DPG Frühjahrstagung (SKM),
Regensburg 13.03.2013

Thermal conductivity of SiGe-based nanostructures

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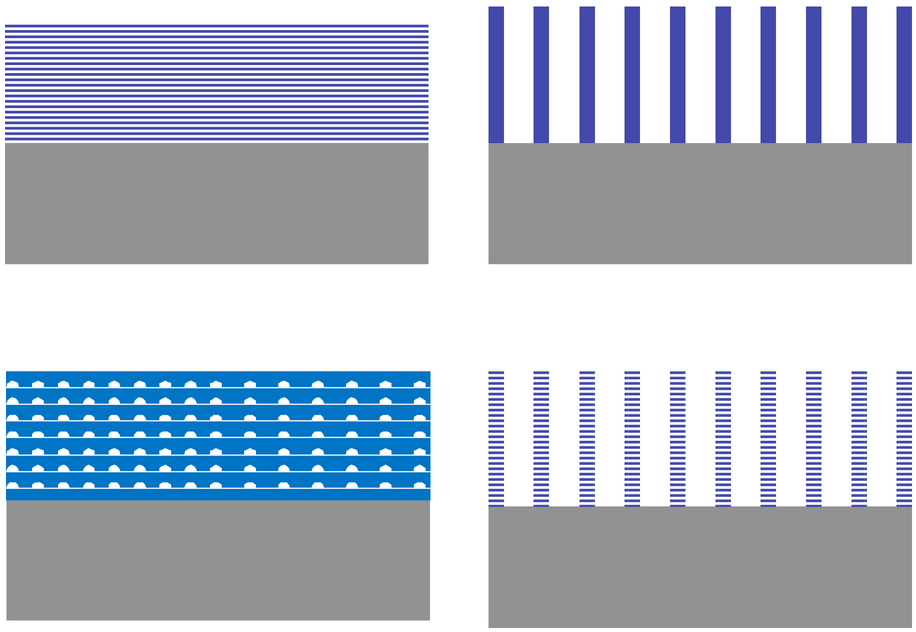
Reduction of the thermal conductivity

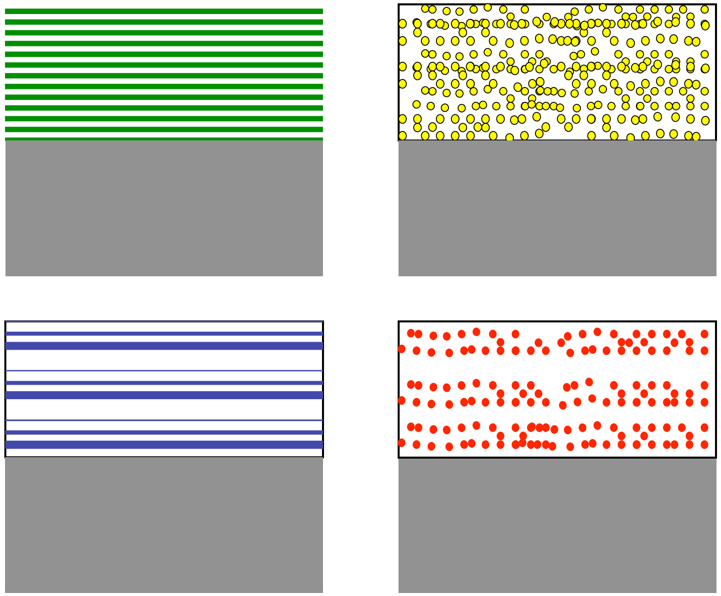
- Different approaches through nanostructures like
  - Superlattices (SL)
  - Nanowires (NW)
  - Quantum-dot superlattices (QDSL)
  - Nanowires containing superlattices (SLNW)



Reduction of the thermal conductivity

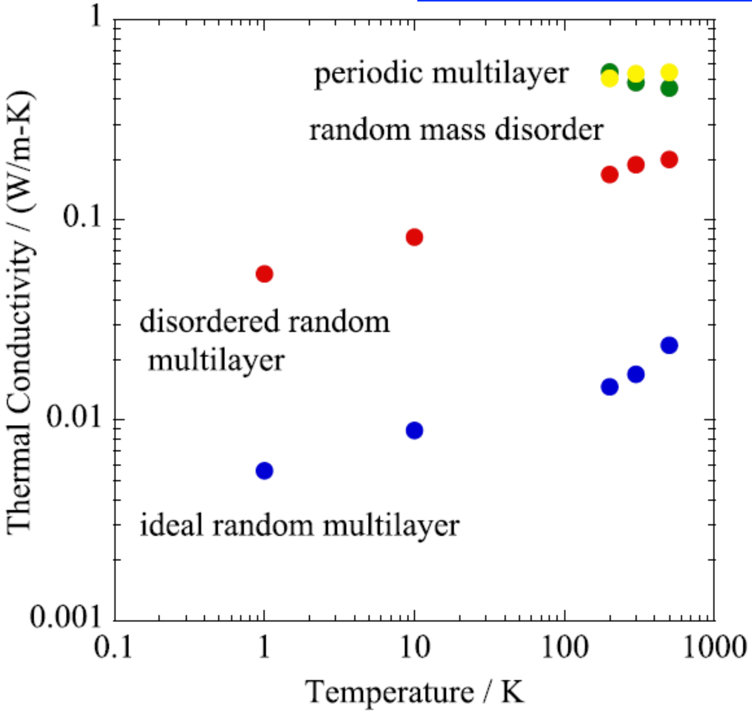
In the case of superlattices a further reduction can be achieved by non-periodic structures

-> localized phonon states



Mass ratio Si:X = 1:10

$Si_{0.8}X_{0.2}$

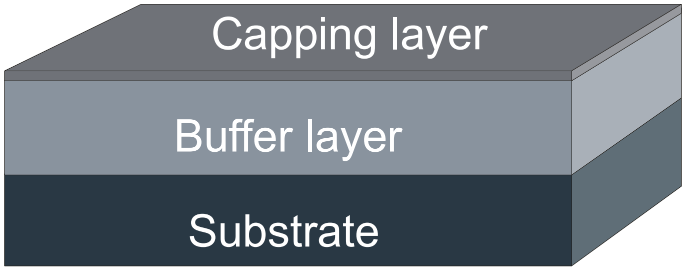


A. Frachioni et al., JAP 112, 014320 (2012)

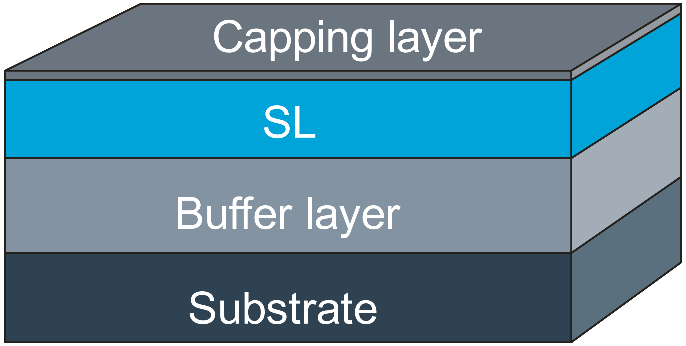
Sample preparation

Periodic and non-periodic SLs were grown by molecular beam epitaxy (MBE)

- Substrate Temperature ~550 K
- Substrate Si (111)
- Si Buffer layer (600 nm)
- Capping layer (10 nm)
- Reference sample without SL



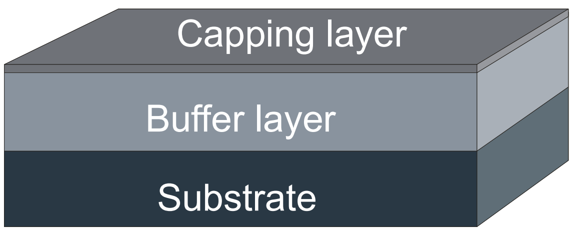
Reference sample

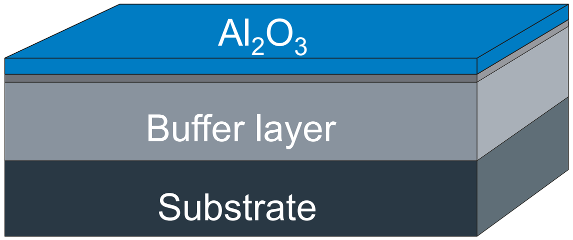


Superlattice sample

Measurement setup

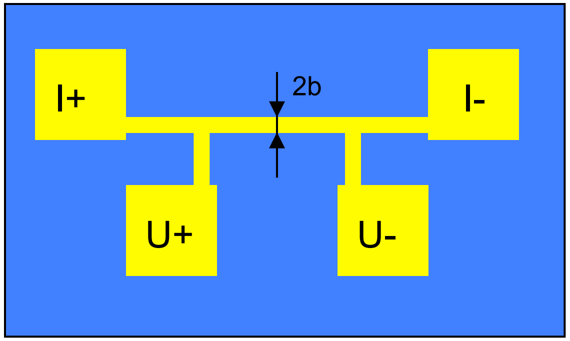
- Thermal conductivity was measured by the 3-Omega method
- Electrical insulating layer -> Al_2O_3
- Bolometer stripes with different lengths (400 µm, 600 µm, 800 µm) and widths (3 µm, 5 µm, 6µm, 8 µm, 10 µm) were deposited on top





$$V = R_0 I_0 \cos\omega t + \frac{R_0 I_0}{2}\alpha \cdot \Delta T \ \cos(\omega t + \varphi) + \frac{R_0 I_0}{2}\alpha \cdot \Delta T \ \cos(3\omega t + \varphi)$$

$$\Delta T = \frac{P_l}{\pi\lambda}\left[-\frac{1}{2}\ln(2\omega) + \frac{1}{2}\ln\frac{\lambda}{\rho c_p b^2} + \eta\right]$$

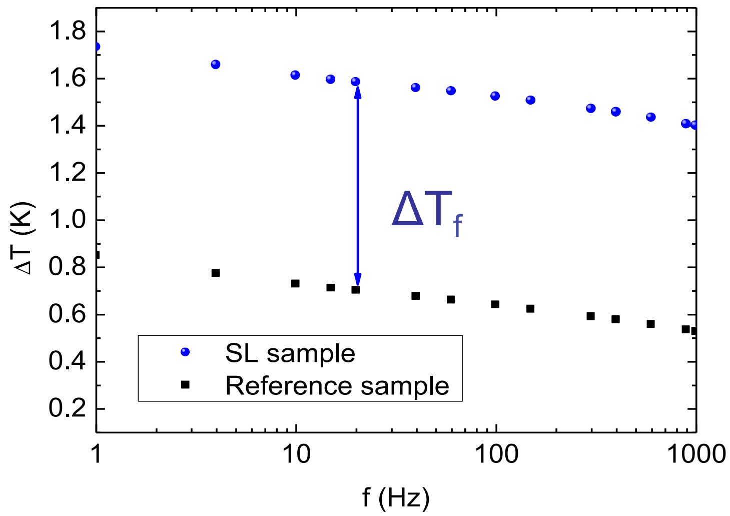


Measurement setup

One-dimensional heat flow:

Measurement with one bolometer stripe ($2b \gg d_f$)

$$\Delta T_f = \frac{P_l d_f}{2b\lambda_{f1D}}$$



Two-dimensional heat flow:

Measurement with different bolometer stripes ($2b_1$, $2b_2$)

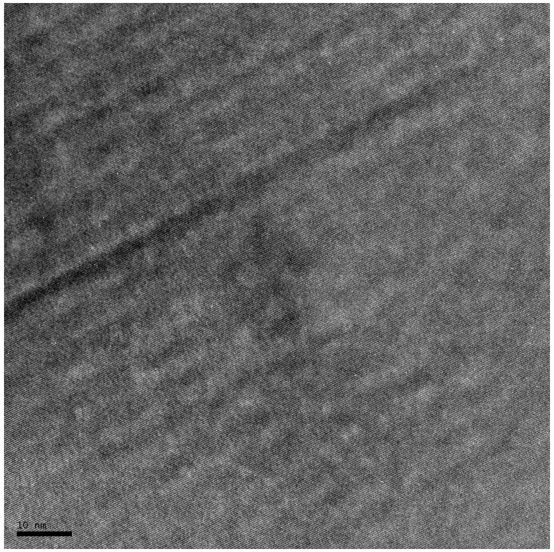
$$\Delta T_f = \frac{P_l d_f}{2b\lambda_{fy}} CS$$

$$C = 1 - \lambda_{fx} \cdot \lambda_{fy} / \lambda_s^{2} \qquad \beta_f = \sqrt{\lambda_{fx} / \lambda_{fy}} \cdot d_s / b$$

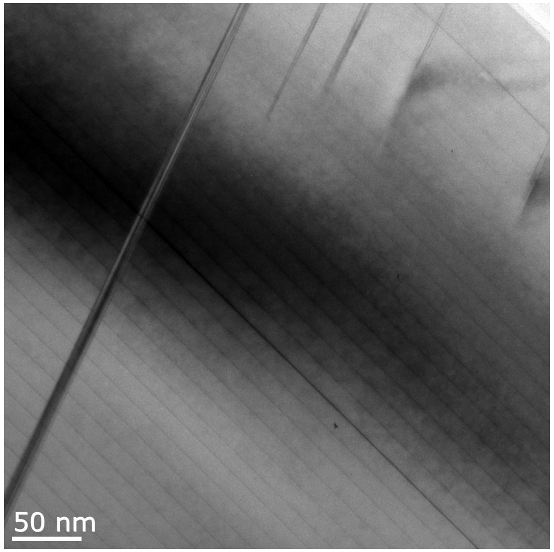
$$S = 2/\pi \int_0^{\infty} \frac{Sin^2\alpha}{\alpha^3} \cdot \frac{Tanh(\alpha \cdot \beta_f)}{(1 + \sqrt{\lambda_{fy} \cdot \lambda_{fx}} / \lambda_s \cdot Tanh(\alpha \cdot \beta_f)) \cdot \beta_f} d\alpha$$

thermal conductivity
in-plane λ_{fx}
cross-plane λ_{fy}

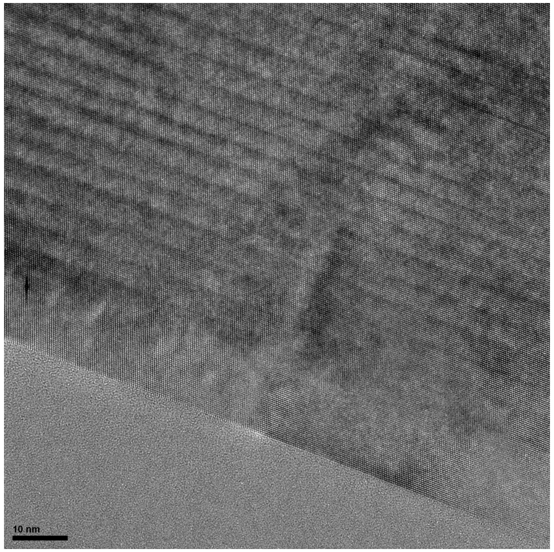
Samples with periodic layer thickness



111026
0.2 nm Ge + 3.3 nm Si
171 times ~ 600 nm



120605
1.6 nm Ge + 12 nm Si
39 times ~ 600 nm

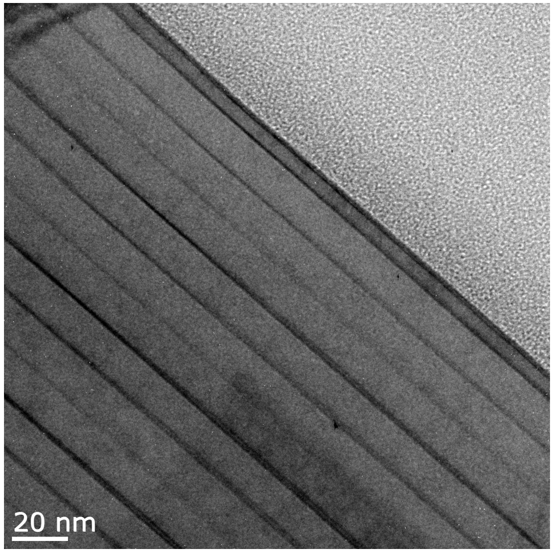


101214
2 nm Ge + 1.5 nm Si
171 times ~ 600 nm

Ge Content

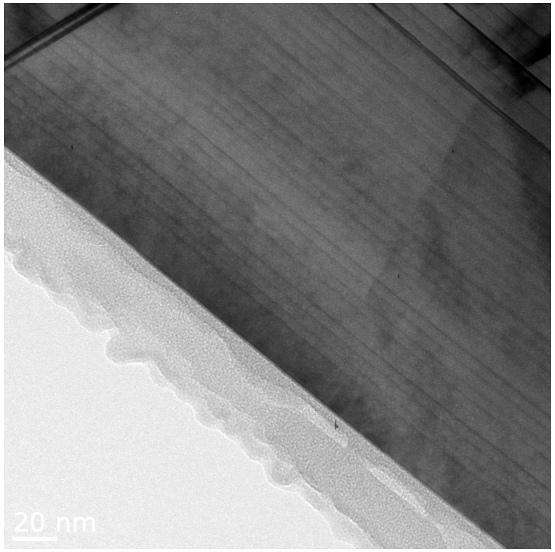
1.7 % — 3.5 % — 17 %

Samples with non-periodic layer thickness



Ge content 2.9 %

1.1 nm Ge + 12 nm Si
1.2 nm Ge + 12 nm Si
1.8 nm Ge + 12 nm Si
1.1 nm Ge + 12 nm Si
0.9 nm Ge + 12 nm Si
1.6 nm Ge + 12 nm Si
6 times ~ 600 nm

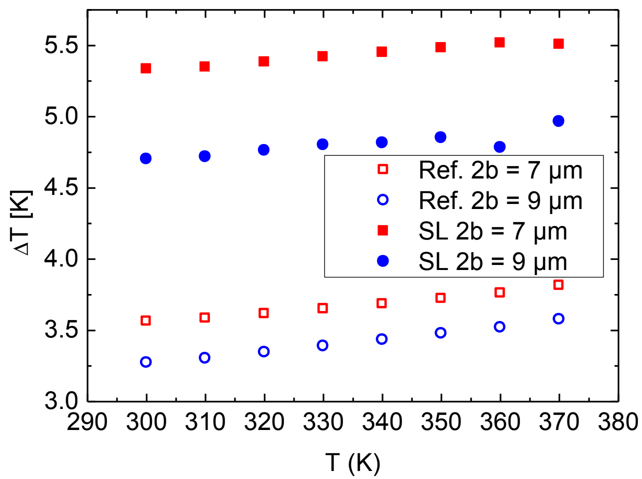


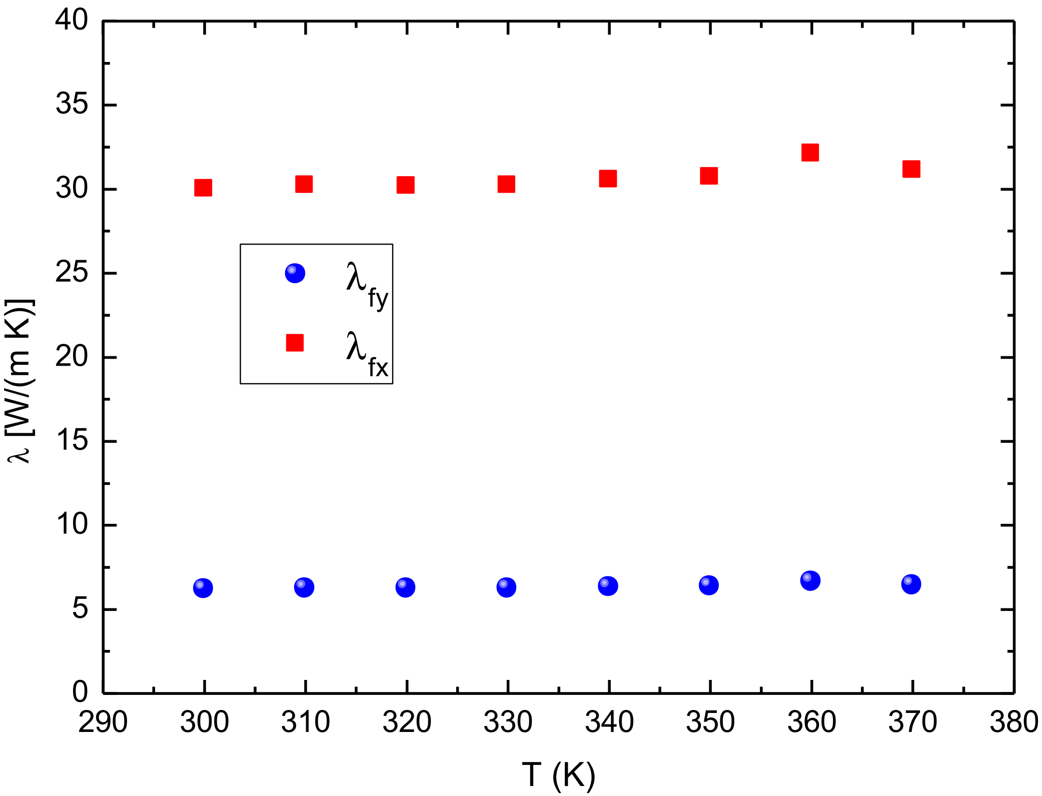
Ge content 3.3 %

0.6 nm Ge + 4.1 nm Si
0.3 nm Ge + 5.1 nm Si
0.8 nm Ge + 4.8 nm Si
0.6 nm Ge + 5.7 nm Si
0.6 nm Ge + 3.8 nm Si
34 times ~ 940 nm

Thermal conductivity of periodic SLs

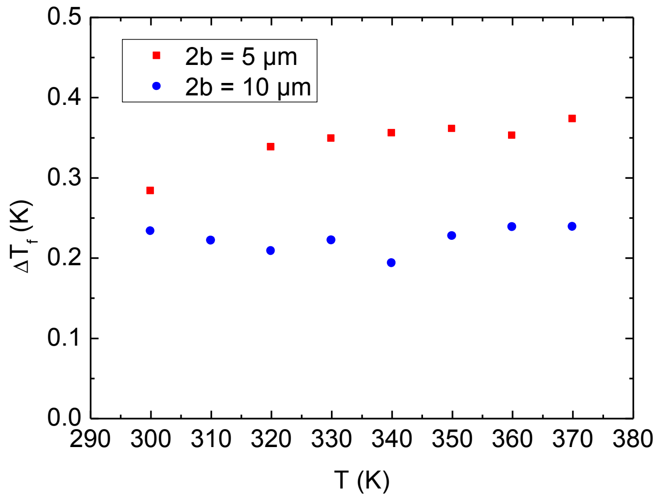
- Ge content 1.7 %

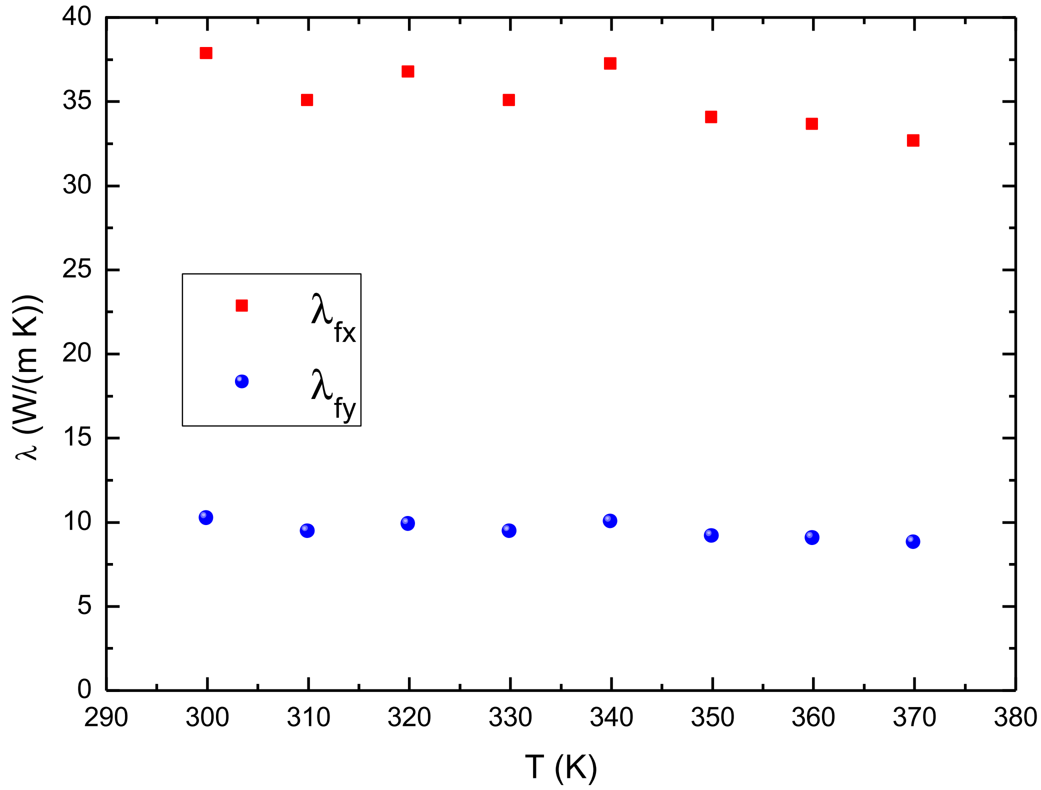




Thermal conductivity of periodic SLs

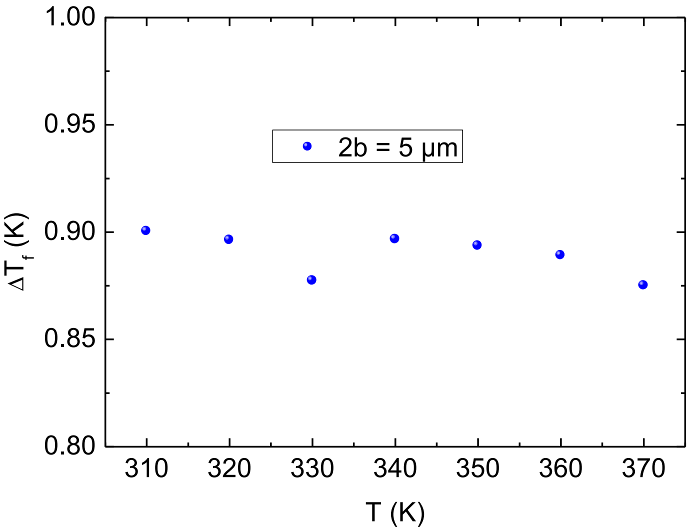
- Ge content 3.5 %

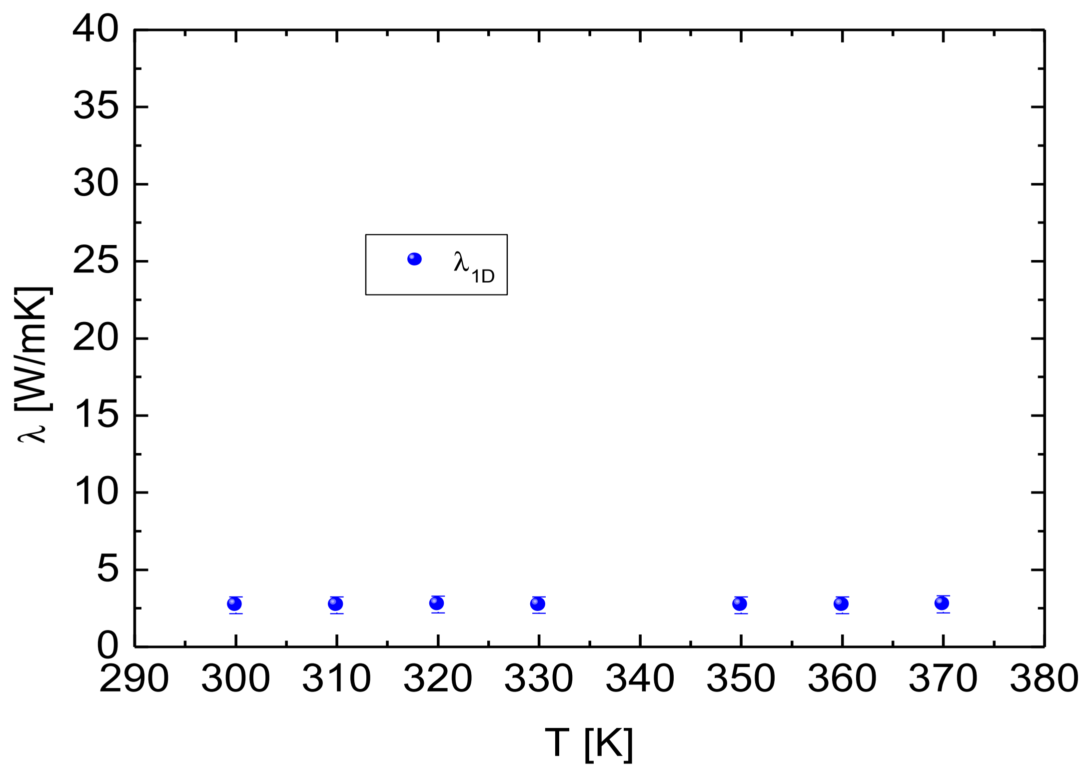




Thermal conductivity of periodic SLs

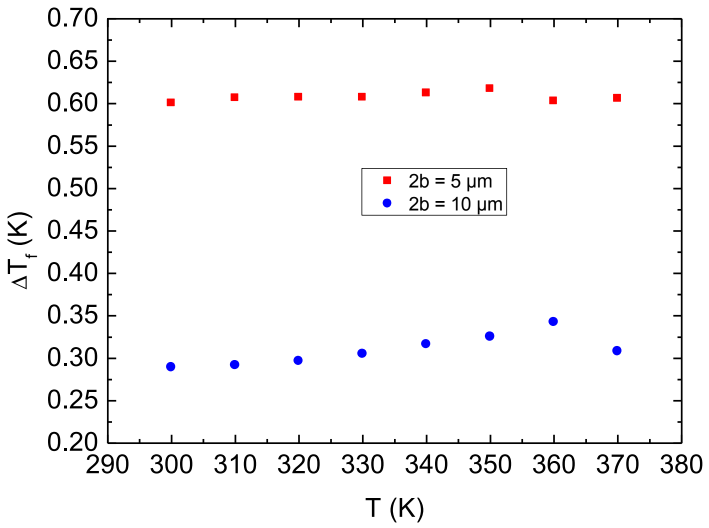
Ge content 17%

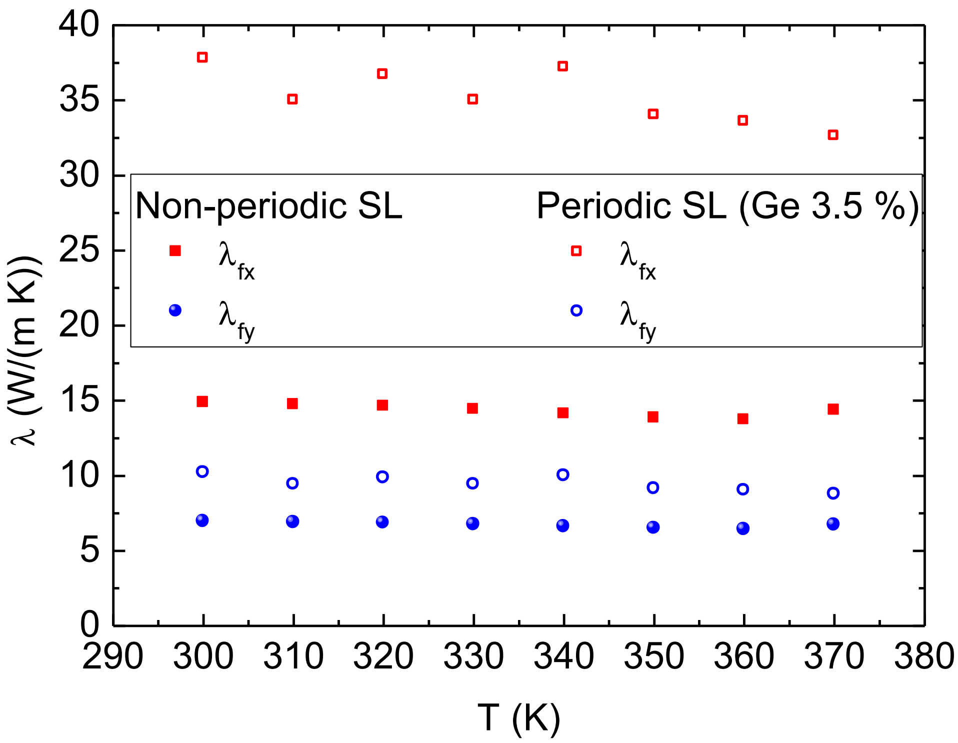




Thermal conductivity of non-periodic SLs

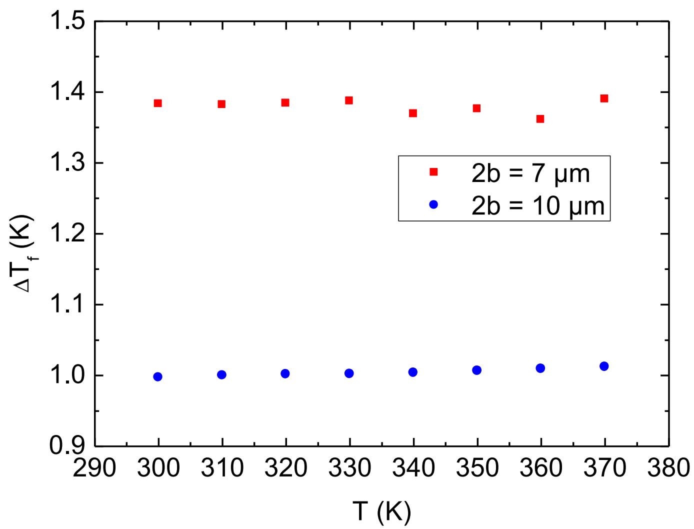
Ge content 2.9 %

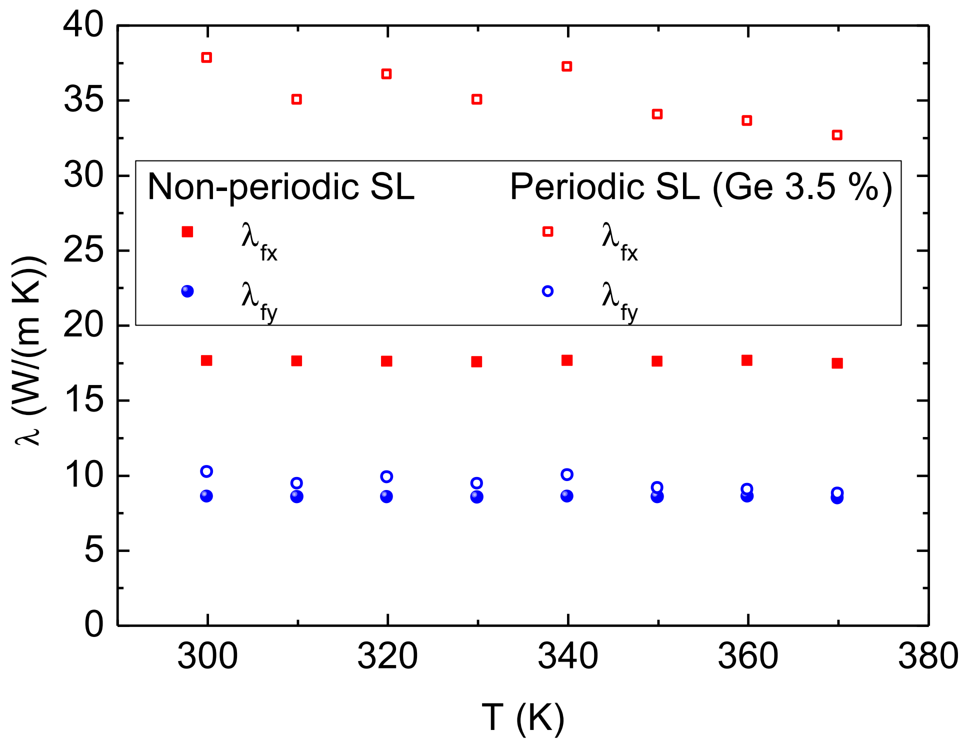




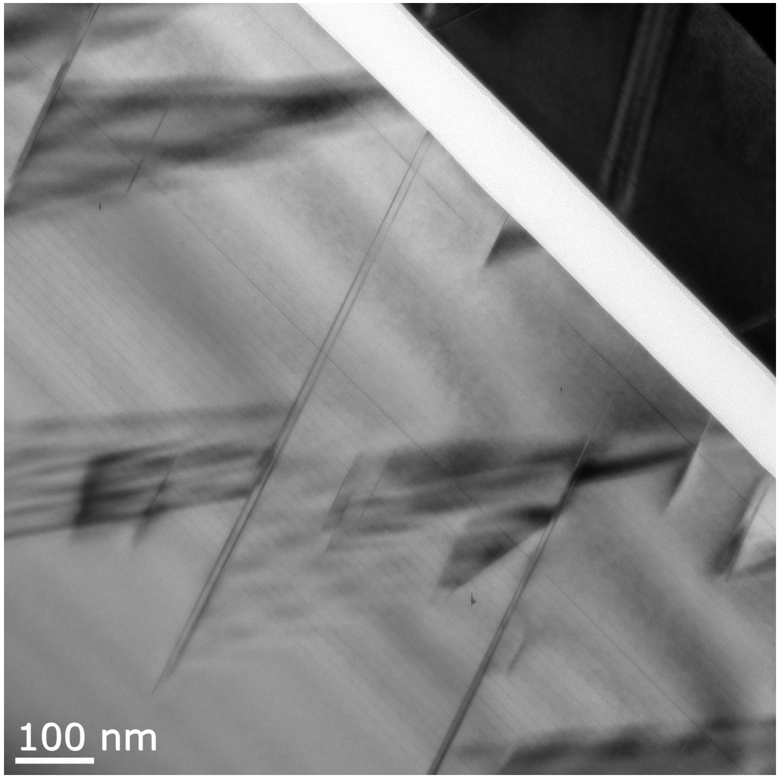
Thermal conductivity of non-periodic SLs

Ge content 3.3 %

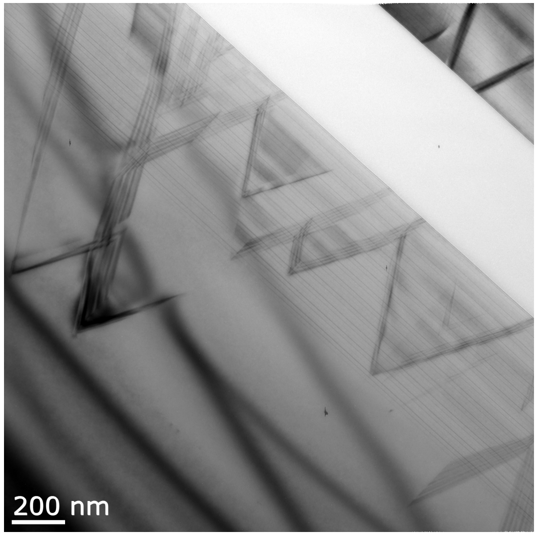




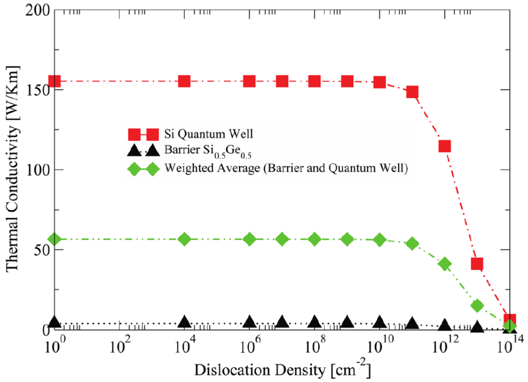
Defects in MBE grown films



Ge content 3.5 %



Ge content 2.9 %

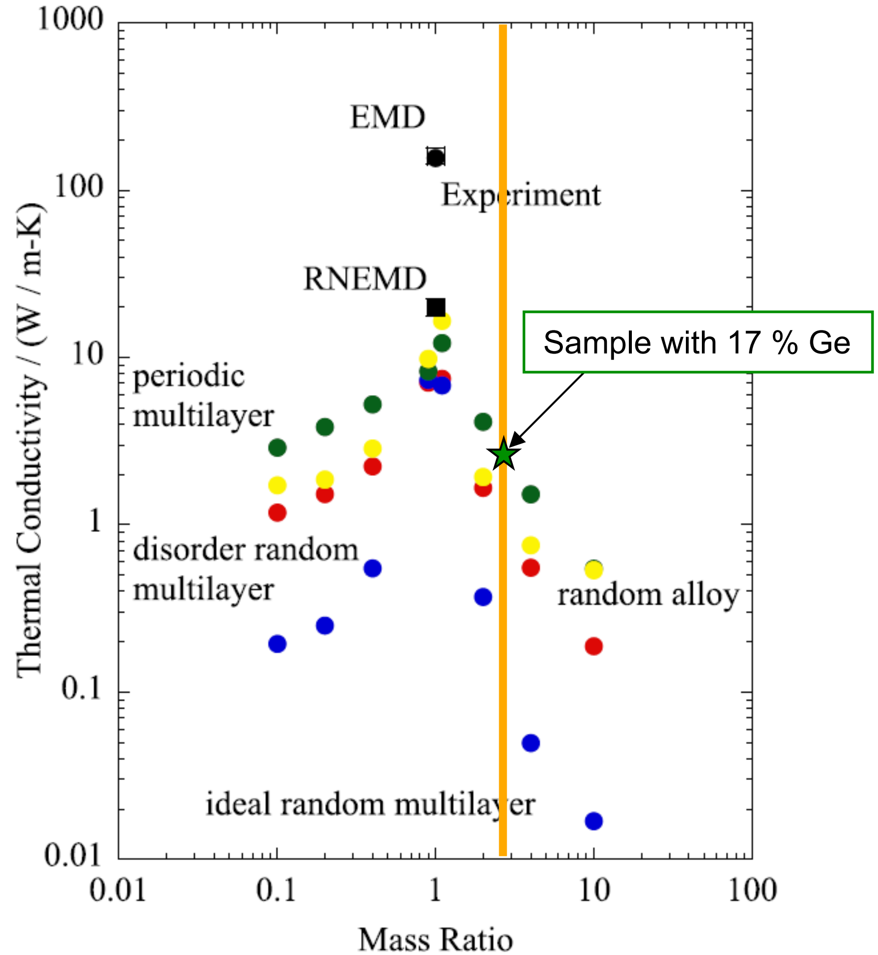


J. R. Watling et al., JAP **110**, 114508 (2011)

Conclusions & Outlook

- lowest thermal conductivity for the periodic SL with the highest Ge concentration
- a distinct reduction of the cross-plane thermal conductivity through non-periodicy was not observed
  - theoretical predictions for a material X concentration of 20% with mass ratio Si:X =1:10
  - ➢ Increase Ge concentration
- non-periodicy leads to a 50 % decrease of the in-plane thermal conductivity

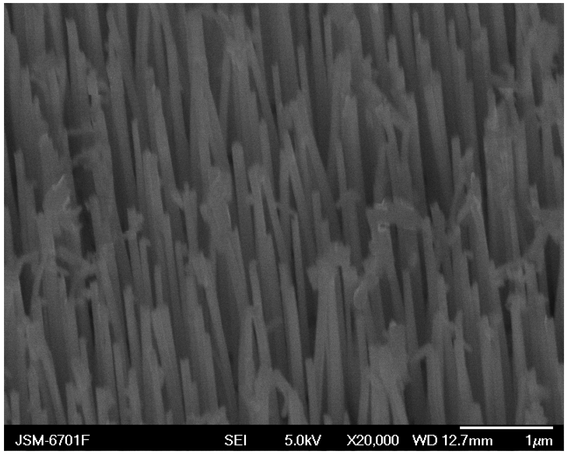
Si:Ge 1:2.6



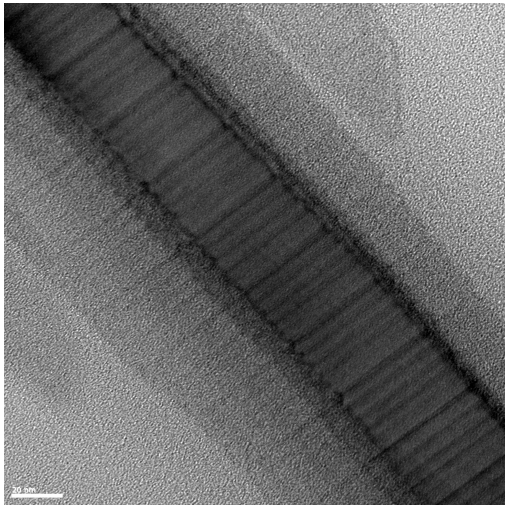
A. Frachioni et al., JAP 112, 014320 (2012)

Conclusions & Outlook

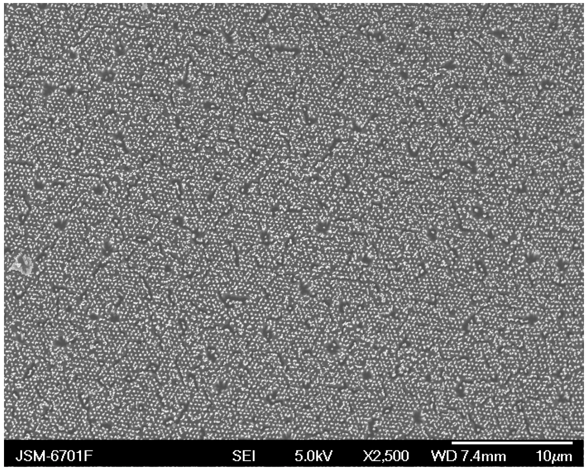
- Thermal conductivity of SLNW Arrays



Array of nanowires



Nanowire containing SiGe SL



Embedded nanowire array for thermal conductivity measurement

Thank you!

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