Hot Carrier Solar Cells: Phonon Bottlenecks to slow Carrier Cooling

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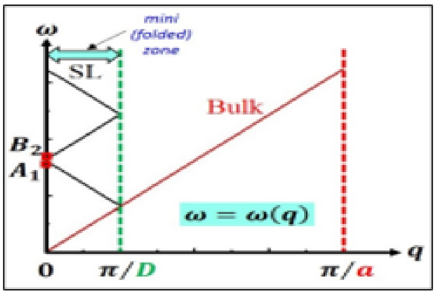
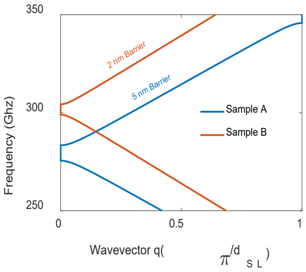
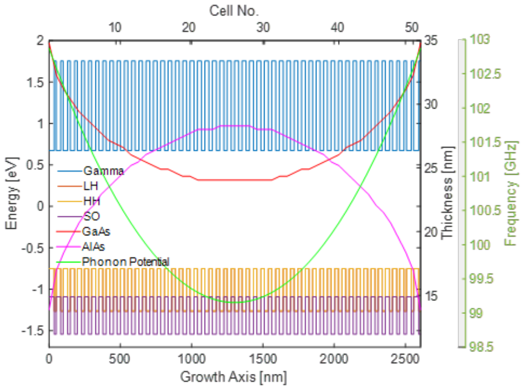
Absorption of photons of energy higher than the semiconductor bandgap results in “hot carriers” that lose their excess energy to the lattice through several phonon interaction processes, collectively called “thermalization”, before undergoing radiative recombination. A greater understanding of this thermalization is valuable in the design of a “hot carrier solar cell” that may have very high efficiency. [1] Quantum well nanostructures have been shown to slow thermalization compared to bulk materials. [2] In this work, we have studied hot carriers effects in epitaxially grown GaAs/AlAs QW heterostructures with both periodic QW structures to give varying acoustic impedance. [3,4,5] And with aperiodic QWs to give a phonon cavity nanostructure. This study will give a greater understanding of thermalization processes and the effects on phonon-phonon and carrier-phonon interactions of phonon modulation QW nanostructures. [6,7]

Phonon bottleneck mechanisms



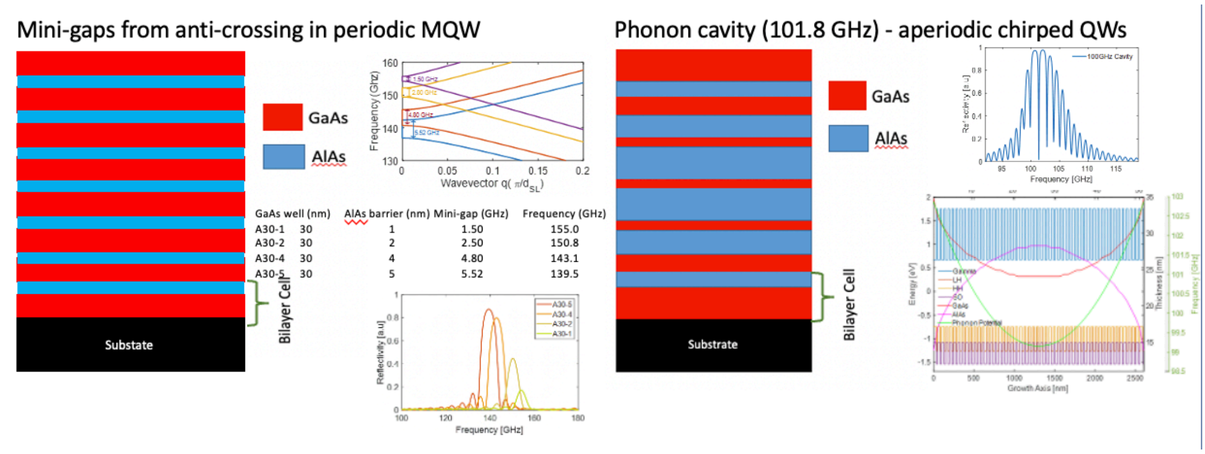


In Multiple Quantum Wells (MQW) folding of acoustic phonon modes gives optical-like modesthat interact with hot electrons. In addition mini-gaps open at zone centre & zone edge due to mis-martch in acoustic impedance. These can interrupt LO-LA phonon interactions and potentially slow carrier cooling.



In Phonon Cavity structures a specific variation in QW/barrier thicknesses to give a chirped structure can give a resonant reflectivity at a certain phonon frequency, (in analogy to band pass structures with alternating refractive index at optical wavelengths). These phonon cavities confine phonons of specific frequency, which can interrupt LO-LA interactions and affect hot-e-LO interactions, possibly reducing carrier cooling rates.

MBE epitaxial growth of phonon bottlenecks



GaAs well (nm)		AlAs barrier (nm)	Mini-gap (GHz)	Frequency (GHz)
A30-1	30	1	1.50	155.0
A30-2	30	2	2.50	150.8
A30-4	30	4	4.80	143.1
A30-5	30	5	5.52	139.5

MQW are grown by epitaxial growth in MBE of equal thickness GaAs/AlAs bilayers. This gives mini-gaps at zone centre, where the mini-gap width increases with barrier:well ratio and the mini-gap energy decreases with barrier:well ratio.

Whereas phonon cavities are also grown by epitaxial growth of GaAs/AlAs but where the bilayers have specifically varying thicknesses. With the appropriate spacing this can give a strong reflection at a specific phonon energy of 101.8 GHz, which will modulate the interaction with ~100 GHz phonons.

Results and Discussion

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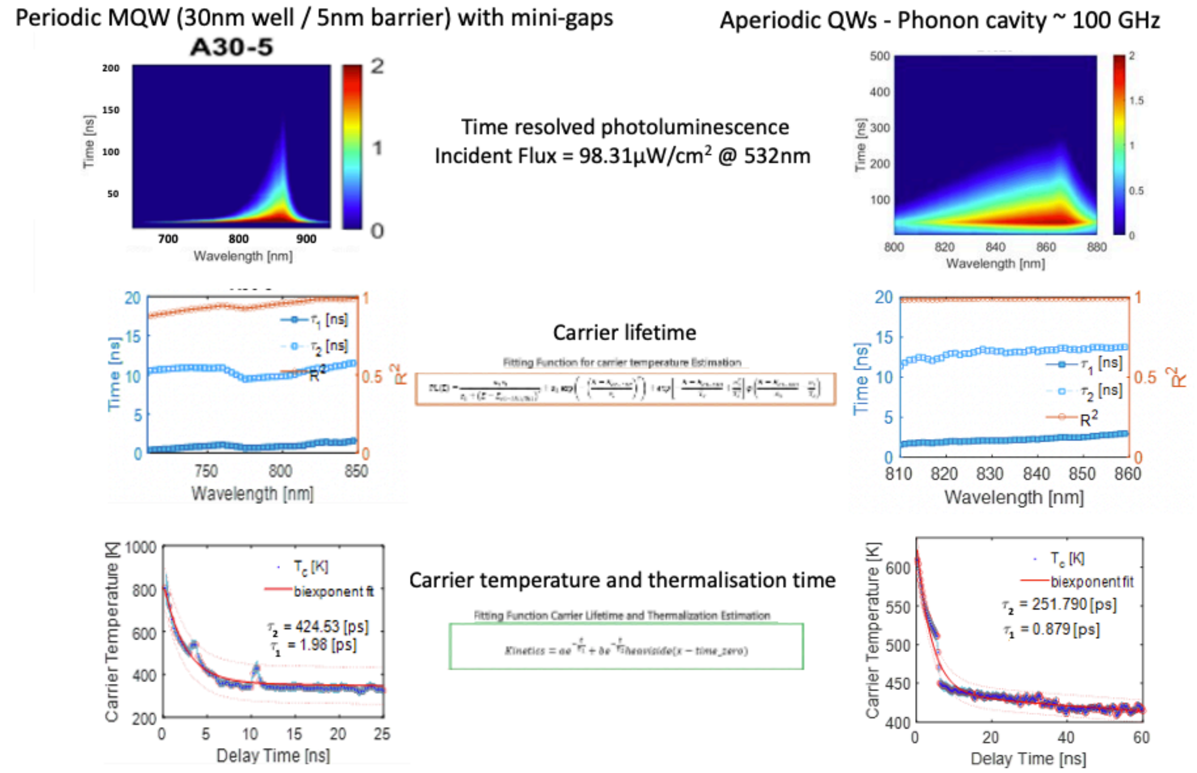


Time resolved photoluminescence
Incident Flux = 98.31μW/cm² @ 532nm

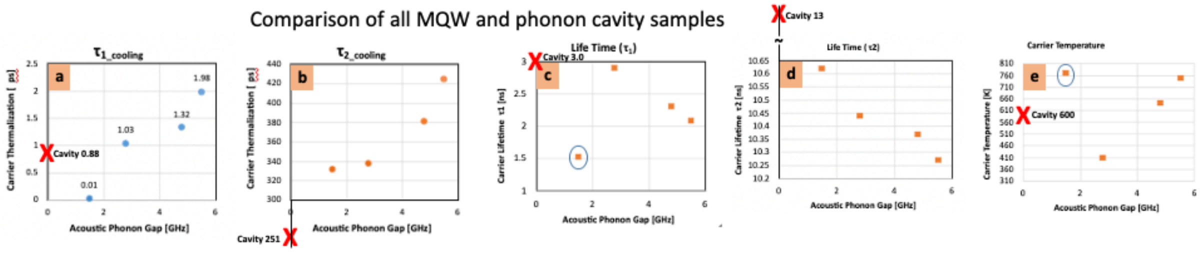
Carrier lifetime

Fitting Function for carrier temperature Estimation

Carrier temperature and thermalisation time

Fitting Function Carrier Lifetime and Thermalization Estimation

$$Kinetics = a e^{-\frac{t}{\tau_1}} + b e^{-\frac{t}{\tau_2}} heaviside(x - time\_zero)$$


Comparison of all MQW and phonon cavity samples

As shown in (a) fast carrier thermalization time shows a linear dependence on acoustic phonon mini-gap. Whereas the phonon cavity has a quite short fast thermalization time close to smallest mini-gap.

(b) shows that a slow carrier thermalization time increases with mini-gap width and that the phonon cavity has a very short acoustic phonon thermalisation time.

(c) & (d) indicate that the fast and slow carrier lifetimes decrease with increasing mini-gap, except for the smallest gap. The phonon cavity also has long lifetimes.

And (e) shows that carrier temperature increases with phonon mini-gap (except for the smallest gap which has the highest temp. The phonon cavity has an intermediate carrier temperature.

Conclusions

Both MQWs and phonon cavities show effects on carrier thermalisation time, due to the mini-gap position and energy in the former and the specific reflection at 100GHz in the latter.

Further work will look at these relationships in more detail and determine there overall effects on carrier cooling rates.

References

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