SAND2018-11365C

Minority Carrier Lifetime and Recombination Dynamics in Strain-Balanced InGaAs/InAsSb Superlattices

P. T. Webster,[1] P. C. Grant,[1,2] E. H. Steenbergen,[1] G. Ariyawansa,[3] C. J. Reyner,[3] J. K. Kim[4], J. F. Klem[4]

[1] Air Force Research Laboratory, Space Vehicles Directorate RVSU, Kirtland AFB, NM 87117

[2] Applied Technology Associates, Albuquerque, NM 87123

[3] Air Force Research Laboratory, Sensors Directorate RYDH, Wright-Patterson AFB, OH 45433

[4] Sandia National Laboratories, Albuquerque, NM 87185

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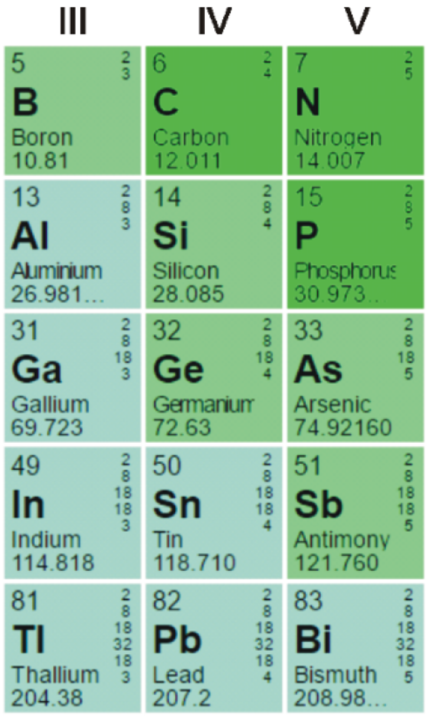
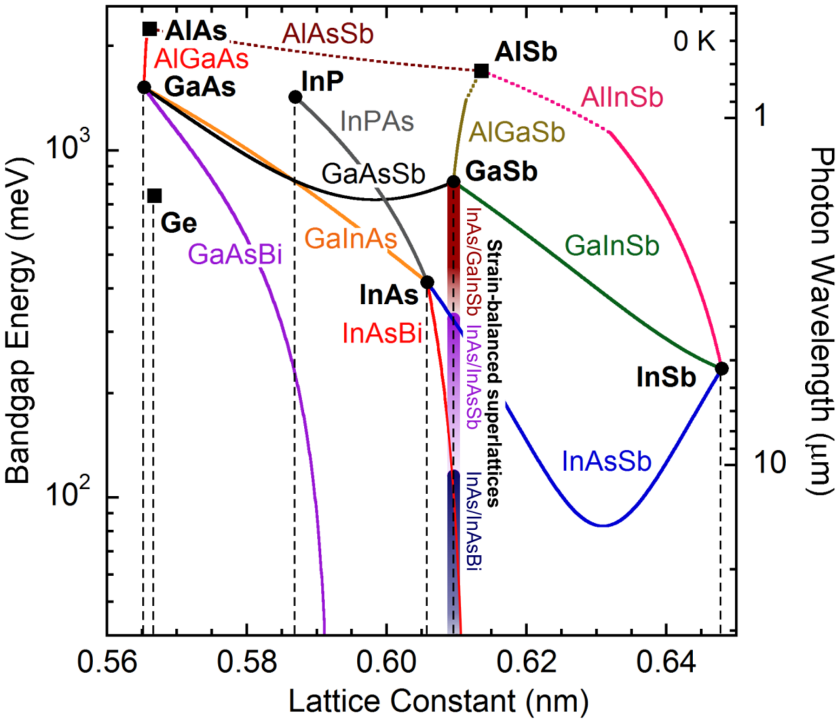
Infrared Materials with Lattice-Matched Substrates





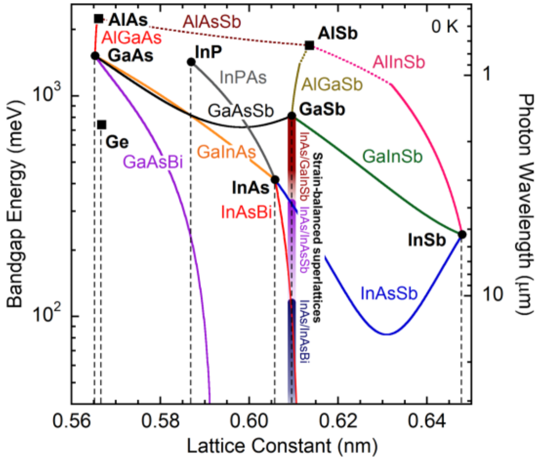
Strain-balanced or lattice-matched superlattices can be grown arbitrarily thick on conventional III-V substrates

Reducing the effective bandgap of the superlattice comes at the expense of reduced absorption (wavefunction overlap) shown by color gradient

The ground state absorption coefficient can be maximized by optimizing the designs for maximum wavefunction overlap

Design freedom afforded by additional alloy constituents allows for simultaneous optimization of band edge alignment and strain profile

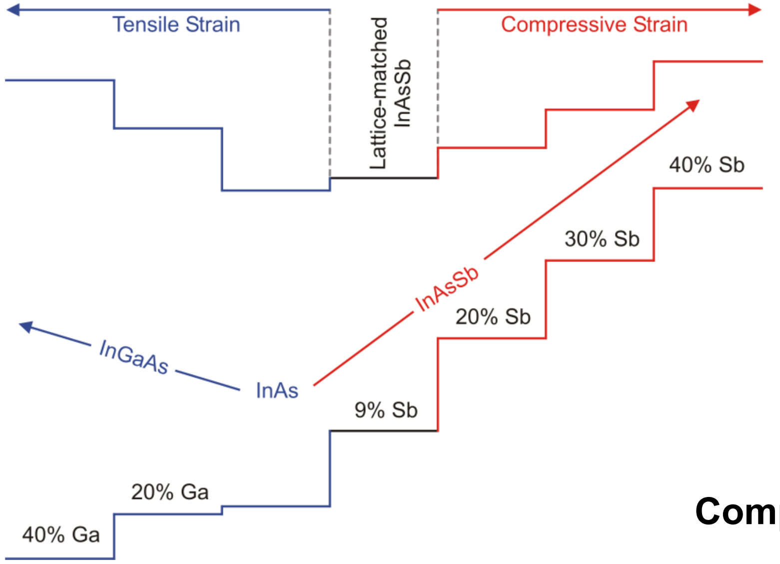
Impact of Adding Ga in InGaAs/InAsSb Superlattices

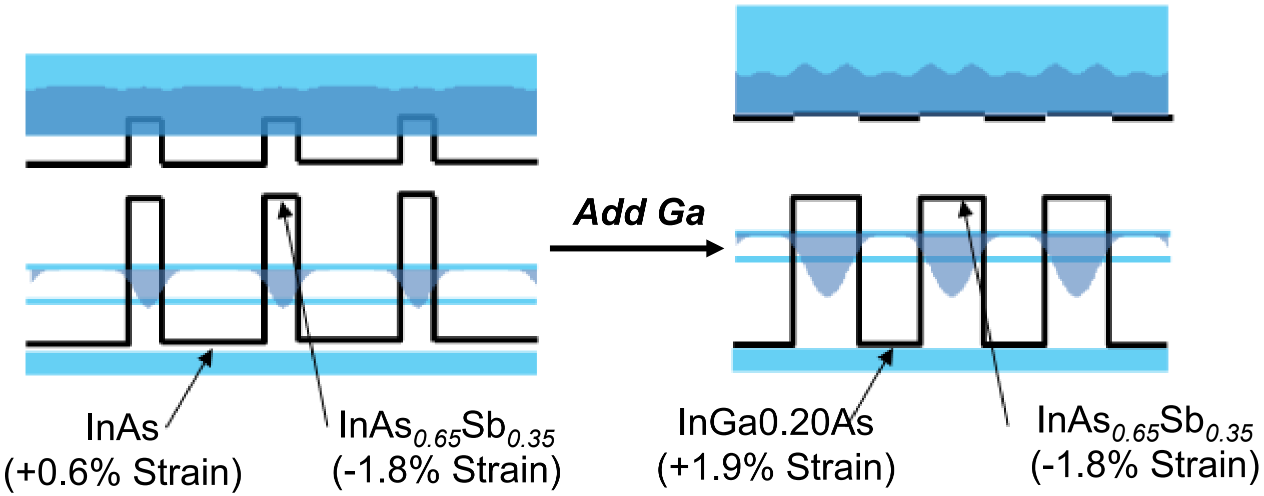


In InAs/InAsSb, the lightly tensile InAs layers must be thicker than the more heavily compressive InAsSb layers to balance the strain

Incorporating Ga into InAs yields increasingly more tensile InGaAs, resulting in a more symmetric strain-balance profile

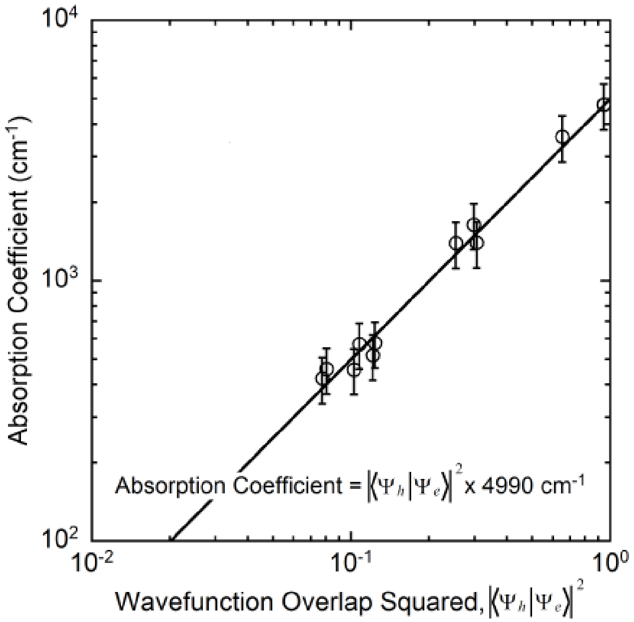
Thinner InGaAs layers act to improve coupling between adjacent hole wells, improving wavefunction overlap





Compare thicknesses (*d*): $d_{InAs} = 3 \times d_{InAsSb}$ $d_{InGaAs} = 0.9 \times d_{InAsSb}$

Absorption Coefficient and Wavefunction Overlap



Transition strength (S) gives a measure of the strength of the optical transition independent of the optical joint density of states

$$S = \left(\frac{2}{m_0}\right) \cdot \frac{\left|\langle \Psi_h \mid \bar{p} \mid \Psi_e \rangle\right|^2}{\hbar\omega} = \left(\frac{2m_0}{\hbar^2}\right) \cdot (\hbar\omega) \cdot \left|\langle \Psi_h \mid \bar{r} \mid \Psi_e \rangle\right|^2$$

Transition strength can be determined from the measured absorption coefficient (α) by backing out the density of states (ρ)

$$S = \left(\frac{2m_0 n c \varepsilon_0}{e^2 \pi \hbar}\right) \cdot \left(\frac{\alpha}{\rho}\right)$$

As wavefunction overlap approaches 100%, the absorption coefficient approaches 4990 cm^{-1} and the transition strength approaches 43.1

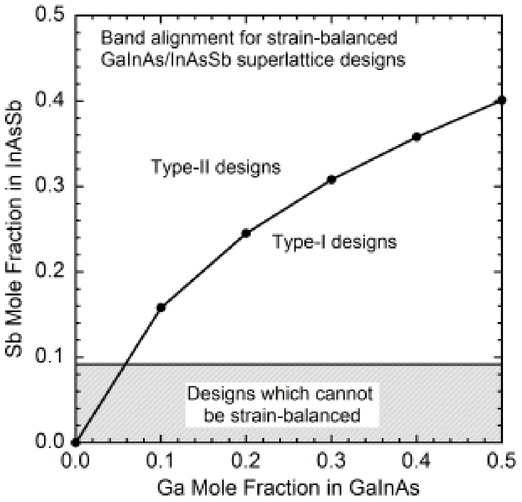
General Observations and Optimal Design

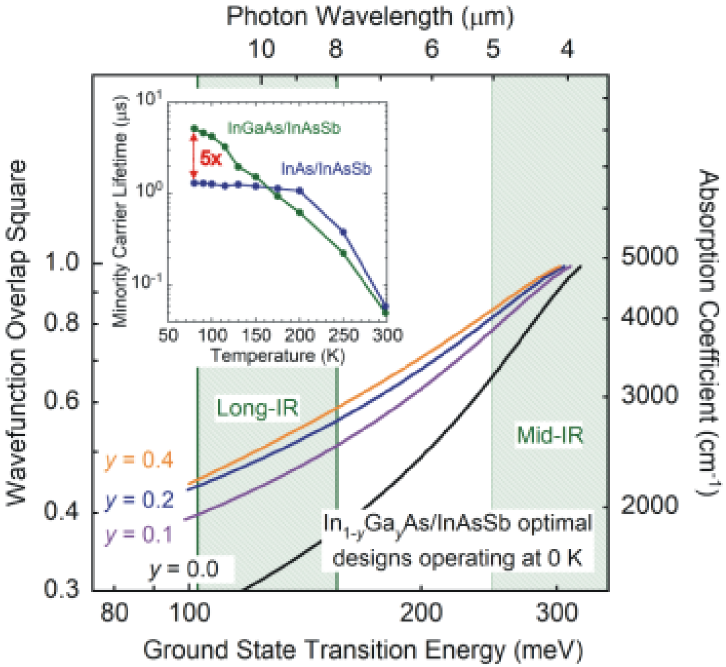
More Sb is required to maintain type-II band alignment with increasing Ga mole fraction

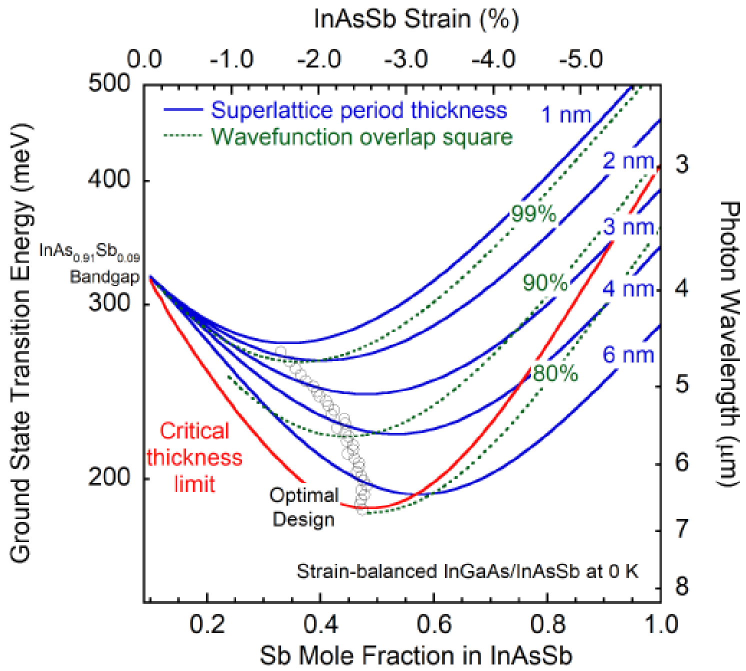
The optimal design calls for short period thicknesses; the individual InGaAs and InAsSb layers are not expected to relax despite heavy strain

Some of the optimal designs are type-I

The optimal designs form ground state transitions through the heavy hole band







Increasing Ga in InGaAs improves wavefunction overlap via a more favorable strain-balance condition

~50% absorption increase in mid-IR, >2x increase in long-IR

InGaAs/InAsSb Growth Conditions

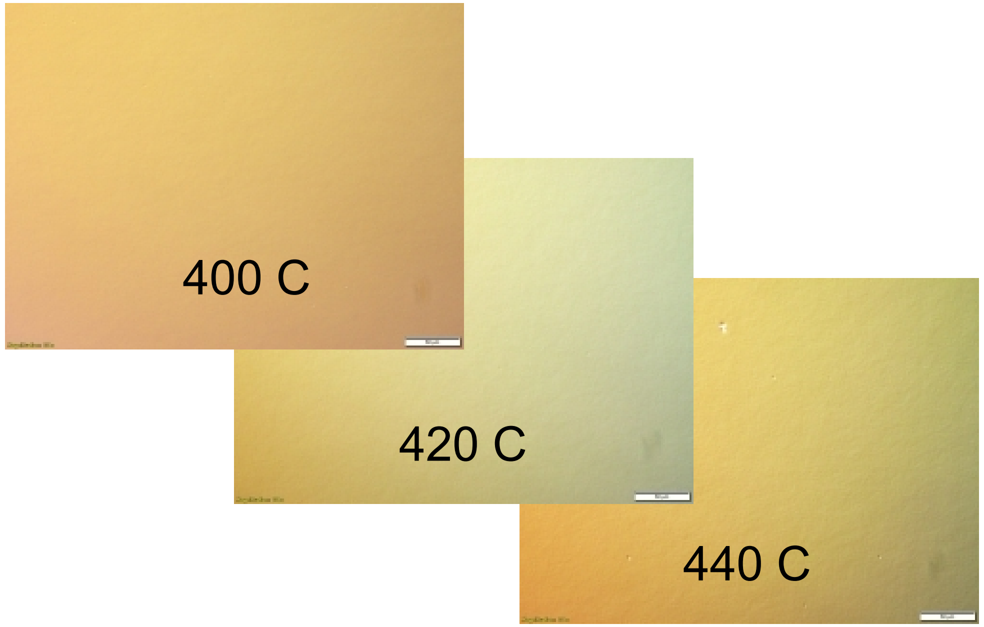
Confinement/Cap
1.0 um n-type InGaAs/InAsSb superlattice
Buffer/Confinement
n-type GaSb substrate

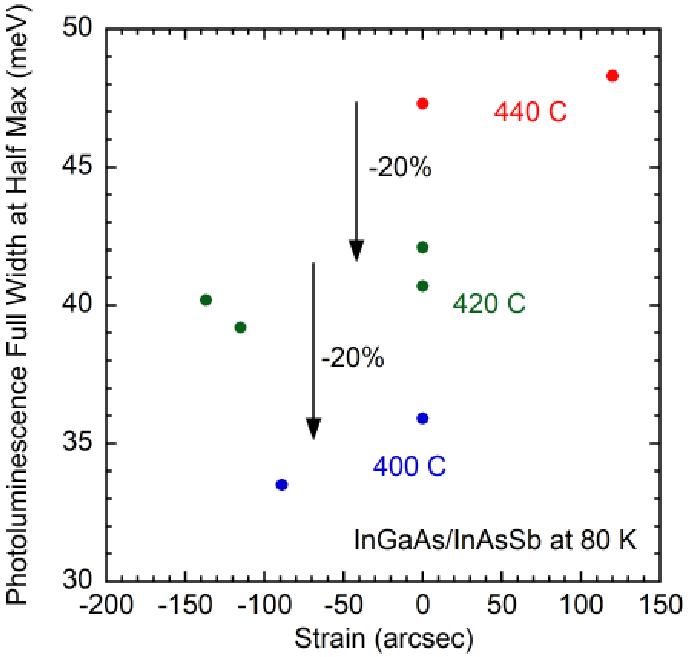
InGaAs/InAsSb characterization structures are 1 μm thick, doped to 5×10^{15} cm^{-3} n-type

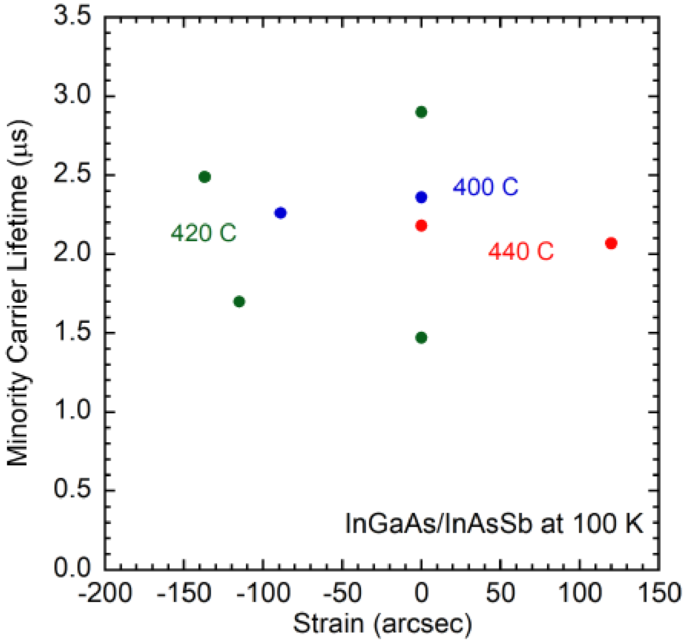
Narrower photoluminescence full width at half max observed at lower growth temperatures

Minority carrier lifetime ~2-3 μs at 100 K for all InGaAs/InAsSb samples

Minority carrier lifetime ~1 us for 5×10^{15} cm^{-3} n-type InAs/InAsSb grown under the same conditions



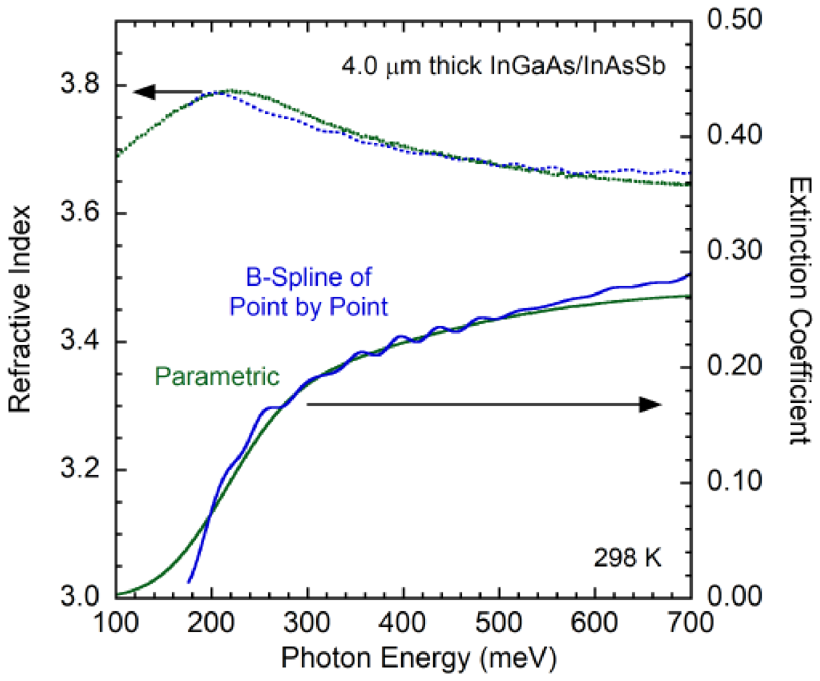


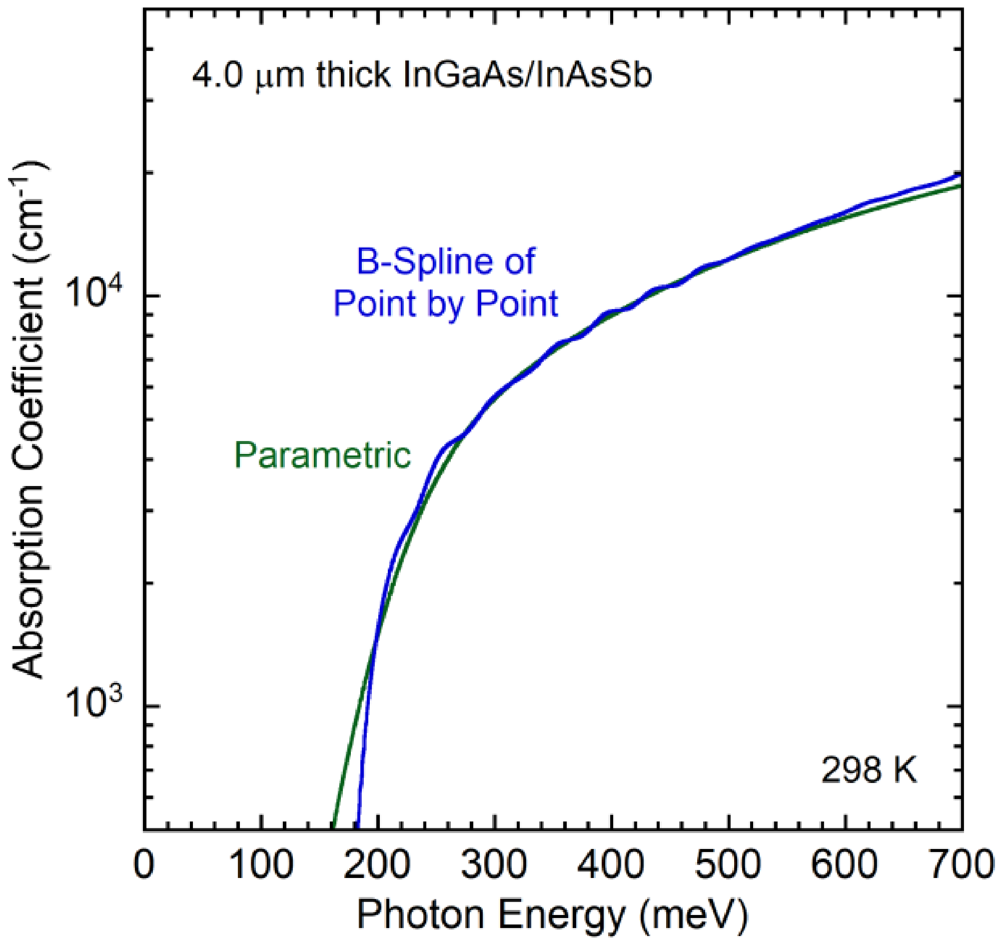


InGaAs/InAsSb Optical Constants

Optical constants of 4.0 μm thick layer of mid-wave InGaAs/InAsSb measured by spectroscopic ellipsometry

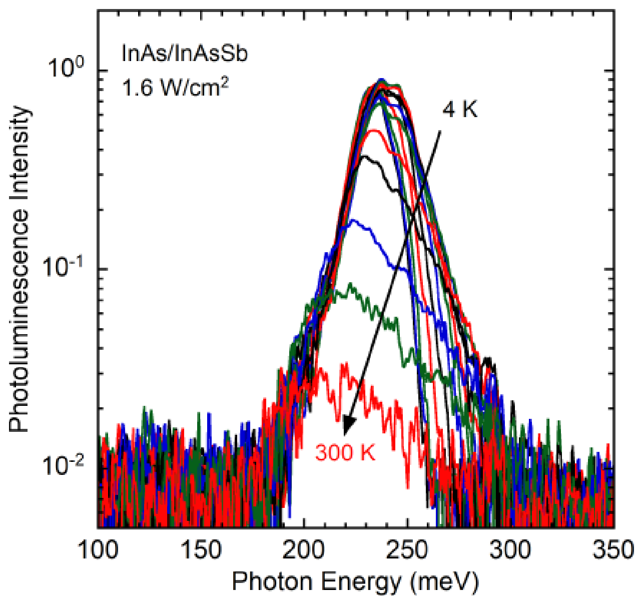
Ground state transition energy shifts to 177 meV (7 μm wavelength) at room temperature

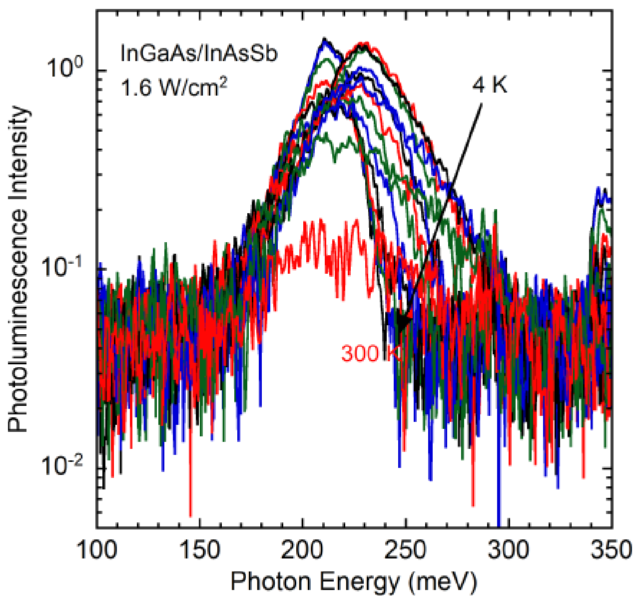


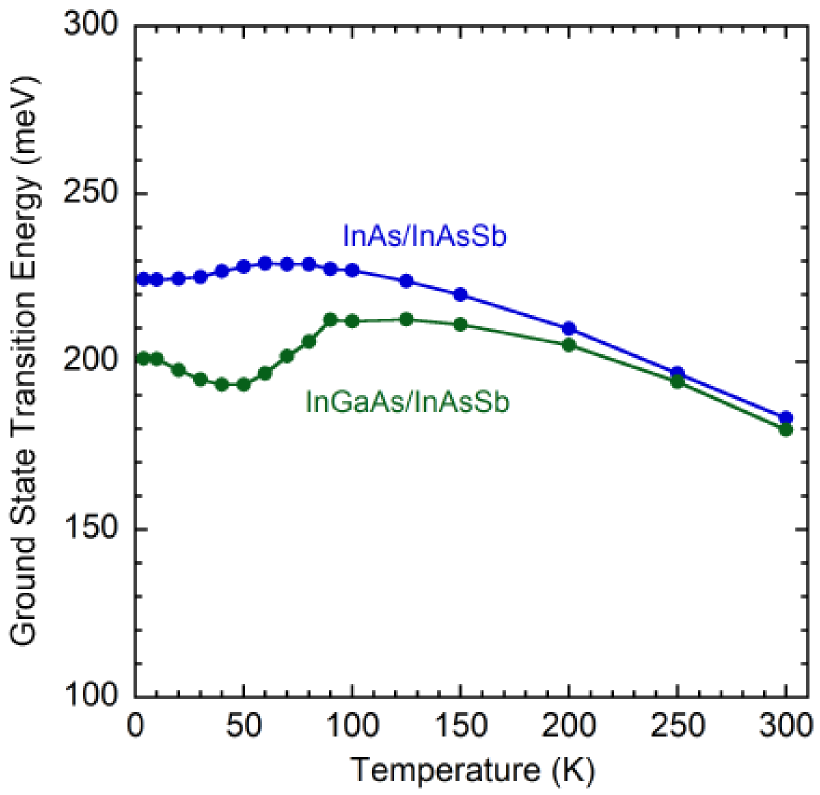


Steady-State Photoluminescence

Photoluminescence shifts to lower energies below 100 K in the InGaAs/InAsSb superlattice, possibly indicating the presence of localized states





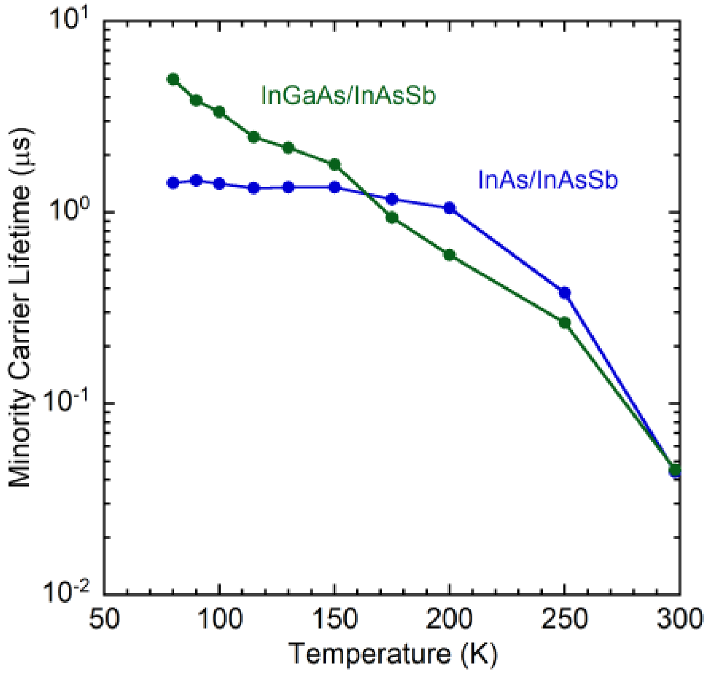


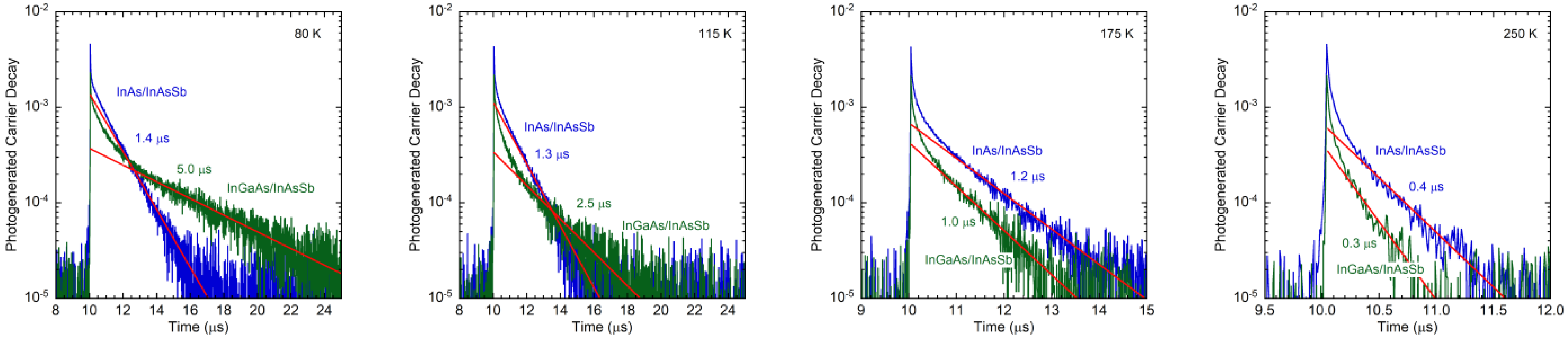
Transient Microwave Reflectance

A microwave probe beam is incident on the sample; the reflected microwave power is a function of the sample conductivity

Samples are excited by a short pulse 1535 nm laser, and the photogenerated carrier population modifies the sample conductivity

The conductivity and corresponding microwave reflectance decay with the photogenerated carrier population



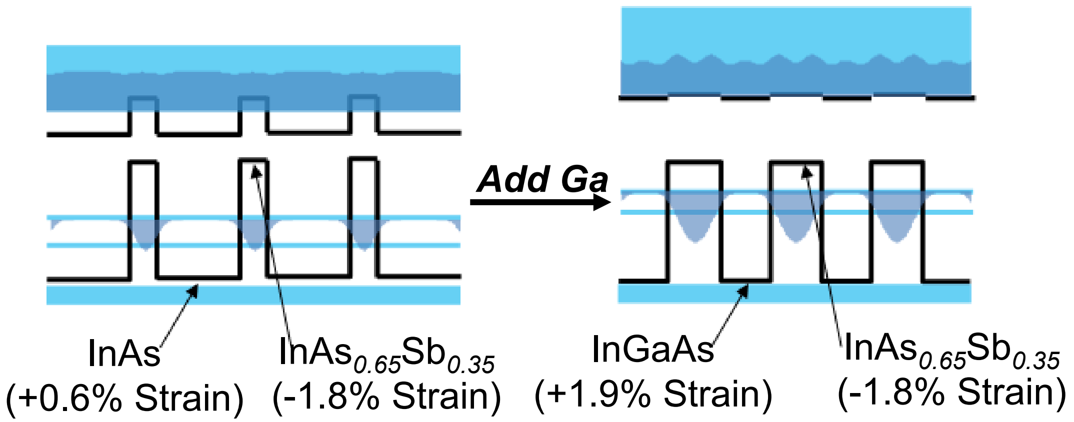


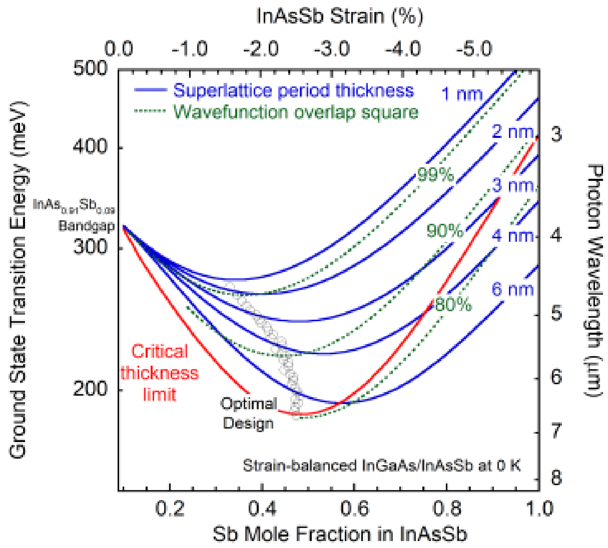
Conclusions

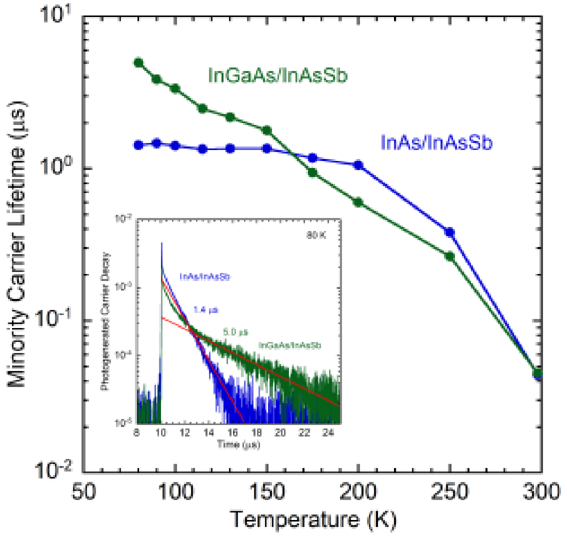
Adding Ga to InGaAs/InAsSb superlattices yields more tensile InGaAs, resulting in a more symmetric strain-balance profile and better wavefunction overlap and absorption

Molecular beam epitaxy growth conditions identified for smooth, high-quality mid-wave InGaAs/InAsSb with long minority carrier lifetime and narrow photoluminescence full-width at half max

Si-doped InGaAs/InAsSb exhibits a 5× longer minority carrier lifetime than identically doped InAs/InAsSb







Acknowledgements

This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. DOE's National Nuclear Security Administration under contract DE-NA-0003525. The views expressed in the article do not necessarily represent the views of the U.S. DOE or the United States Government.