IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), April 2017.
Oral presentation at IWSSD 2016. No manuscript was submitted for hardcopy journal publication.

Govenius et al., PRL 117, 030802 (2016)

Detecting zJ microwave pulses

– using calorimetry and electrothermal feedback

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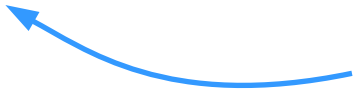
Motivation

Lack of an efficient photodetector
for itinerant microwave photons



But there's progress!
e.g., Inomata et al., Nature Comm. 7, 12303 (2016)

Applications:

- quantum computing/communication protocols
  Examples: Govenius et al., PRA **92**, 042305 (2015)
  & references therein.
- quantum thermodynamics
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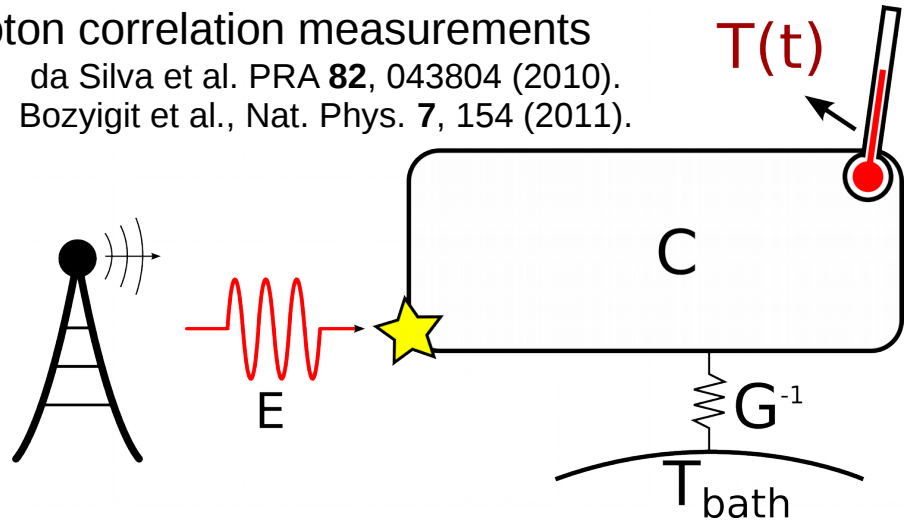

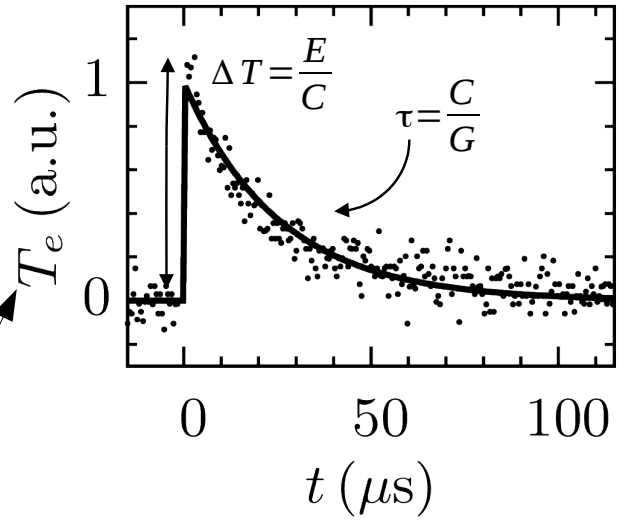

Can we use calorimetry?

Good review on THz calorimeters:
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$\Delta E = h \times 23\ \mathrm{THz} = 15\ \mathrm{zJ}$

in

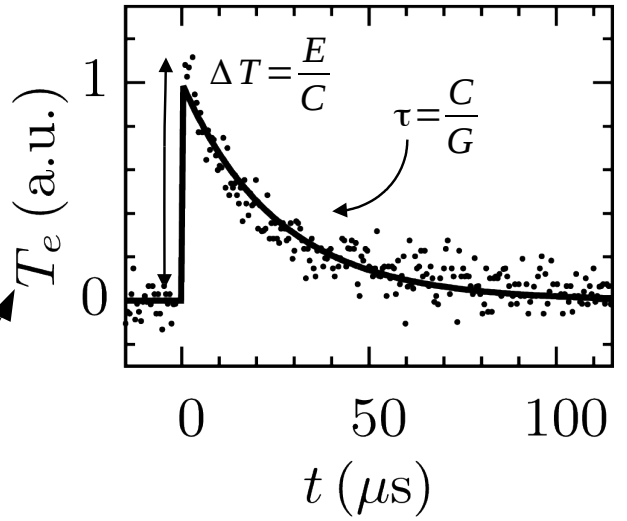
Santavicca et al., APL **96**, 083505 (2010).
Karasik et al., APL **101**, 052601 (2012).

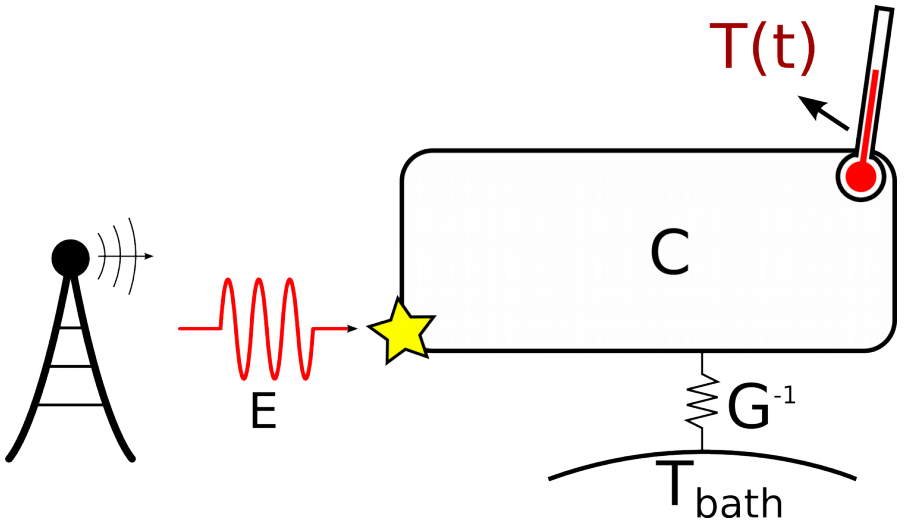
Ours: $200 \times h \times 8.4\ \mathrm{GHz} = 1.1\ \mathrm{zJ}$

= -110 dBm x 100 ns

Outline

- Principle of operation (“linear response”)
- Electrothermal nonlinearity
- Detection of zJ pulses
- (Noise equivalent power)





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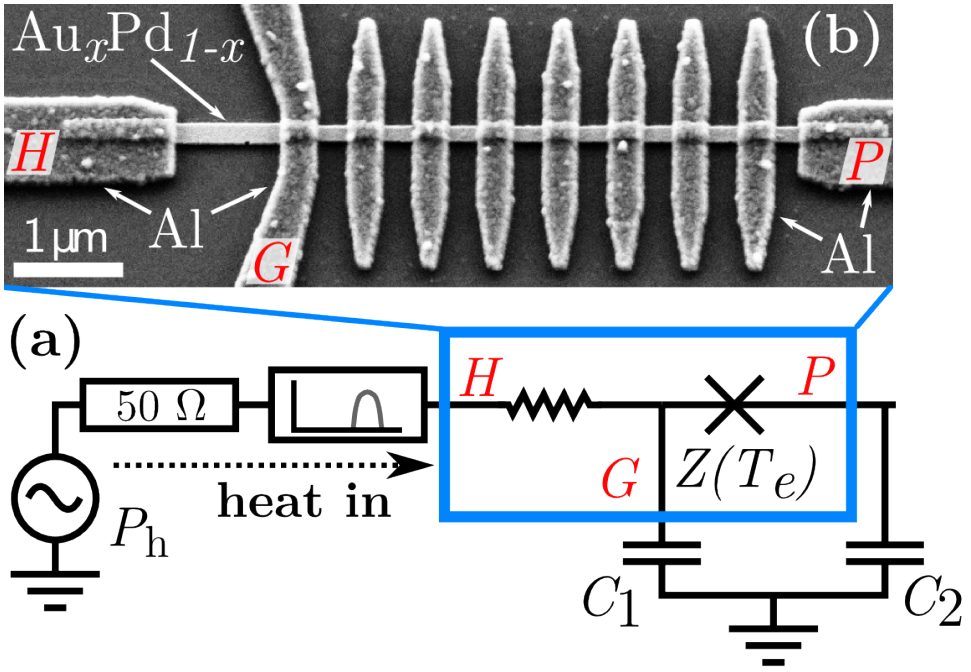
Principle of operation

8 GHz microwave power → T_e → 750 MHz electrical output



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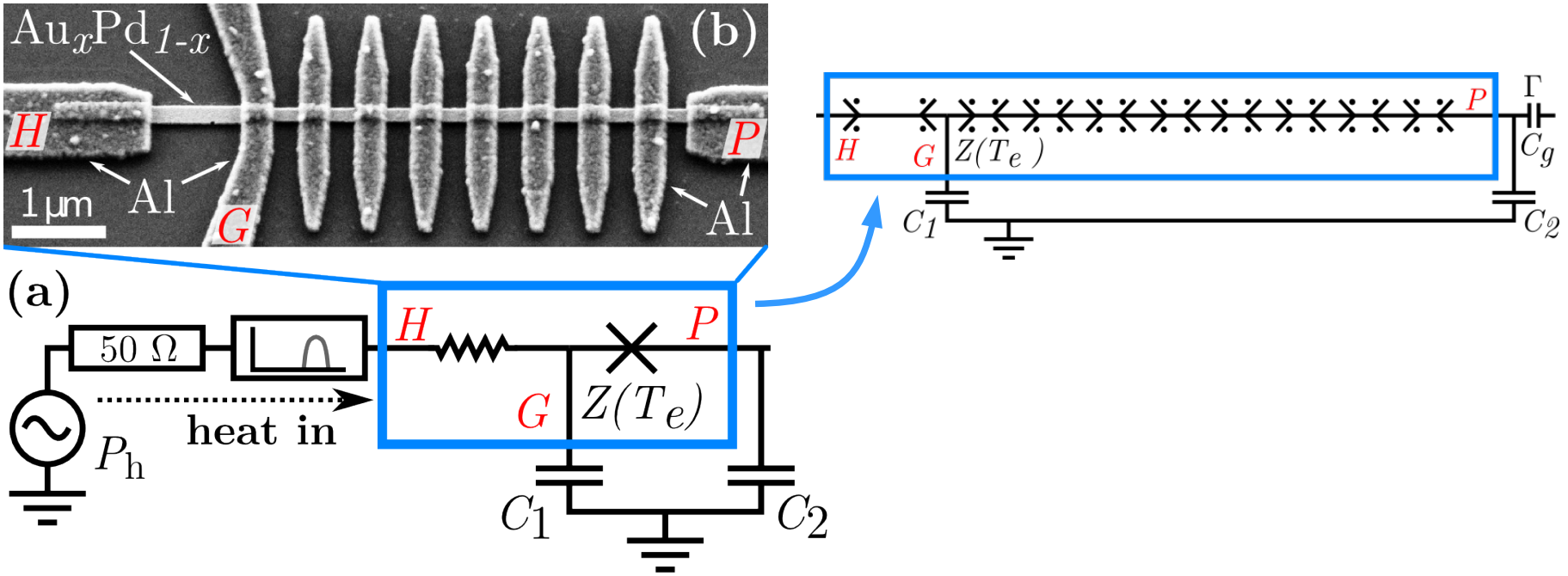

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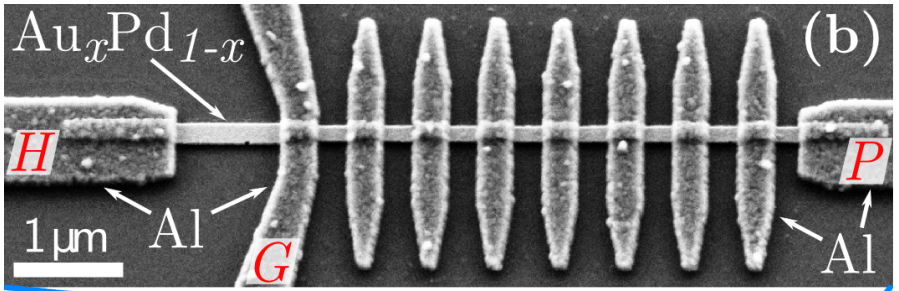

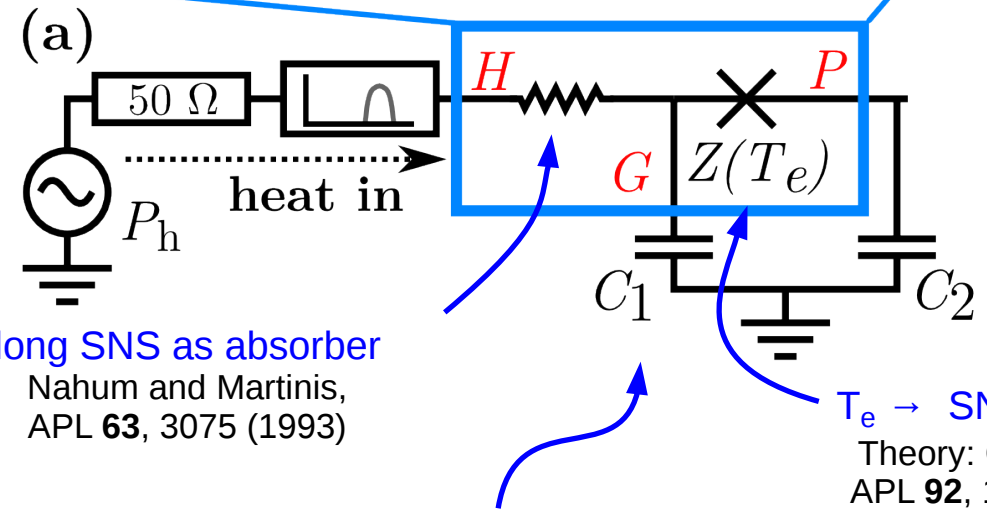

long SNS as absorber
Nahum and Martinis,
APL **63**, 3075 (1993)

T_e → SNS inductance
Theory: Giazotto et al.,
APL **92**, 162507 (2008).

Alternative: T_e → SIN resistance + RF readout
Schmidt, Yung and Cleland, APL 83, 1002 (2003).
Gasparinetti et al., Phys. Rev. Appl. **3**, 014007 (2015)

Principle of operation

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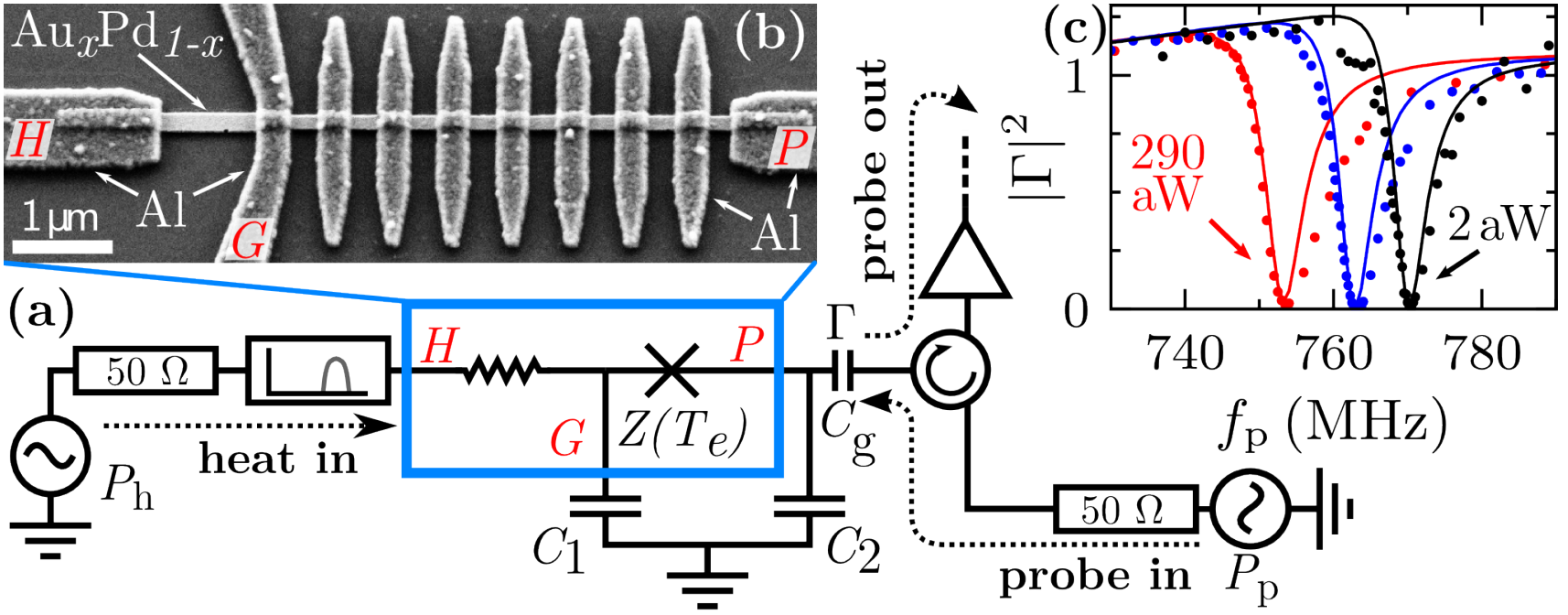
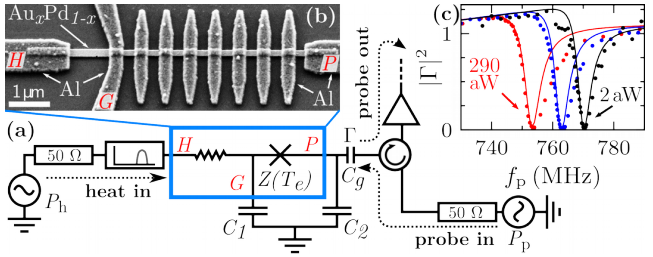
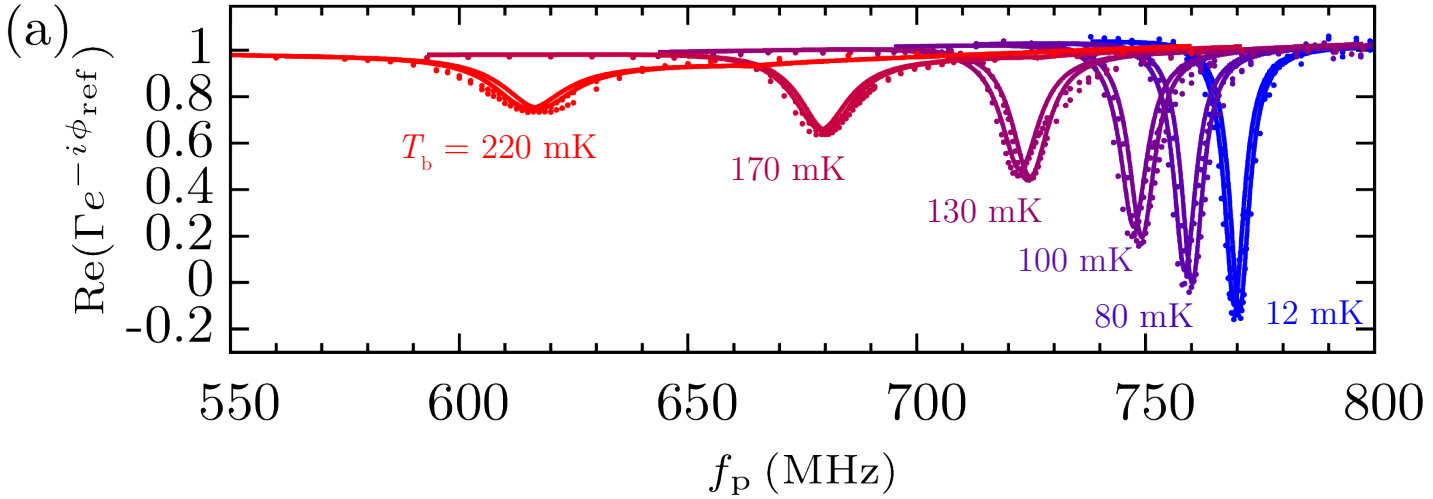
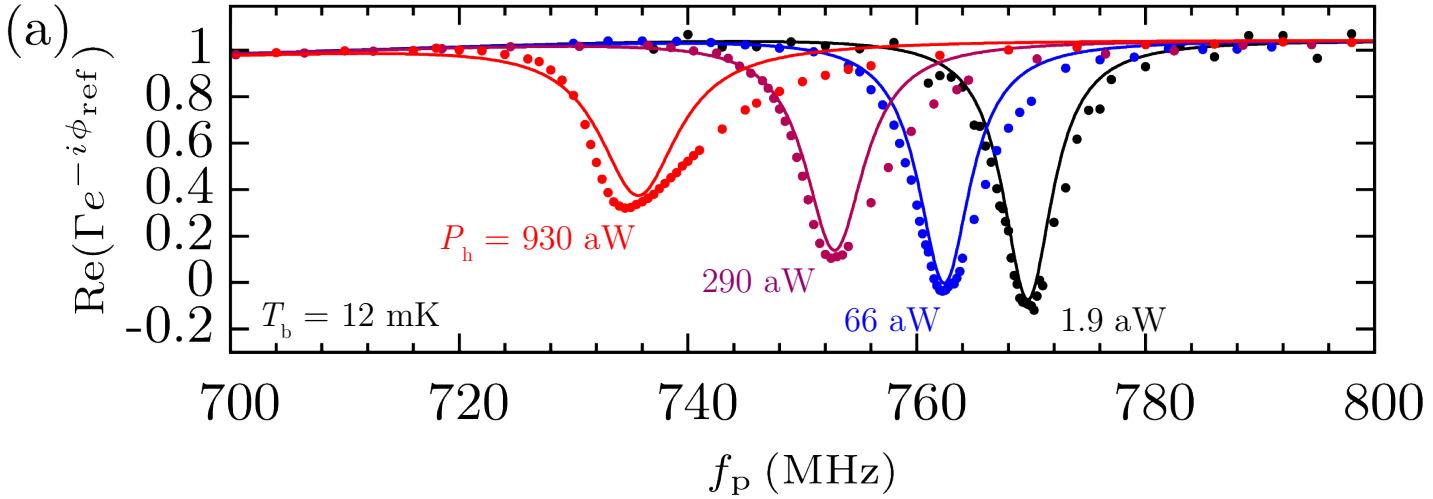




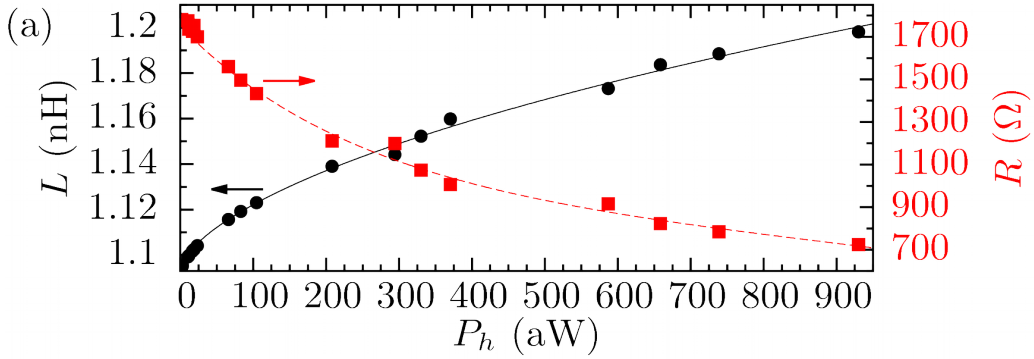
Effect of T_b and P_h

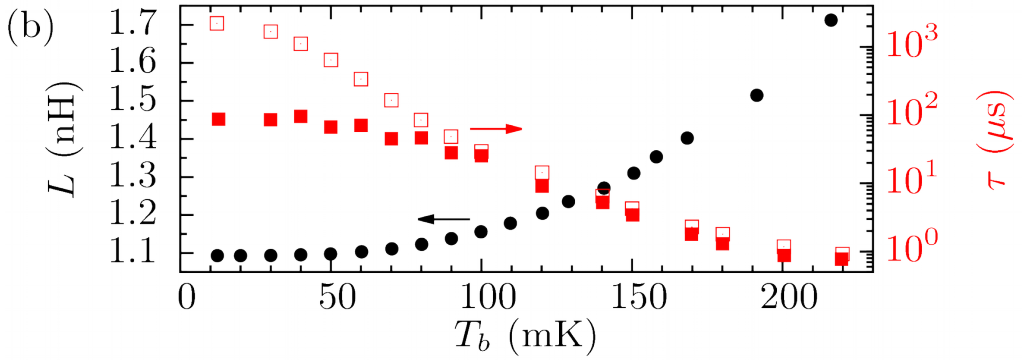
- linear response

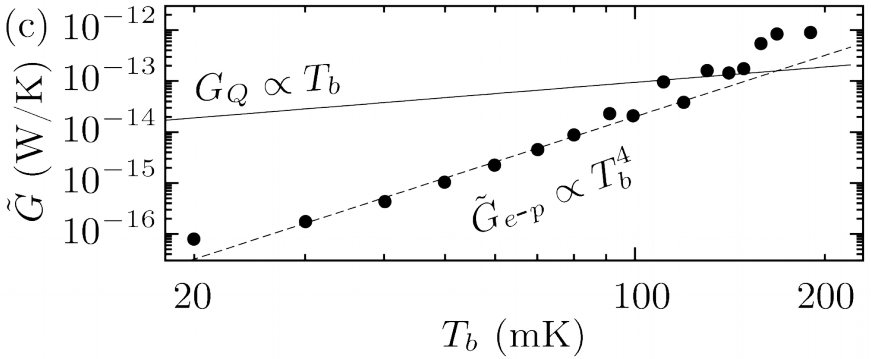


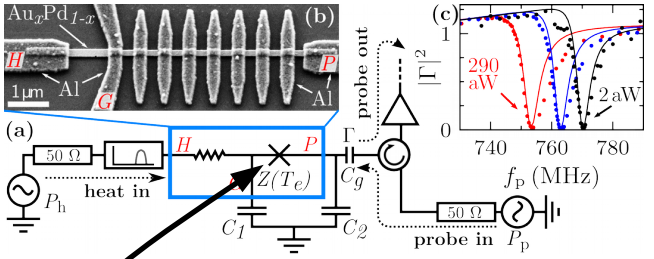


Linear response

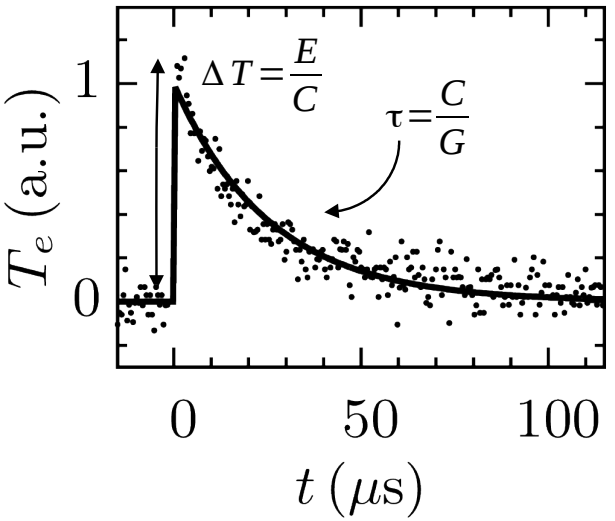








$$Z^{-1} = R^{-1} + (i\omega L)^{-1}$$



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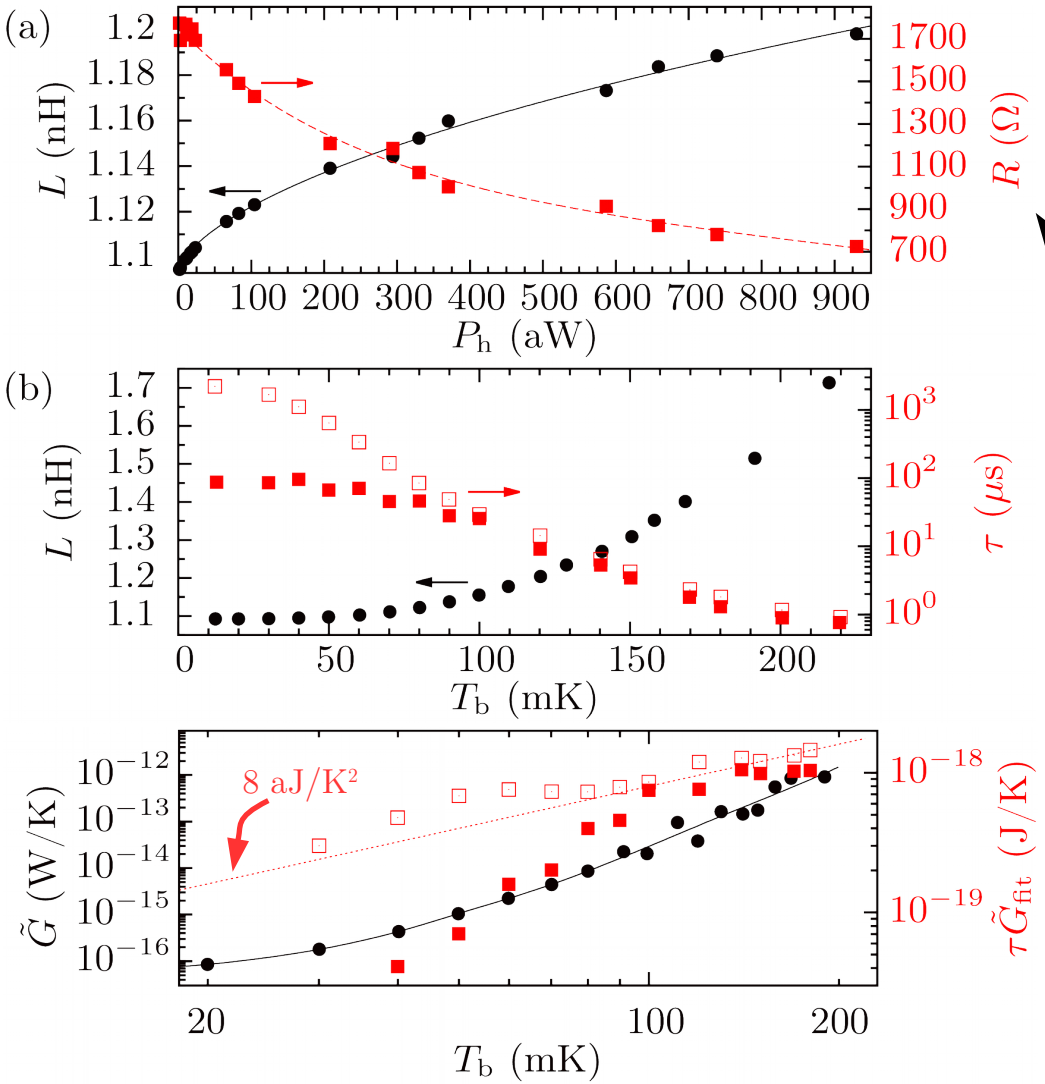

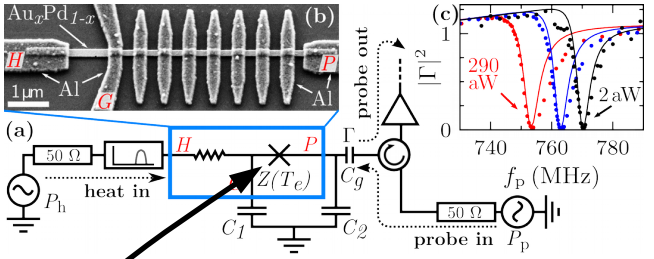

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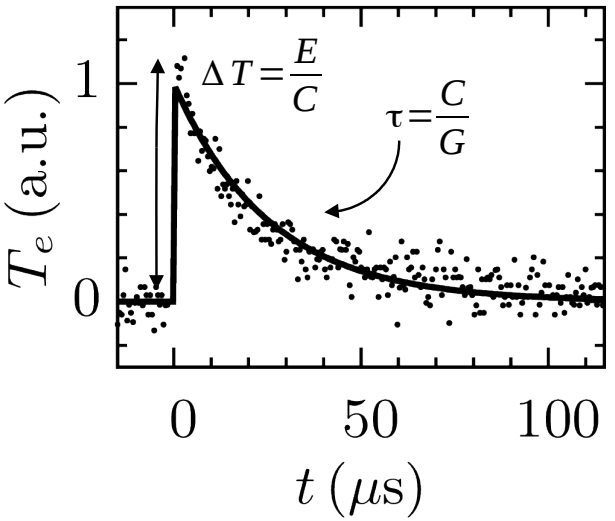
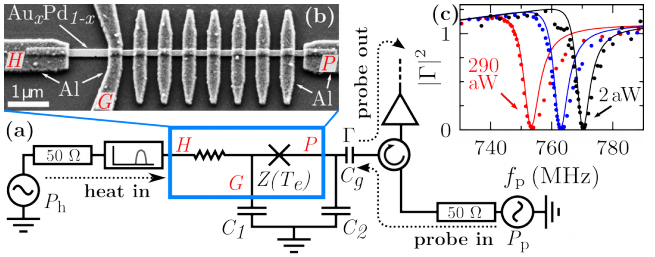
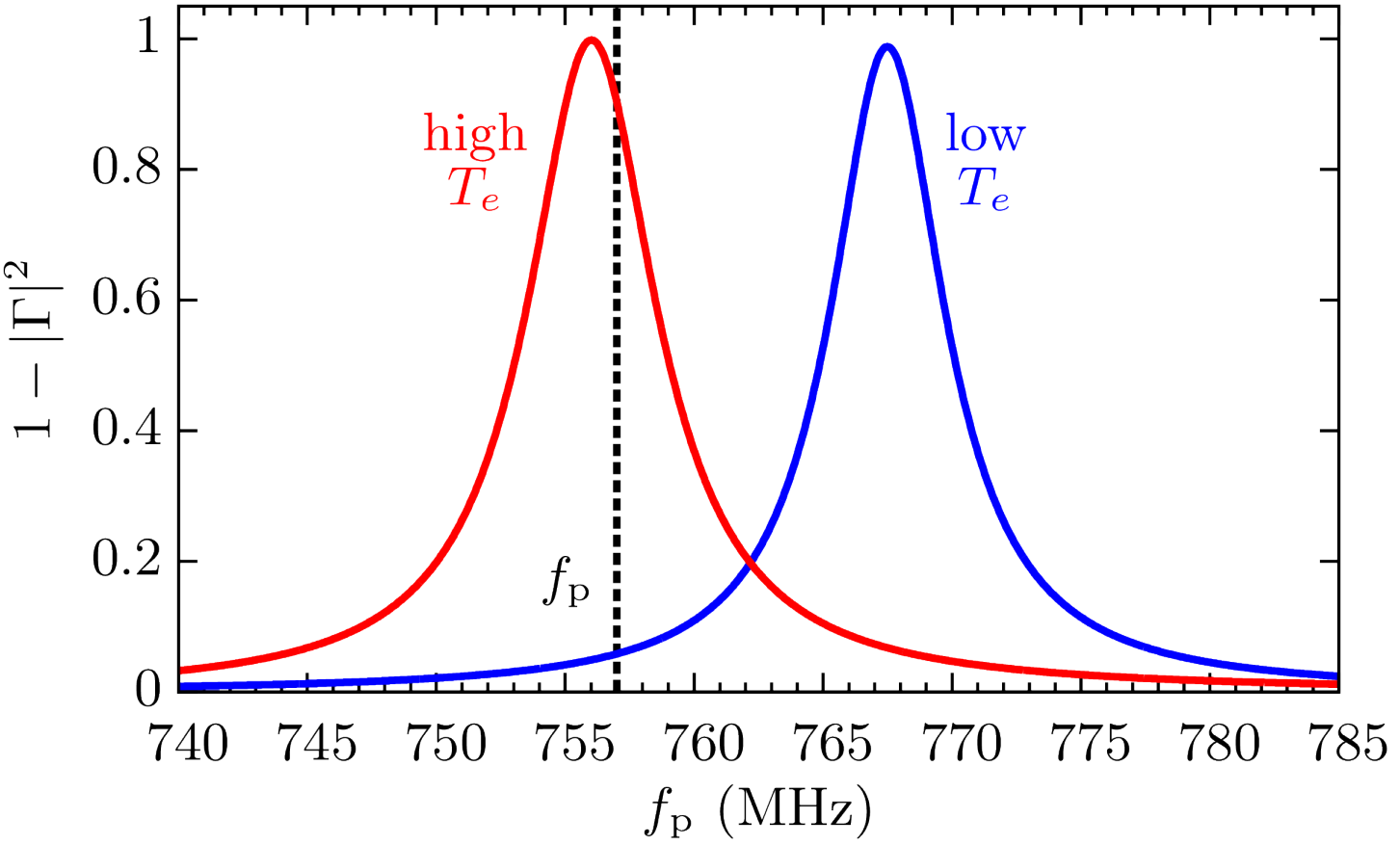


Electrothermal non-linearity





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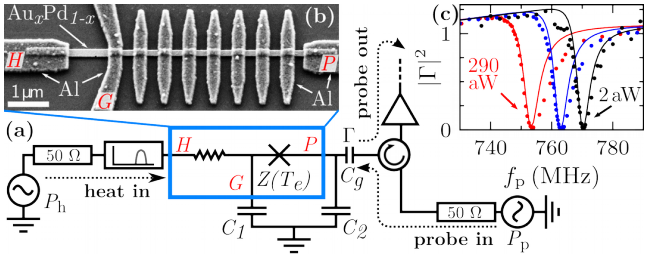


heat flow to thermal bath

heater power

probe power

probe freq.

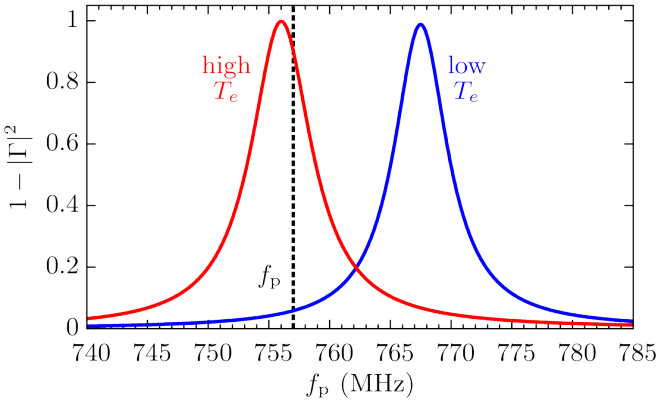
"Thermal" power balance

$$C_e\left(T_e\right)\dot{T}_e = -P_{e-b}\left(T_e, T_b\right) + P_x + P_h + \left(1 - \left|\Gamma\left(T_e, \omega\right)\right|^2\right)P_p$$

"Electrical" response

$$\Gamma\left(T_e, \omega\right) = \frac{Z_L\left(T_e\right) - Z_0}{Z_L\left(T_e\right) + Z_0},$$

$$\text{where } Z_L\left(T_e\right) = \frac{1}{i\omega C_g} + \left[i\omega C_2 + \left(Z^{-1}\left(T_e\right) + i\omega C_1\right)^{-1}\right]^{-1}$$



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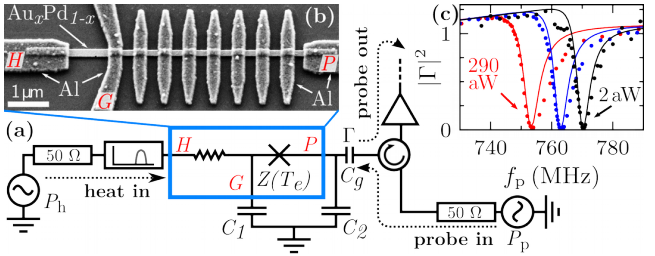


heat flow to thermal bath

heater power

"Thermal" power balance

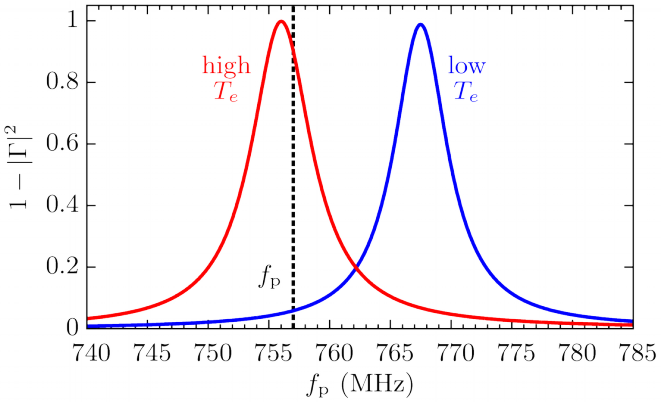
$$C_e(T_e)\dot{T}_e = -P_{e-b}(T_e, T_b) + P_x + P_h + (1 - |\Gamma(T_e, \omega)|^2)P_p$$

probe power

probe freq.

Change of variable from T_e to

$$\Delta(T_e) = P_{e-b}(T_e, T_b) - P_x$$



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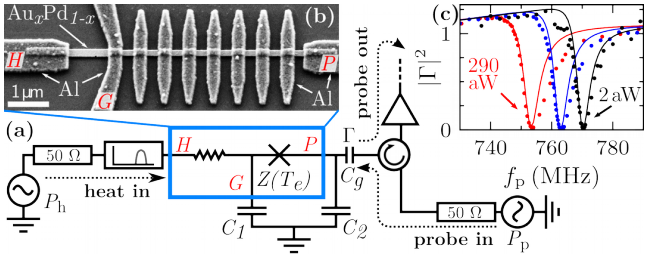

heat flow to thermal bath

electrothermal nonlinearity

"Thermal" power balance

$$\rightarrow \tau(\Delta)\dot{\Delta} = -\Delta + P_h + (1 - |\Gamma(\Delta, \omega)|^2)P_p$$

heater power

Change of variable from T_e to

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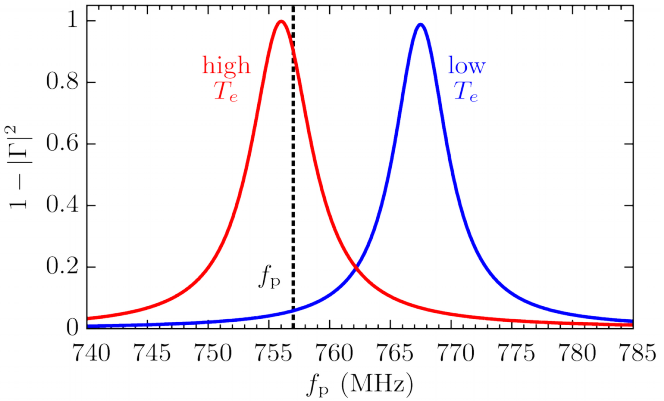

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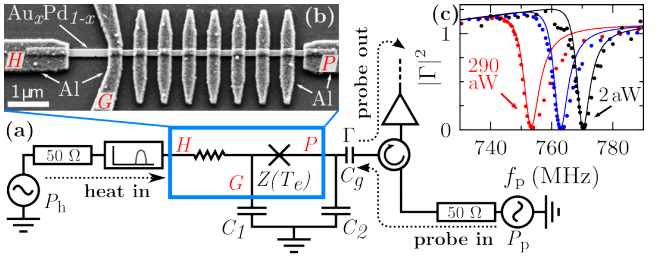


heat flow to thermal bath

electrothermal nonlinearity

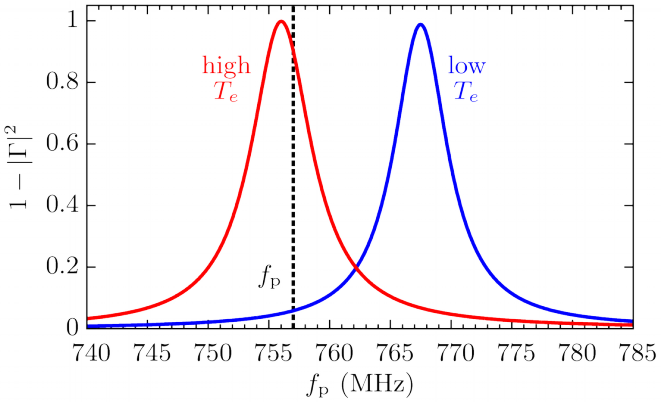
"Thermal" power balance

$$\tau(\Delta)\dot{\Delta} = -\Delta + P_h + (1 - |\Gamma(\Delta,\omega)|^2)P_p$$

heater power

Susceptibility

$$\chi = \left.\frac{\partial\Delta}{\partial P_h}\right|_{\dot{\Delta}=0}$$



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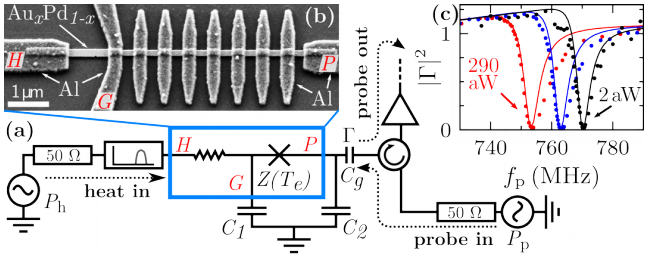


heat flow to thermal bath

electrothermal nonlinearity

"Thermal" power balance

$$0 = -\Delta + P_h + (1 - |\Gamma(\Delta,\omega)|^2)P_p$$

heater power

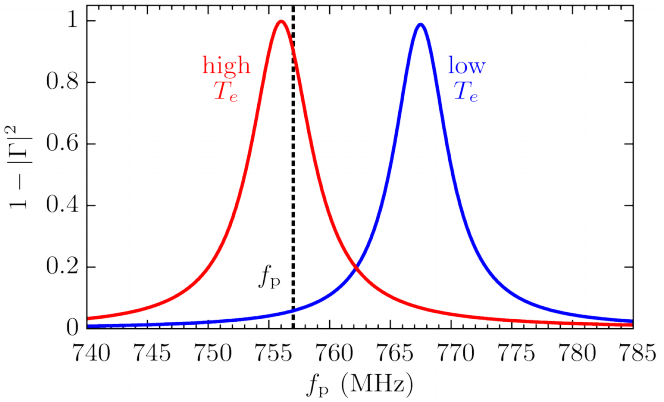
$$\frac{\partial}{\partial P_h}$$

Susceptibility

$$0 = 1 - \frac{\partial}{\partial P_h}|\Gamma(\Delta,\omega)|^2 P_p$$

$$0 = 1 - P_p \frac{\partial \Delta}{\partial P_h}\frac{\partial |\Gamma(\Delta,\omega)|^2}{\partial \Delta}$$

$$\chi = \left(1 + P_p \frac{\partial |\Gamma(\Delta,\omega)|^2}{\partial \Delta}\right)^{-1}$$



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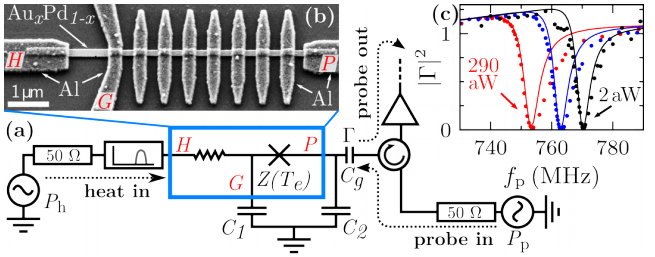
Electrothermal non-linearity



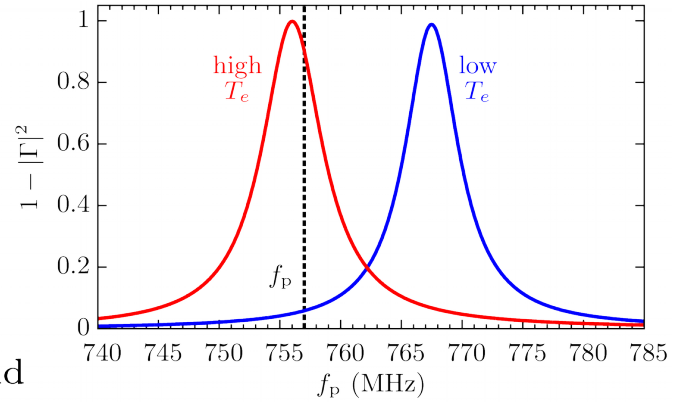
heat flow to thermal bath

electrothermal nonlinearity

"Thermal" power balance

$$0 = -\Delta + P_h + (1 - |\Gamma(\Delta, \omega)|^2) P_p$$

heater power



Susceptibility

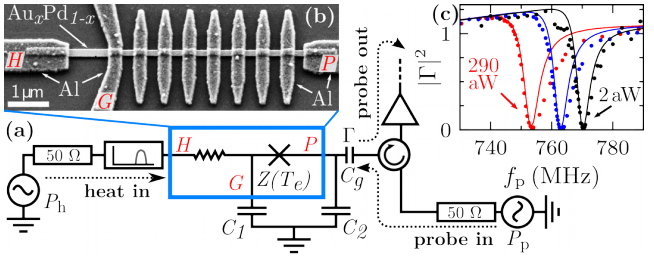
$$P_p \to -\left(\frac{\partial |\Gamma(\Delta, \omega)|^2}{\partial \Delta}\right)^{-1} \equiv P_{p,\text{threshold}}$$

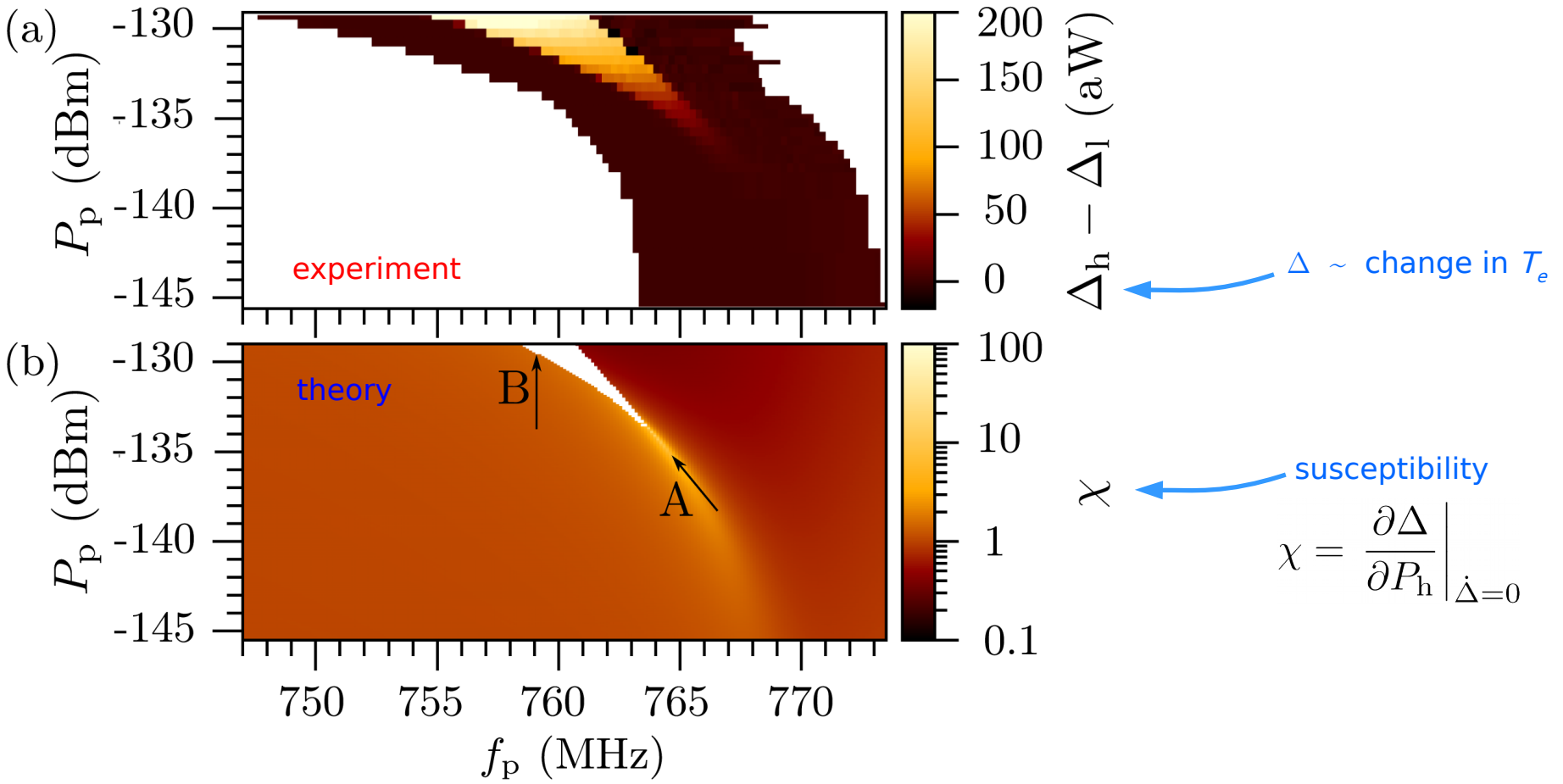
$$\chi = \left(1 + P_p \frac{\partial |\Gamma(\Delta, \omega)|^2}{\partial \Delta}\right)^{-1}$$

$$\chi = \left.\frac{\partial \Delta}{\partial P_h}\right|_{\dot{\Delta}=0}$$

Electrothermal non-linearity

– "phase diagram"



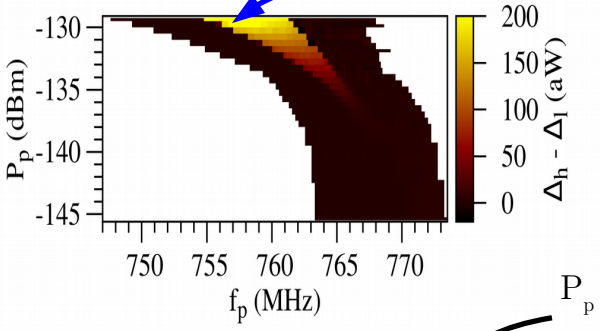


Δ ~ change in T_e

susceptibility

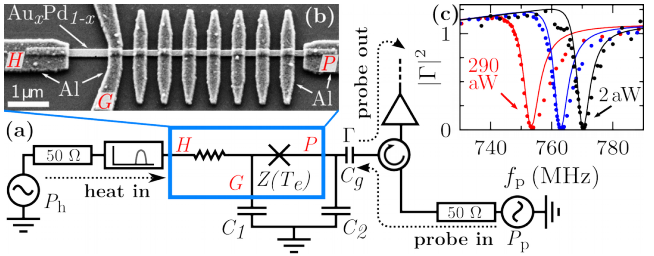
$$\chi = \left.\frac{\partial \Delta}{\partial P_h}\right|_{\dot{\Delta}=0}$$

Threshold detection
– pulse sequence



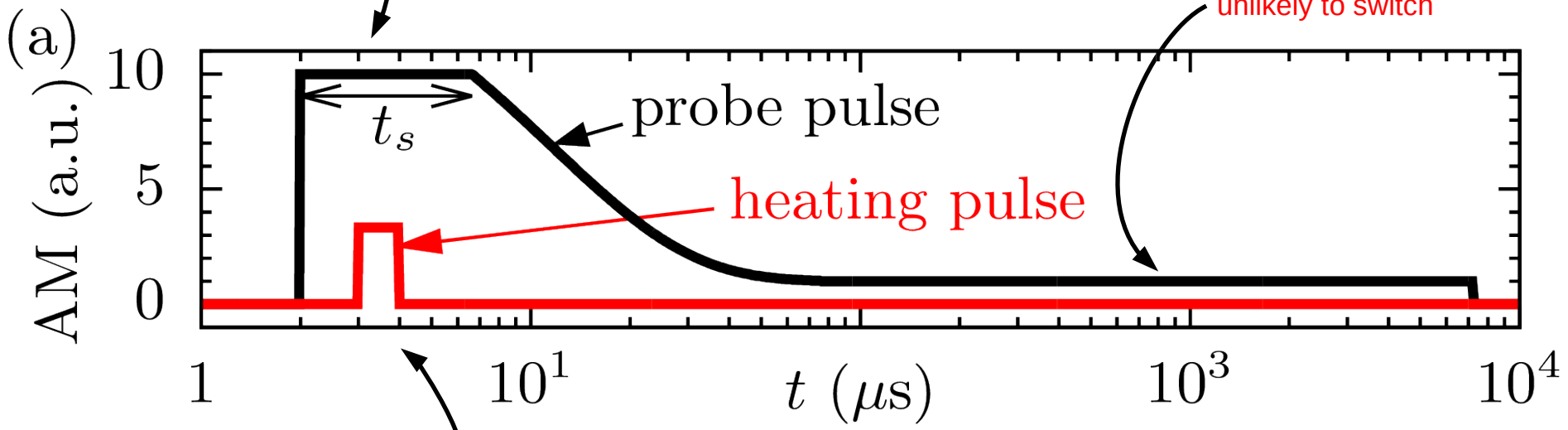
$f_{probe} = 757$ MHz

$P_{probe} = -130$ dBm



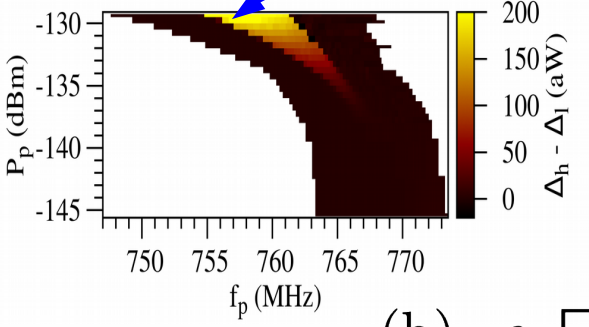
P_p increased
→ switches easily

bistable but very
unlikely to switch



$P_{heater} = -120$ dBm for 1 μs
→ $200\times(h\times 8.4\,GHz)$ of power

Threshold detection
– histograms



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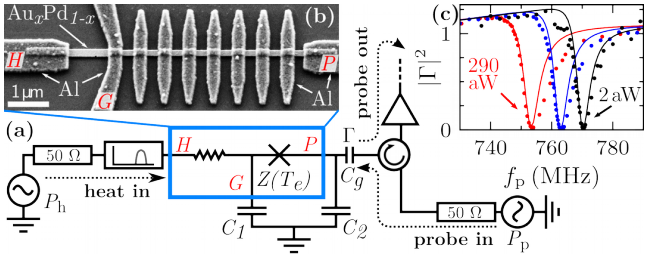
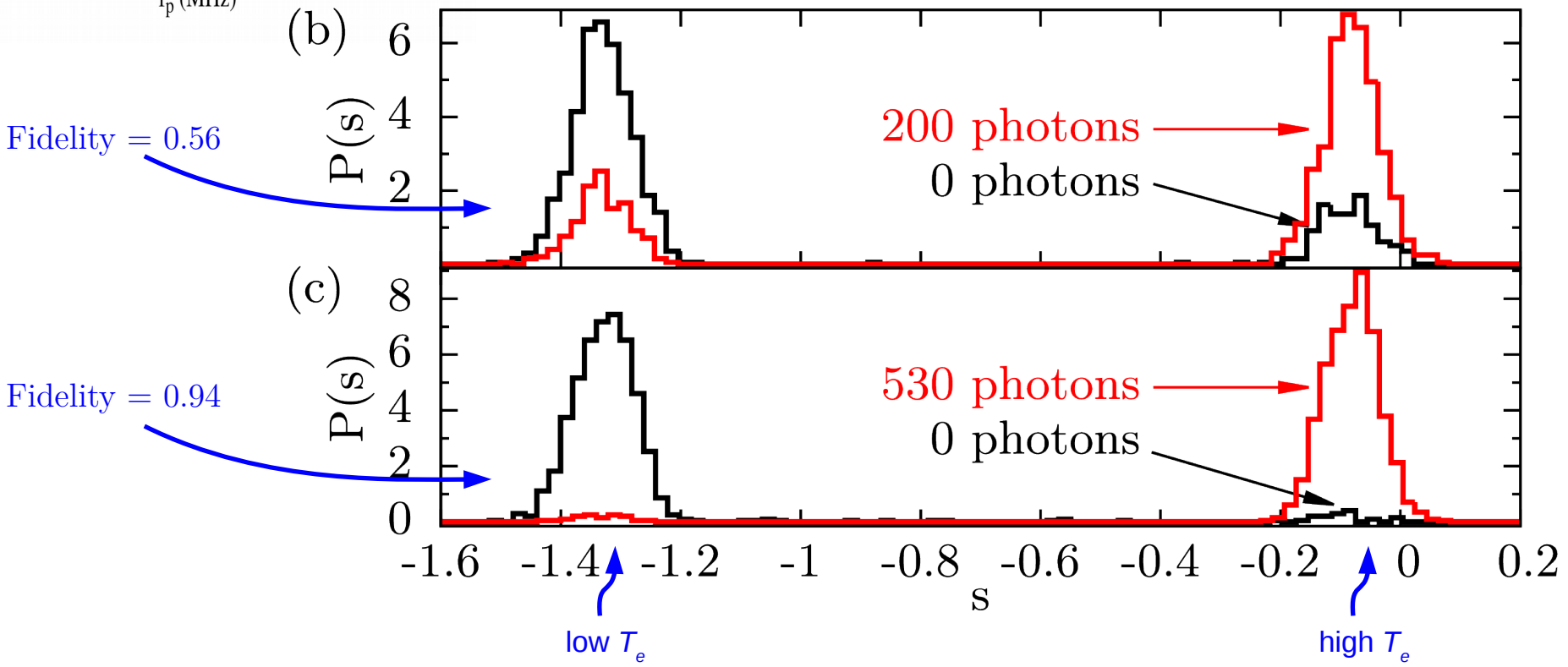
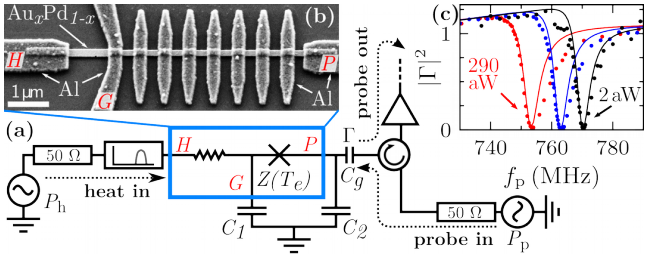




Fidelity = 0.56

Fidelity = 0.94

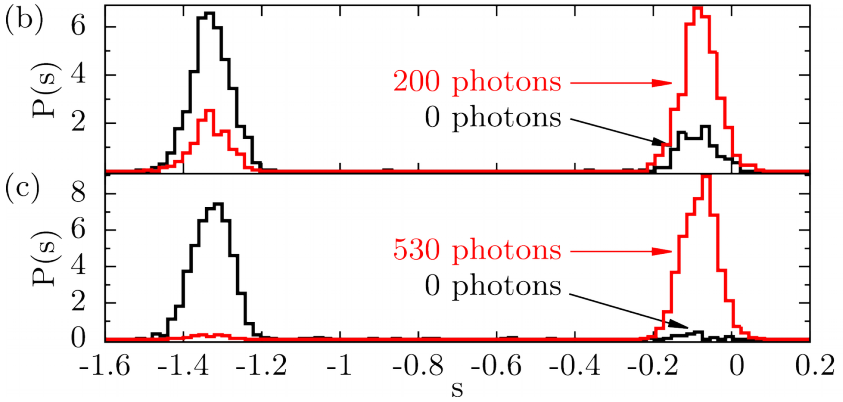
Summary



Details in Govenius et al., PRL 117, 030802 (2016).

- detected ~200 x h x 8.4 GHz = 1.1 zJ pulses

- using positive electrothermal feedback



The last slides on preliminary
noise equivalent power measurements
have been removed
from this online version.