Time Resolved Photo-luminescent Decay Measurements of Infrared Materials

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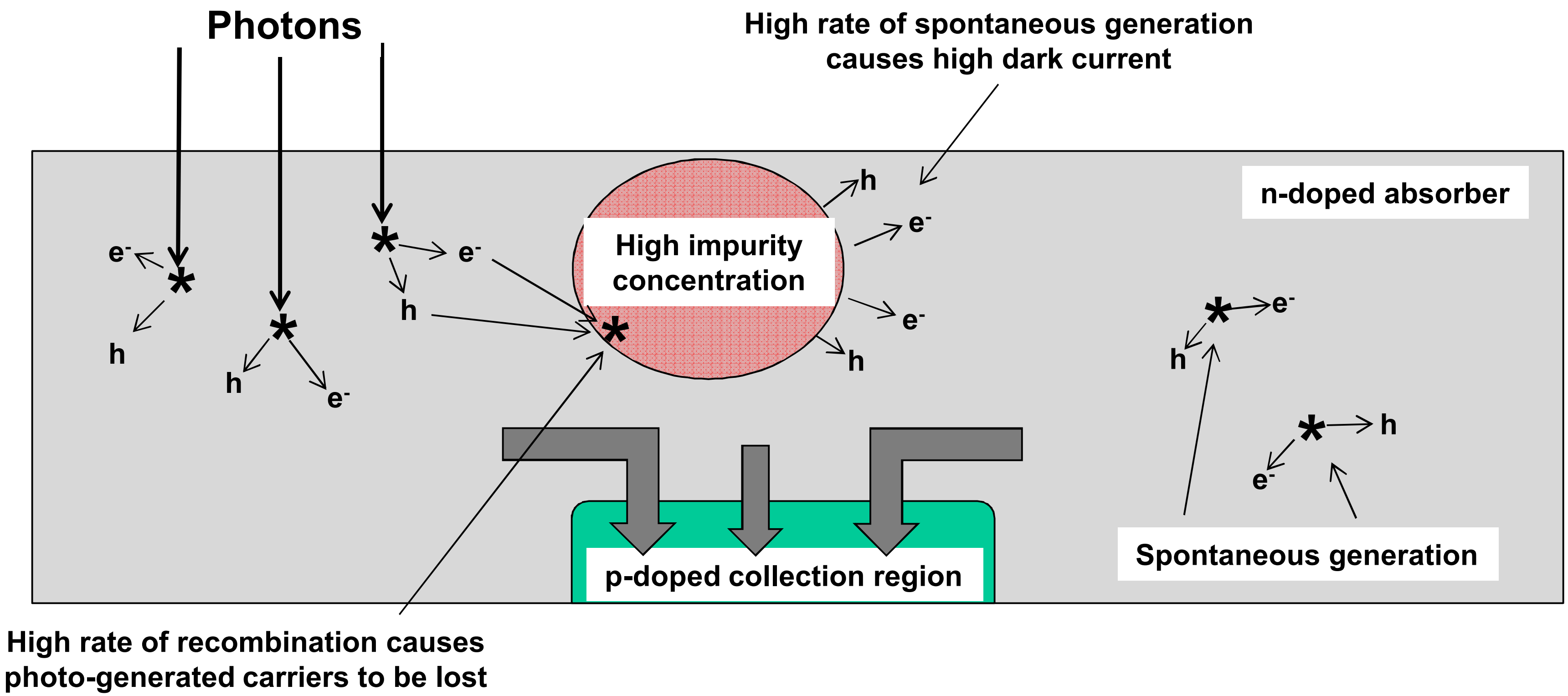
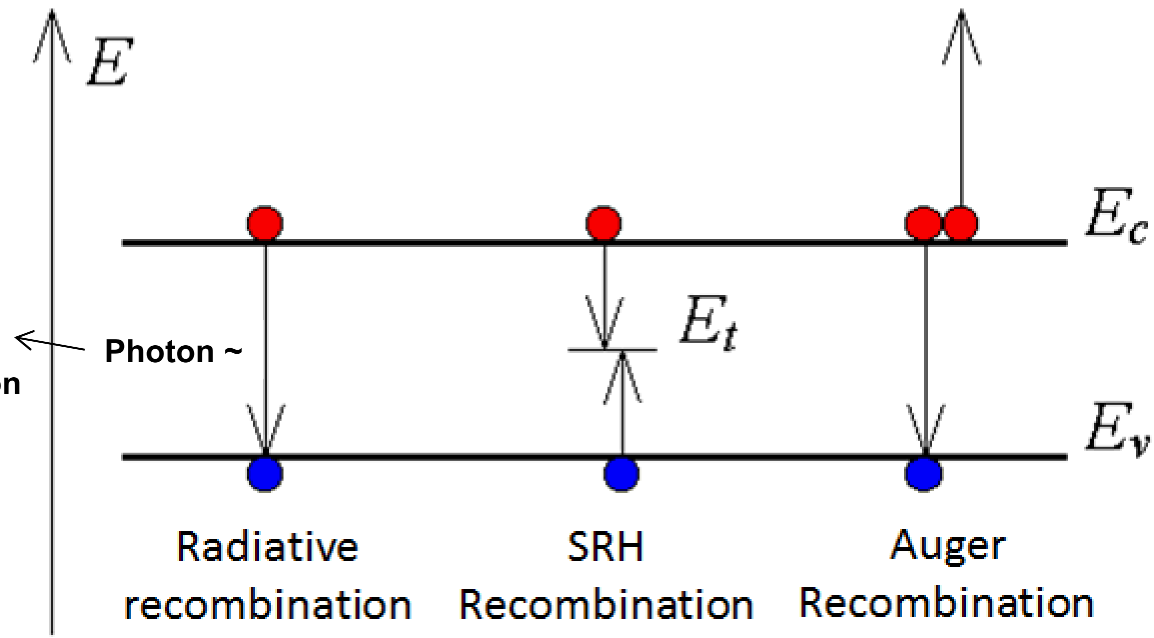
Carrier generation/recombination in a photo-sensitive device



- Carriers generated from photons that are collected are the signal we want
- Carriers spontaneously generated that are collected are dark current
- Carriers generated from photons that recombine contribute to reduced sensitivity

Semiconductor carrier recombination mechanisms

Opportunity to detect photons produced by radiative recombination



- **Radiative and auger recombination rates are fixed for a given material composition**
- **SRH recombination occurs because impurities introduce energy states within the band gap that provide a path for carriers to recombine.**
  - **The rate varies depending on the impurity concentration(s)**

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Carrier recombination equations

Recombination Rates

$$U_{rad} = B(np - n_i^2)$$

Rates all dependent on a power of this term indicating the deflection of the system from equilibrium

$$U_{aug} = C_n(n^2p - n_0^2p_0) + C_p(np^2 - n_0p_0^2)$$

$$U_{SRH} = \frac{(np - n_i^2)}{\tau_{SRH-n}(p + p_1) + \tau_{SRH-p}(n + n_1)}$$

SRH time constants

SRH densities

$$\frac{\partial n}{\partial t} = \frac{\partial p}{\partial t} = G_{optical} - (U_{aug} + U_{rad} + U_{SRH})$$

Generation rate from photon absorption

Net recombination rates (includes spontaneous generation rates)

Undoped

$$n_0 = p_0 = n_i$$

Intrinsic Concentration – material property

Doped

$$n_0 = \frac{N_D - N_A}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2}$$

$$p_0 = \frac{N_A - N_D}{2} + \sqrt{\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2}$$

$$n_0 p_0 = n_i^2$$

$n_0 \neq p_0$ for doped materials, but this equation always holds true

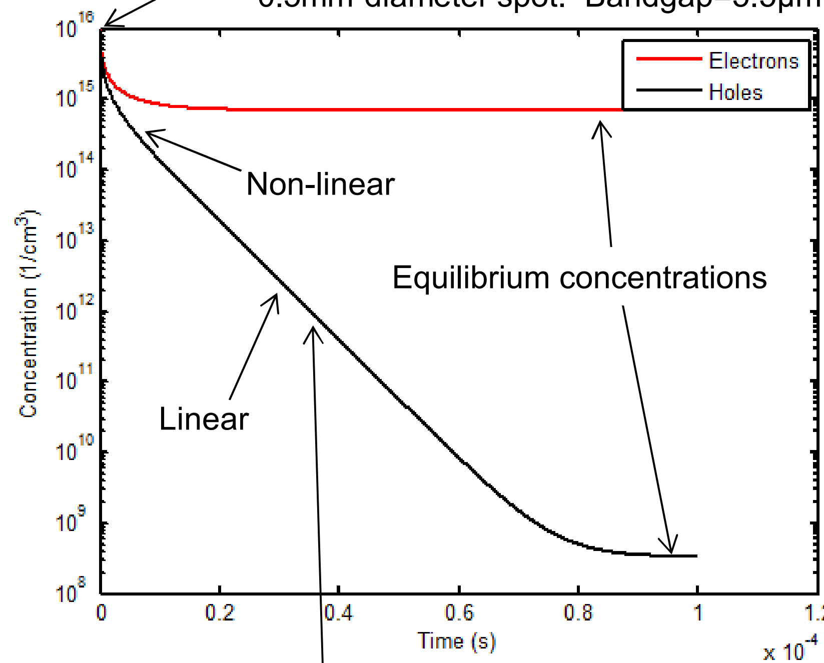
Carrier recombination numerical simulation

Inputs: starting concentrations $n(t_0)$ and $p(t_0)$ and laser pulse in time $G_{optical}(t)$

$$n(t + \Delta t) = n(t) + \Delta t \cdot G_{optical}(t) - \Delta t \cdot (U_{aug} + U_{rad} + U_{SRH})$$
$$p(t + \Delta t) = p(t) + \Delta t \cdot G_{optical}(t) - \Delta t \cdot (U_{aug} + U_{rad} + U_{SRH})$$

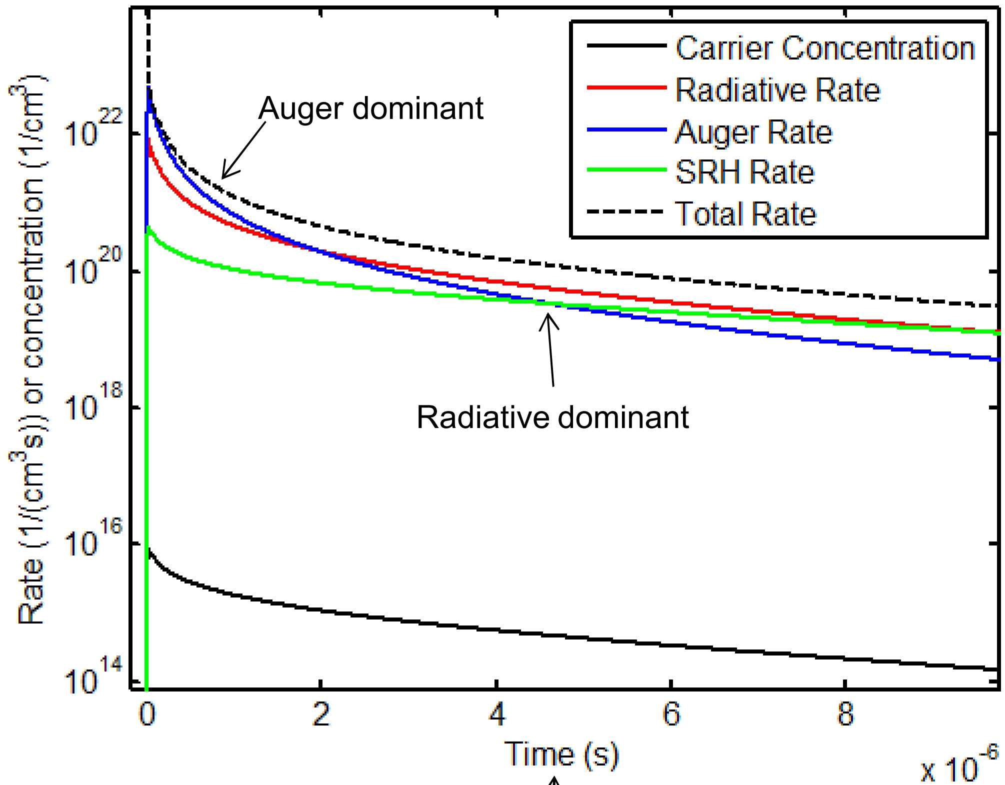
Δt is set at each iteration so the concentrations don't change by >0.1% for any given time step

1nJ laser pulse ($G_{optical}$) for 10ns at start, exciting a 6μm thick MCT sample with 0.5mm diameter spot. Bandgap=5.5μm



Note: the deflection from equilibrium runs through ~6 orders of magnitude, cannot measure this much with an experiment

Recombination rates and carrier concentration



SRH becomes dominant

Concentration becomes linear

Time scale is short in this case, and carrier concentration (holes) does not reach equilibrium

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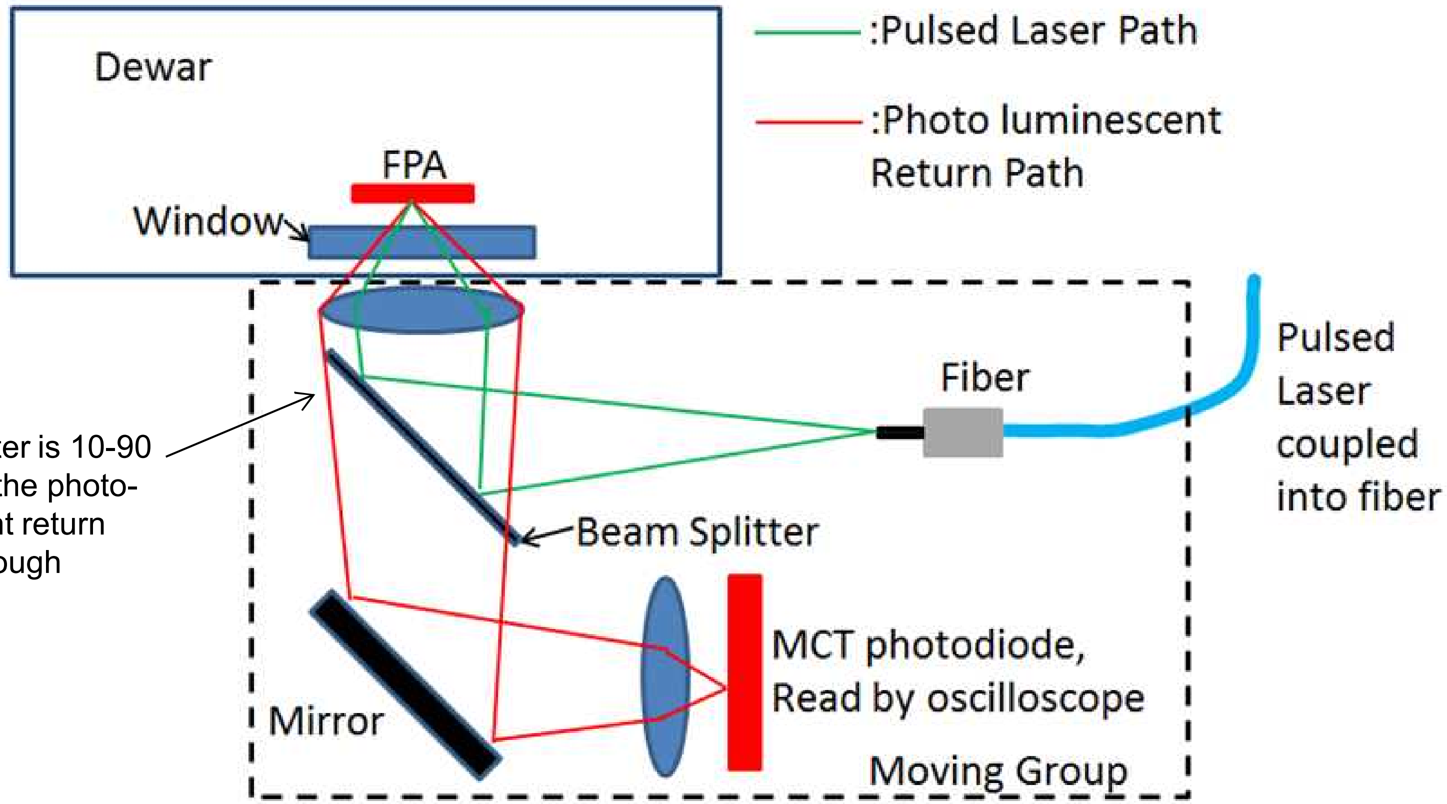
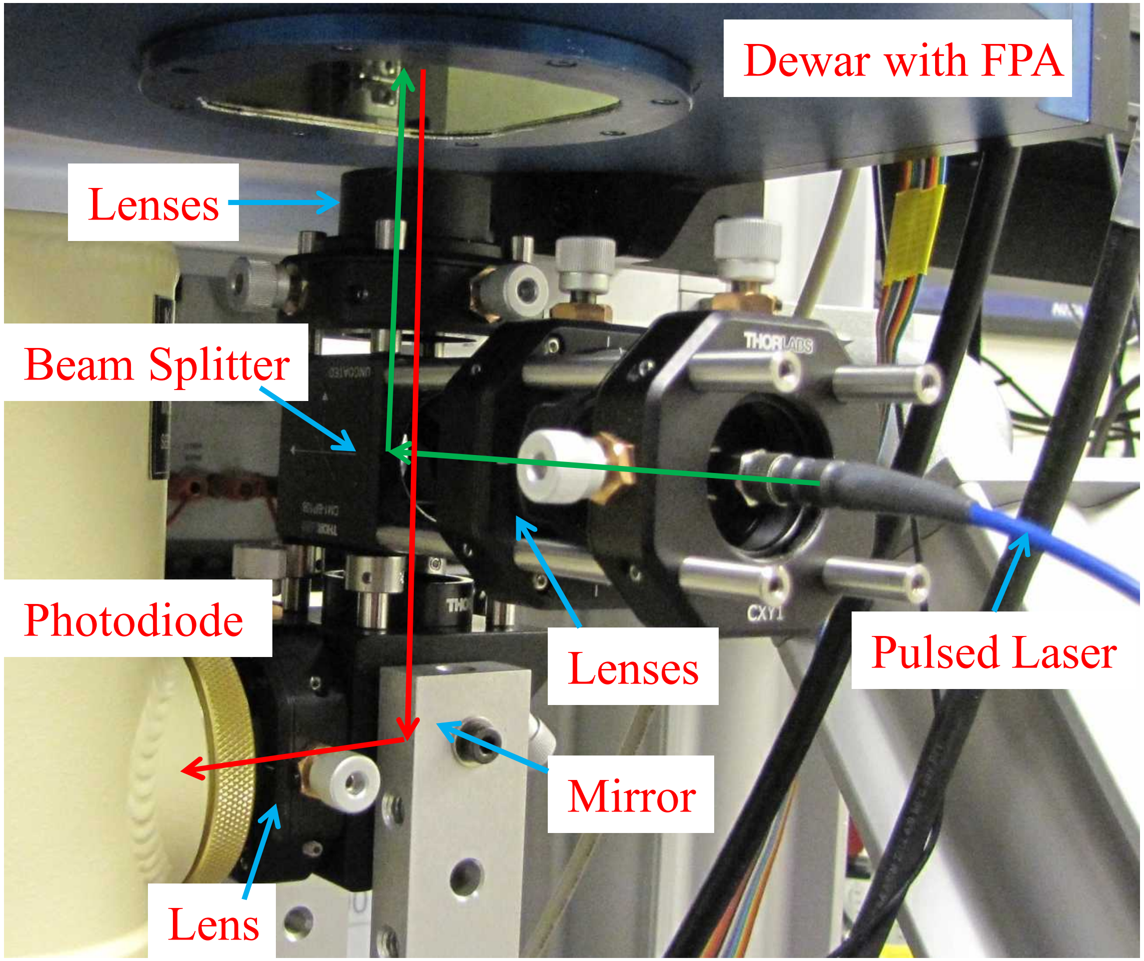
Time resolved photo-luminescent decay experiment diagram



Beam splitter is 10-90 so 90% of the photo-luminescent return passes through

Picture of measurement station

8mm thick silicon window



Kolmar 1mm diameter MCT photodiode

Ekspla OPO laser, tunable from 2500-4450nm

Newport XMS and GTS series stages

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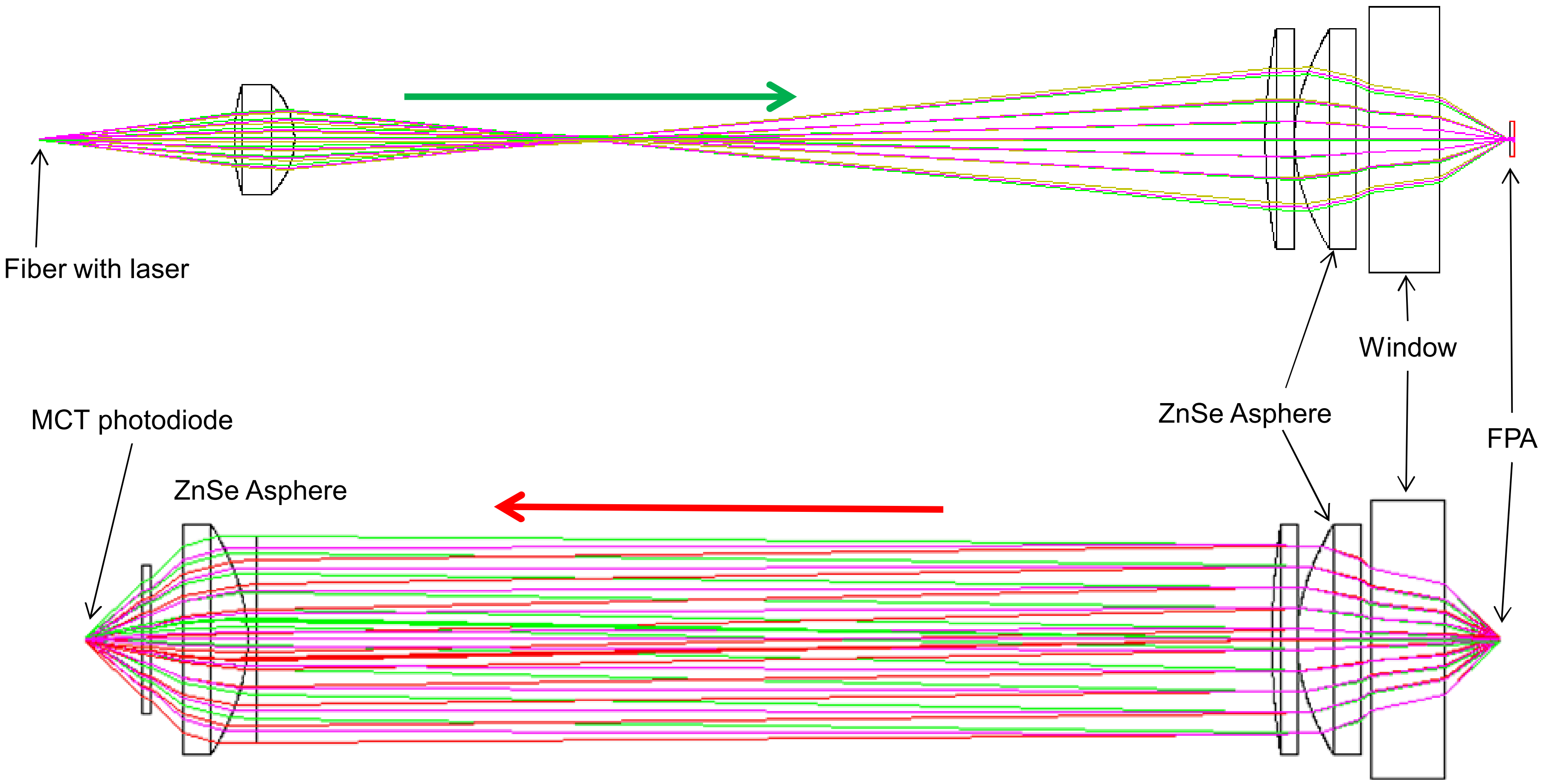
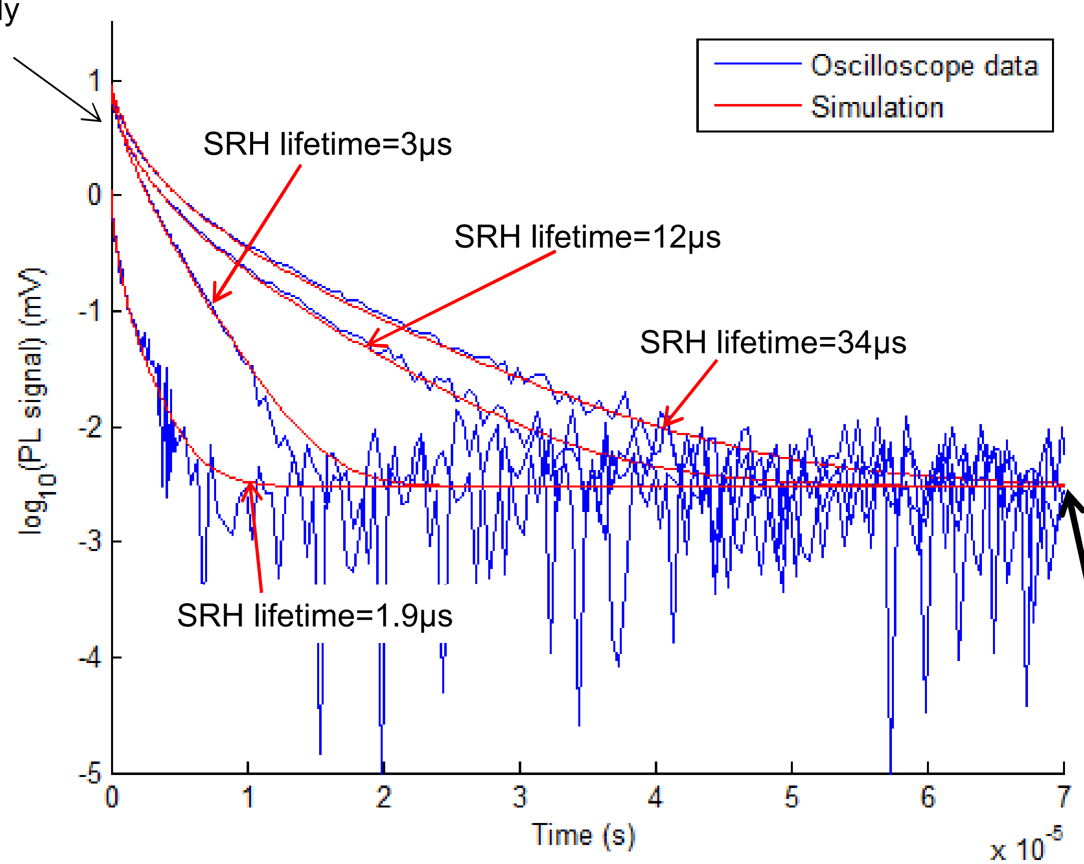
Optical design



Comparison of data from different locations on an FPA

Time 0 for the simulation and optimization is actually set at 100-500ns after the laser pulse to avoid scattered laser light and detector rise/fall times affecting the signal

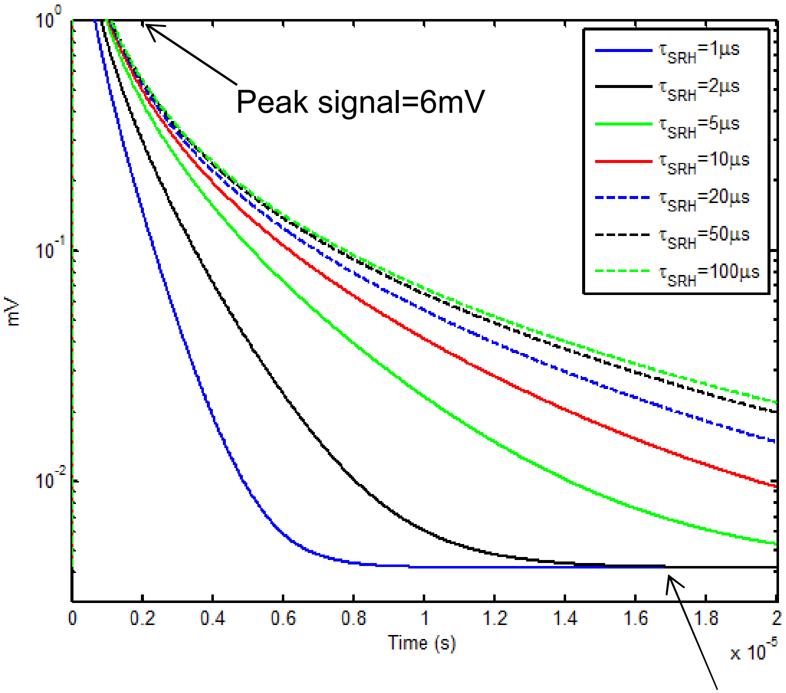


Oscilloscope noise floor incorporated into simulation

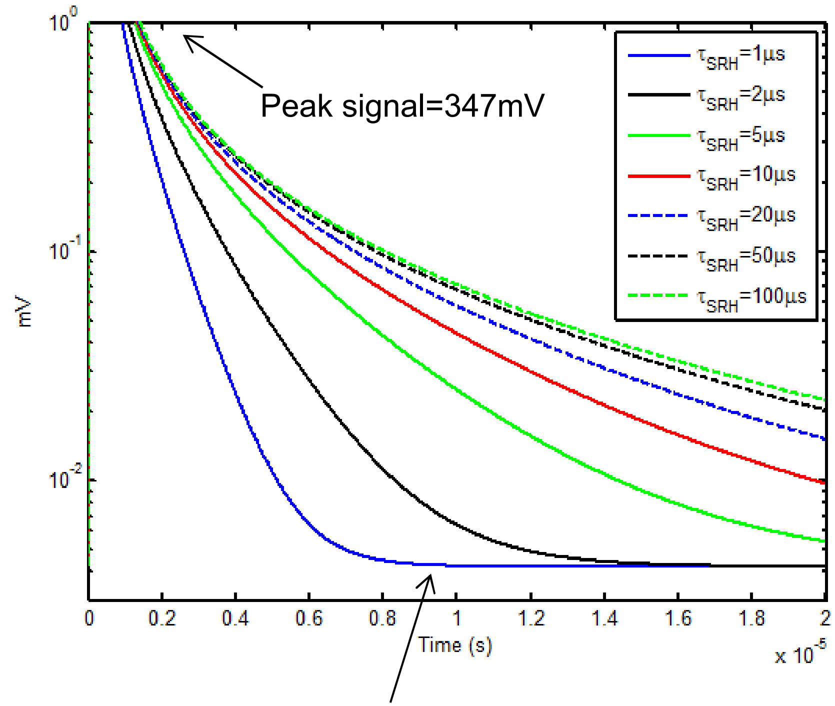
- The radiative recombination rate is proportional to the photon flux leaving the sample
- The simulation is used to scale the resulting radiative recombination rate to the oscilloscope trace
- The error between the simulation and data is optimized using Matlab fminsearch

Simulation - effect of increasing excitation power

10ns, 0.5nJ pulse



10ns, 5nJ pulse

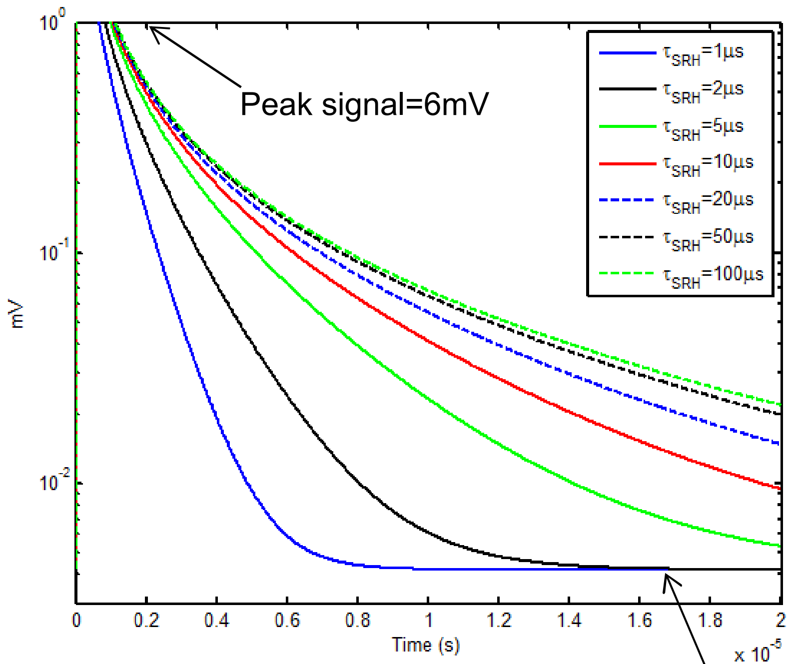


Typical noise floor was included in simulation

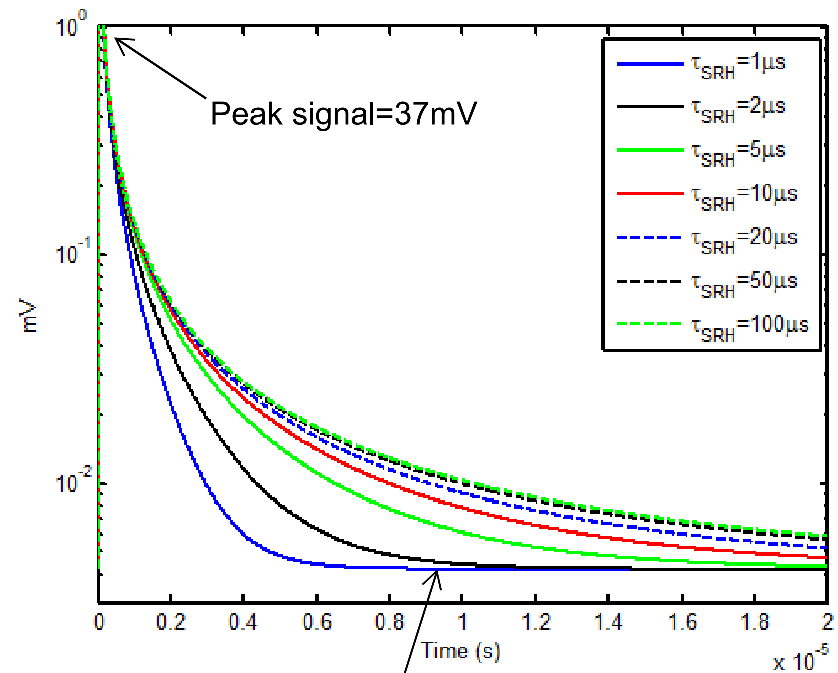
- Spot diameter is 0.5mm for all simulations
- Increasing the laser power only increases the magnitude of the short initial peak leaving the rest of the decay where the SRH lifetimes differentiate from each other nearly unchanged

Simulation - effect of decreasing spot size

10ns, 0.5nJ pulse, 0.5mm spot diameter



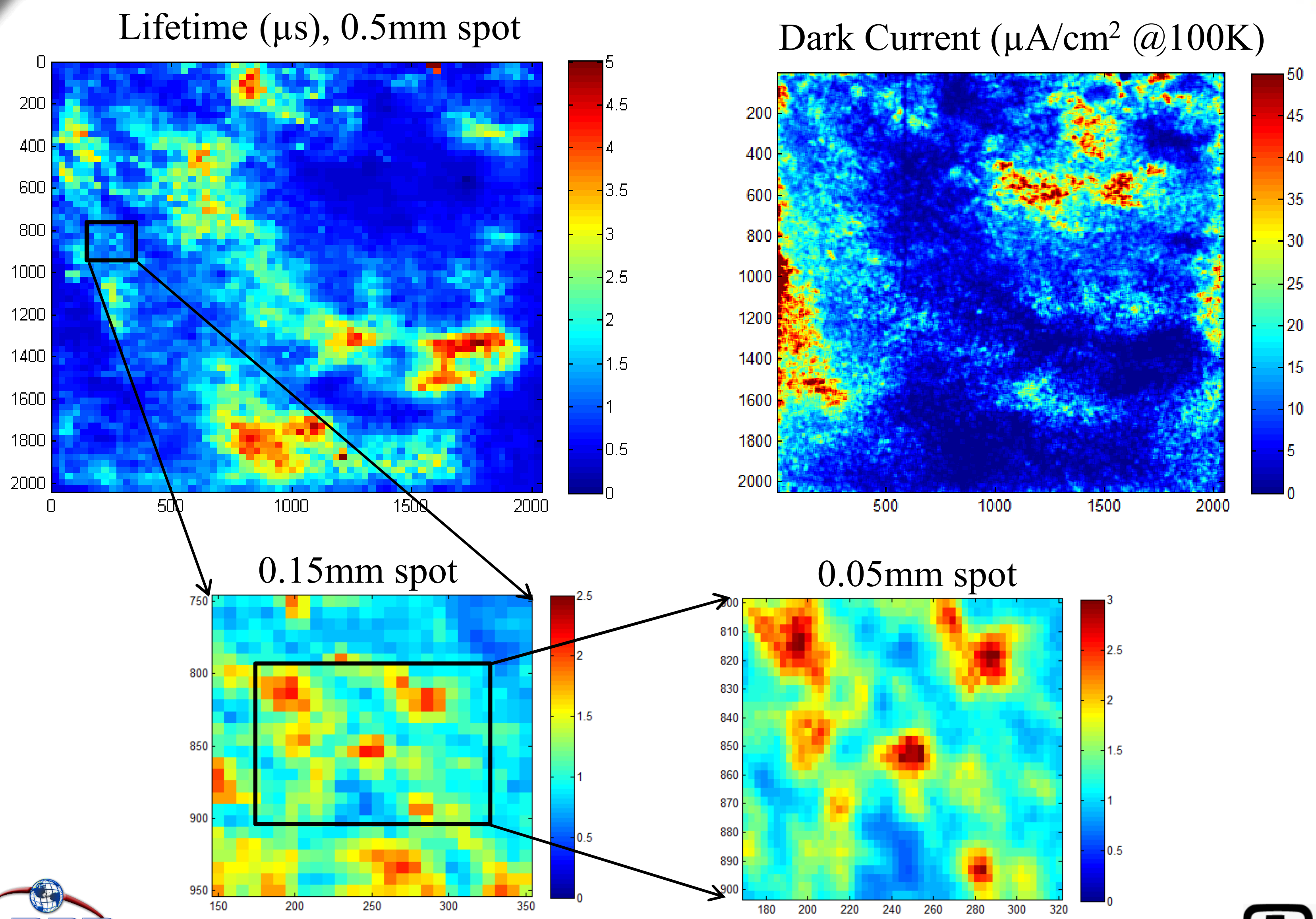
10ns, 0.5nJ pulse, 0.15mm spot diameter



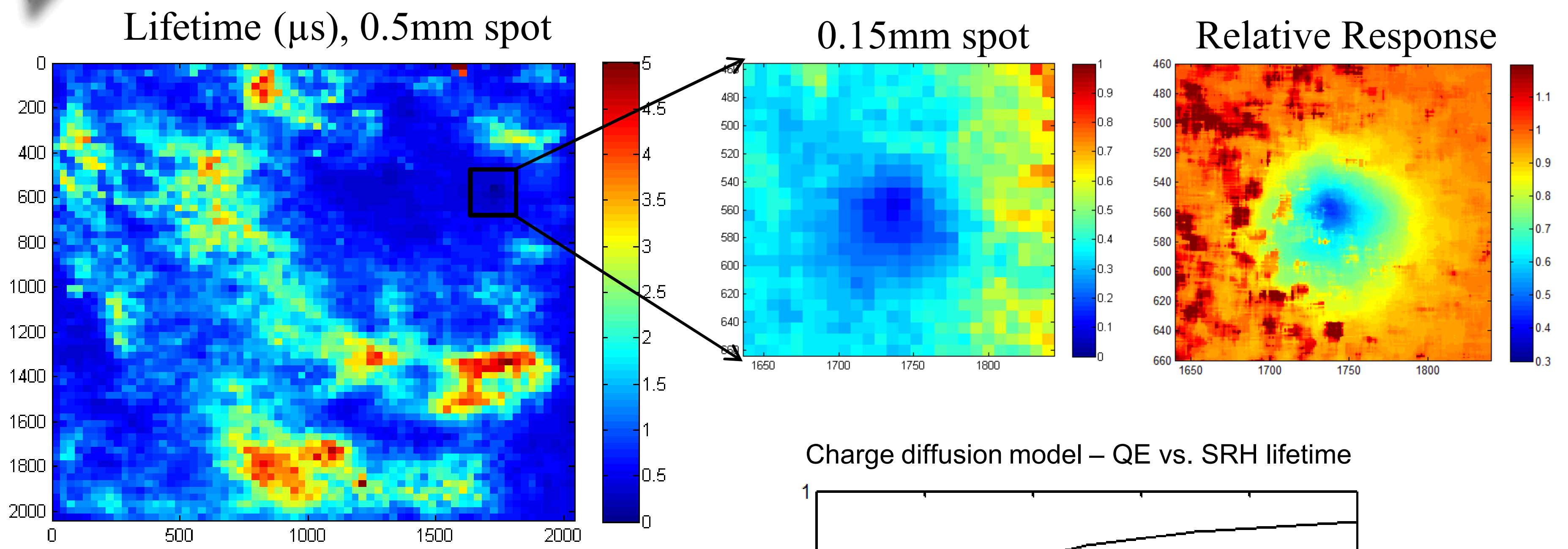
Typical noise floor was included in simulation

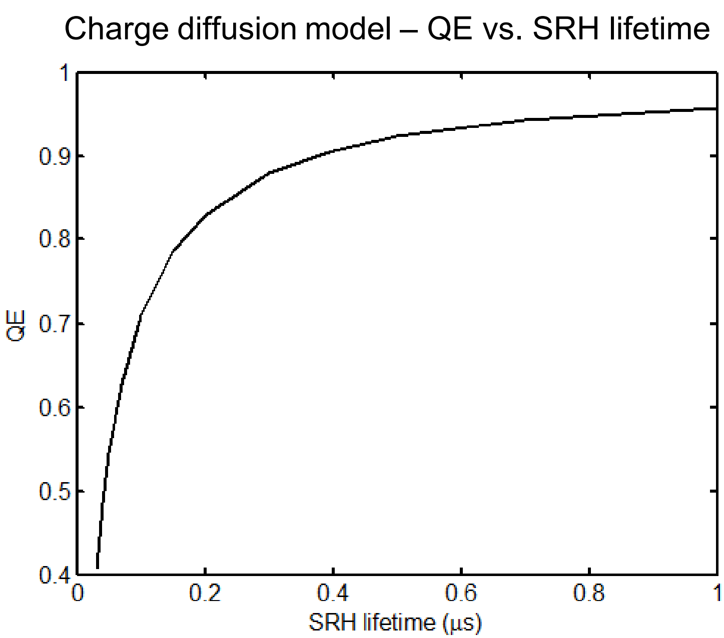
- The smaller spot diameter excites less volume, so less radiative photons are produced in the time range at which SRH lifetimes become distinguishable

Lifetime maps for SWIR FPA #1



Lifetime and relative response for SWIR FPA #1

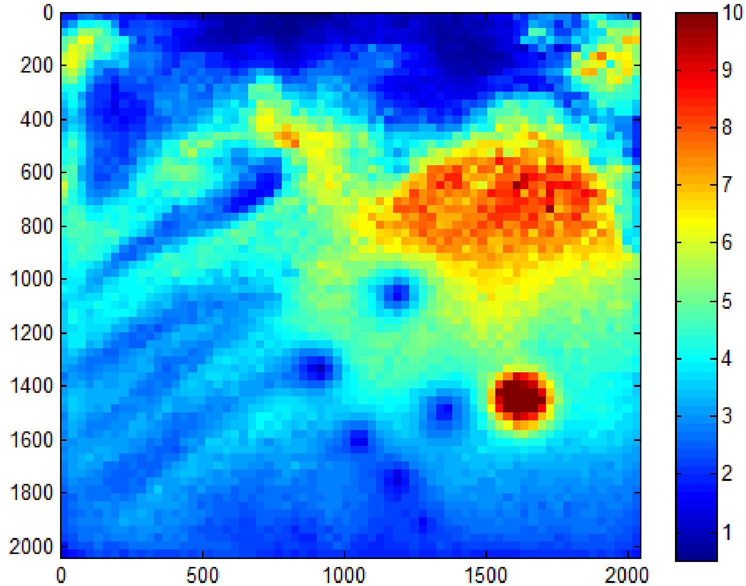




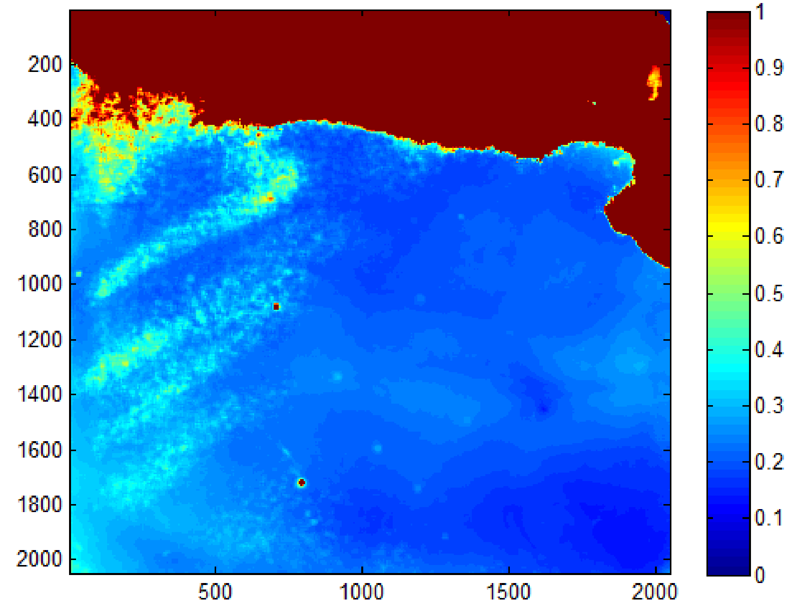
- Defect was found with ~100ns lifetime, the lowest of any region in any of the 4 FPAs tested
- Charge diffusion model previously developed indicated that recombination before collection would reduce the QE at this short lifetime
- Relative response map confirms this

Lifetime map for SWIR FPA #2

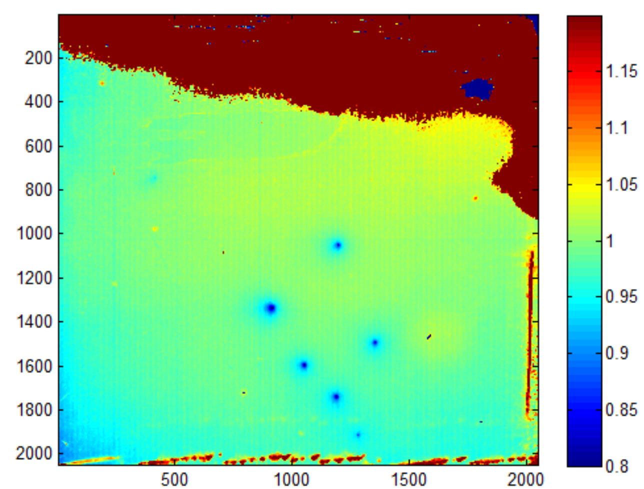
Lifetime (µs), 0.5mm spot size



Dark Current (µA/cm^2 @150K)



Relative response



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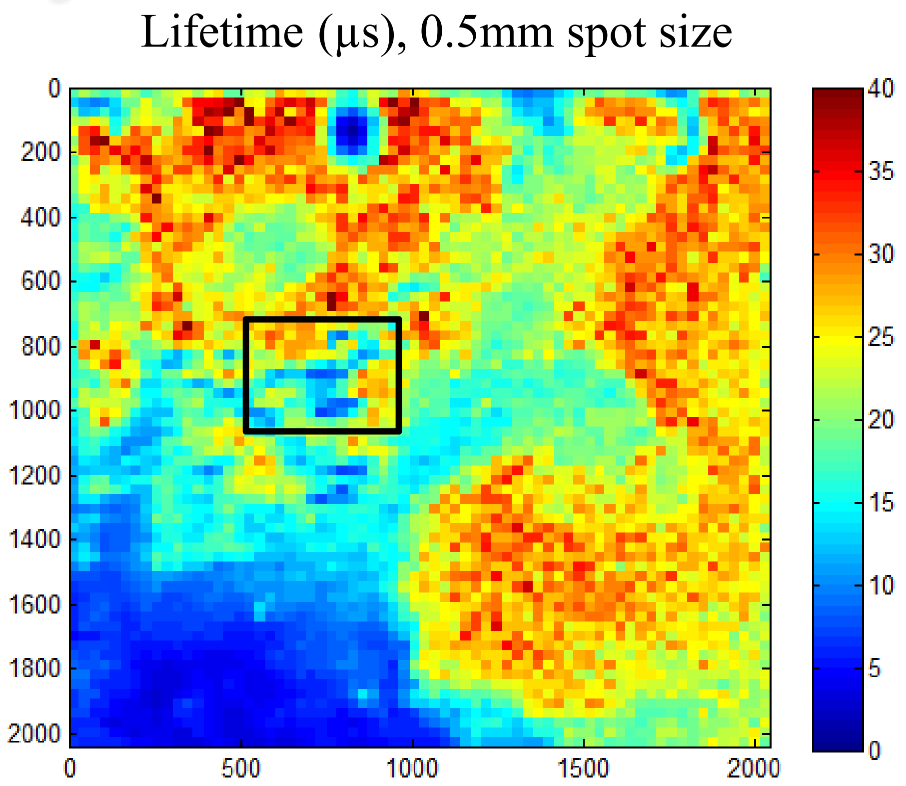
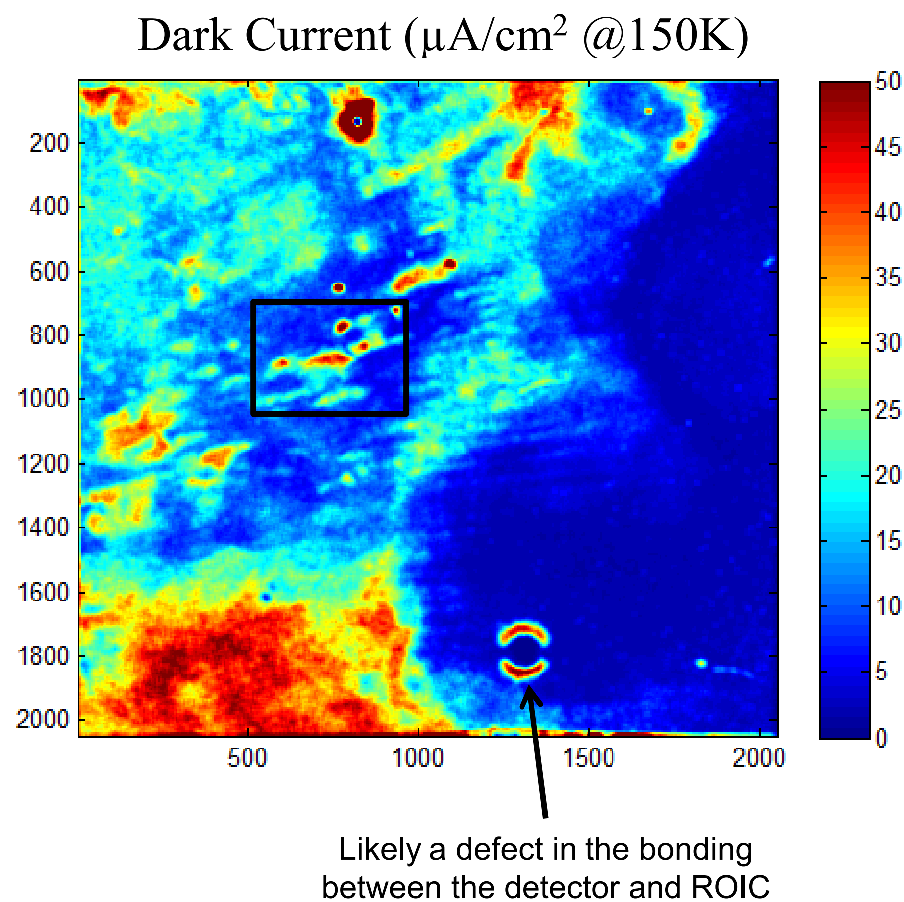
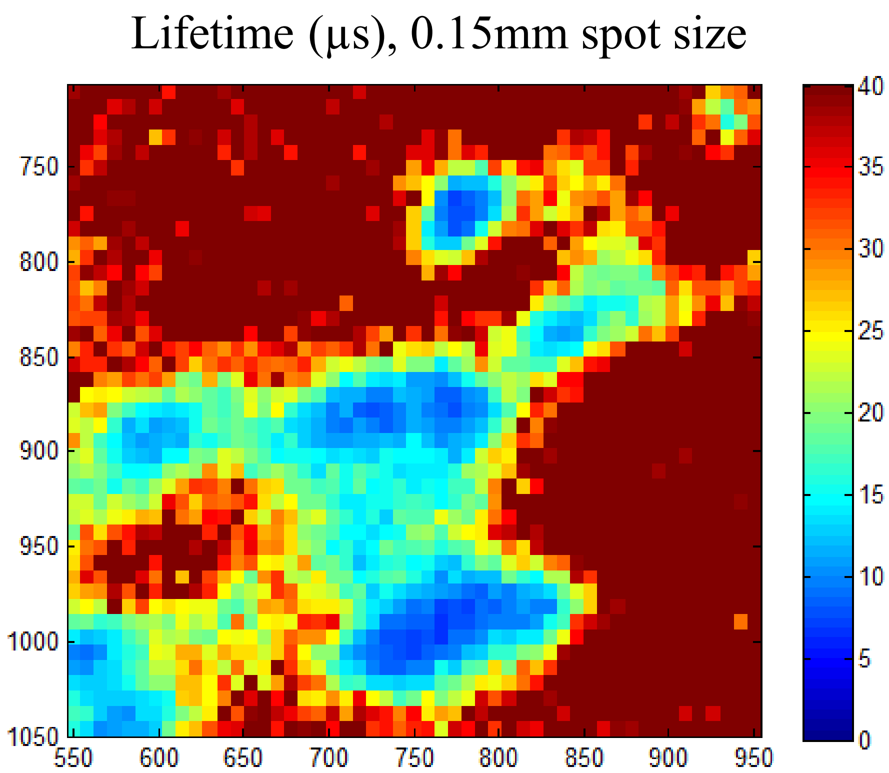
Lifetime map for MWIR FPA #1

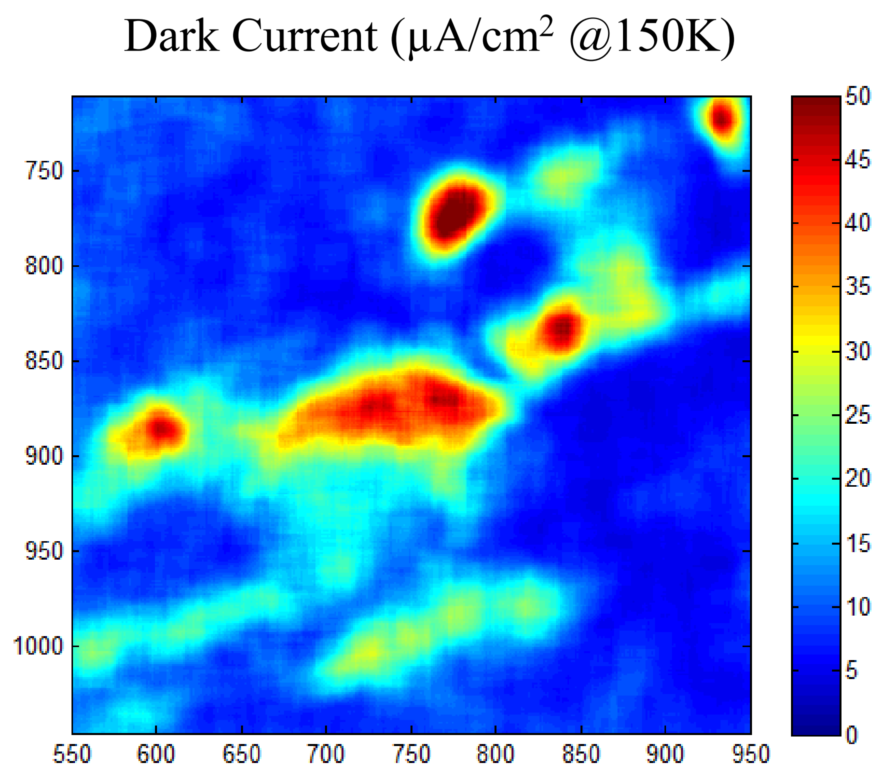




- Black boxes indicate the high resolution area of interest scan found on the following slide

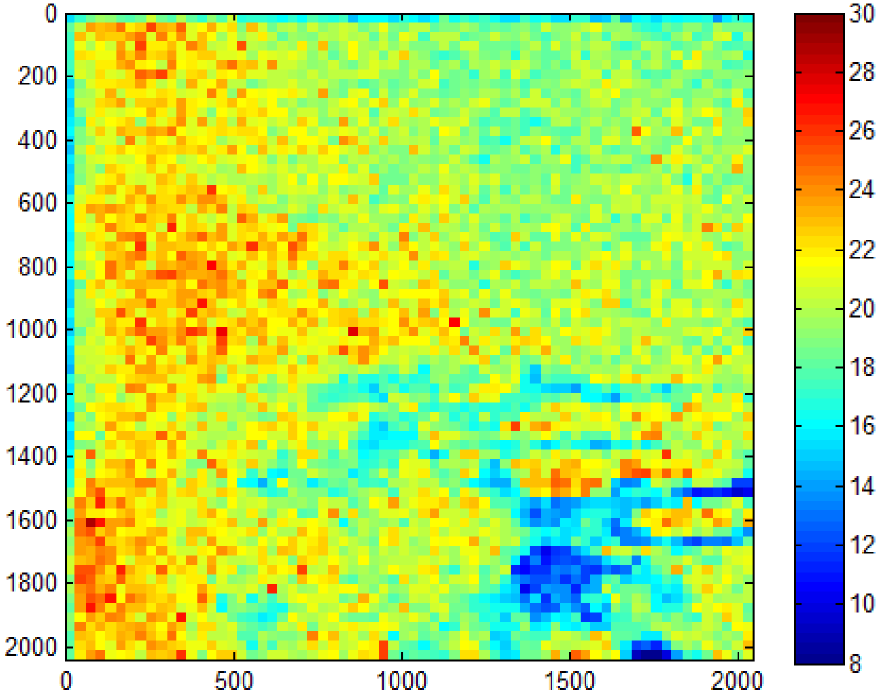
Lifetime map in area of interest, MWIR FPA #1



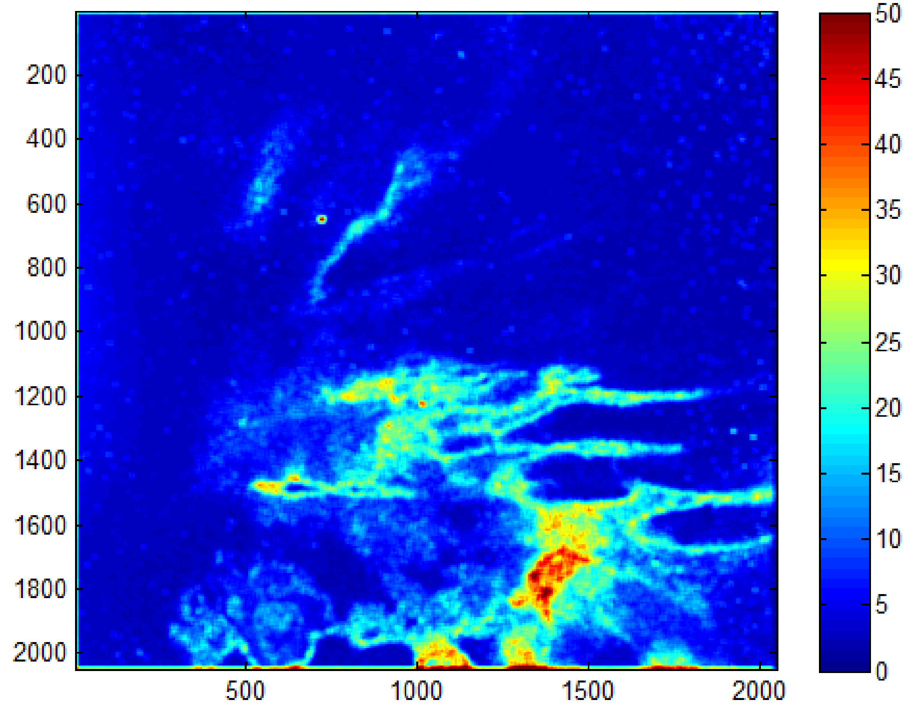


Lifetime map for MWIR FPA #2

Lifetime (μs), 0.5mm spot size



Dark Current (μA/cm^2 @150K)



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