Cryogenic Light Detectors for the CRESST Experiment

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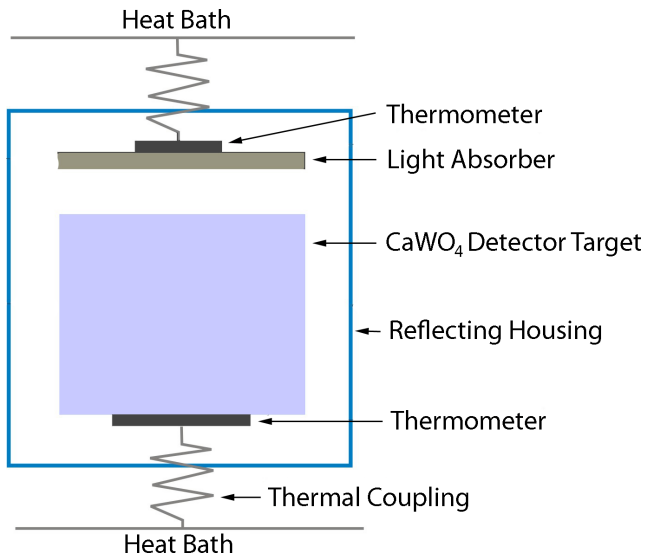
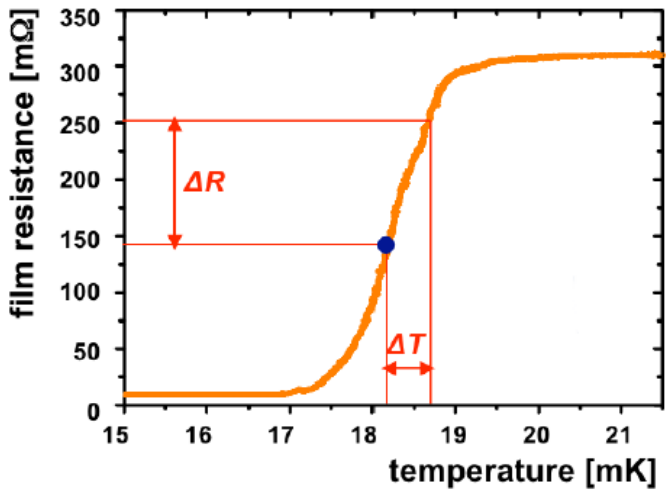
IMPRS Workshop at Castle Ringberg
July 26th, 2012

CRESST Detector Module

- Measurement of phonon and light signal
  - Phonon Channel
  - Light Channel



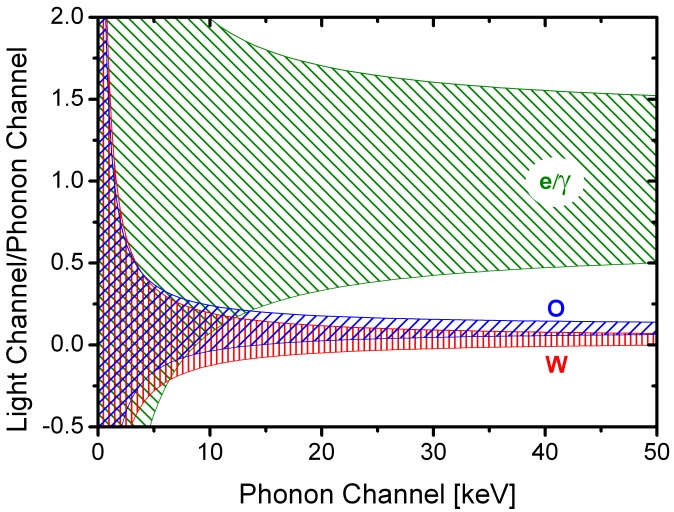
- Signals measured with Transition Edge Sensors (TES) as thermometers



Light-Phonon-Plane

Coincident light phonon measurement enables event identification

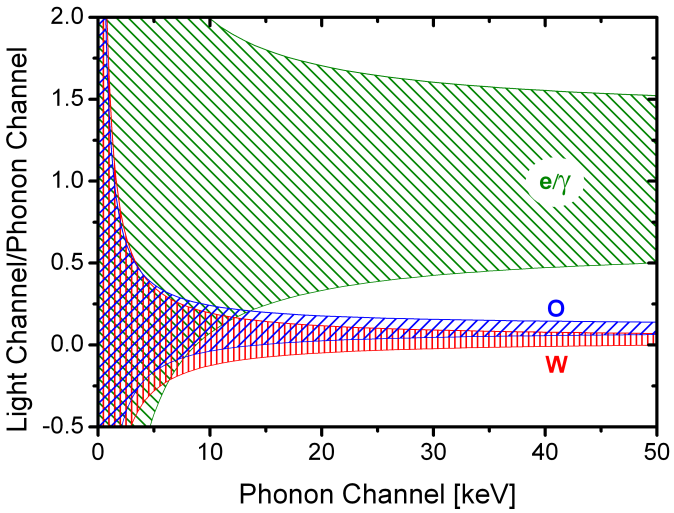
- Typical energy resolution of current detector module

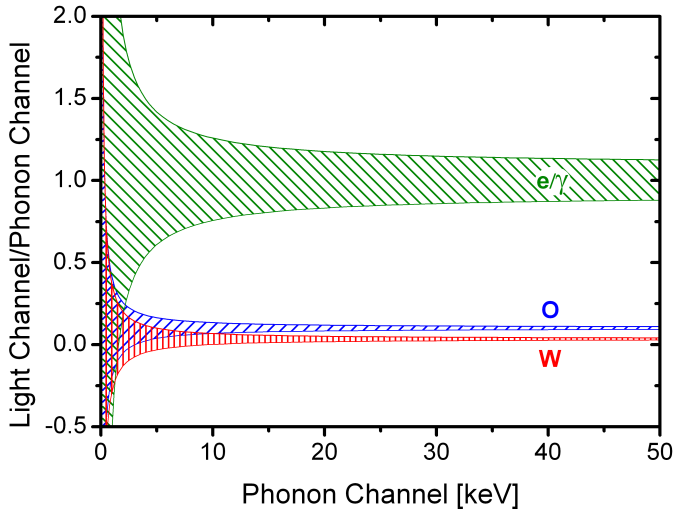


Light-Phonon-Plane

Coincident light phonon measurement enables event identification

- Typical energy resolution of current detector module
- Light channel energy resolution improved by a factor of 5



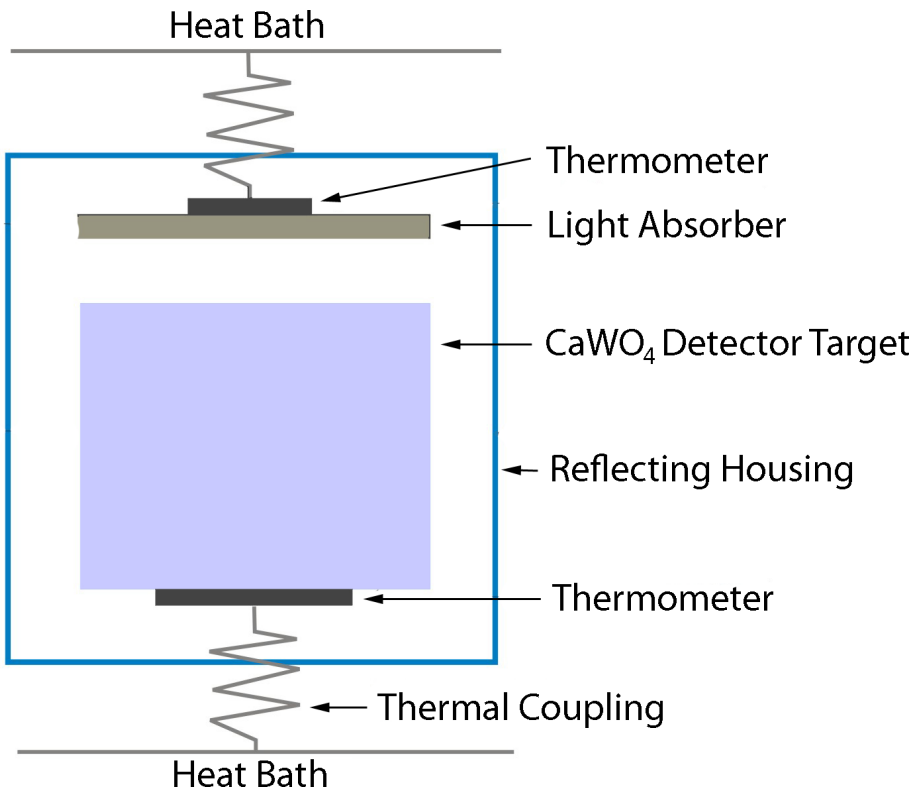


Width of the bands is determined by the light channel energy resolution

Goal

Improvement of the light channel's signal-to-noise ratio $\frac{E}{\Delta E}$

Energy Signal measured in the Light Channel



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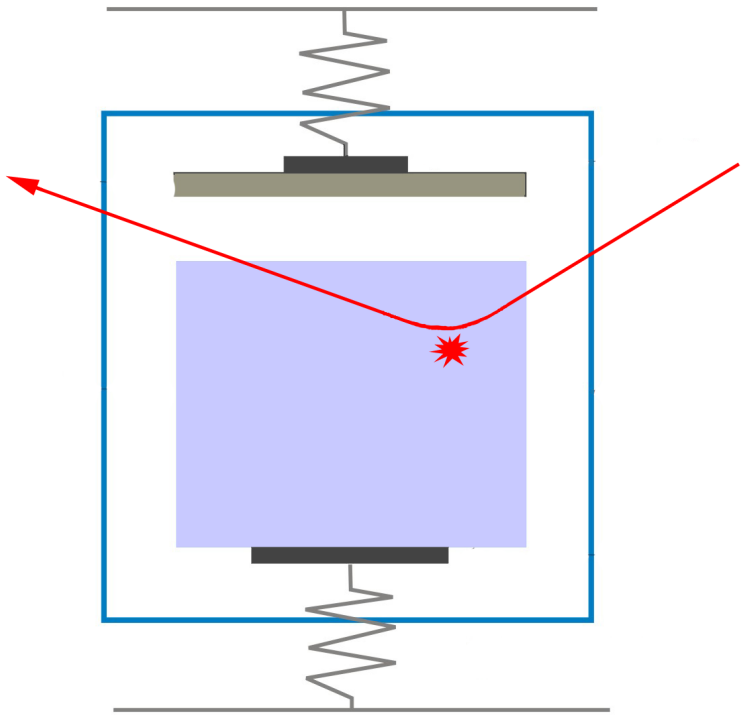
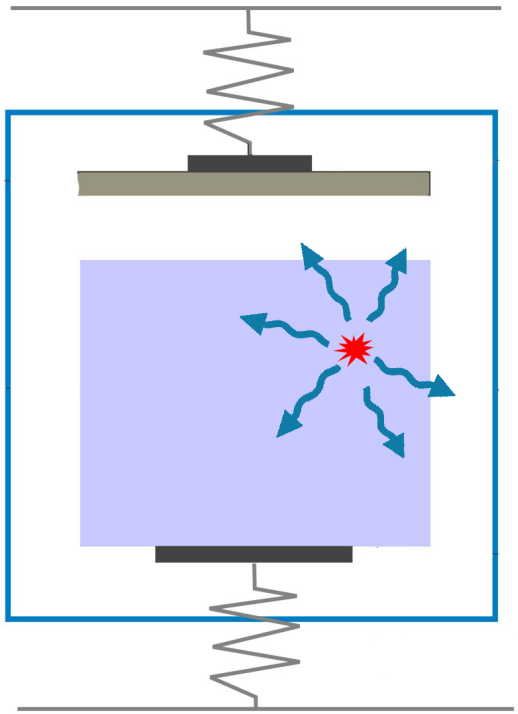


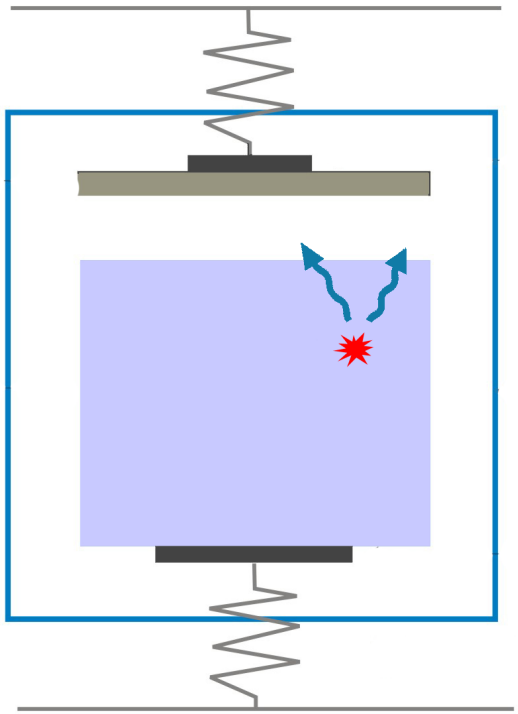
E_{dep}

Energy Signal measured in the Light Channel



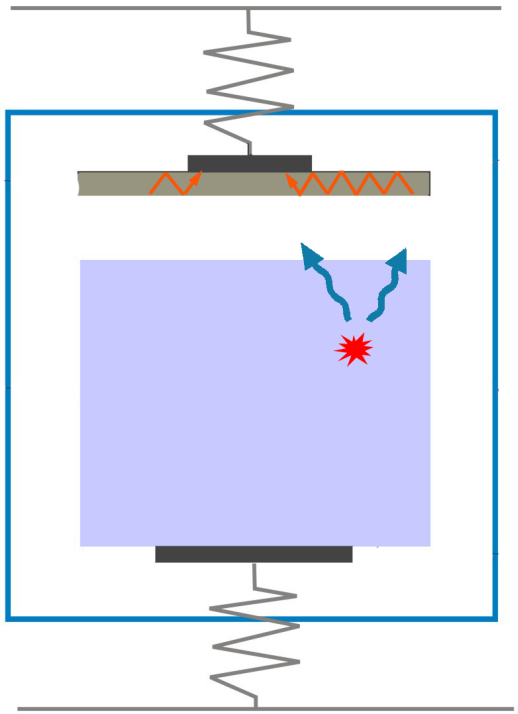
$$p \quad \cdot E_{dep}$$

Energy Signal measured in the Light Channel



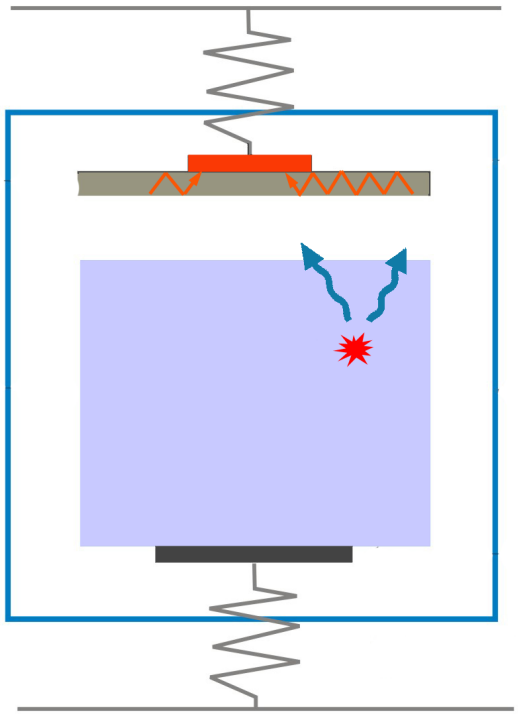
$$p \cdot q \cdot E_{dep}$$

Energy Signal measured in the Light Channel



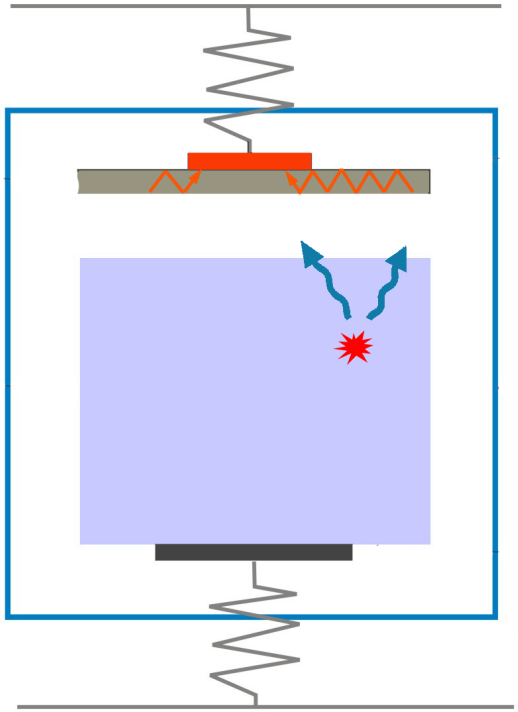
$$r \cdot p \cdot q \cdot E_{dep}$$

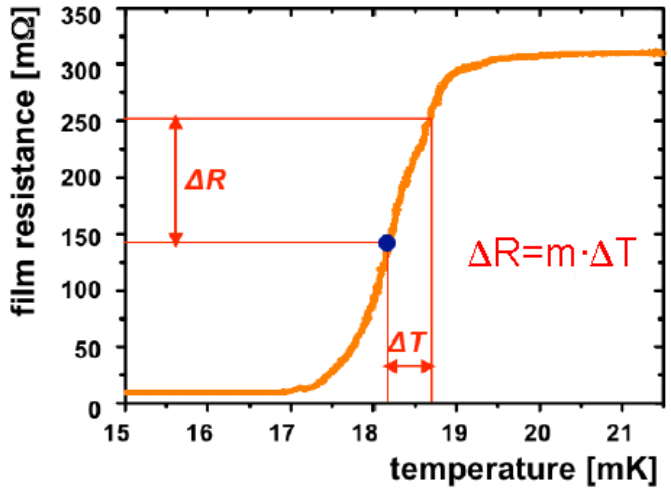
Energy Signal measured in the Light Channel



$$\frac{r}{C_T} \cdot p \cdot q \cdot E_{dep}$$

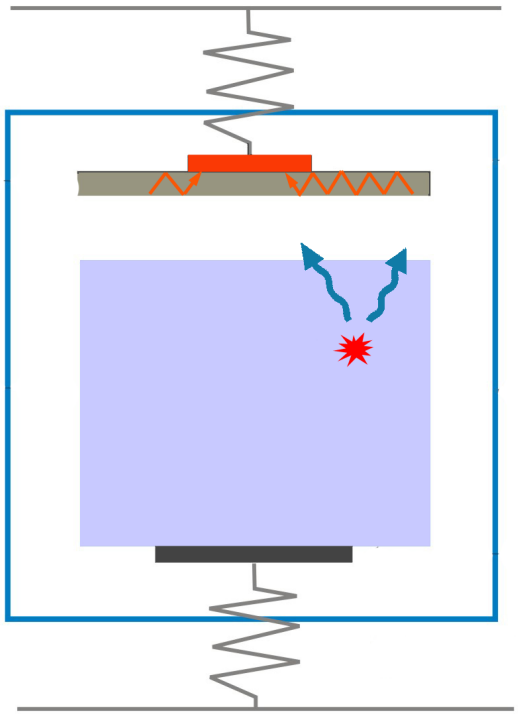
Energy Signal measured in the Light Channel

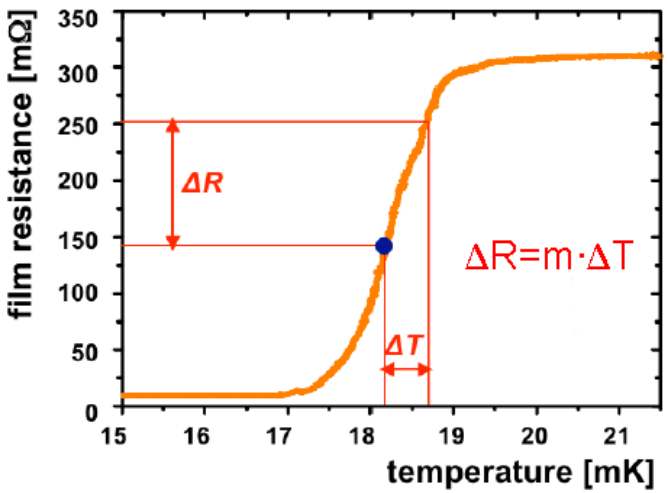


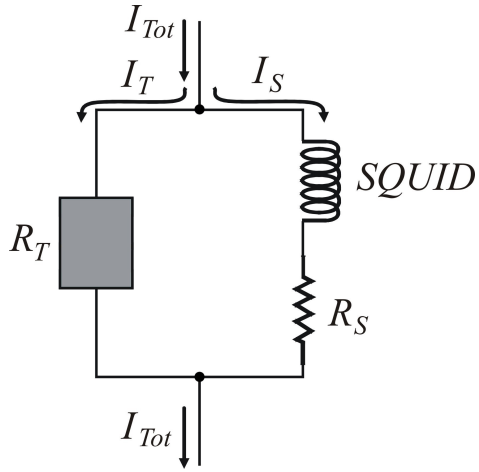


$$m \cdot \frac{r}{C_T} \cdot p \cdot q \cdot E_{dep}$$

Energy Signal measured in the Light Channel



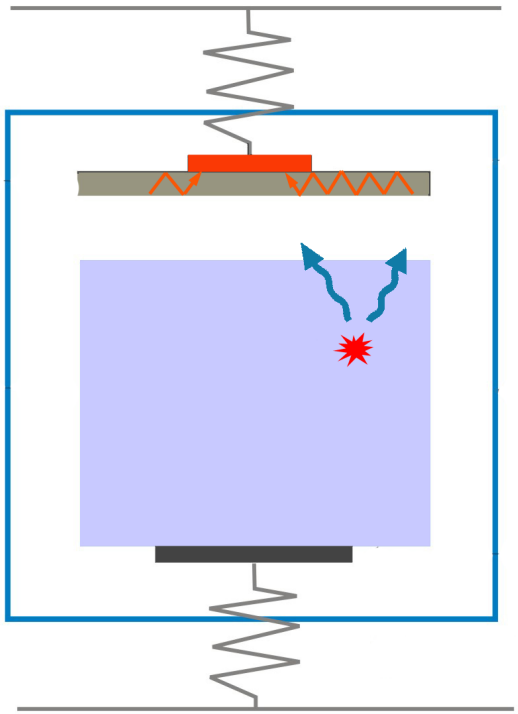


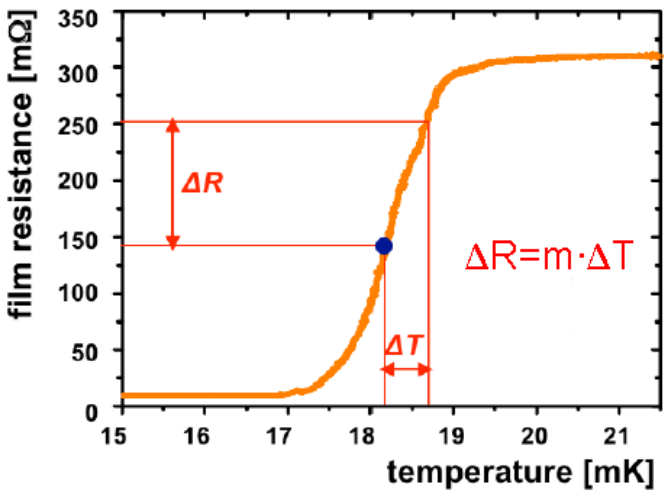


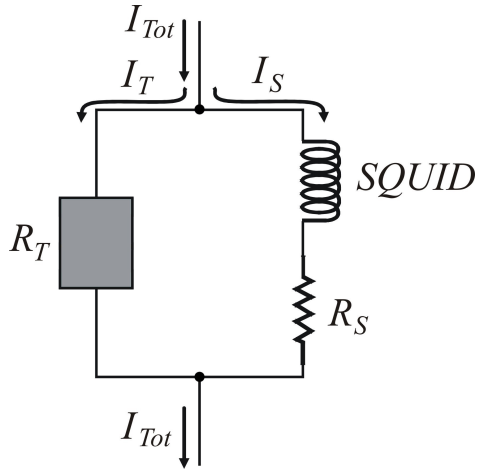
$$\Delta I_S = \frac{I_T}{R_S+R_T} \cdot \Delta R_T$$

$$\frac{I_T}{R_S+R_T} \cdot m \cdot \frac{r}{C_T} \cdot p \cdot q \cdot E_{dep}$$

Energy Signal measured in the Light Channel



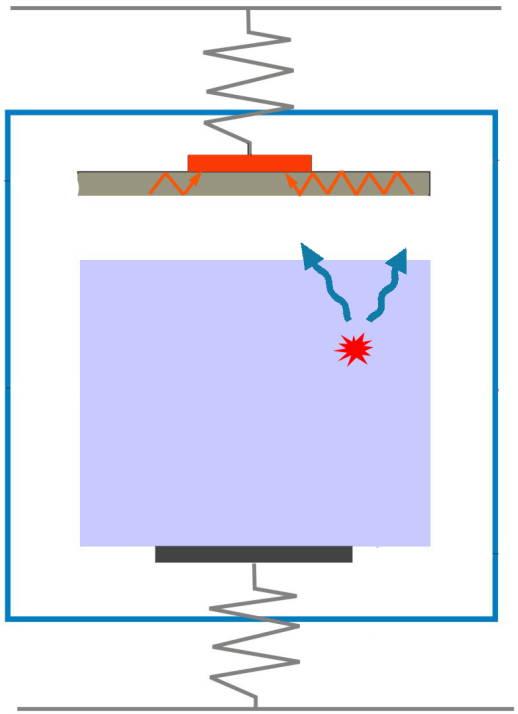


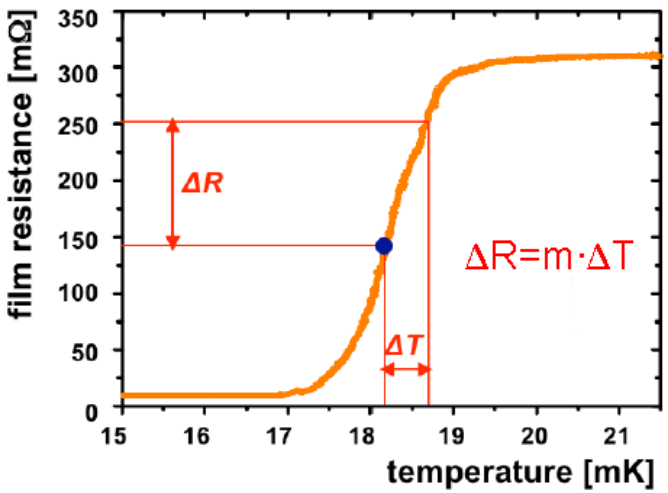


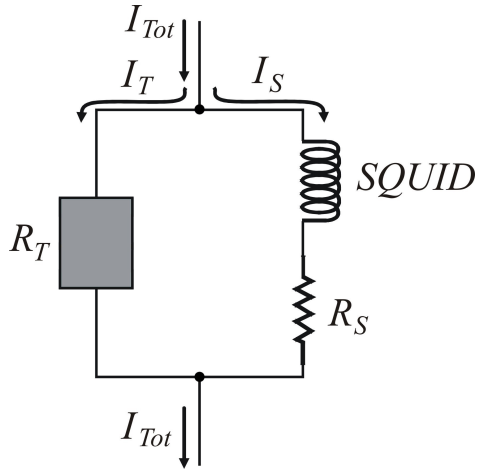
$$\Delta I_S = \frac{I_T}{R_S+R_T} \cdot \Delta R_T$$

$$\frac{\partial U}{\partial \Phi_0}\frac{\partial \Phi_0}{\partial I} \cdot \frac{I_T}{R_S+R_T} \cdot m \cdot \frac{r}{C_T} \cdot p \cdot q \cdot E_{dep}$$

Energy Signal measured in the Light Channel







$$\Delta I_S = \frac{I_T}{R_S+R_T} \cdot \Delta R_T$$

$$E = c \cdot \frac{\partial U}{\partial \Phi_0}\frac{\partial \Phi_0}{\partial I} \cdot \frac{I_T}{R_S+R_T} \cdot m \cdot \frac{r}{C_T} \cdot p \cdot q \cdot E_{dep}$$

Light Channel's Signal-to-Noise Ratio

Measured Energy

$$E = c \cdot \frac{\partial U}{\partial \Phi_0} \frac{\partial \Phi_0}{\partial I} \cdot \frac{I_T}{R_S + R_T} \cdot m \cdot \frac{r}{C_T} \cdot pq \cdot E_{dep}$$

Noise ($@E = 0$)

$$\Delta E = \sqrt{I_J^2 + I_{SQ}^2 + I_{1/f}^2} = \sqrt{\frac{4k_B(T_C R_T + T_S R_S)}{(R_T + R_S)^2} + c_{SQ}^2 + f^2 \left(\frac{R_T}{R_n}\right)}$$

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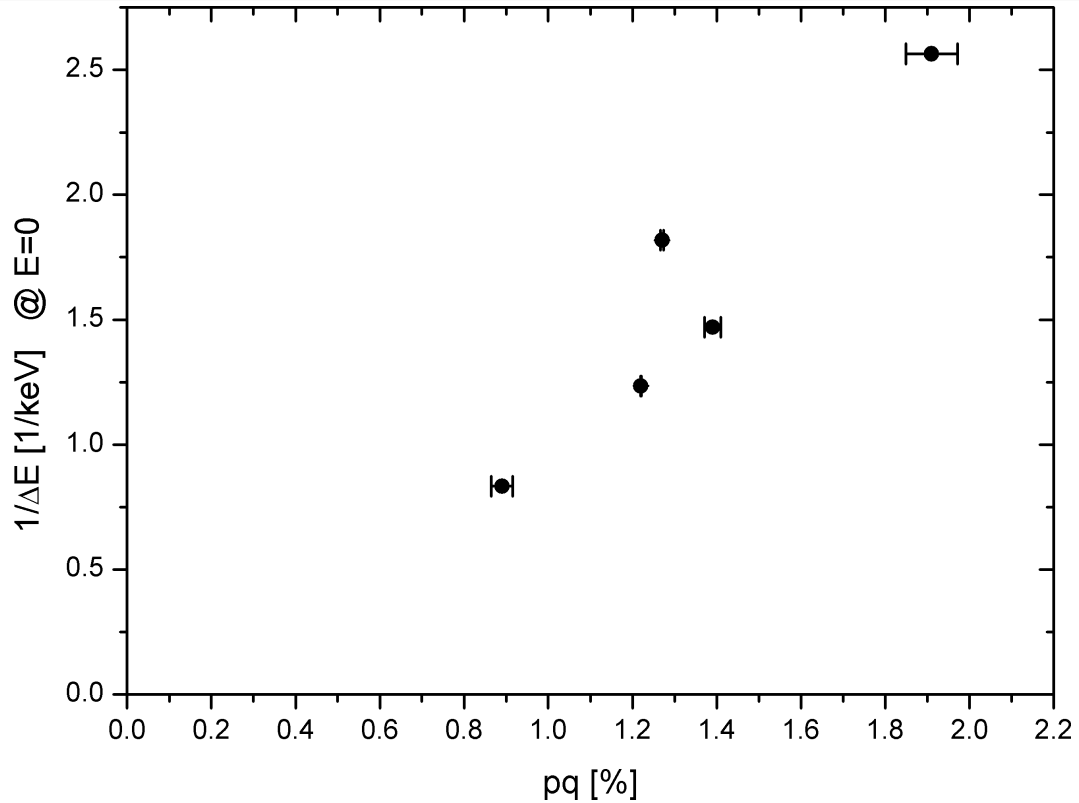
Energy Fraction Absorbed by the Light Detector *pq*

$$\frac{E}{\Delta E} \sim pq \ (@E = 0)$$



Data of CRESST Light Detectors

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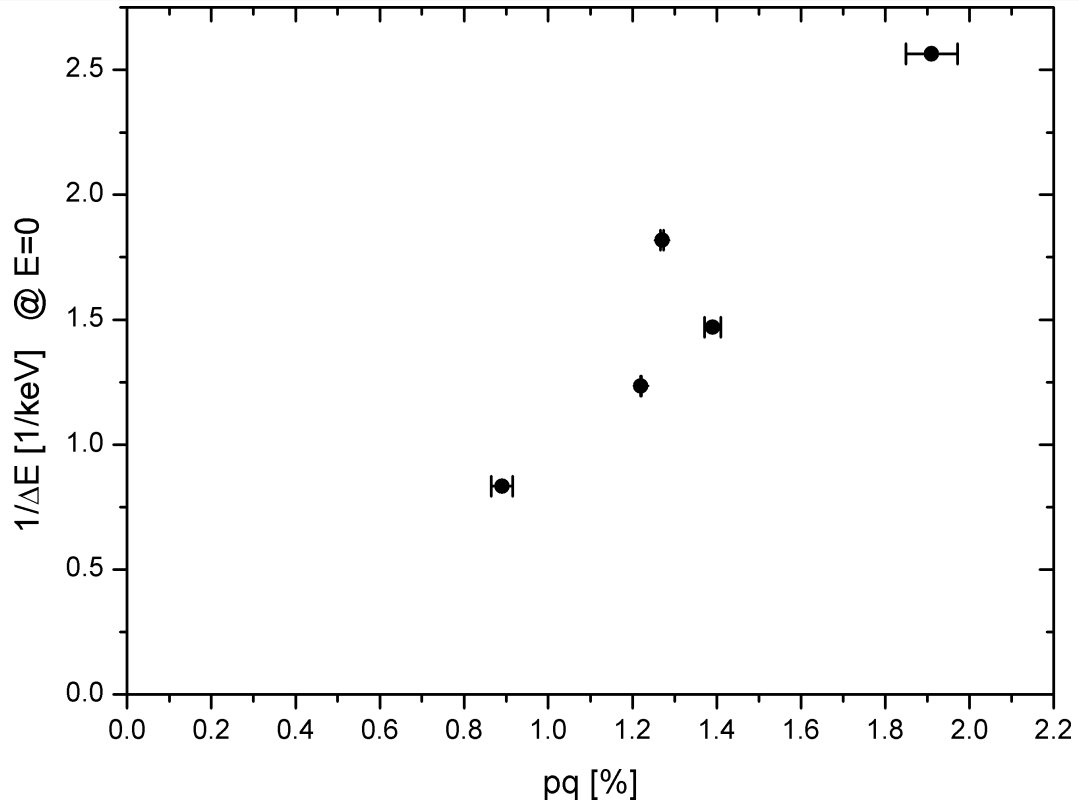

Data of CRESST Light Detectors

Increased sensitivity for improved light-production, -transport or -absorption

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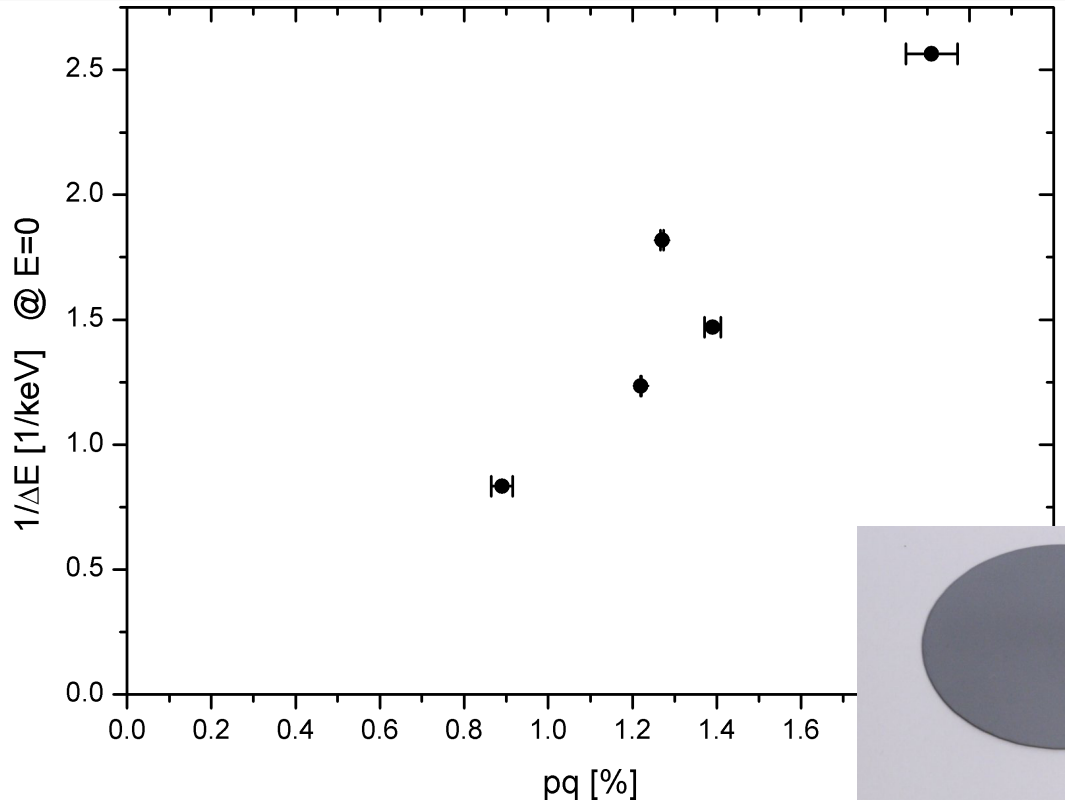

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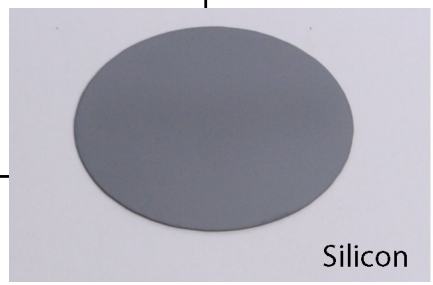
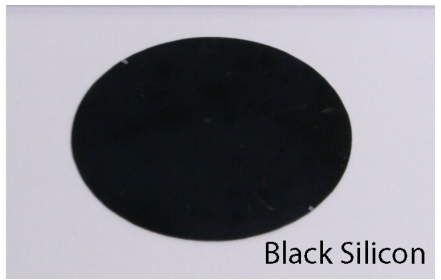
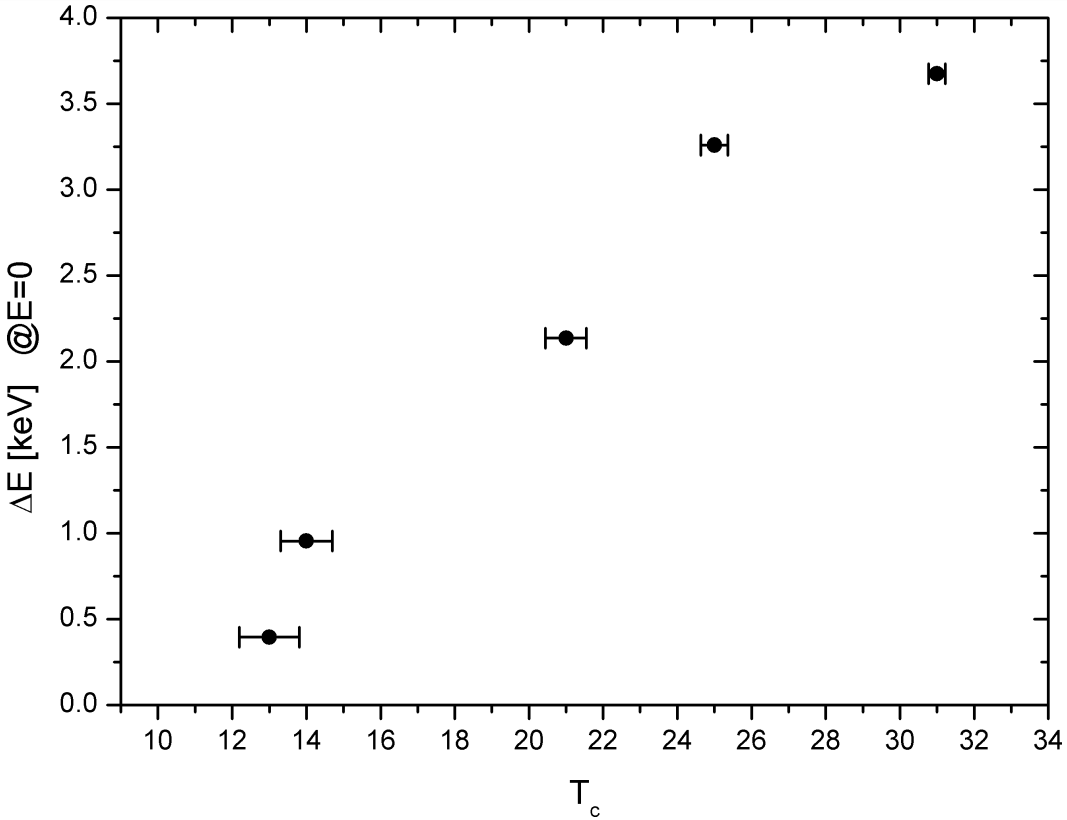




Increased sensitivity for improved light-production, -transport or -absorption $\rightarrow$ Black silicon

Transition Temperature T_C

$$\frac{E}{\Delta E} \sim \frac{1}{C_T \cdot f(T_C)} \sim \frac{1}{T_C{}^{(1+\varepsilon)}}$$



Data of CRESST Light Detectors

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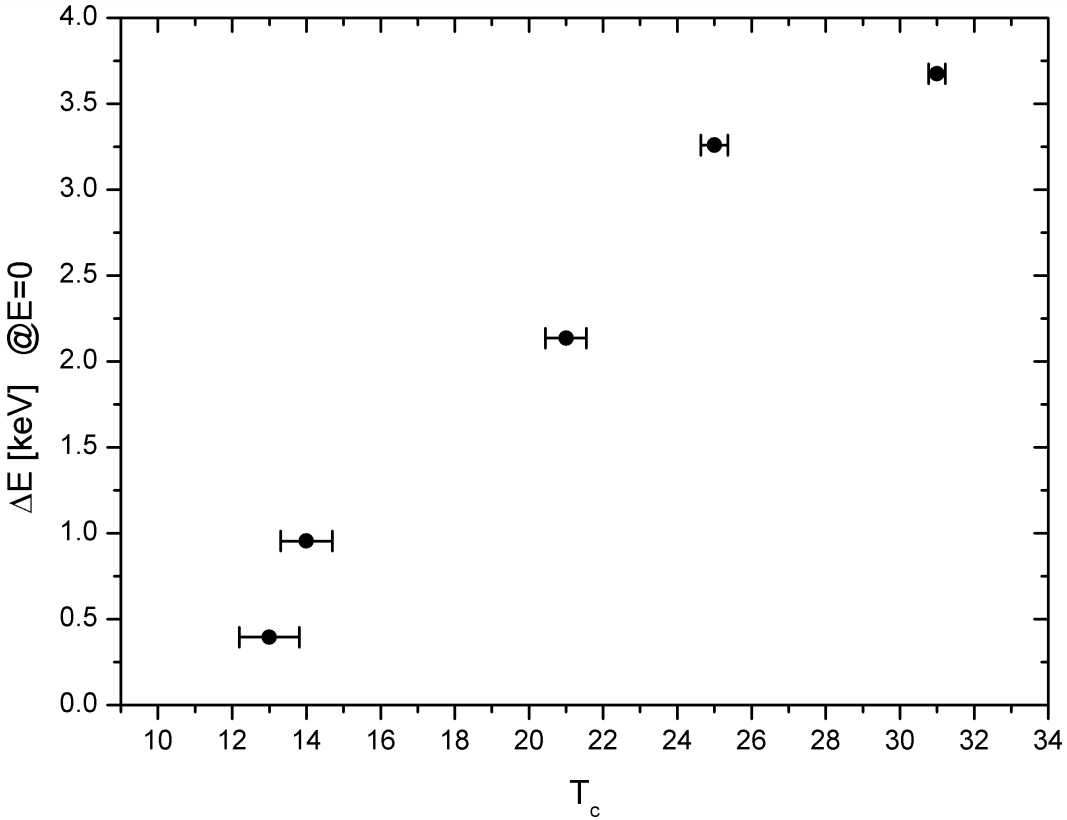
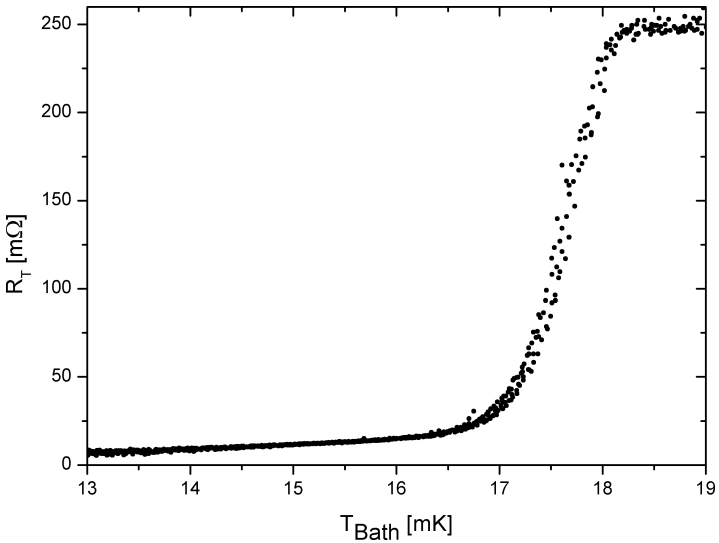


Data of CRESST Light Detectors

Sensitivity improves for lower transition temperature

Transition Slope m

$$\frac{E}{\Delta E} \sim m = \frac{\Delta R}{\Delta T}$$



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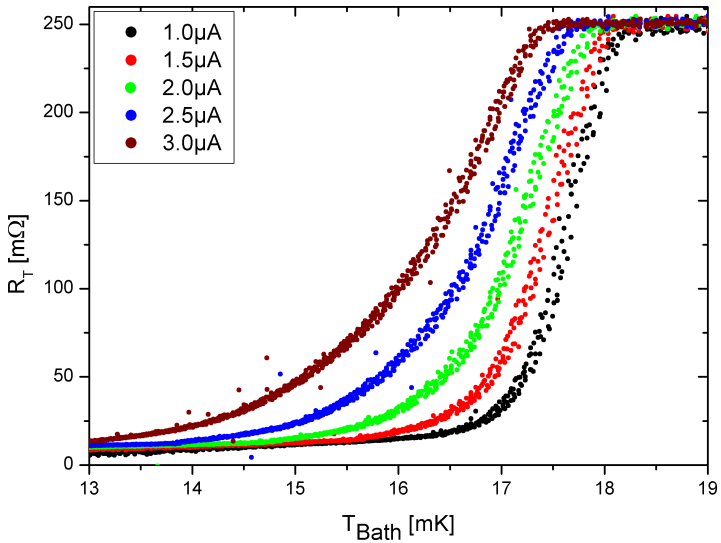

Transition slope m depends on read-out current

- Self-heating effect
- Critical current effect

Transition Slope m

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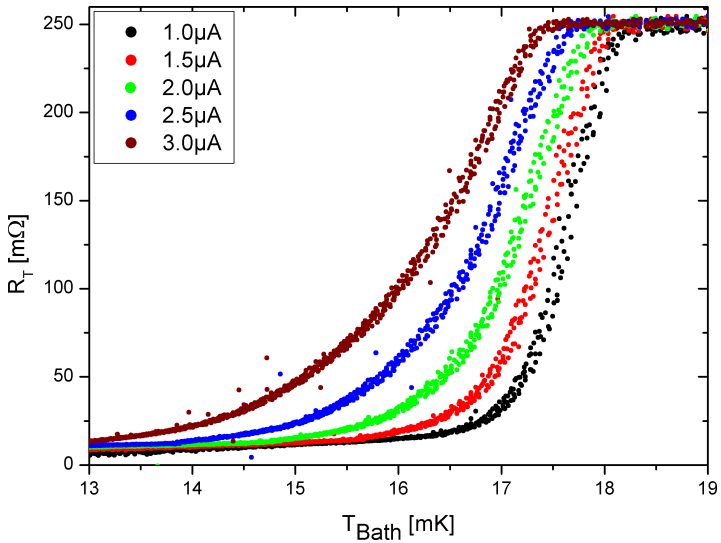
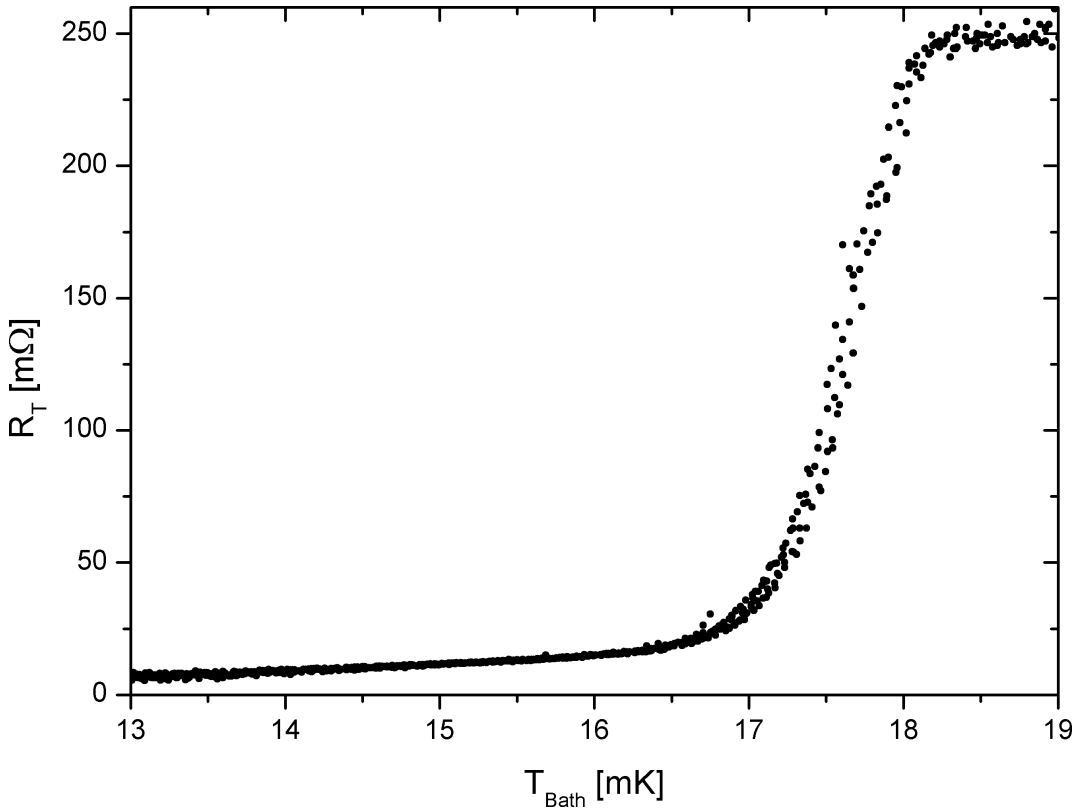


Transition slope m depends on read-out current

- Self-heating effect $\rightarrow \Delta T_{Shift} = \frac{P_T}{G_{BT}}$
- Critical current effect $\rightarrow$ expected in the lower part of the transition

Calculation of the Self-Heating Effect



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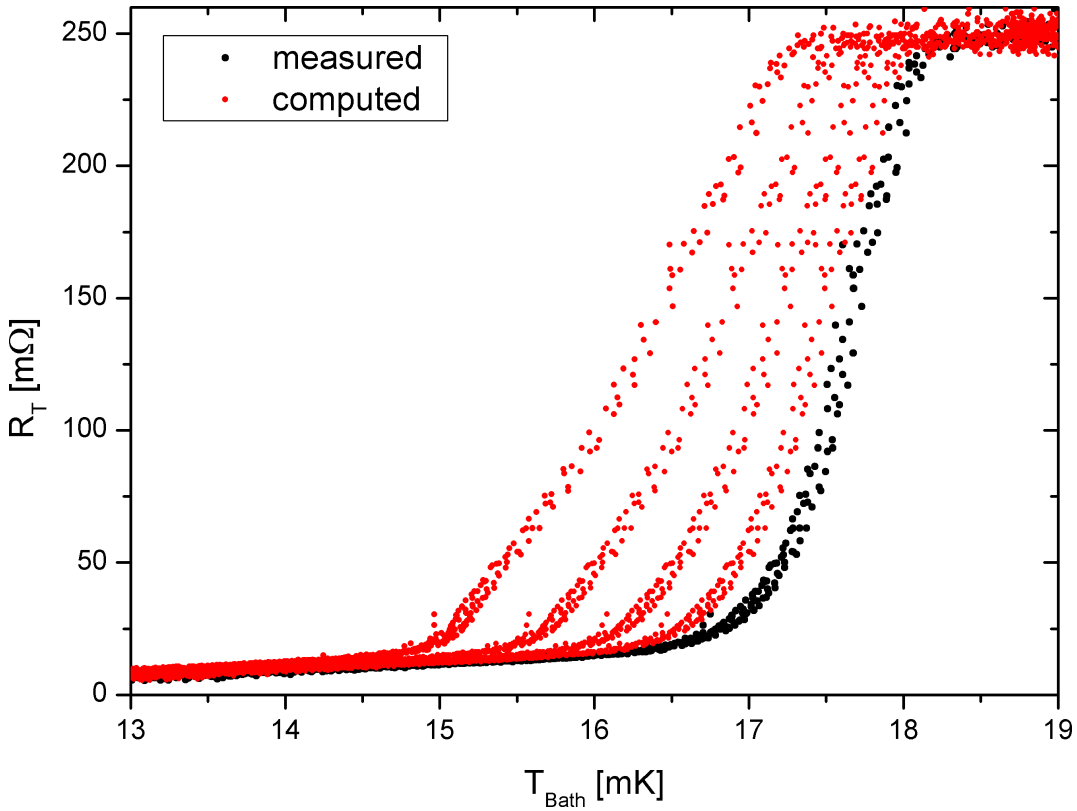

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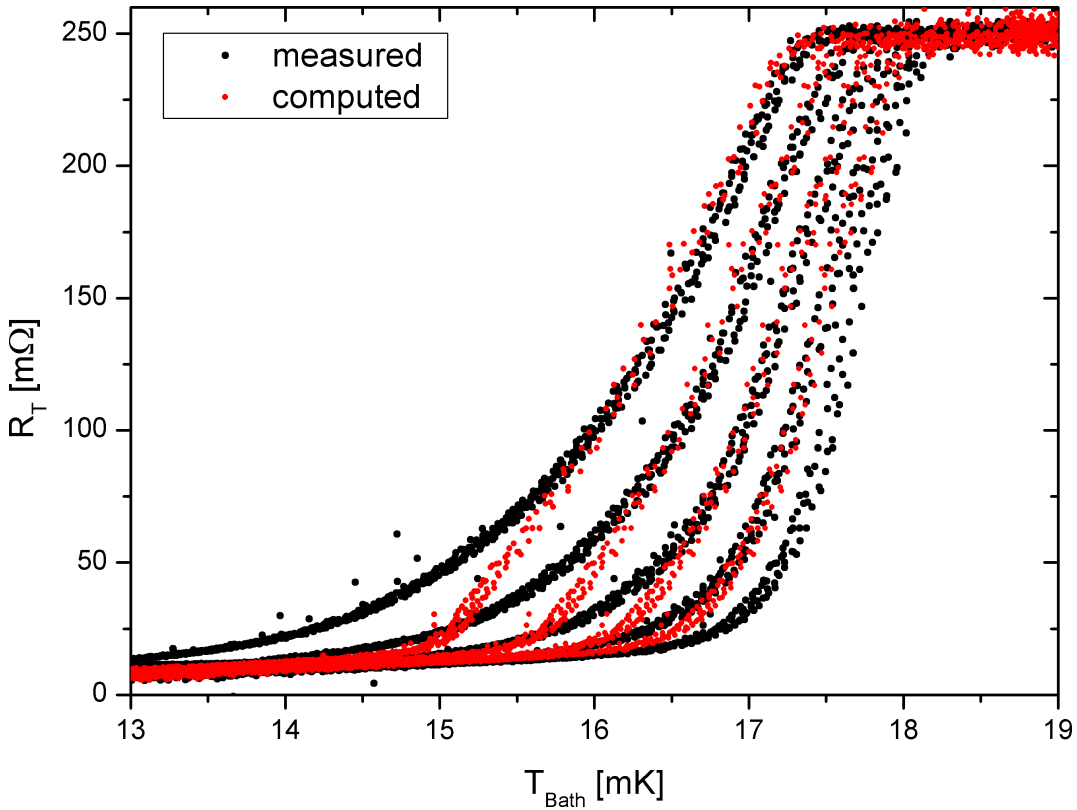
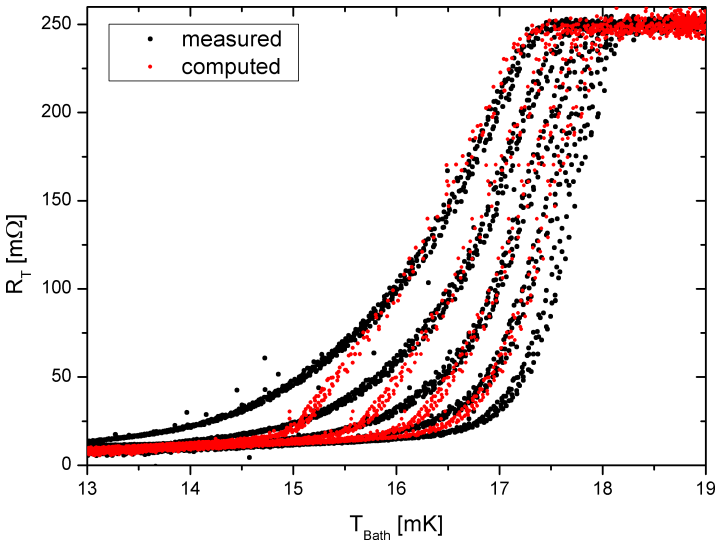
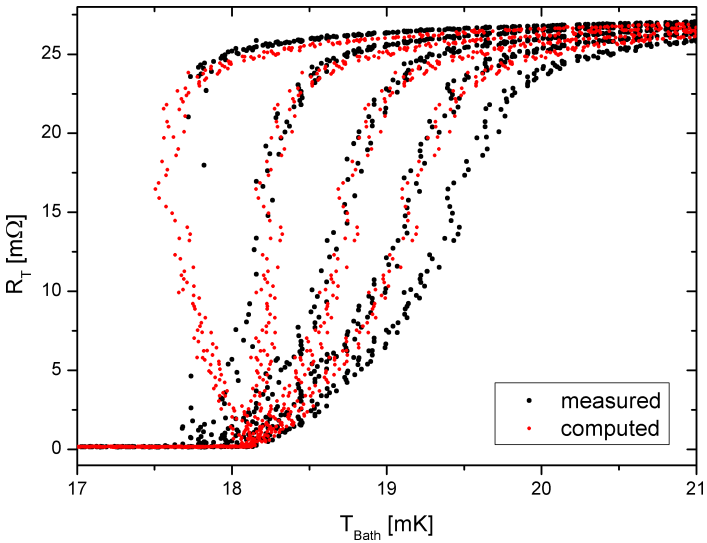


- Upper part of the transition can be explained with the self-heating effect
- Difference in the lower part of the transition due to the critical current effect

Reduction of the Normal Conducting Resistance R_n



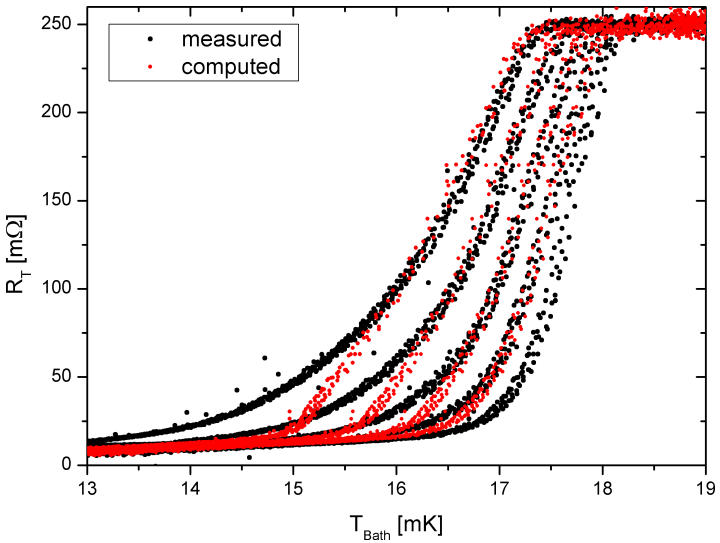
large R_n



small R_n

Reduced critical current effect for small R_n

Reduction of the Normal Conducting Resistance R_n



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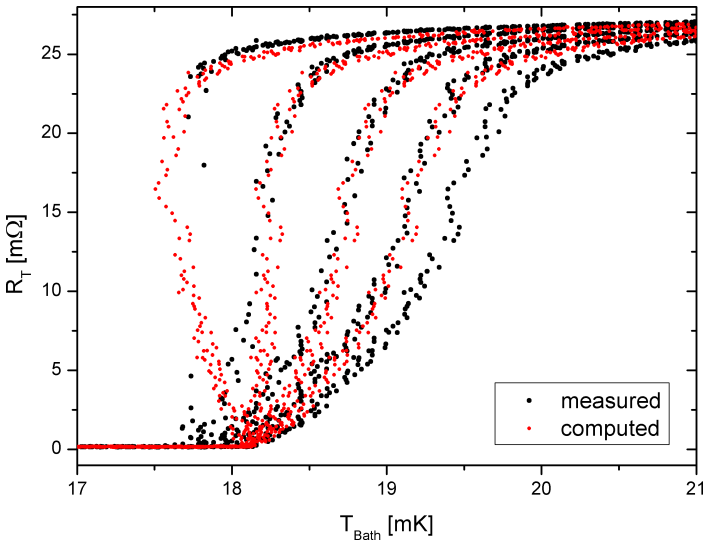


small R_n

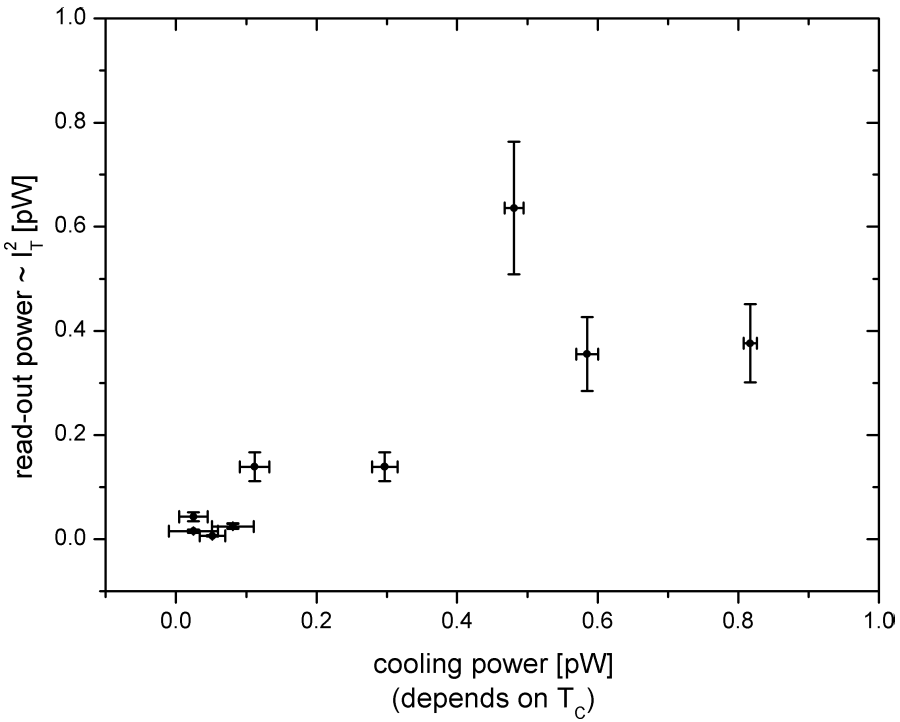
Reduced critical current effect for small R_n

small R_n opens the possibility for large transition slopes

Thermometer Current I_T

$$\frac{E}{\Delta E} \sim I_T$$

- Each light detector ist optimized for best signal-to-noise $\rightarrow$ I_T fixed
- Limiting factors of thermometer current?



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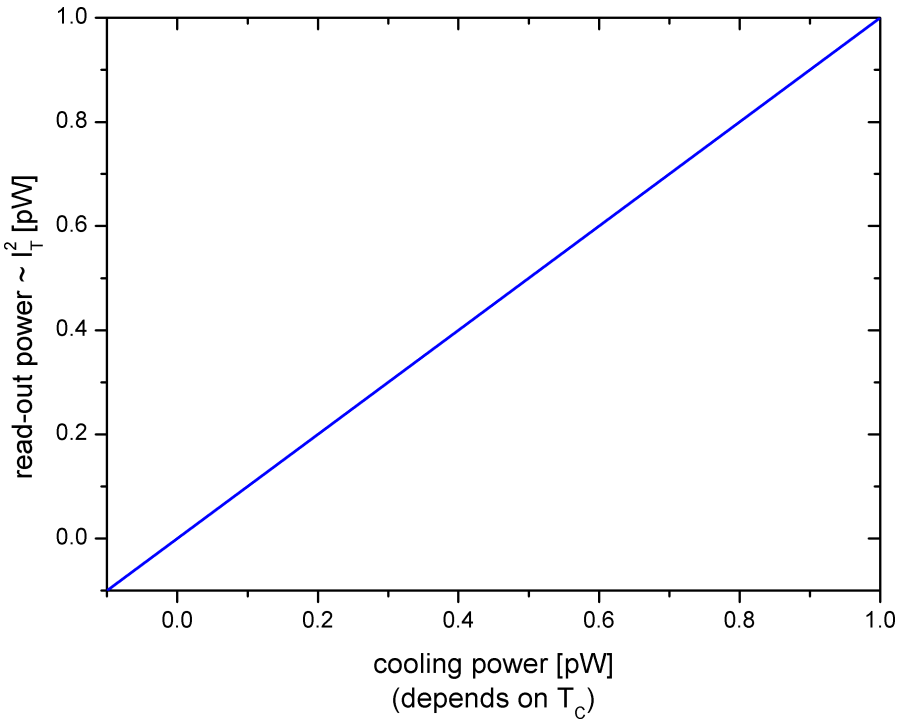

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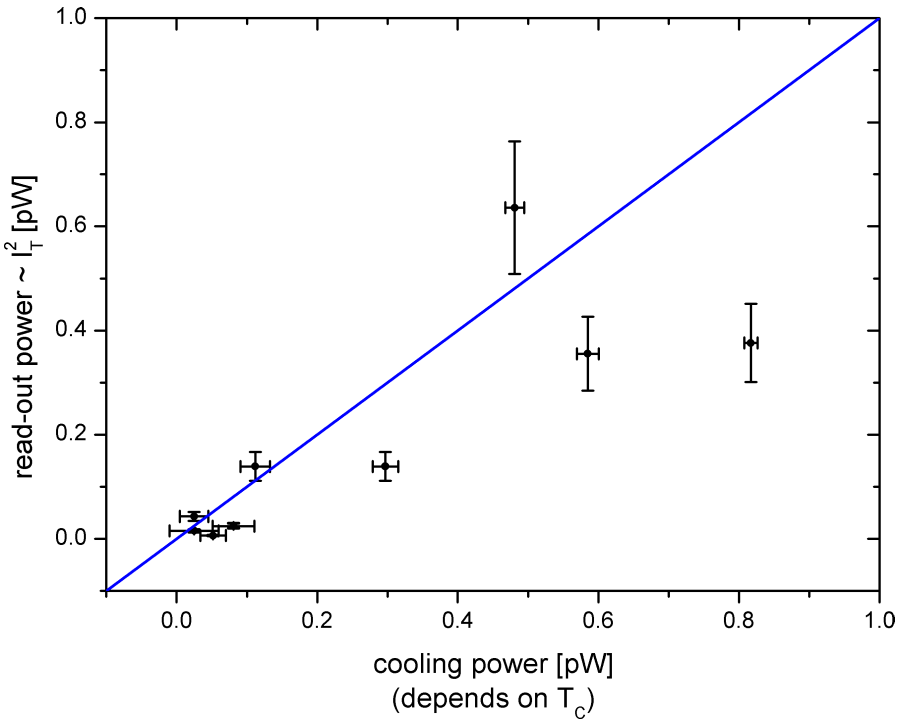

Thermometer current is mostly limited by cooling power

Thermal Coupling between Bath and Thermometer G_{BT}

- Increase of thermometer current I_T requires increase of cooling power $P_{BT} = G_{BT}(T_C - T_B)$
- Transition temperature T_C and bath temperature T_B fixed
- Only thermal coupling G_{BT} can be adjusted

$\rightarrow$ Increase of thermal coupling

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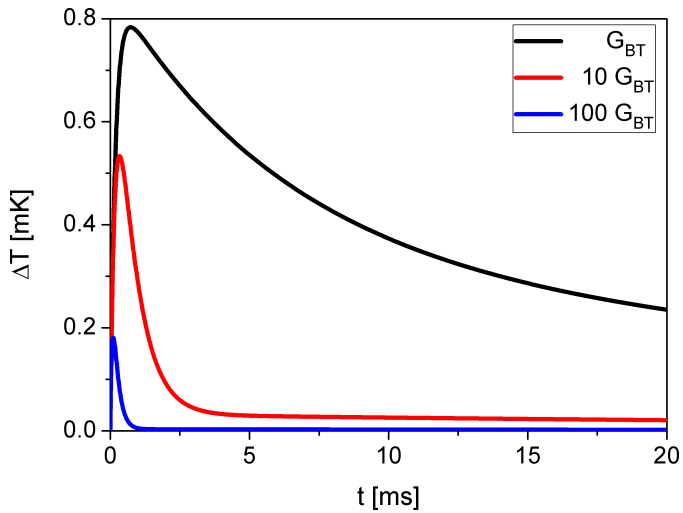
→ Increase of thermal coupling

- Temperature rise for given energy deposition reduced with larger thermal coupling



→ Reduction of thermal coupling

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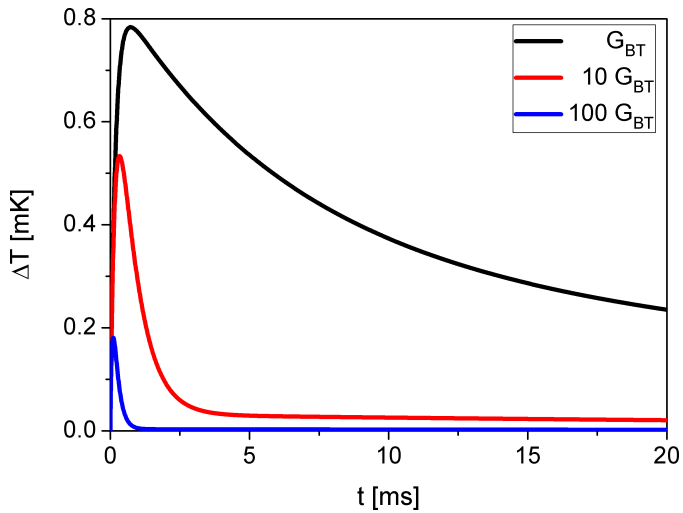
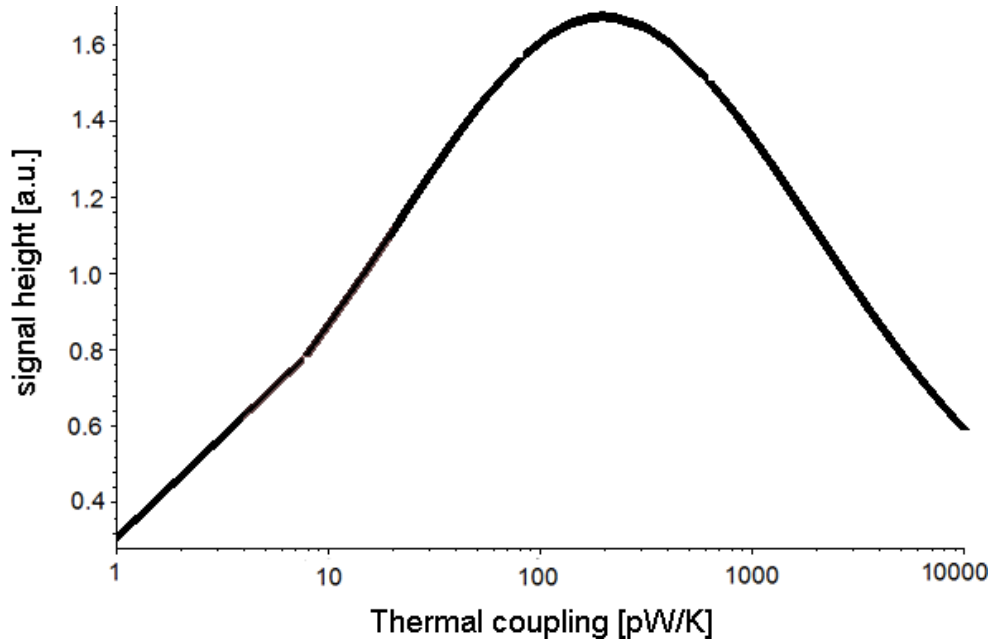


→ Reduction of thermal coupling

→ Optimization of thermal coupling

Optimization of the Thermal Coupling G_{BT}

Signal height calculated for different thermal couplings



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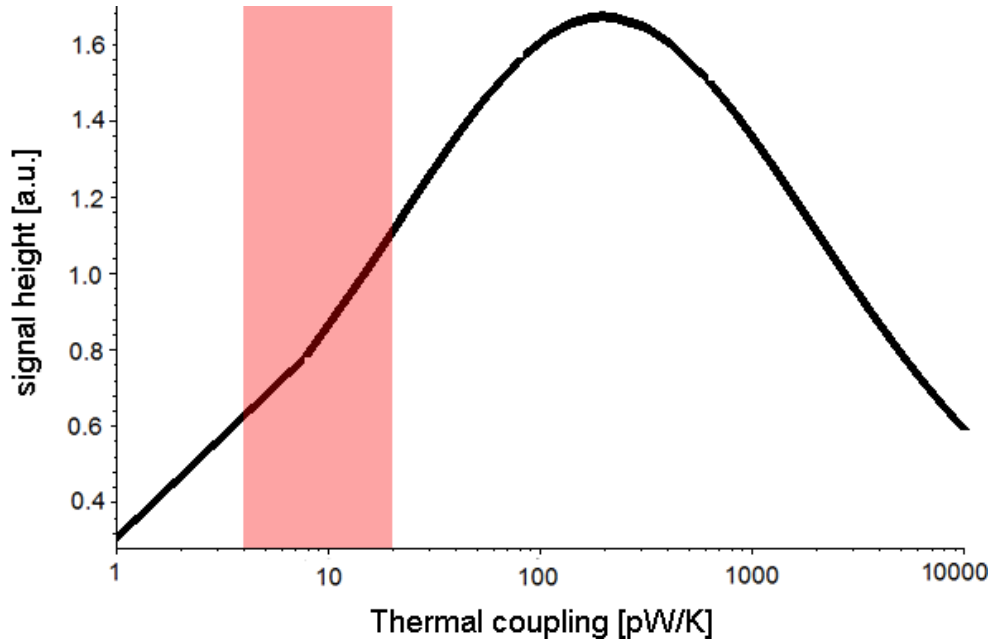
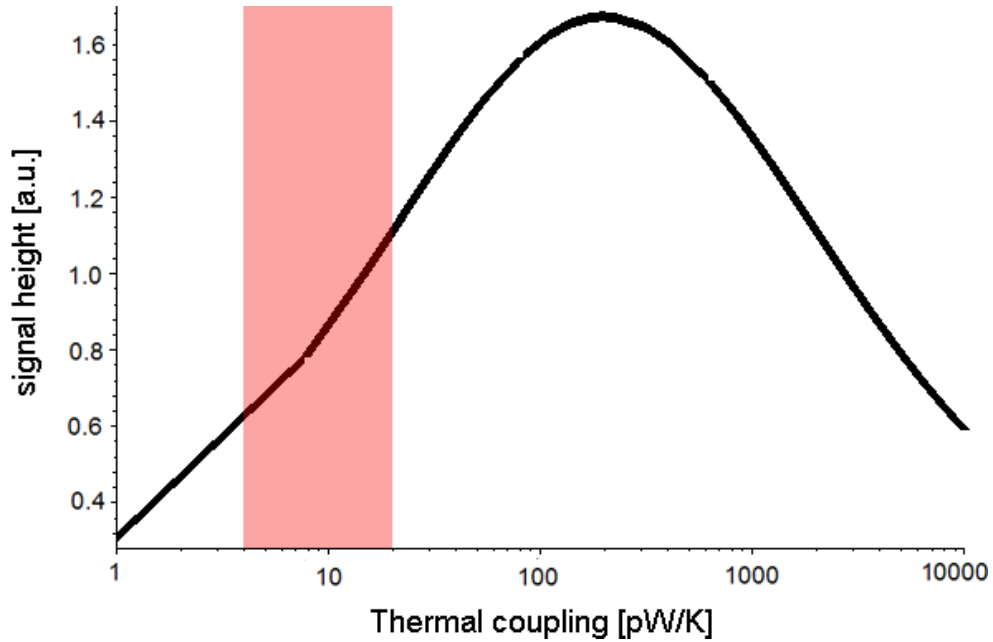


Optimization of the Thermal Coupling G_{BT}

Signal height calculated for different thermal couplings



Largest signal expected for about ten times larger coupling

Summary and Outlook

Motivation

Light channnel energy resolution is the crucial factor for CRESST

Results

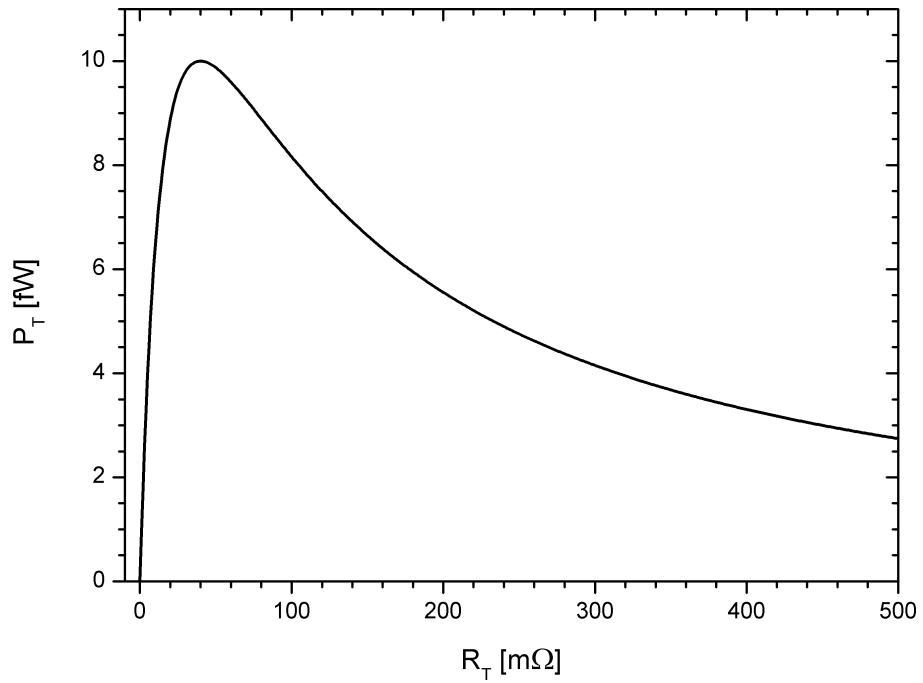
- Increase of light-production, -transport or -absorption
  $\rightarrow$ Black Silicon
- Lower transition temperature
  $\rightarrow$ Transition temperature of about 15 mK
- Larger transition slope
  $\rightarrow$ Reduction of critical current effect with smaller normal-conducting resistance
- Increased read-out current with optimized thermal coupling

Thank you for your attention

Backup

Self-Heating Effect

$$P_T = R_T I_T^2 = R_T I_{Tot}^2 \frac{R_S^2}{(R_S+R_T)^2}$$

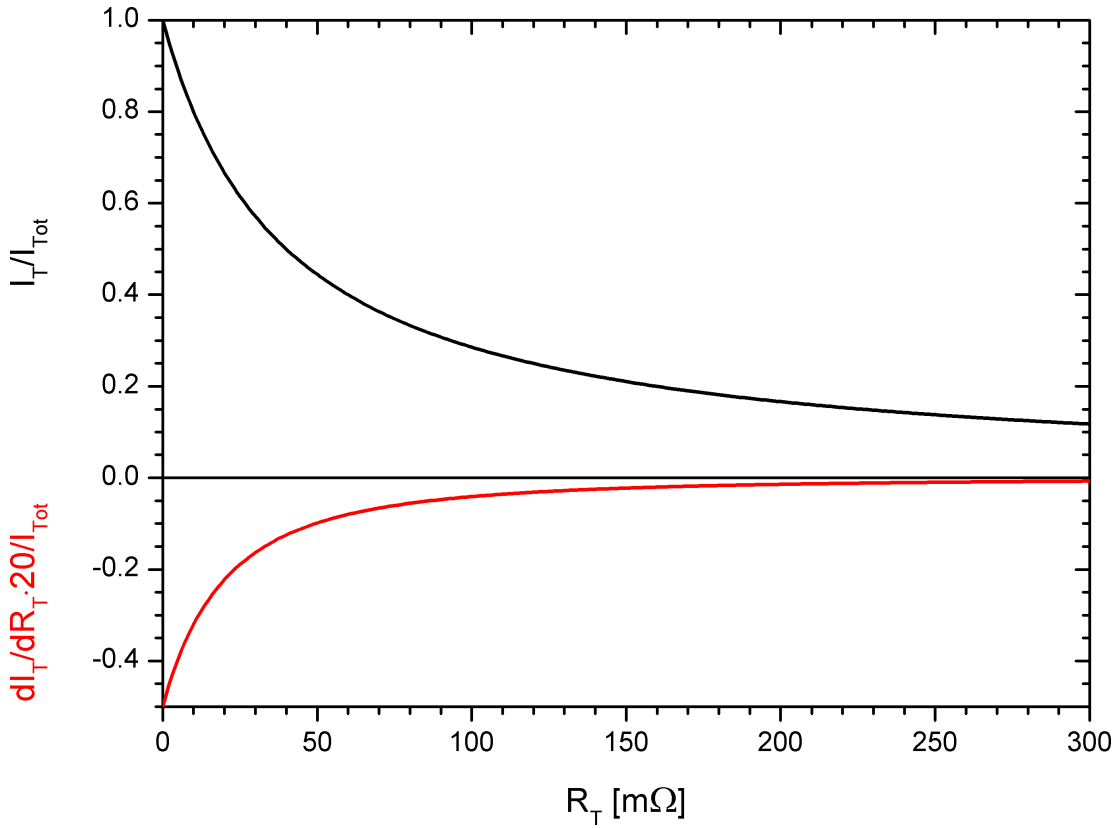


cooling power: $P_{BT} = (T_T - T_B)G_{BT}$

$\rightarrow$ measured $\Delta T_{Shift} = T_T - T_B = \frac{P_T}{G_{BT}}$

Critical Current Effect

the thermometer current I_T influences the measured resistance



the change of the current dI_T influences the observed transition
$\rightarrow$ critical current effect is expected to appear for $R_T \lesssim R_S$

Temperature Rise in the Thermometer

$$\Delta T_T = A_+ \left(e^{-\frac{t}{\tau_+}} - e^{-\frac{t}{\tau_N}} \right) + A_- \left(e^{-\frac{t}{\tau_-}} - e^{-\frac{t}{\tau_N}} \right) \tag{1}$$

$$= A_+(t) \qquad\qquad + A_-(t) \tag{2}$$

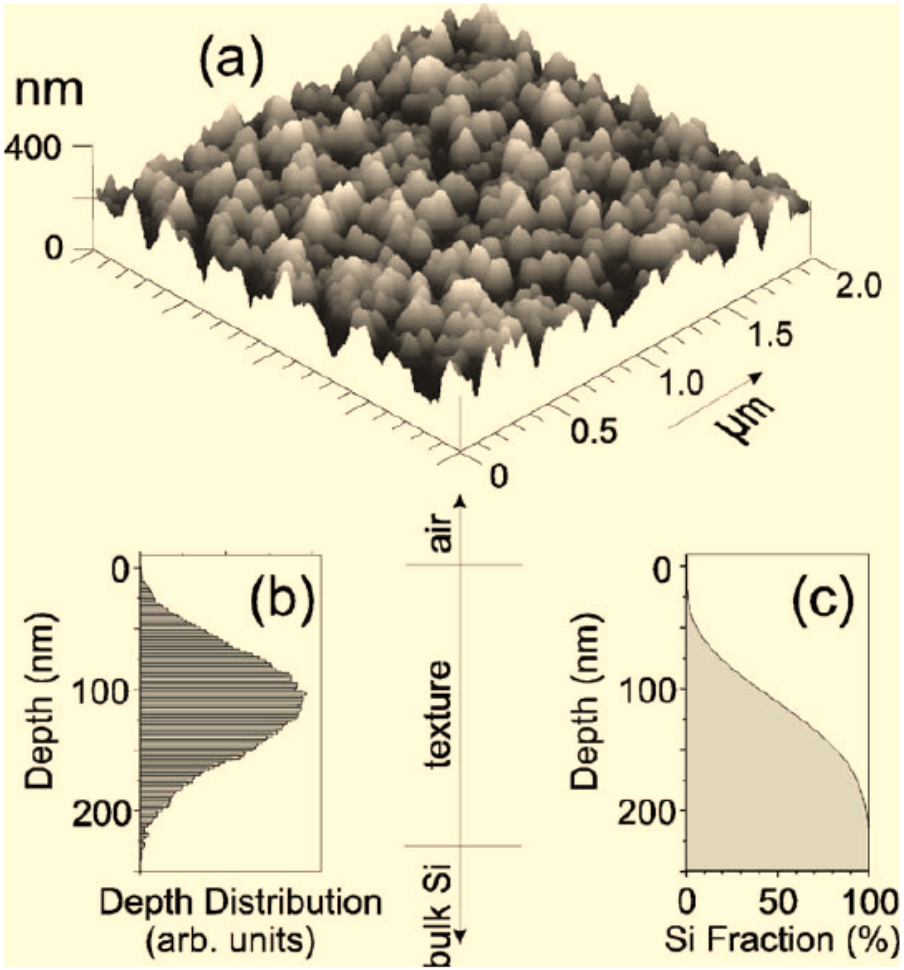
$$A_\pm = \frac{1}{1 - \frac{\tau_N}{\tau_\pm}} \cdot \frac{1}{\frac{1}{\tau_\mp} - \frac{1}{\tau_\pm}} \cdot \left[\varepsilon \cdot \left(\frac{1}{\tau_\mp} - \frac{G_{AT} + G_{BT}}{C_T} \right) + (1 - \varepsilon) \cdot \frac{G_{AT}}{C_A} \right] \cdot \frac{E_{LD}}{C_T} \tag{3}$$

$$\tau_\pm = \frac{2}{a \pm \sqrt{a^2 - 4b}} \tag{4}$$

$$a = \frac{G_{AT} + G_{BT}}{C_T} + \frac{G_{AT} + G_{AB}}{C_A} \tag{5}$$

$$b = \frac{G_{AT} G_{BT} + G_{AT} G_{AB} + G_{BT} G_{AB}}{C_T C_A} \tag{6}$$

Black Silicon



Detector Module