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MBE and Material Characteristics of T2SL for IR Photodetection

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- Michael Weimer: Texas A&M University
- Yong-Hang Zhang: University of Arizona

Government Labs

- AFRL, ARO, etc

Industry

Outline

Motivation/History of SLS on GaSb for IR Photodetection

- Need for size and performance scaling
- History and background

How Material Parameters Affect Photodetection

- Dark current and minority carrier lifetime
- Responsivity and diffusion length, absorptivity

Material Properties

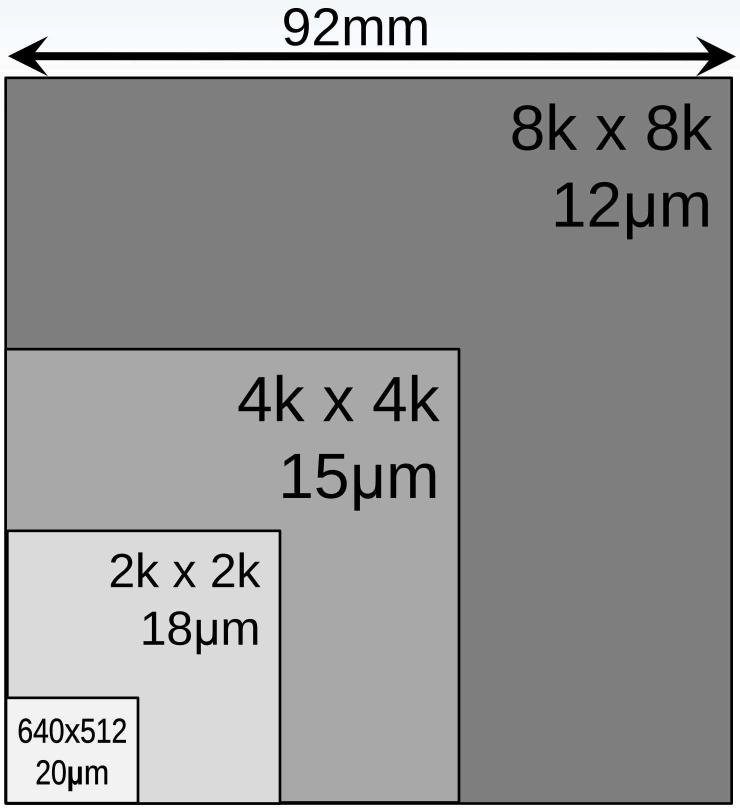
- InAs/GaSb SL, InAs/GaInSb SL
- InAs/InAsSb SL, InAsSb/InAsSb SL

Conclusion

Background / Motivation

Needs:

- Larger FPAs
- Better operability
- Higher sensitivity
- Higher operating T



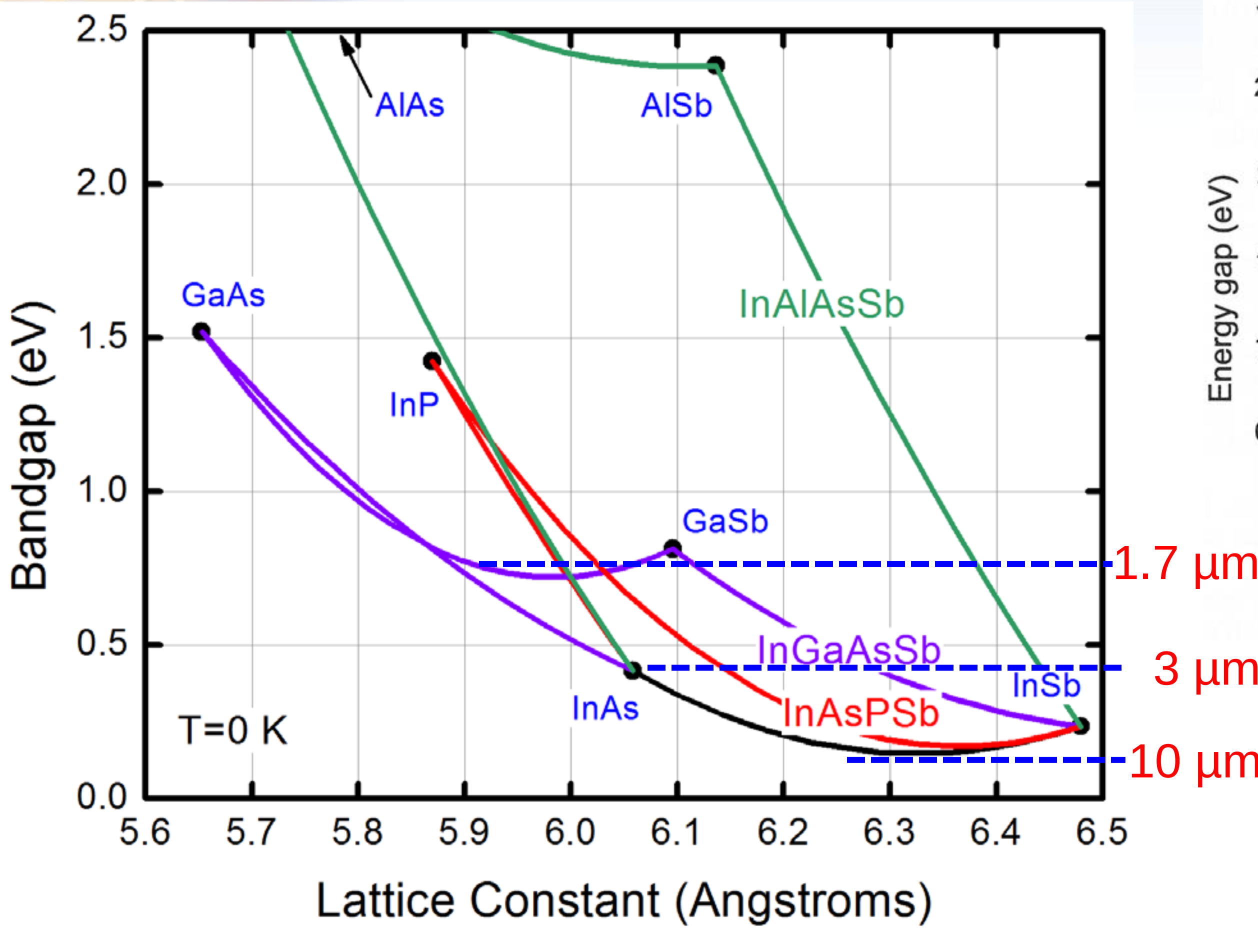
Problems:

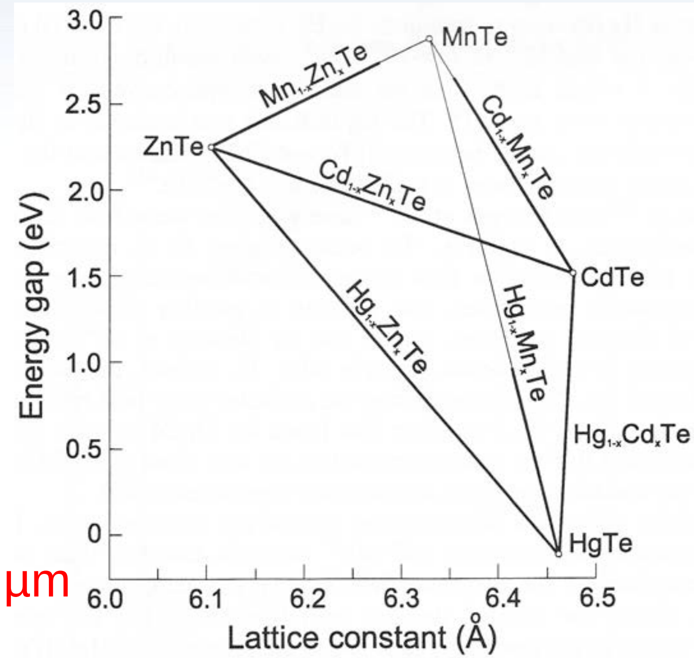
- MCT is hard to manufacture
    - Performance & cost penalty
- Substrates are limited in size and quality

Solutions:

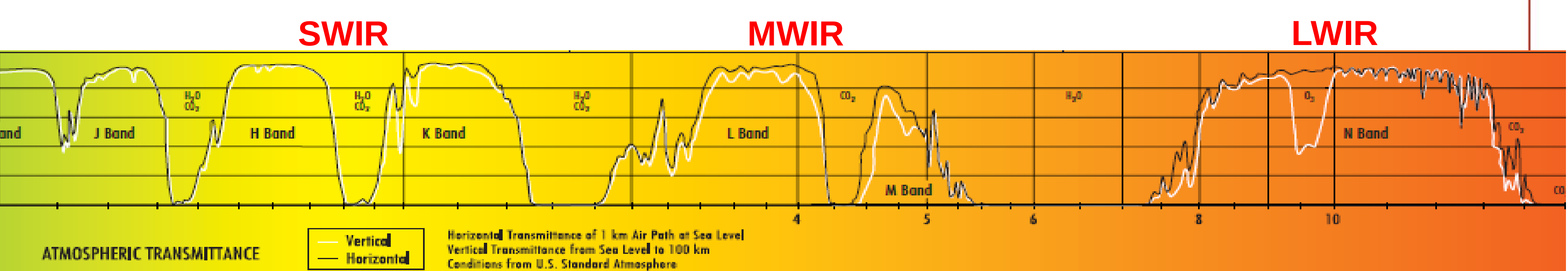
- III-V materials: higher pixel density, better uniformity, large (domestic) substrates
- T2SL: lower dark current, higher operating T

Absorber Material Choices



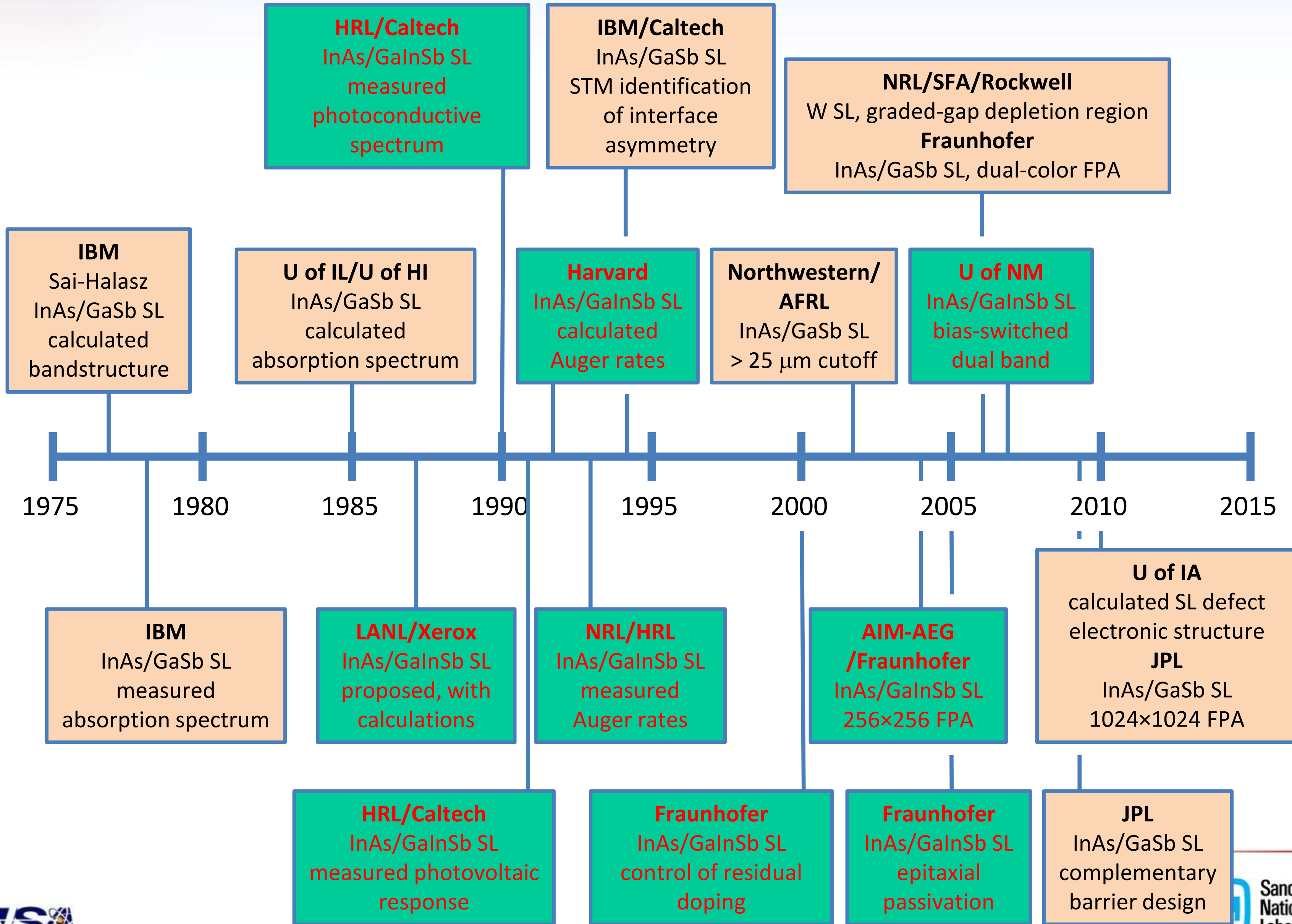


InAs/GaSb SL
InAs/GaInSb SL
InAs/InAsSb SL
InAsSb/InAsSb SL

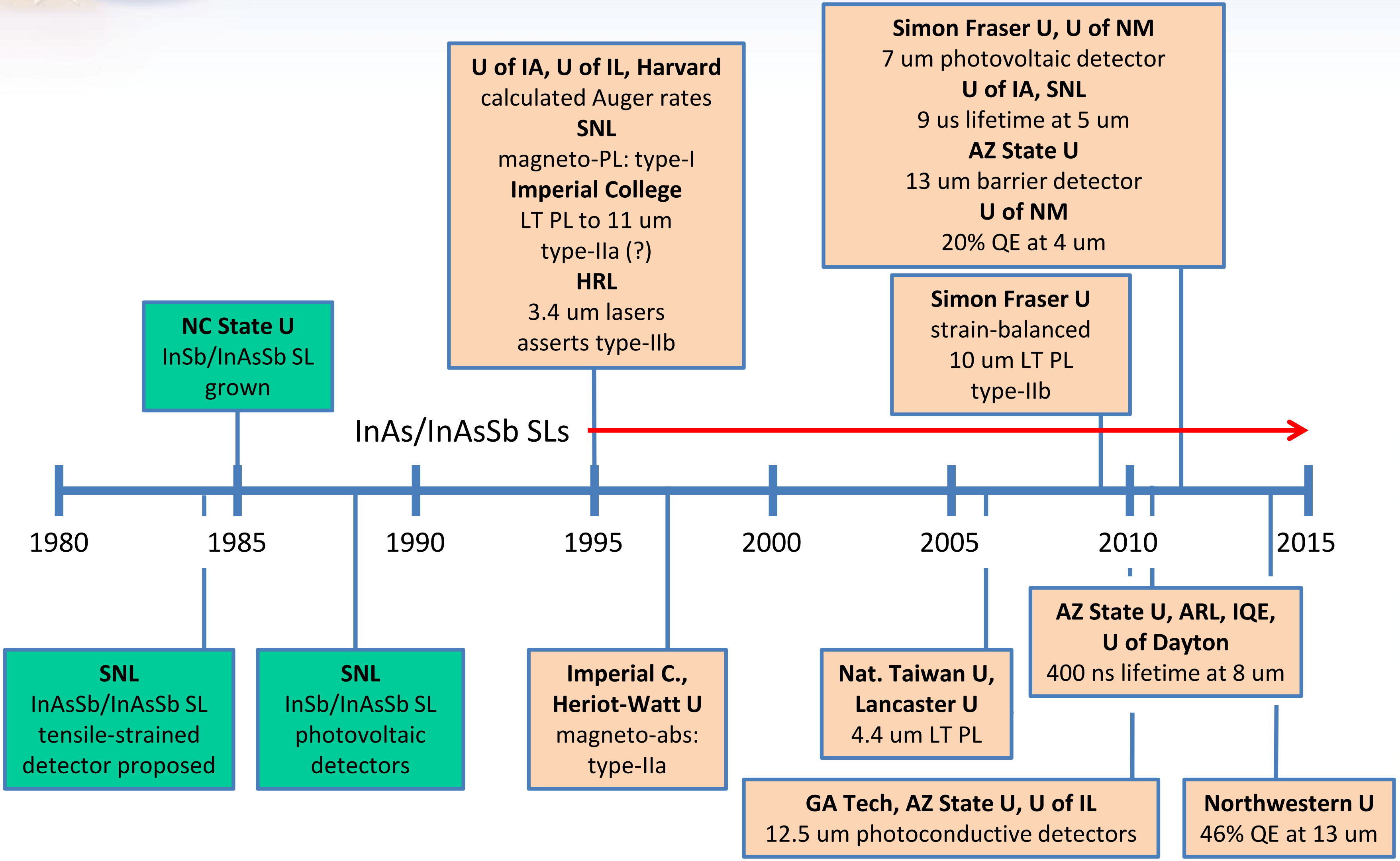


History of T2SL

Landmarks in the Development of InAs/Ga(In)Sb Type-II SL PDs



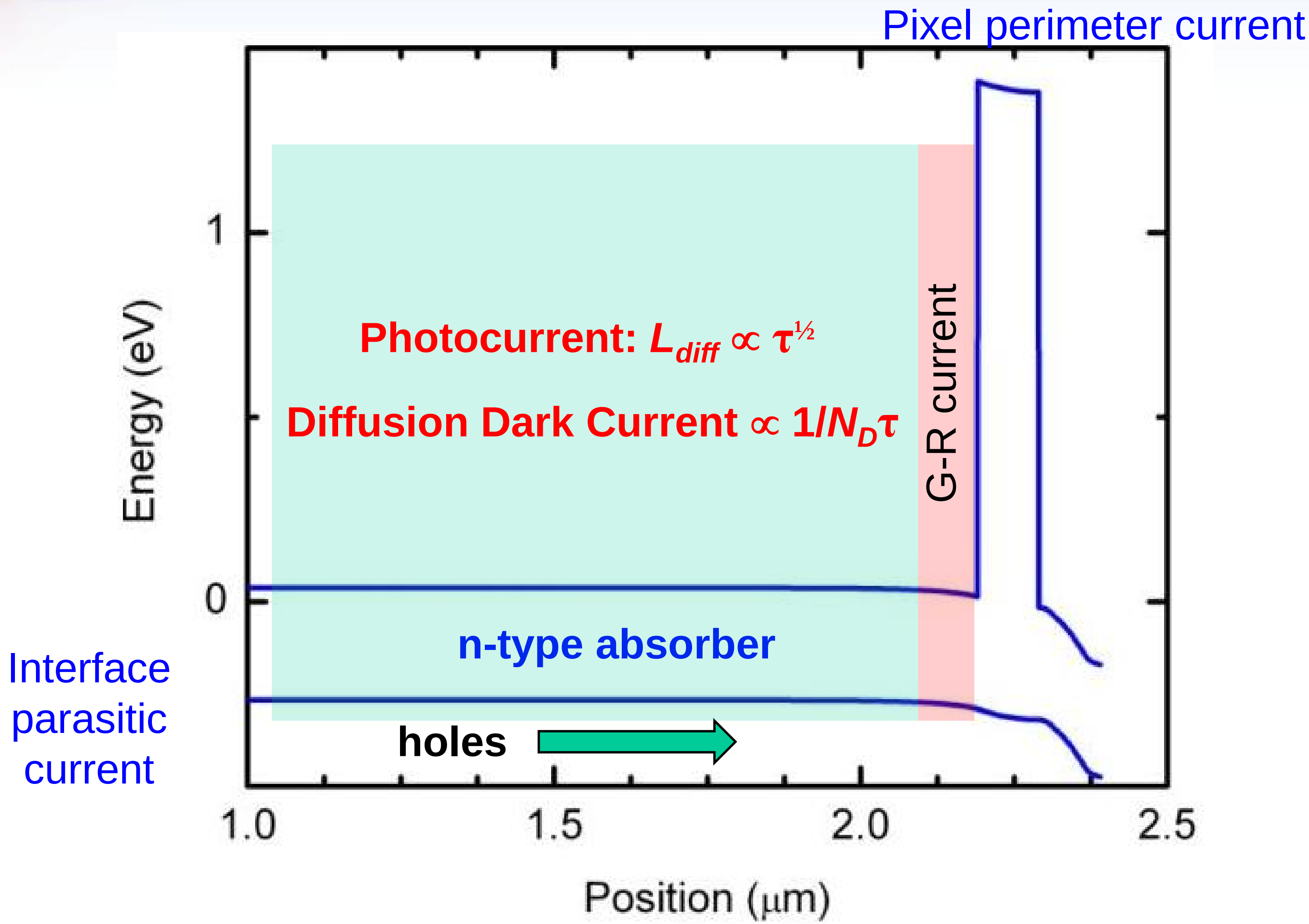
Development of In(As)(Sb)/InAsSb T2SL Detectors



How Material Parameters

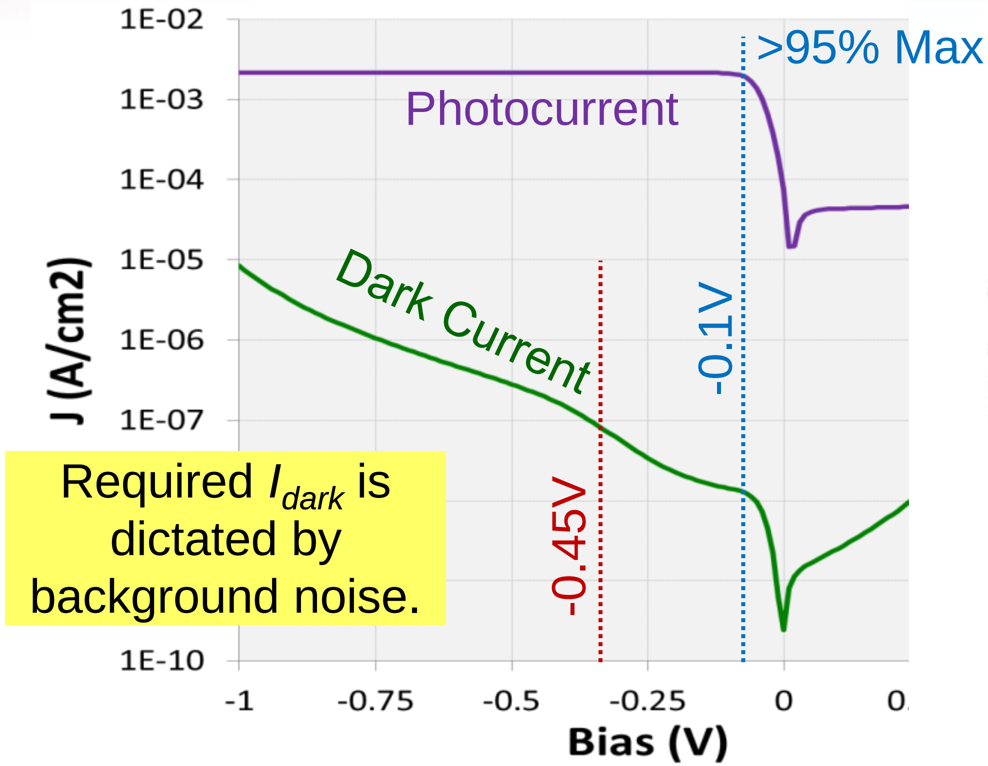
Affect Photodetection

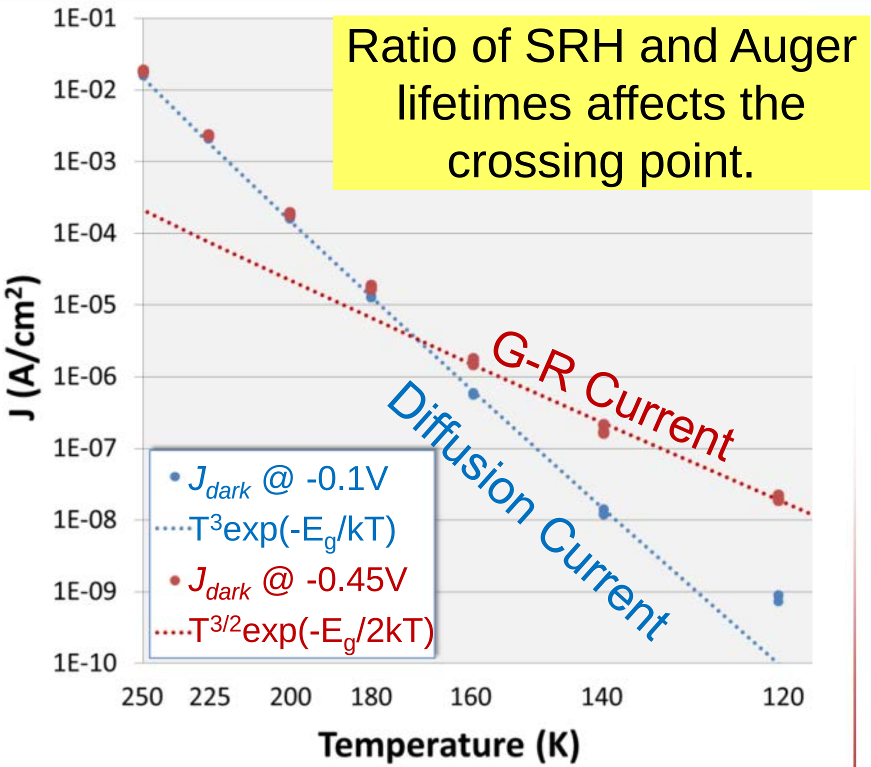
Dark Current Mechanisms



Long τ is key to all major performance parameters.

InAsSb Photodetector Dark Current Components





Diffusion Current ∝ $T^3 \exp(E_g/kT)$

$G_{SRH} = n_i^2 / (\tau_{p\_SRH}\, n)$

$G_{Rad} = 0$

$G_{Aug} = C_n n_i^2 n$

G-R Current ∝ $T^{3/2} \exp(E_g/2kT)$

$G_{SRH} = n_i / (\tau_{p\_SRH} + \tau_{n\_SRH})$

$G_{Rad} = 0$

$G_{Aug} = 0$

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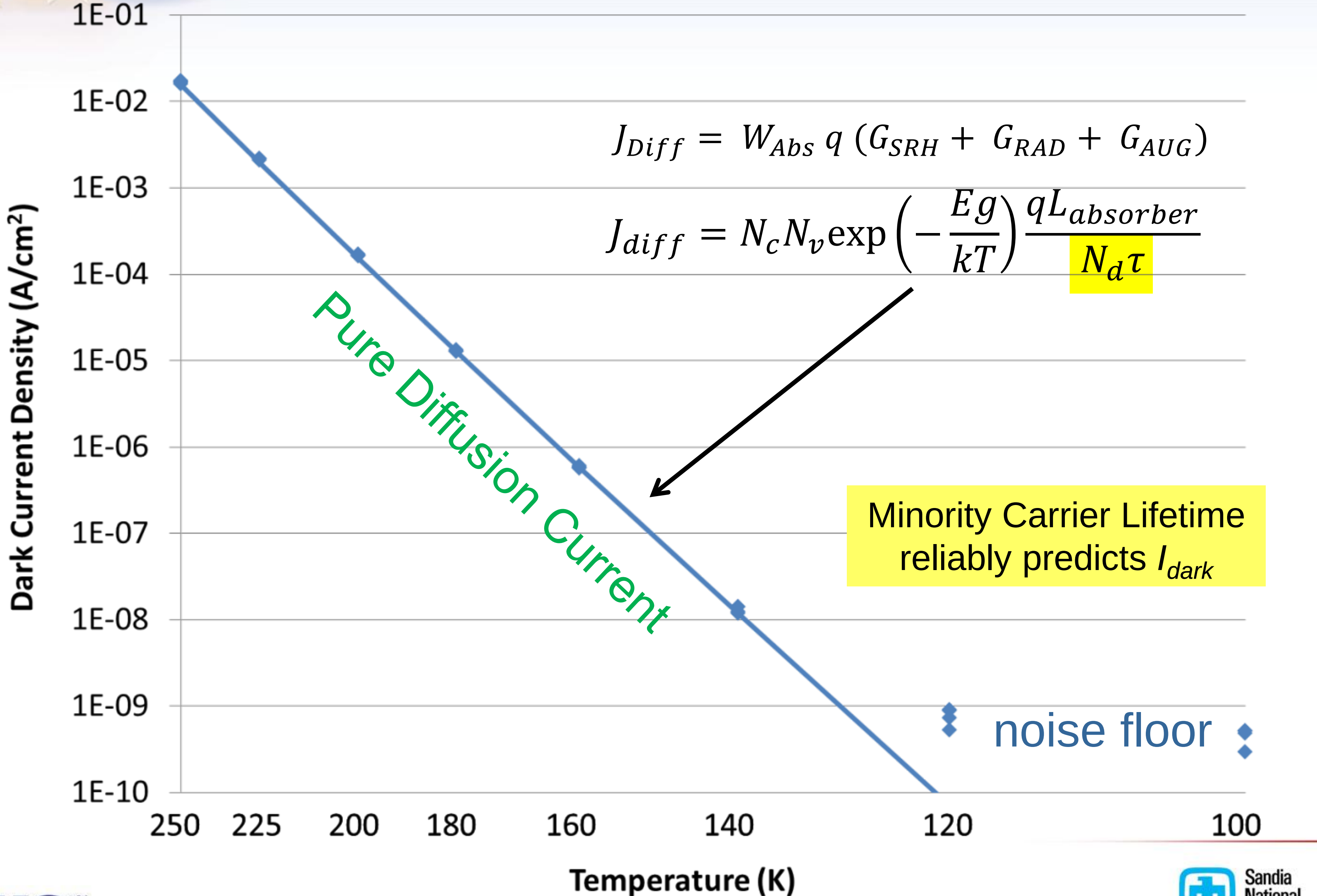
InAsSb PD Predicted and Measured Dark Currents



$$J_{Diff} = W_{Abs}\, q\, (G_{SRH} + G_{RAD} + G_{AUG})$$

$$J_{diff} = N_c N_v \exp\left(-\frac{Eg}{kT}\right) \frac{qL_{absorber}}{N_d \tau}$$

Minority Carrier Lifetime reliably predicts I_{dark}

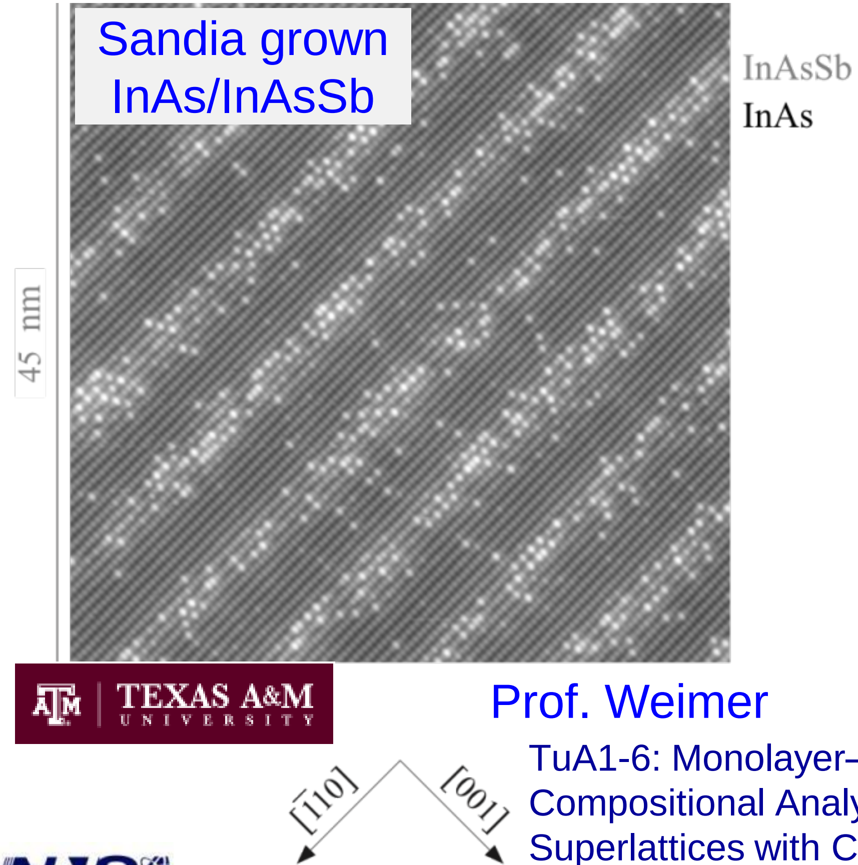
Other Material Parameters of Interest in Photodetectors

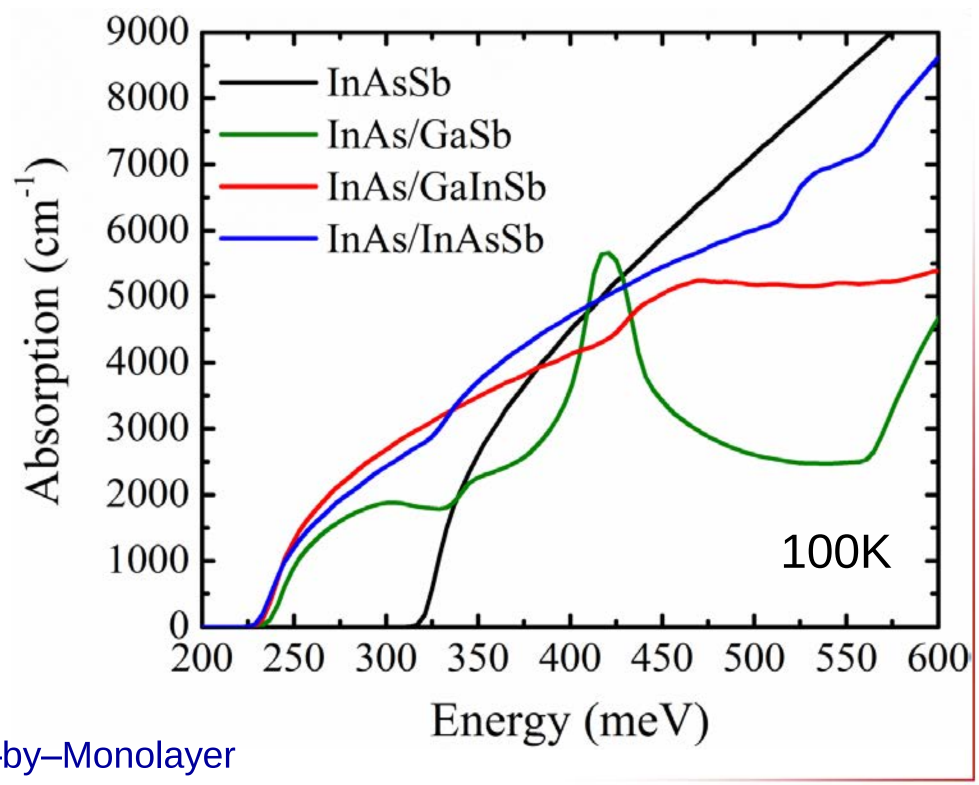
- Minority carrier lifetime: dark current
- Minority carrier diffusion length: QE
- Absorptivity: spectral response

} sensitivity (NEI, NEdT), operating T

- Diffusivity asymmetry: pixel crosstalk (MTF)

Sandia grown InAs/InAsSb





TEXAS A&M UNIVERSITY

Prof. Weimer

TuA1-6: Monolayer–by–Monolayer Compositional Analysis of InAs / InAsSb Superlattices with Cross–Sectional STM

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Material Properties

Characteristics of InAs/GaSb Superlattices

Superlattices initially proposed by Sai-Halasz, Tsu, and Esaki: Appl. Phys. Lett. 30, 651 (1977)

Features and comparisons

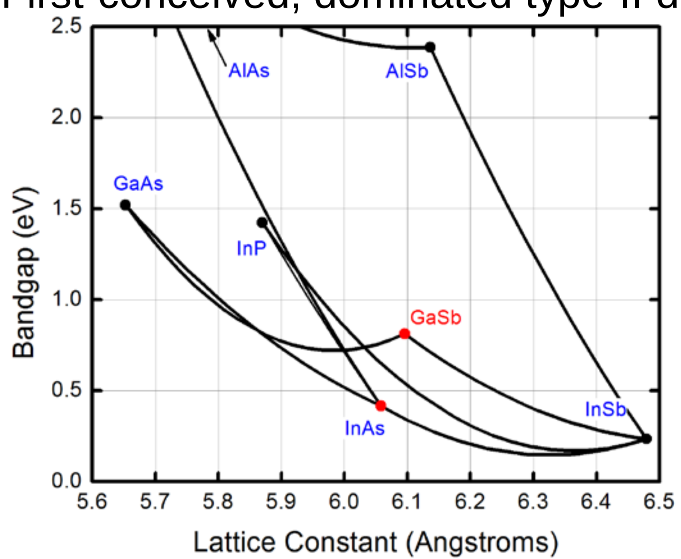
- Common to all 6.1Å type-II superlattice family:
    - Binary (GaSb) substrates with good commercial availability
    - Electron effective mass > HgCdTe, should reduce tunneling current
    - Surface passivation problematic
- Broken-gap type-II alignment allows arbitrarily long cutoff wavelength
- Notionally simple binary-binary materials
- Lattice matching achieved by control of interface bonding (GaAs/InSb)

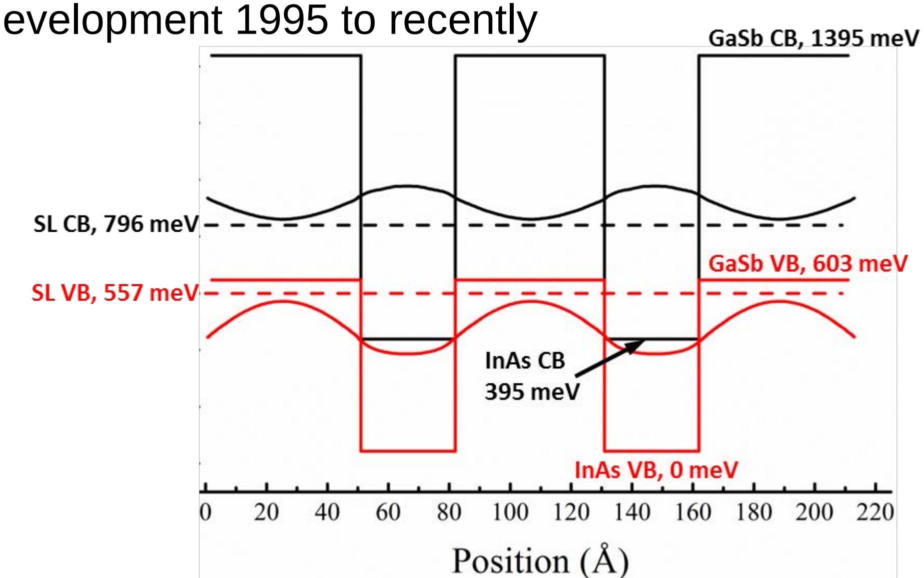
Limitations

- No common anions/cations in constituent layers
    - Characteristics significantly affected by interface nonidealities
- Short SRH lifetimes (~ 100 ns or less) observed

Adoption

- First-conceived; dominated type-II development 1995 to recently





Characteristics of $InAs/Ga_{1-x}In_xSb$ Superlattices

Initially proposed for IR detectors by Smith and Mailhot, J. Appl. Phys. 62, 2545 (1987)

Features and comparisons

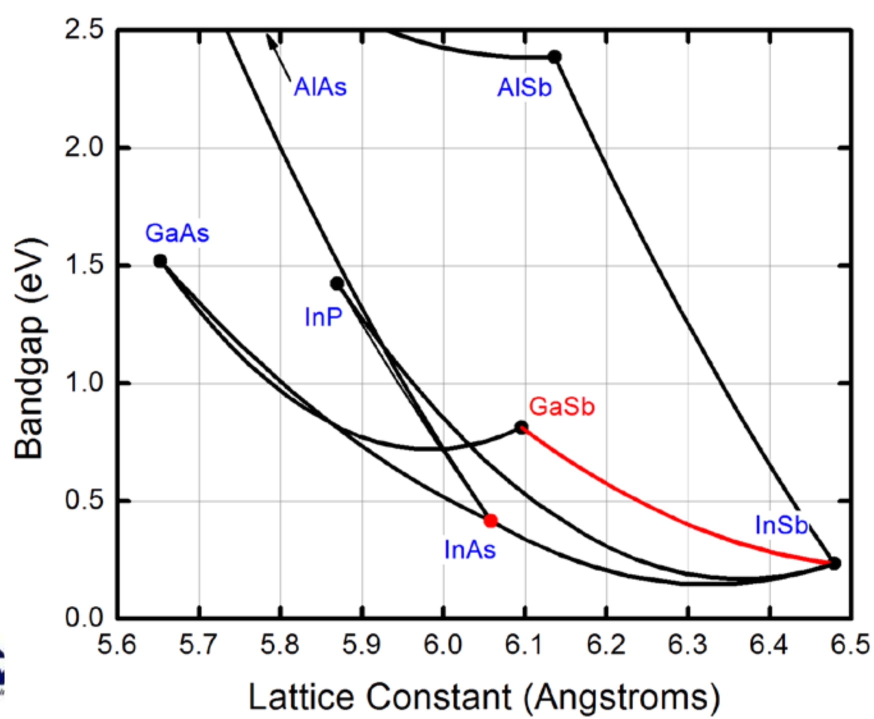
- Adding In to GaSb reduces bandgap, allowing use of thinner SL layers than InAs/GaSb
- Thinner layers increase electron/hole overlap and absorption
  - Absorption coefficient similar to HgCdTe near threshold
- Calculated Auger-7 lifetimes >> HgCdTe

Limitations

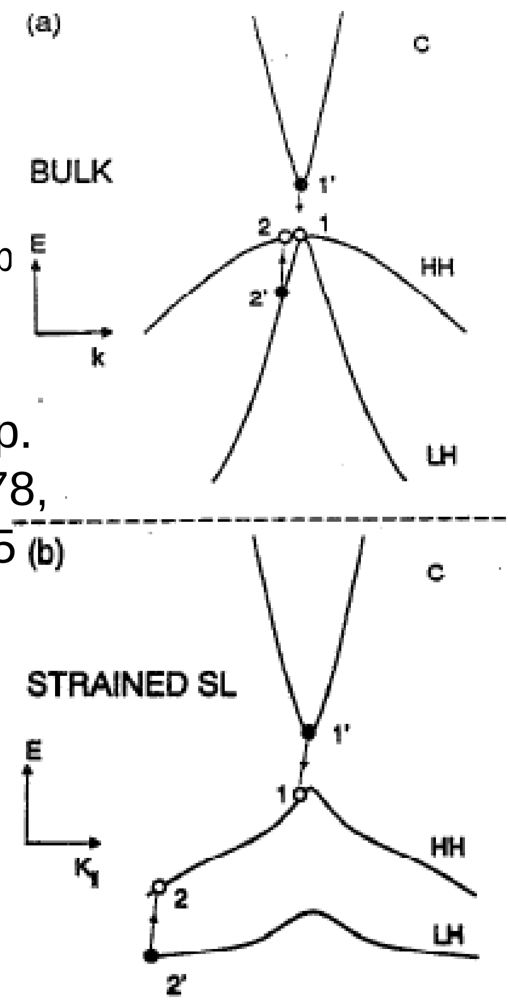
- Indium content is constrained by lattice matching to GaSb
- Short SRH lifetimes observed

Adoption

- Intensively studied ~1990-2005, largely given way to InAs/GaSb



Grein: J. App. Phys., Vol. 78, No. 12, 1995



Characteristics of Sb-Rich InAsSb/InAsSb Superlattices

Proposed to take advantage of small bandgap of InAsSb: Osbourn, J. Vac. Sci. Technol. B 2, 176 (1984)

- InAsSb has smallest bandgap of conventional III-V ternaries
- Tensile strain used to further reduce bandgap

Features and comparisons

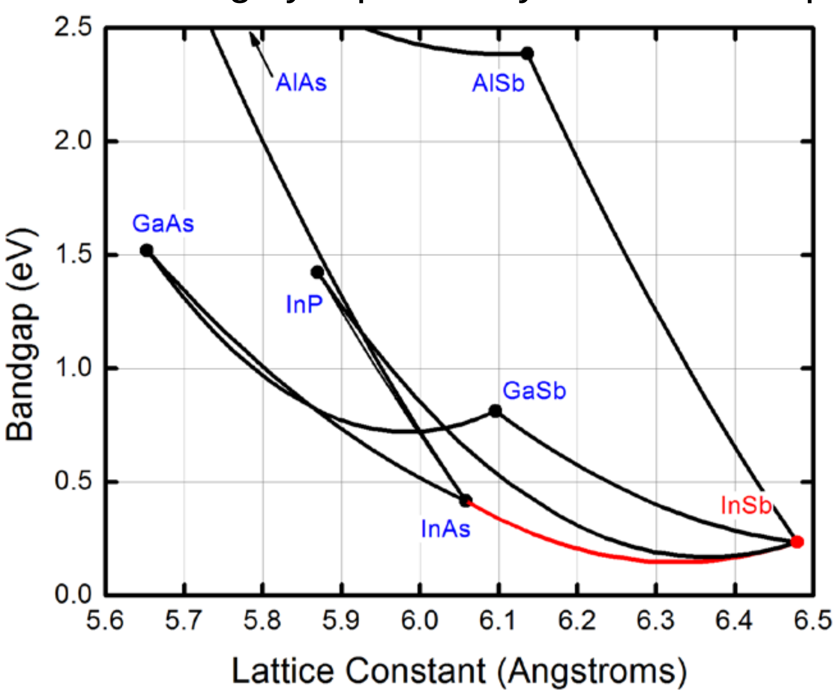
- InAsSb with ~60% Sb content chosen for lowest possible bandgap
- Composition-insensitive bandgap

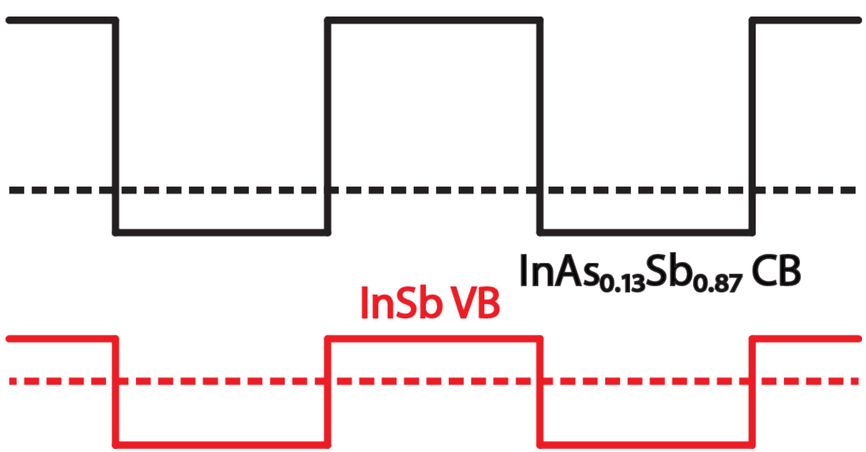
Limitations

- Typically lattice-mismatched to available substrates
- InSb-based incarnations (tensile) suffered from microcracking

Adoption

- Largely replaced by SLs with compressively-strained InAsSb by mid-1990s





Kurtz, Proc. IEDM, 1988

Characteristics of InAs/InAsSb Superlattices

Type-II design initially demonstrated for laser active regions: Zhang, Appl. Phys. Lett. 66, 118 (1995)

Features and comparisons

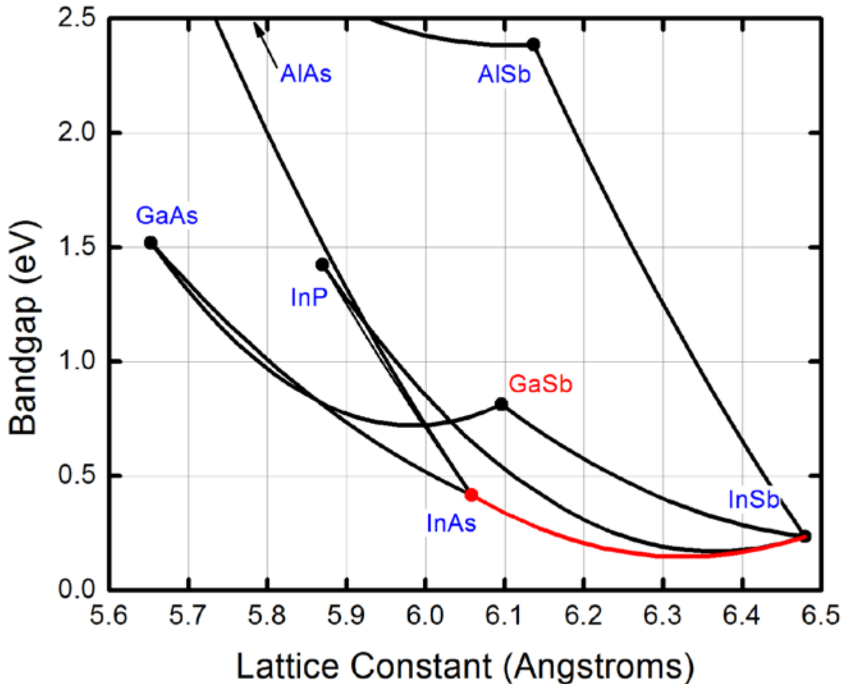
- May be strain-balanced for growth on GaSb substrates
- Relatively simple growth
- Long SRH lifetimes
- Larger Auger coefficient (shorter Auger lifetime) than InAs/GaInSb

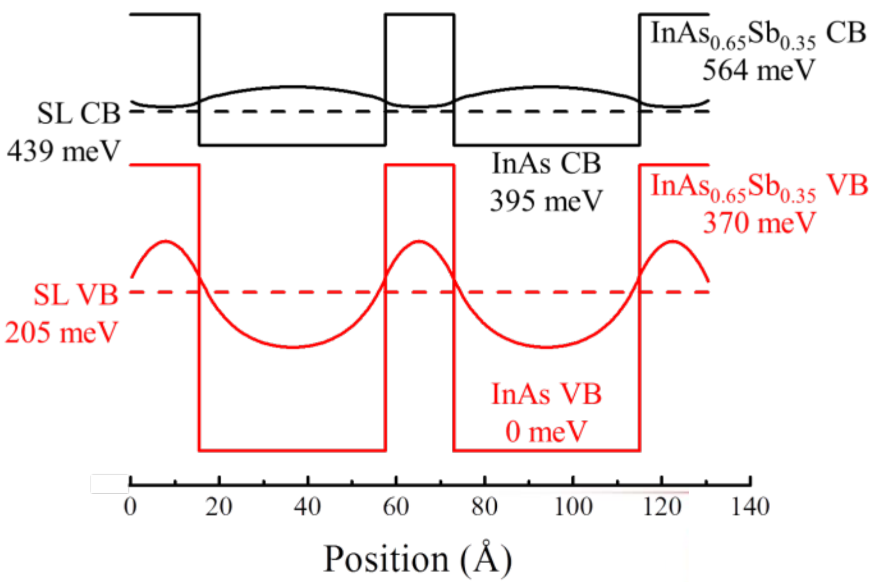
Limitations

- High Sb content (and strain) required for long-wavelength designs
- Relatively small absorption coefficient

Adoption

- Eclipsed by InAs/(GaIn)Sb work in 1990s; recently rediscovered and rapidly advancing





SLS Comparison

- Doping density affects minority carrier generation rates

	Carrier Density (cm^{-3})	SRH Lifetime (μs)	Rad Lifetime (μs)	Auger Lifetime (μs)	Rad Coeff (cm^3/s)	Auger Coeff (cm^6/s)
InAs/ GaSb	5×10^{15}	0.1	0.57	400	3.5×10^{-10}	1×10^{-28}
InAs/ InAsSb	4×10^{14}	14	17.9	390	1.4×10^{-10}	1.6×10^{-26}
InAsSb	1×10^{15}	16	7.1	100	1.4×10^{-10}	1.0×10^{-26}
HgCdTe	1.5×10^{15}	> 100	31.8	18	2.1×10^{-11}	$2\text{-}3 \times 10^{-26}$

Measurements

T2SL&InAsSb data from B. V. Olson et al., Appl. Phys. Lett. 103, 052106 (2013)
HgCdTe data from W.E. Tennant, *Prog. In Quant. Electron.* 36, 273-292 (2012)

- Auger lifetime of InAs/GaSb SL would be 63 ms if doping could be reduced to 4×10^{14} cm^{-3}.
- Auger lifetime of HgCdTe could be increased by reducing doping.

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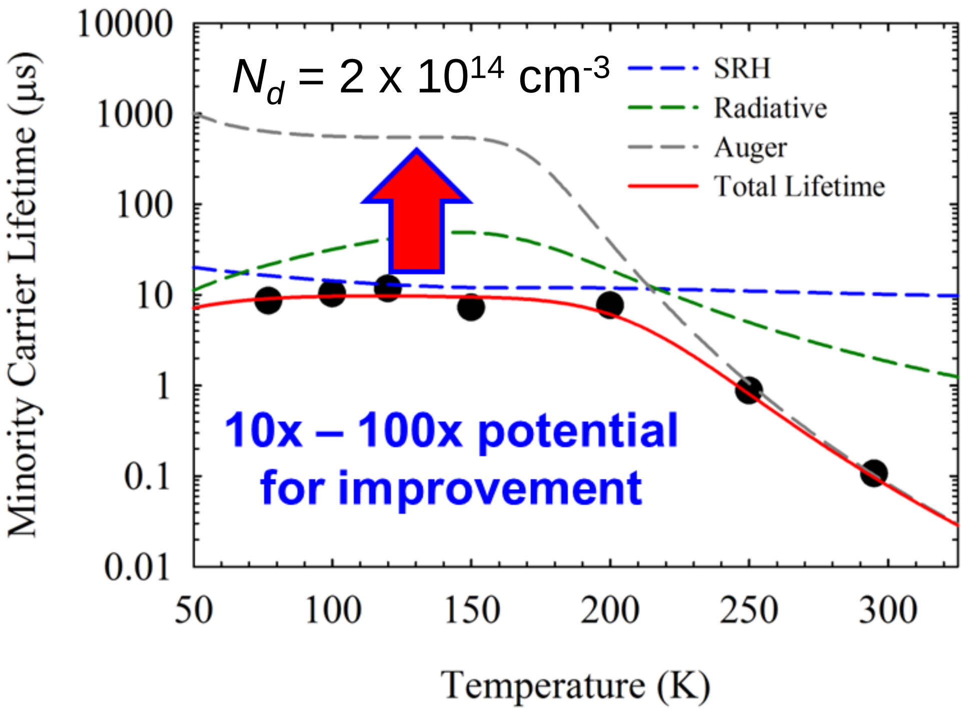
InAs/InAsSb SL Properties

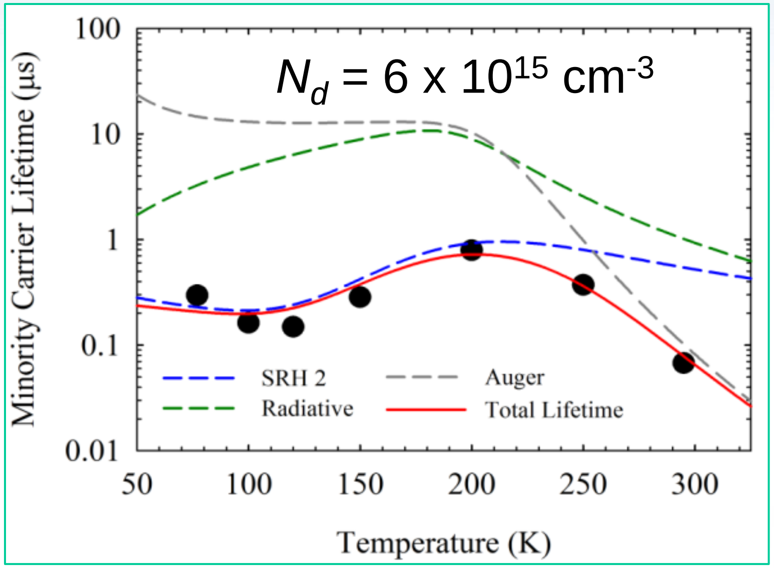
T2SL Minority Carrier Lifetime

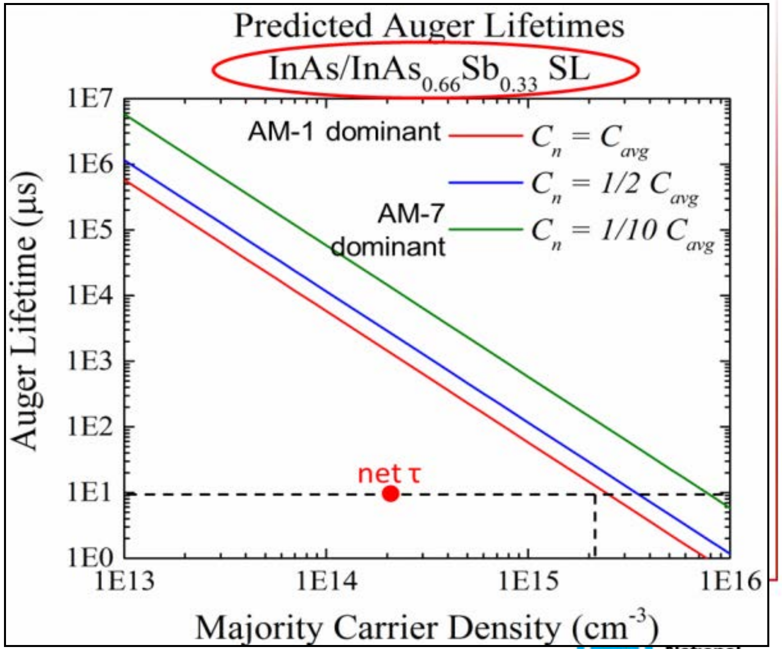
T2SL carrier lifetime: 10μs, 100K-200K

Limited by SRH (defects)

$N_D\tau$ ~ constant w/ doping





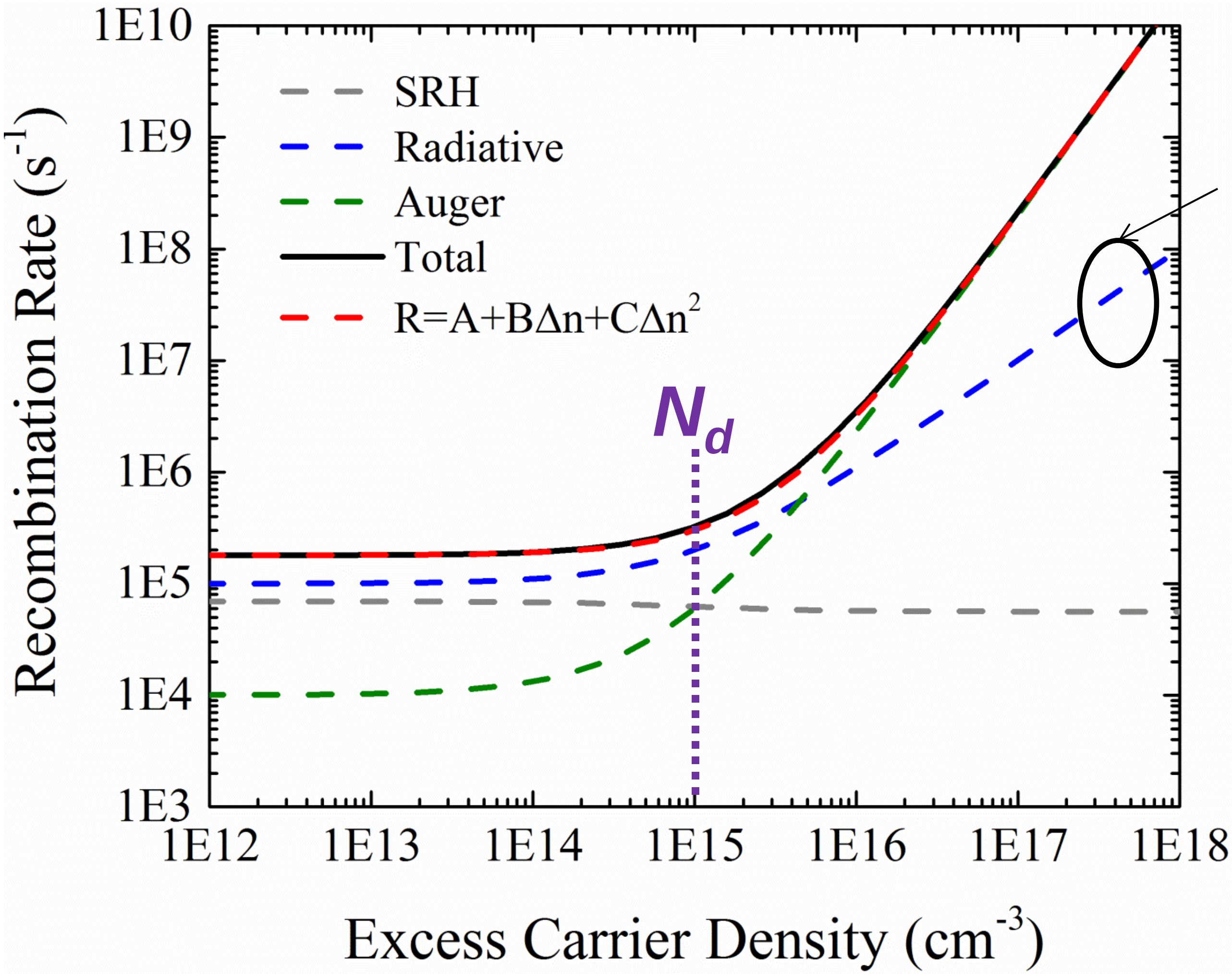


Olson et al., Appl. Phys. Lett. 103, 052106 (2013)

Experimentally Resolving Recombination Processes

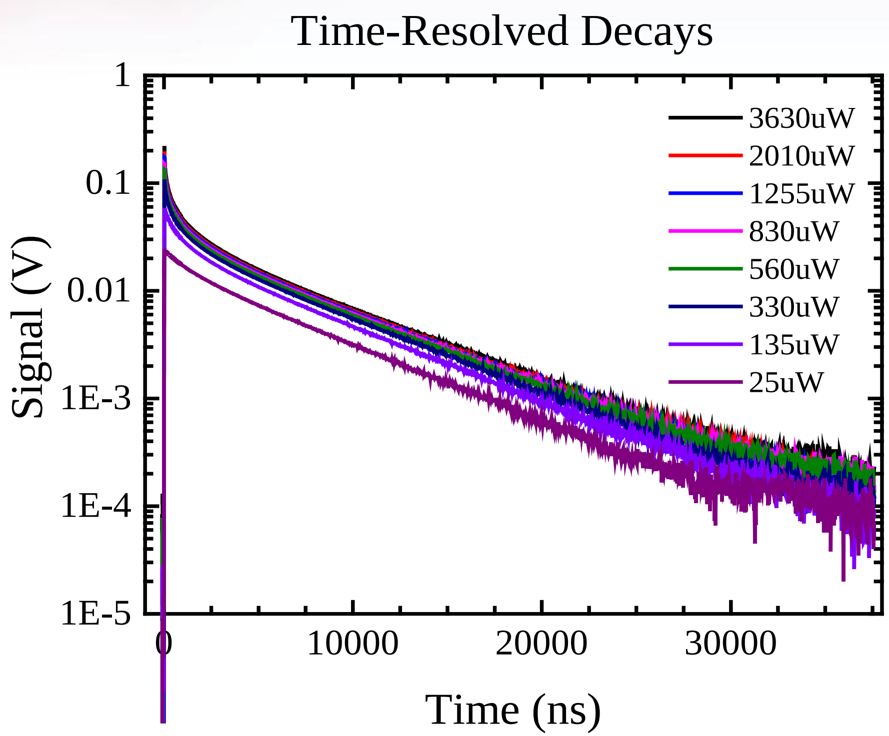
J. Blakemore, *Semiconductor Statistics* (1962)

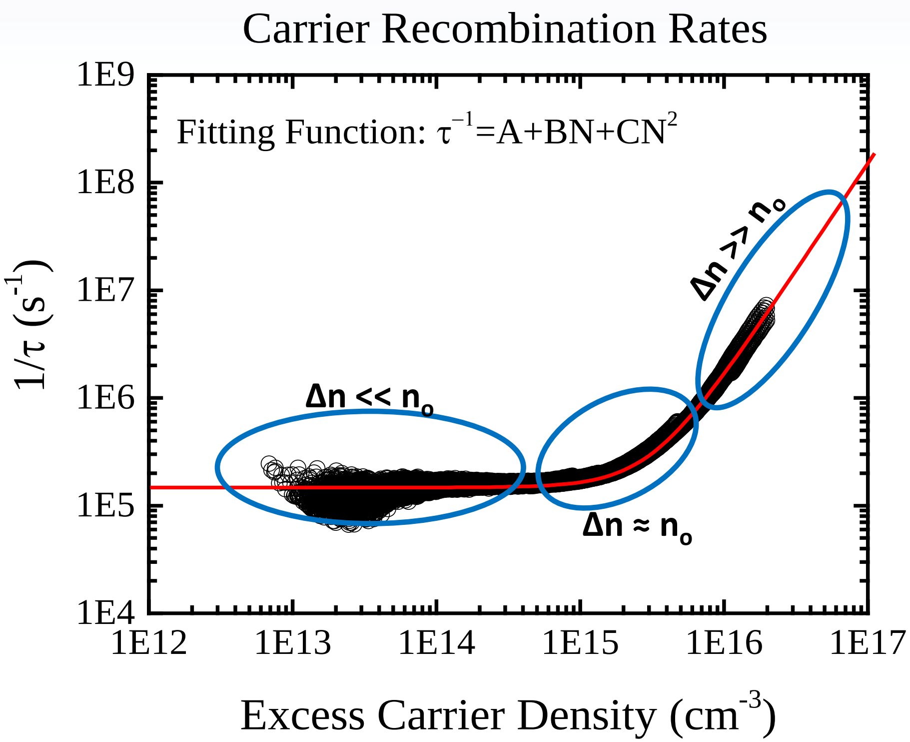
$$-\frac{\partial \Delta n}{\partial t} = \Delta n \times R = \frac{np - n_o p_o}{\tau_{no}(p + p_1) + \tau_{po}(n + n_1)} + [\varphi_{PR} B_r (np - n_o p_o)] + [C_n(np - n_o p_o)n + C_p(np - n_o p_o)p]$$



Includes photon recycling

Experimentally Resolving Recombination Processes





Carrier Density Probe Techniques

Photoluminescence
Pump-Probe
Microwave reflectance

Lifetimes Resolving Techniques

Time-resolved decays

CW frequency response

Typical lifetime measurement error with microwave system is < 300 ns.

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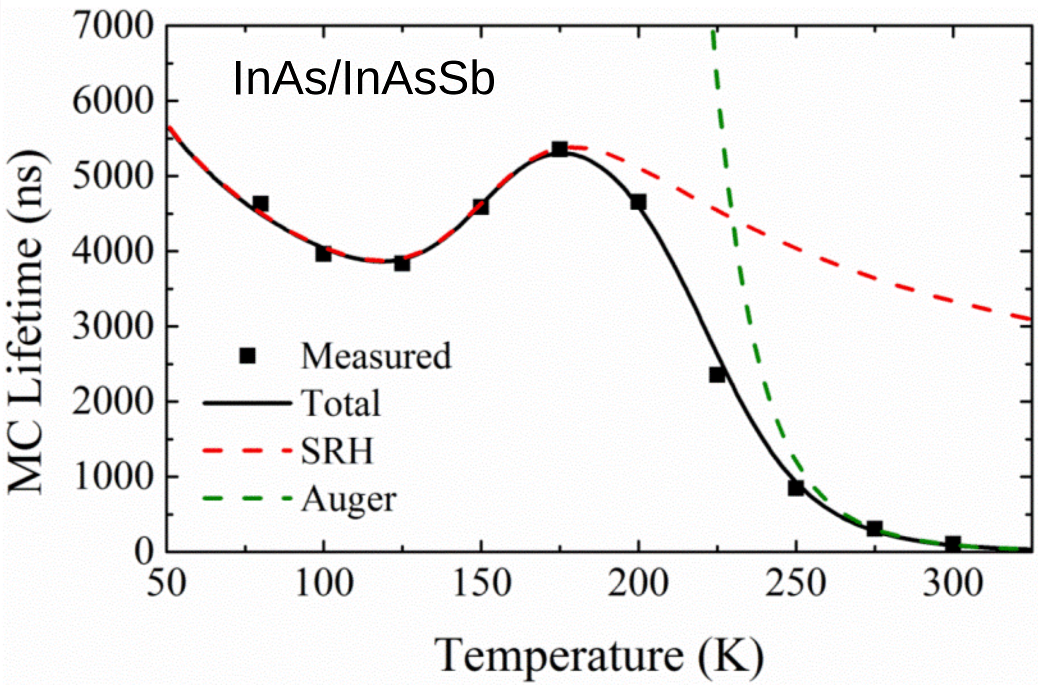
Determining Trap Energy Level(s)

J. Blakemore, *Semiconductor Statistics* (1962)

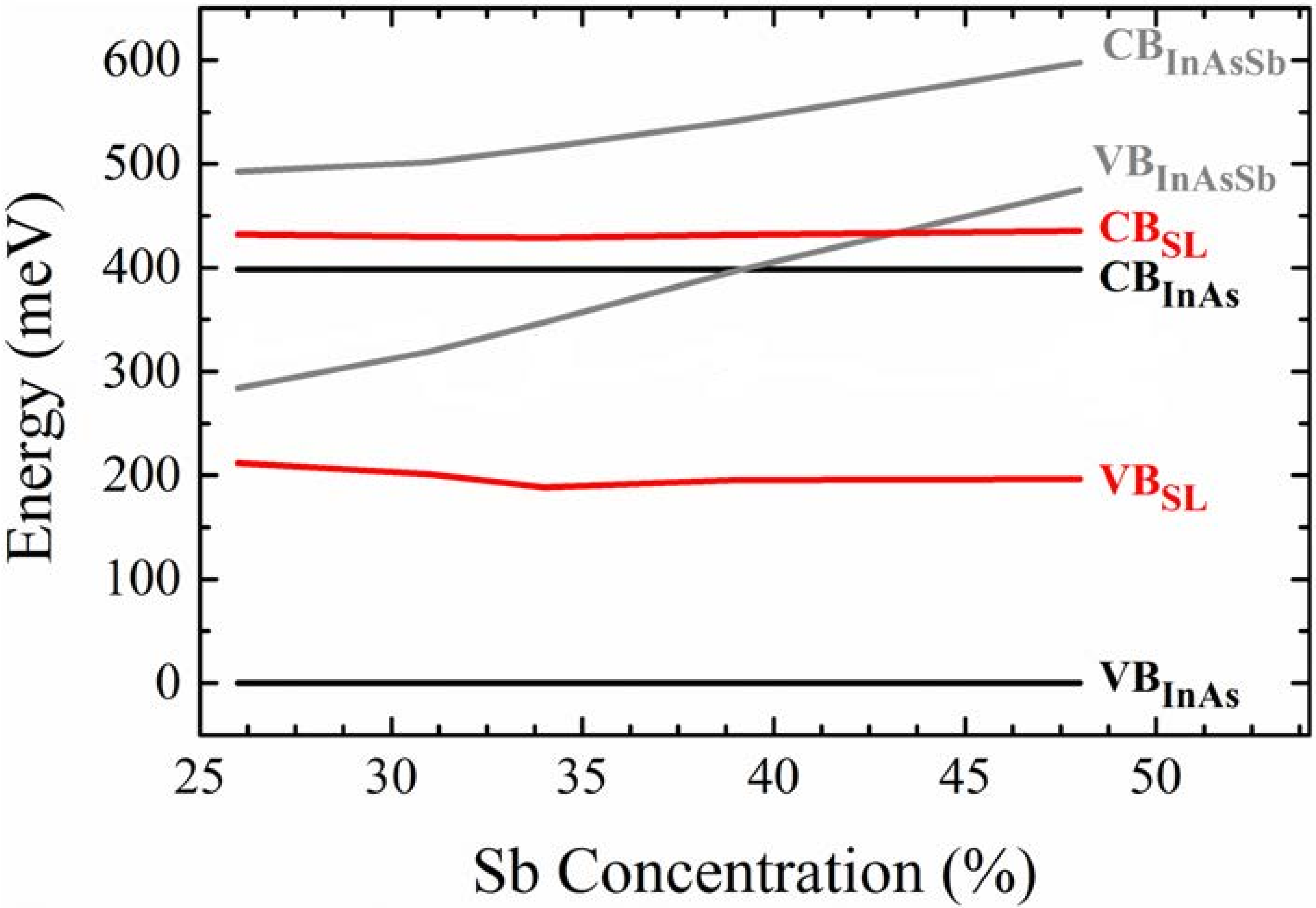


- $\tau_{total}^{-1} = \tau_{SRH}^{-1} + \tau_{auger}^{-1}$
- $\tau_{SRH} = \frac{\tau_{po}(n_o+n_1)+\tau_{no}(p_o+p_1)}{n_o+p_o}$
- $\tau_{auger} = \frac{2n_i^2}{n_o^2+n_o p_o}\tau_{A1}^i$

- Measured data fit with SRH and Auger-1 theory
- Important fitting parameters are trap energy, E_T, capture cross section*trap density, σN_T, and Auger overlap function, |*F1F2*|
- SRH model converges for 2 different trap energies: E_T and $\tilde{E}_T$ where one is relative to SL CB edge and the other to the SL VB edge
- Radiative lifetime not included as data showed long radiative lifetimes

Also refer to Aytac et al., Appl. Phys. Lett. 105, 022107 (2014)

MWIR T2SL Lifetime/Defects Study



Collaboration with Professors Boggess, Flatte, & Grein

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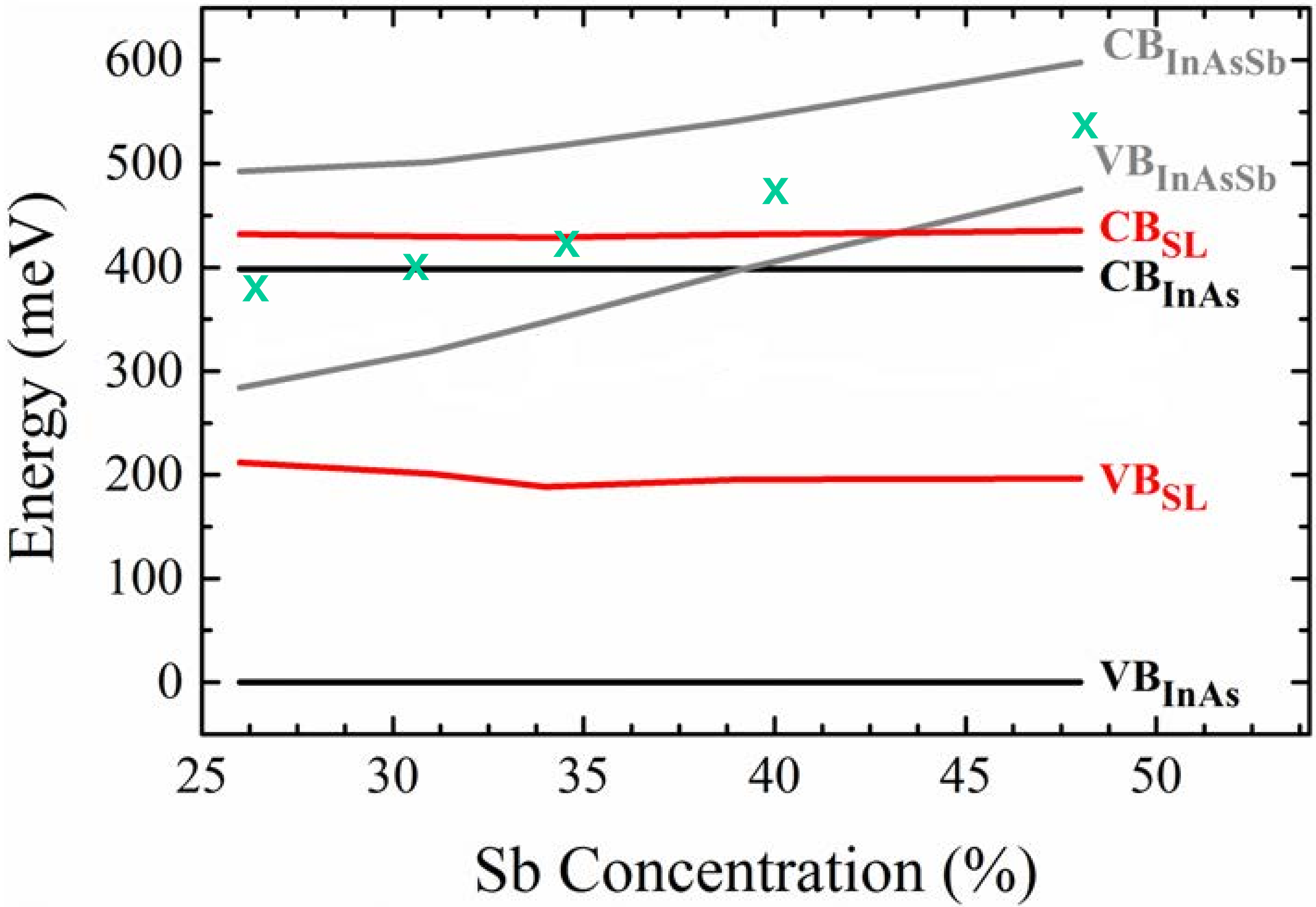
MWIR T2SL Lifetime/Defects Study



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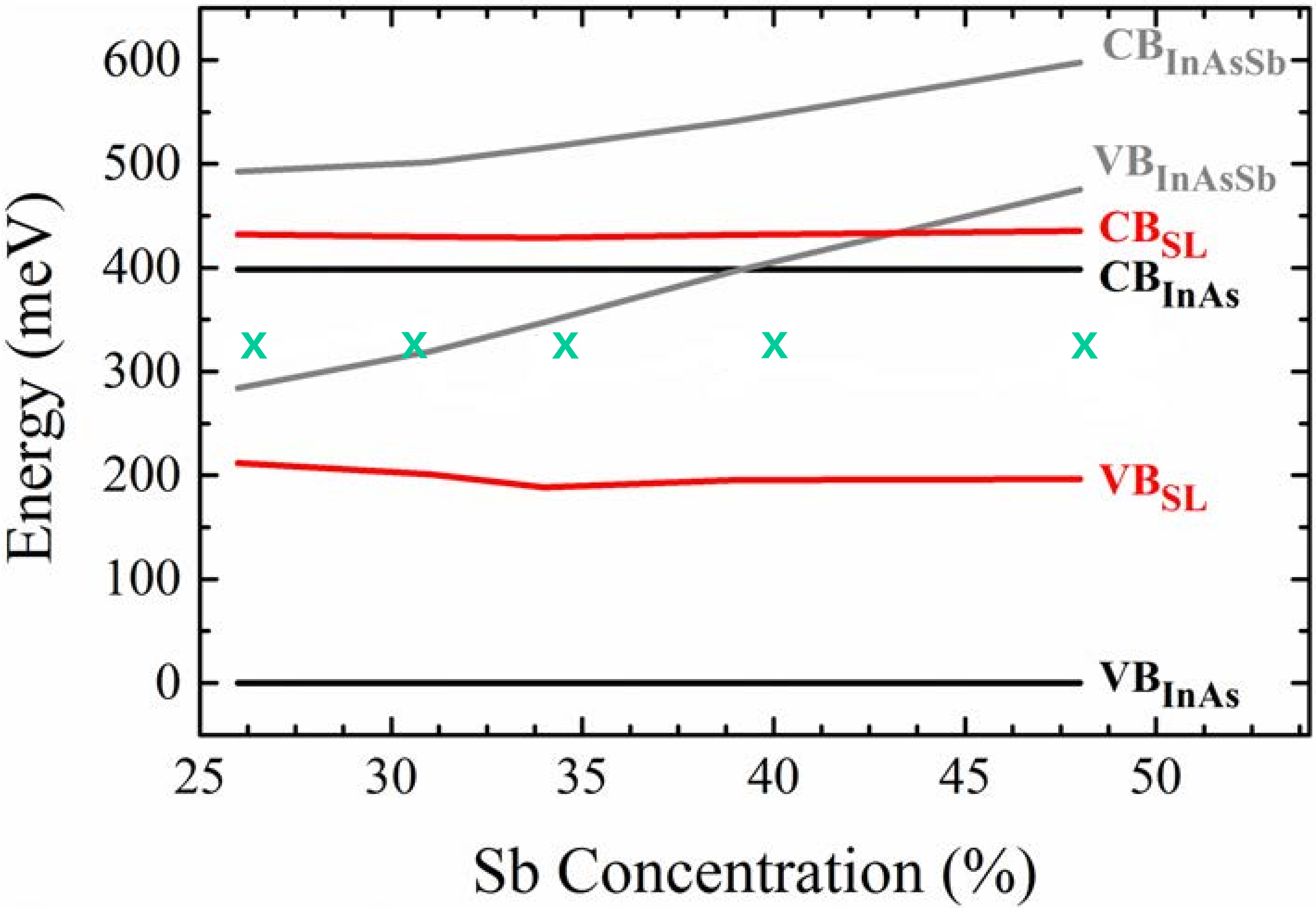
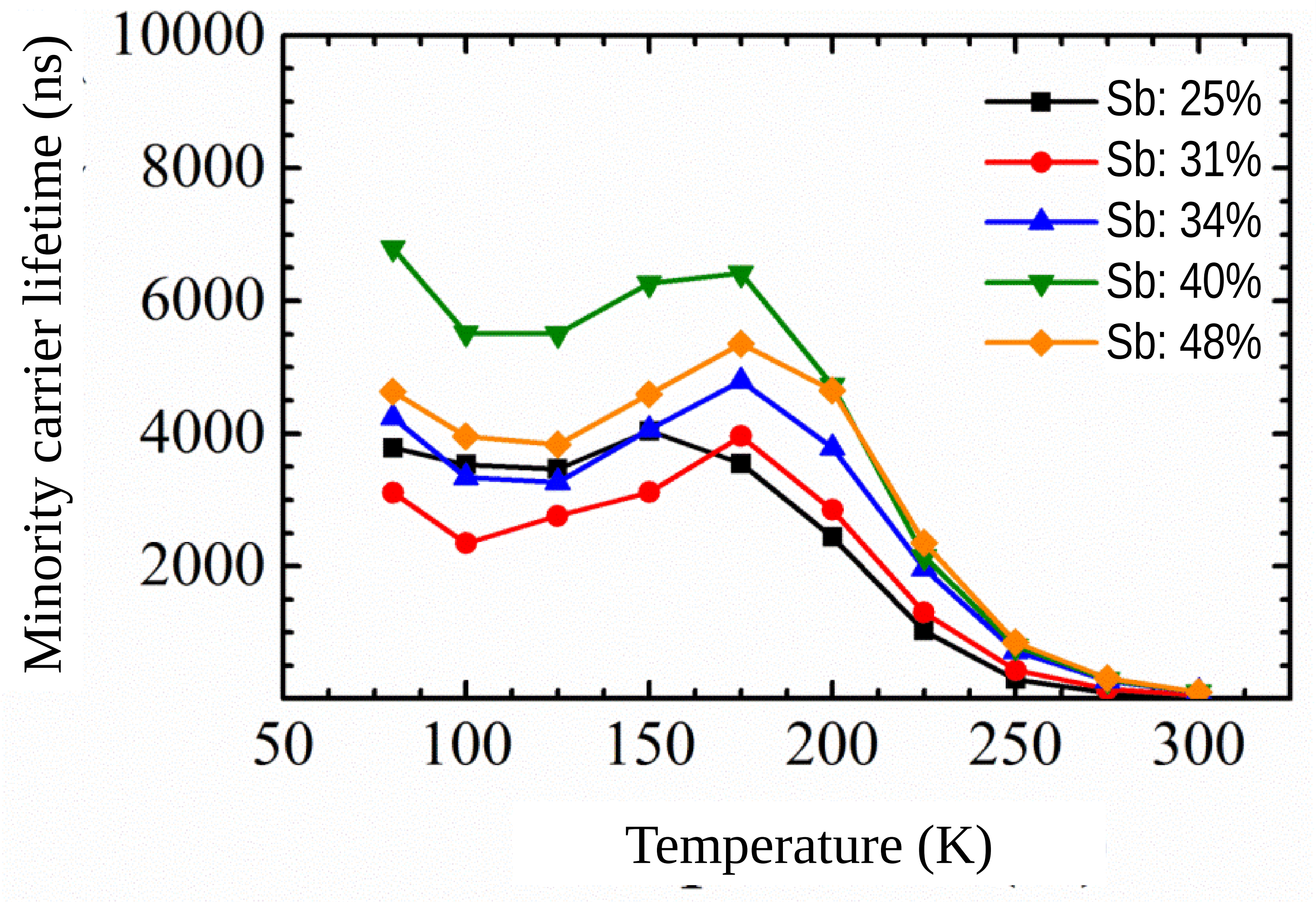


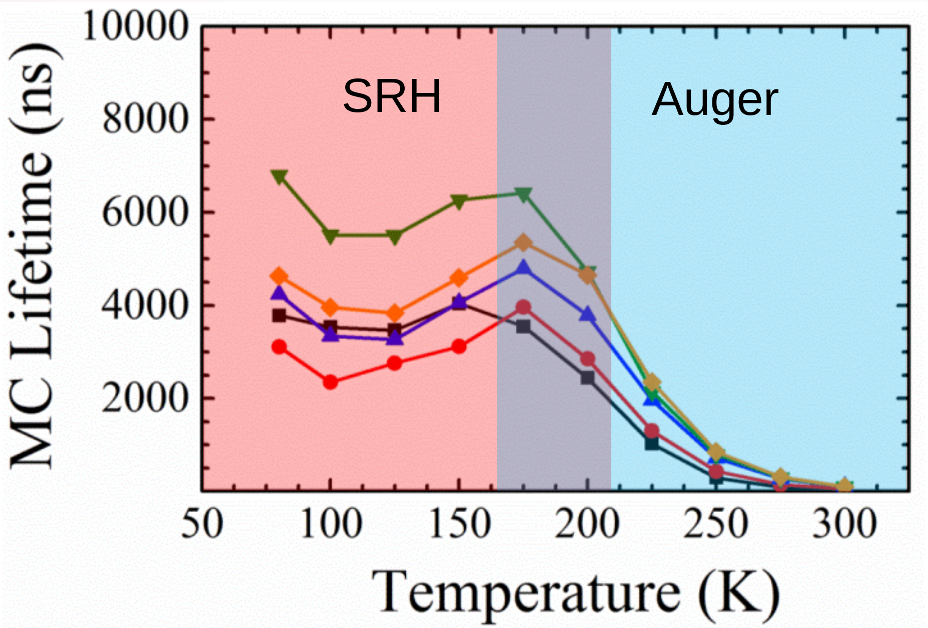
Collaboration with Professors Boggess, Flatte, & Grein

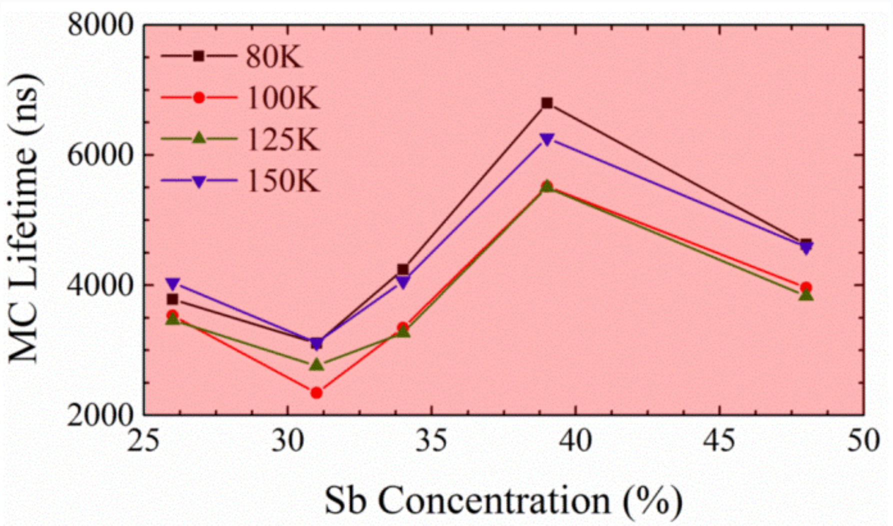
InAs/InAsSb Hole Lifetimes

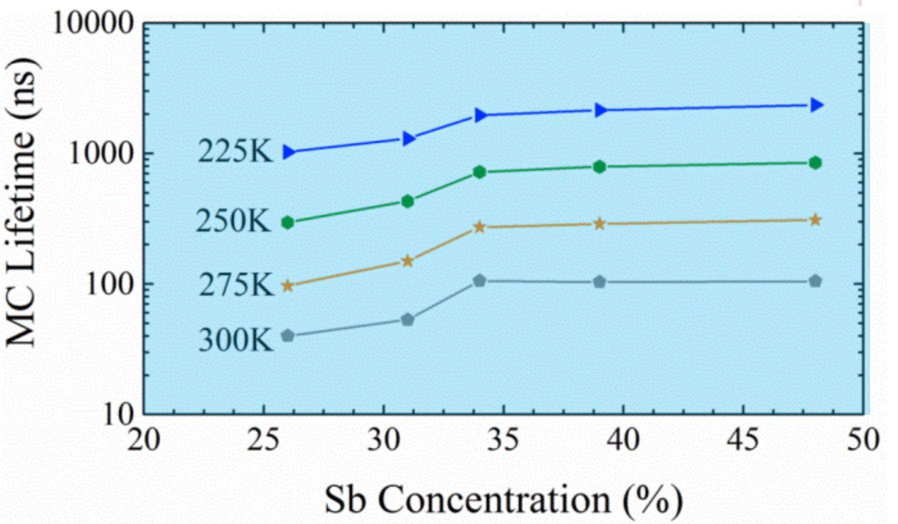


Also refer to Aytac et al., Appl. Phys. Lett. 105, 022107 (2014)

Minority Carrier (MC) Lifetime Trend

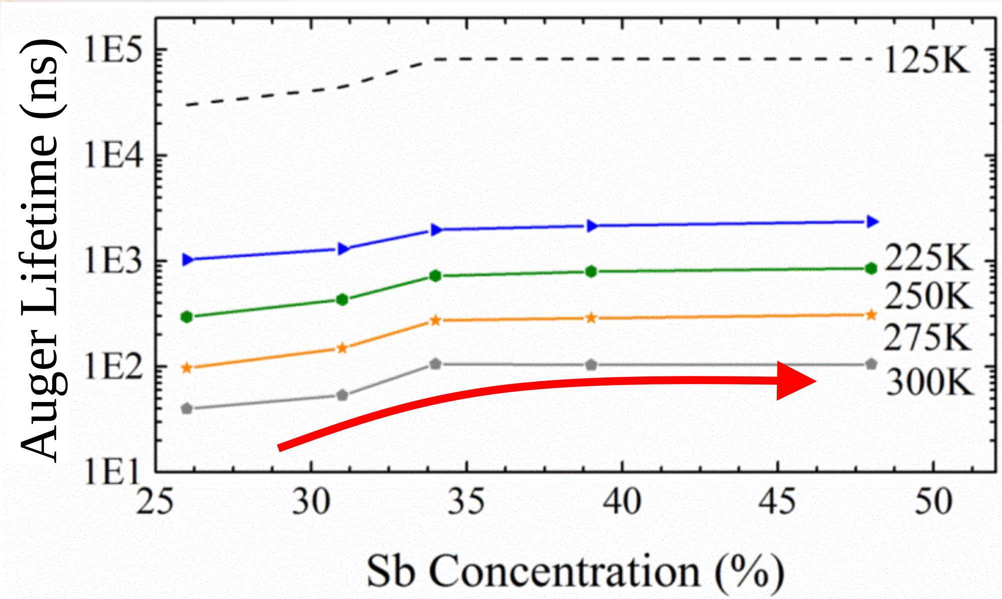






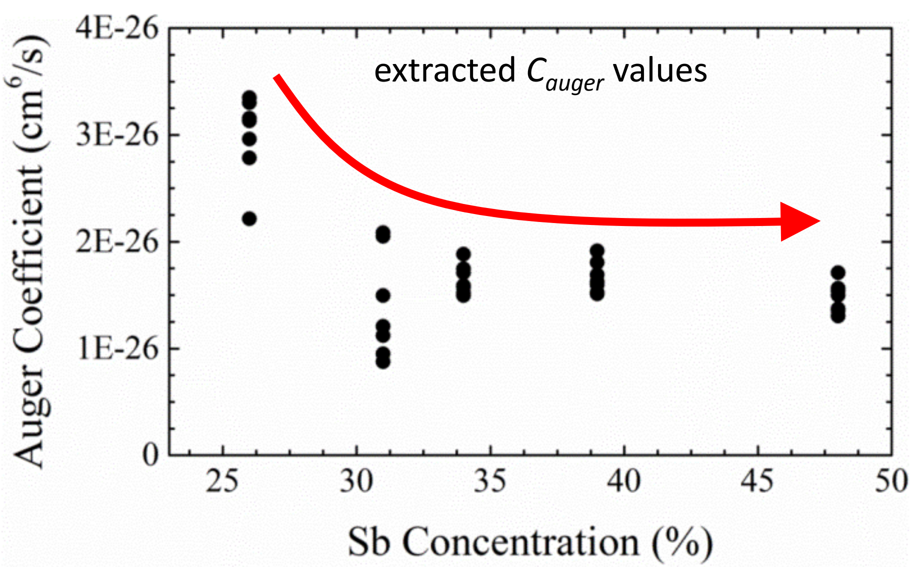
- Two distinct temperature regions
  - SRH for T<150K
  - Auger for T>225K
  - Mix of the two for 150-225K
- 38% Sb has best SRH lifetime
- Auger lifetime increases with Sb concentration

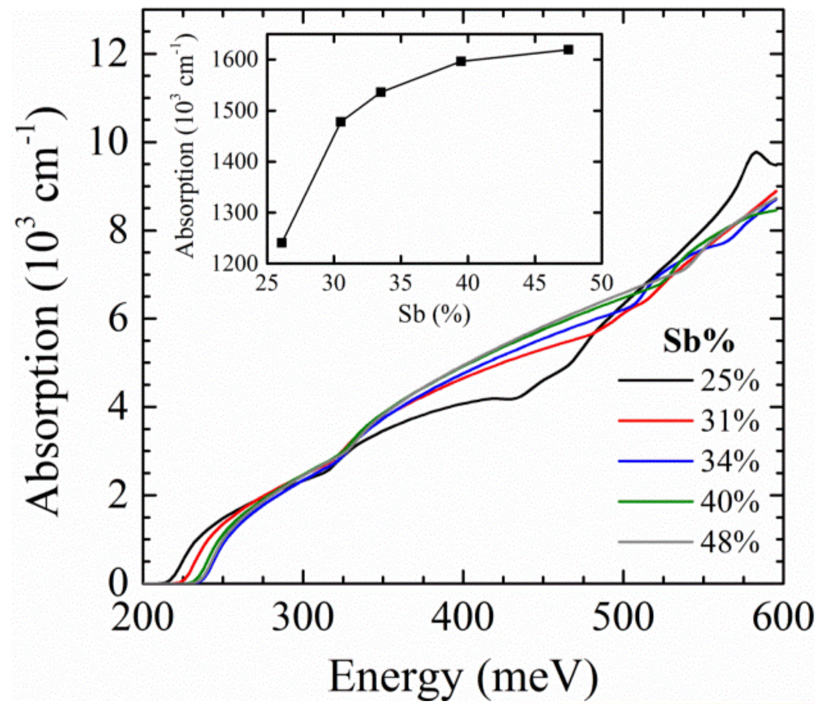
Auger Lifetime vs. Sb %



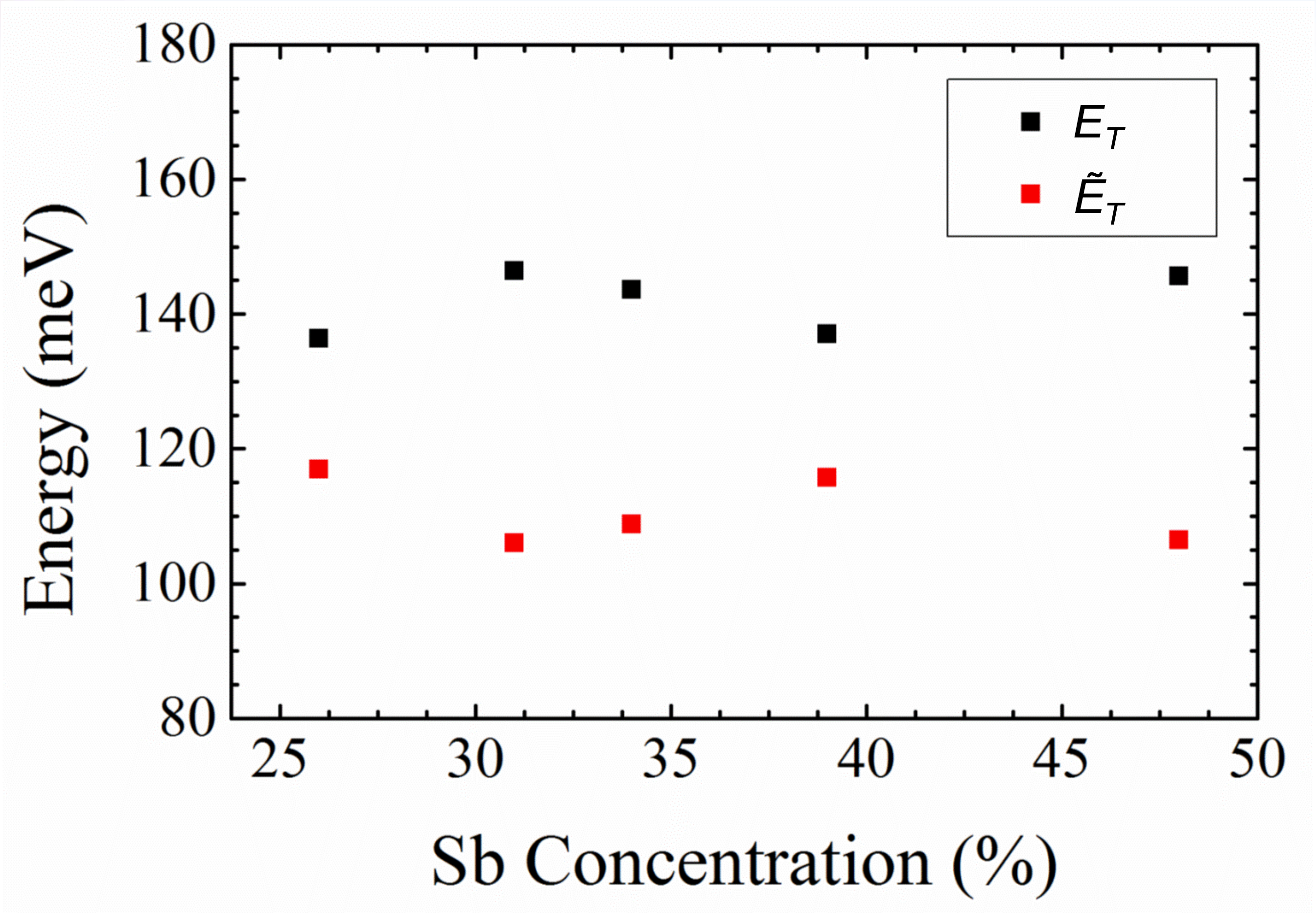
Calculated 125K Auger lifetimes for $N_d = 1 \times 10^{15}$ cm^{-3}

Measured high temp MC lifetimes



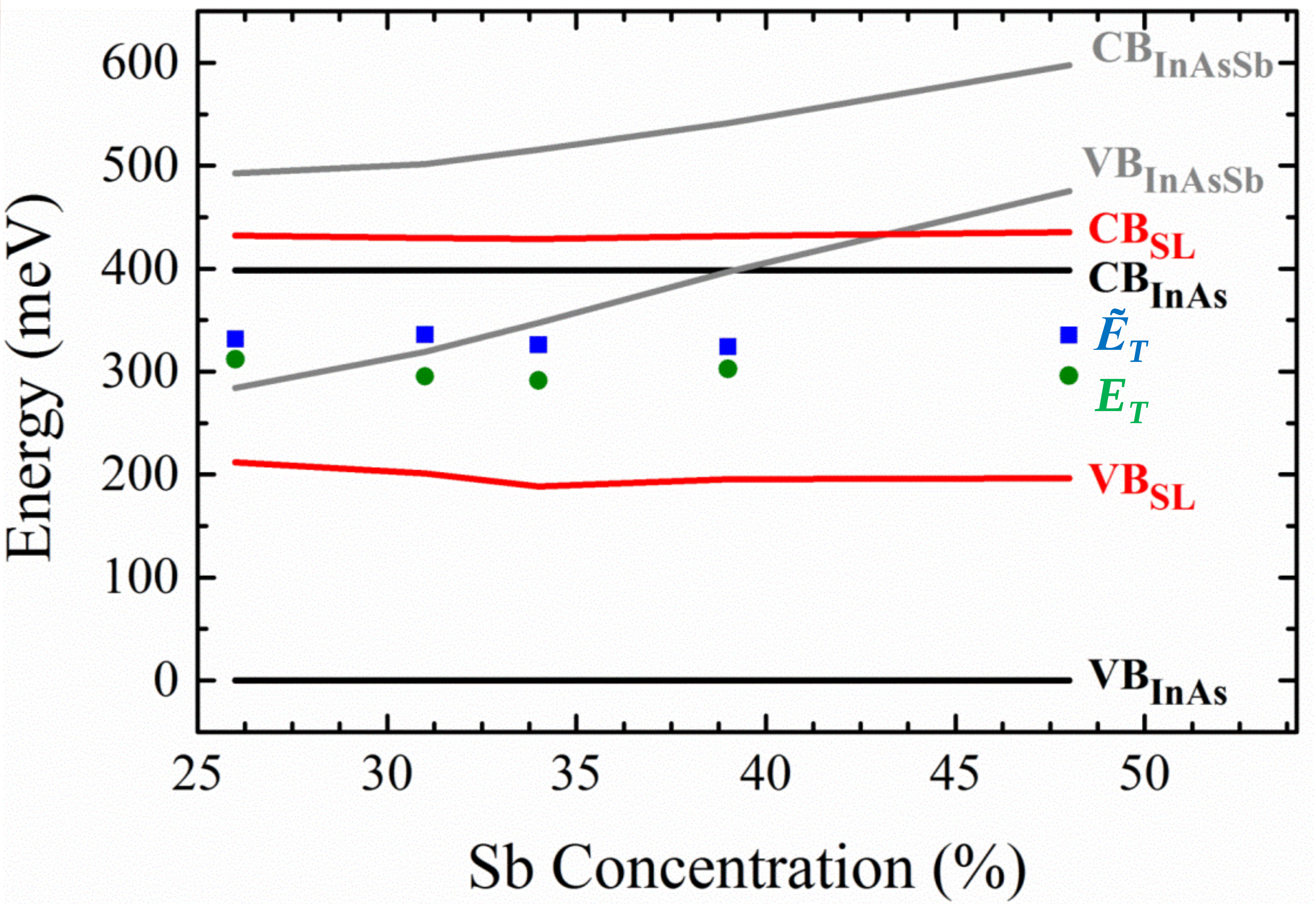


Extracted Trap Energy vs. Sb%



- Trap energies have approximately 10 meV maximum change across the Sb range
- Single trap state gives two energy levels (unresolvable), relative to CB or VB.

Trap Energy Level Trend



- The two potential trap levels do not follow the InAsSb band edges
- CB_{SL} has ~5meV shift, VB_{SL} has ~30meV shift, trap energies ~10meV shift
- Uncertainty in extracted trap energy greater than any observed trend

Conclusion

Summary

- III-V materials proving to be superior alternative to HgCdTe
  - I_{dark}, responsivity, tunability, uniformity, affordability
- InAs/Ga(In)Sb SL: short carrier lifetime, limited usefulness
- InAs/InAsSb SL: longest carrier lifetime, low N_D, most useful
- InAs/InAsSb defects are mid-gap, lifetime is SRH limited
- Potential 10-100x improvements in minority carrier lifetime

Suggested Future Work

- Growth optimizations to further reduce defects in InAs/InAsSb
- Identification of defects
- Investigate effects of diffuse interfaces on lifetime, transport

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