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Rapid PL Imaging For Defect Identification in Semiconductor Sensors

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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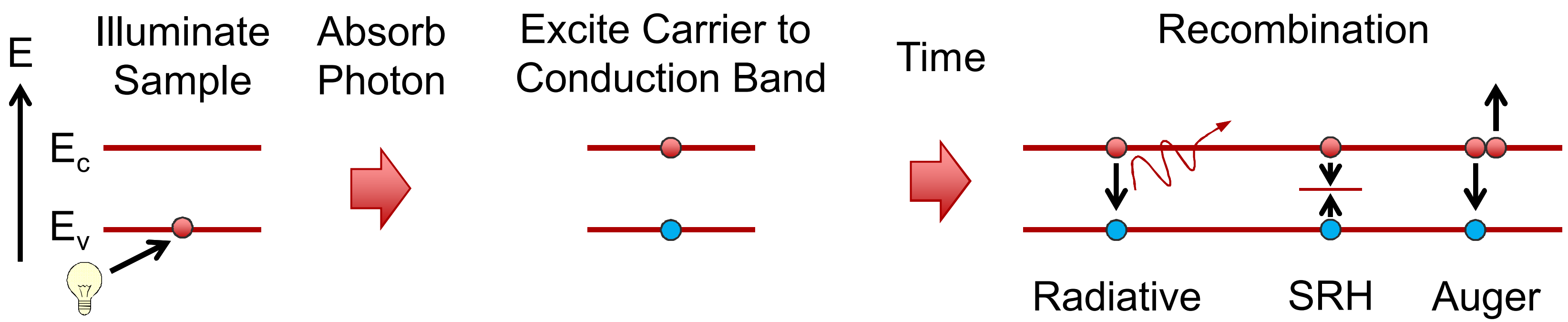
Overview

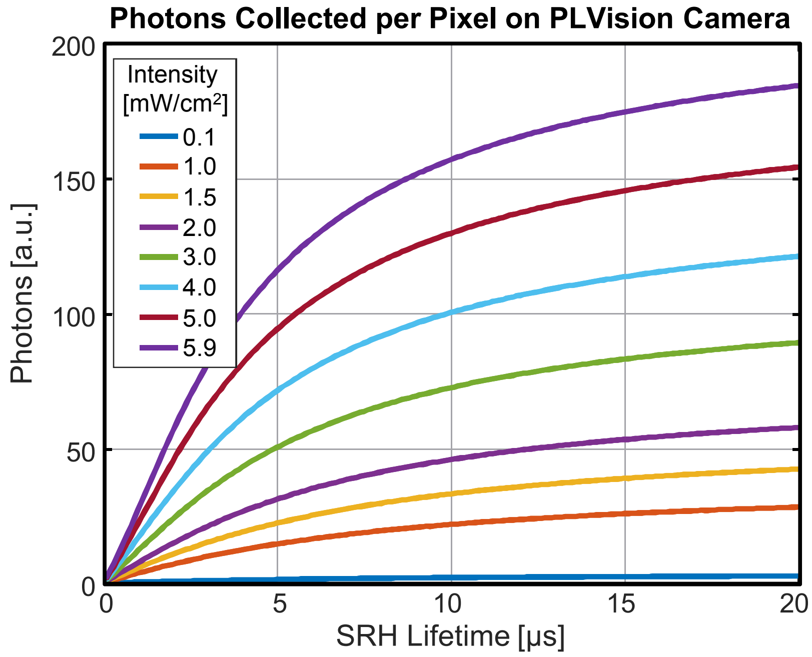
- **Goal: identify defects early in production to increase yield and quality of large IR FPAs**
- Photoluminescence (PL)
  - Lifetime and intensity depend on carrier recombination time
  - Provides direct indication of material quality
  - Doesn't require finished device: works equally well at any stage from unpatterned wafers to finished devices
- Previously showed lifetime mapping could identify defects in MCT FPAs
  - Only need *variation* in lifetime to identify defects
- *PLVision:* image mid-IR PL intensity with camera
  - Correlates well with lifetime variation and defects in arrays
  - Fast: collect from a large area at once, potentially room-temperature sample
  - Much simpler setup
- Focus on short-wave IR MCT arrays

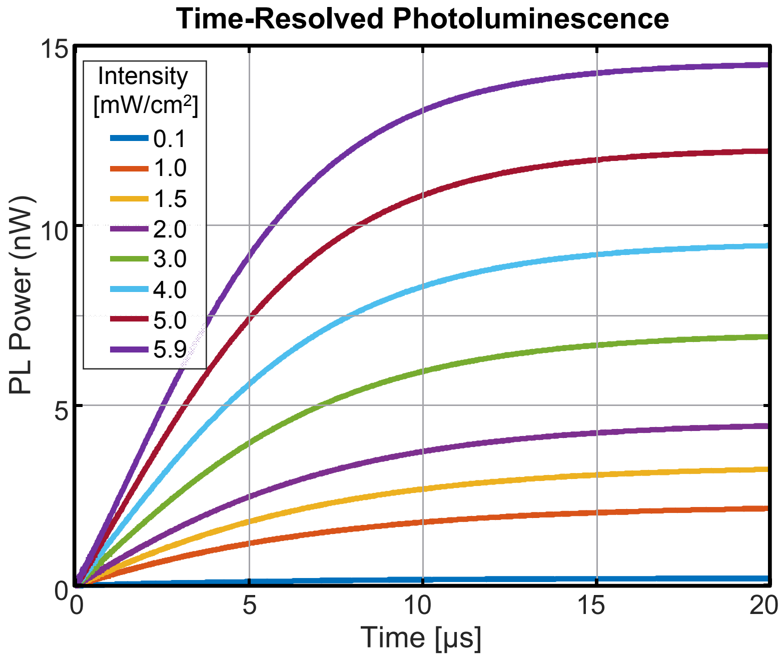
Photoluminescence



- Three primary decay mechanisms: Radiative, SRH, and Auger
- Radiative recombination: photoluminescence
- Relative rate of decay mechanisms control intensity
- More defects → more trap states → increase SRH rate → reduced PL & reduced performance

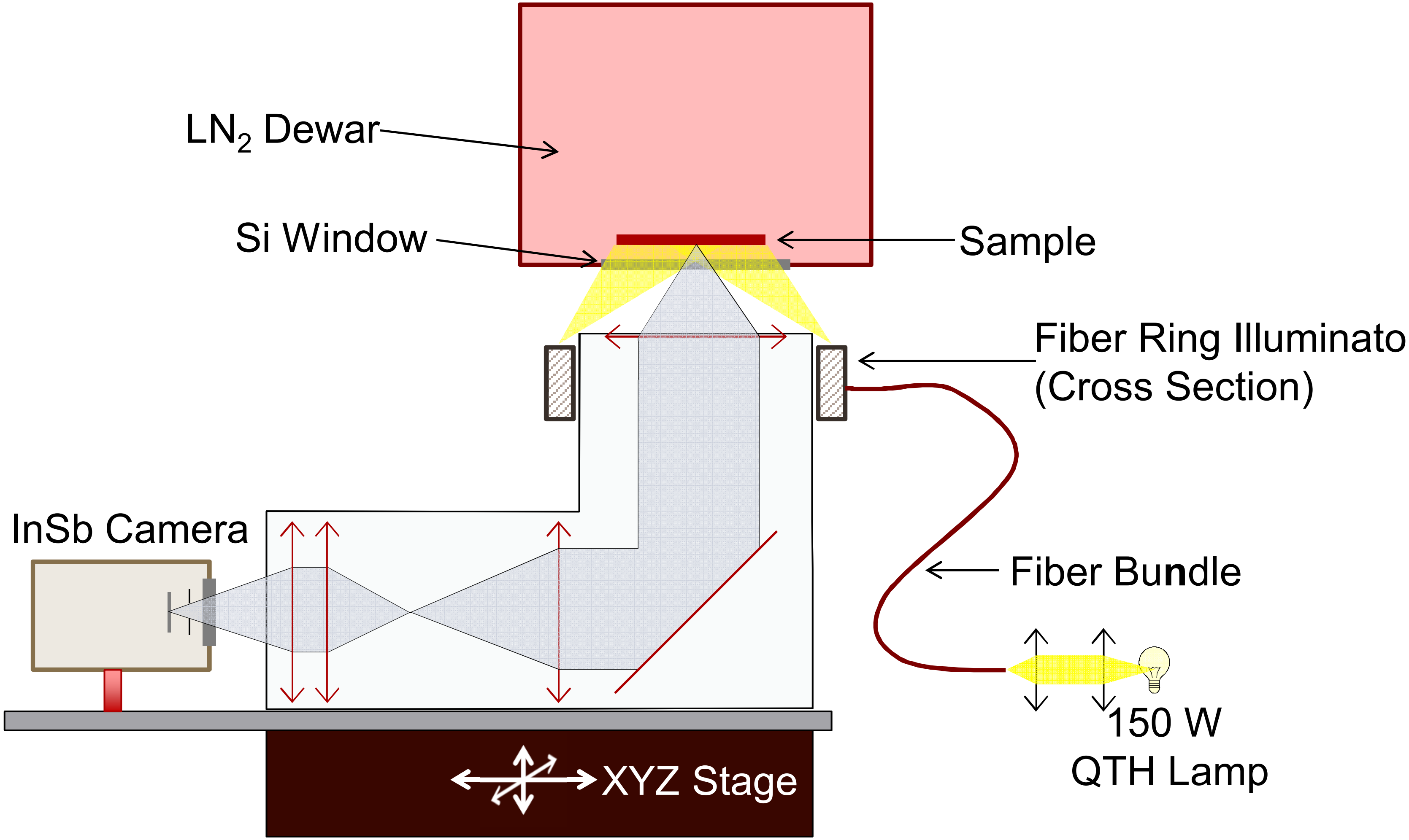
Lifetime → Observed PL





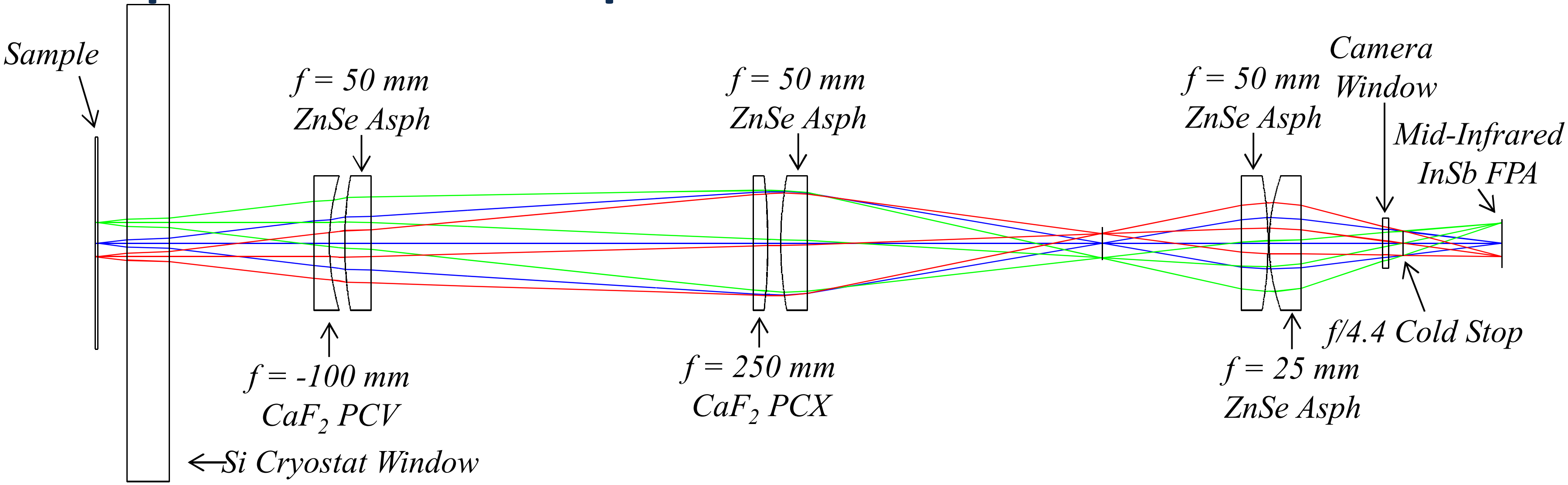
- Carrier recombination simulation with CW excitation starting at T = 0
- SRH lifetime for FPA #1 is in this range
- PL Intensity vs. lifetime not linear, but clearly can identify differences in lifetime simply by imaging PL intensity
- Input intensity important:
  - High intensity: PL contrast only for short SRH lifetimes
  - Low intensity: No signal

Experiment: Overview

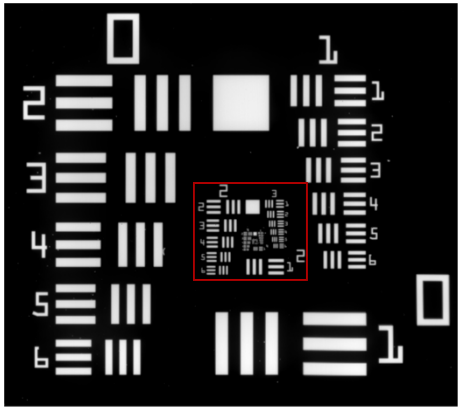


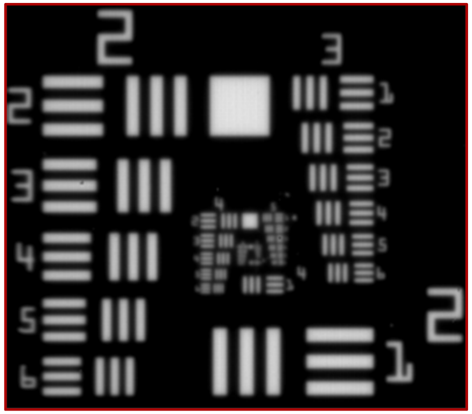
- Illuminate at angle: dark field measurement, filter unnecessary
- Optics + Camera on XYZ stage to image large samples

Experiment: Optics



- Re-imaging design: high cold stop efficiency (low vignetting), object-side telecentric
- Stitching: distortion, vienetting very obvious
- Resolution: element (4,5) = 25 lp/mm = .04 mm/lp, close f/4 limit





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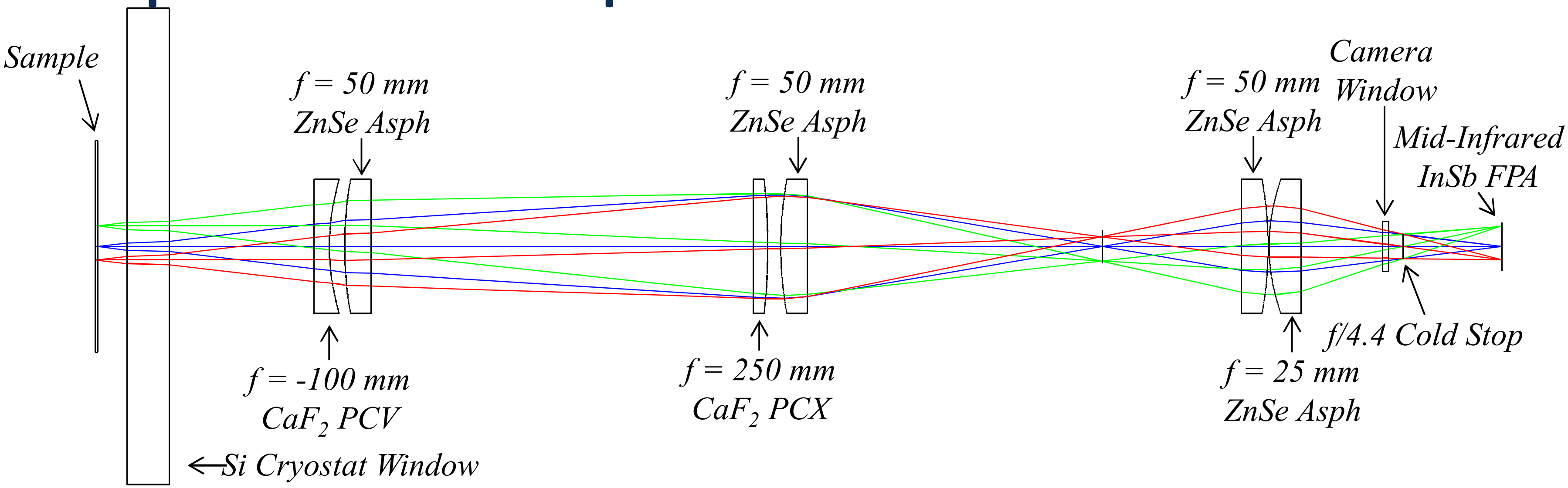

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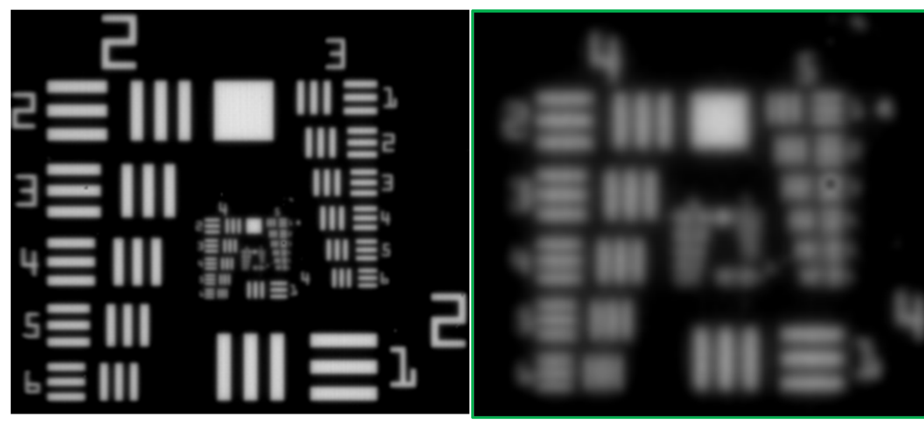
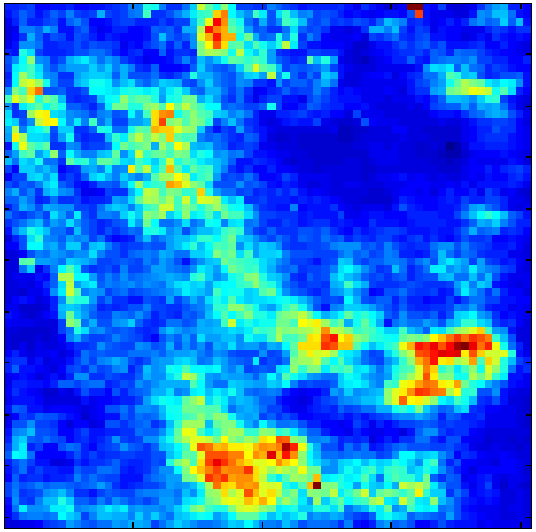
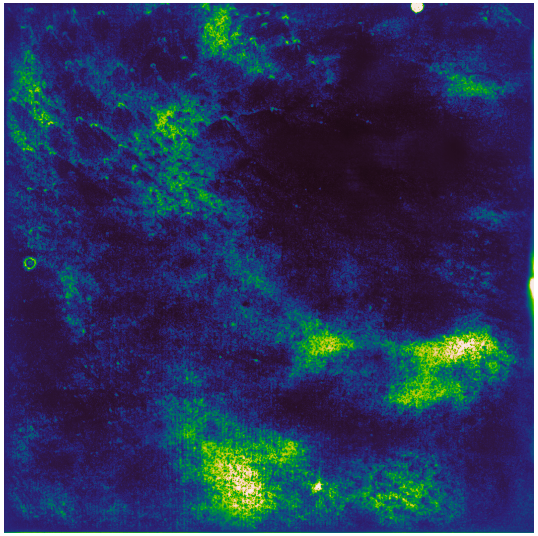


Results: PL, Dark Current, Response

Lifetime



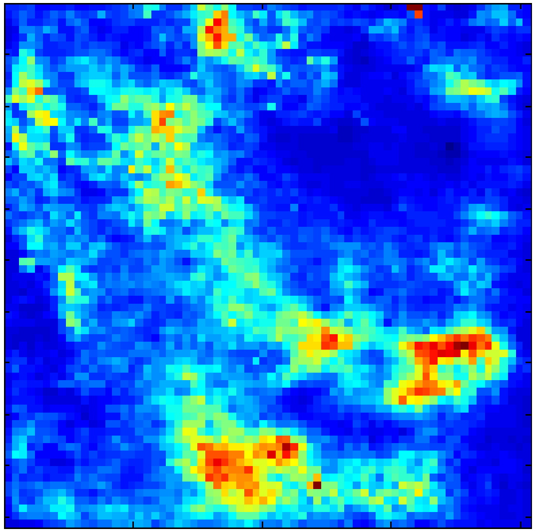
Intensity



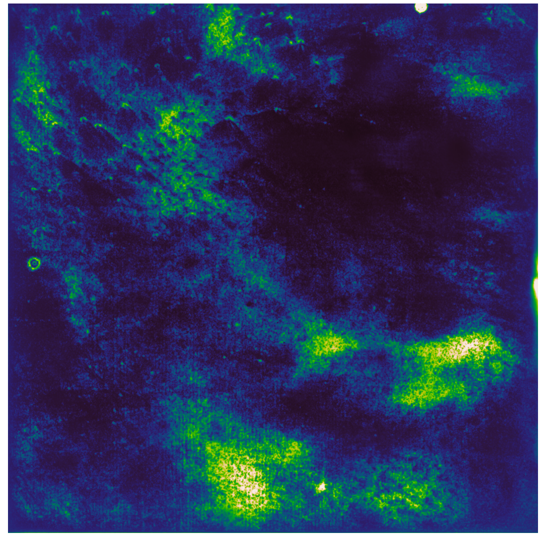
Bright areas = good: long lifetime, high PL intensity

Results: PL, Dark Current, Response

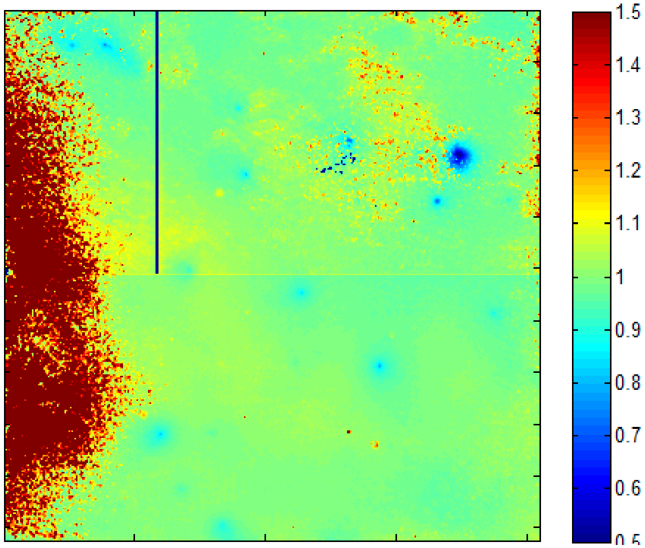
Lifetime



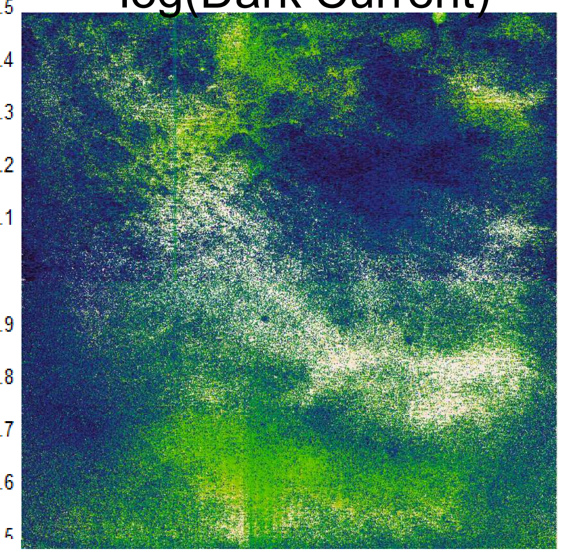
Intensity



Relative Response



-log(Dark Current)



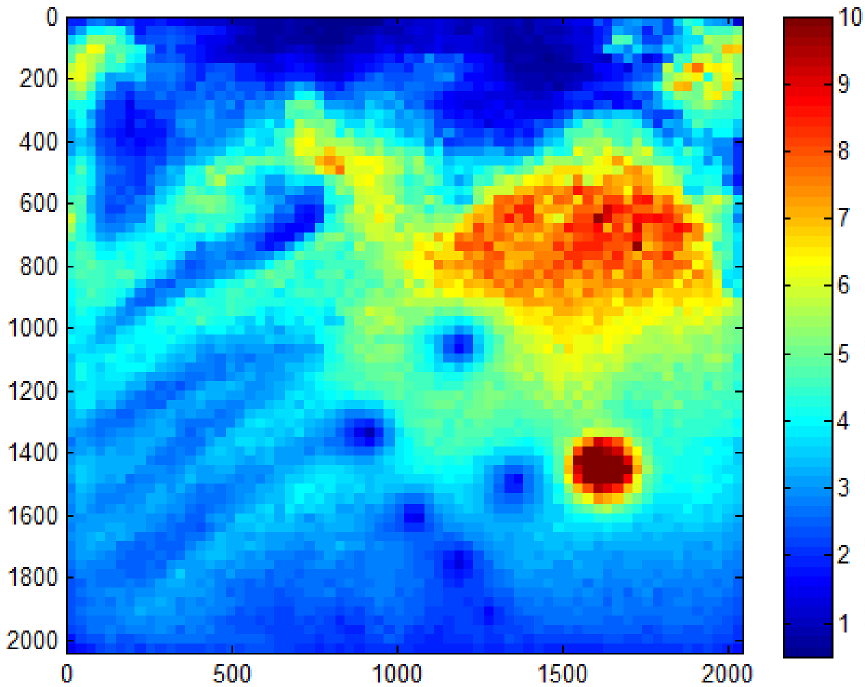
Bright areas = good: long lifetime, high PL intensity, low dark current ∴ low defect density

Dark current measured at 100K, PL at 110K

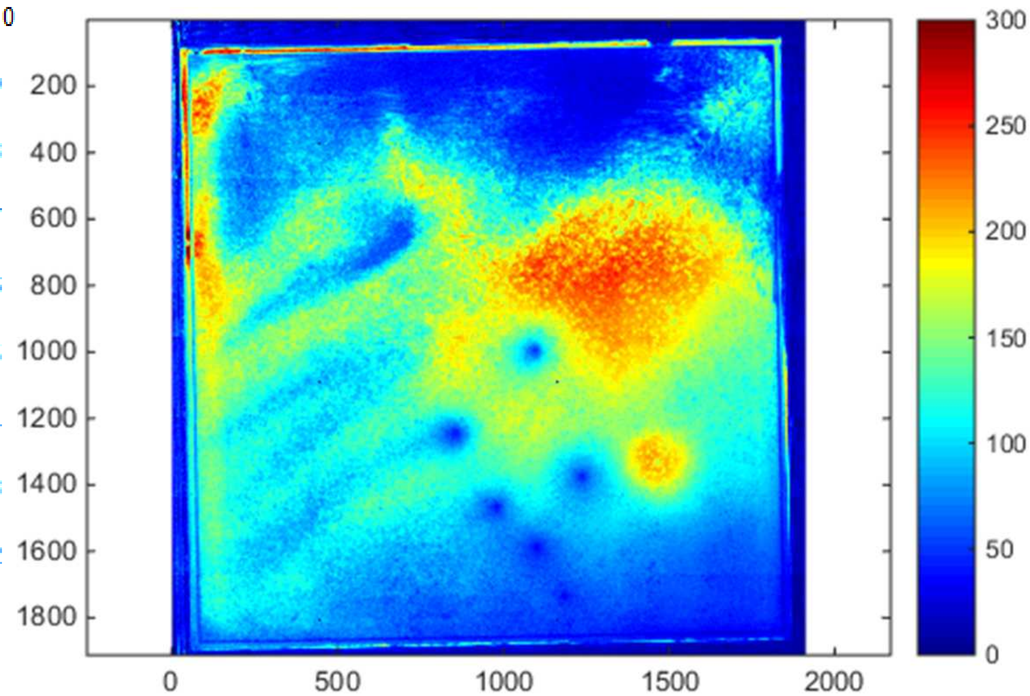
Note inverted scale on dark current!

Results: FPA #2

Lifetime (µs), 0.5mm spot
Point-By-Point Mapping



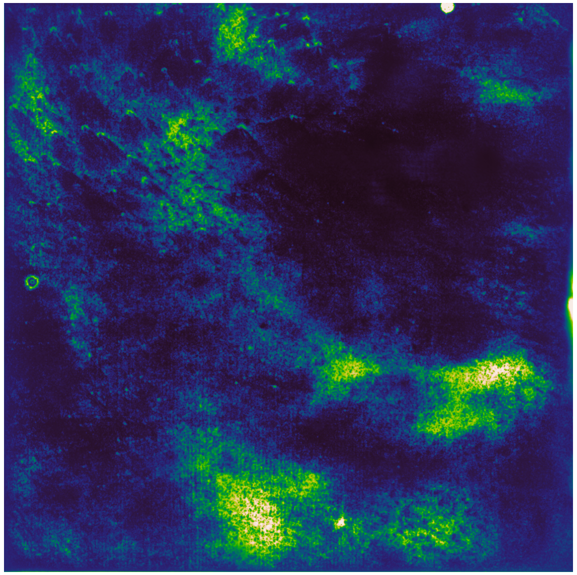
PL Intensity (a.u.)
CW Lamp Excitation, IR Camera



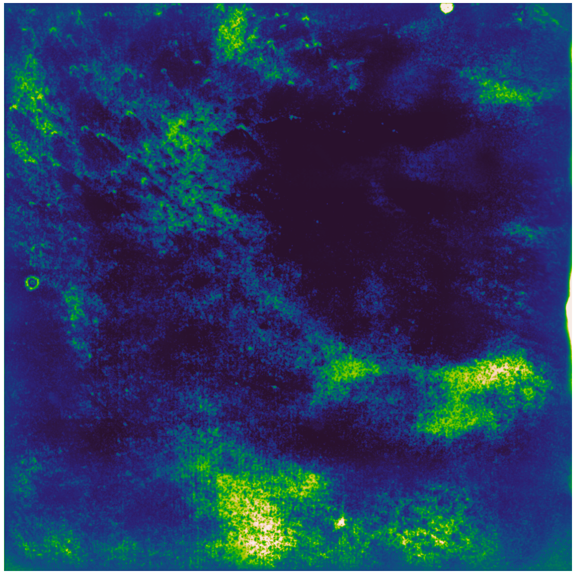
- Again see good correspondence between intensity and lifetime images

Temperature

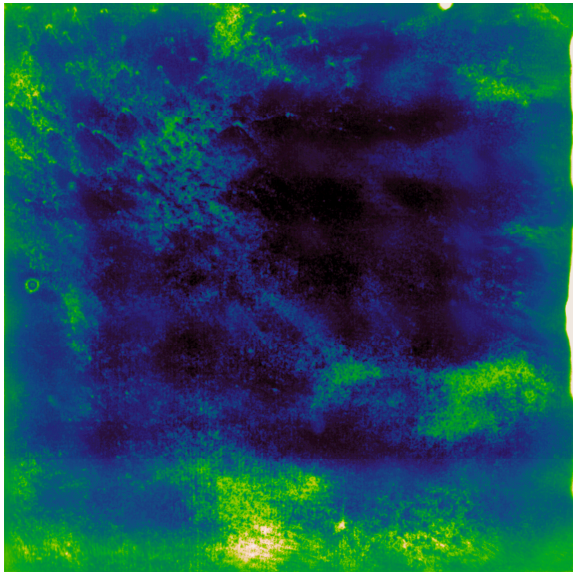
110 K



200 K



295 K

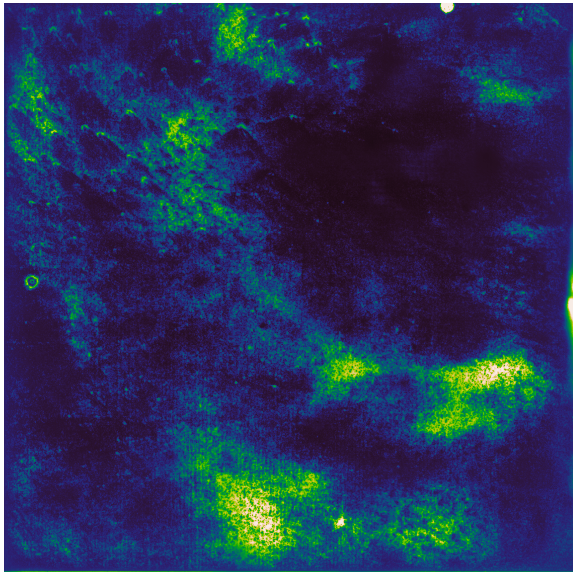


Most time consuming part of measurement is cooling!

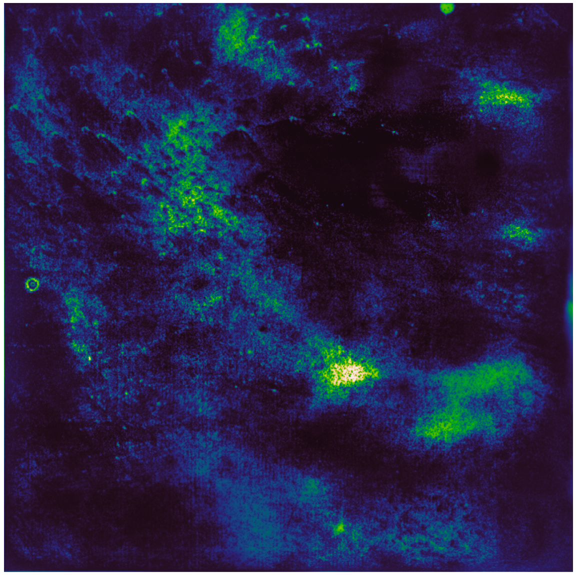
- 110 K: high vacuum pump-down + ~3 hours depending on safe cooling rate
- 200 K (-73 C): PL still very clear, potentially dry air or N_2 environment, easy to put optics in same environment which would reduce background
- 295 K: Increased background, still easy to identify good areas at RT!
  - PL Intensity ~ 4x lower than 110 K
  - Thermal self-emission from features near focus (e.g. top & bottom surface of detector, surrounding electronics), but not a problem if screening identical samples

Super-resolution

Mean of 10 Frames



Super-Resolution



- Collected 10 frames with 4.1 ms integration time for every image
- Camera closed-cycle cooler vibrates: ~1 px shift between frames when taking this set of images
- Left: averaged frames
- Right: Iterative coupled blind deconvolution and registration
- Only modest gains observed thus far

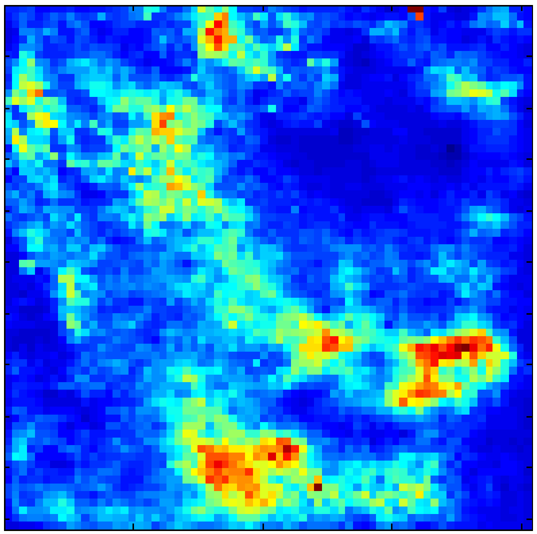
Conclusions

Demonstrated PL intensity can be used to rapidly screen semiconductor detectors for defects

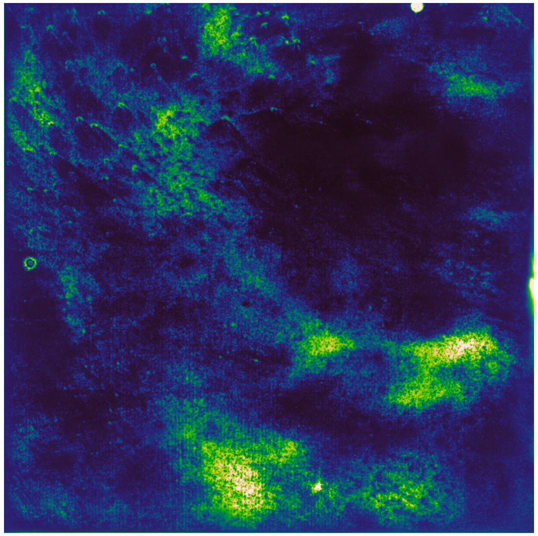
- Applicable at multiple stages in fabrication process from wafers to completed hybridized FPAs
- Measurement can be performed in moderate environments for rapid screening, or at the target operating temperature of the FPA
- Potentially allows for increasing fabrication yield: bin wafers after active layer growth, decide which sensors to hybridize, etc.
- Helps identify source of issues: differentiate between electrical issues and issues in active layer

Results: PL & Dark Current

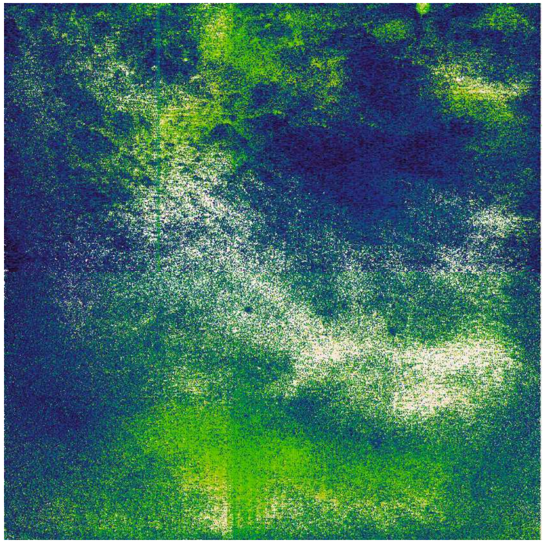
Lifetime



Intensity

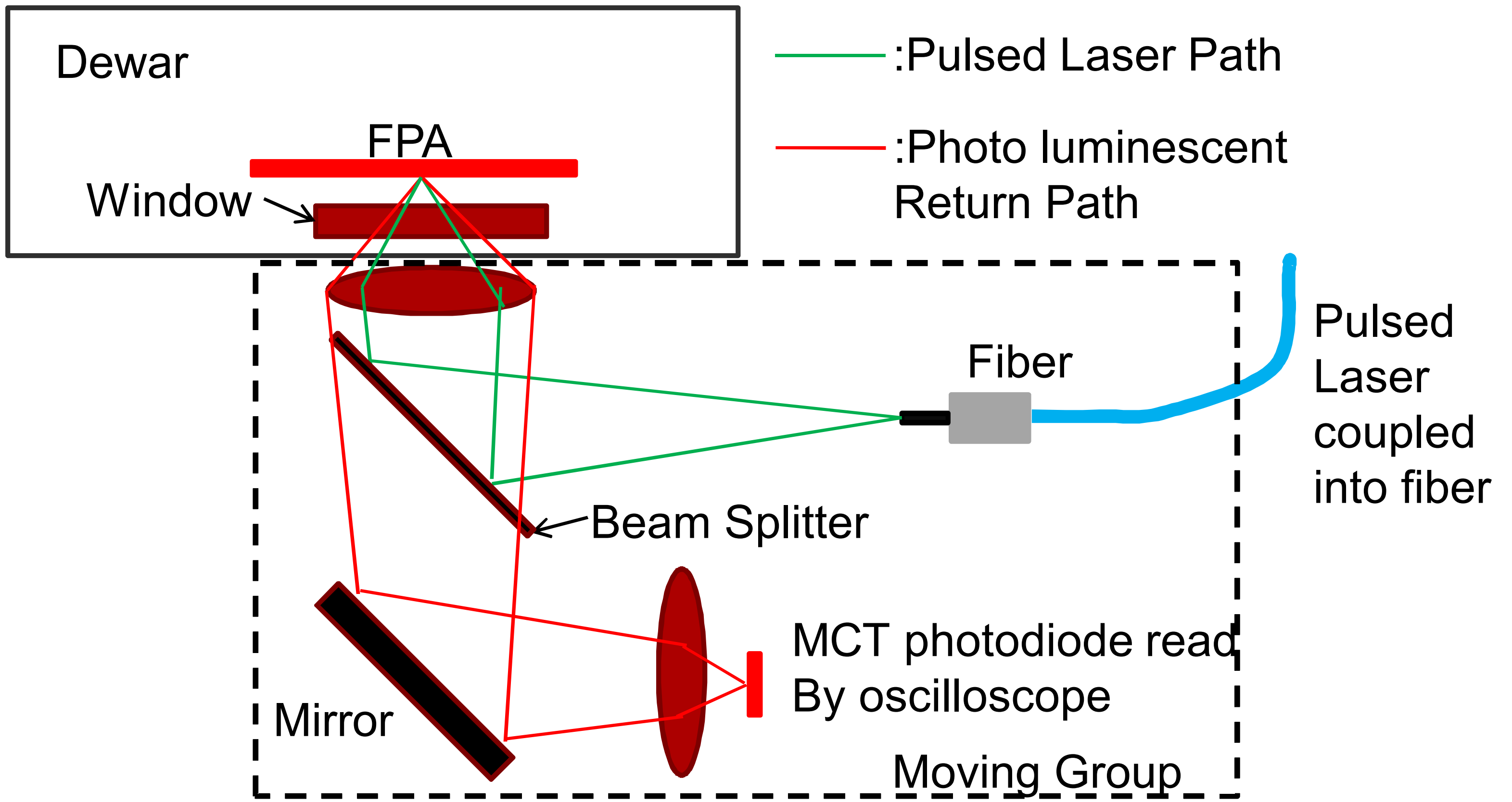


-log(Dark Current)
(bright = low!)

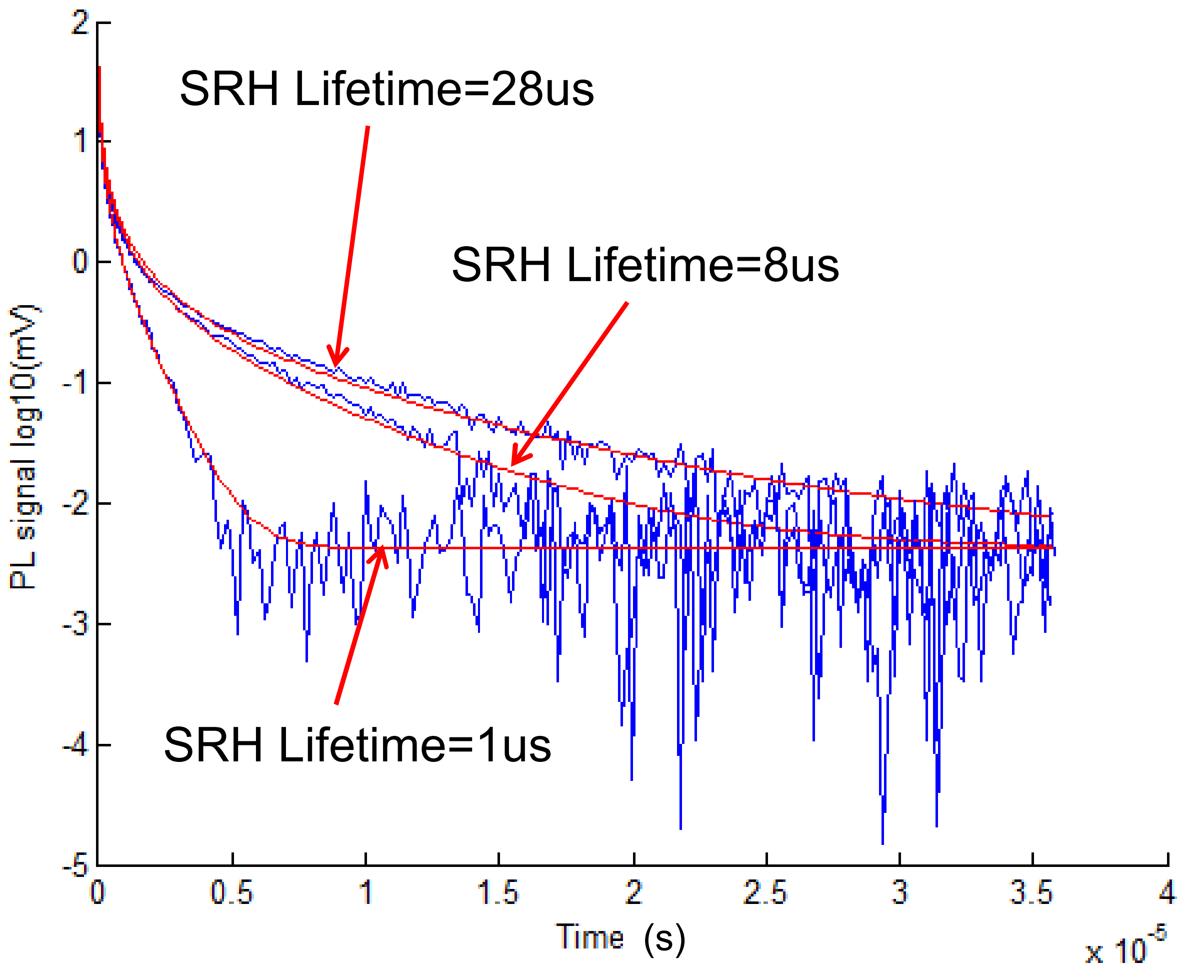


- Dark current measured at 100K, PL at 110K
- Bright areas = good: long lifetime, high PL intensity, low dark current
  ∴ low defect density
- *Note inverted scale on dark current!*

Time Resolved PL Experiment



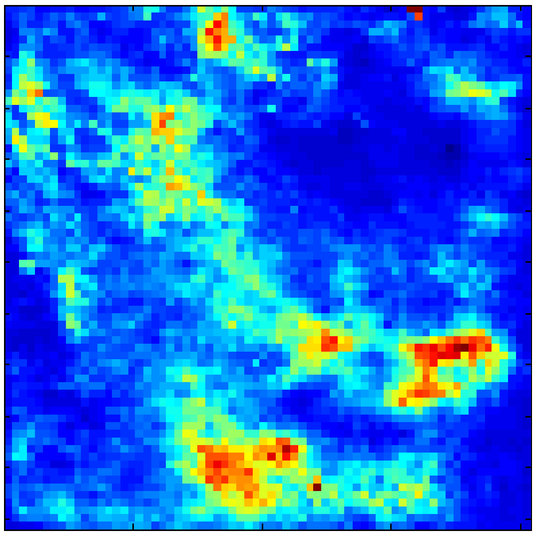
Time Resolved PL: Signal & Fit



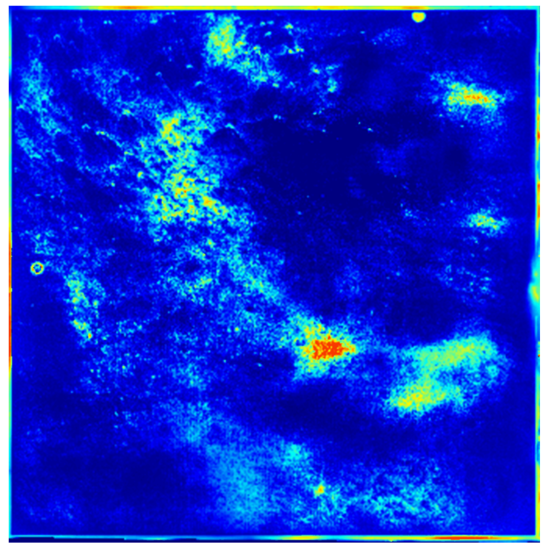
- The measurement is good enough to distinguish SRH lifetimes up to ~50us (beyond which the differences are below the noise floor)

BTB102 PL & Dark Current

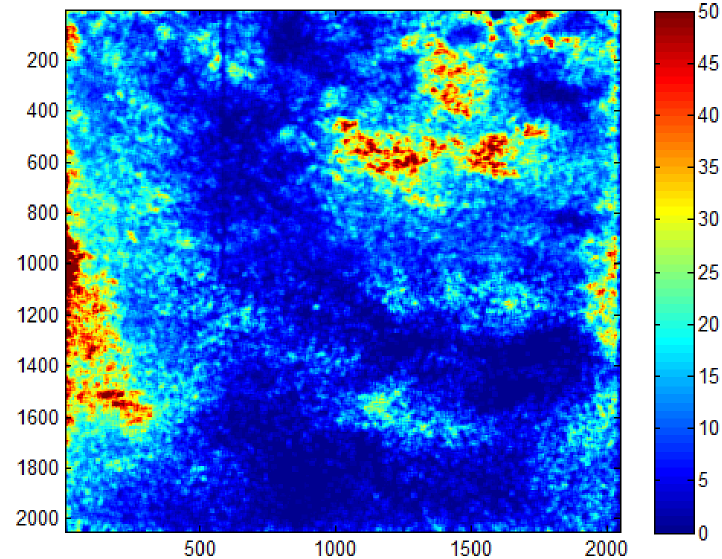
Lifetime



Intensity



Dark Current (μA/cm^2 @100K)



- Dark current measured at 100K, PL at 110K
- Dark areas in lifetime and intensity (high recombination rate) = poor areas of detector = bright areas in dark current