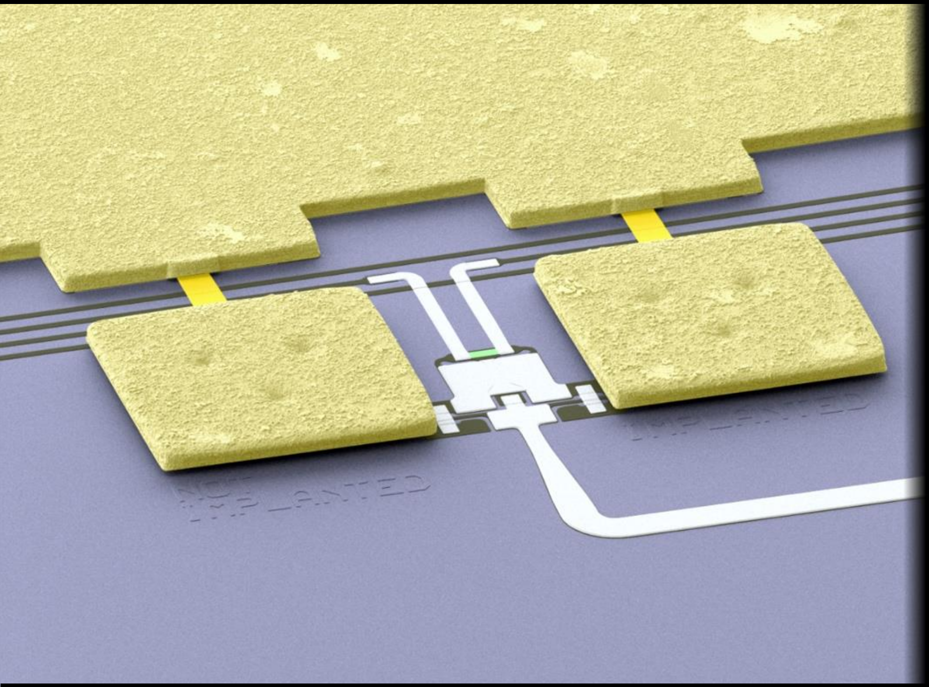
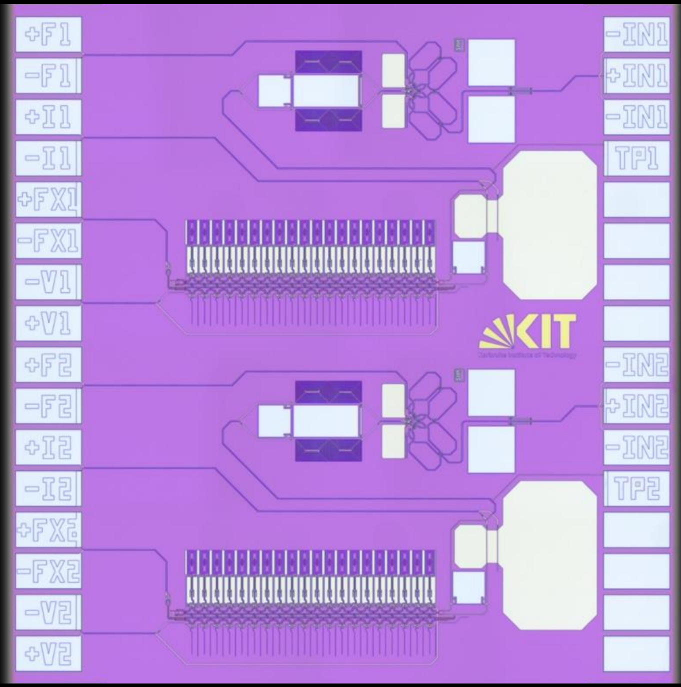
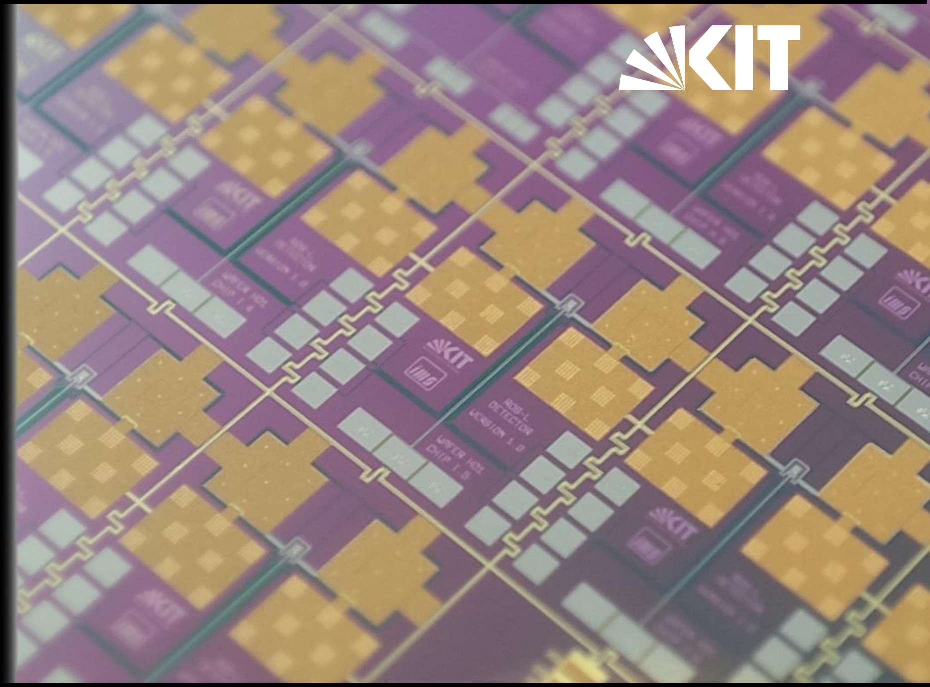




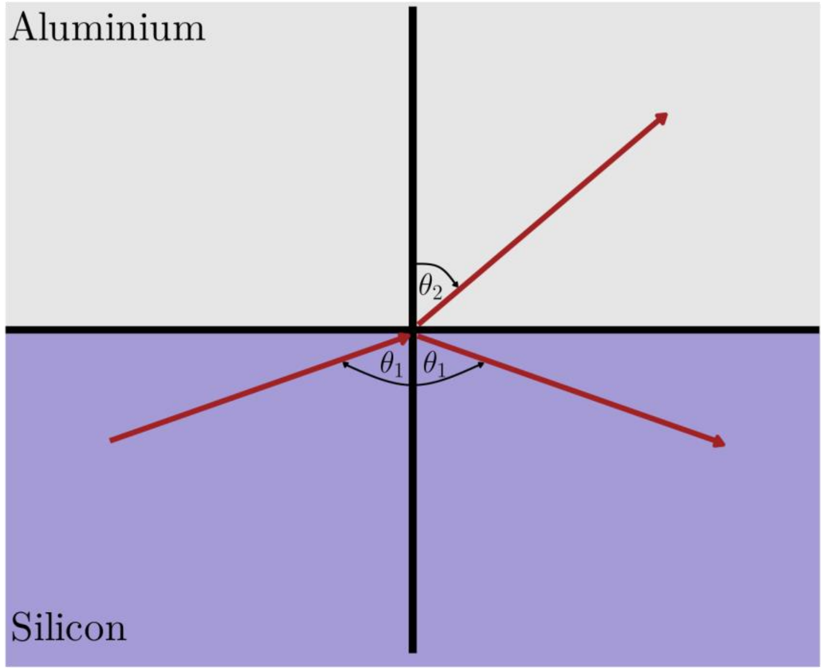


MMC R&D: Thermal and Athermal Detector Experiment

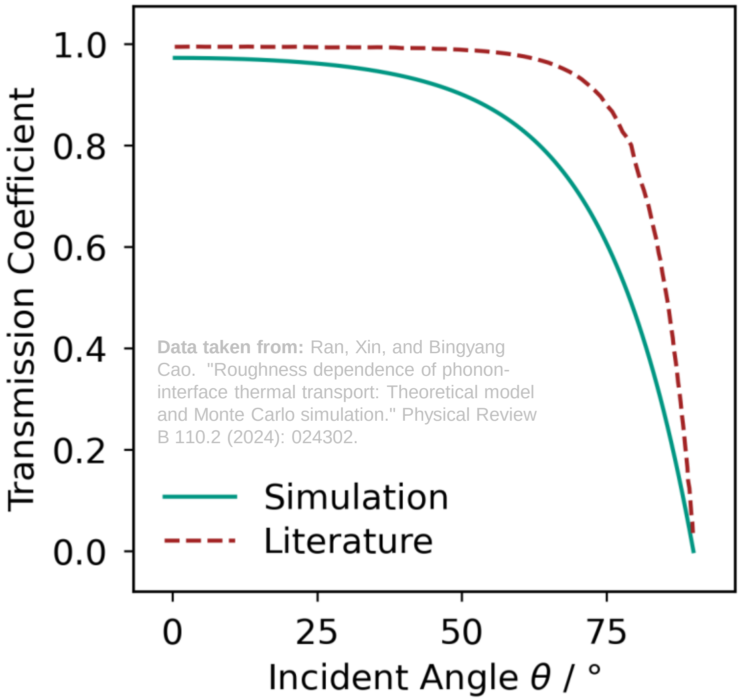
Friedrich Wagner
Institut für Mikro- und Nanoelektronische Systeme (IMS)
DELight Collaboration Meeting | Freiburg | 18th June, 2025

Rise Time Simulations – Athermal Detector

- Phonon collection time depends on transmission coefficient and collector coverage of crystal surface



Assuming flat surface and constant phonon velocities

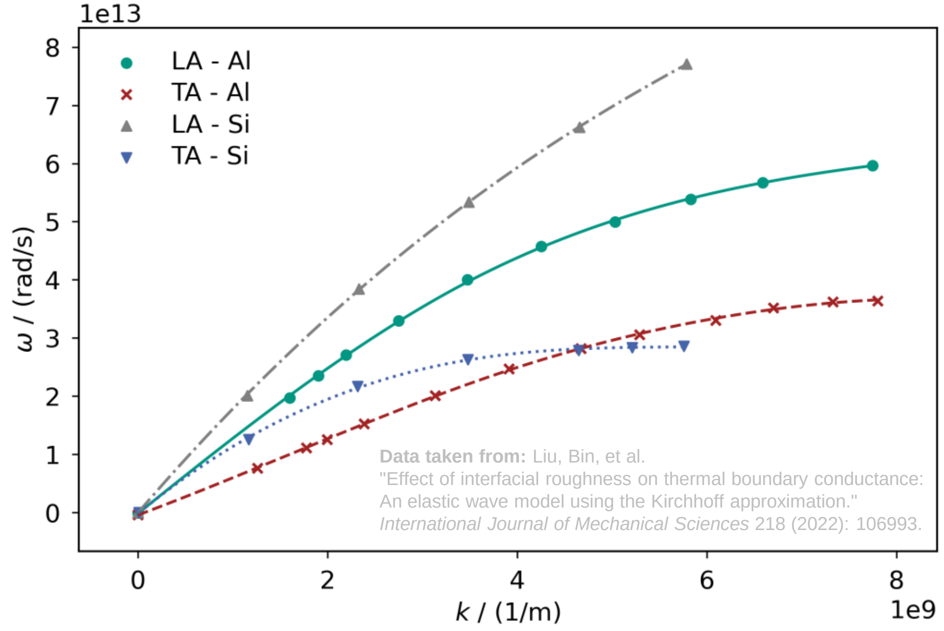


- Acoustic Mismatch Model:
  - Transmission coefficient depends on material densities, phonon velocities, and phonon incident angle.

Simulation values deviate significantly from literature ☹

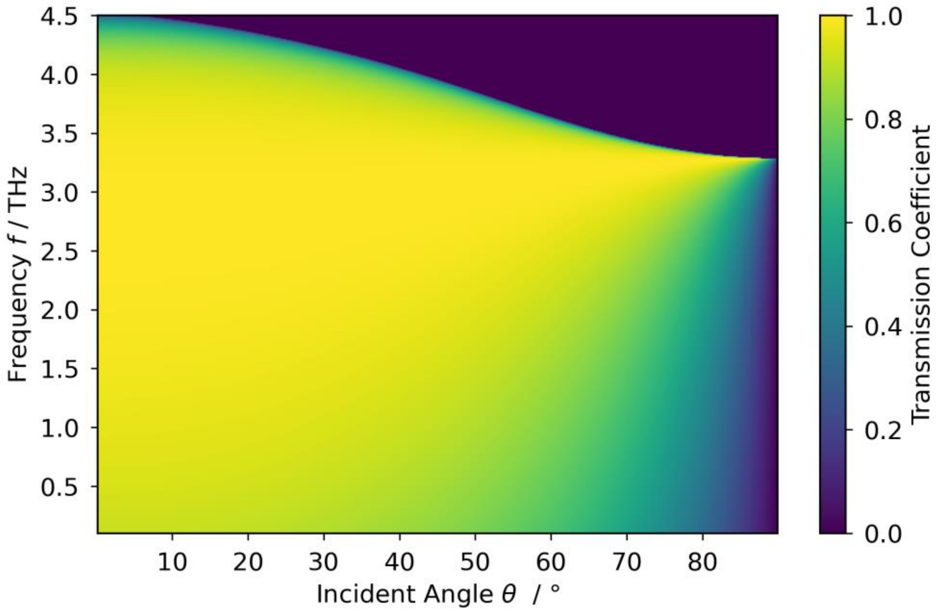
Rise Time Simulations – Phonon Frequency Consideration

Phonon Frequencies



- Calculate $v_g = \frac{\delta\omega}{\delta k}$ using Si/Al dispersion relation data

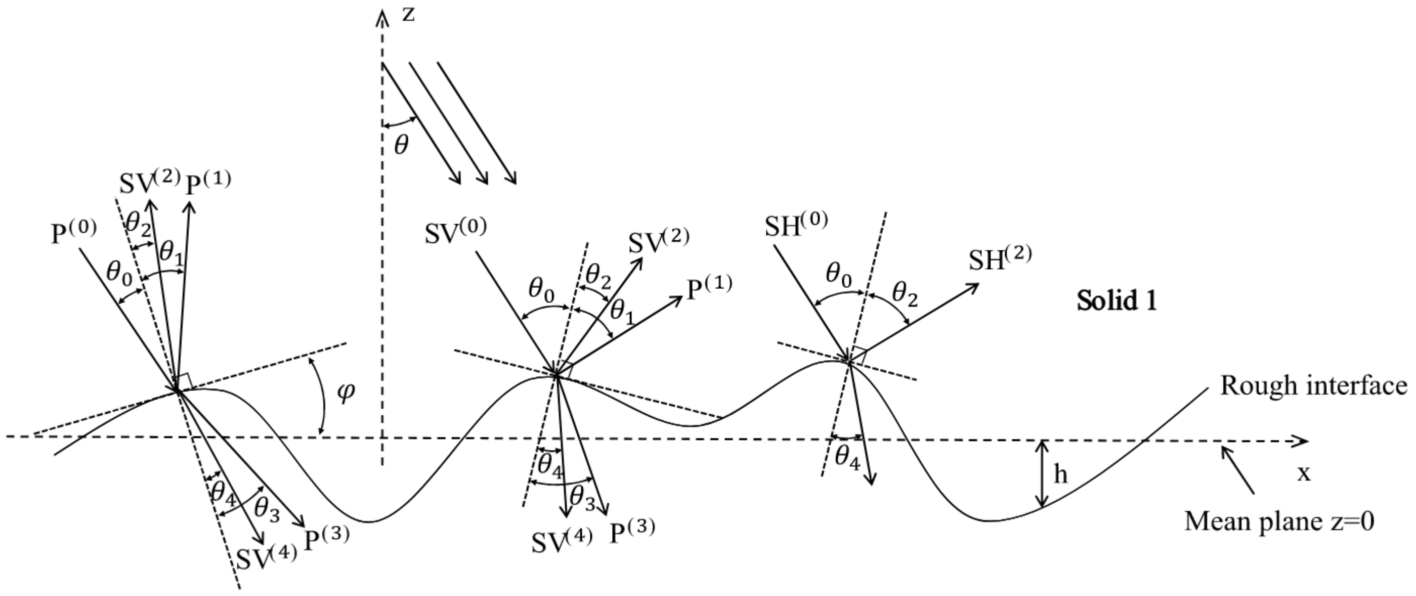
Transmission Coefficient



- Calculated with Acoustic Mismatch Model

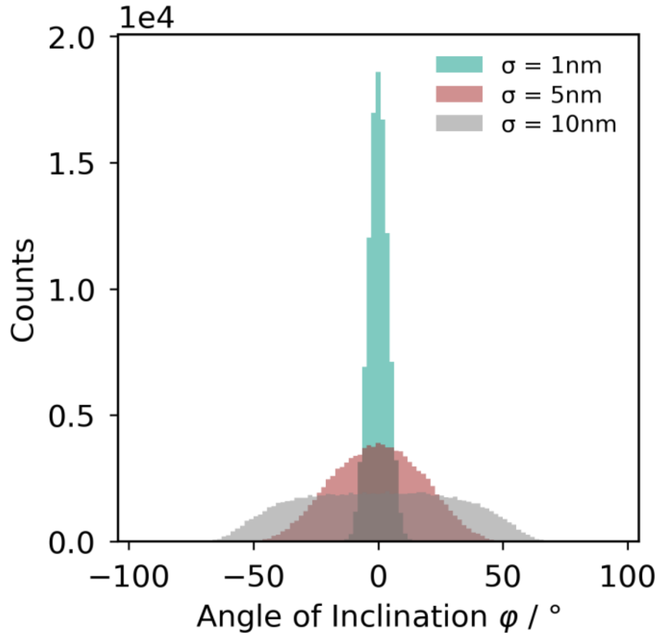
Rise Time Simulations – Surface Roughness Consideration

Recalculation of incident angle (Θ) dependent on angle of inclination (φ)



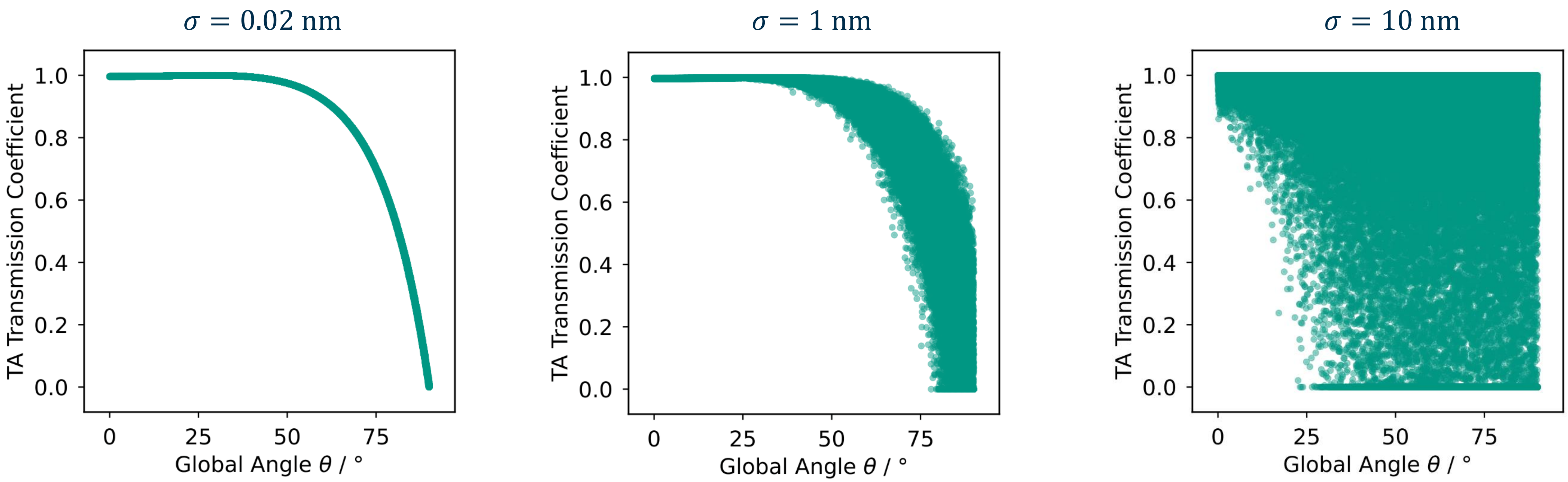
Liu, Bin, et al. "Effect of interfacial roughness on thermal boundary conductance: An elastic wave model using the Kirchhoff approximation." *International Journal of Mechanical Sciences* 218 (2022): 106993.

Distribution angle of inclination (φ)



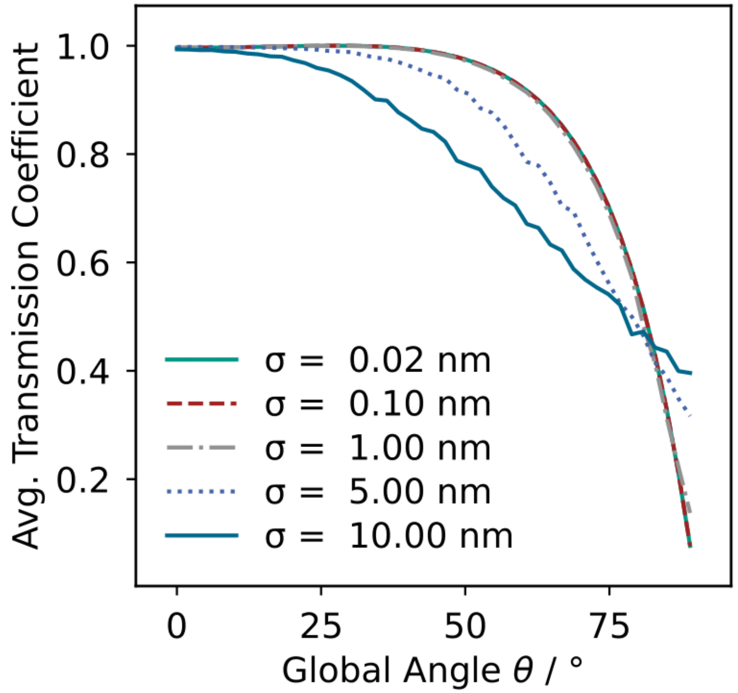
Rise Time Simulations – Surface Roughness Consideration

- Monte carlo simulation different surface roughnesses (σ):
  - Taking $n_\theta = 100000$ global incident angles (uniformly distributed between 0 and 90°)
  - Taking $n_\phi = 100000$ angles of inclination (using the gausian distribution function)
  - Calculating actual incident angle and transmission coefficients using phonons with $f = 3.18\ \mathrm{THz}$



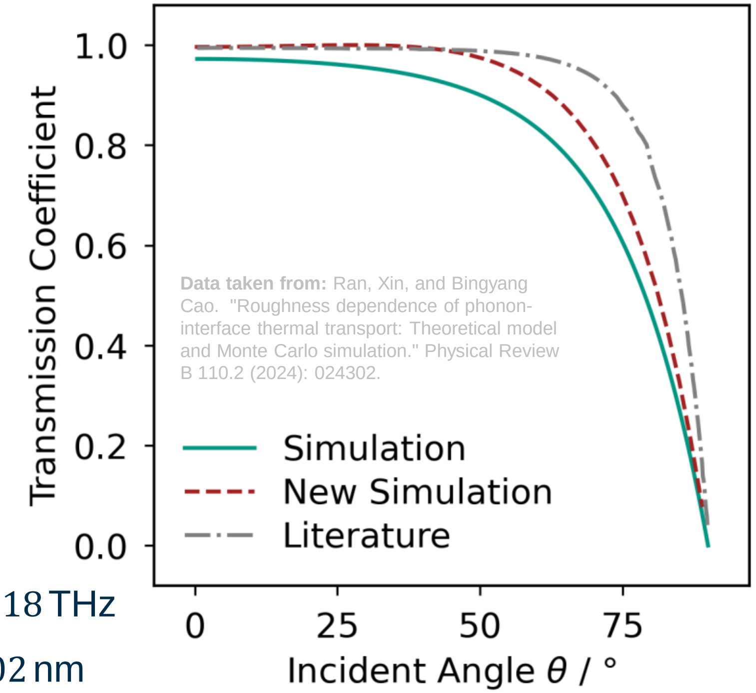
Rise Time Simulations – Transmission Coefficient

Taking the Transmission Coefficient Averages for All Incident Angles



- A higher surface roughness results in a smaller transmission coefficient.

Comparison with Literature

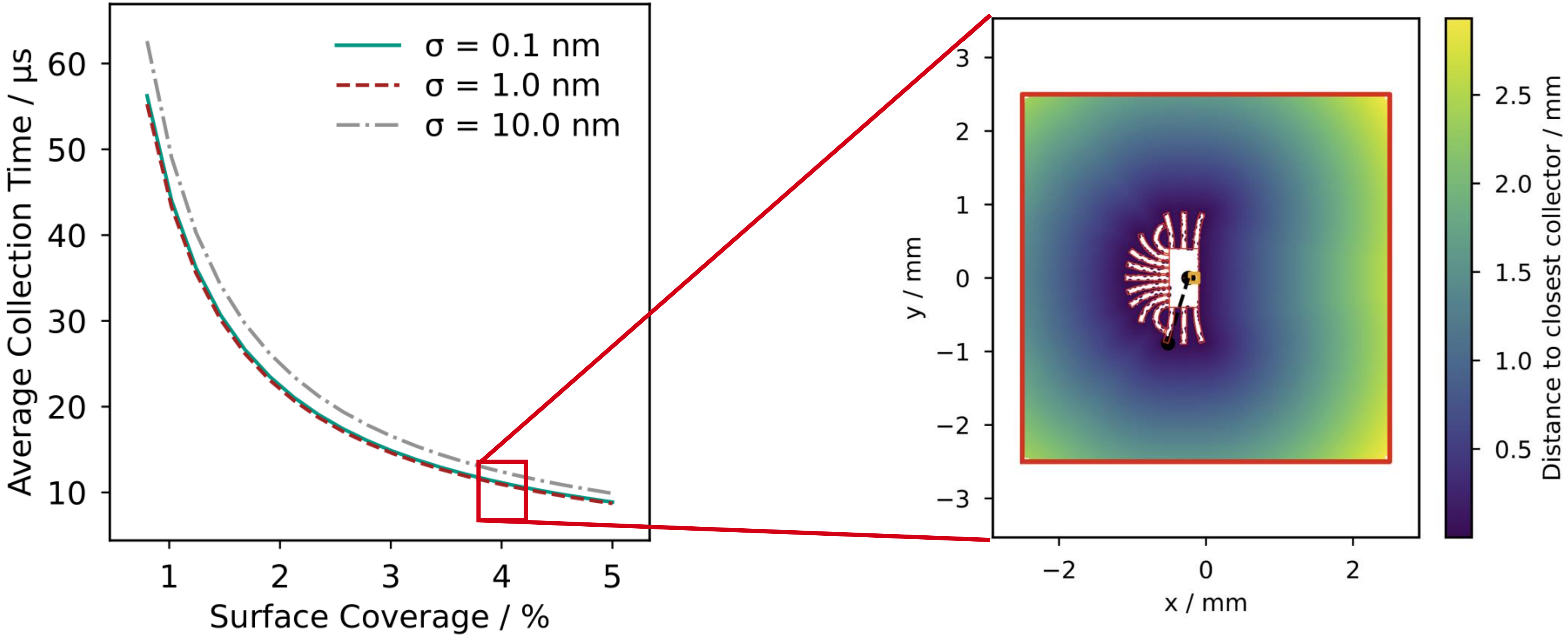


$f = 3.18\,\mathrm{THz}$

$\sigma = 0.02\,\mathrm{nm}$

- Not perfect but better

Rise Time Simulations – Prototype Athermal Detector

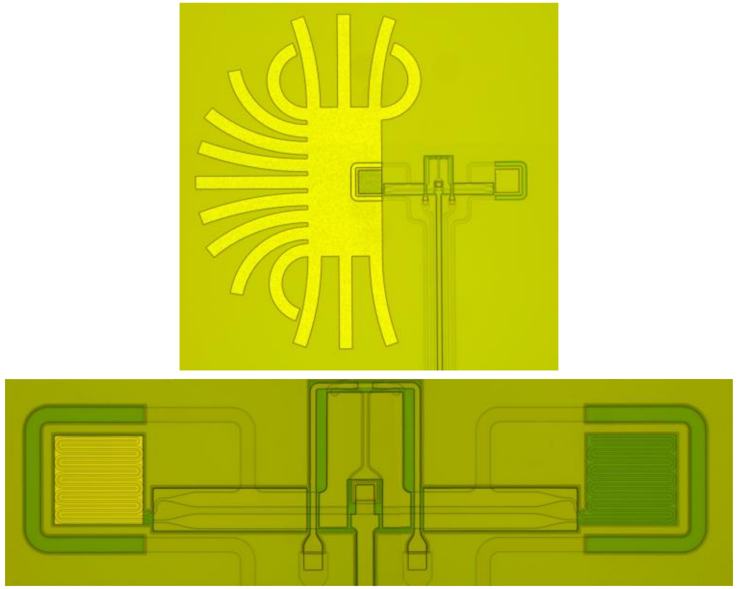


Using transmission coefficient to calculate phonon collection time

Prototype 4% collector coverage ~10 µs simulated rise time.

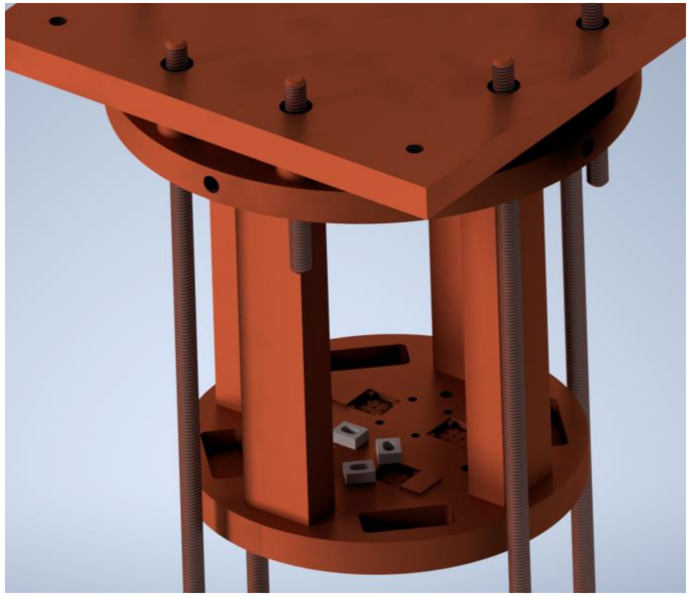
Current Status of the Experiment

Detector Chips



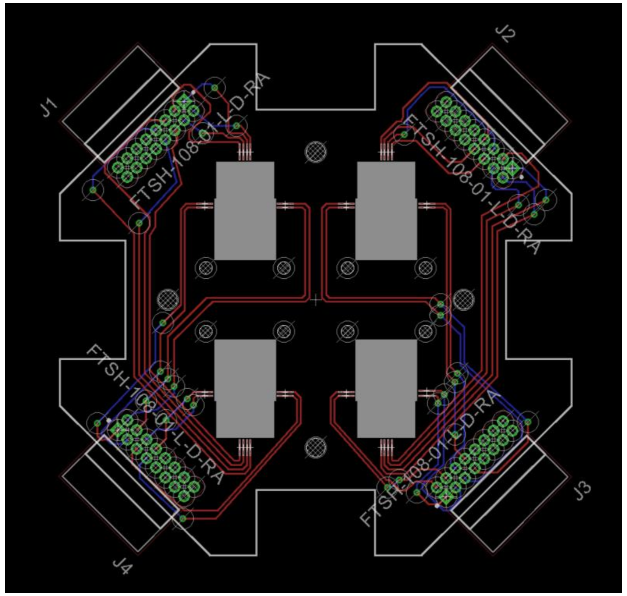
- Detector chips have been fabricated

Measurement Setup



- Measurement setup is currently in production by the workshop

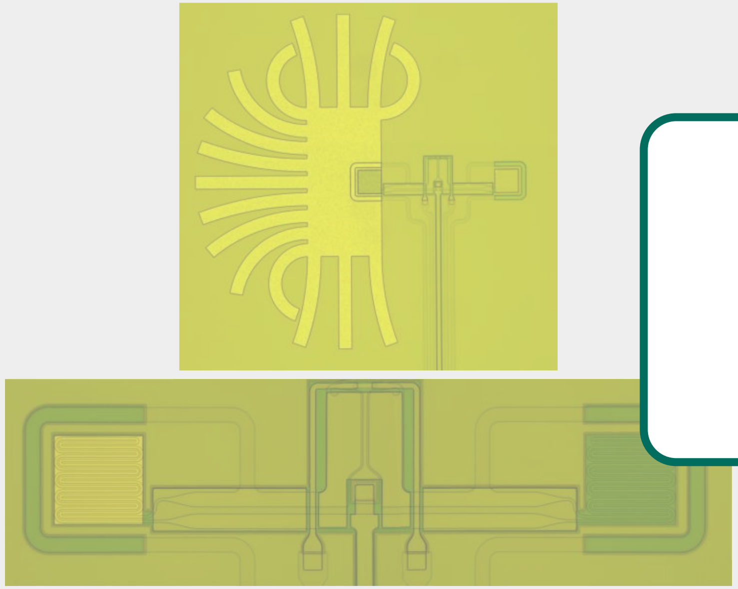
Custom PCB



- Custom printed circuit board has been designed

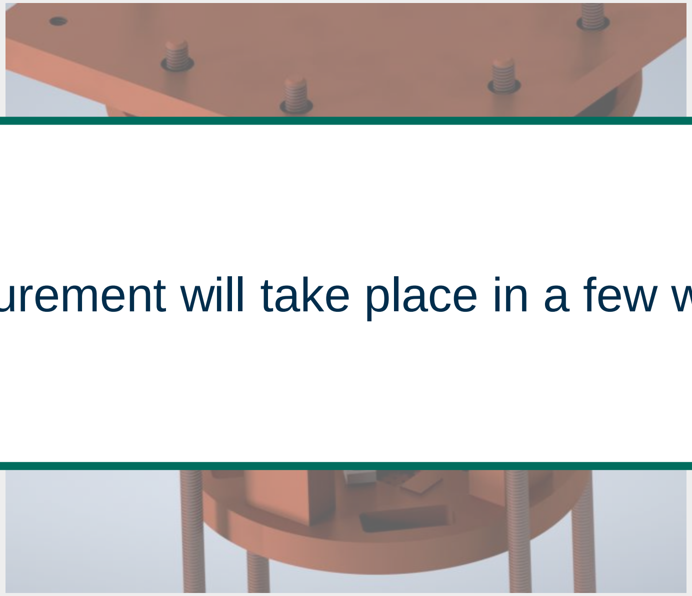
Current Status of the Experiment

Detector Chips



- Detector chips have been fabricated

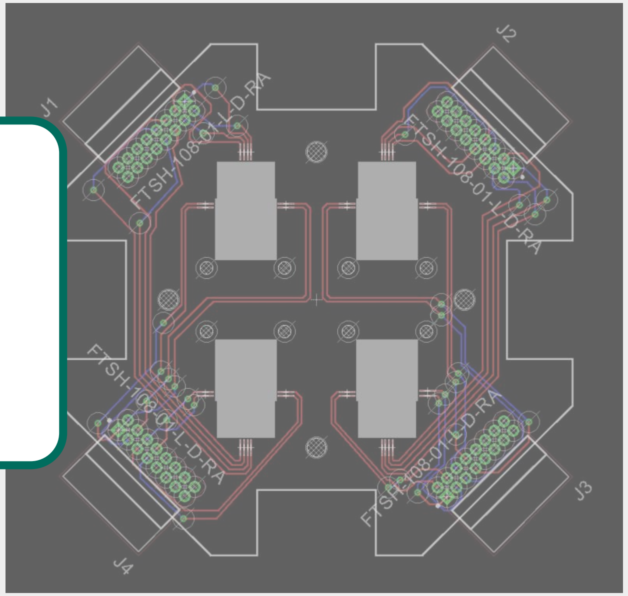
Measurement Setup



- Measurement setup is currently in production by the workshop

Measurement will take place in a few weeks!

Custom PCB

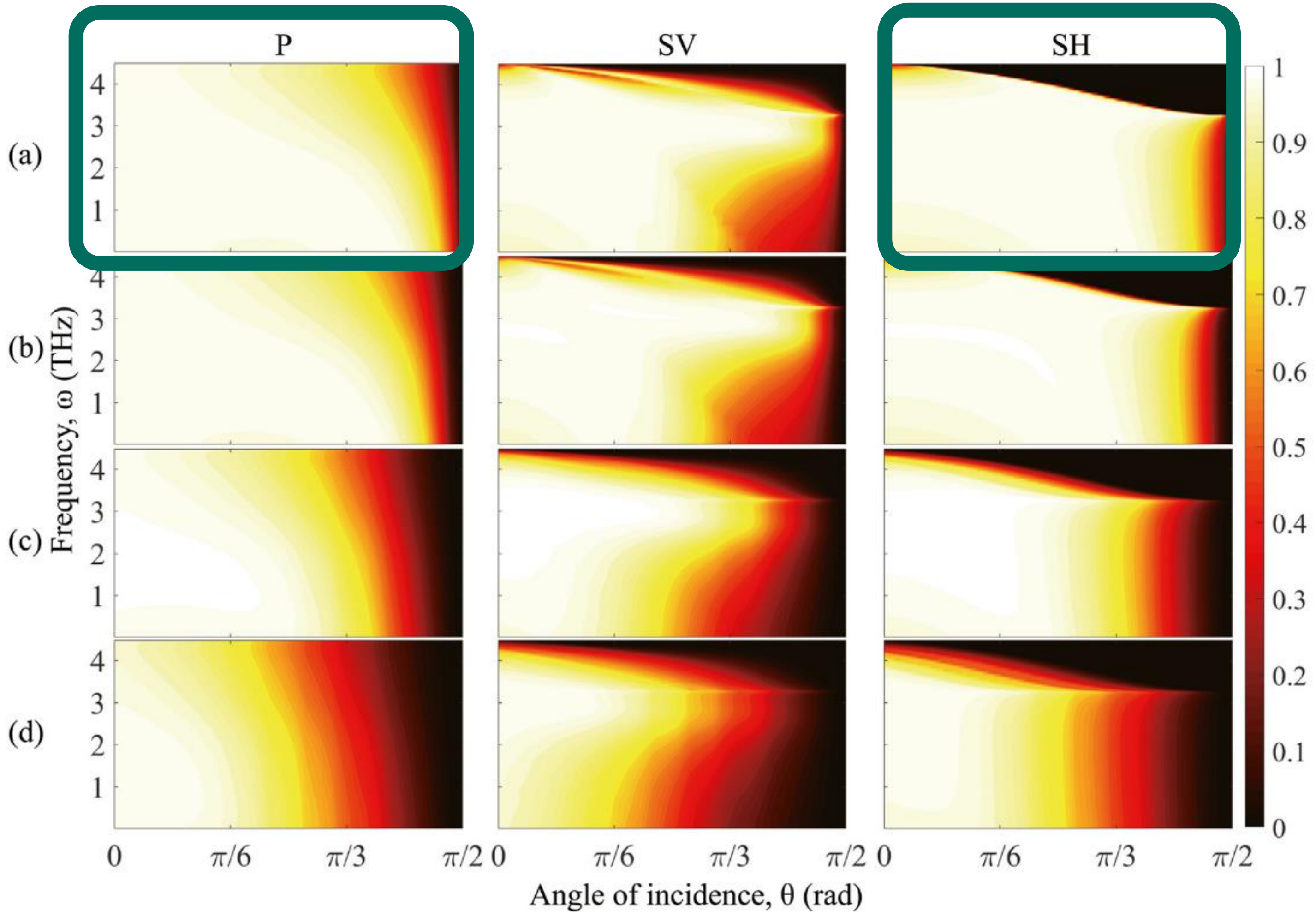


- Custom printed circuit board has been designed

Appendix: Acoustic Mismatch Model

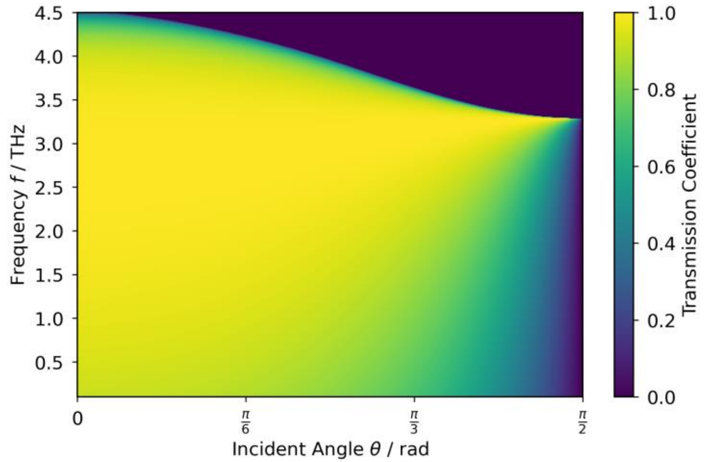
$$\nu_{1\to 2} = \frac{4Z_1 Z_2 \cos(\Theta_1)\cos(\Theta_2)}{(Z_1\cos(\Theta_2) + Z_2\cos(\Theta_1))^2}$$

Appendix: Transmission Coefficient Frequency Dependence Literature



Liu, Bin, et al. "Effect of interfacial roughness on thermal boundary conductance: An elastic wave model using the Kirchhoff approximation." *International Journal of Mechanical Sciences* 218 (2022): 106993.

Transverse phonons



Longitudinal phonons

Appendix: Angle of Inclination Probability Distribution

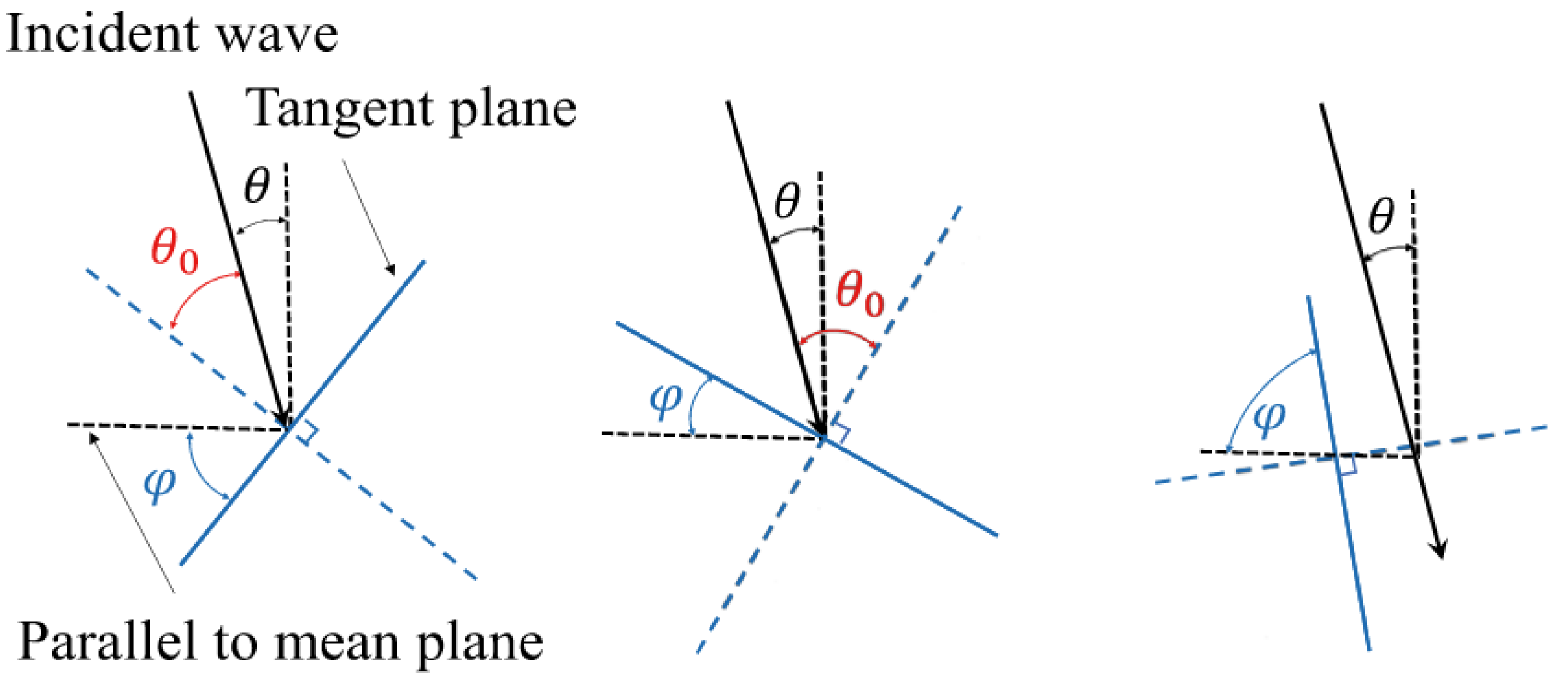
$$\boxed{P(\varphi) = \frac{1}{\sqrt{2\pi}\,\gamma\cos(\varphi)^2} \cdot \exp\left(\frac{-\tan(\varphi)^2}{2\gamma^2}\right)}$$

with $\gamma = \frac{\sigma}{L}$

σ - surface roughness

L - correlation length, characterizes
the lateral variation of the height (set to 15 nm)

Appendix: Angle Recalculation



(1) $-\frac{\pi}{2} \leq \varphi < -\theta$

$\theta_0 = -\theta - \varphi$

(2) $-\theta \leq \varphi < \frac{\pi}{2} - \theta$

$\theta_0 = \theta + \varphi$

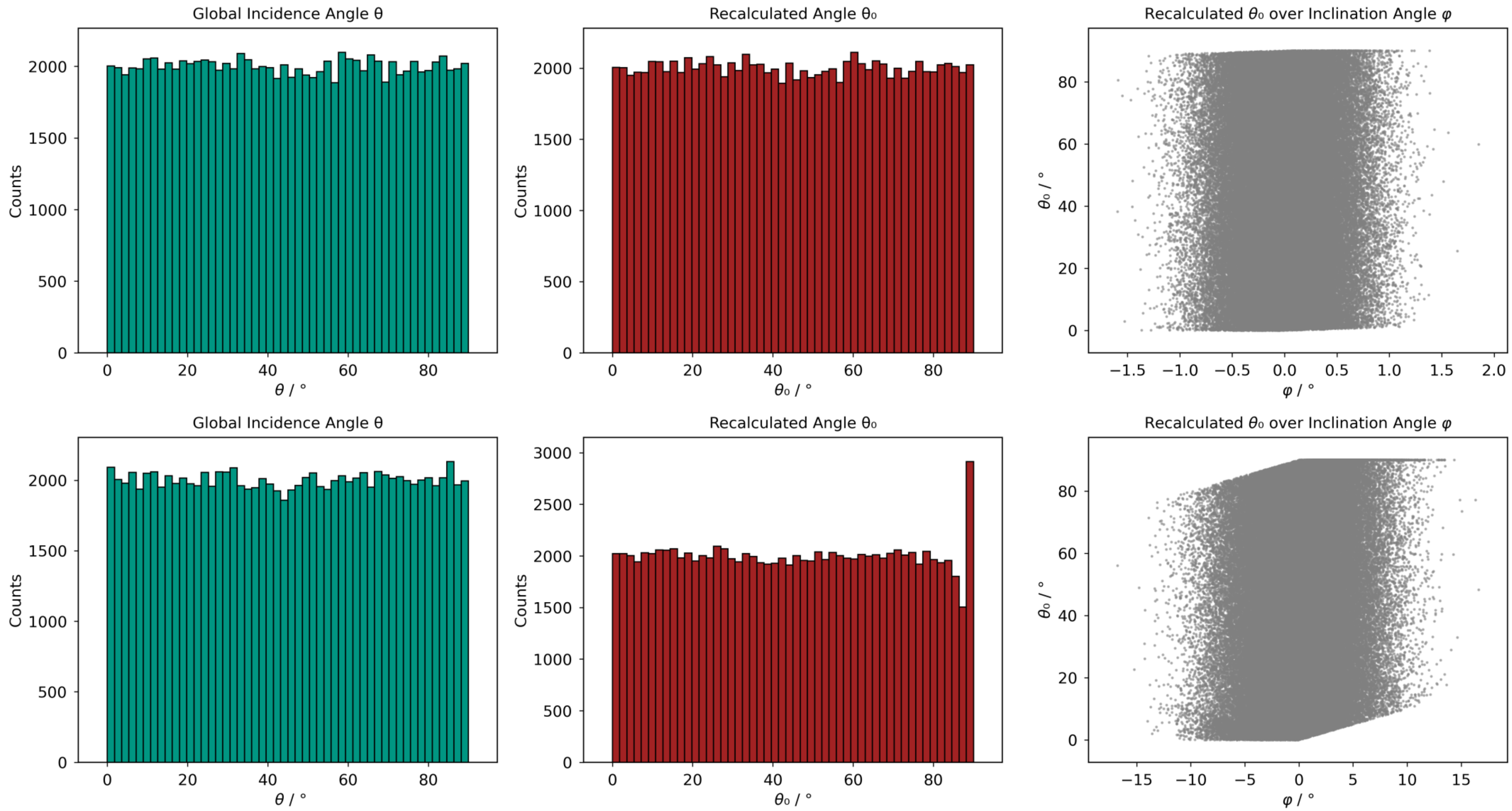
(3) $\frac{\pi}{2} - \theta \leq \varphi < \frac{\pi}{2}$

Equivalent to $\theta_0 = \frac{\pi}{2}$

Appendix: Angle Recalculation

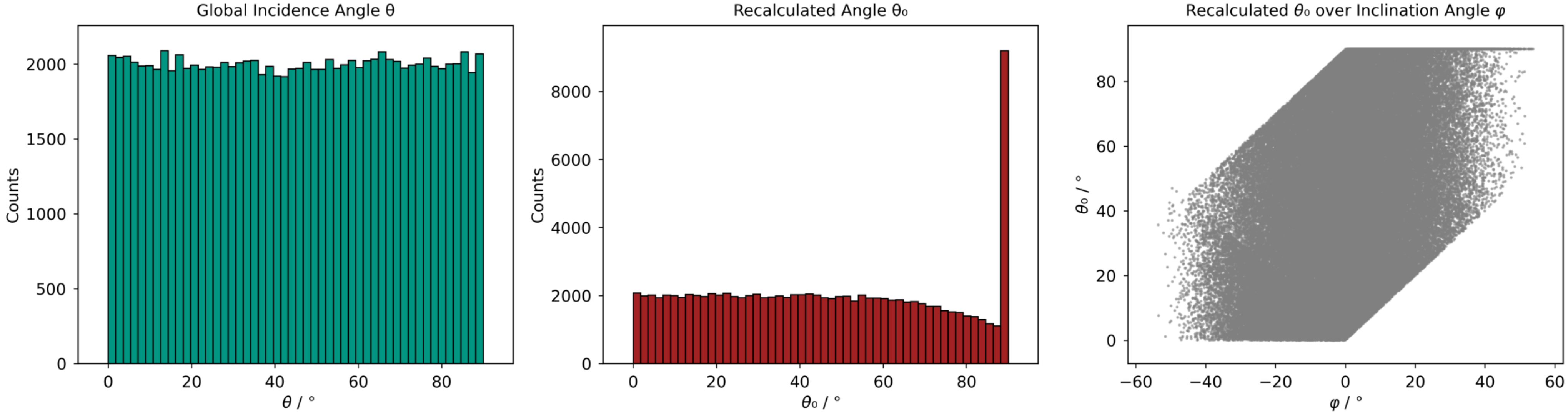
$\sigma = 0.1\ \mathrm{nm}$

$\sigma = 1.0\ \mathrm{nm}$

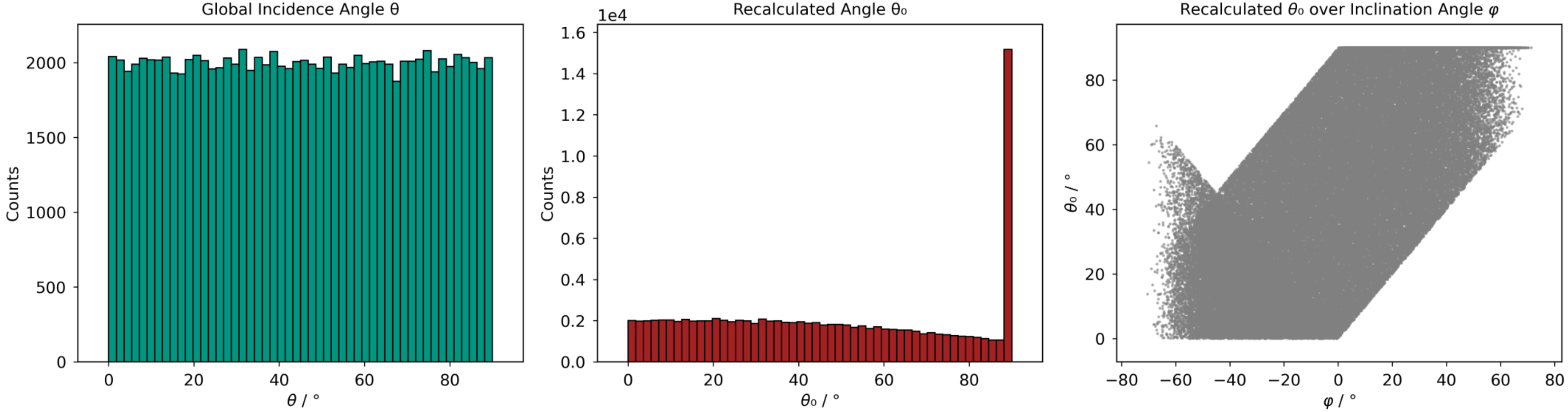


Appendix: Angle Recalculation

$\sigma = 5.0\ \mathrm{nm}$

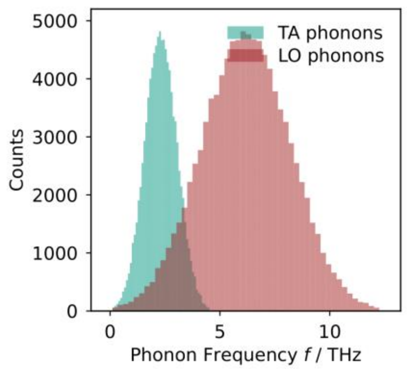


$\sigma = 10\ \mathrm{nm}$

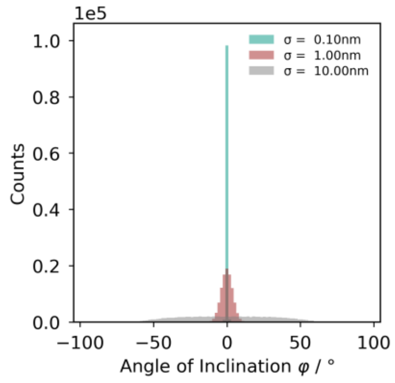


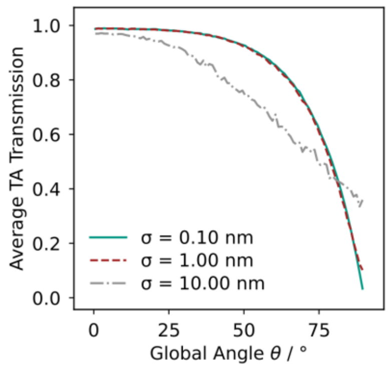
Appendix: Rise Time Calculation

Dummy Phonon frequency distribution



Surface Roughness – Angle Recalculation





$$\mathrm{p_{abs}} = \nu_{\mathrm{Si}\rightarrow\mathrm{Al}} \cdot \xi$$

$$p_{\mathrm{abs}} \cdot \sum_{i=0}^{n_{\mathrm{refl}}} [1 - p_{\mathrm{abs}}]^i > 0.90$$

$$\tau = n_{\mathrm{refl}} \cdot \frac{2 \cdot d_{\mathrm{wafer}}}{c_{\mathrm{ph}}}$$

Use for each phonon its frequency dependent velocity