“Real-time” millikelvin thermometry in a semiconductor-qubit architecture

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(Received 25 August 2023; revised 16 February 2024; accepted 17 May 2024; published 17 June 2024)

We report local time-resolved thermometry in a silicon-nanowire quantum dot device designed to host a linear array of spin qubits. Using two alternative measurement schemes based on rf reflectometry, we are able to probe either local electron or bosonic bath temperatures with microsecond time scale resolution and a noise-equivalent temperature of 3 mK/$\sqrt{\text{Hz}}$. Following the application of short microwave pulses, causing local periodic heating, time-dependent thermometry can track the dynamics of thermal excitation and relaxation, revealing clearly different characteristic time scales. This work opens important prospects to investigate the out-of-equilibrium thermal properties of semiconductor quantum electronic devices operating at very low temperature. In particular, it may provide a powerful handle to understand heating effects recently observed in semiconductor spin-qubit systems.

Motivation

There is unintentional local heating by the high-frequency signal used with spin qubits due to dissipation (Joule, dielectric)

These local temperature changes affect the spin qubits

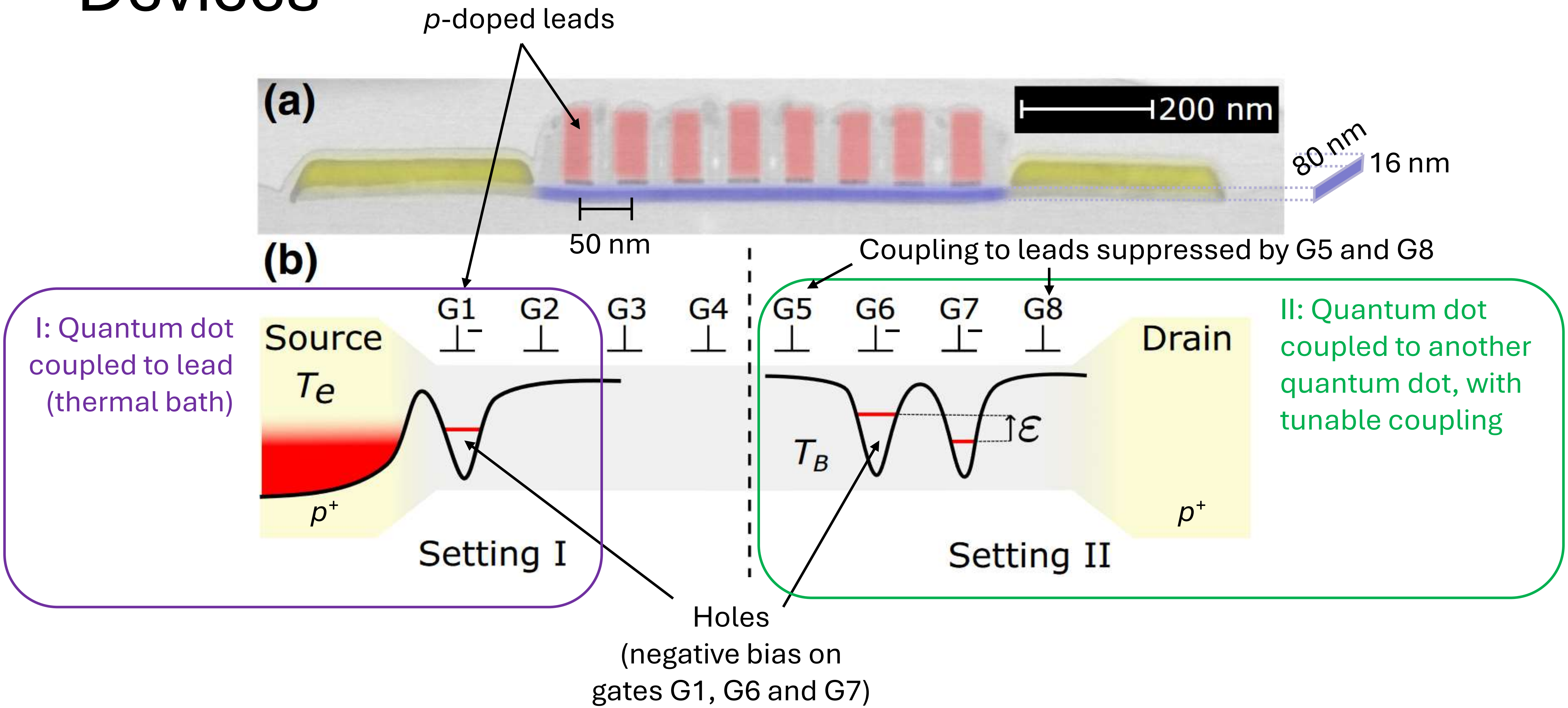
Temperature-dependence of spin qubit properties (Larmor frequency)

Spin decay and dephasing due to heating

Operating at higher overall temperature reduces the effect of this unintentional local heating, but sacrifices coherence

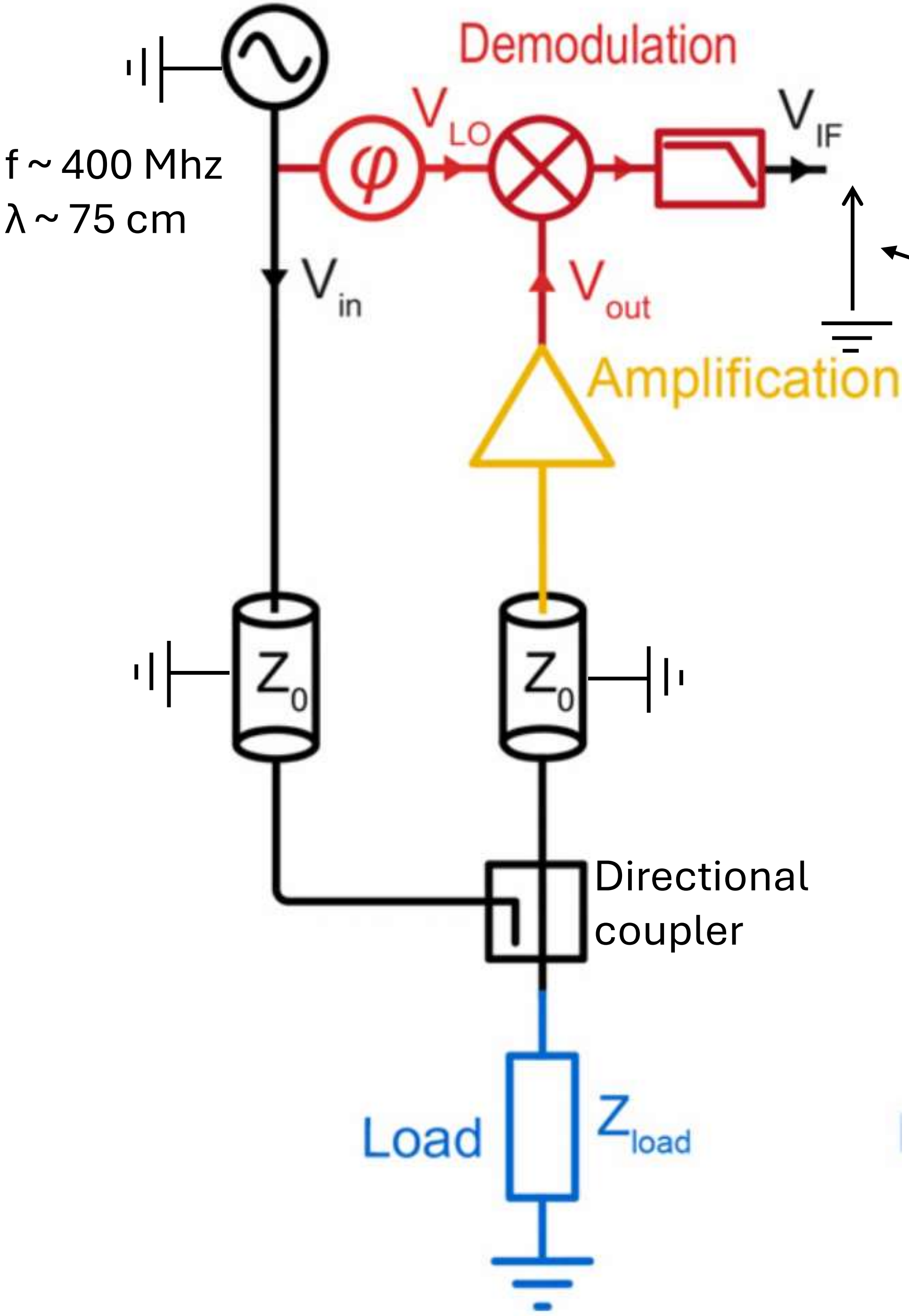
To improve qubits and have more qubits it is important to understand better these local heating effect

Devices



p-doped leads
(a)
200 nm
80 nm
16 nm
50 nm
(b)
Coupling to leads suppressed by G5 and G8
I: Quantum dot coupled to lead (thermal bath)
Source
Te
p+
G1
G2
G3
G4
Setting I
G5
G6
G7
G8
Drain
TB
ε
p+
Setting II
II: Quantum dot coupled to another quantum dot, with tunable coupling
Holes
(negative bias on gates G1, G6 and G7)

RF reflectometry



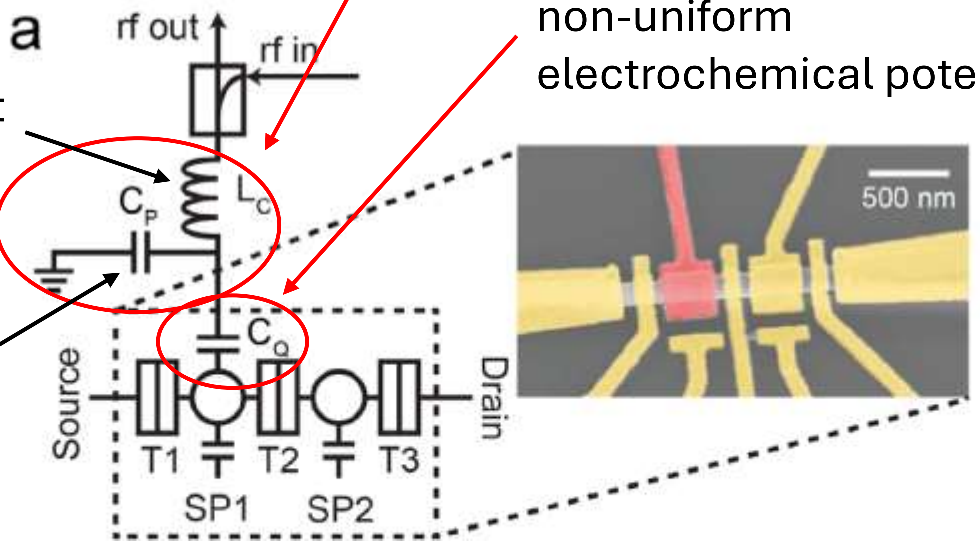
Reflected signal

LC resonator tank circuit

Additional "quantum" capacitance C_q due to non-uniform electrochemical potential

Surface-mount inductor

Parasitic capacitance



Adapted from Florian Vigneau *et al*; Probing quantum devices with radio-frequency reflectometry. Appl. Phys. Rev. 1 June 2023; 10 (2): 021305. https://doi.org/10.1063/5.0088229

RF reflectometry with LC resonator

Fitting amplitude of reflected signal

$$S_{21,\mathrm{dB}} = 20\log\left|1 + \frac{Q_\mathrm{i}\mathrm{e}^{i\varphi}}{Q_\mathrm{c}\left[1 + 2iQ_\mathrm{i}\left(\frac{f - f_\mathrm{r}}{f_\mathrm{r}}\right)\right]}\right|$$

At 52 mK:
$Q_\mathrm{i} = 385$
$Q_\mathrm{c} = 62$
$Q = Q_\mathrm{i} \,//\, Q_\mathrm{c} = 53.4$

$S_{21,\mathrm{dB}}$ amplitude in dB of reflected signal
Q_i internal quality factor
Q_c external quality factor

Time resolution limit ~ $\tau = \frac{Q}{2\pi f_0} =$ 20 ns @ $f_0 = 400\ \mathrm{MHz}$

Quantum capacitance, dot-lead situation

$$\boxed{C_\mathrm{q}(\varepsilon) = \alpha^2 e^2 [f * g](\alpha e \varepsilon)}$$

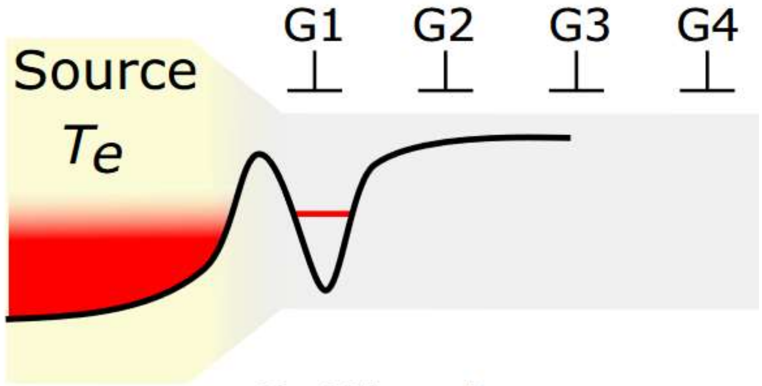
$$f(E) = \frac{1}{4k_\mathrm{B}T_\mathrm{e}} \cosh\left(\frac{E}{4k_\mathrm{B}T_\mathrm{e}}\right)^{-2}$$

Derivative of Fermi distribution in the lead broadened by $k_\mathrm{B}T_\mathrm{e}$

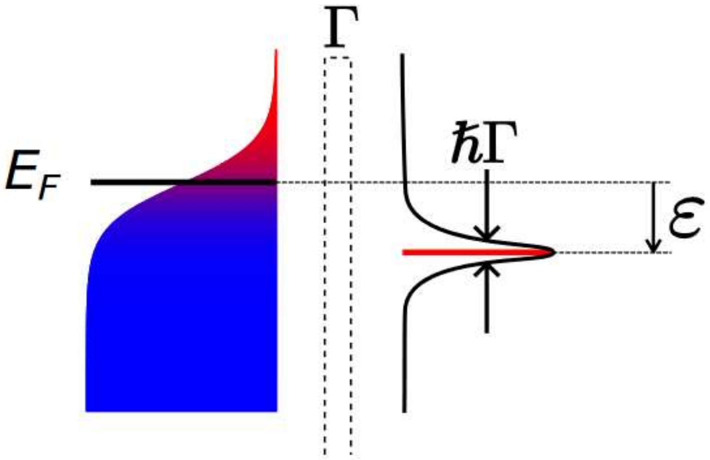
$$g(E) = \frac{\hbar\Gamma}{(\hbar\Gamma)^2 + E^2}$$

Dot density of states modeled by Lorentzian of width $\hbar\Gamma$

Regime: $\hbar\Gamma < k_\mathrm{B}T_\mathrm{e}$



Setting I



α gate lever-arm parameter
ε detuning in gate voltage
Γ tunnelling rate between dot and lead (angular frequency)
T_e electron temperature in the lead

e electron charge
k_B Boltzmann constant
$\hbar$ reduced Planck constant)

$$[f * g](x) = \int_{-\infty}^{+\infty} f(x-u)g(u)\,\mathrm{d}u \;\text{“=”} \int_{u+v=x} f(u)g(v)$$

Quantum capacitance, double dot situation

$$C_q(\varepsilon) = \alpha^2 e^2 \frac{2t^2}{\left((\alpha e\varepsilon)^2 + 4t^2\right)^{3/2}} \tanh\left(\frac{\left((\alpha e\varepsilon)^2 + 4t^2\right)^{1/2}}{2k_B T_B}\right)$$

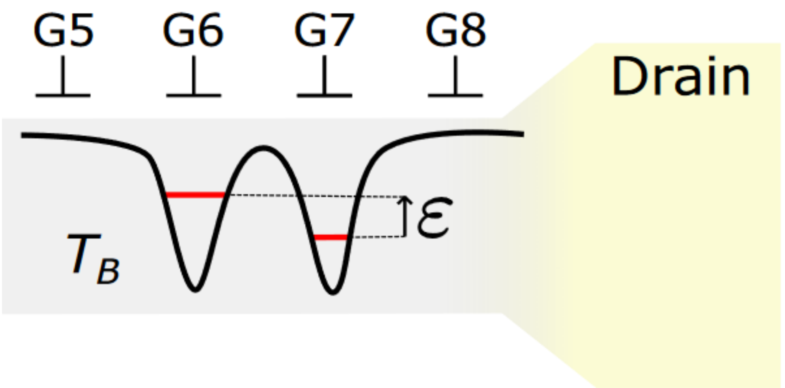
where $k_B T_B = \dfrac{2t}{\ln\left(\dfrac{P_{|+\rangle}}{P_{|-\rangle}}\right)}$

Regime: t $\lesssim k_B T_B$

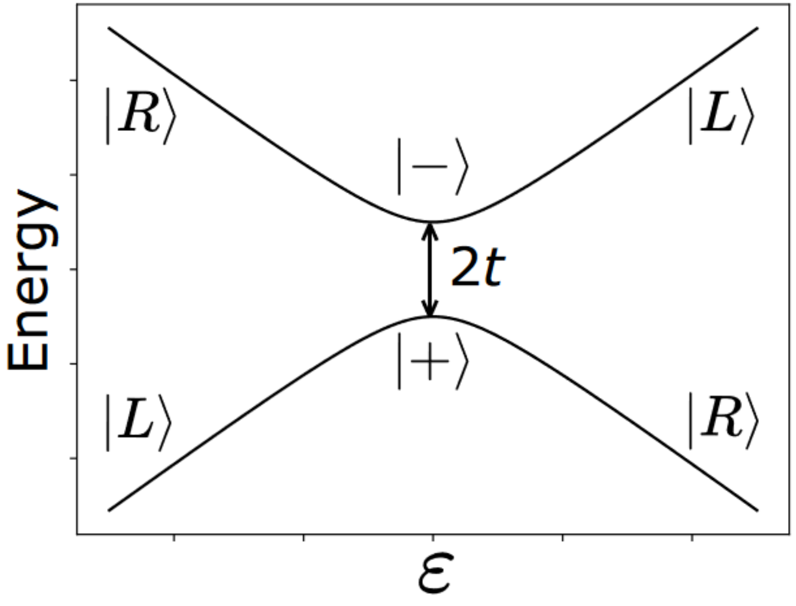
From Boltzmann distribution on two states

α gate lever-arm parameter
ε detuning in gate voltage
t tunnel coupling between the two dots (energy)
$P_{|+\rangle}$ and $P_{|-\rangle}$ populations of $|+\rangle$ or $|-\rangle$ states
(hybridised (bonding and antibonding) states, at detuning ε = 0)

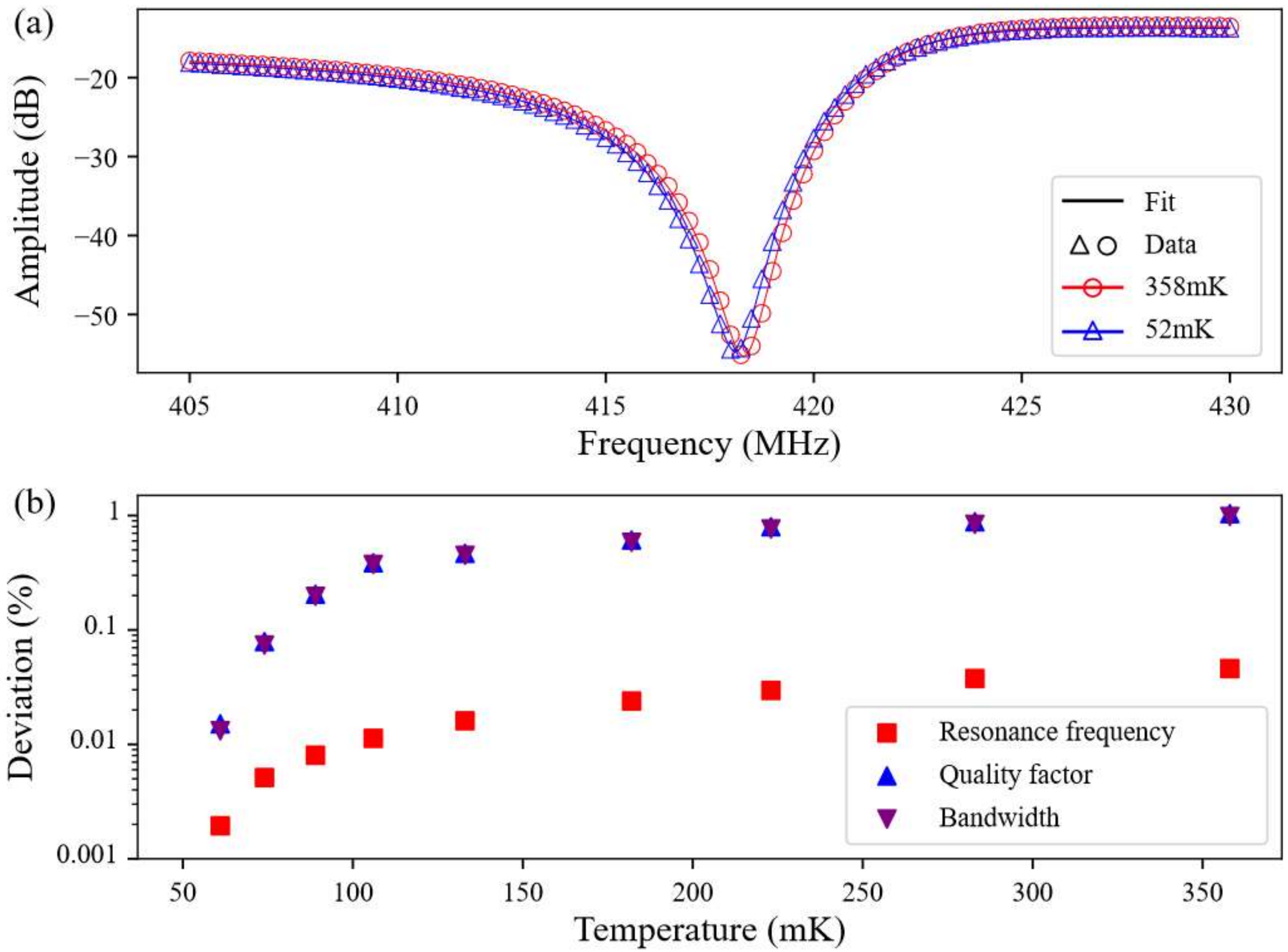
e electron charge
k_B Boltzmann constant
$\hbar$ reduced Planck constant)



Setting II

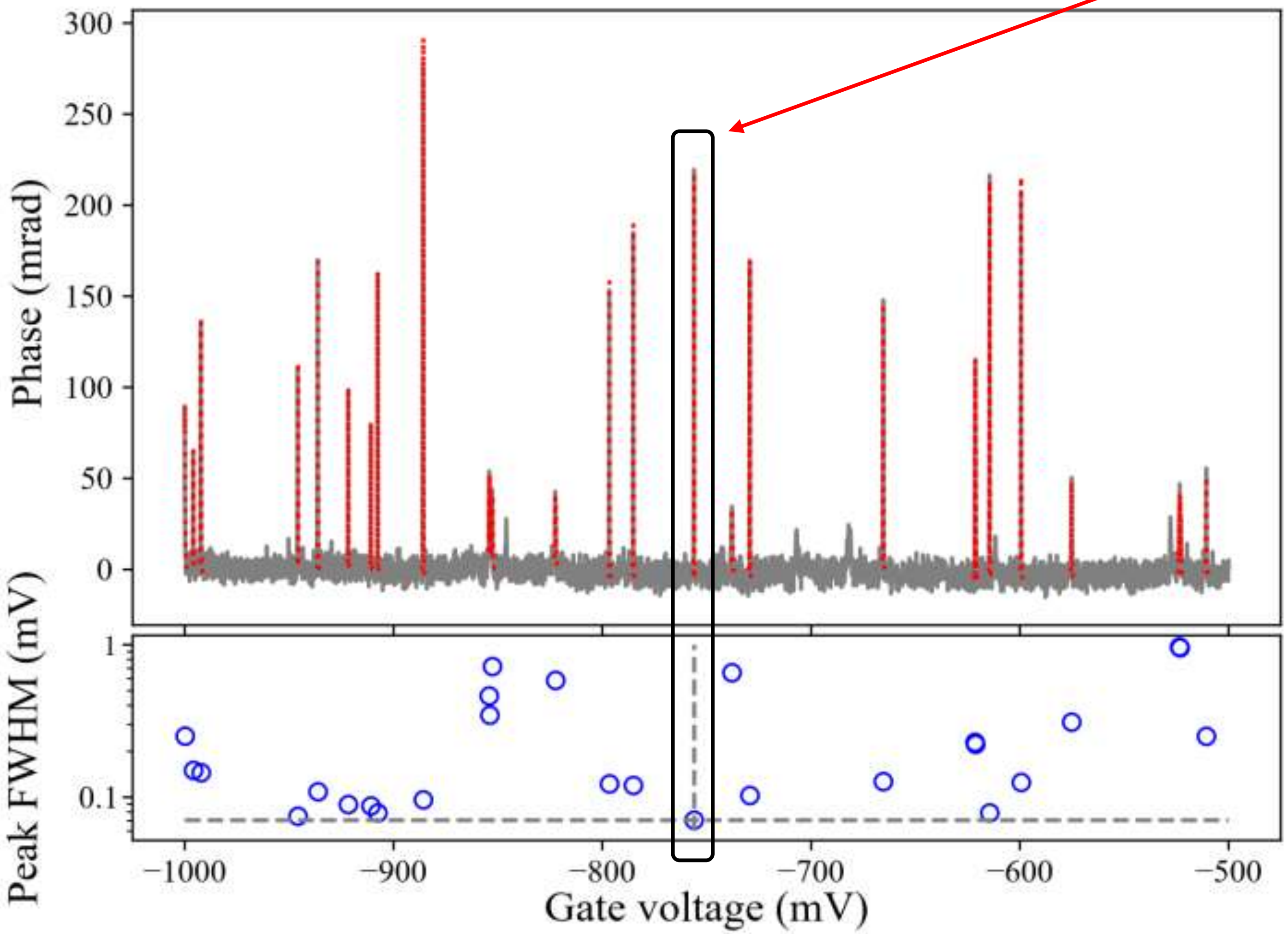


Preliminary checks and setup: LC resonator



Preliminary checks and setup: dot-lead transition selection (setting I)

Narrowest peak: lowest tunnelling rate *Γ*, quantum capacitance most sensitive to temperature in lead



$\Gamma/2\pi$ = 383 ± 38 MHz

Preliminary checks and setup: temperature sensitive regime for double quantum dot, with low tunnel coupling (setting II)

t/h = 2.03 ± 0.04 GHz

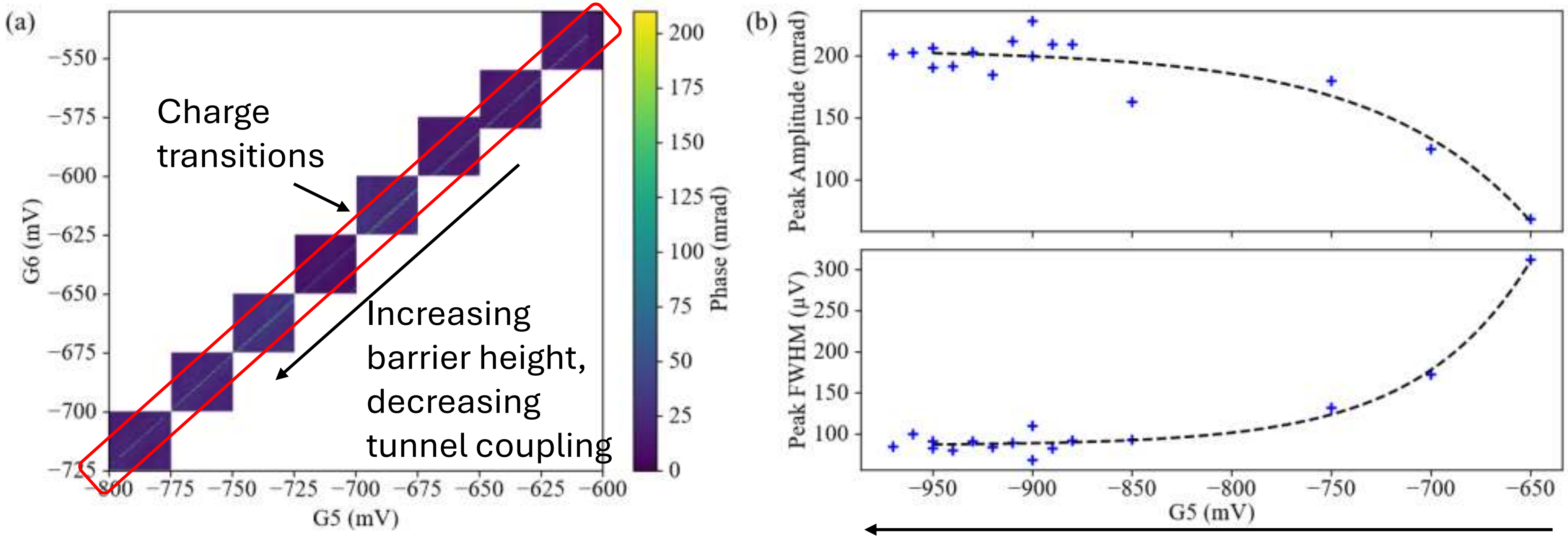
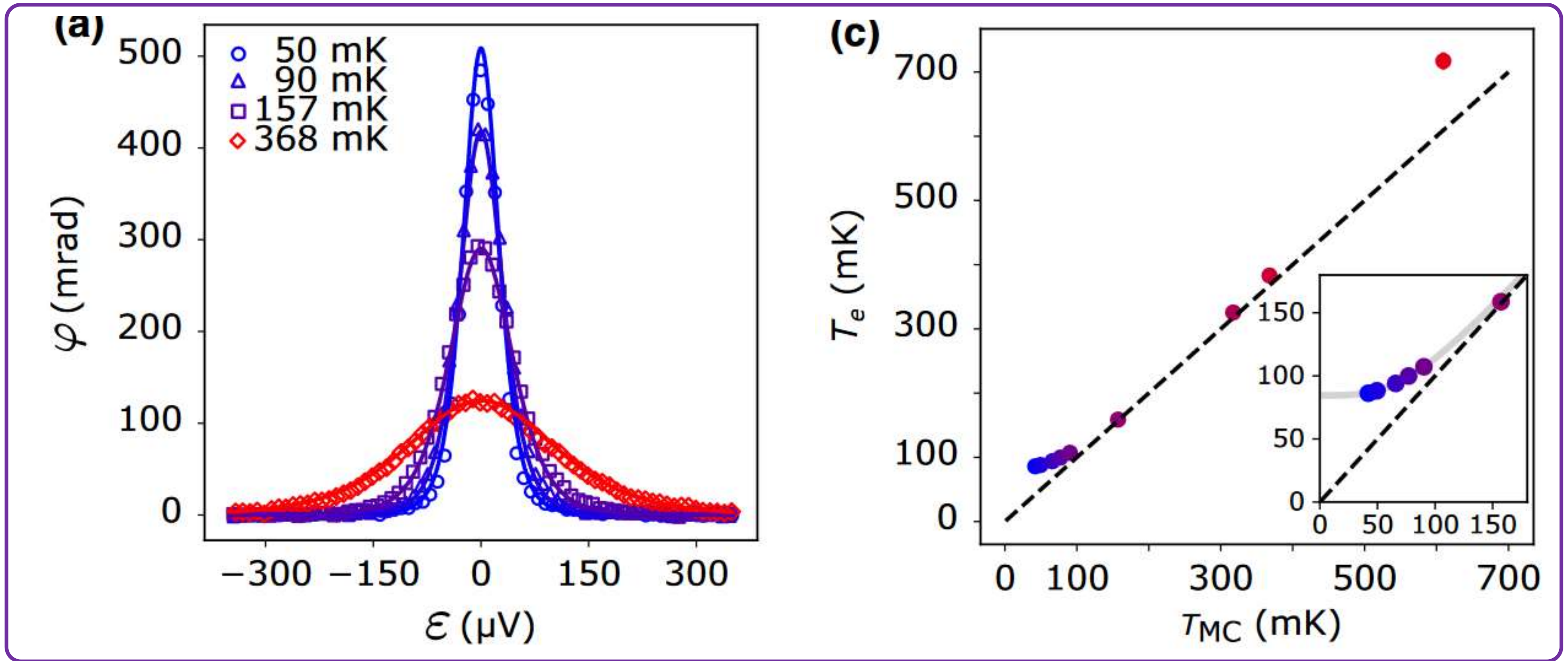


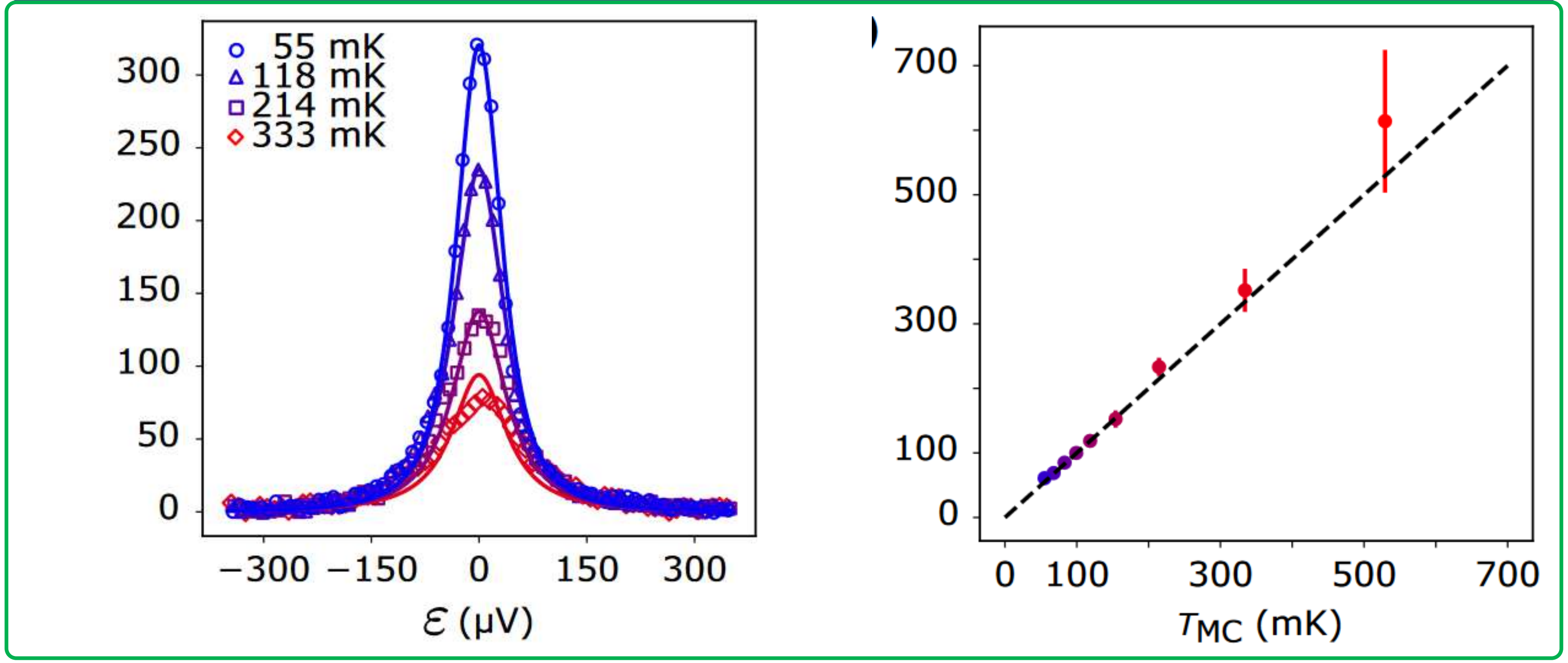
FIG. S3. **Isolated double dot charge stability diagram.** **(a)** Charge stability diagram showing 'infinite' interdot transitions. **(b)** Peak amplitude and width as a function of the gate voltage, showing a way to reduce the tunnel coupling.

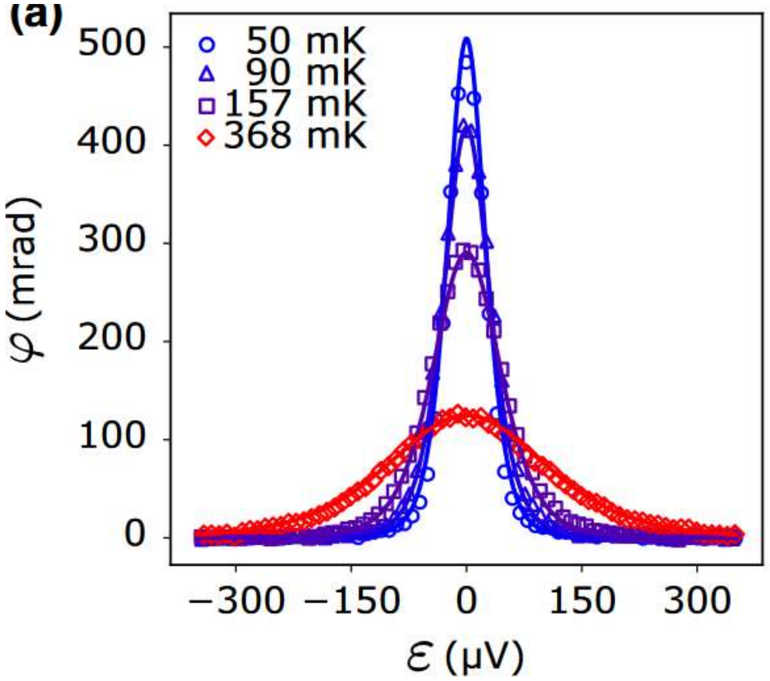
Results

I: Quantum dot coupled to lead (thermal bath)



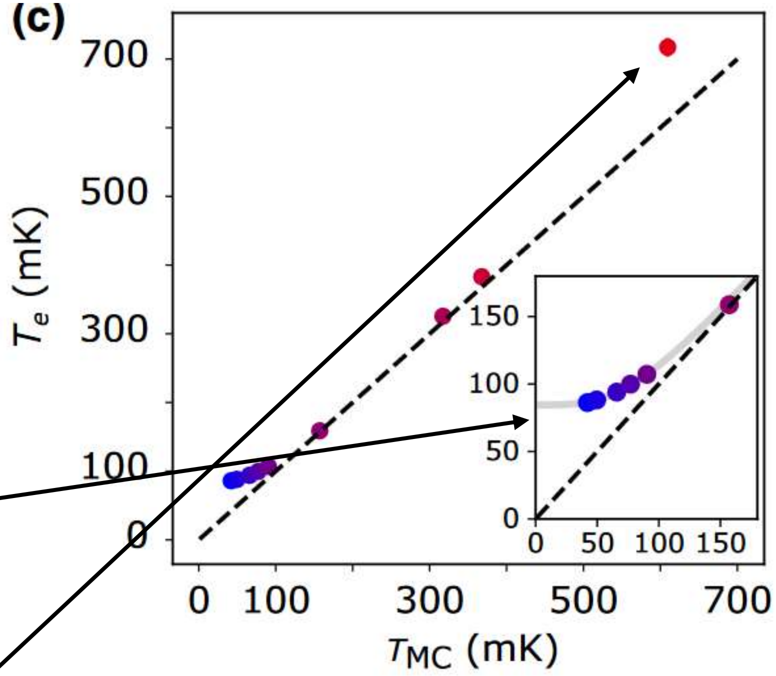
II: Quantum dot coupled to another quantum dot, with tunable coupling

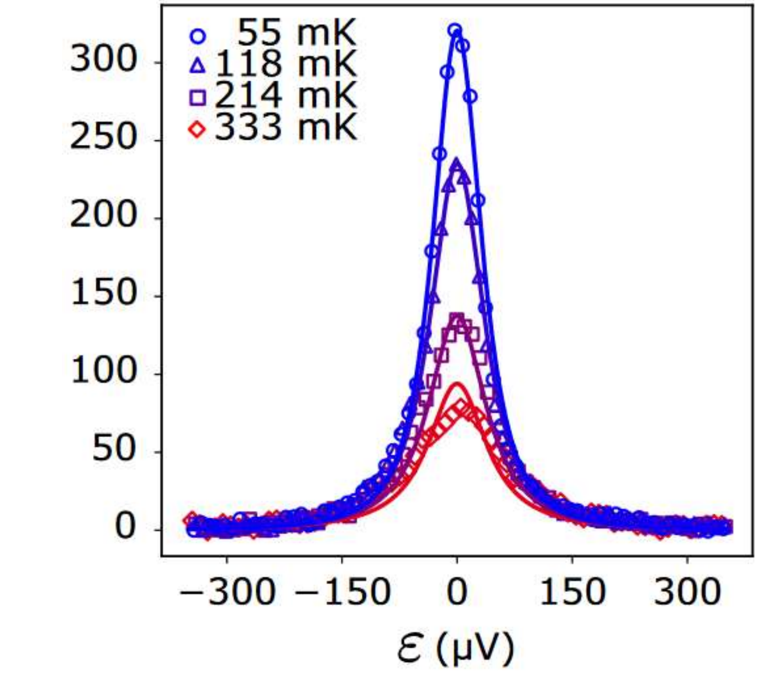




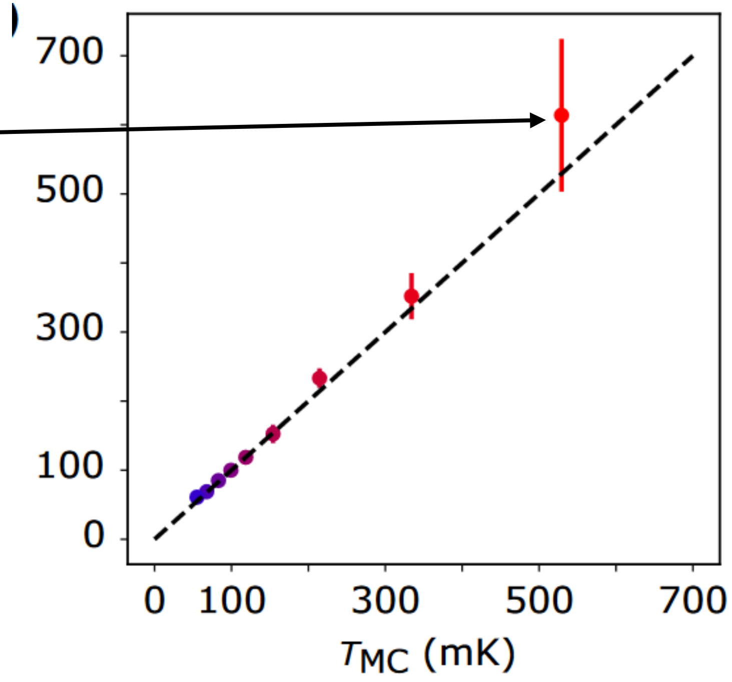
Fitting $T_\mathrm{e} = (T_\mathrm{MC}^n + T_0^n)^{1/n}$

$T_0 = 84$ mK and $n = 3.4 \neq 5$

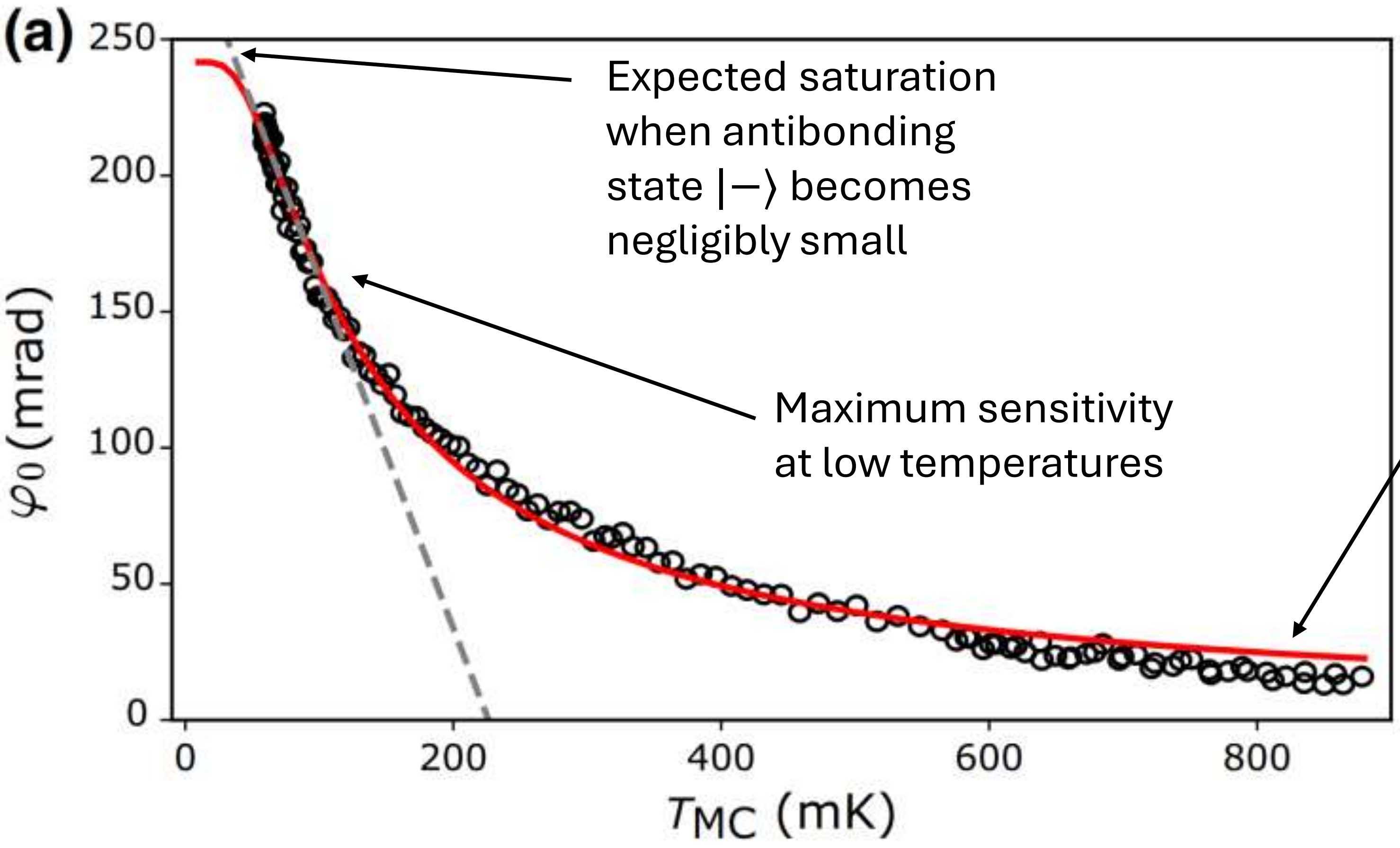




Higher energy quantum dot levels not accounted for in model



Calibration of double quantum dot thermometer: reflected signal phase at zero detuning (ε = 0)



Function fitted in red:

$$\varphi_0 = \kappa \times \frac{1}{2t} \tanh\left(\frac{t}{k_B T_{MC}}\right)$$

(from quantum capacitance formula at ε = 0 and $T_B = T_{MC}$)

t/h = 1.72 ± 0.04 GHz

(In principle not needed: Landau-Zener-Stückelberg interference)

Noise-equivalent temperature

Expression of noise-equivalent temperature:

$$\mathrm{NET} = \frac{S_{\varphi\varphi}}{\left|\frac{\partial \varphi_0}{\partial T_{\mathrm{MC}}}\right|}$$

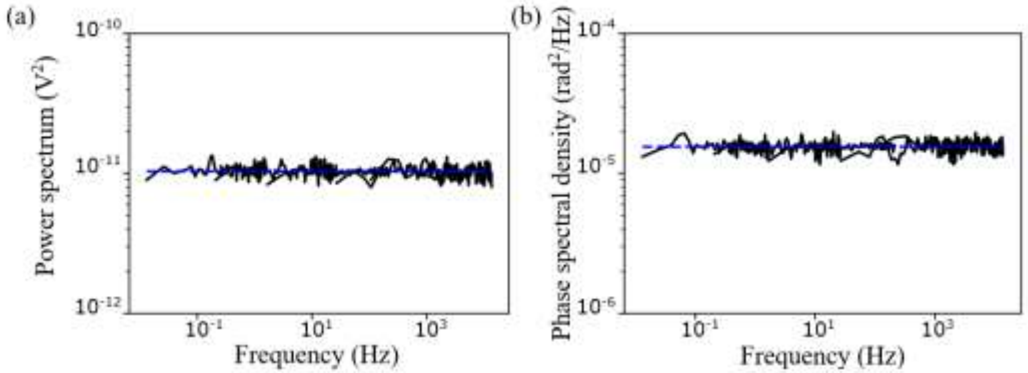


FIG. S4. **Noise spectrum.** **a)** Power spectrum computed using Welchs'method[9], showing a white noise spectrum with a noise floor $S_P = 1.03 \pm 0.09 \times 10^{-11}\mathrm{V}^2$. **b)** Phase spectral density, showing a white noise spectrum with a noise floor $S_{\varphi\varphi} = 3.9 \pm 0.2$ mrad/$\sqrt{\mathrm{Hz}}$

$S_{\varphi\varphi} = 3.9 \pm 0.2\ \mathrm{mrad}/\sqrt{\mathrm{Hz}}$ is the phase-noise amplitude

In the region of maximum sensitivity (temperature close to base temperature ~55 mK)

$$\mathrm{NET} = 3.0 \pm 0.2\ \mathrm{mK}/\sqrt{\mathrm{Hz}}$$

(with $\left|\frac{\partial \varphi_0}{\partial T_{\mathrm{MC}}}\right| = 1.28\ \mathrm{mrad/mK}$ fitted in previous plot)

Could be improved with better impedance matching

Noise-equivalent temperature

Starting from the expression of reflected signal phase at zero detuning fitted previously

$$\varphi_0 = \kappa \times \frac{1}{2t}\tanh\left(\frac{t}{k_\mathrm{B}T_\mathrm{MC}}\right))$$

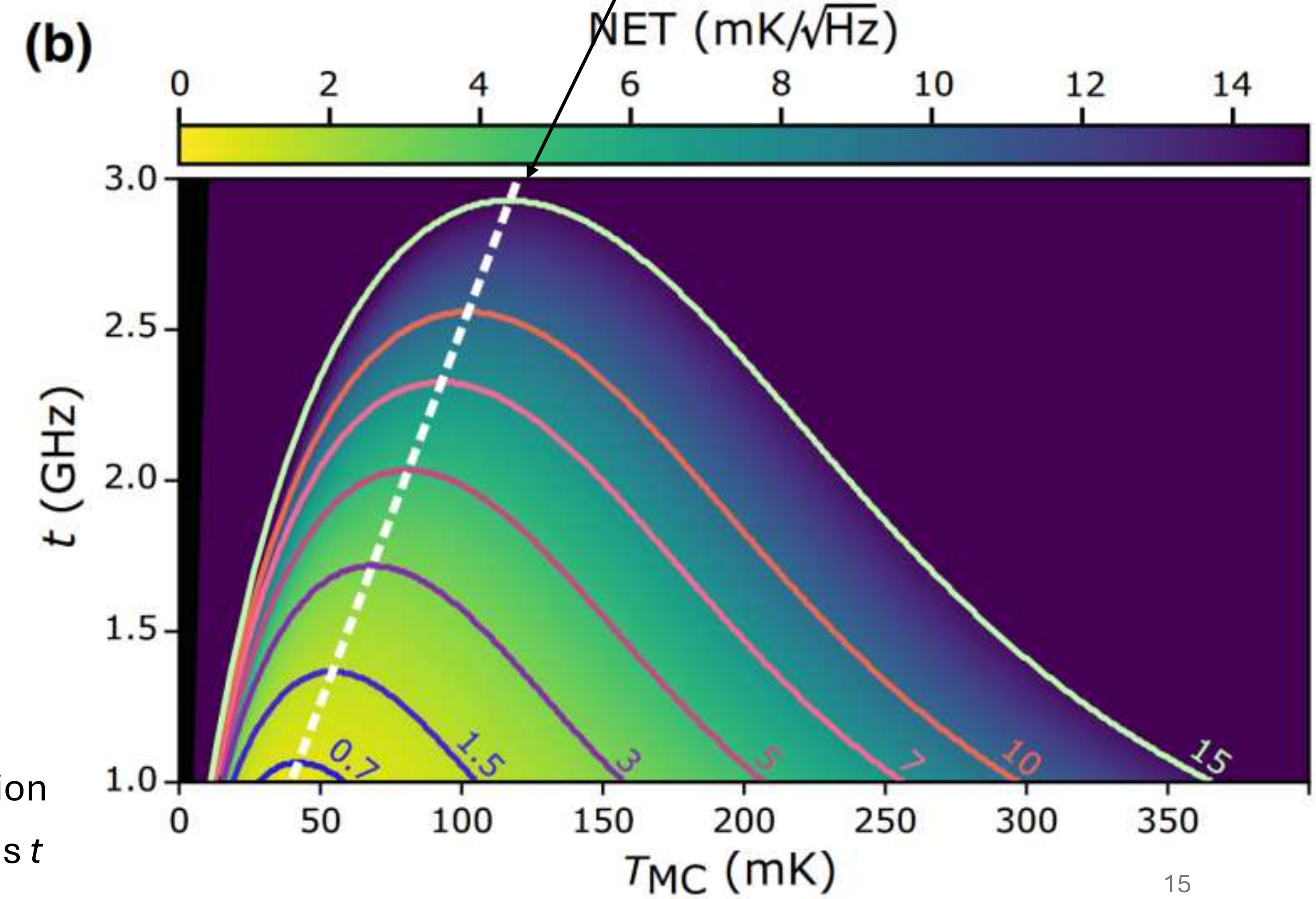
Assuming dispersive coupling between the *LC* resonator and the isolated double quantum dot implies:

$$\kappa = A_0\left(\frac{1}{2t+f_\mathrm{r}} + \frac{1}{2t-f_\mathrm{r}}\right)$$

Resonance frequency of “tank” circuit

Now t is used as parameter and the expression the $\mathrm{NET} = \frac{S_{\varphi\varphi}}{\left|\frac{\partial\varphi_0}{\partial T_\mathrm{MC}}\right|}$ can be calculated at various t

Optimal tunnel coupling depending on temperature



“Real-time” thermometry (proof of concept)

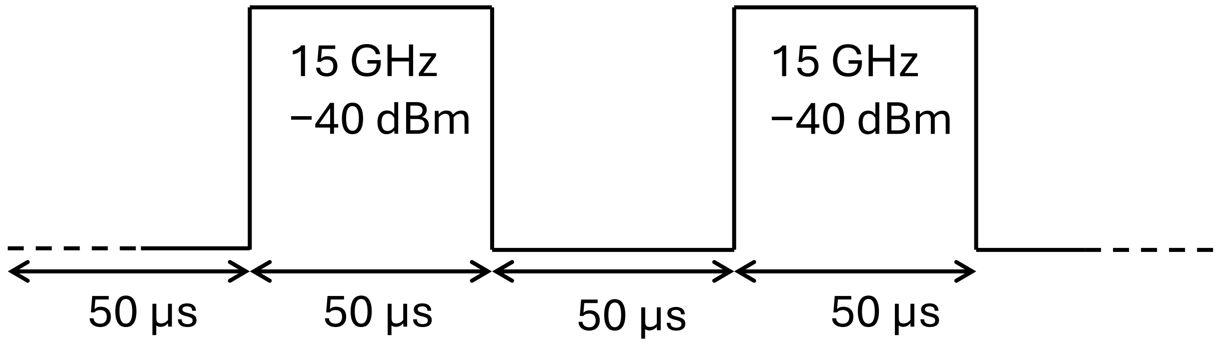
- Noise-equivalent temperature is too large to resolve temperature fluctuations at microsecond scale
- But noise can be reduced with averaging if heating event is periodic or deterministic/reproducible
- For example, microwave bursts used for operation of spin-qubit devices

Limiting bandwidths

- Response time of measurement apparatus (~ 20 ns)
- Charge relaxation time T1 toward a thermal state (~ 15 ns)

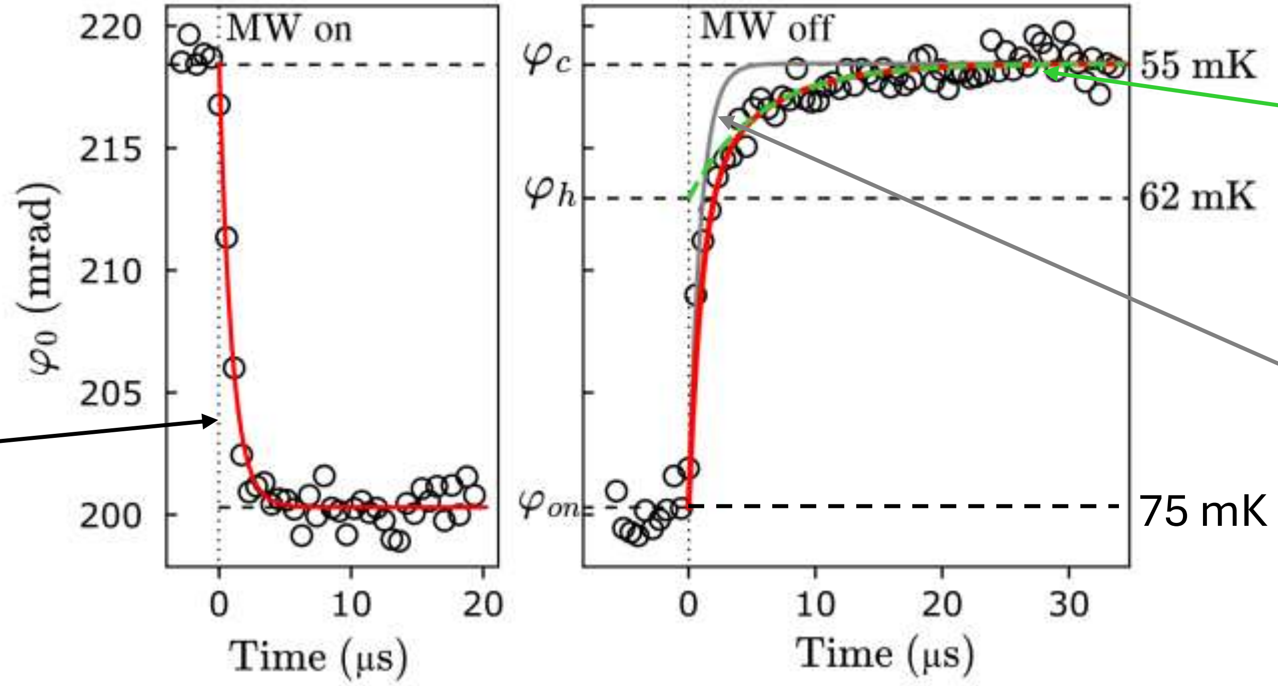
Hence few MHz resolution

Proof of concept: periodic microwave burst on nearby gate



(20 kHz)

Lockin parameters:
1.7 MHz
400 ns integration window



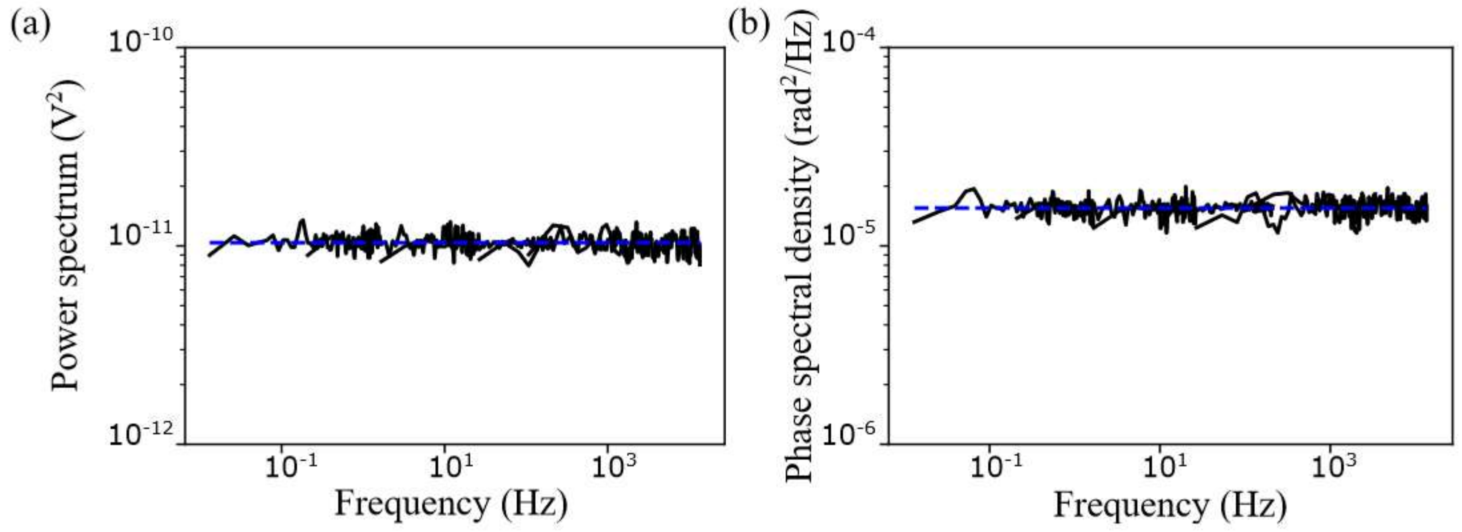
Exponential decay
τ = 0.93 ± 0.35 μs
(too short)

Slow exponential decay (τ = 67.0 ± 1.5 μs): relaxation of the heat bath?

Fast exponential decay: T1 relaxation?

Conclusion and outlook

- “Noninvasive, nongalvanic thermometers”
- Both Fermi reservoir (dot-lead setting) and local bosonic temperature in semiconductor quantum dot (double quantum dot setting)
- State-of-the-art noise-equivalent temperature of $3\ \mathrm{mK}/\sqrt{\mathrm{Hz}}$
- Temperature variations measured on microsecond scale when averaging is possible
- Technique demonstrated in silicon MOS device, could be applied on other platforms: Si-Ge-based heterostructures?



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The two quadratures of the demodulator I and Q are measured for different sampling frequencies to access noise spectrum in a wide frequency range. From the noise floor we can access to the noise temperature NT :

$$NT = \frac{S_P}{10^{\frac{G_{dB}}{10}} B \times 4k_B R} \tag{S16}$$

Where S_P is the noise floor, G_{dB} is the gain in dB of the room temperature amplifier, B is the bandwidth of the demodulator and R is the 50Ω-impedance of the transmission line. We find a $NT = 1.9 \pm 0.3$ K, where as the cryogenic amplifier (LNF-LNC 0.2-3 A s/n 1410Z) used in this experiment has a noise temperature of around 2 K