U.S. Department of Energy
Energy Efficiency and Renewable Energy

ANALYSIS OF TECHNIQUES FOR MEASURING CARRIER RECOMBINATION LIFETIME

Richard K Ahrenkiel, Fellow Emeritus

National Renewable Energy Laboratory,
Golden, CO

and

Lakewood Semiconductor,

Lakewood, Colorado

Collaborators: Steve Johnston and Darius Kuciauskas NREL

TECHNIQUES AVAILABLE

All Contactless

- **Time Resolved Photoluminescence (TRPL).**
- **Transient Photoconductivity by Microwave Reflection (μPCD).**
- **Quasi-Steady-State Photoconductivity (QSSPC).**
- **Resonant Coupled Photoconductive Decay (RCPCD).**
- **Transmission Modulated Photoconductive Decay (TMPCD).**
- **Pump-Probe measurement of free carrier absorption (FCA).**

Commercially available

NREL/Lakewood Semiconductors

MEASUREMENT PHYSICS

- TRPL: Measure rate at which photons are emitted from excess carriers excited by pulsed light and other means. Measure: $\Delta n(t)$.
- PCD: Measure excess conductivity induced by pulsed or steady state light sources. Measure: $\Delta n(t)*\mu(t)$.

Complications

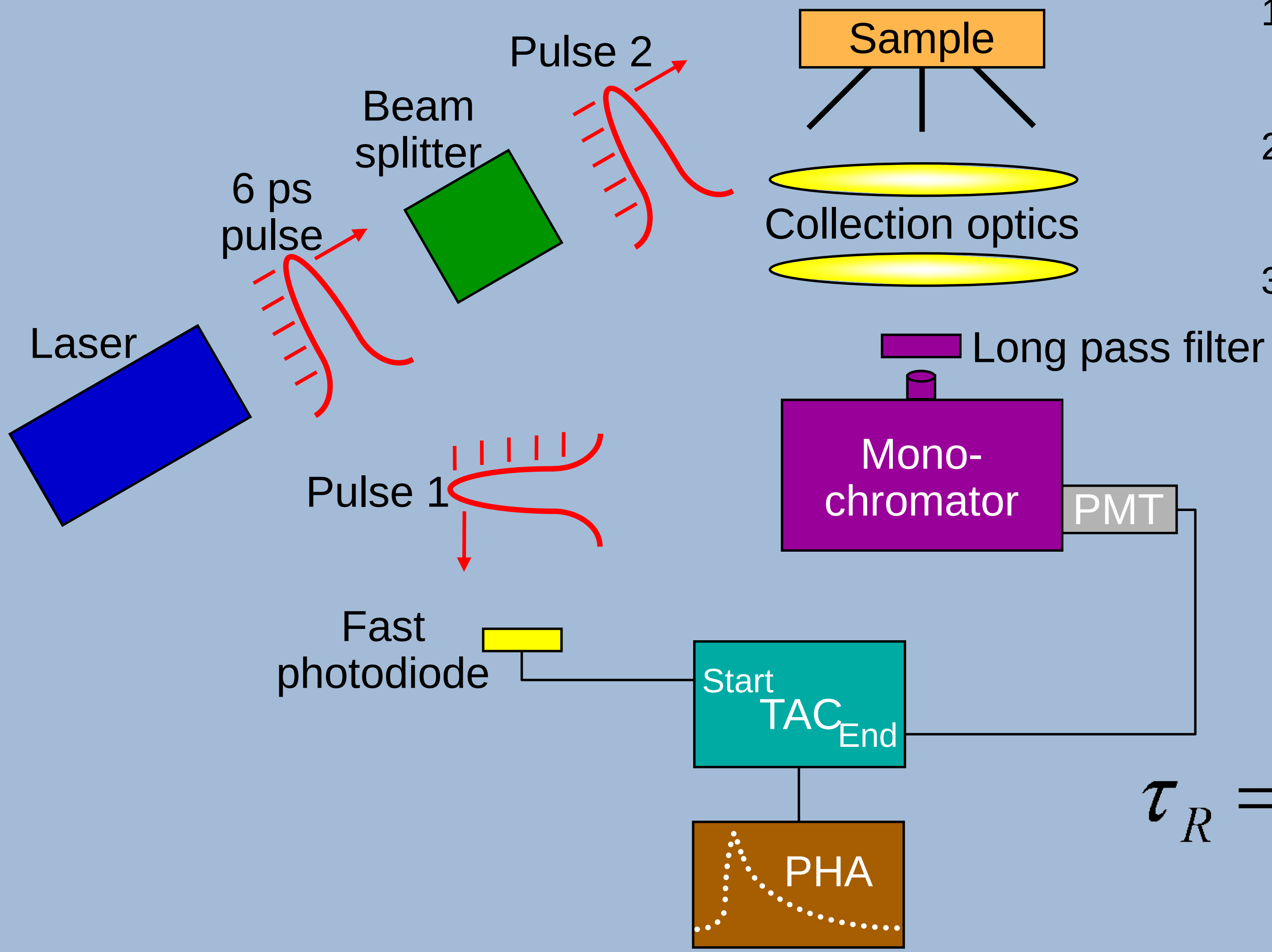
Limelime is dependent on injection level.

Artifacts

Surface Recombination Velocity
Shallow Traps

(TRPL)

Single photon counting schematic

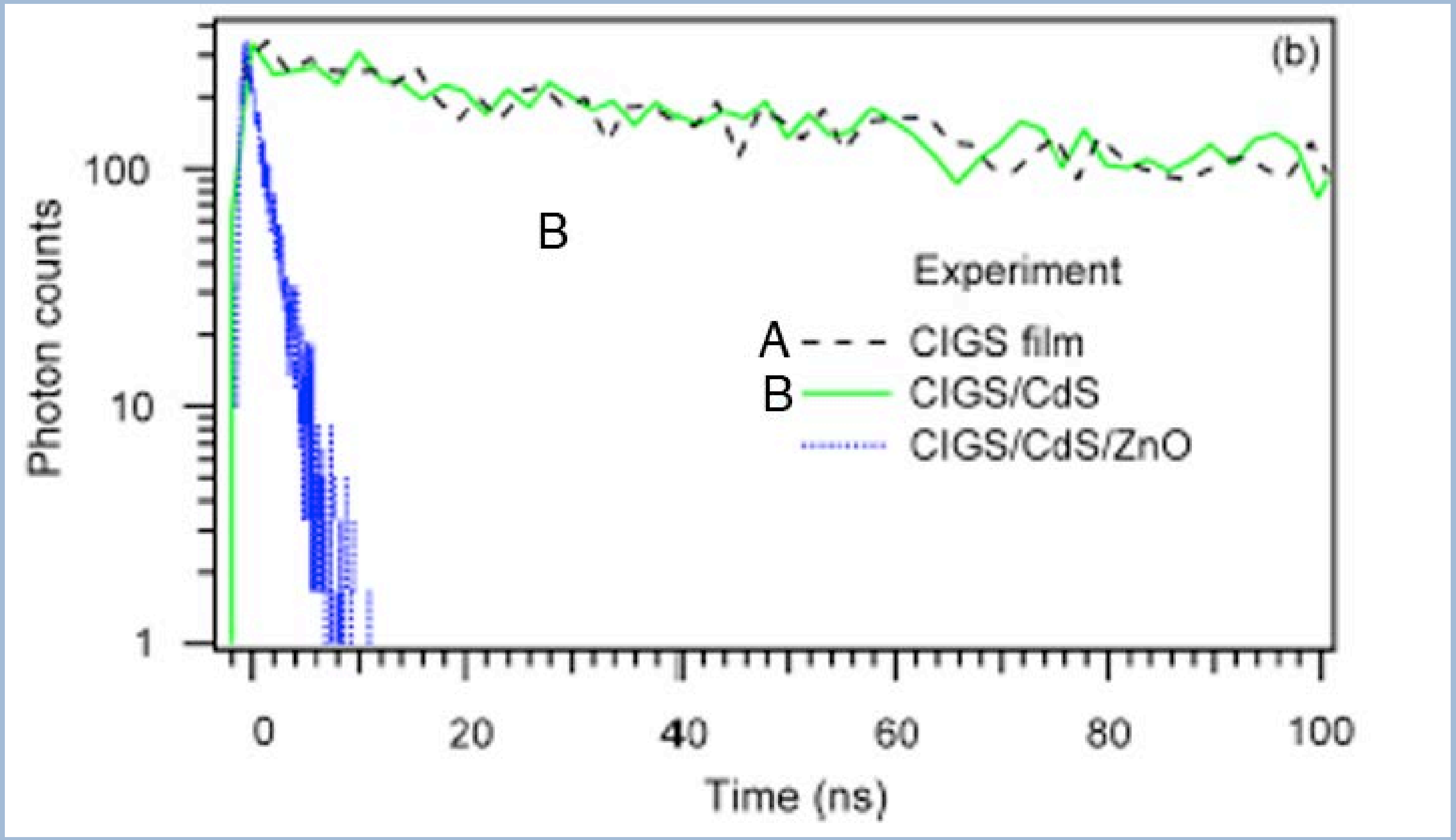


1. We detect photon once every 300 attempts.
2. Pulse rate is about 1 million/second.
3. The apparatus produces a histogram of photon counts vs. time.

$$\tau_R = 1/(B * N)$$

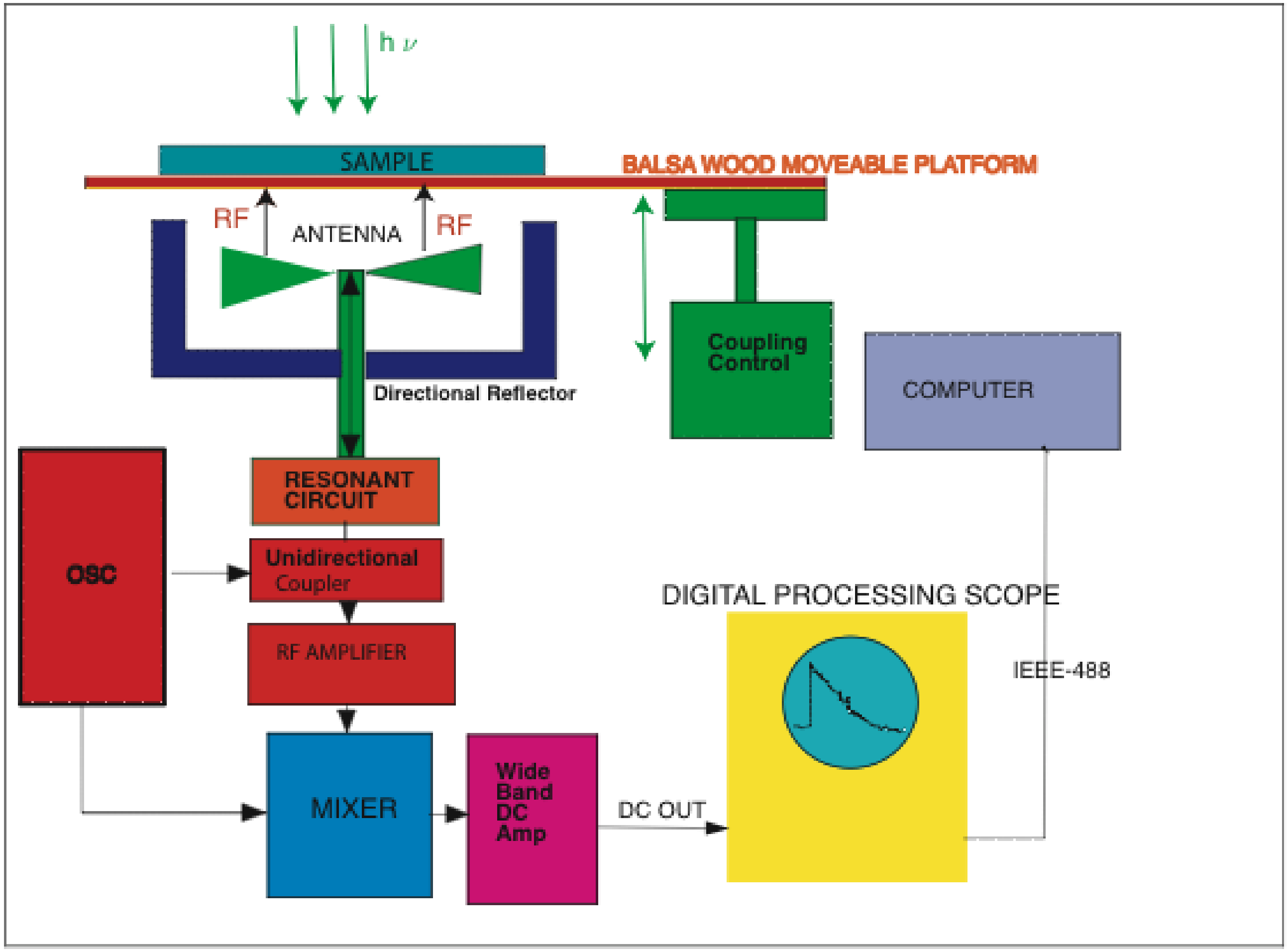
Why is CIGS more efficient than CdTe?

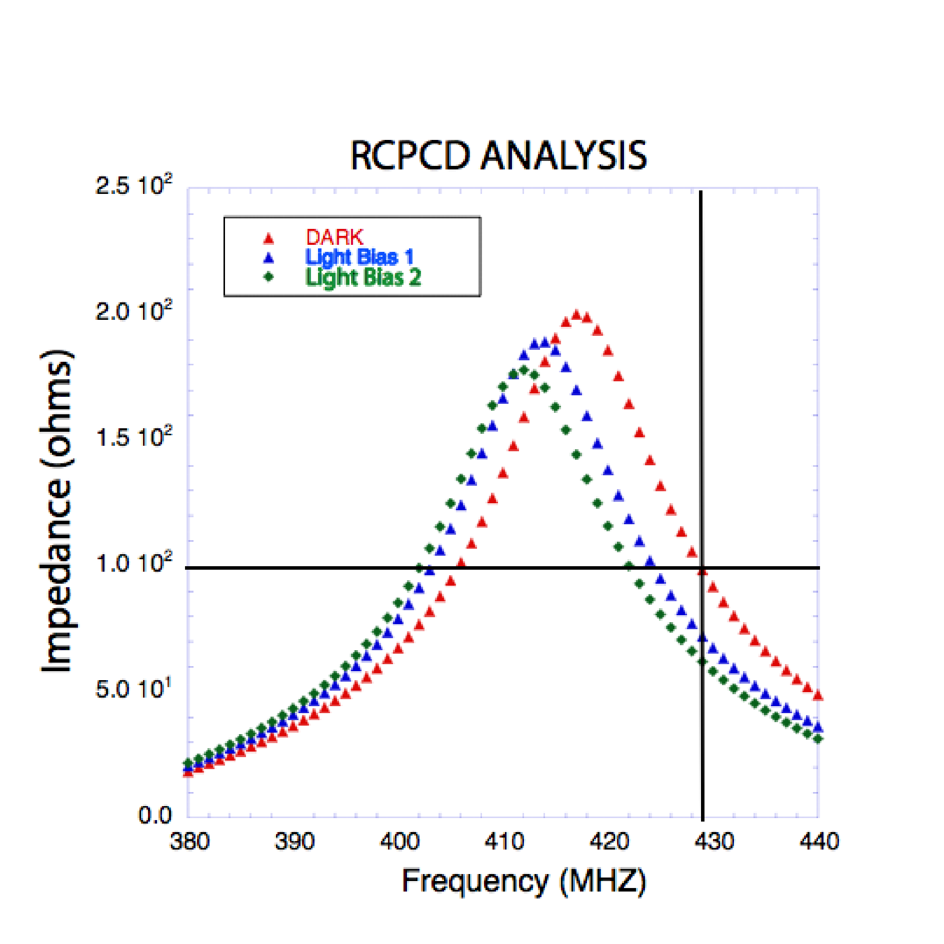
TRPL of CIGS



- Metzger et al, APL 93, 022110 (2008).

RESONANT COUPLED PHOTOCONDUCTIVE DECAY APPARATUS

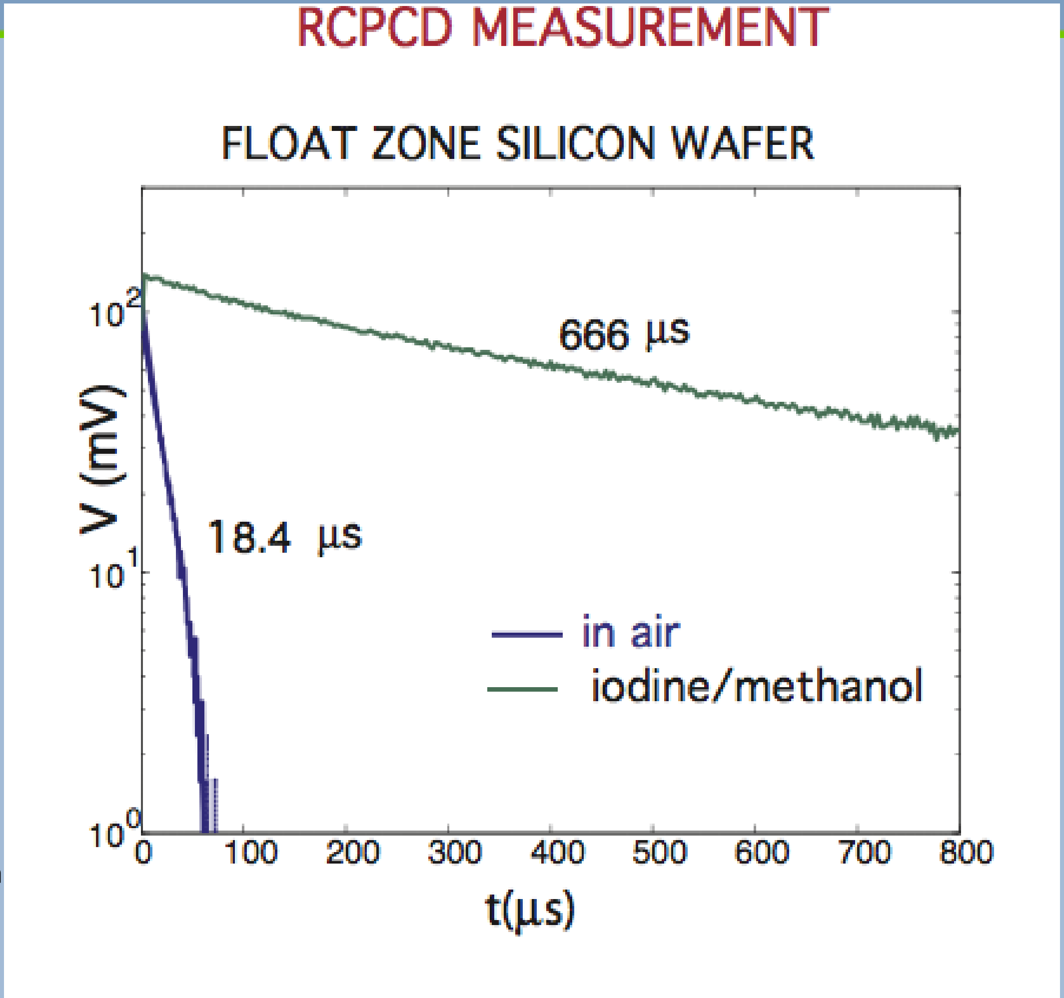




Float Zone Silicon Wafer (undoped)

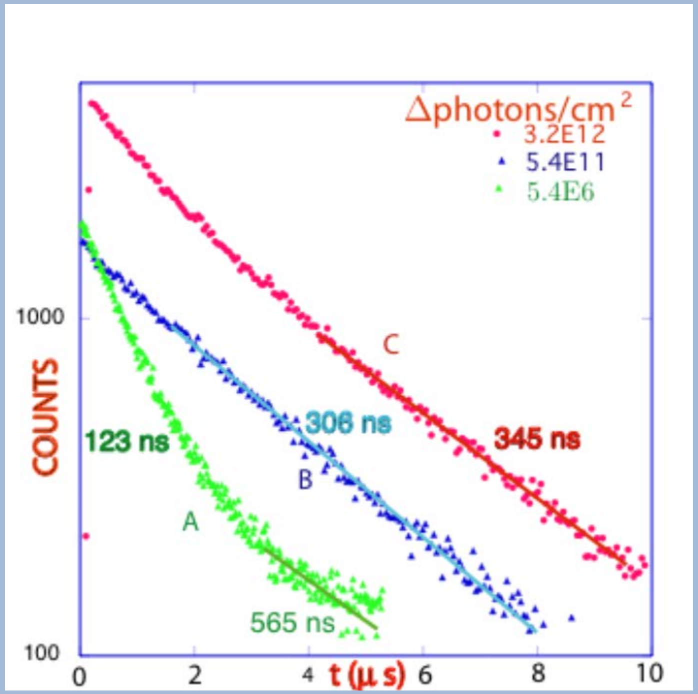
- High Q provides high sensitivity
- Response time varies as 1/Q. Poorer time resolution

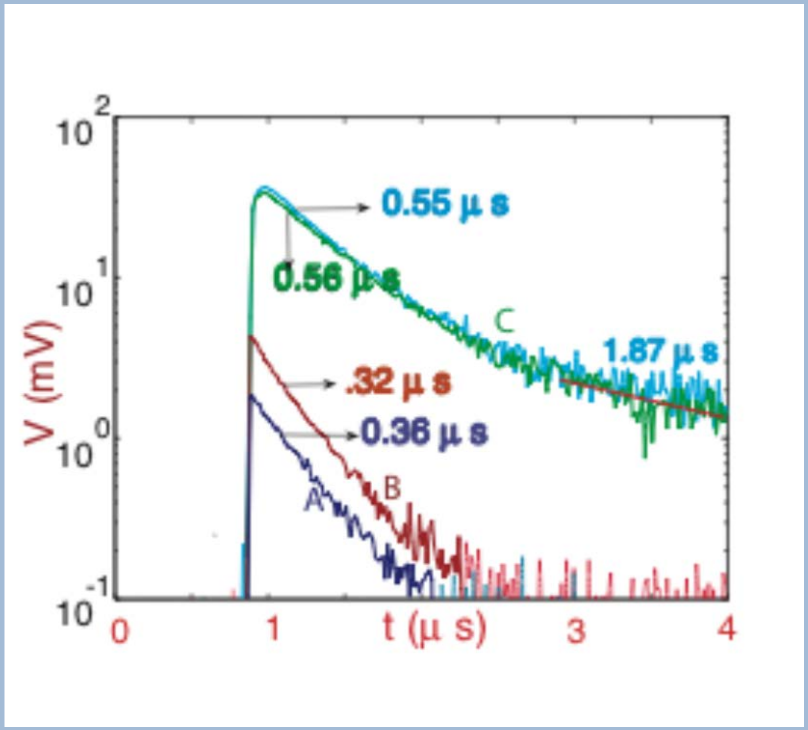
RCPCD MEASUREMENT OF WAFER IN SOLUTION



- Solution
- Sample

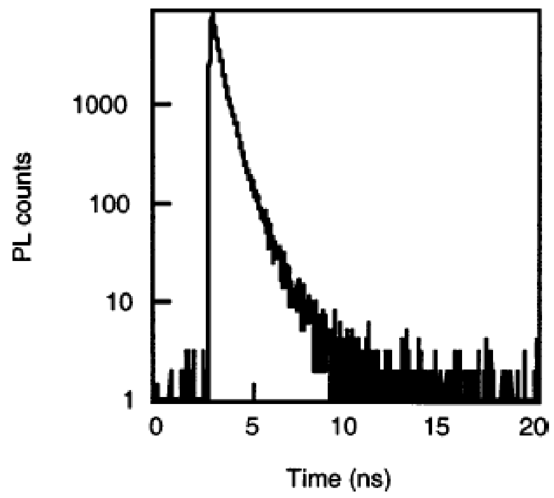
TRPL vs RCPCD



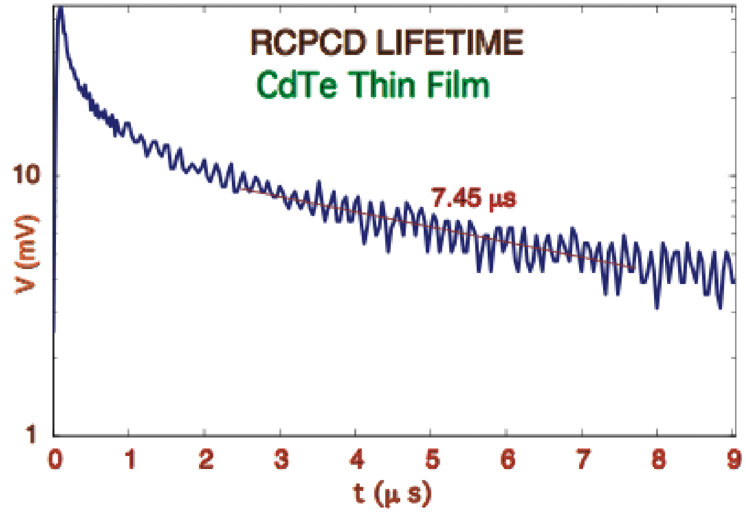


The GaAs absorber was grown to a thickness of 2 μm and the p-type doping density is 2.4×10^{17} cm^{-3}. The sample is clad by p-type layers of GaInP that are approximately 100 A in thickness.

Polycrystalline CdTe

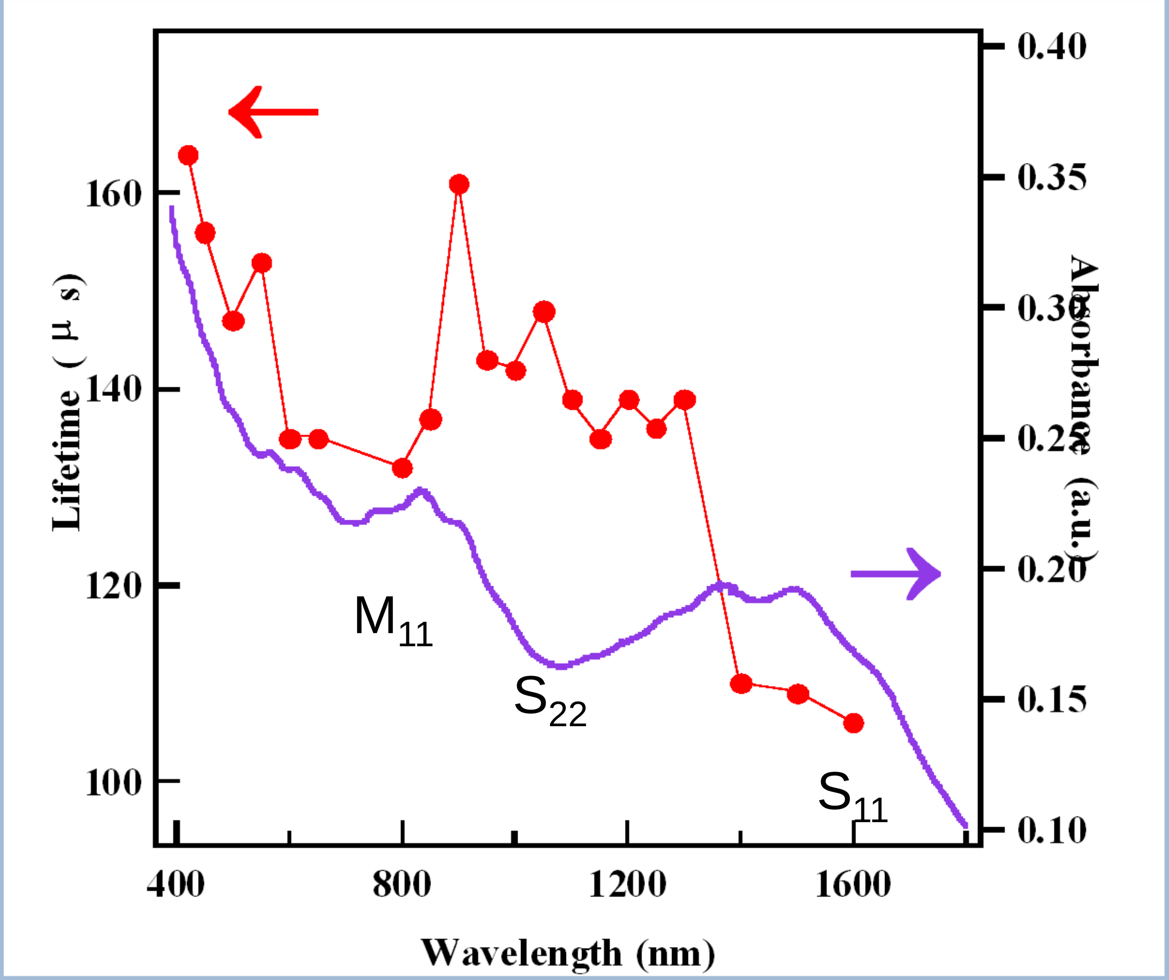


TRPL lifetime measured on a typical NREL device.



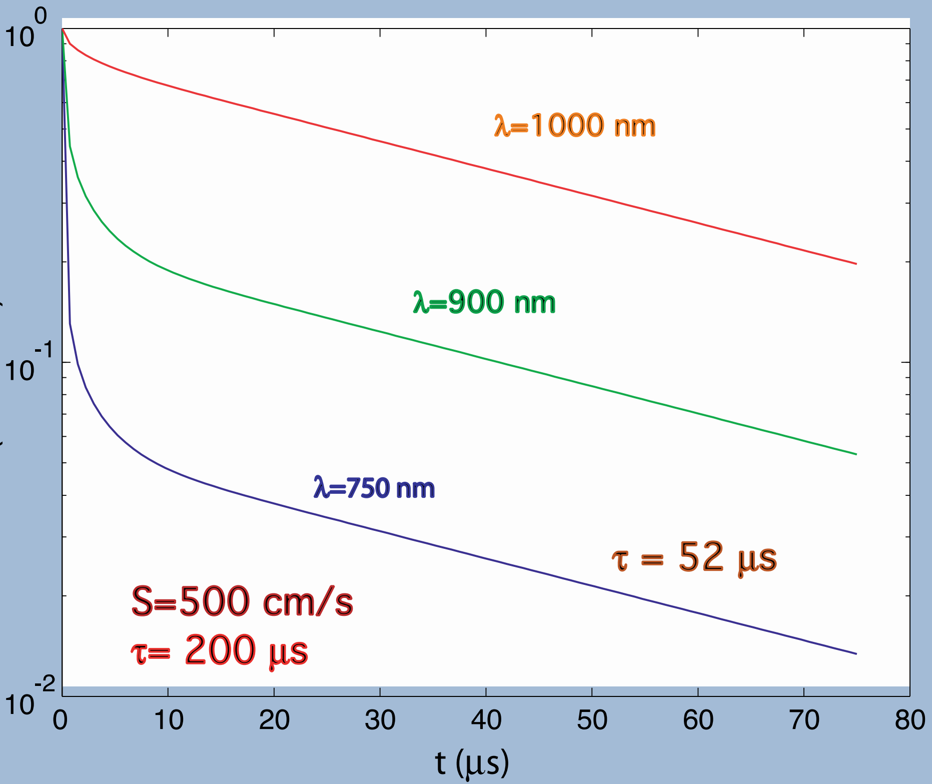
Left: TRPL of CdTe thin, CSS-grown film, shows primary recombination lifetime.
Right: RCPCD of similar film shows only shallow trapping at grain boundaries.
W. K. Metzger,a) D. Albin, D. Levi, P. Sheldon, X. Li, B. M. Keyes, and R. K. Ahrenkiel
JAP 94, 3549 (2003).

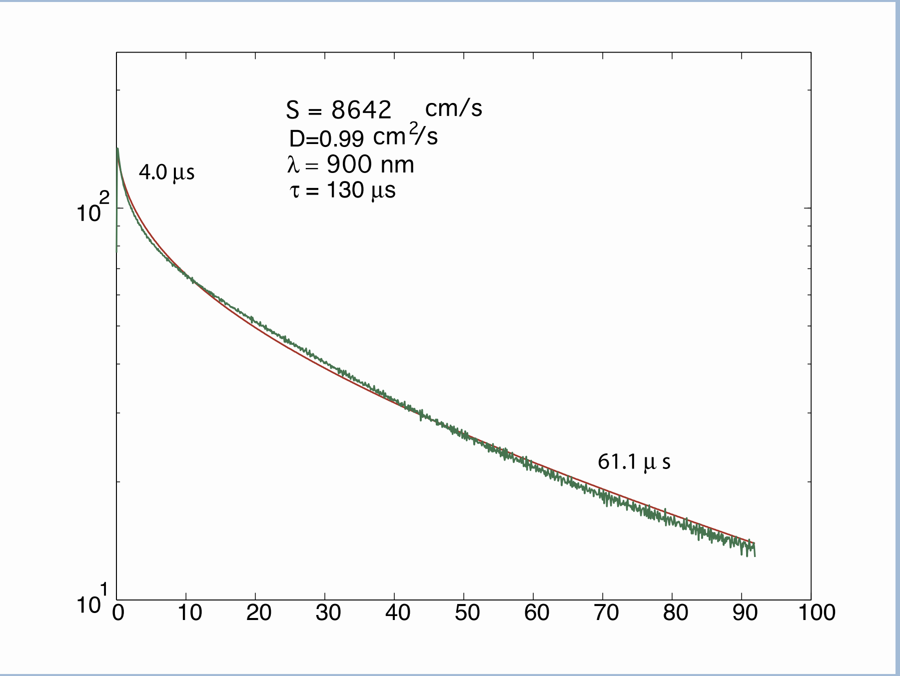
Photoconductive lifetimes are wavelength dependent



HiPCO SWNT lifetime in nafion as a function of excitation wavelength. Charge transfer/charge separation mechanism.

Surface Recombination from Variable Excitation Wavelength

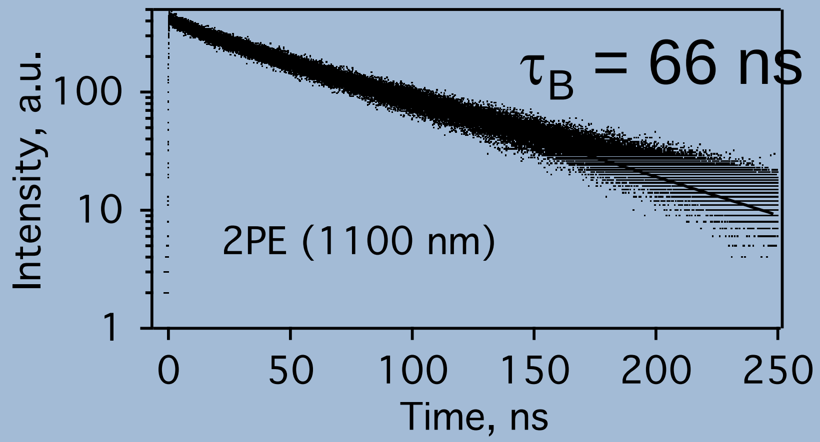


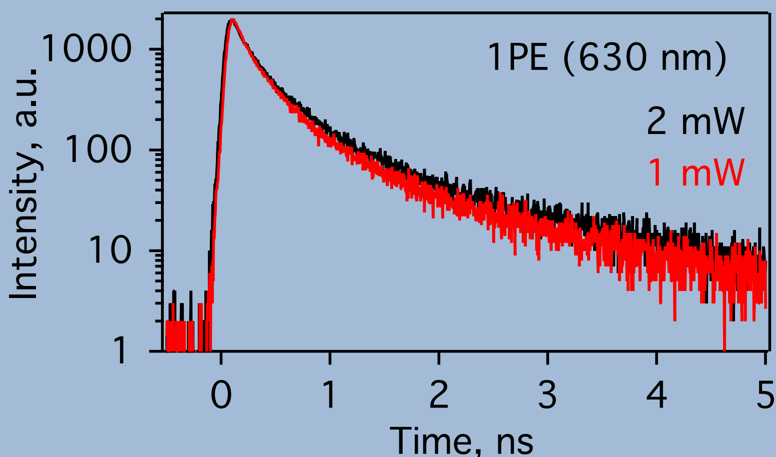


Model calculation using Fourier Mode analysis. Silicon wafer ~300 µm thick.

Data fit to Fourier Series. Silicon wafer data.

2PE TRPL lifetime analysis – bulk lifetime





Bulk lifetime in undoped (p_0 = 3.5×10^{14} cm^{-3}) CdTe is 66 ns.

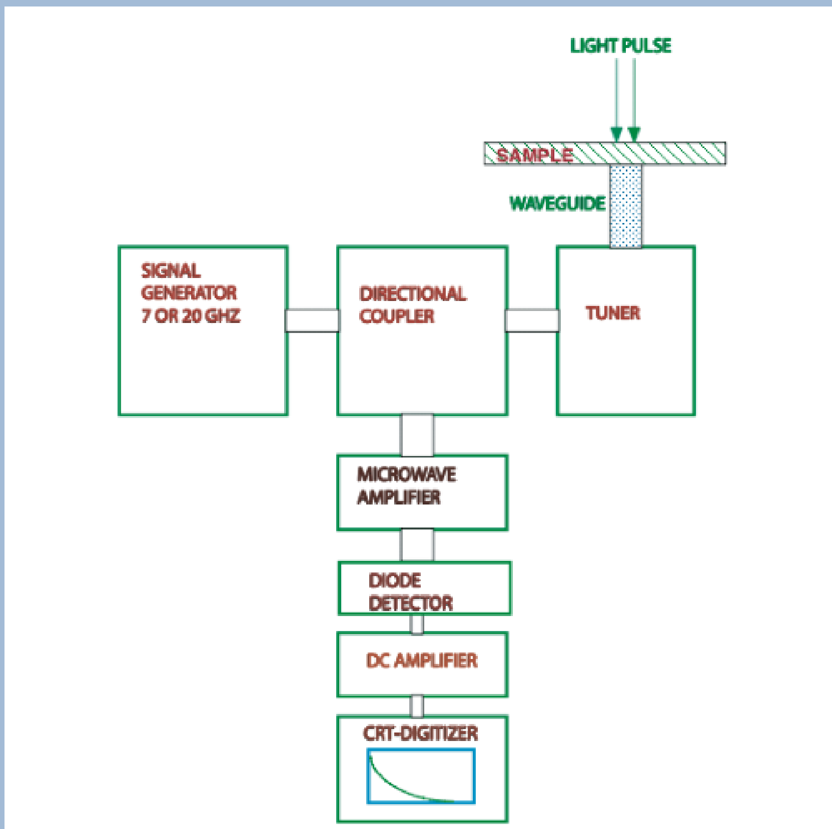
Estimate for radiative lifetime:

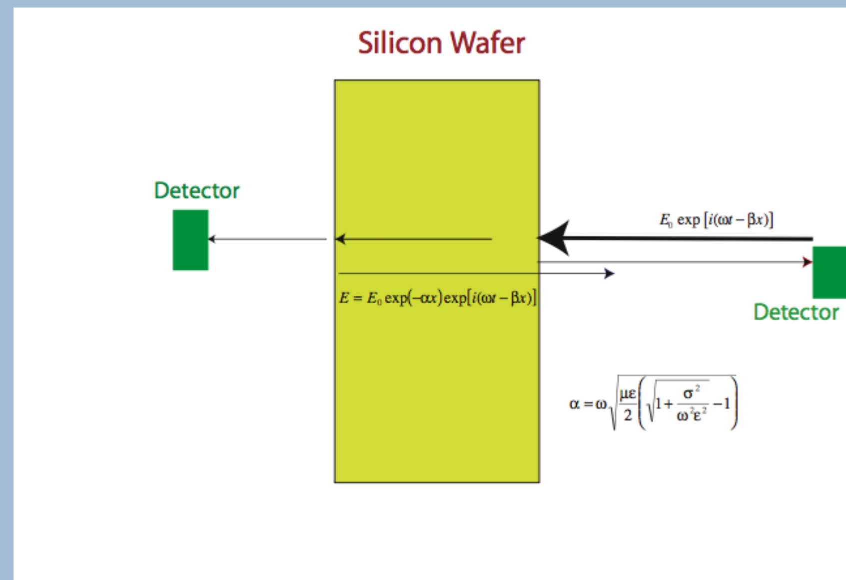
$$\tau_R = \frac{1}{Bp_0} \approx 950\ ns$$

TRPL analysis for materials with large S:
1PE gives estimate for S,
2PE gives bulk lifetime

D.Kuciauskas, A.Kanevce, J. M. Burst, J. N. Duenow, R. Dhere, D. S. Albin, D. H. Levi, and R. K. Ahrenkiel
Journ of PV (in press)/.

MICROWAVE REFLECTION

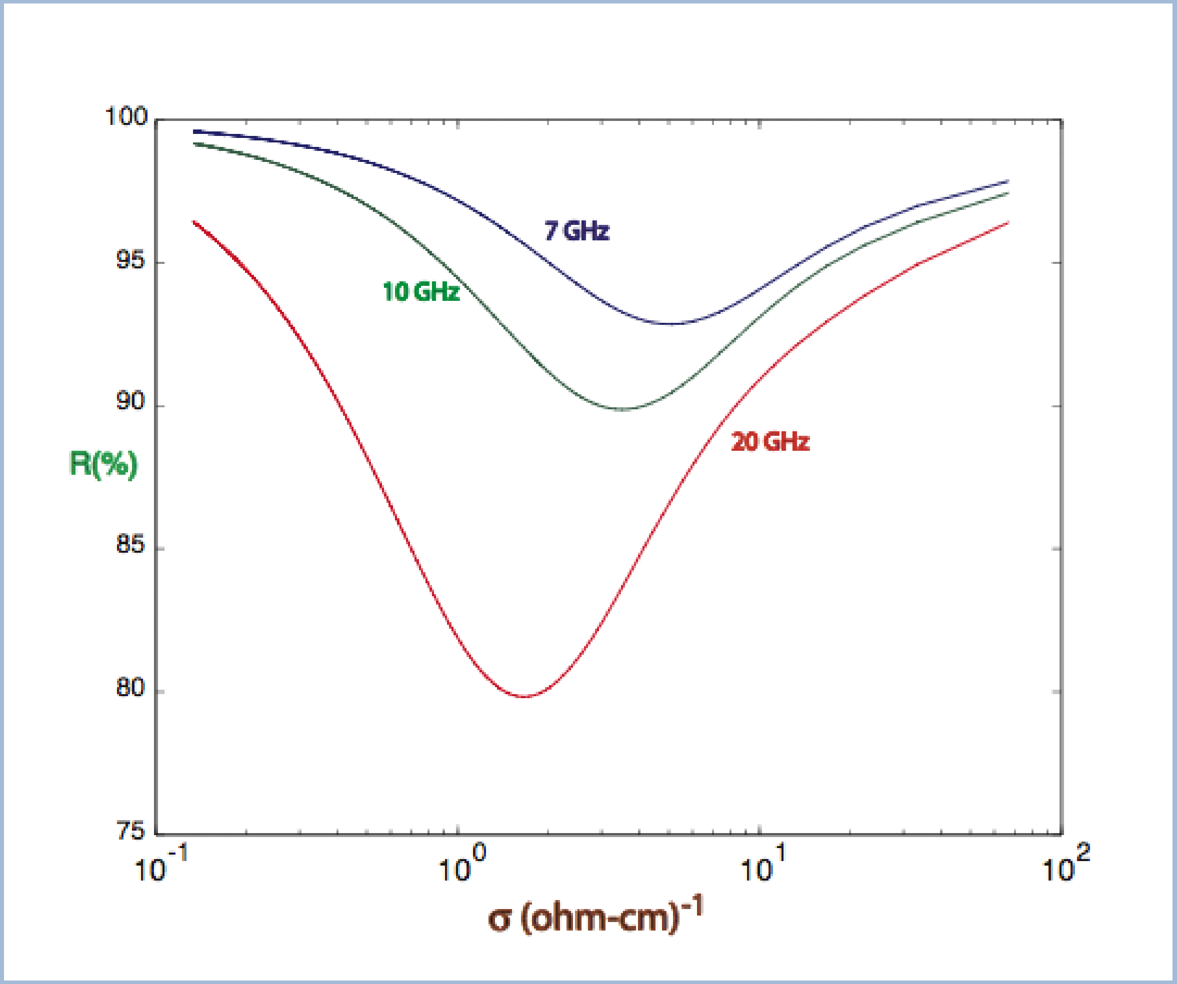




MICROWAVE APPARATUS

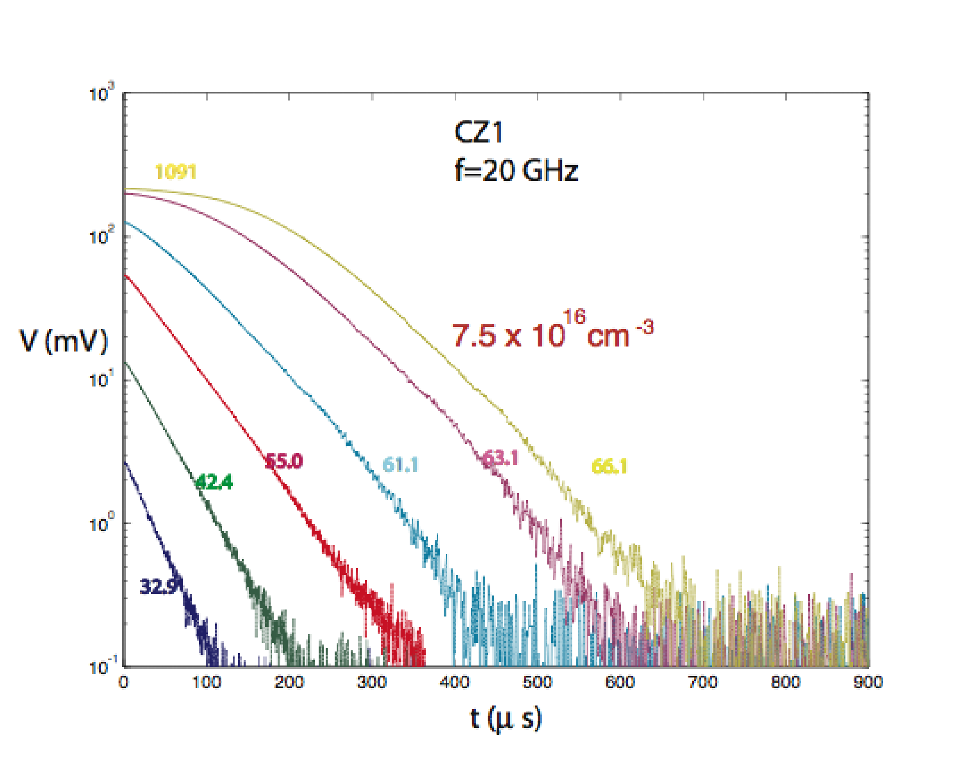
Reflection at and back surfaces.
Absorption in volume by free carriers.

Maxwells Equations Soluktion



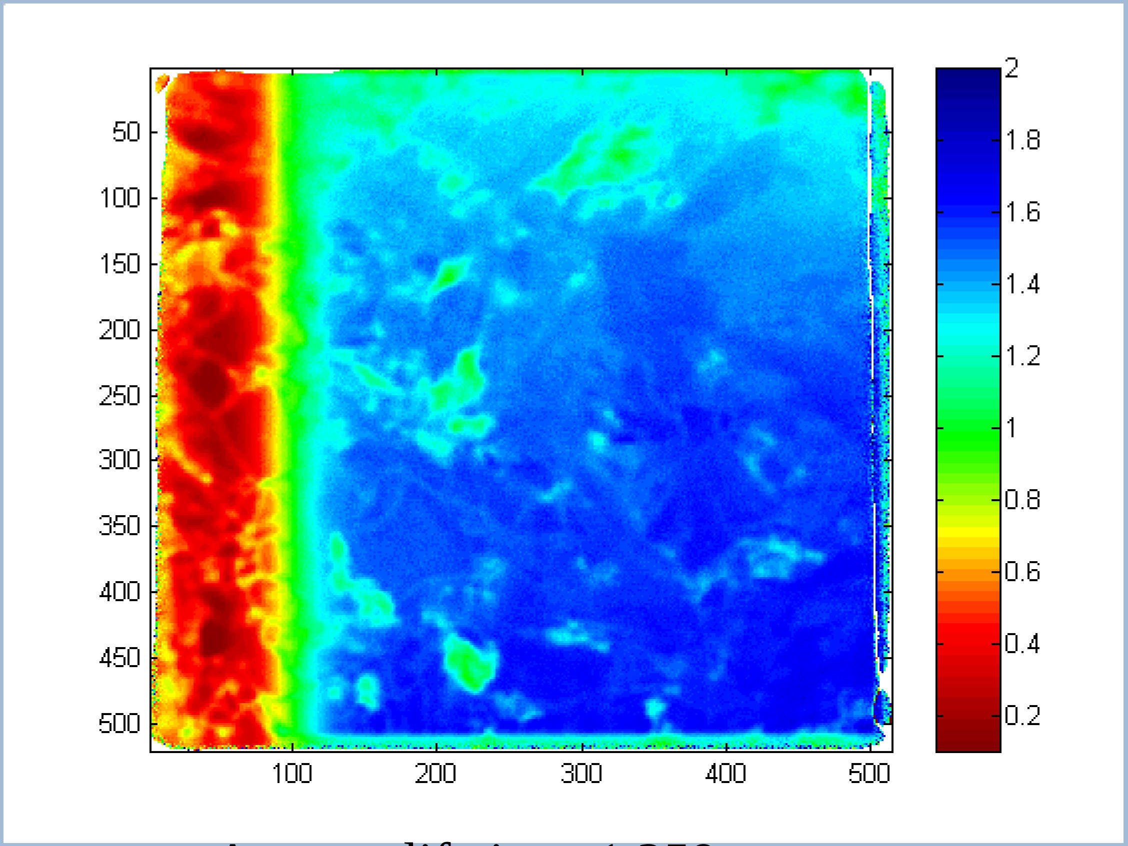
- Metallic reflector at back surface. Microwaves and light incident from the same side.

NREL Data at 20 GHz



- σ =0.0057 (ohm-cm)$^{-1}$

Recombination Lifetime in Multi-crystalline Silicon

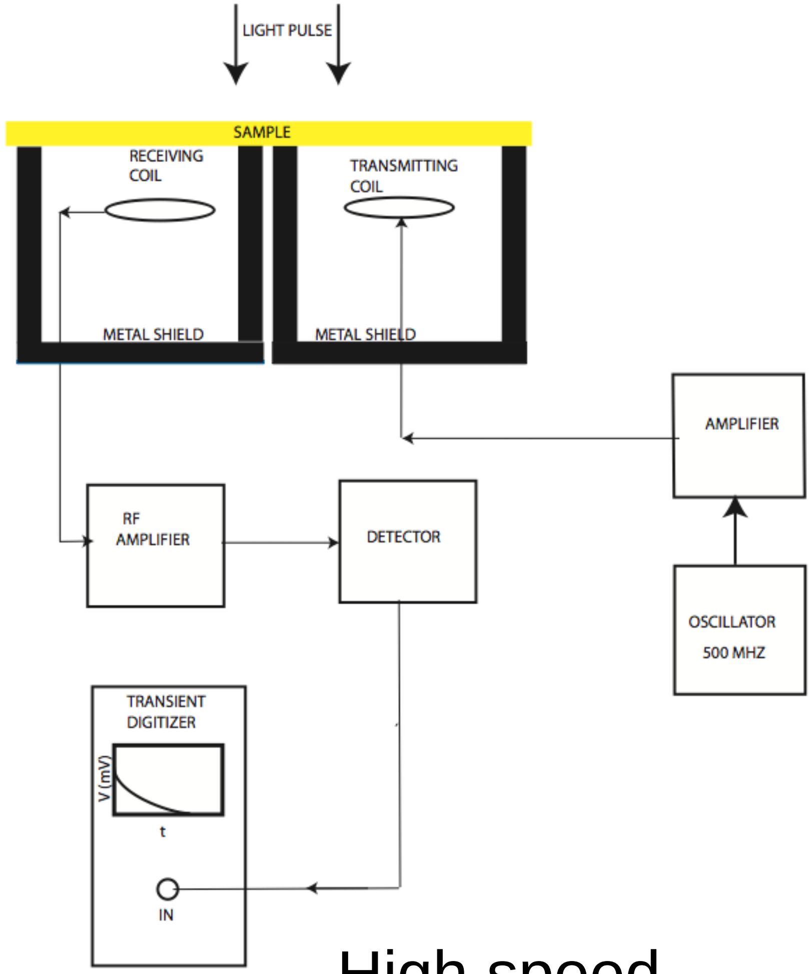


Average lifetime: 1.259µs

- **Semilab map** of wafer # ING07. Thickness is
- 250 microns. Doping about 1E16 p-type

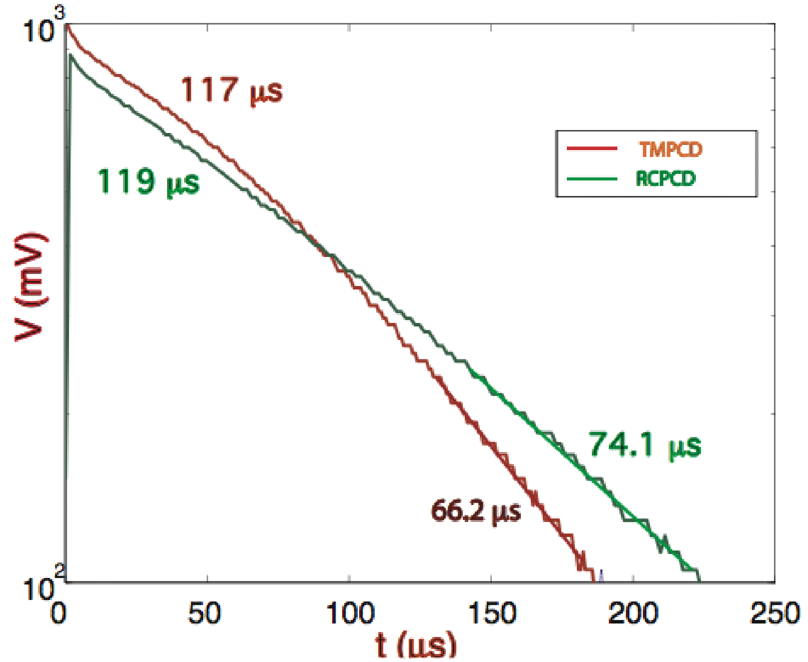
TMPCD

Apparatus Block Diagram

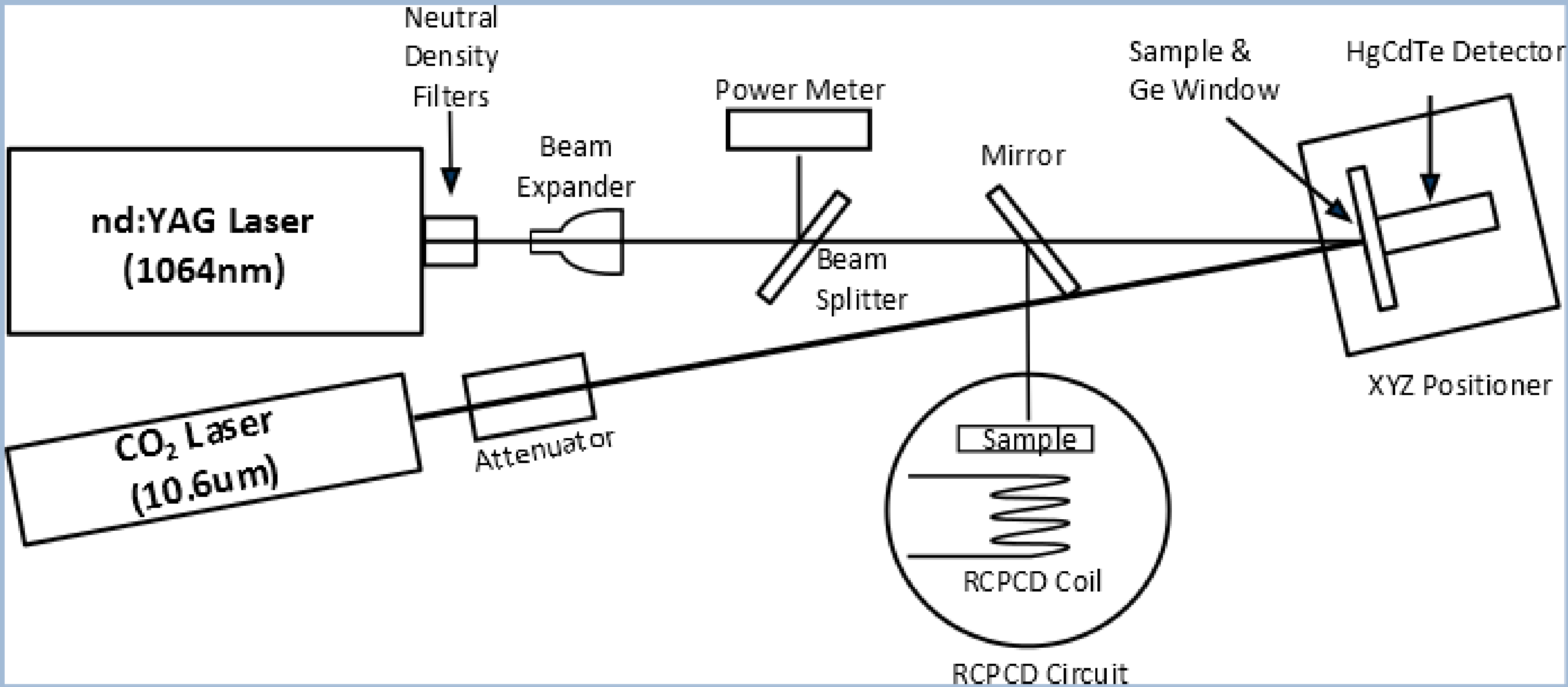


High speed
High sensitivity

Float zone grown Silicon wafer with SiN passivation



PCD-FCA Combination



FCA

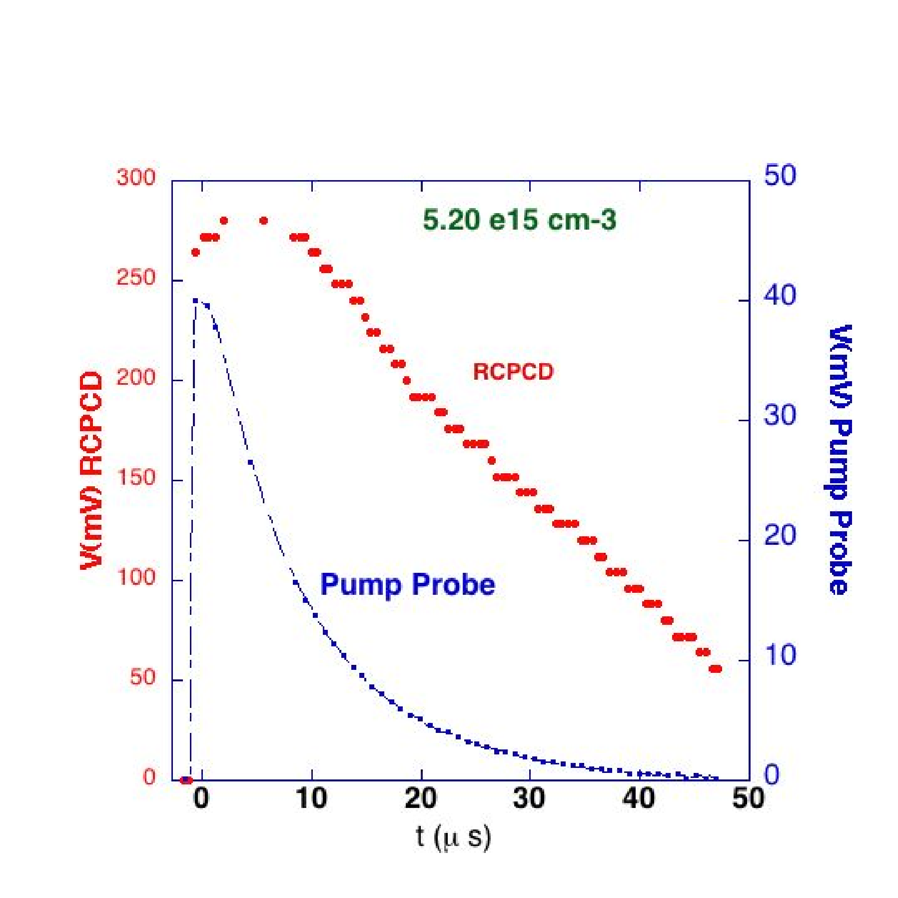
$$\Delta\alpha = \frac{\lambda^2 \Delta n}{\mu}$$

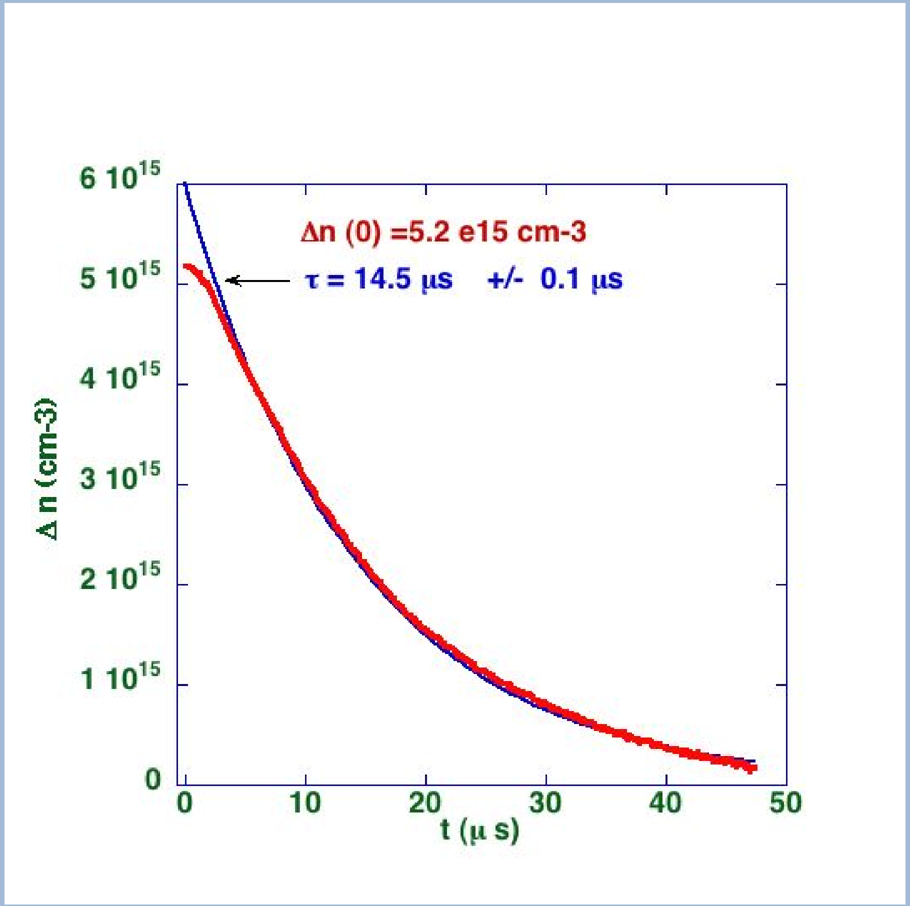
$$\Delta\sigma = q\Delta n(t)\mu$$

$$\sqrt{\Delta\sigma(t)\Delta I_t(t)} = \sqrt{qI_0kd} * \lambda\Delta n(t)$$

PUMP-PROBE DATA

P-Type CZ Silicon Wafer



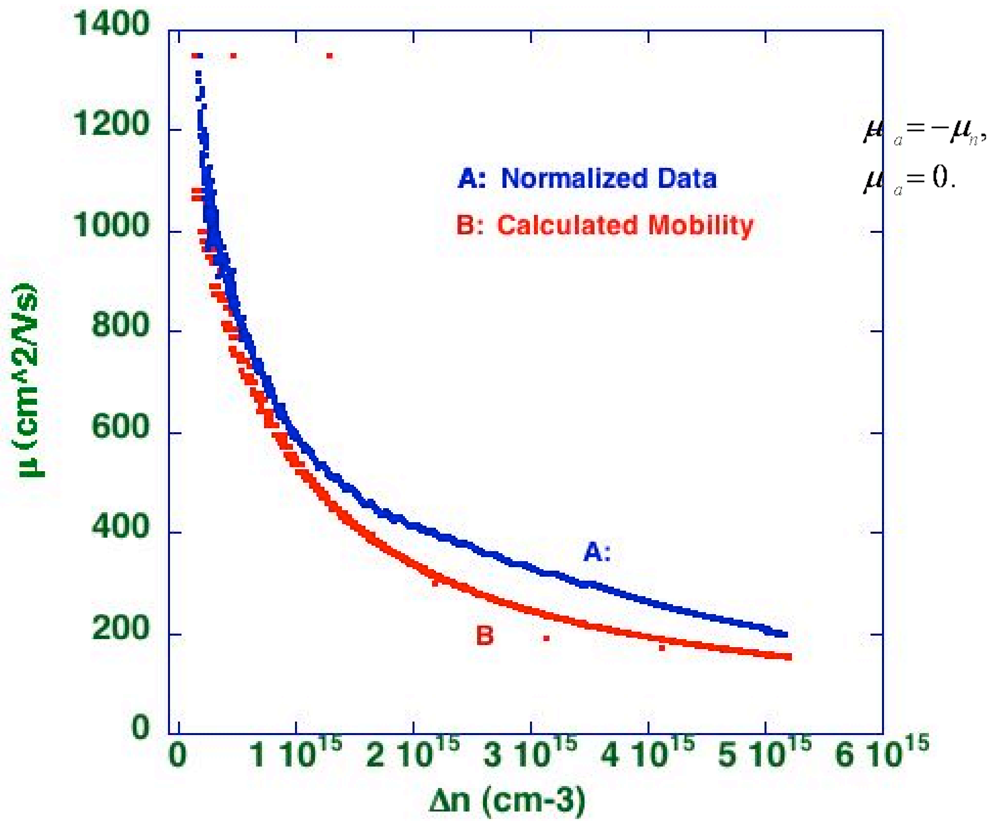


RCPCD/PUMP-PROBE OVERLAY

Mobility calculated from product

Mobility Variation with Injection Level

Predicted and measured Mobility



Continuity Equation

$$\frac{\partial n, \partial p}{\partial t} = -div(J_n, J_p).$$

$$\frac{\partial E}{\partial x} = q\frac{(\Delta p - \Delta n)}{\varepsilon}.$$

$$D = \frac{n\mu_n D_p + p\mu_p D_n}{n\mu_n + p\mu_p}.$$

$$\mu_a = \frac{\mu_n \mu_p (n-p)}{n\mu_n + p\mu_p}.$$

$\mu_a = -\mu_n,$ Low injection

$\mu_a = 0.$ n~p

NREL-LAKEWOOD SEMICONDUCTOR AWARD

Non-Proprietary Partnering Opportunities (NPO)

Combine TMPCD and TRPL to measure
Both PL and PCD decay simultaneously

Separate recombination from trapping!

MEASUREMENT ISSUES (+/-)

TRPL

- Works best (only) for direct bandgap materials.(-)
- Resolves short lifetimes easily (ps or less).(+)
- Does not work well for long lifetimes (1.0 μs or longer).(-)
- Insensitive to shallow traps; no signal unless carriers are recombining via band-to-band transition.(-)

MEASUREMENT ISSUES (+/-)

PCD

- Very sensitive to weak signals and low injection.(+)
- Sees minority-carriers in shallow traps via the conductivity of companion majority carrier. I.e very sensitive to shallow traps.(+)
- Mobility variation with $\Delta n(t)$ complicates data analysis.(-)

SUMMARY

TRPL: Excellent for short lifetimes in direct bandgap materials. Weaker for long lifetimes. Low sensitivity to traps.

μPCD:Easy to use. Fast response. Low sensitivity And low low dynamic range. Mapping capability.

RCPCD: Very sensitive to weak signals and traps. Slow time Response (20-40 ns). High dynamic range. Mobility correction Required.

TMPCD: High sensitivity and good time response. Relatively untested. Mobility correction.

FCA: Free carrier absorption: Low sensitivy. Enables Mobility correction when combined with PCD.

QSSPC: Single crystal silicon only.

NO MAGIC BULLET !!!