2013 MRS SPRING MEETING & EXHIBIT

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Symposium V: Nanoscale heat transport – From fundamentals to devices

Thermal conductivity of Si–Ge-based nanostructures

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GEFÖRDERT VOM Bundesministerium für Bildung und Forschung

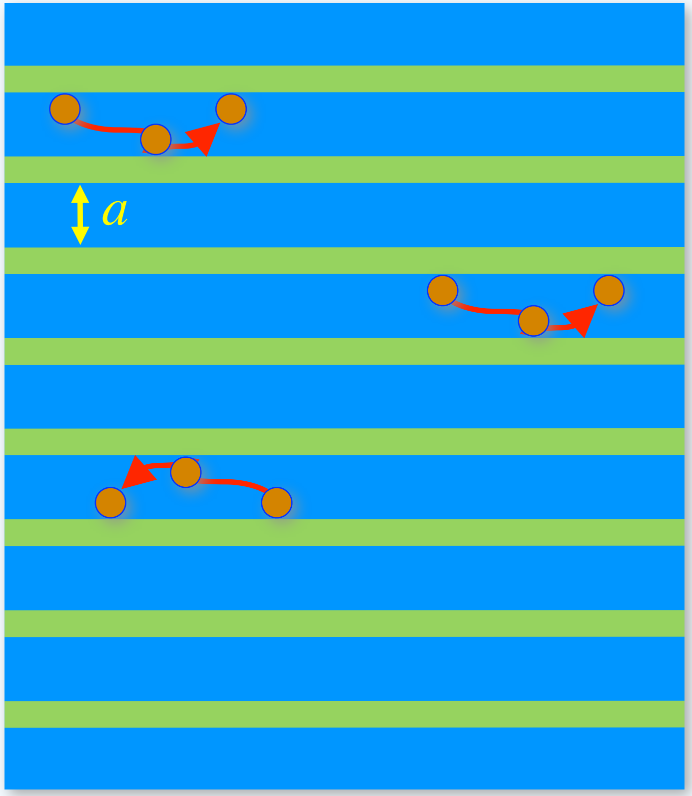
WING Werkstoffinnovationen für Industrie und Gesellschaft

Reduction in thermal conductivity

Cross-plane transport in SL → Coherent phonon scattering at interfaces

$$\kappa_{\mathrm{ph}} = \frac{1}{3} C v \ell$$

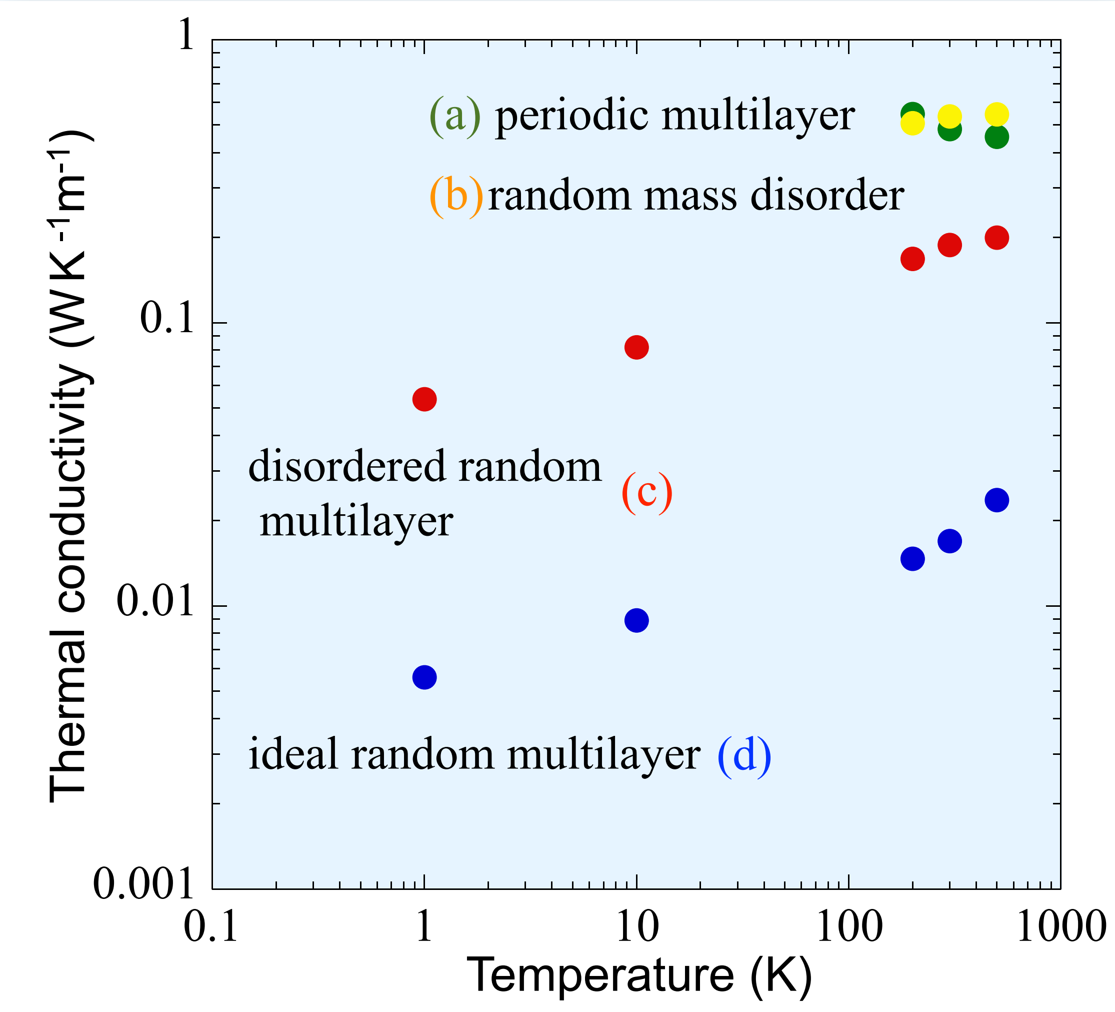
(C lattice heat capacity, v speed of sound,
ℓ mean free path of phonons)

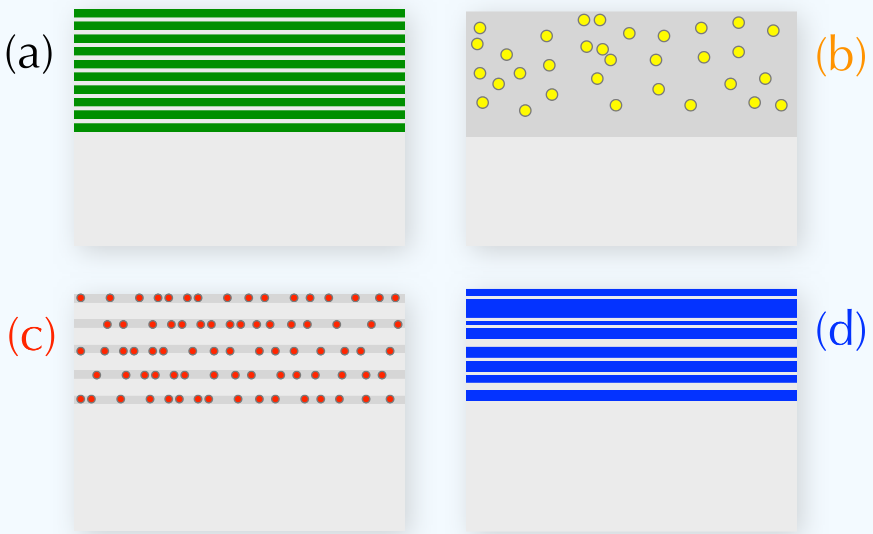


If layer thickness $a < \ell$, the thermal conductivity of the lattice κ_{ph} is reduced.

Phonon scattering

Superlattices, composites, quantum dot SLs, random multilayers





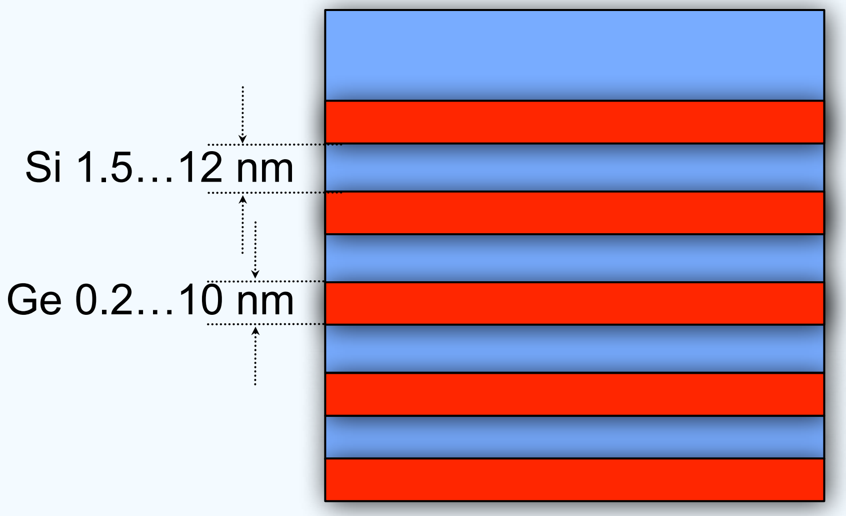
Anderson localization of phonons in **nonperiodic structures**

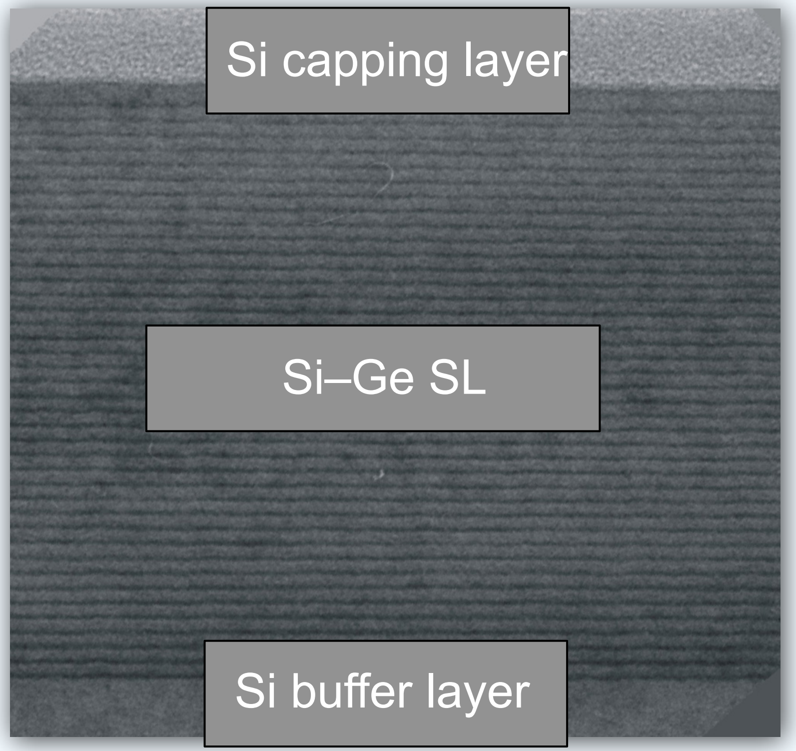
MD Simulation

[Frachioni, White: J Appl Phys **112** (2012) 14320]

MBE of Si–Ge layers

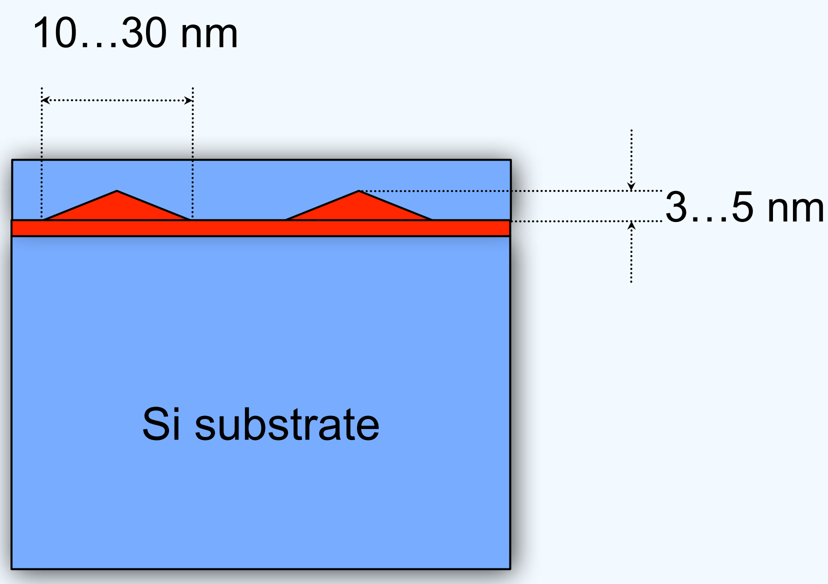
- Stack of alternating layers of Si and a $Si_{1-x}Ge_x$ alloy
- Precision of single layers: ± 0.2 nm

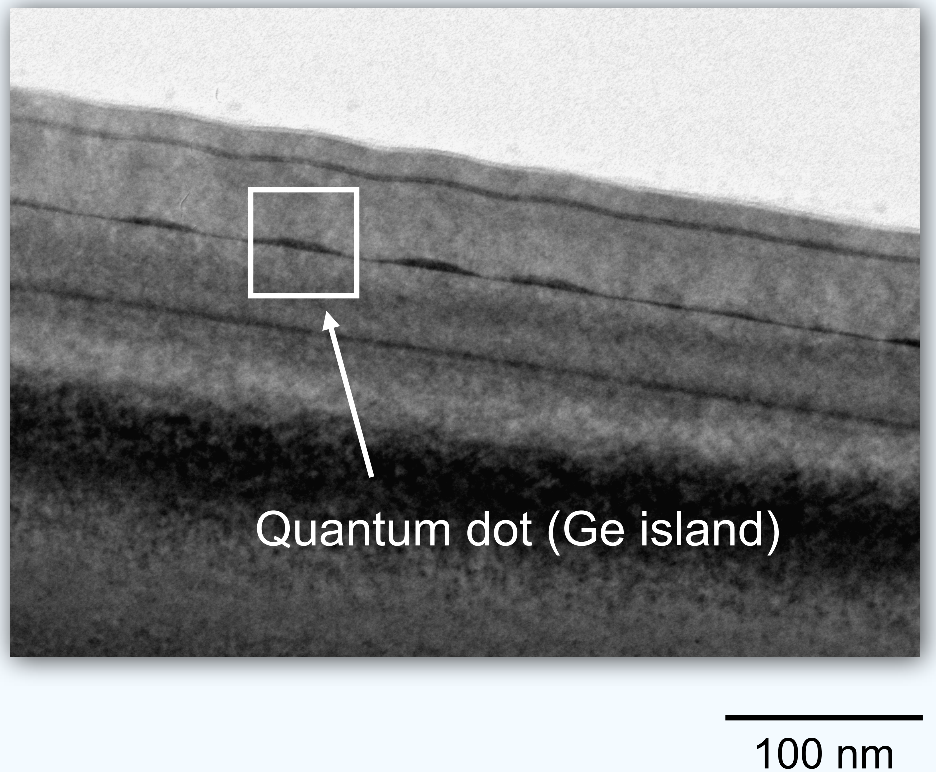




Quantum dot Si–Ge superlattice

- (001), (111) orientation of the Si substrate
- Si (111) → flat layers
- Si (100) → Ge islands (density ~ $10^9 \ldots 10^{11}$ cm^{-2})

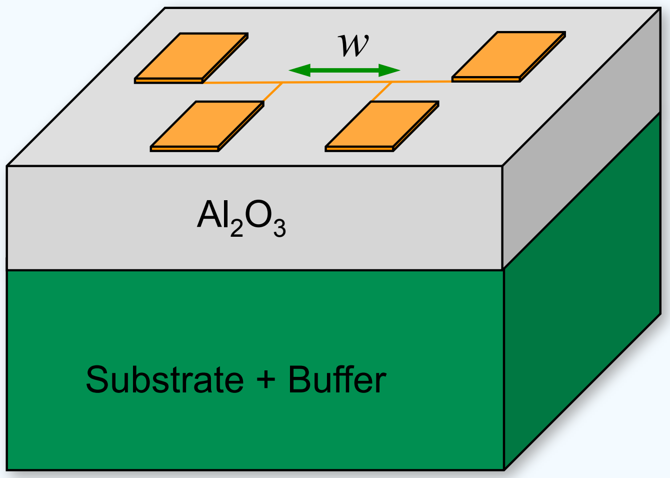


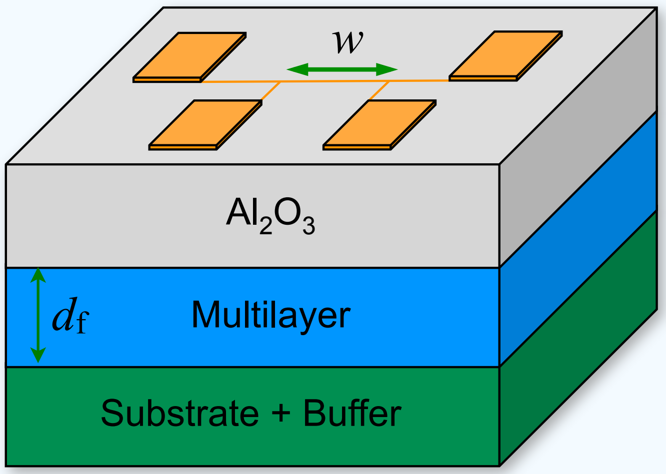


AA Tonkikh *et al* Thin Sol Films (2011)
doi: 10.1016/j.tsf.2011.10.049

3ω measurements

- Deposition of a 100 nm insulating Al_2O_3 layer by ALD
- Reference sample without the multilayer structure
- Differential 3ω measurement of the thermal conductivity of thin films, $U_{3\omega} = f(\kappa)$





Thin film thermal conductivity

1D heat flow

Measurement with one bolometer stripe, width $2b \gg d_f$

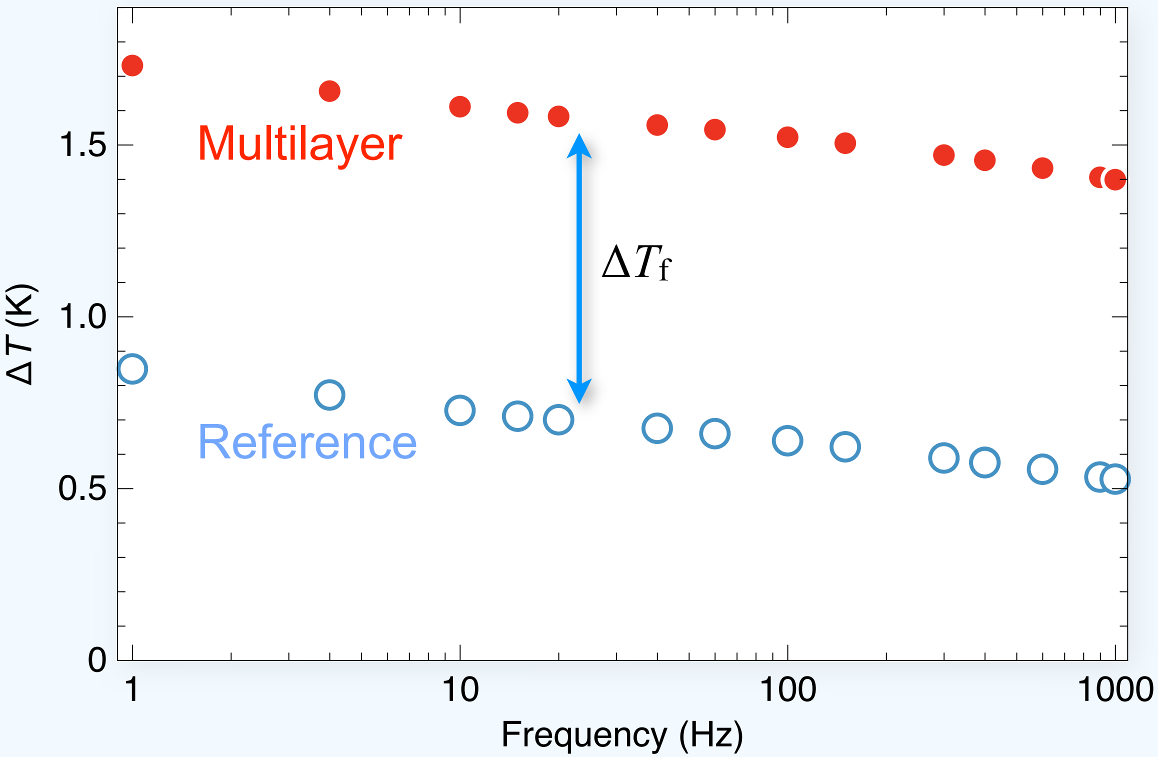
$\Delta T_f \rightarrow$ 1D thermal conductivity κ_{1D}

2D heat flow

Measurements with two bolometer stripes, b_1 and b_2

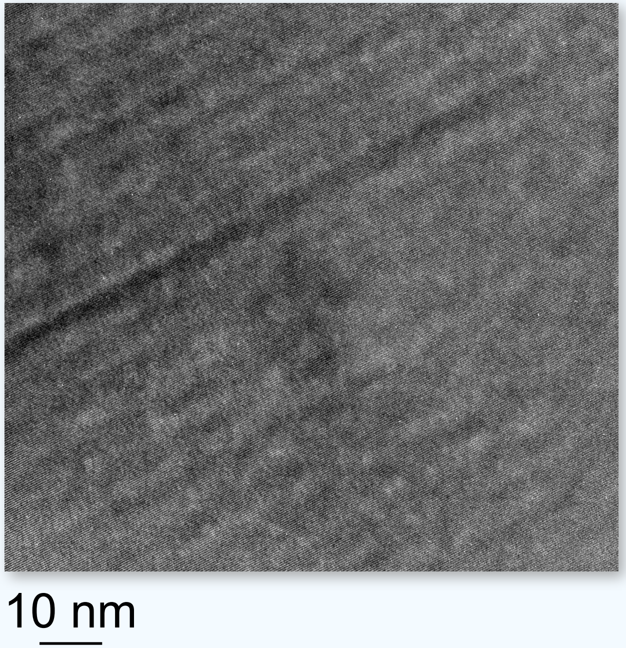
$\Delta T_f \rightarrow$ in-plane thermal conductivity $\kappa_{\parallel}$

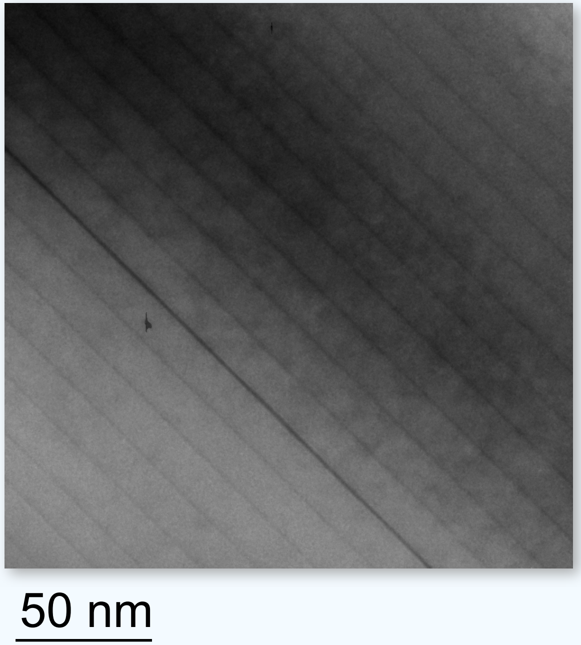
$\rightarrow$ cross-plane thermal conductivity $\kappa_{\perp}$

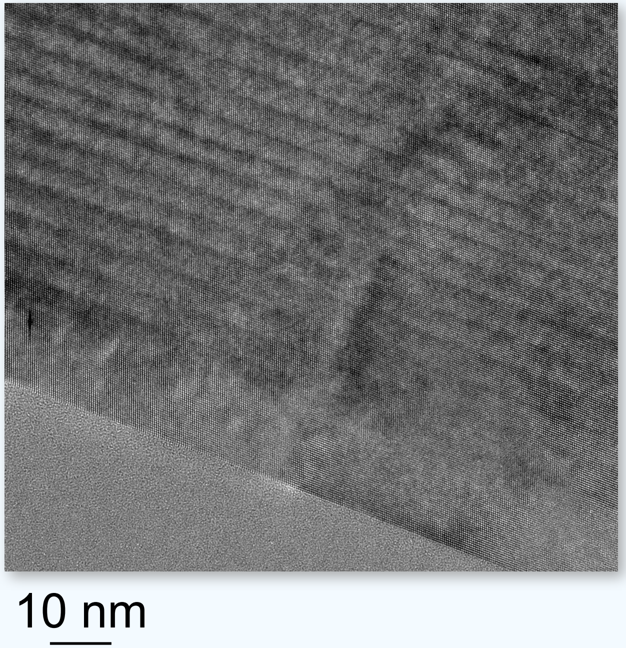


Bolometric temperature increase ΔT measured in a multilayer and a reference sample as a function of the frequency

Superlattices







0.2 nm Ge + 3.3 nm Si
171×, ≈ 600 nm

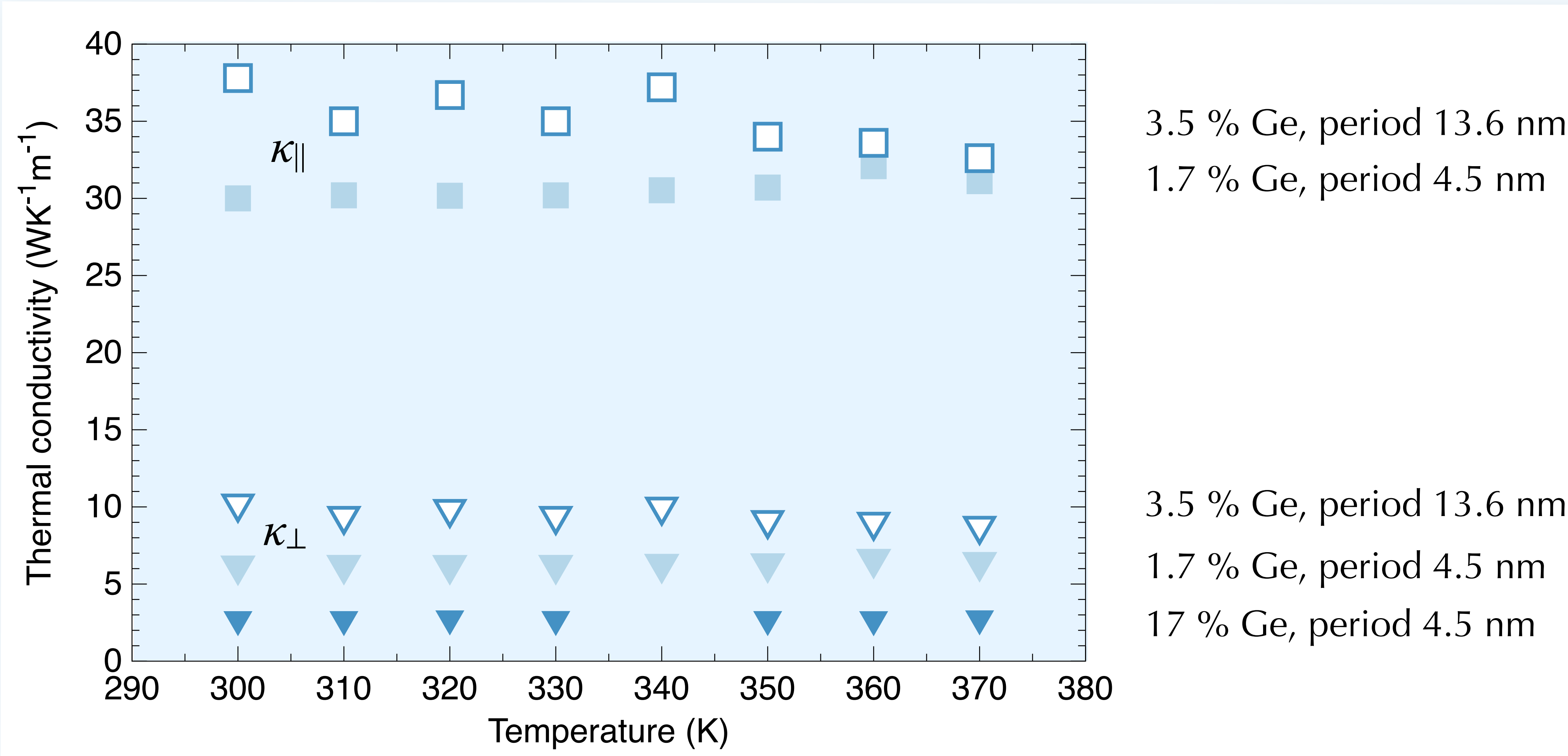
1.6 nm Ge + 12 nm Si
39×, ≈ 600 nm

2 nm Ge + 1.5 nm Si
171×, ≈ 600 nm

Ge content

1.7 %	3.5 %	17 %

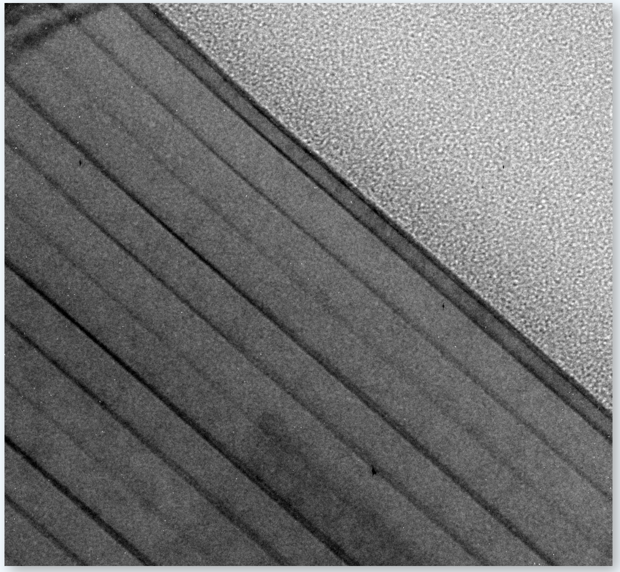
Thermal conductivity of periodic SL

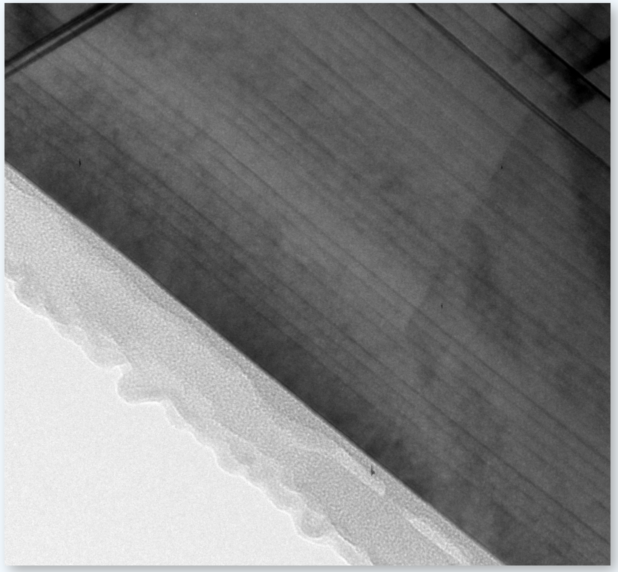


In-plane and cross-plane thermal conductivities for SLs with different Ge contents and periods

Random multilayers

20 nm



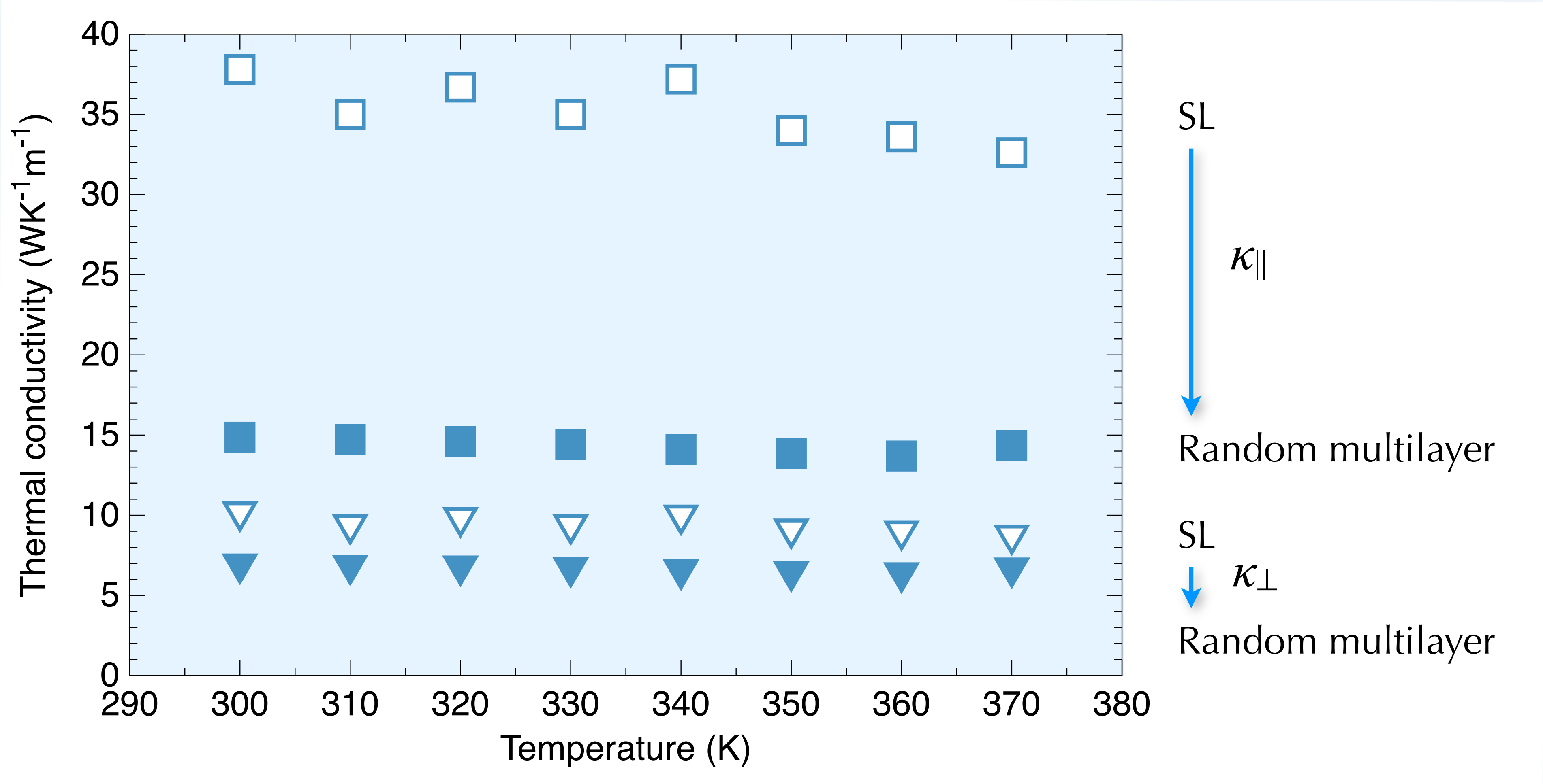


1.2 nm Ge + 12 nm Si	0.6 nm Ge + 4.1 nm Si
1.2 nm Ge + 12 nm Si	0.3 nm Ge + 5.1 nm Si
1.8 nm Ge + 12 nm Si	0.8 nm Ge + 4.8 nm Si
0.9 nm Ge + 12 nm Si	0.6 nm Ge + 5.7 nm Si
1.6 nm Ge + 12 nm Si	0.6 nm Ge + 3.8 nm Si
6×, ≈ 600 nm	34×, ≈ 940 nm

Ge content

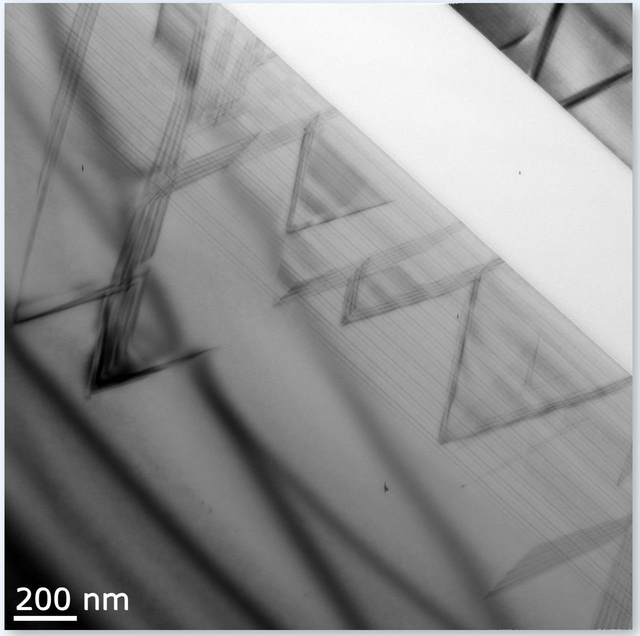
2.9 %	3.3 %

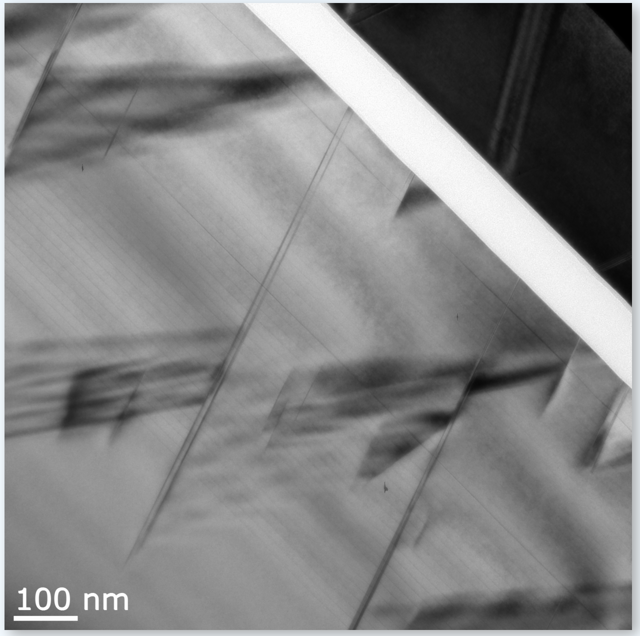
Results of random multilayers

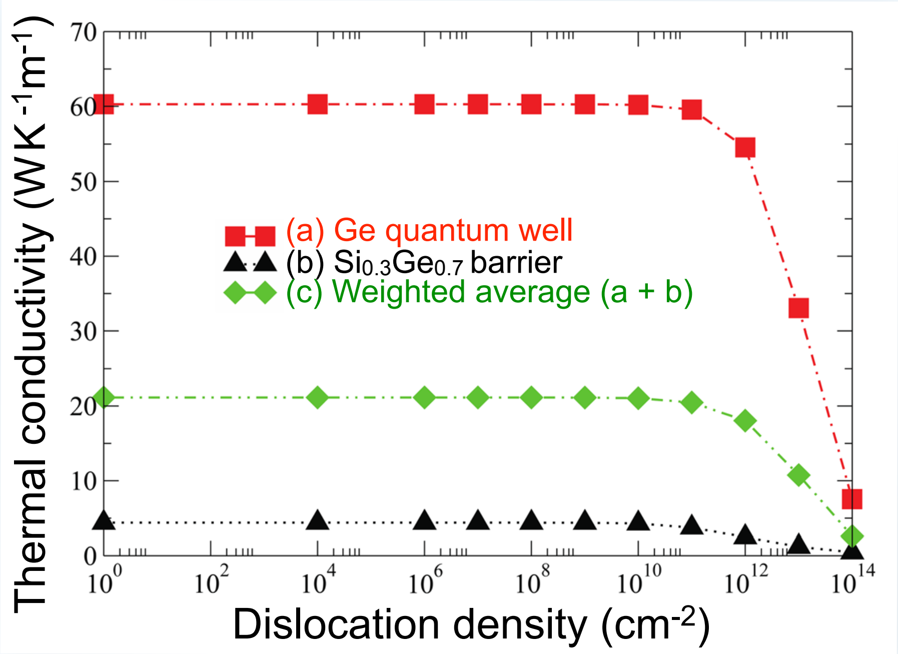


Thermal conductivities in a random multilayer (2.9 % Ge)
in comparison to a superlattice(3.5 % Ge).

Defect issues







[Watling, Paul: J Appl Phys **110** (2011) 114508]

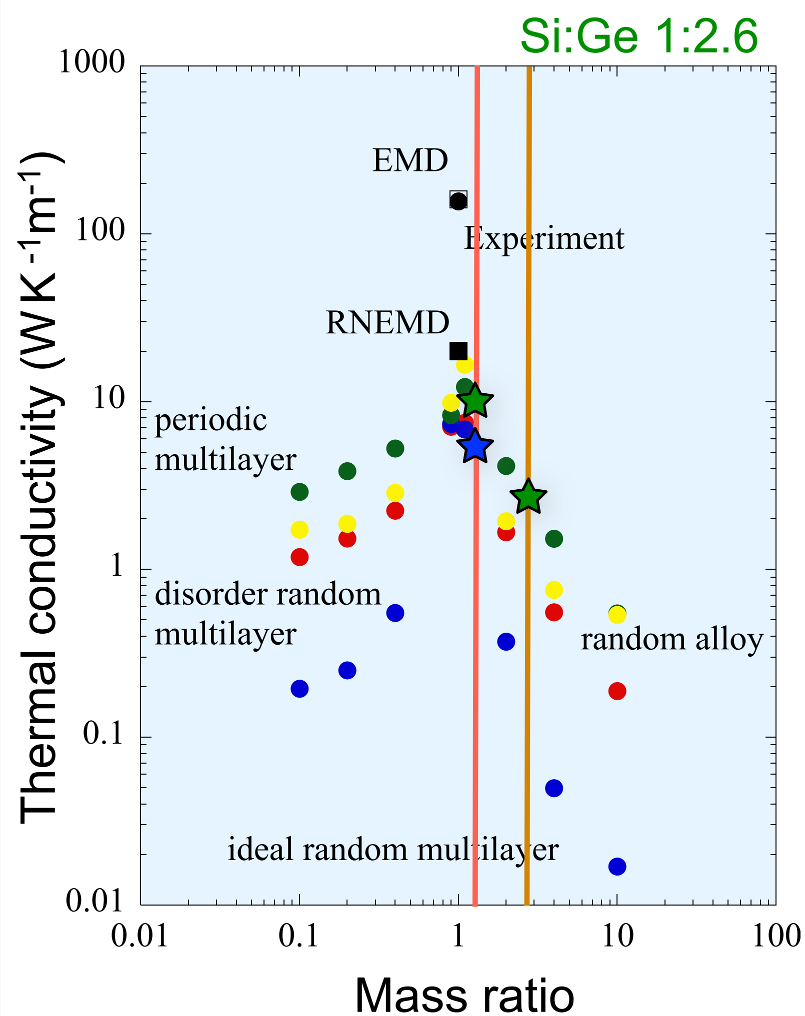
Conclusions

- Lowest $\kappa_\perp$ for SL with highest Ge content
- $\kappa_\perp$ a function of the SL period

  [cf. *e. g.* Rawat *et al*: J Appl Phys 105 (2009) 024909]
- Only a small reduction in $\kappa_\perp$ for random multilayers★ compared to SL★ observed due to low mass ratio in the multilayers investigated so far

  → With higher Ge content,

  0.1 W K^{-1}m^{-1} may be expected **!**
- Random multilayers exhibit a decrease in $\kappa_\parallel$ by ≈ 50 %



[Frachioni, White: J Appl Phys **112** (2012) 14320]

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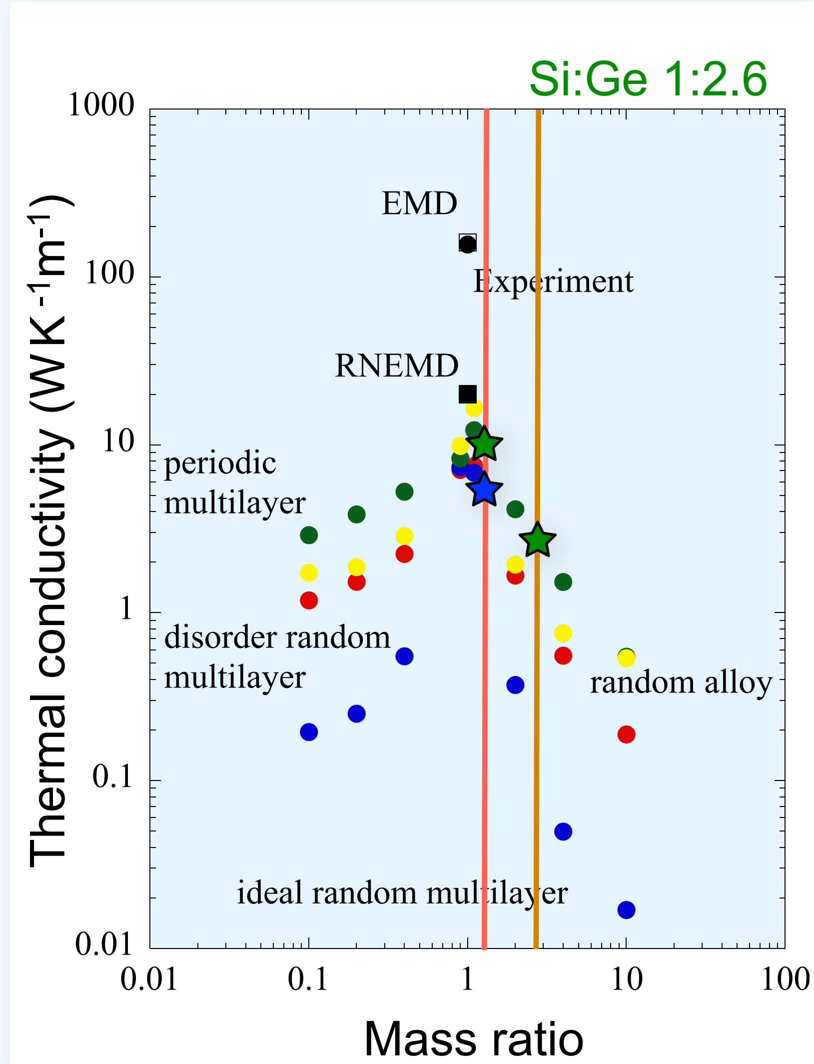

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References

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