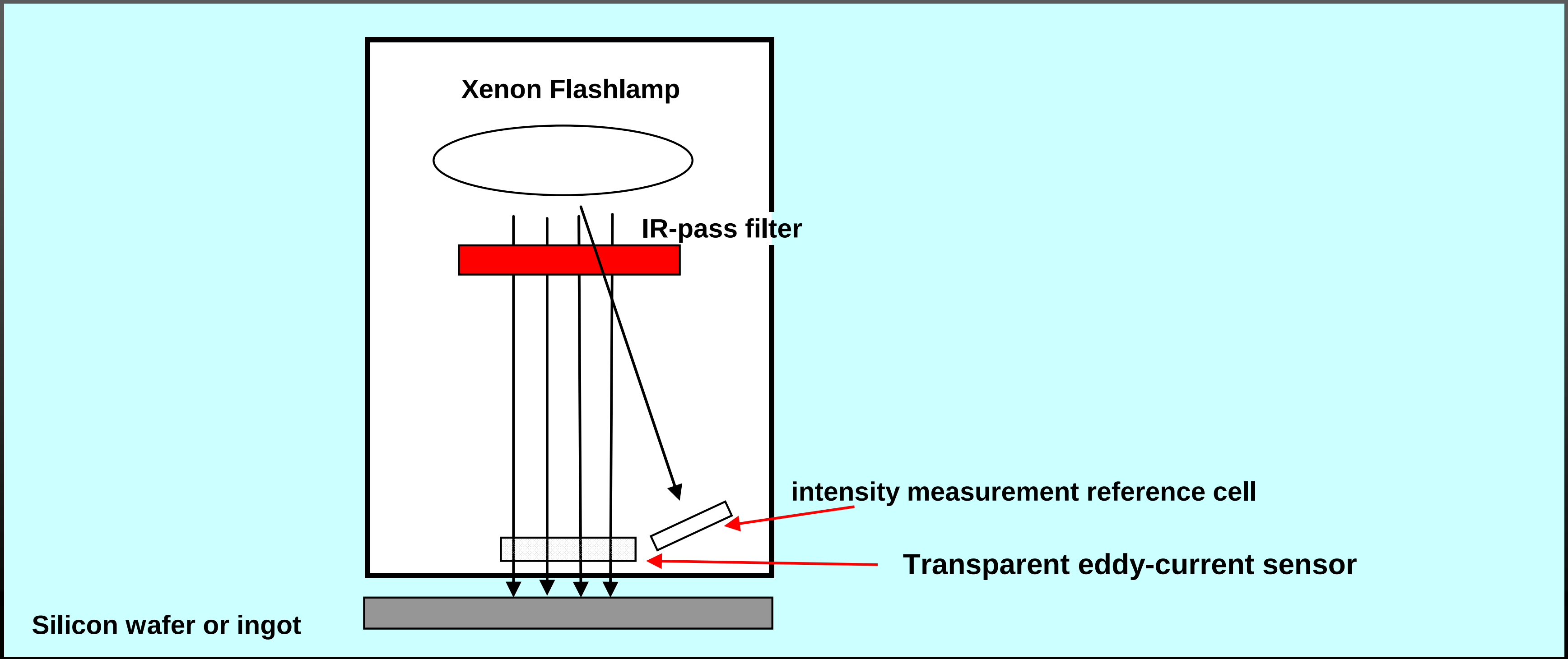
Instrument Parameters:

Parameter description	Value	Units
Light time profile		
Calibration of photogeneration		
Sensor type		
Calibration to Δn		
Sense depth		cm,µm
Detection area		
Area		
Number of points		
Method of averaging points [if any]		

One specific example:

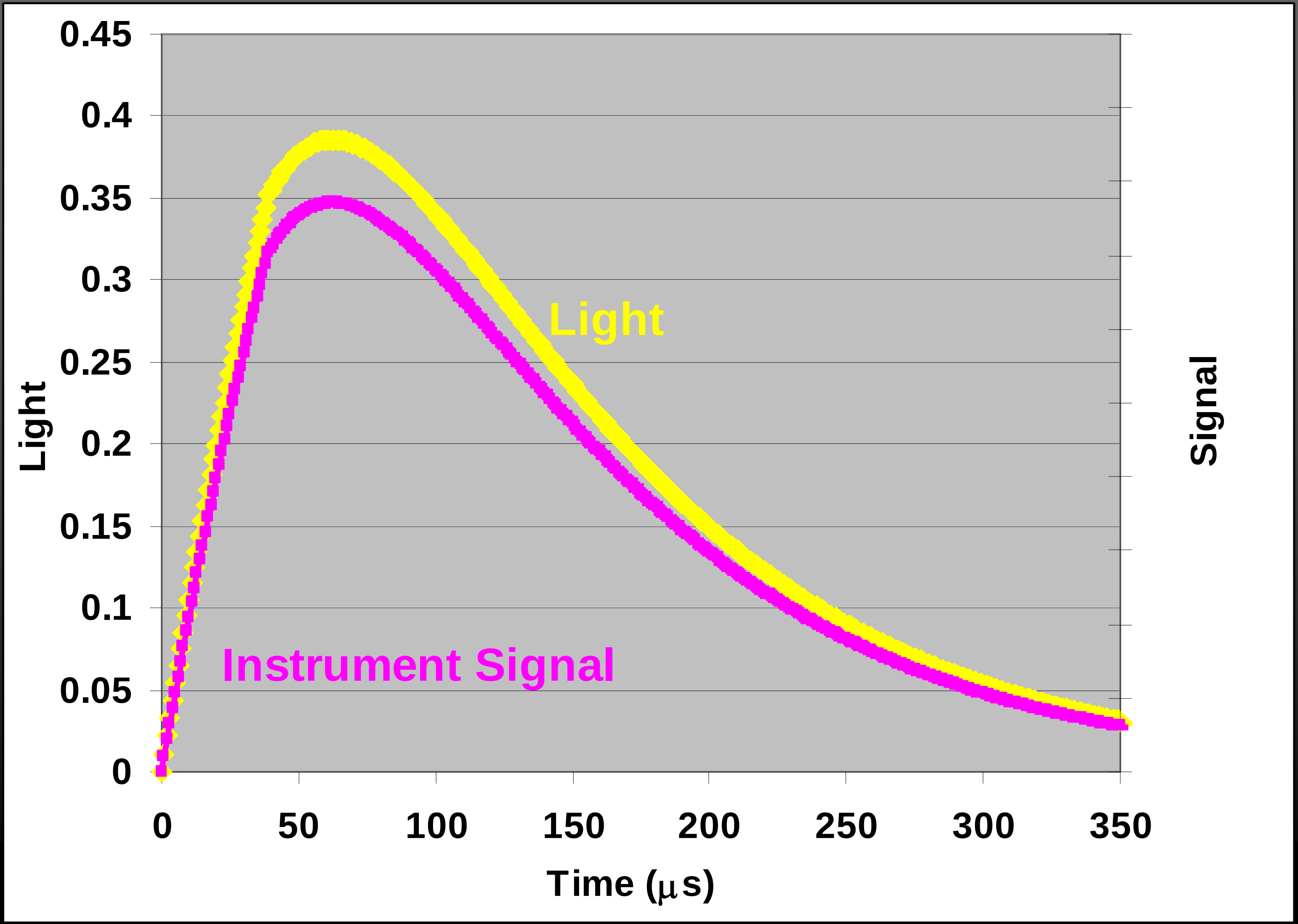
Carrier recombination measurements using an RF-eddy-current conductance sensor

(RF-QSSPC, RF Transient PCD)

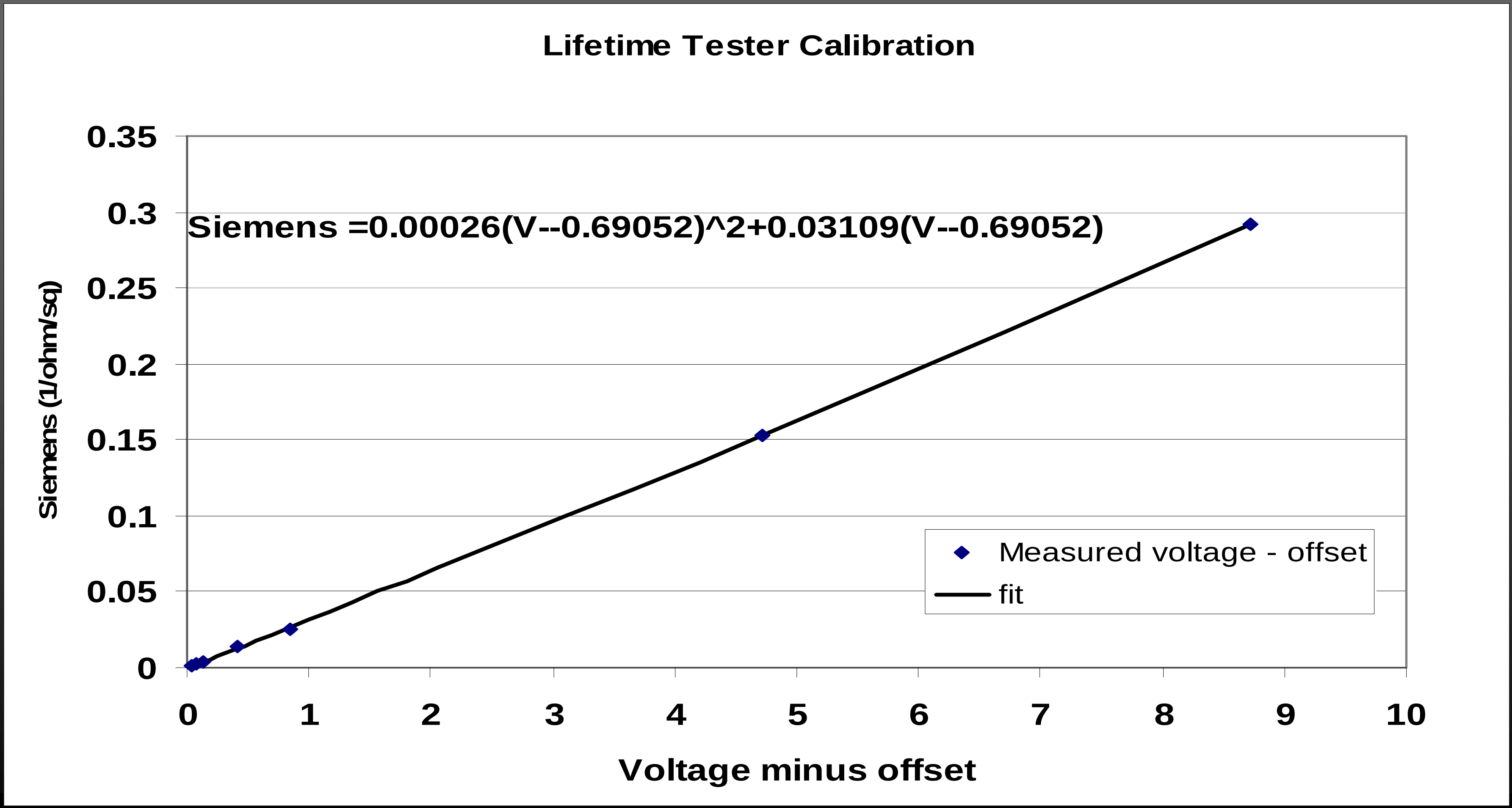


Light source, reference intensity sensor, and photoconductance sensor.

Step 1: Take data.



Step 2: Conductance Calibration: Traceable to 4-point-probe

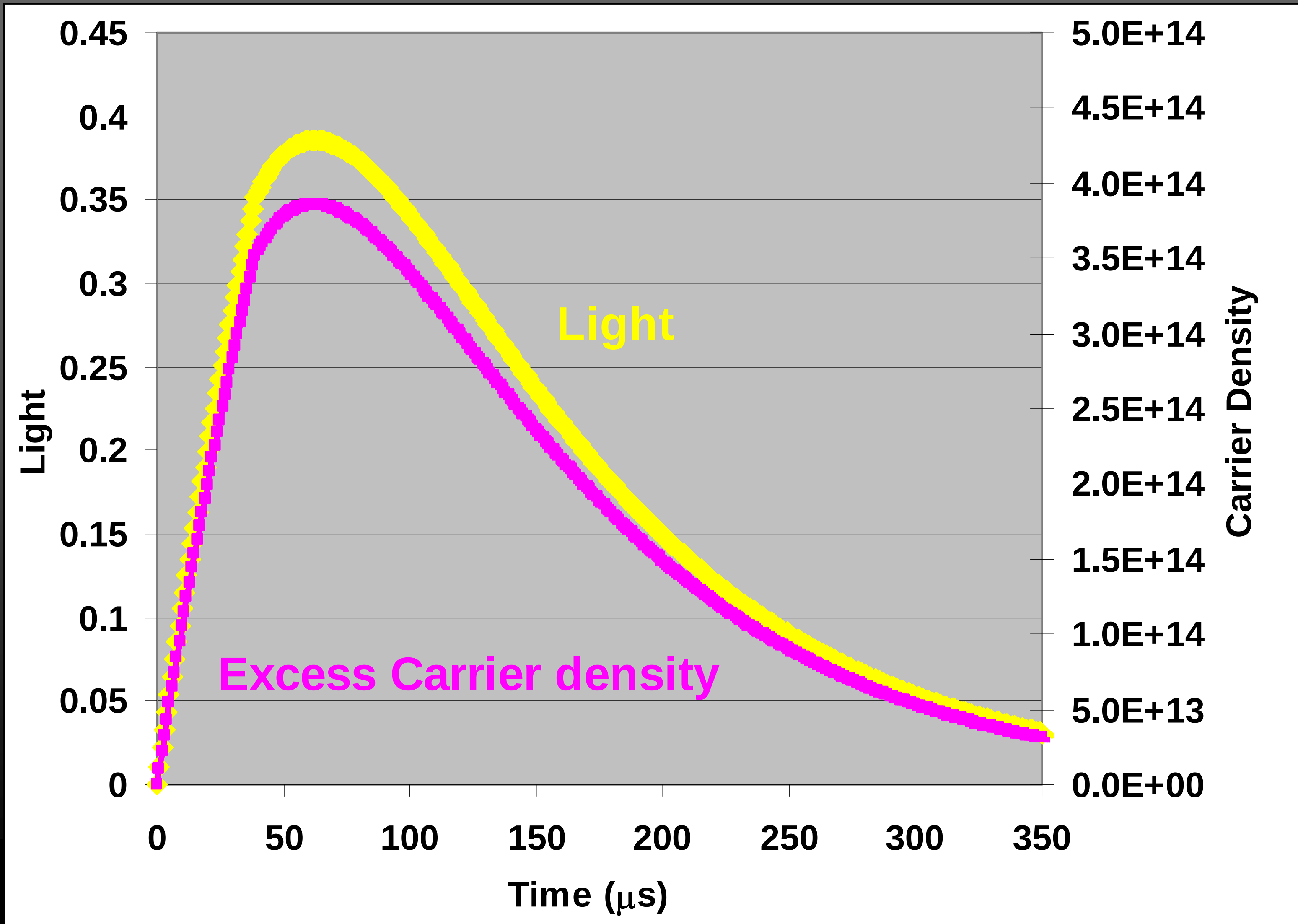


Step 3: Photoconductance & Carrier Density

- The mobility equation converts the conductivity to an average carrier density.

$$\Delta n = \frac{\Delta \sigma}{qW\left(\mu_n(\Delta n, N_A) + \mu_p(\Delta n, N_A)\right)}$$

Step 4: Carrier density vs. time & light.



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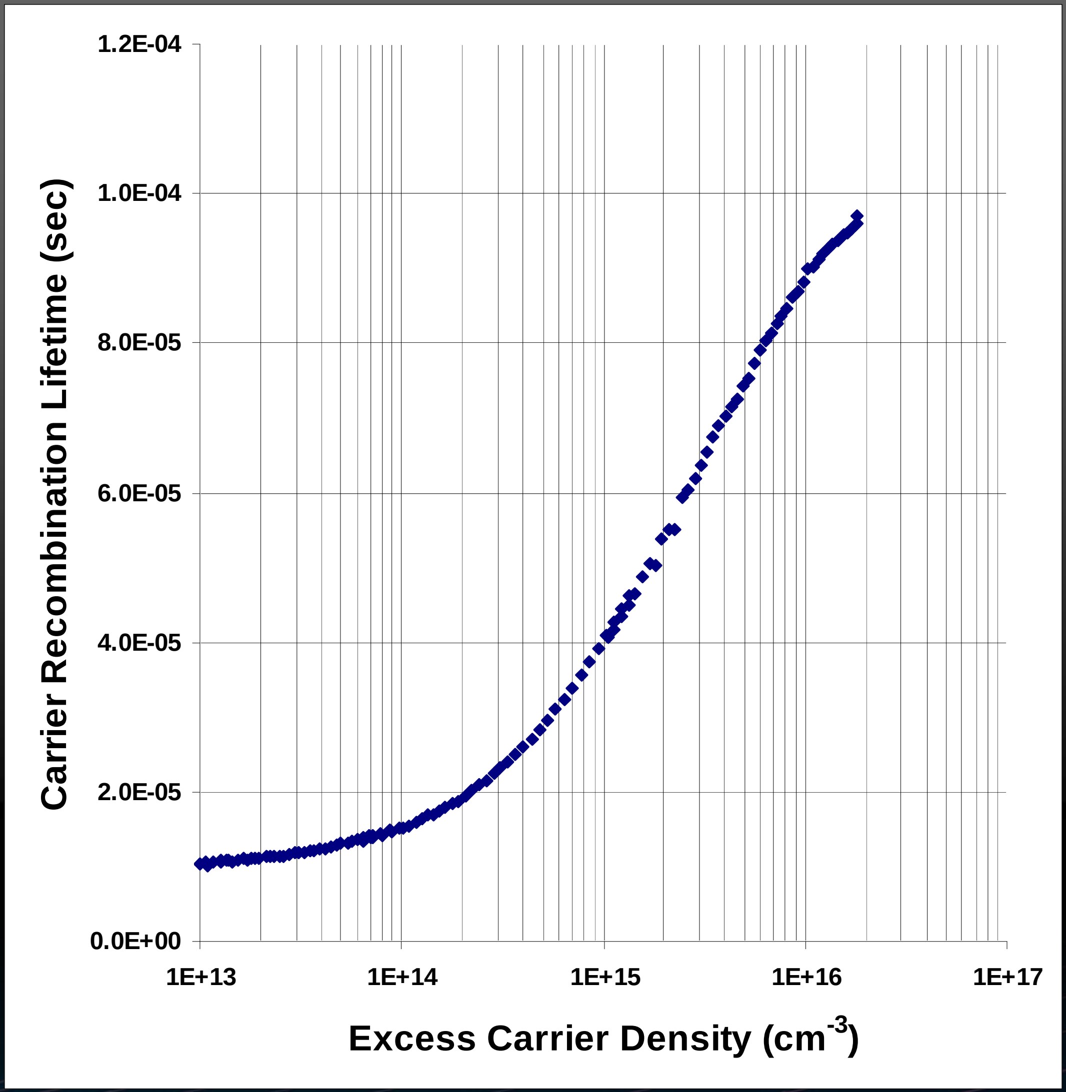

Fig. 1. The recombination lifetime of a 3-ohm-cm B-doped CZ sample after degradation of the B:O defect[1]. This data was obtained by the QSSPC method[2] and has uncertainties less than 10% in both the lifetime and carrier-density axis.

Conclusions:

White Paper: A consensus on a fundamental framework for silicon PV carrier recombination lifetime testing.

The analysis applies to any sensor, facilitating comparisons between labs and methods.

Results based on this framework are physically rigorous and suitable for use in solar-cell modeling, optimization, and process control.