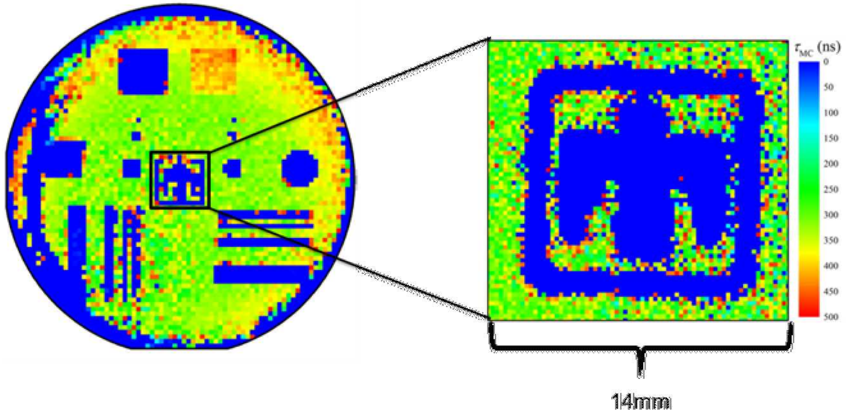
SAND2018-9690C

Microwave Based Lifetime Measurements and Analysis for Detector Materials



PRESENTED BY

Eric Shaner

Clark Kadlec, Michael Goldflam, Ed Bielejec, Preston Webster, Evan Anderson, Sam Hawkins, Ben Olson, Emil Kadlec, Anna Tauke-Pedretti, Wes Coon, Torben Fortune, Jin Kim, Peter Schultz, John Klem

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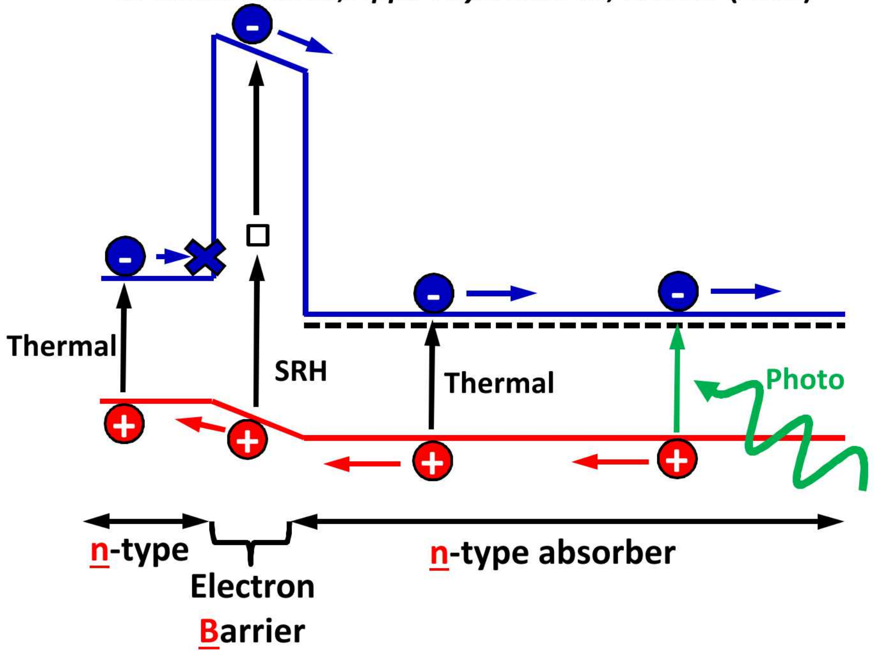
Microwave Based Lifetime Measurements and Analysis for Detector Materials

- Time-resolved microwave reflection lifetime measurements
  - Motivation for IR detectors
  - Time-resolved Photoluminescence
  - Microwave measurements and dark current
- Things you can do with lifetime measurements
  - Auger, Radiative, SRH extraction and dark current
  - Wafer mapping for growth problems
  - Predicting device performance from carrier lifetime
  - In situ radiation studies
  - Vertical mobility
- New concepts
  - Non-contact absorption coefficient
  - Top hat beam & Size limits
  - Doppler

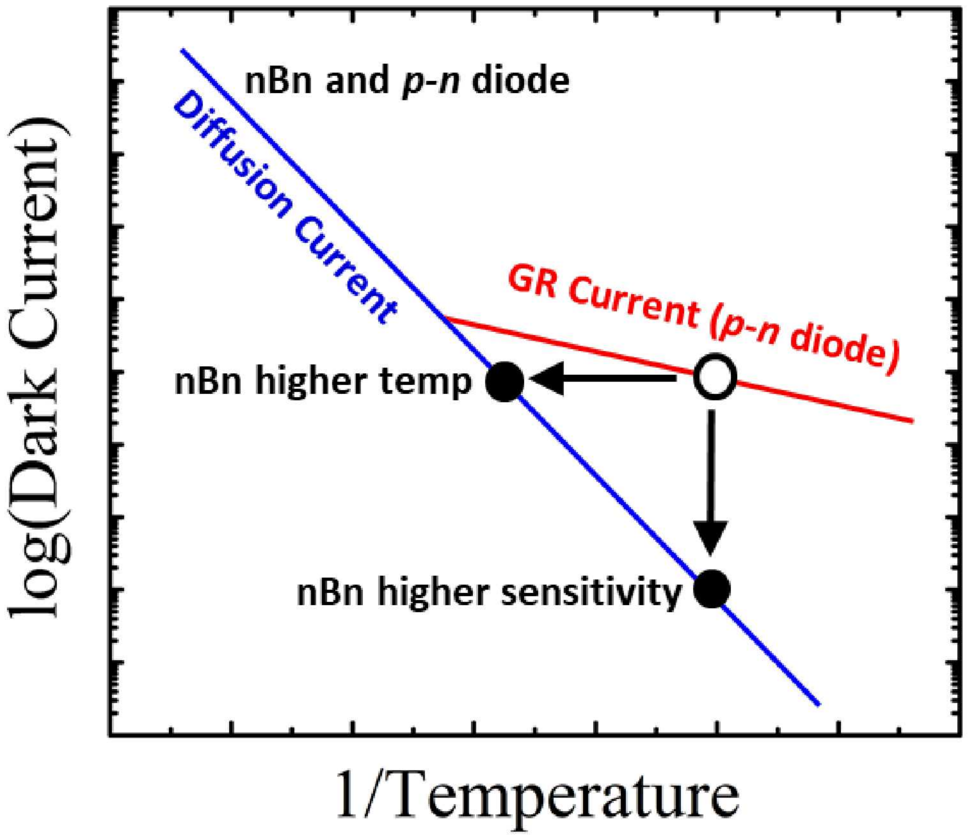
Relevant for IR Detectors – nBn

nBn Photodetector

S. Maimon et al., *Appl. Phys. Lett.* 89, 151109 (2006)



G-R and Diffusion current



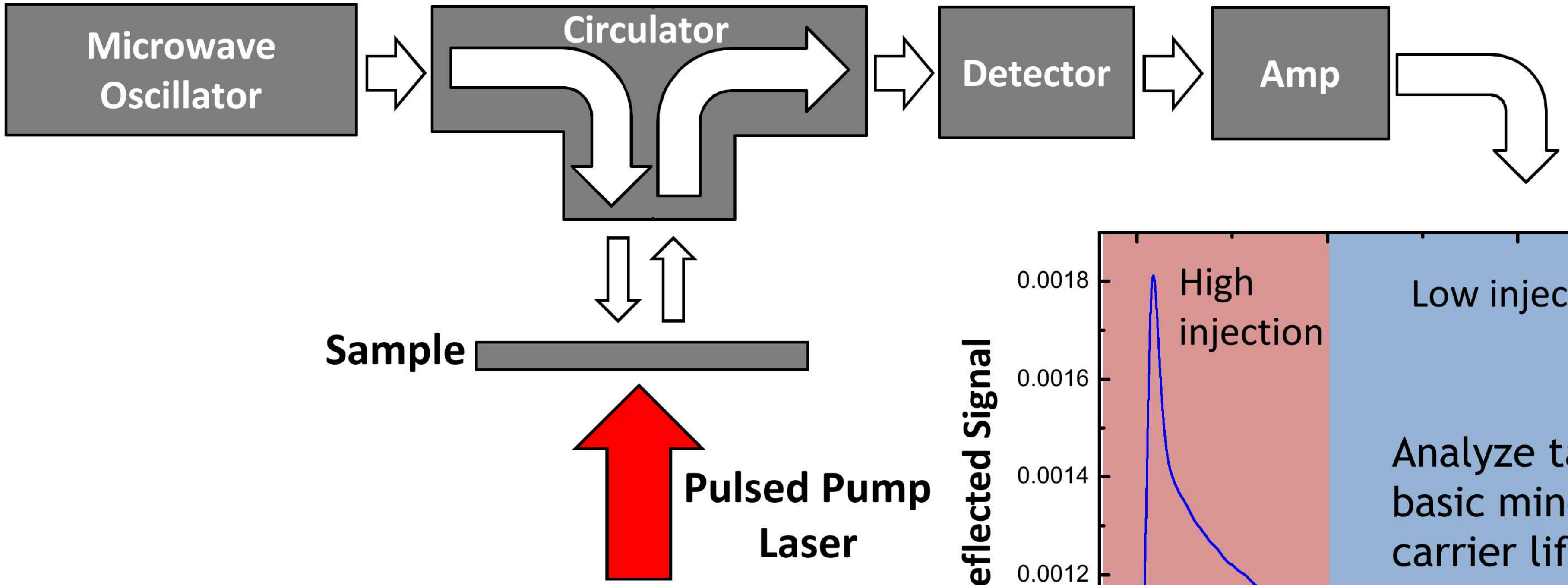
Diffusion Current: thermal generation in neutral regions
Generation-Recombination Current: Shockley-Read-Hall (SRH) generation in depletion regions from defect levels

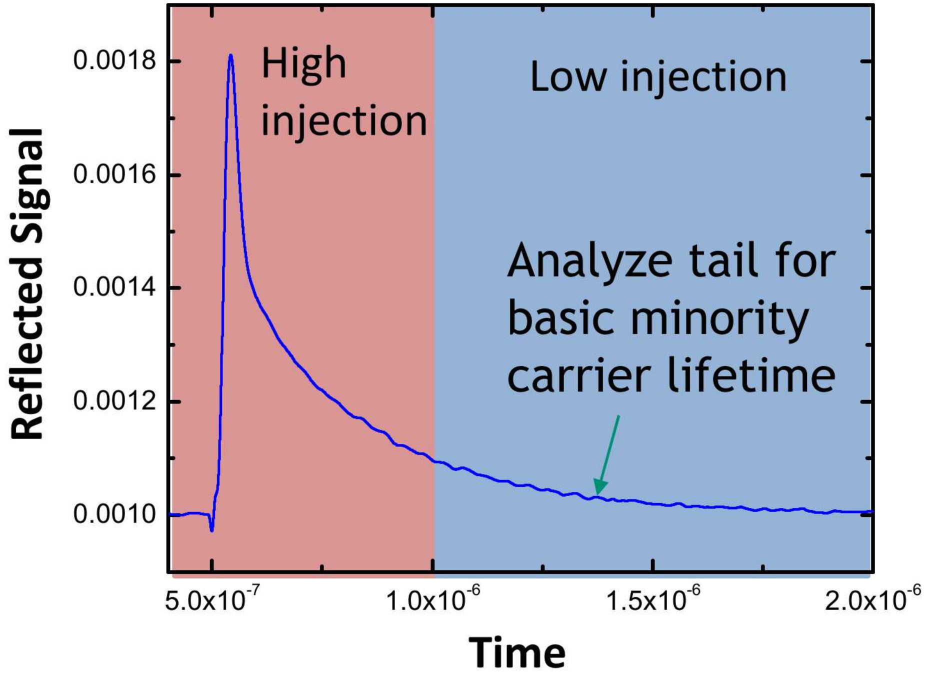
$$J_{GR} = q\frac{n_i L_{depl}}{\tau_{po} + \tau_{no}} \qquad J_{Diff} = q\frac{n_i^2 L_{abs}}{N_d \tau_{MC}}$$

$$n_i \sim exp(-E_g/2kT) \qquad n_i^2 \sim exp(-E_g/kT)$$

Minority carrier lifetime defines dark current

Microwave Reflectance



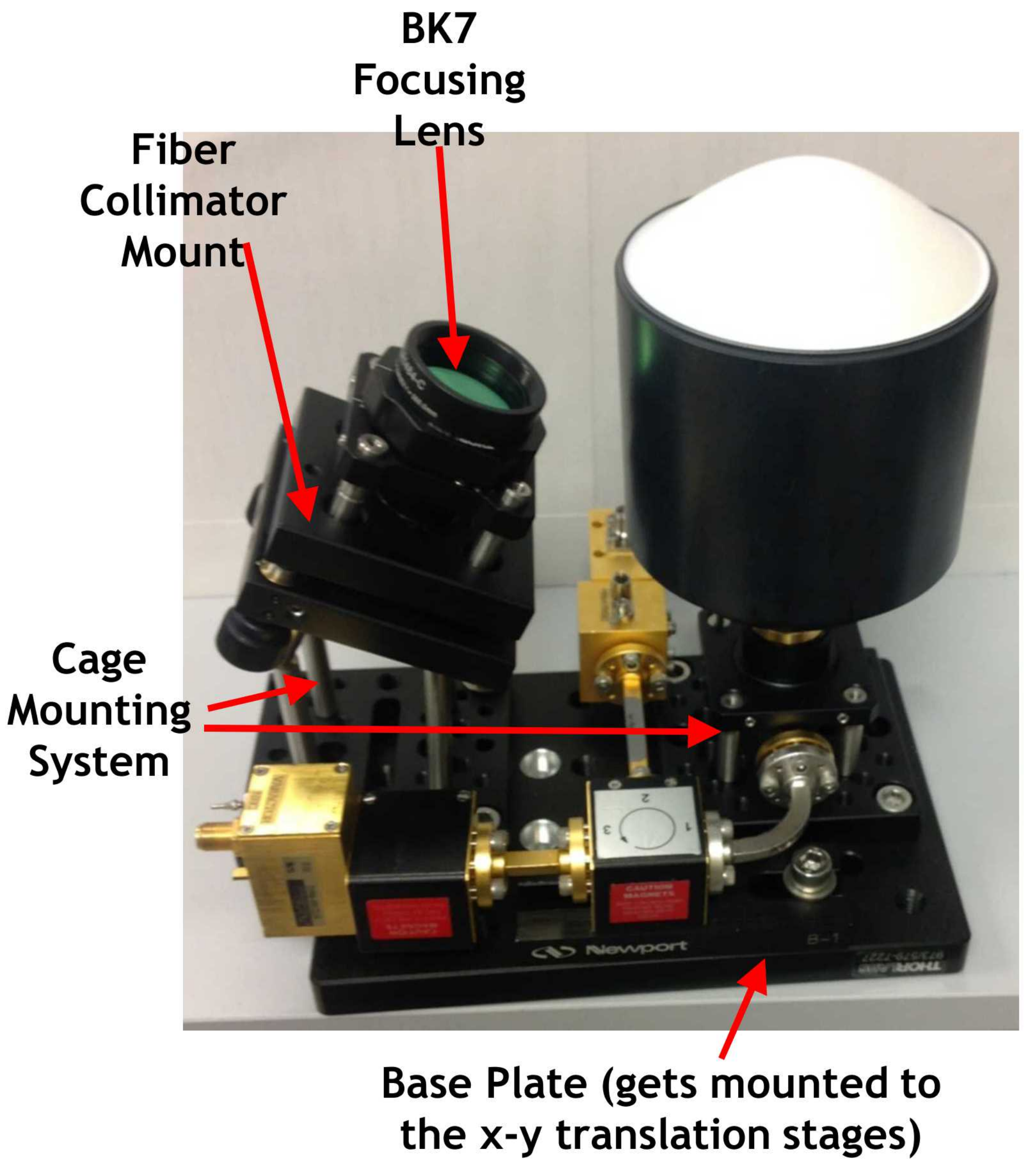


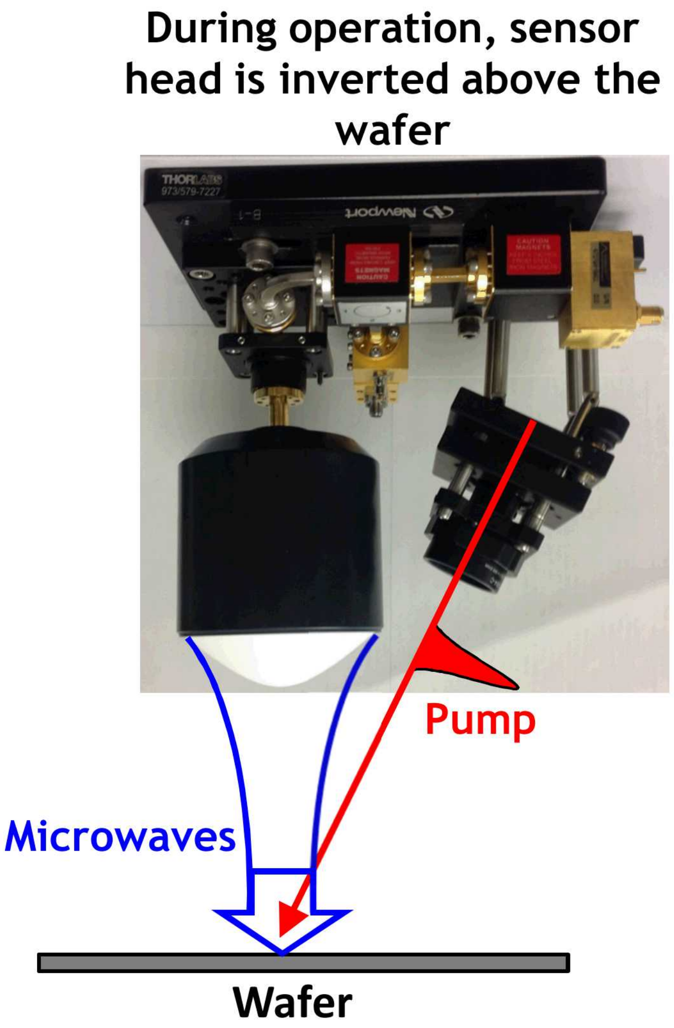
Rate Equation:

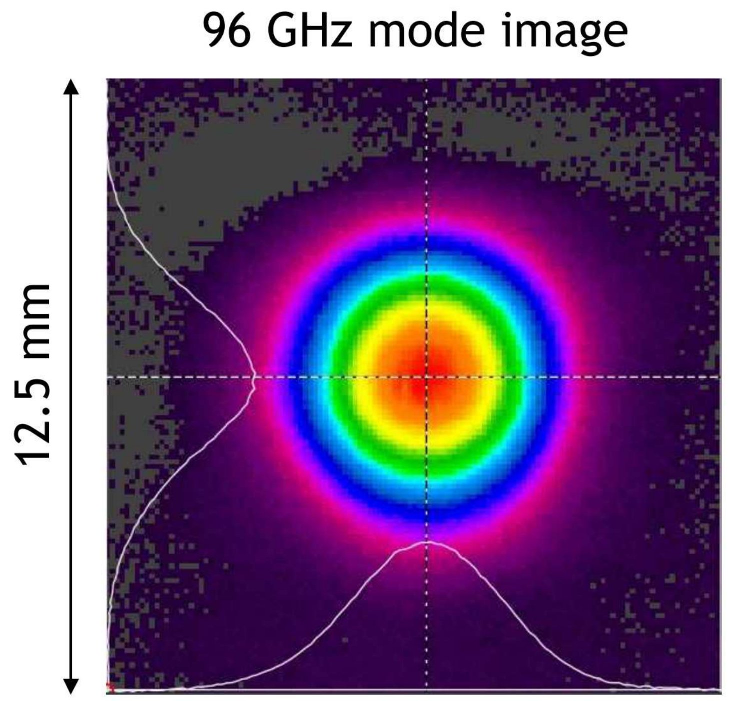
$$R = A + B(n_0 + \Delta n) + C_n(n_0 + \Delta n)^2$$

- **Pump Pulse excites charge carriers in IR absorber layer, altering the conductivity of the sample**
- **Microwaves reflected from sample surface detect this change and monitor their decay back to equilibrium (i.e. the carrier lifetime)**
- **Approximate 2 ns time resolution, fast acquisition/high throughput, and extremely sensitive**

Microwave Reflectance

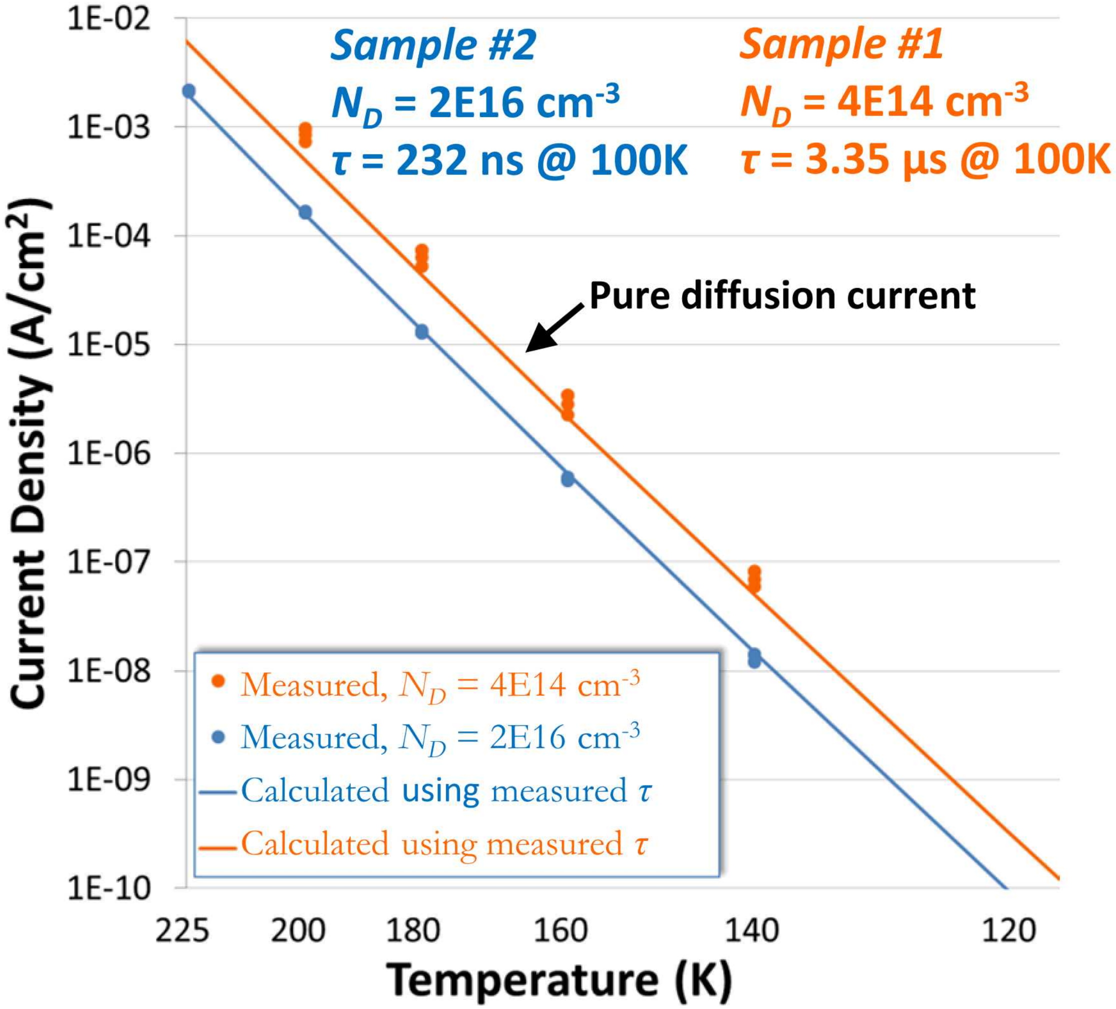






Lifetime and Dark Current

MWIR InAsSb alloy nBn



n-type doping reduced dark current

Dark Diffusion Current

$$J_{Diff} = q\frac{n_i^2 L_{abs}}{N_d \tau_{MC}}$$

τ_{MC} = minority carrier lifetime
n_i = intrinsic carrier density
N_d = doping level
L_{abs} = absorber width

Lifetime is a good indicator of the dark current!

Olson et al. *Appl. Phys. Lett.* 107, 183504 (2015)

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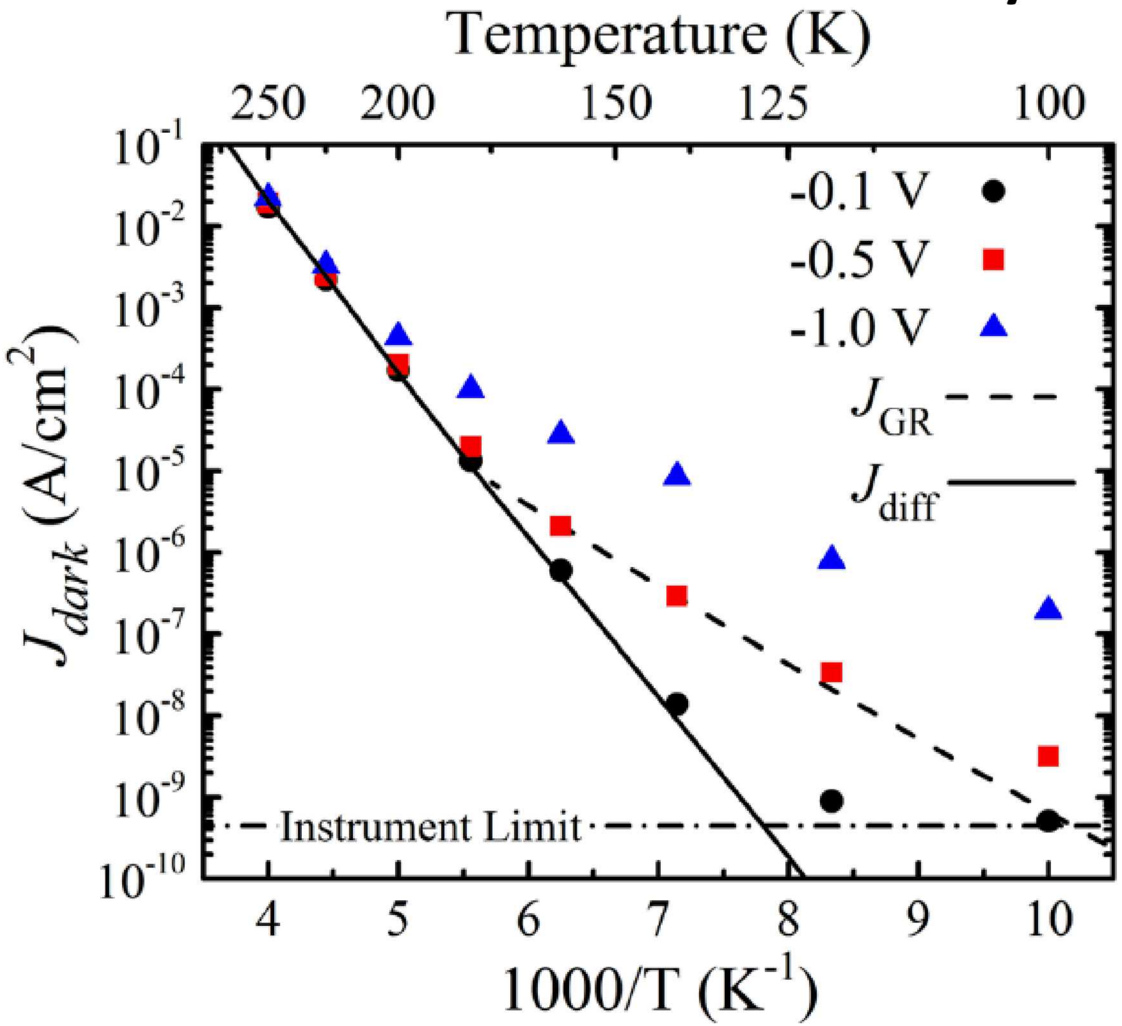

Lifetime ~400 ns, N_D = 7E15 cm^{-3}

Intentionally deplete to turn G-R on

Dark Diffusion Current

$$J_{Diff} = q\frac{n_i^2 L_{abs}}{N_d \tau_{MC}}$$

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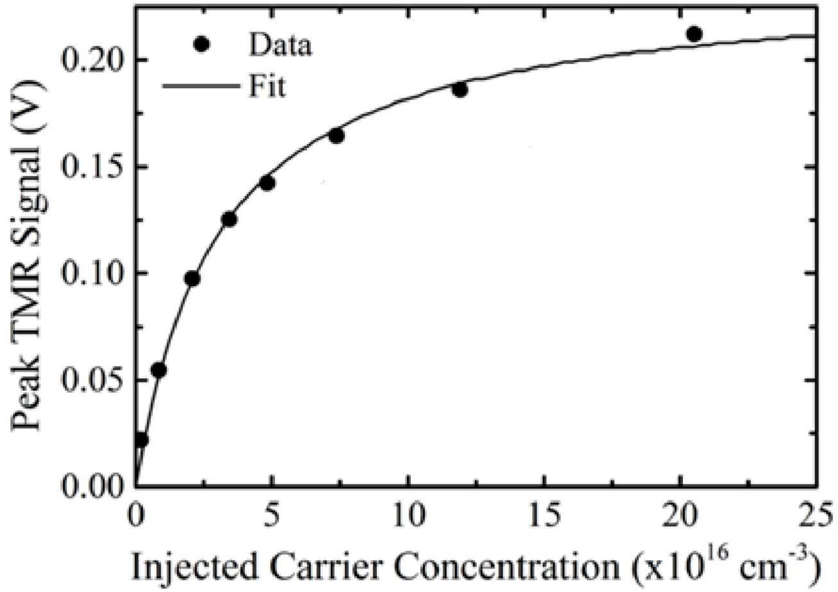
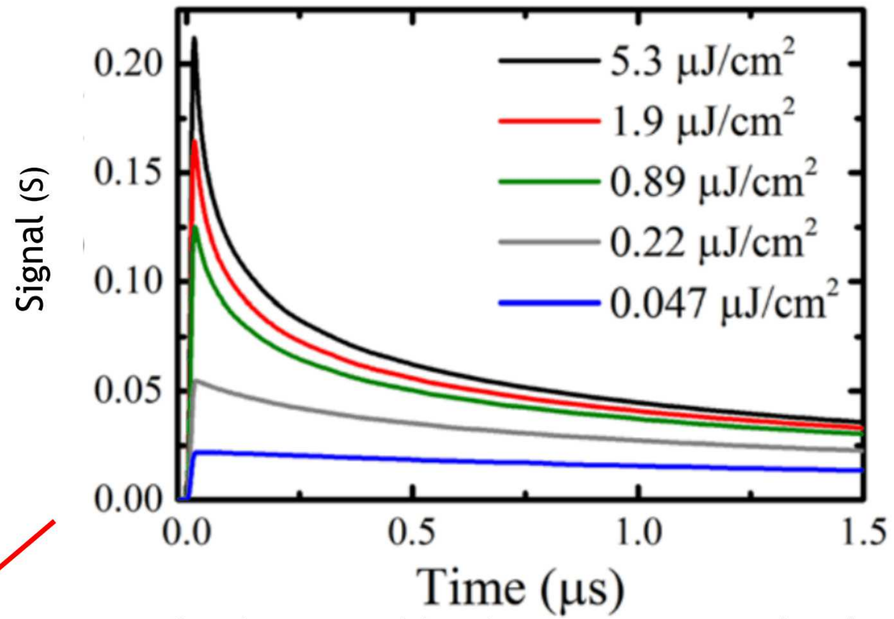
Microwave Reflectance: More advanced, Auger, Radiative, SRH

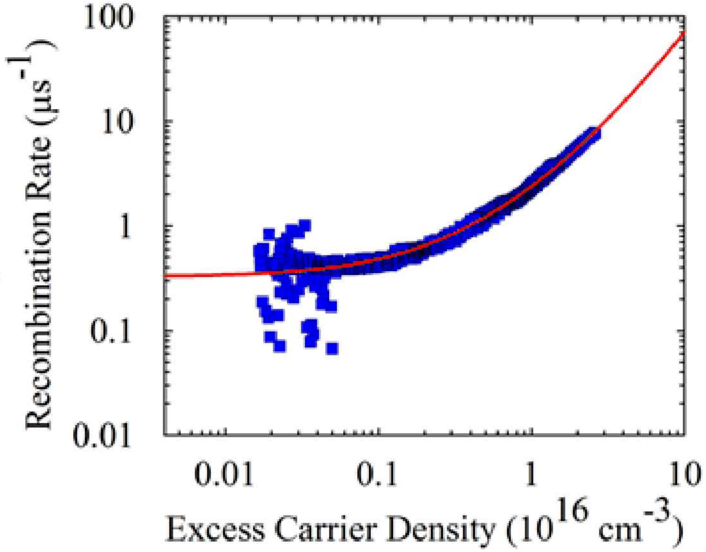
Peak Signal (S) vs. initial optically generated carrier density



Time-resolved Signal (S) as a function of time



Carrier recombination vs excess carrier density



$$R = -\frac{1}{\Delta n}\frac{\partial \Delta n}{\partial t} = -\frac{1}{\Delta n}\frac{\partial \Delta n}{\partial S}\frac{\partial S}{\partial t}$$

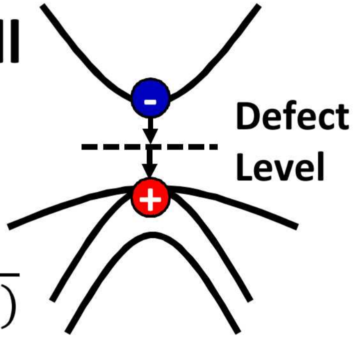
M. E. Flatte, C. H. Grein, T. C. Hasenberg, S. A. Anson, D. J. Jang, J. T. Olesberg, and T. F. Boggess. Carrier recombination rates in narrow-gap InAs/Ga 1x In x Sb-based superlattices. Phys. Rev. B, 59(8):5745-5750, 1999.

More advanced, Auger, Radiative, SRH

Shockley Read Hall

(defect mitigated)

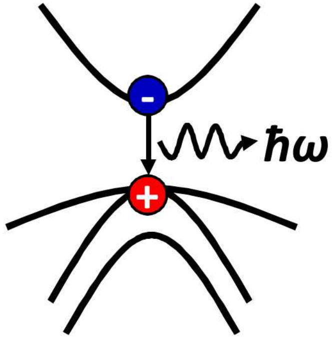
$$\tau_{srh}^{-1} \approx \frac{N_d + \Delta n}{\tau_{no}\Delta n + \tau_{po}(N_d + \Delta n)}$$



Radiative

(intrinsic)

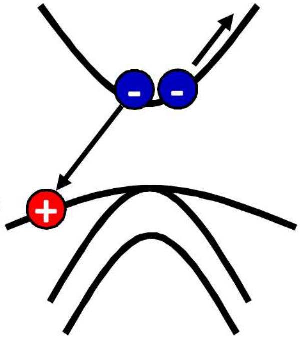
$$\tau_{rad}^{-1} \approx B(N_d + \Delta n)$$



Auger

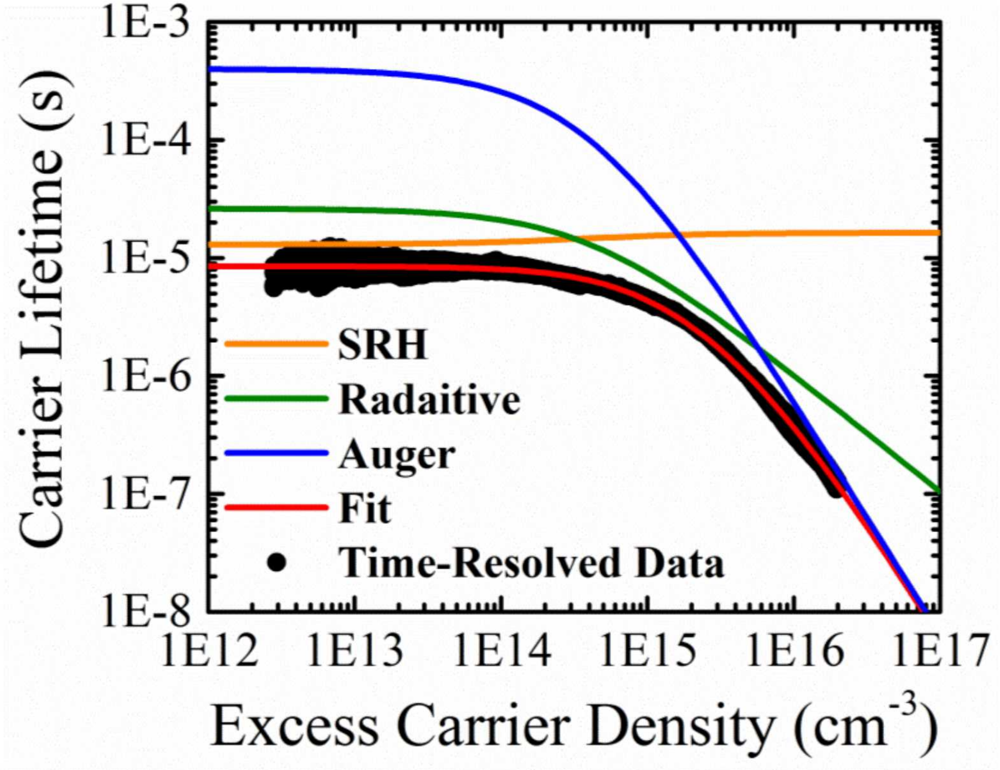
(intrinsic)

$$\tau_{auger}^{-1} \approx C(N_d + \Delta n)^2$$



R = $\tau_{meas}^{-1} = \tau_{srh}^{-1} + \tau_{rad}^{-1} + \tau_{auger}^{-1}$

MWIR InAs/InAsSb T2SL



Minority Carrier Lifetime (τ_{MC}) = 8.5 μs
Radiative Coefficient (B_r) = 1.0x10^{-10} cm^3/s
Auger Coefficient (C_n) = 1.6x10^{-26} cm^6/s
Doping (N_d) = 4x10^{14} cm^{-3}

Olson et al. *Phys. Rev. Appl.* 3, 044010 (2015)

More advanced, Auger, Radiative, SRH

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(defect mitigated)

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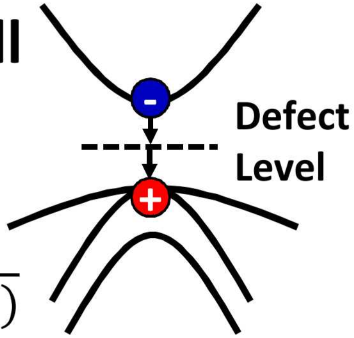
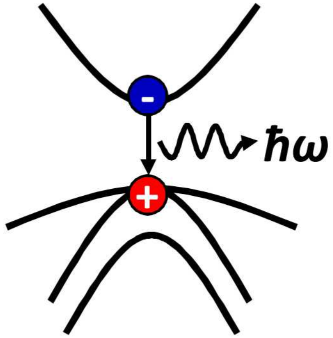


Radiative

(intrinsic)

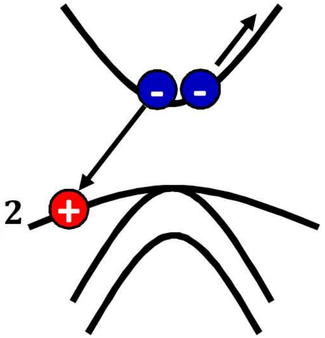
$$\tau_{rad}^{-1} \approx B(N_d + \Delta n)$$



Auger

(intrinsic)

$$\tau_{auger}^{-1} \approx C(N_d + \Delta n)^2$$



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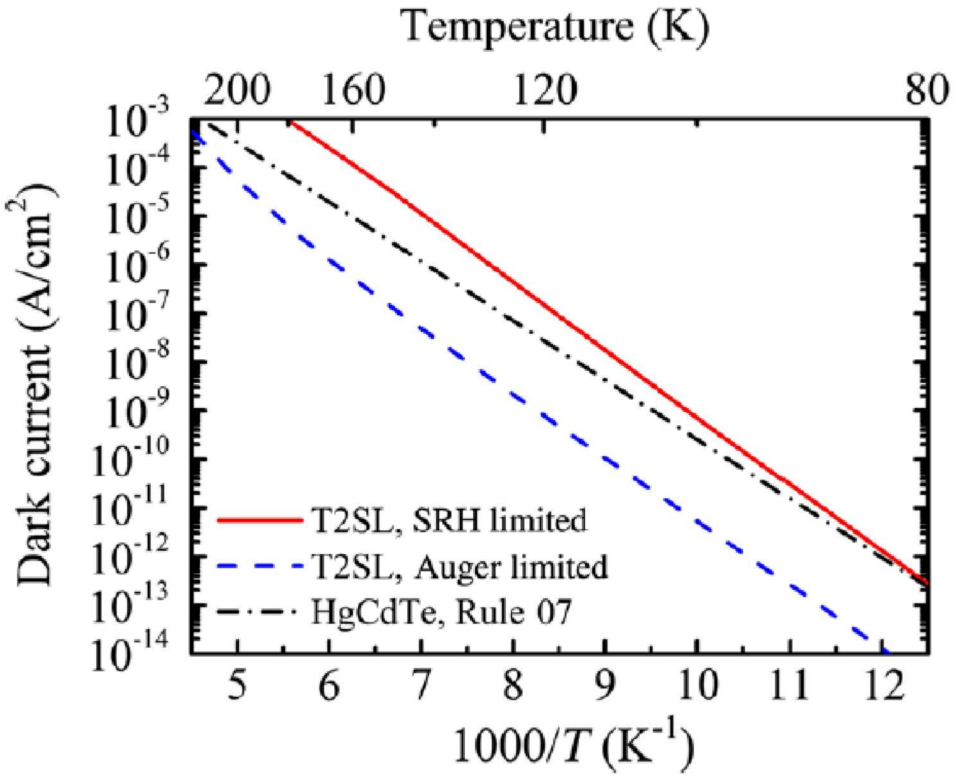

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More advanced, Auger, Radiative, SRH

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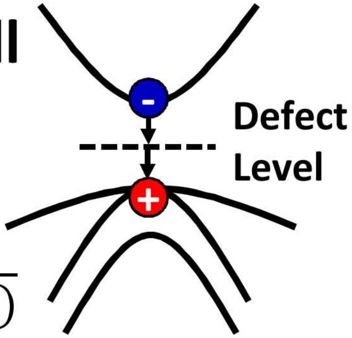
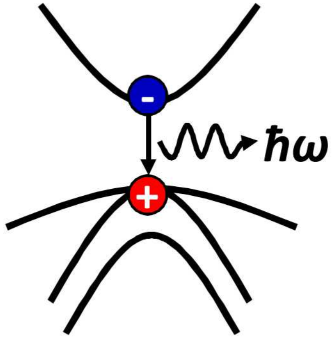
(defect mitigated)

$$\tau_{srh}^{-1} \approx \frac{N_d + \Delta n}{\tau_{no}\Delta n + \tau_{po}(N_d + \Delta n)}$$



Radiative
(intrinsic)

$$\tau_{rad}^{-1} \approx B(N_d + \Delta n)$$



Auger
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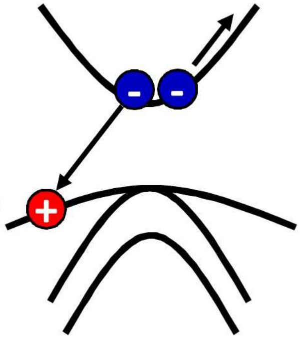

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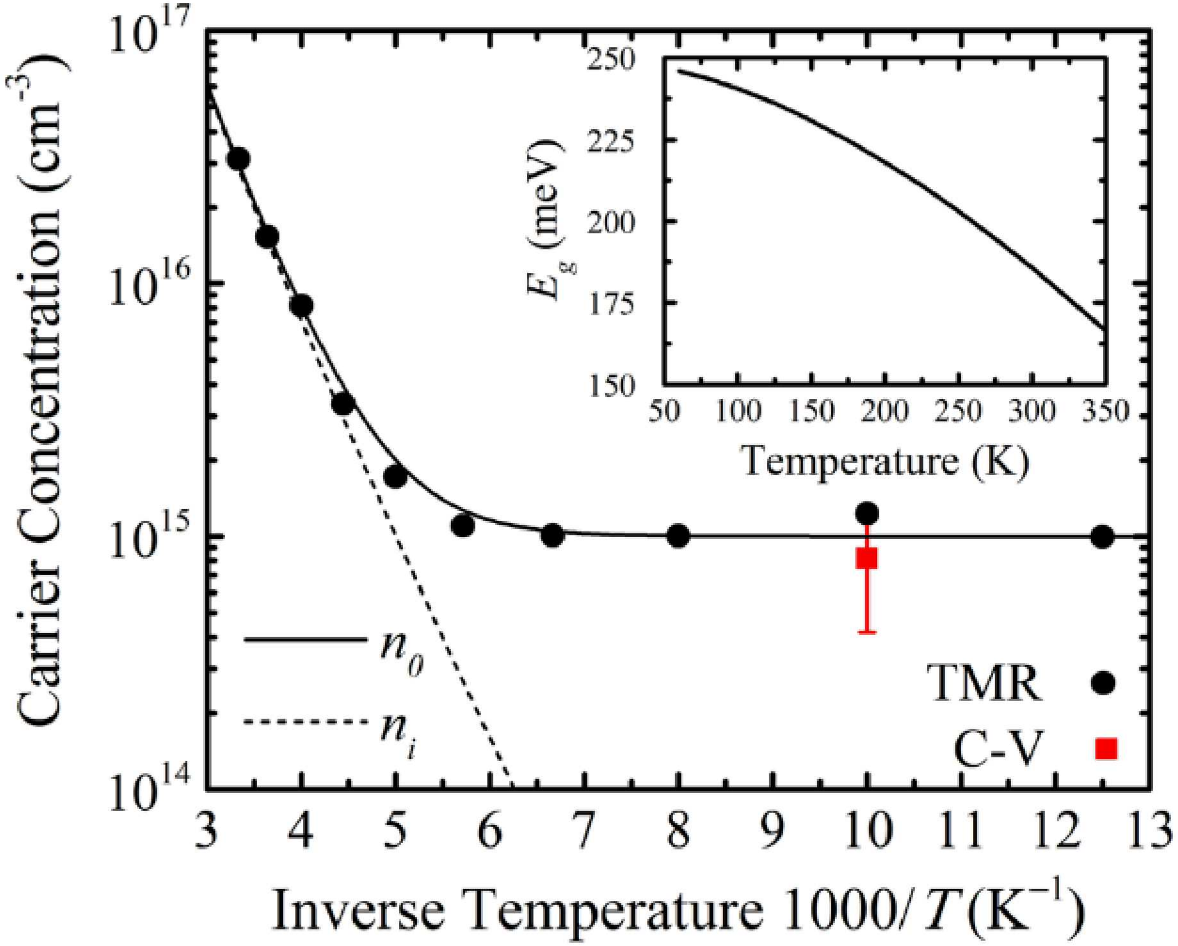
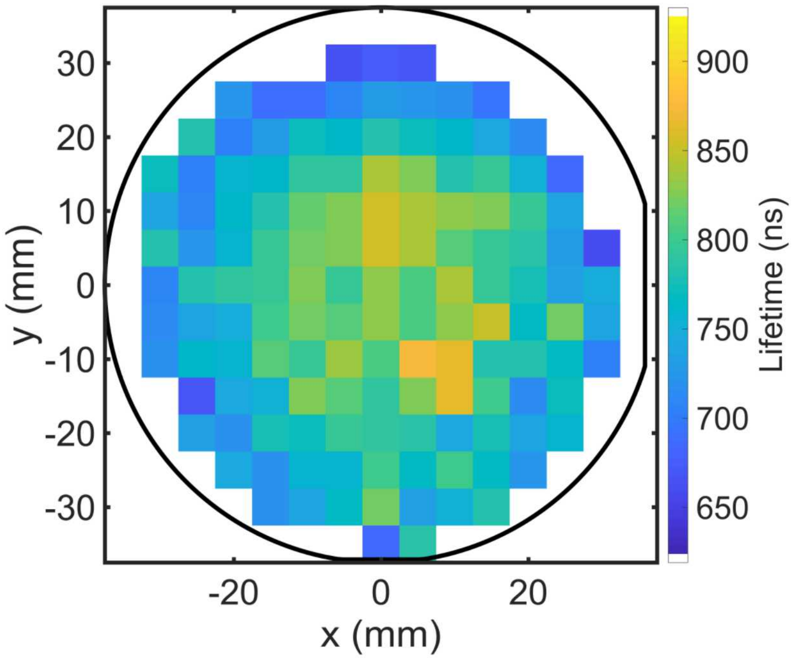


Doping (N_d) = 1x10^{15} cm^{-3}

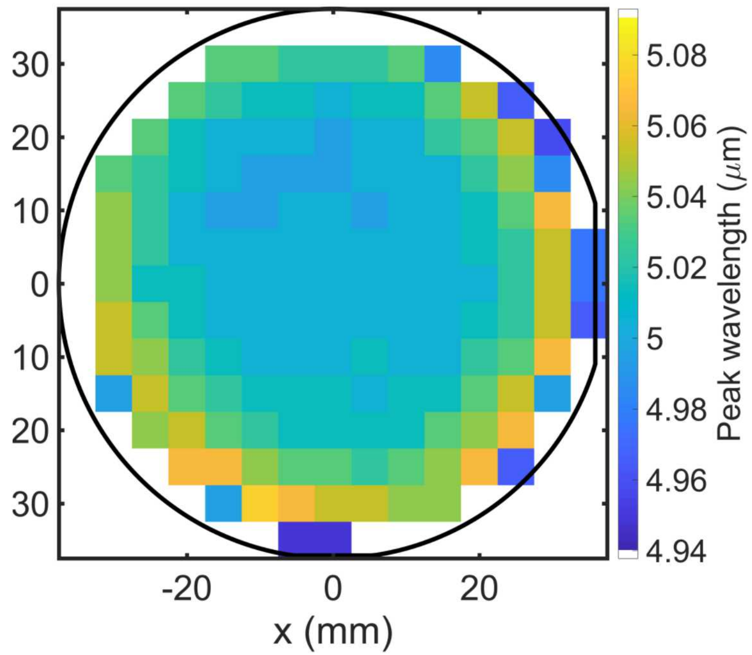
Olson etal. APPLIED PHYSICS LETTERS, 109, 022105 (2016)

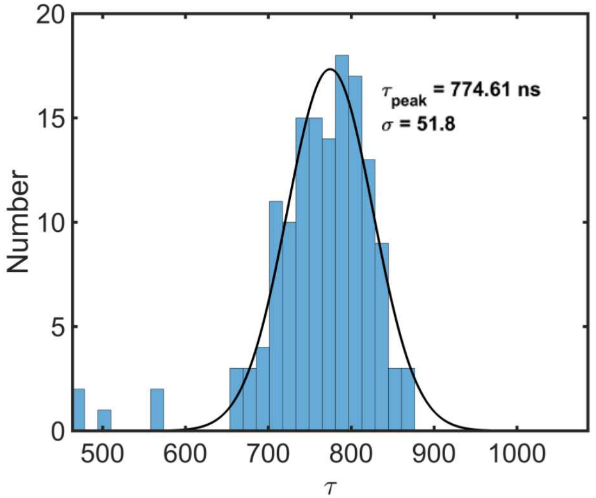
Wafer Mapping

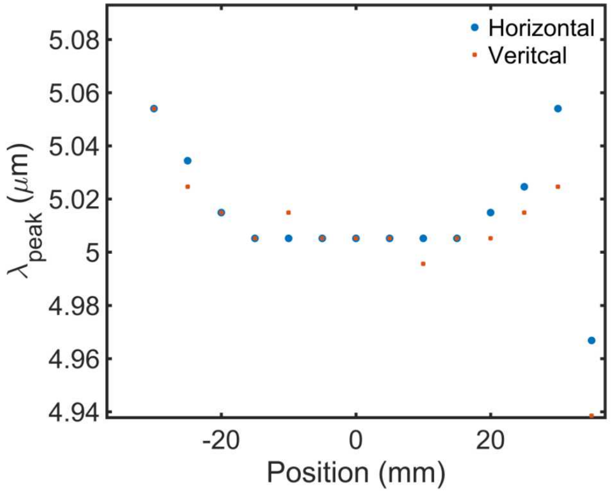
Lifetime



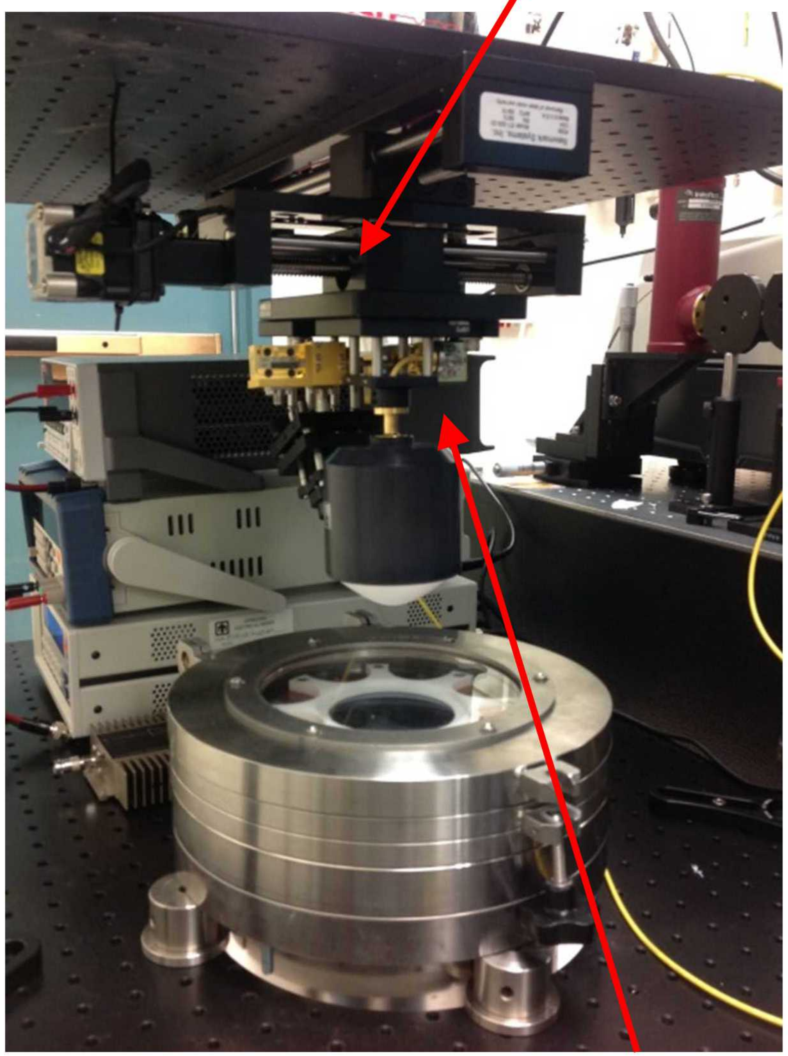
PL





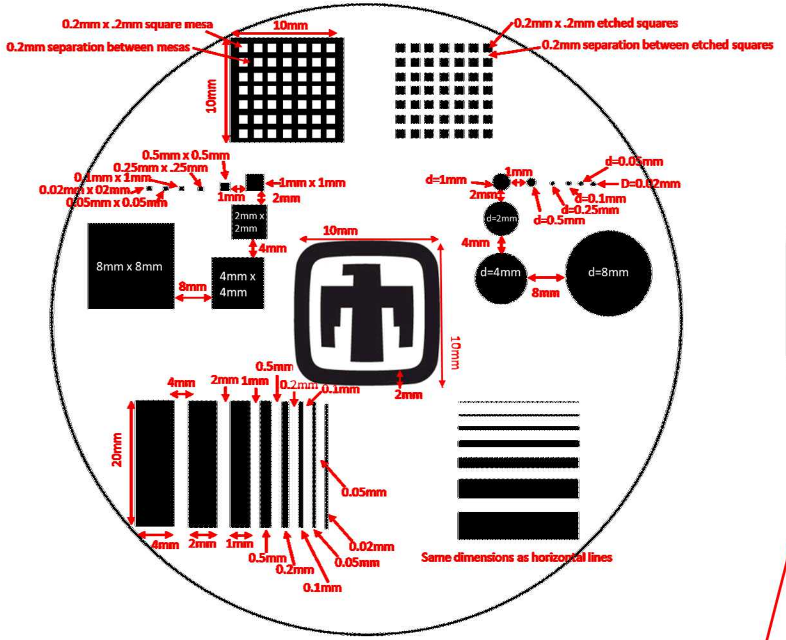


X-Y stages. 300mm stage used to move sensor head out of the way to provide clearance for quick access door to open

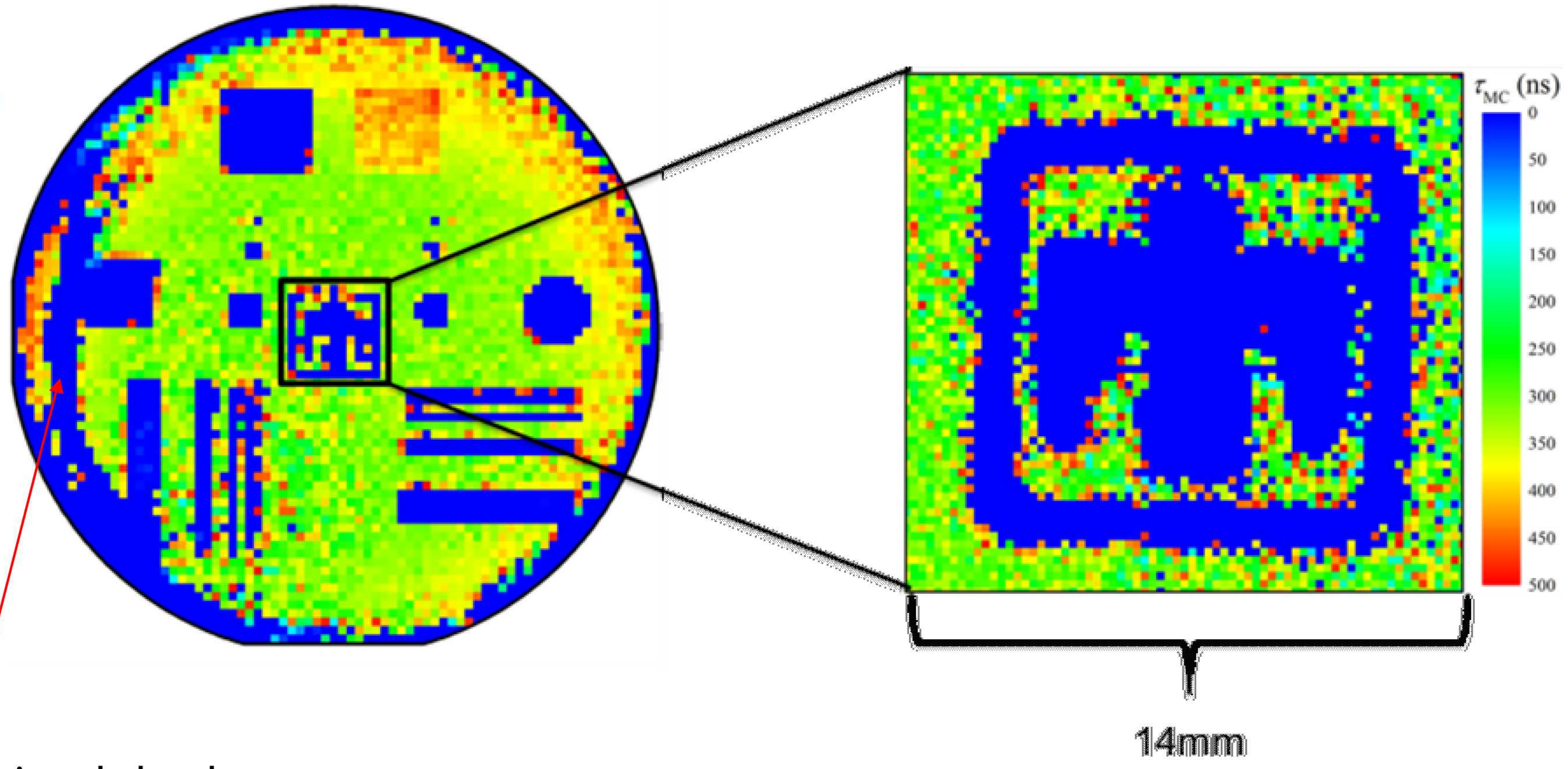


Lifetime Sensor Assembly

Wafer Mapping



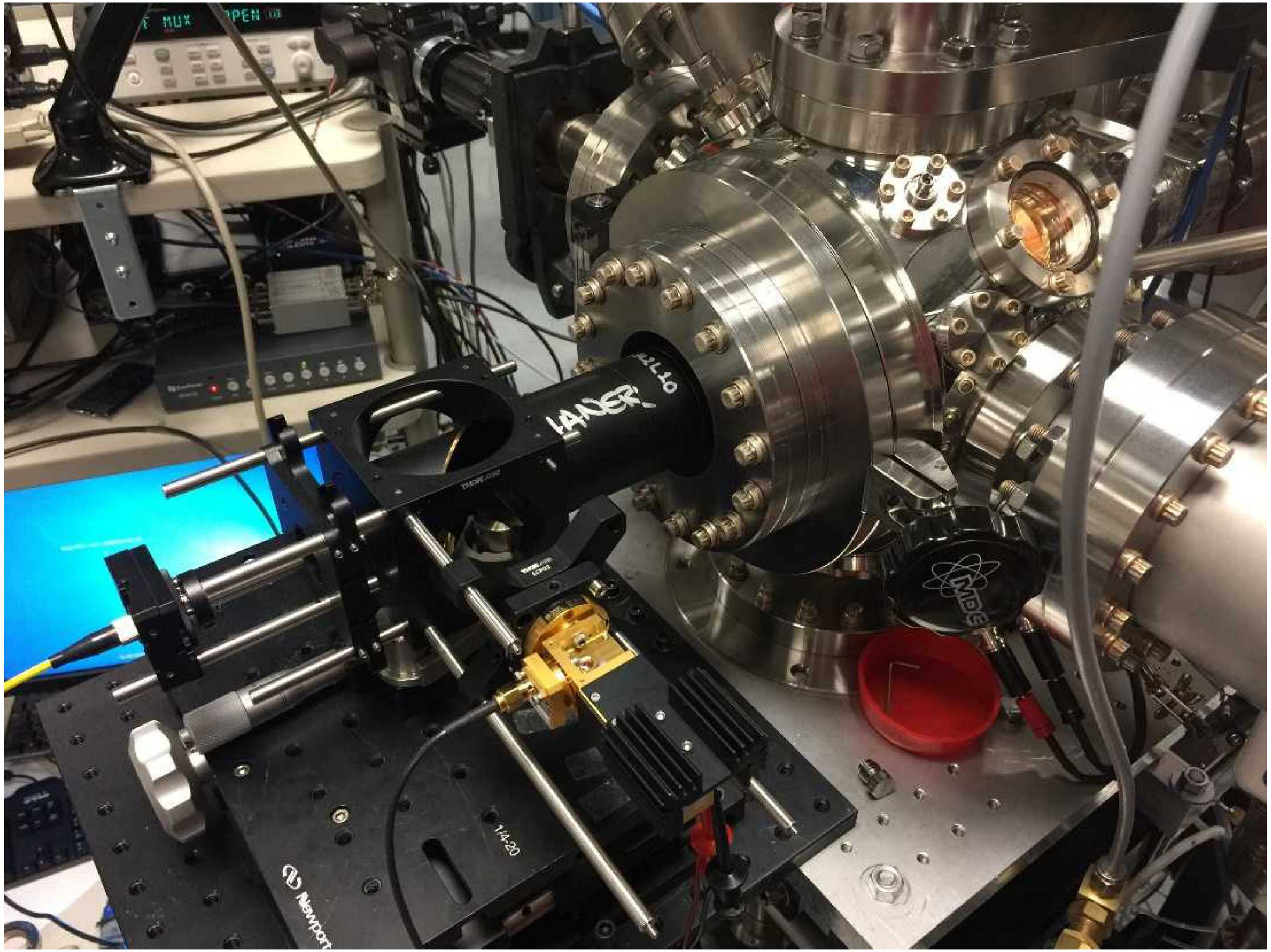
High resolution possible



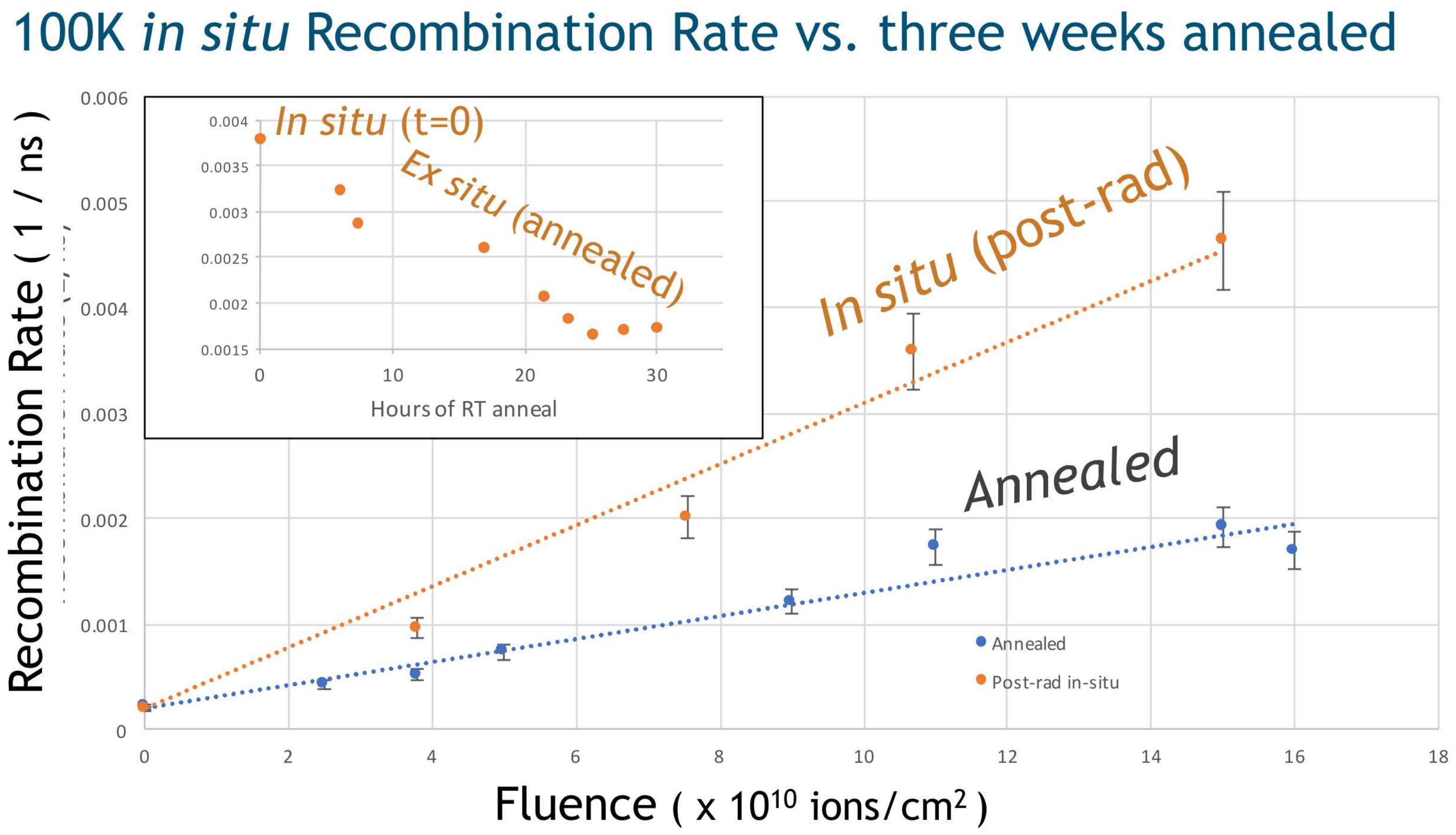
Used to get occasional dead zones

In situ TMR installed at Ion Beam Lab (IBL, Sandia)

- 4.5 MeV proton radiation
- Rad chamber equipped with cryostat to dose at operating temperature



Radiation Effects: T2SL Pre-anneal vs. Post-anneal



- **Post-anneal requires long waits for comparable data**
- **Pre-anneal offers more direct information about radiation induced defects**

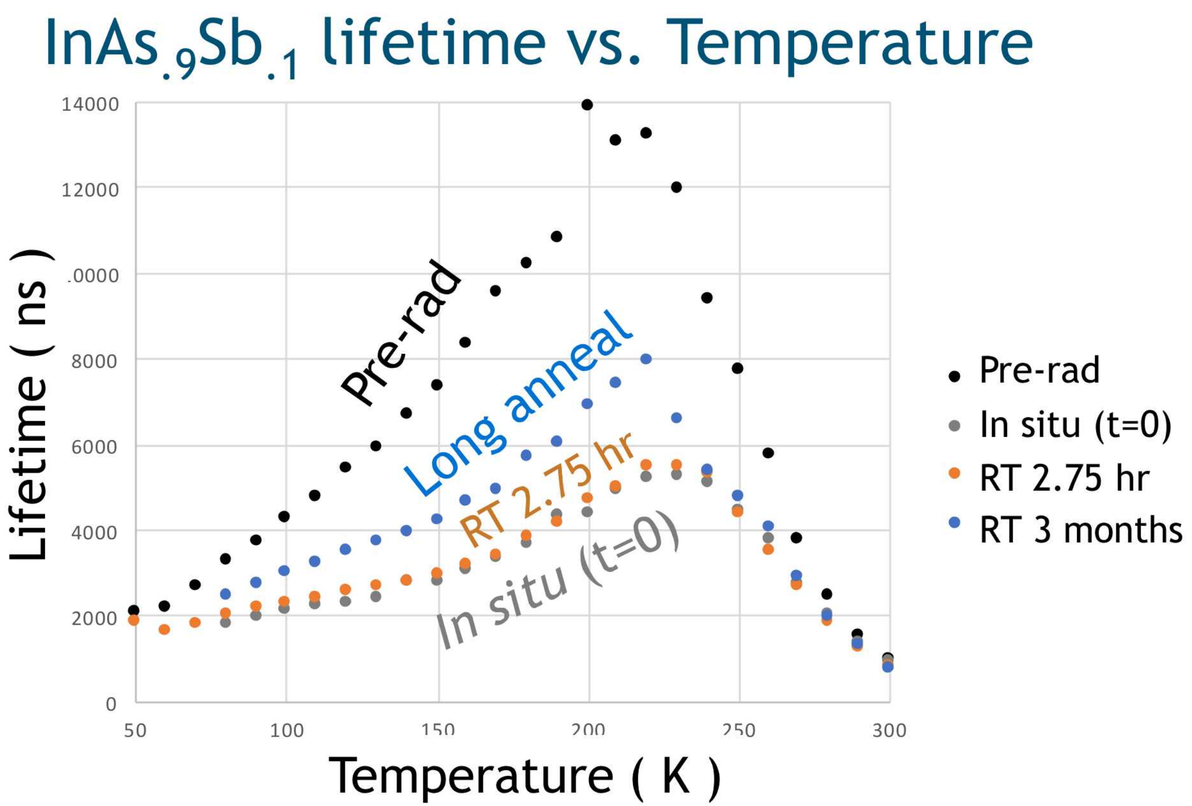
Radiation Effects: $InAs_{0.9}Sb_{0.1}$ Trap Extraction

with low injection:

$$\tau_{srh}^{-1} \approx \frac{n_0 + p_0}{\tau_{p0}(n_0 + n_1) + \tau_{n0}(p_0 + p_1)}$$

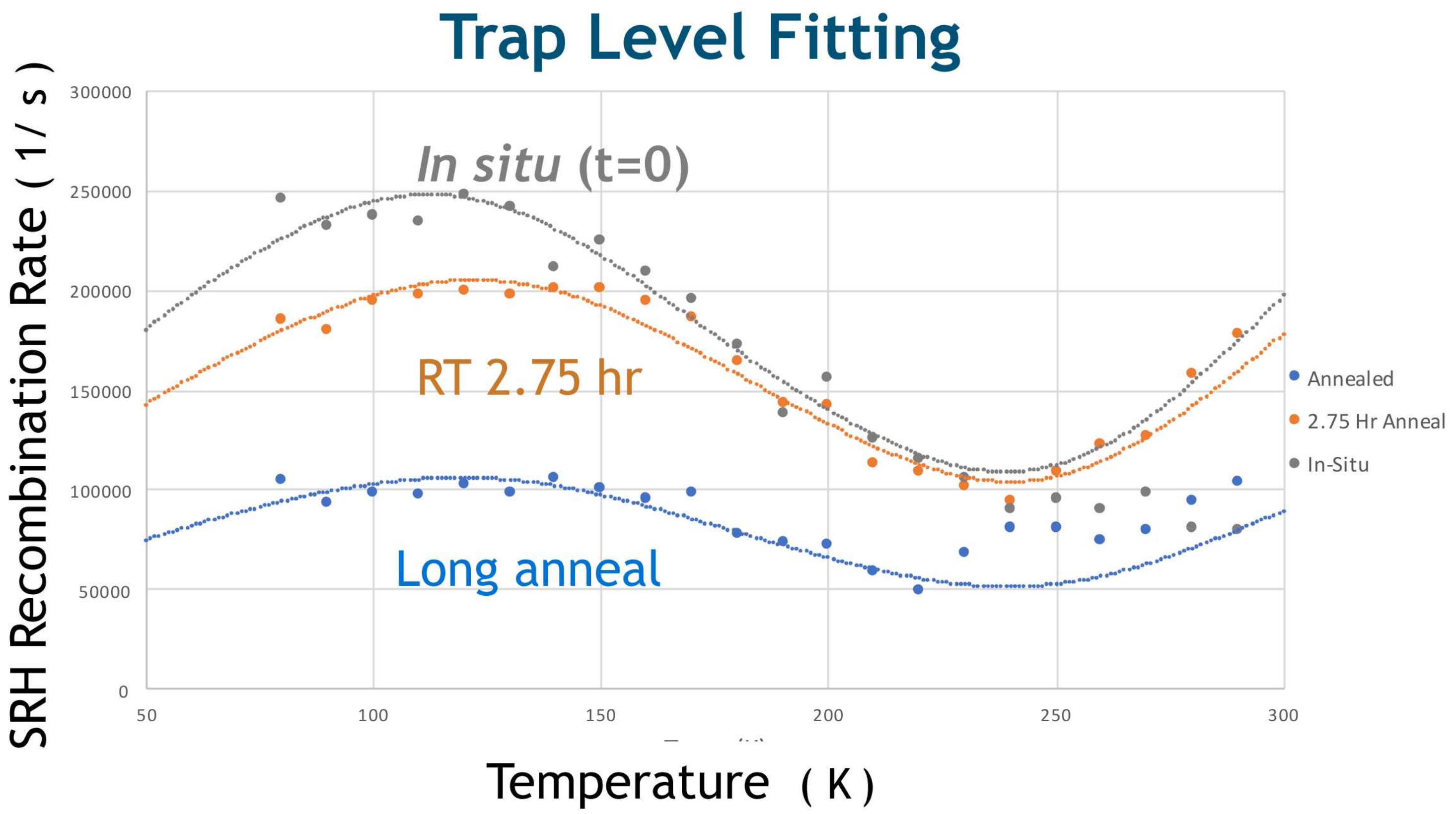
$$\tau_{p0} = (\sigma_p v_p N_t)^{-1}$$
$$\tau_{n0} = (\sigma_n v_n N_t)^{-1}$$
$$n_1 = n_i e^{(E_t - E_i)/kT}$$
$$p_1 = n_i e^{(E_i - E_t)/kT}$$

Assumption: $\sigma_n = \sigma_p = \sigma$



- **Dominant radiation-induced defect behaves as SRH trap**
- **Compare pre- and post- rad, assume SRH change is radiation-defects**
- **With plausible assumptions, extract trap energy E_T and σ N_T**

Radiation Effects: $InAs_{0.9}Sb_{0.1}$ Trap Level and Annealing



$$\frac{1}{\tau_{post-rad}} = \frac{1}{\tau_{pre-rad}} + \frac{1}{\tau_{rad-defect}}$$

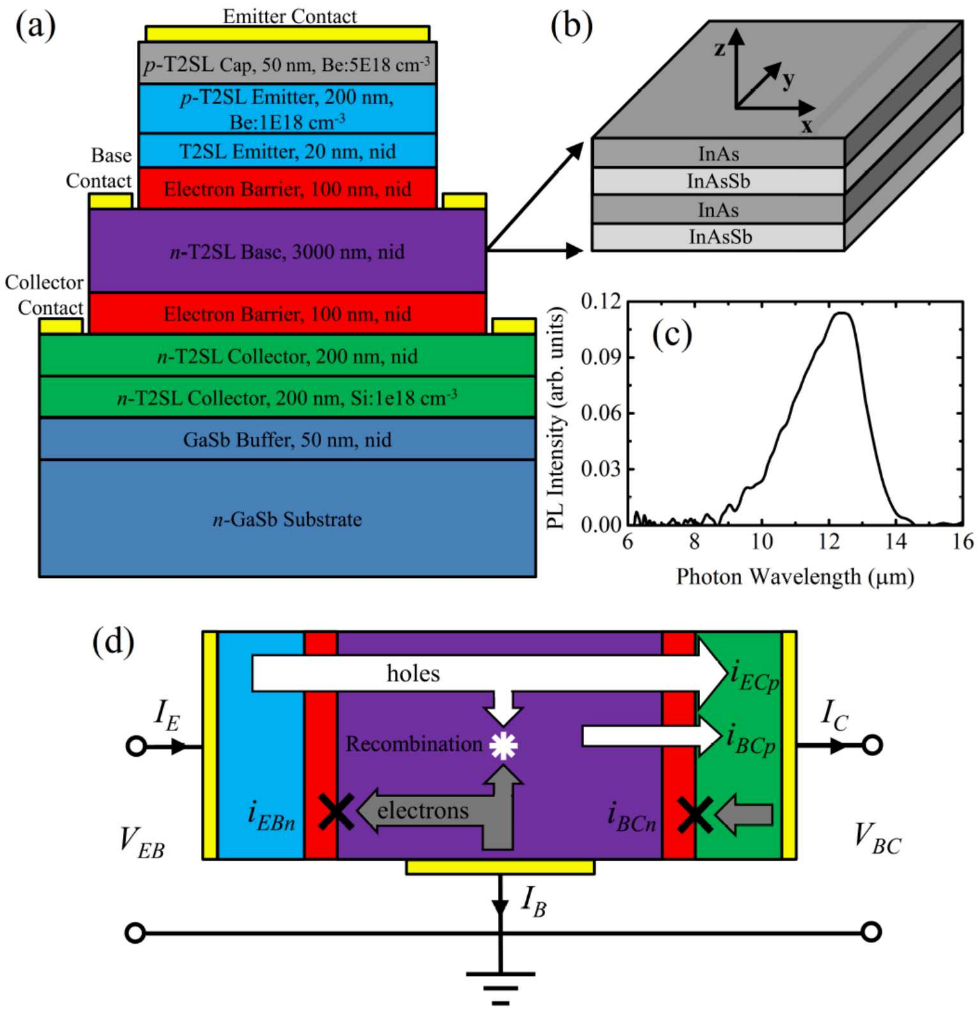
Requires temp dependent PL

Preliminary results	σN_T (cm^1)	E_T (meV)
In situ	.0209	45.5
2.75 Hour anneal	.0171	49.9
Annealed	.0088	48.7

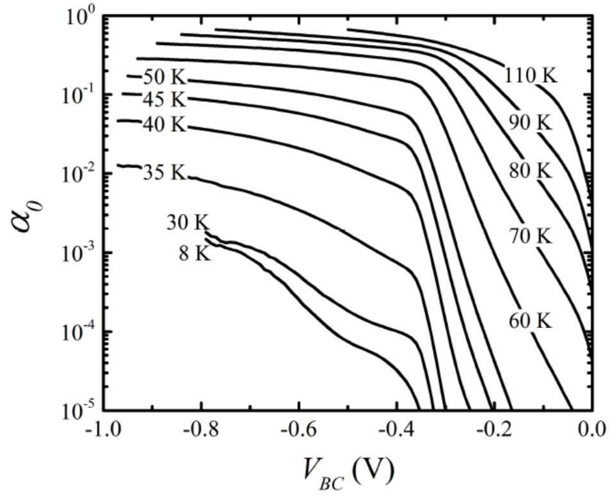
Annealing → σN_T decreases

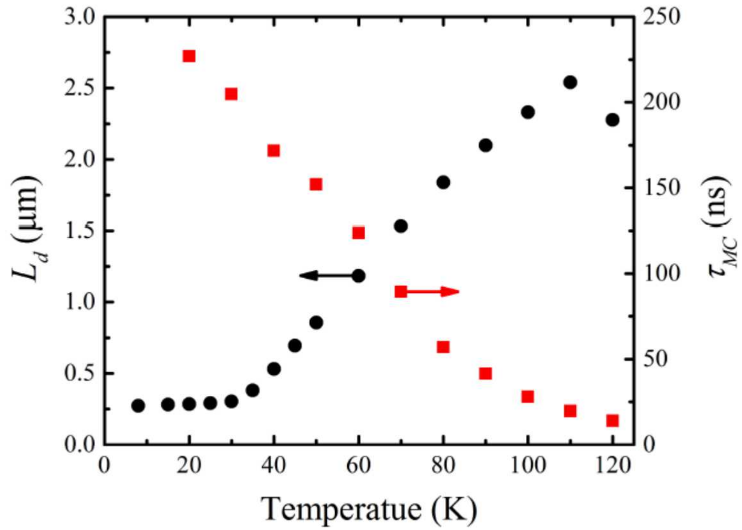
- ***in situ*** **fit deviations likely due to temperature measurements?**
- **Dominant trap level E_T remains at (CBE - ~48 meV)**
- **Reduced population of same initial radiation defect**

Vertical Mobility



$$\alpha_0 = \frac{i_{ECp}}{I_E} = \frac{1}{\cosh(W/L_d)}$$



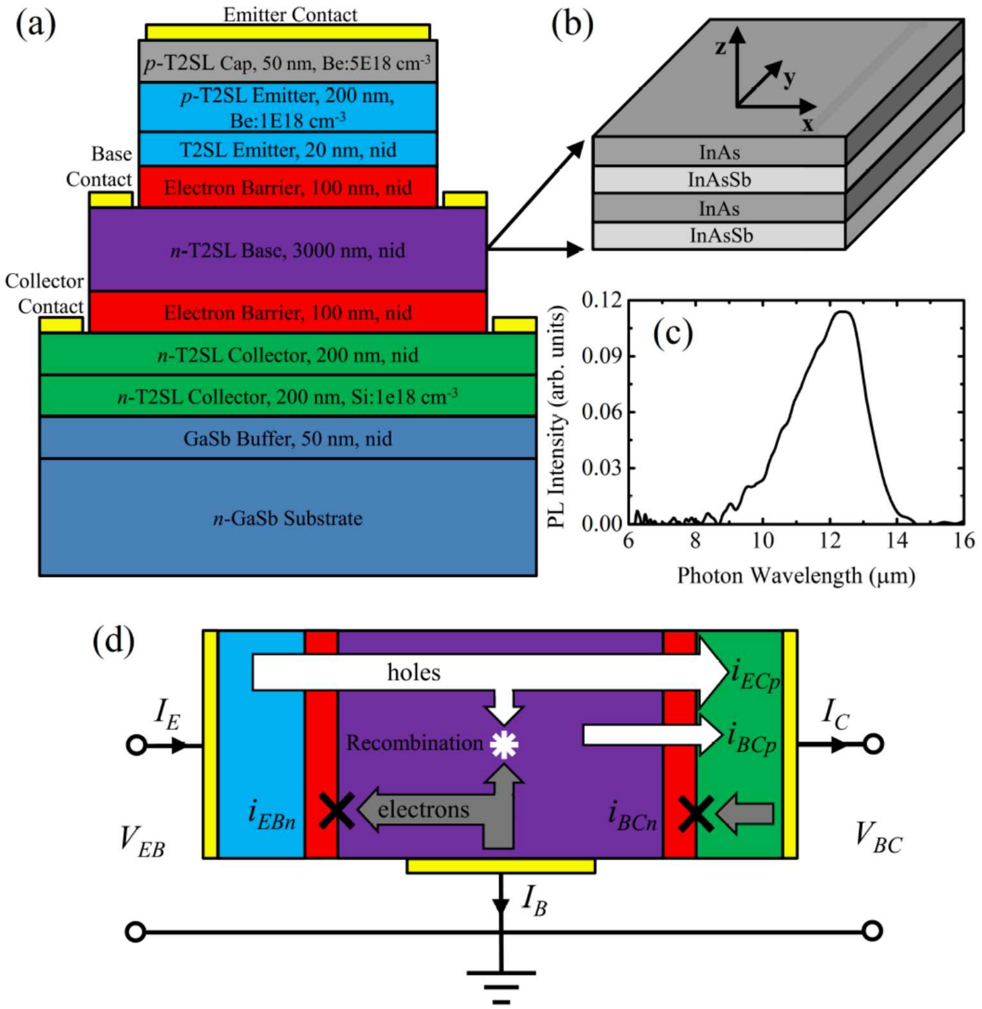


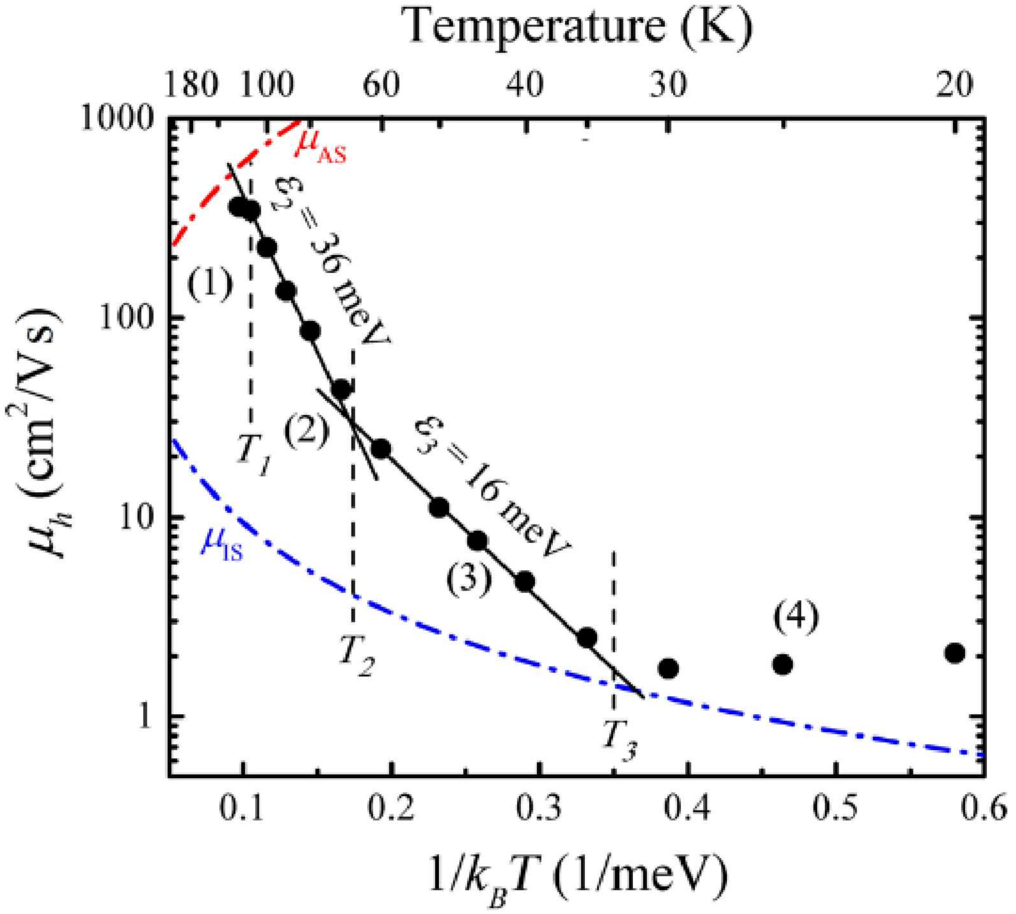
PHYSICAL REVIEW APPLIED 7, 024016 (2017)
B. V. Olson, J. F. Klem, E. A. Kadlec, J. K. Kim, M. D. Goldflam, S. D. Hawkins, A. Tauke-Pedretti, W. T. Coon, T. R. Fortune, and E. A. Shaner

Vertical Mobility

$$D = \frac{kT}{q}\mu = \frac{L_D^2}{\tau_m}$$

$$\mu_h = (qD_h)/(k_B T)$$





EBIC: Journal of Applied Physics 122, 074503 (2017), N. Yoon, C. J. Reyner, G. Ariyawansa, J. M. Duran, J. E. Scheihing, J. Mabon, and D. Wasserman

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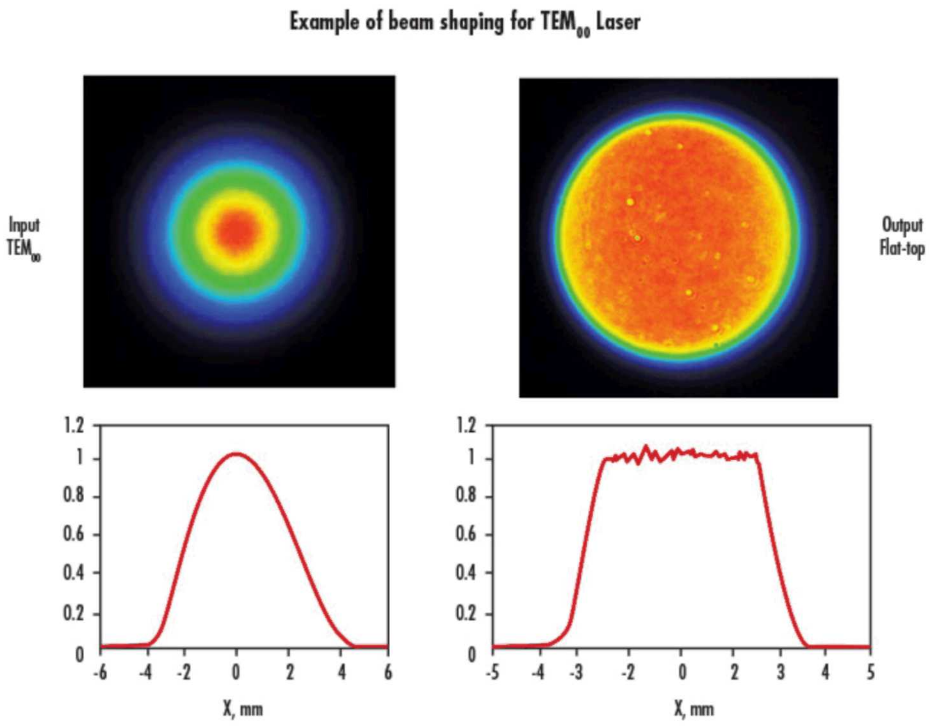
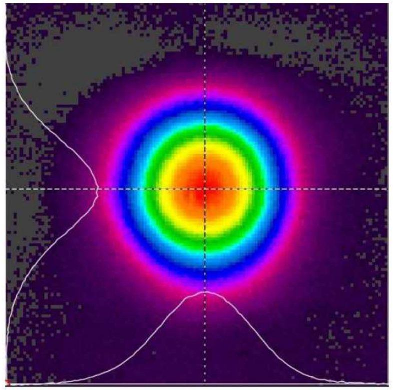
Flat Beam and size limitations

Edmund optics | worldwide

Flat-top beam spot



Microwave beam spot



Hopefully, greatly eases requirements for carrier density calibration and uncertainty for Auger, Radiative

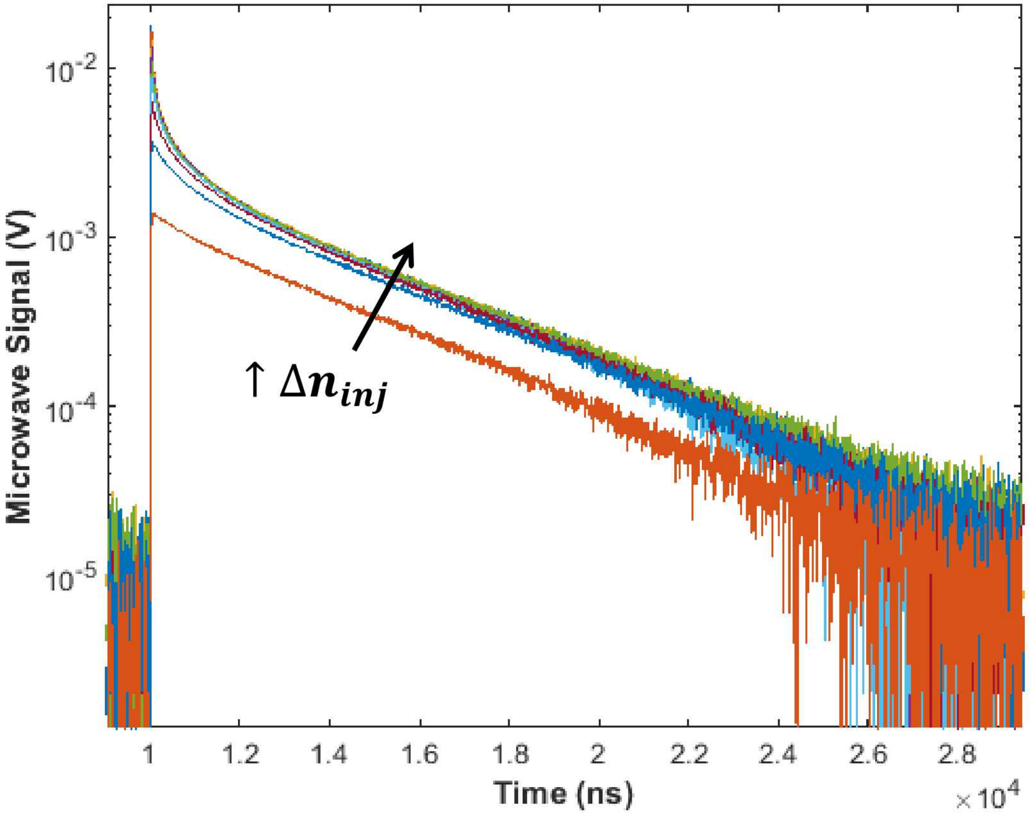
Similar effect can be possibly be obtained by using smaller samples/mesa etching

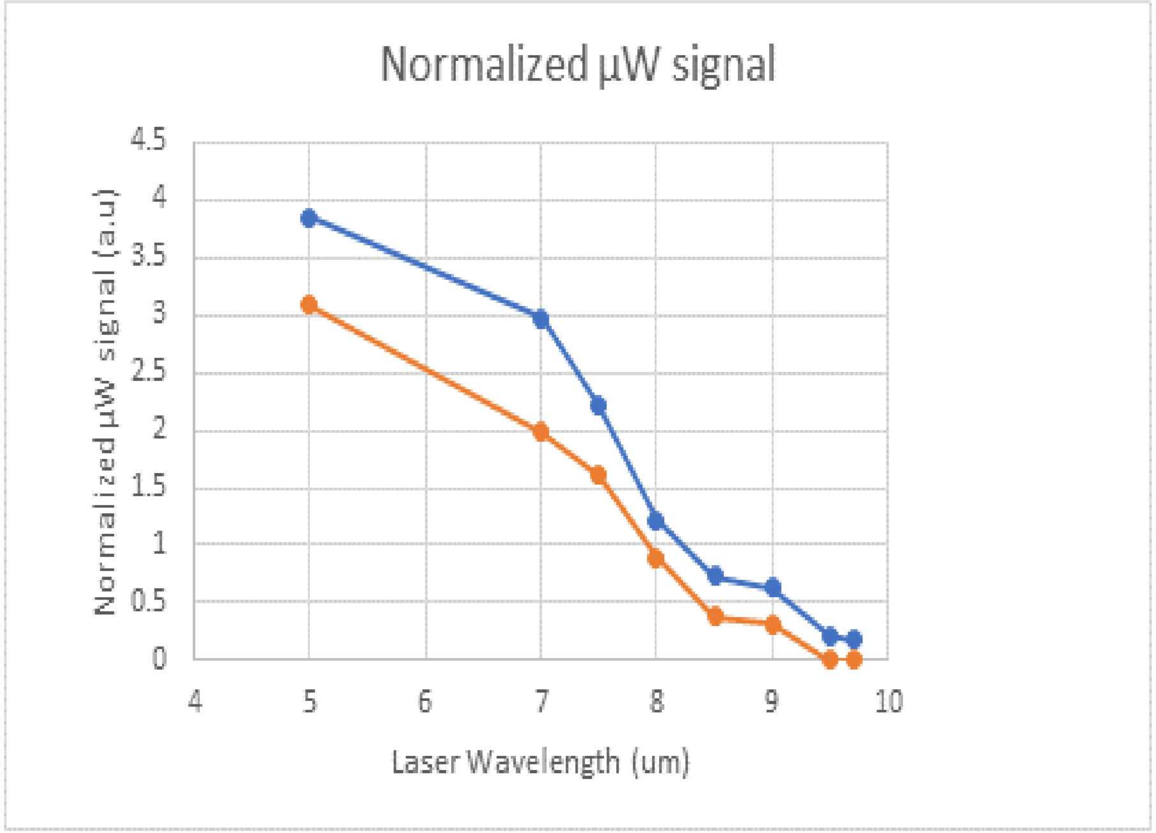
Alternative: Journal of Applied Physics 119, 215705 (2016), Aytac etal.

ThC5.5 Electrical Readout of Carrier Dynamics in Micro-Scale Infrared Materials, Sukrith Dev

Non-destructive absorption coefficient measurement

TMR signal for various pump energy





Plot PEAK position vs. wavelength to map out band edge

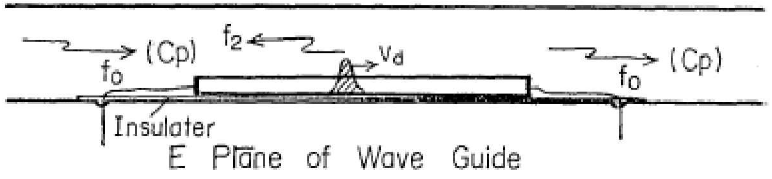
If properly calibrated with a short wavelength excitation, should be able to extract absorption coefficient

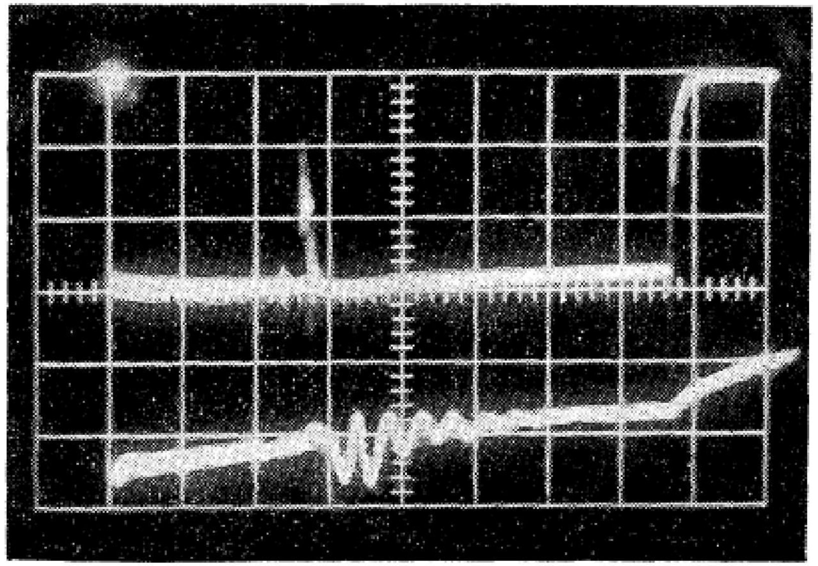
Doppler Shift

JAPANESE JOURNAL OF APPLIED PHYSICS VOL. 4, No. 11, NOVEMBER, 1965

The Doppler Effects of the Drifting Plasma in Semiconductors

Tetsuya ARIZUMI, Masayoshi UMENO and Sohachi IWAI





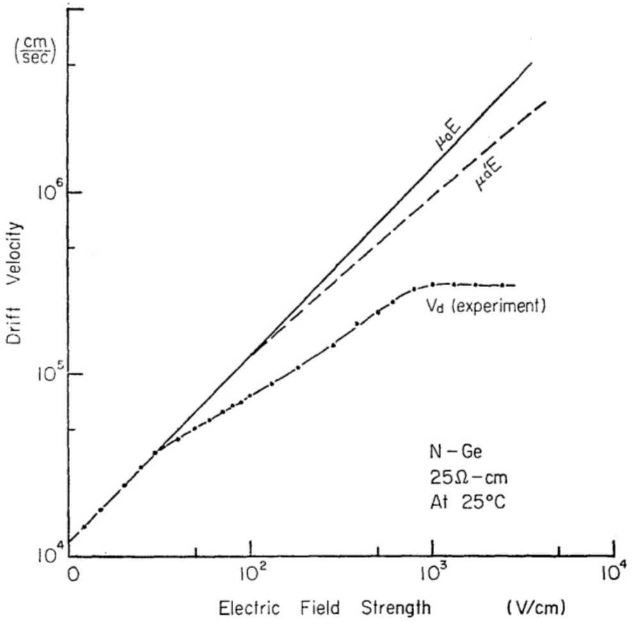
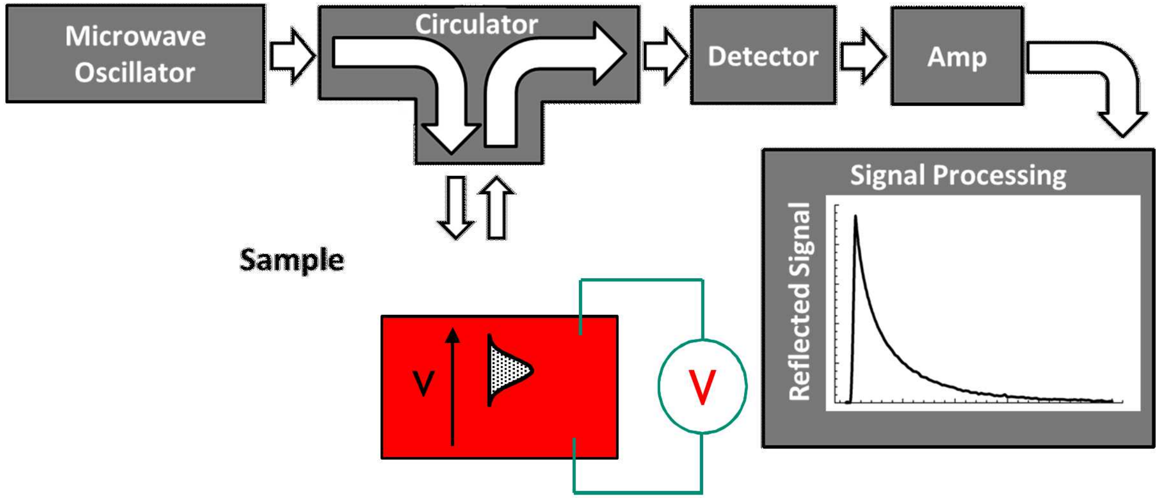


Fig. 6. Dependence of drift velocity on electric field strength. (N type Germanium).

Doppler shift

Add: Heterodyne with mixer

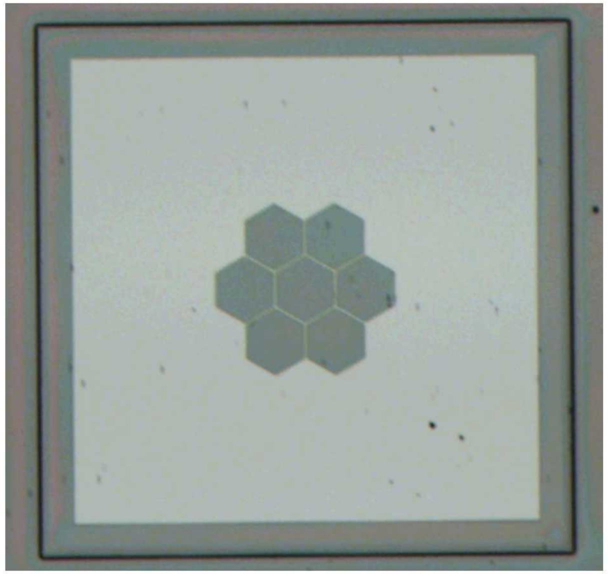


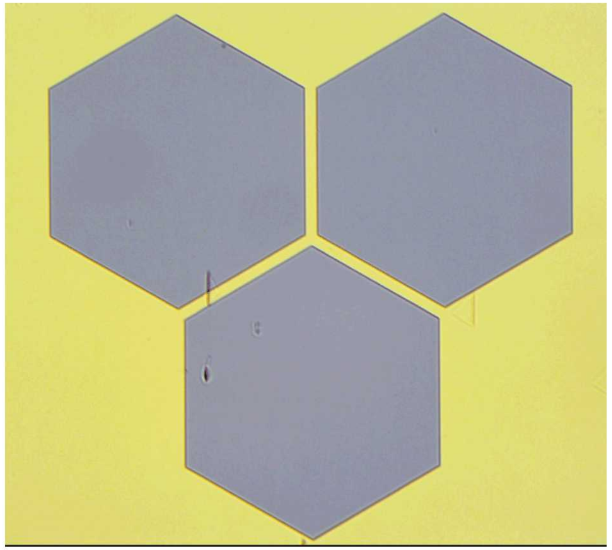
Back reflection Doppler shift: $\Delta f = \frac{2v}{c} f_o$

$\mu = v/E$

Need known applied electric field to get mobility, okay to start with. Can do much more if the technique works.

Try something easy, optimized for current spreading:
1 um GaAs:Si 4e18; u=2600
20 um GaAs:Si 1e15; u = 8400
(need ~0.1 um GaAs:Si 2e18 buffer layer)
n+ substrate





Summary: Many uses for lifetime measurements

Minority Carrier Lifetime only

- Non-destructive cryogenic wafer diagnostics, find growth issues and predict performance
- Dark current prediction (with knowledge of doping)
- SRH Trap level extraction (with knowledge of PL)
- Vertical Mobility (with knowledge of Diffusion length)
- In situ radiation studies

- **Auger, Radiative, SRH extraction**
  - Determine ultimate performance limits
  - Non-destructive Background doping and n_i extraction
  - Requires attention to detail on carrier densities

Still room to grow

- Non-destructive absorption coefficient
- Top hat beam & Size limits
- Doppler