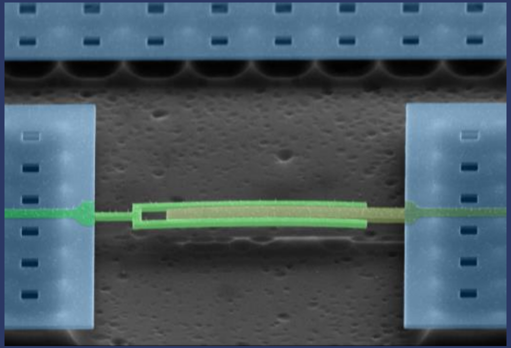
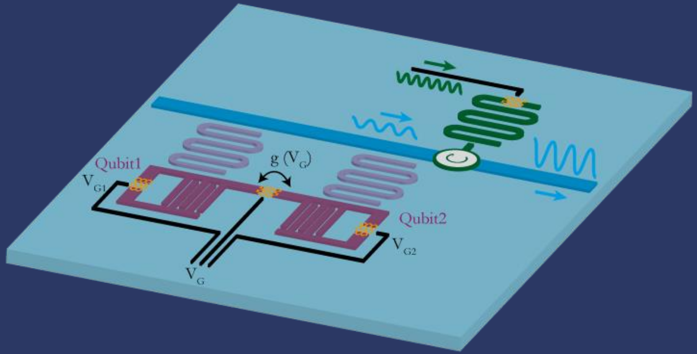
TiN high impedance superconducting circuits

(+ second part about graphene superconducting circuits)





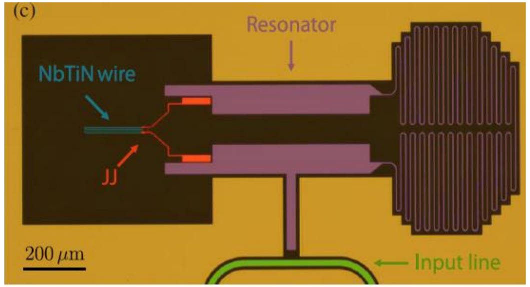
Julien Renard

Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel

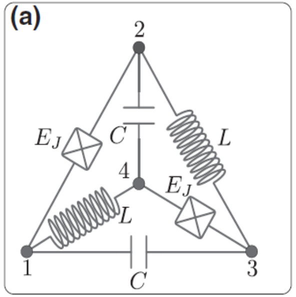
julien.renard@neel.cnrs.fr

Superinductance

Protected Qubits

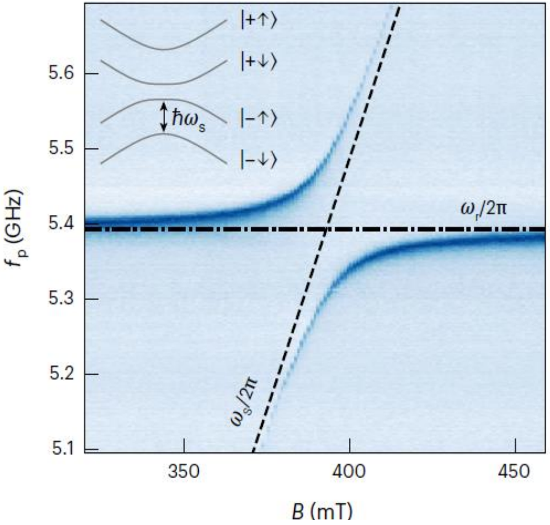


T.M. Hazard et al Phys. Rev. Lett. 2019
V. Manucharyan et Science 2009



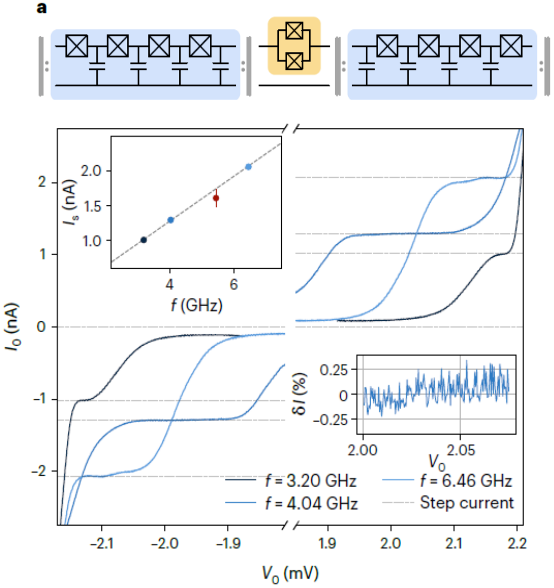
A. Gyenis et al Phys. Rev. Quantum 2021

Spin-photon coupling



C. Yu et al Nature Nano 2023

Dual Shapiro steps

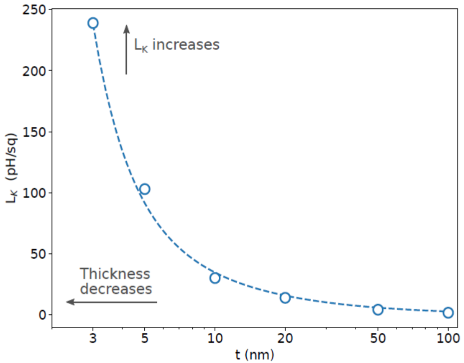


N. Crescini et al Nature Phys 2023
R. S. Shaikhaidarov et al Nature 2022

Outline

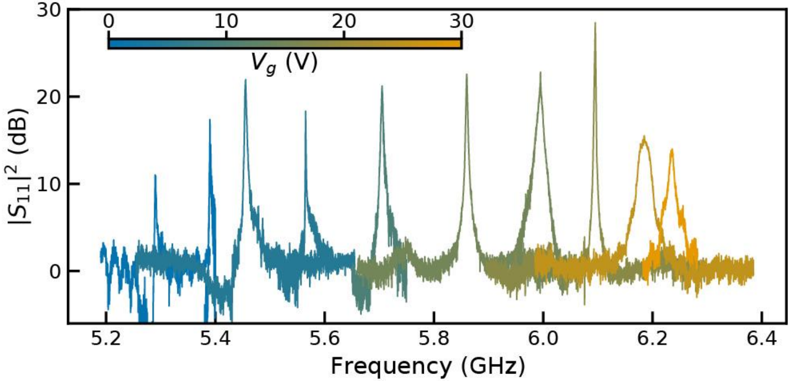
TiN high impedance superconducting circuits

K. Rafsanjani Amin et al Appl. Phys. Lett (2022)



Graphene based superconducting quantum circuits

G. Butseraen et al Nature Nano (2022)

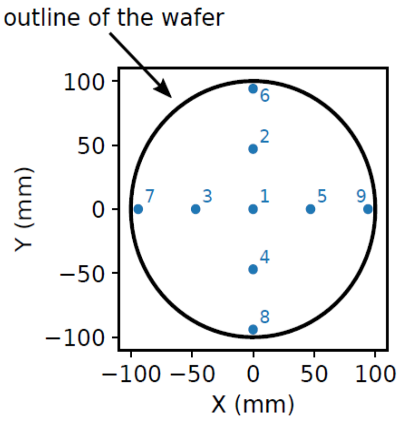


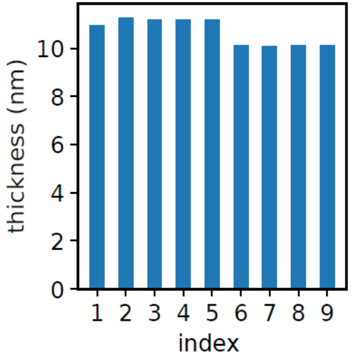
TiN growth

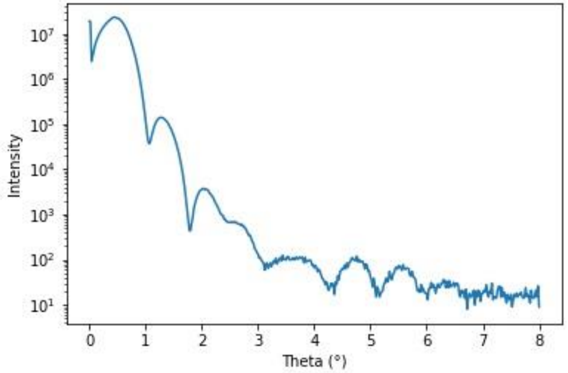
Sputtering @ 350°C on highly resistive Si (200 mm wafers)

Structural characterization: ellipsometry, XRR, XRD

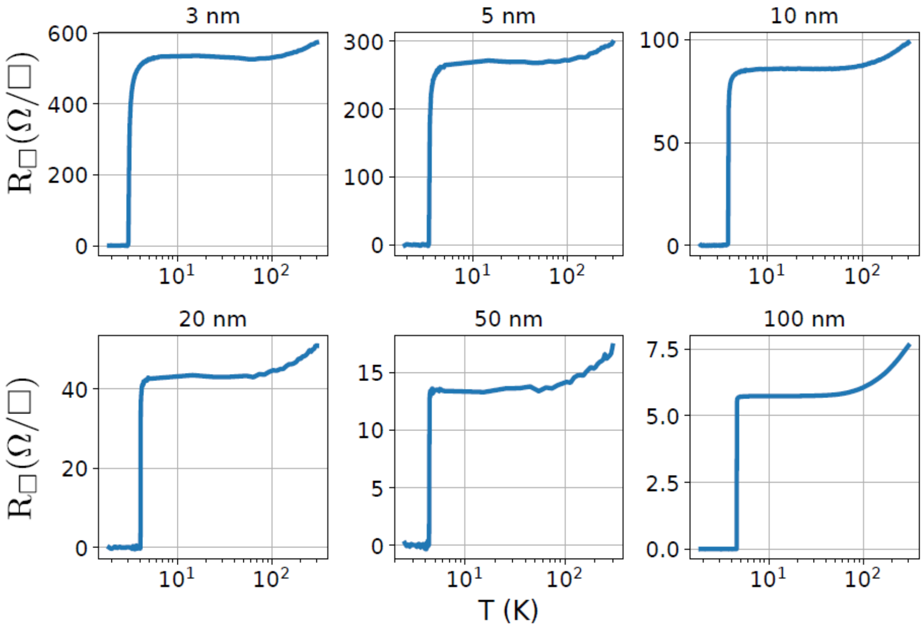
→excellent thickness uniformity





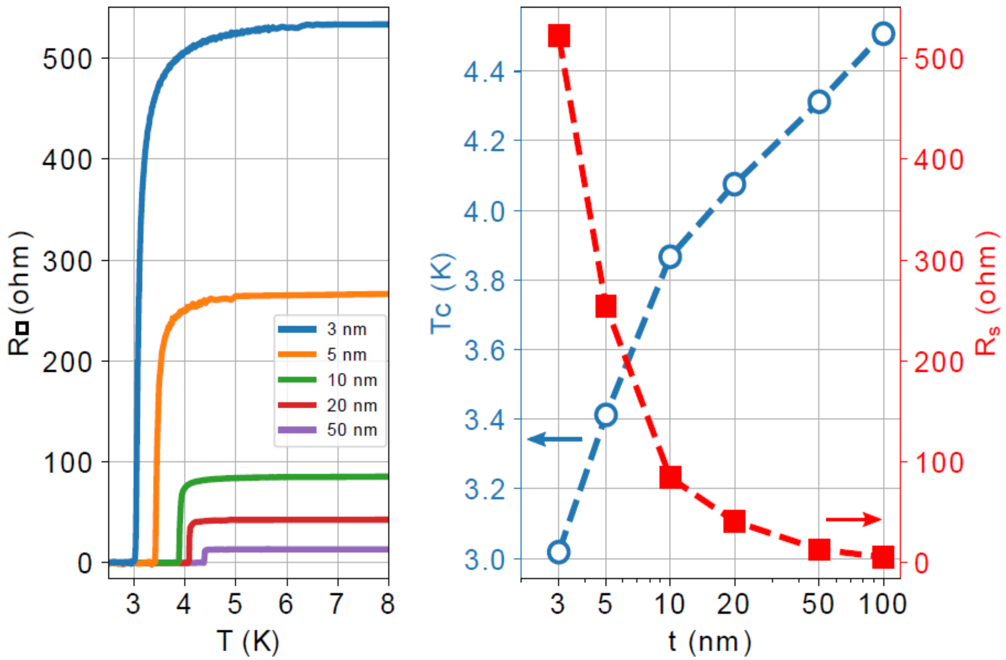


DC characterization



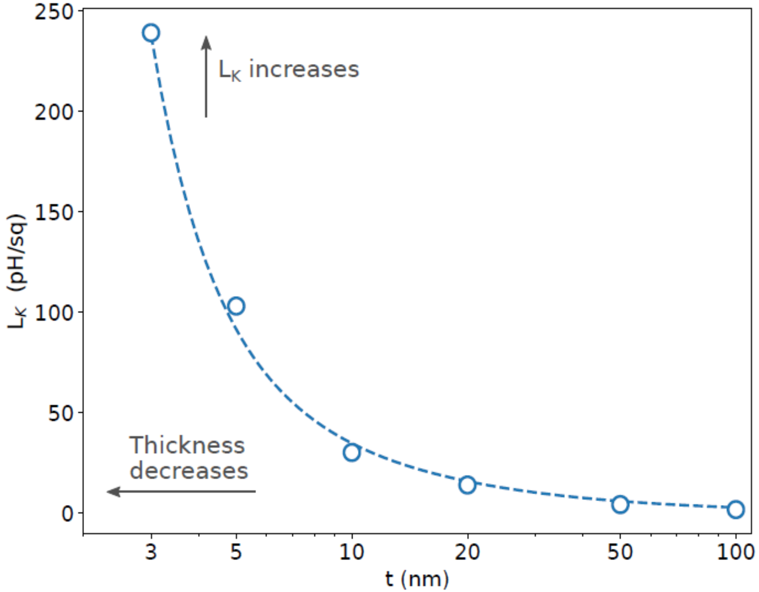
Superconductivity down to 3 nm thickness

Thickness dependence of T_c



Low disorder in ultrathin TiN films (usually closer to SIT @3nm)

Thickness dependence of kinetic inductance



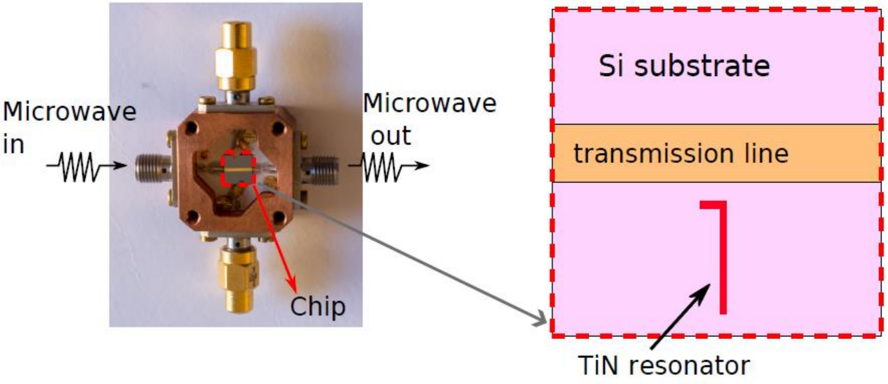
Use BCS formula: $L_K = \dfrac{\hbar R_\square}{\pi \Delta_0}$

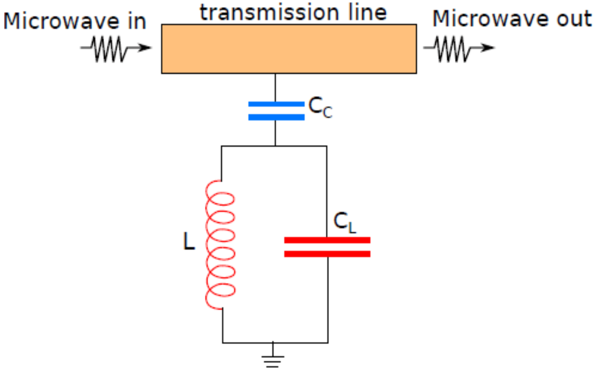
Thickness (nm)	RRR	T_C (K)	R_S (Ω/□)	L_K (pH/□)
3	1.10	3.0	522.0	239.0
5	1.17	3.4	254.4	103.0
10	1.17	3.9	93.5	33.4
20	1.23	4.1	41.2	14.0
50	1.25	4.3	13.3	4.2
100	1.33	4.5	5.7	1.7

Similar values to Shearrow et al APL 2018 (but much thinner films in our case)

Up to ~240pH/□ for 3nm thick film

Kinetic inductance : DC vs microwave

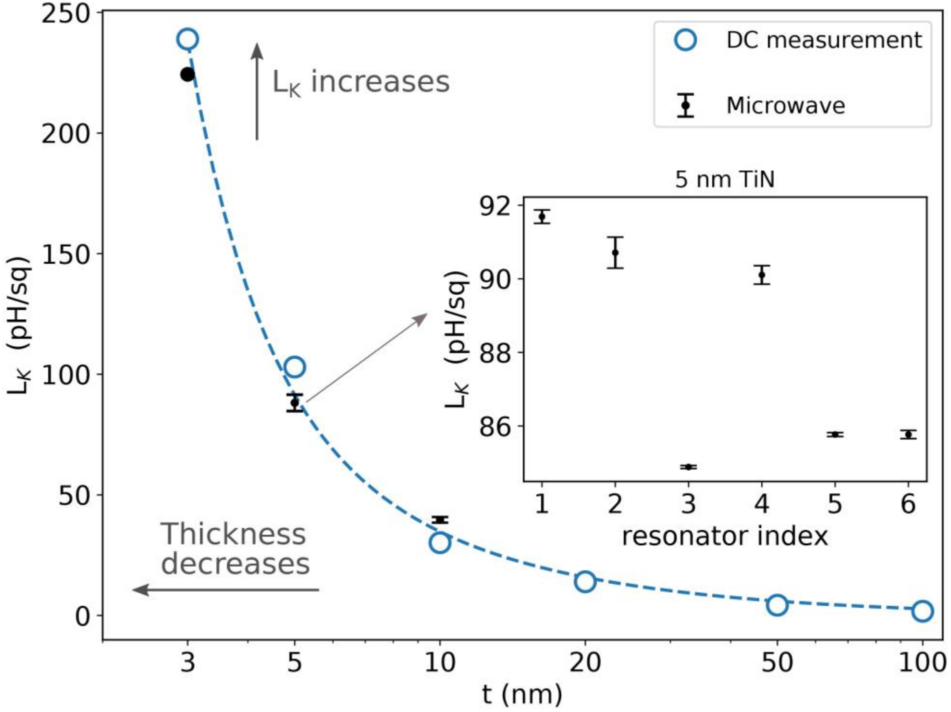




$$\omega = \frac{1}{\sqrt{LC}}, \text{ with } L \sim L_K$$

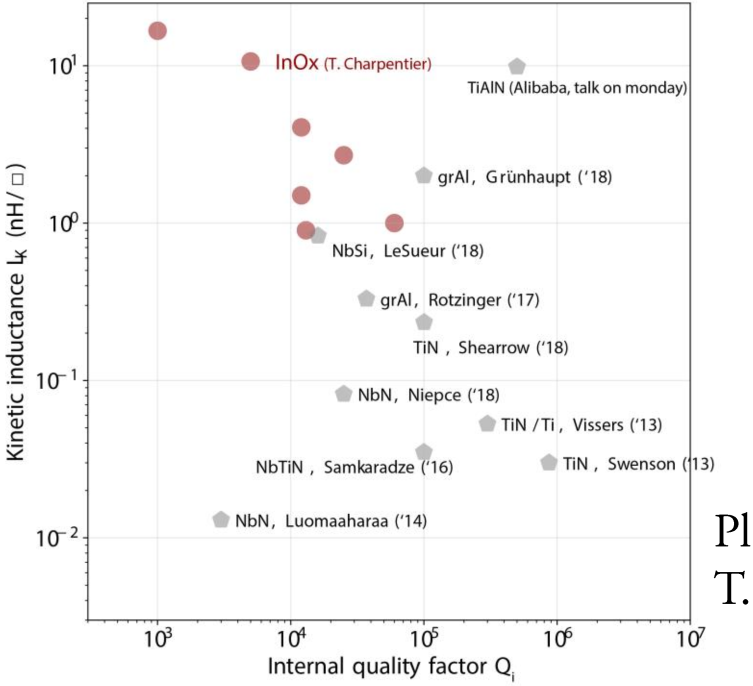
Directly determine L_K from resonance frequency

Kinetic inductance : DC vs microwave



DC and microwave L_K fully consistant and wafer scale homogeneity

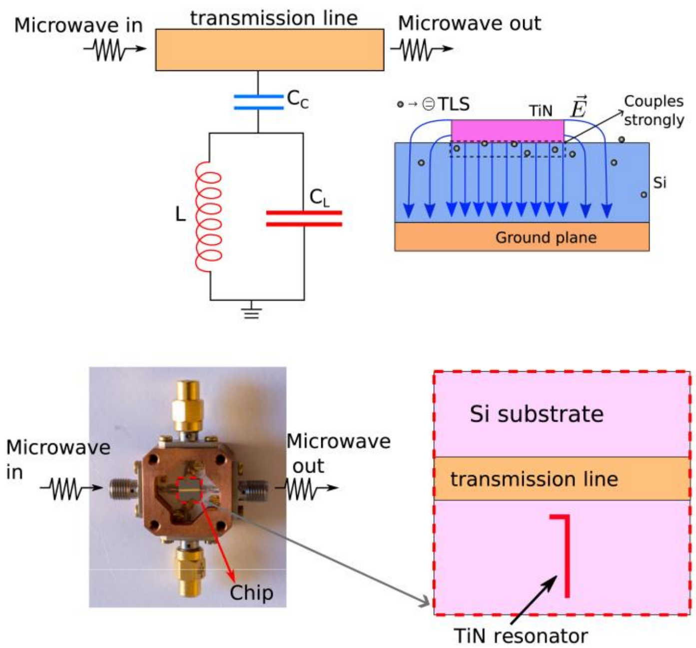
High L_K materials : microwave losses?

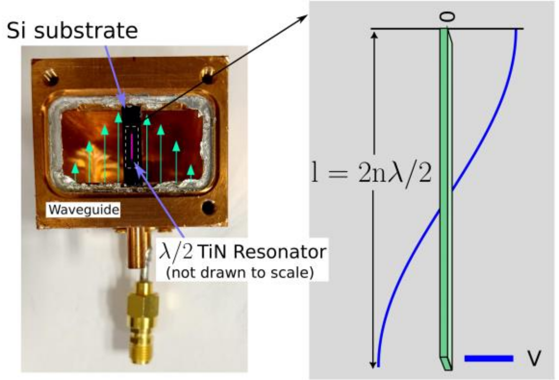


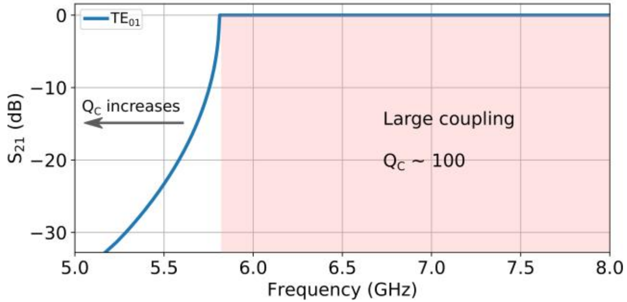
Plot courtesy of
T. Charpentier

→ Study of losses (and mechanisms) in TiN thin films

From 2D to 3D geometry

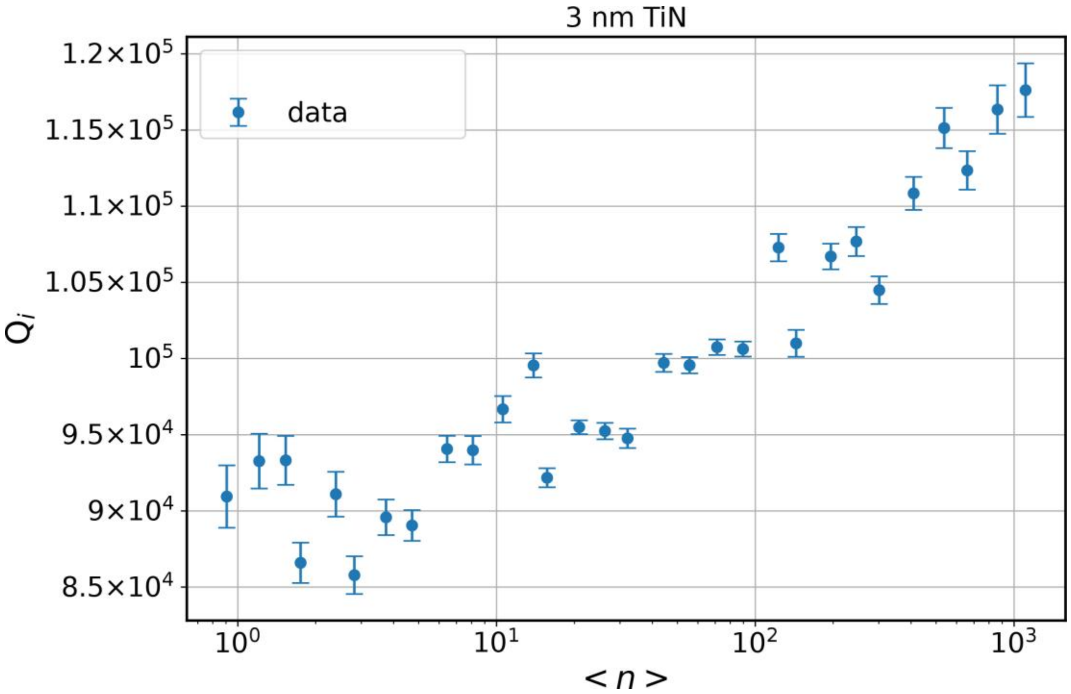






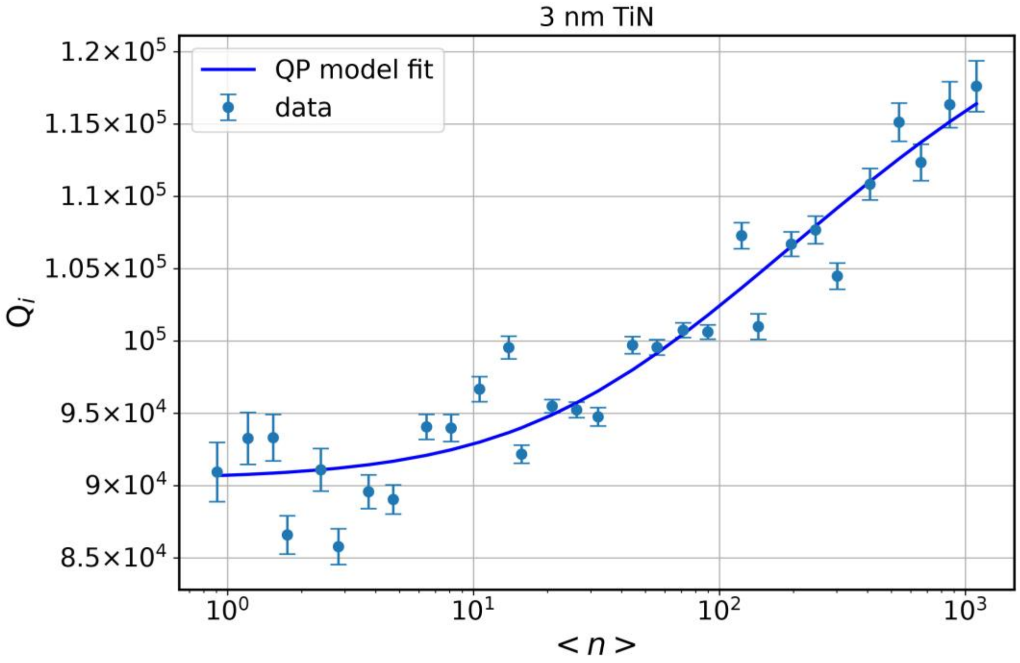
→ Study of losses (and mechanisms) in TiN thin films

Photon number dependence of Qi



→ Modest increase with photon number

Photon number dependence of Qi



$$\frac{1}{Q_i} = \frac{1}{Q_0} + \beta\left(\frac{1}{1+\frac{\gamma n}{1+\frac{1}{2}(\sqrt{1+4\gamma n}-1)}} - 1\right)$$

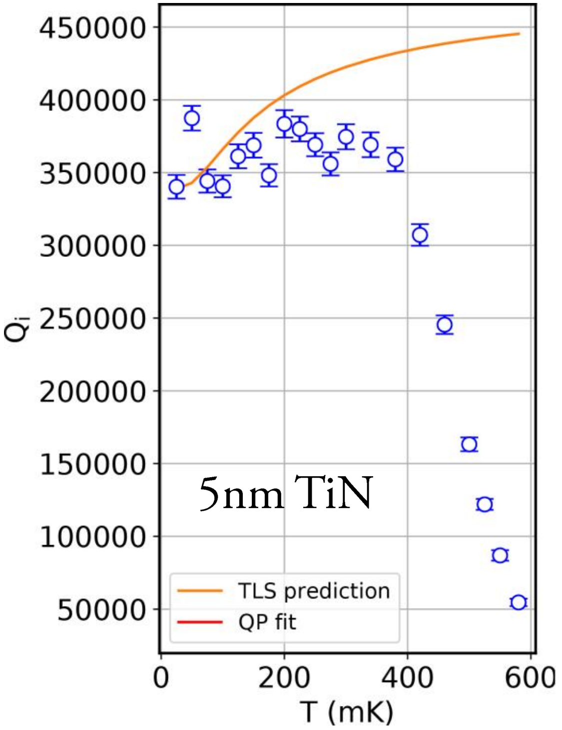
Follow L. Grünhaupt et al, Phys Rev Lett 2018

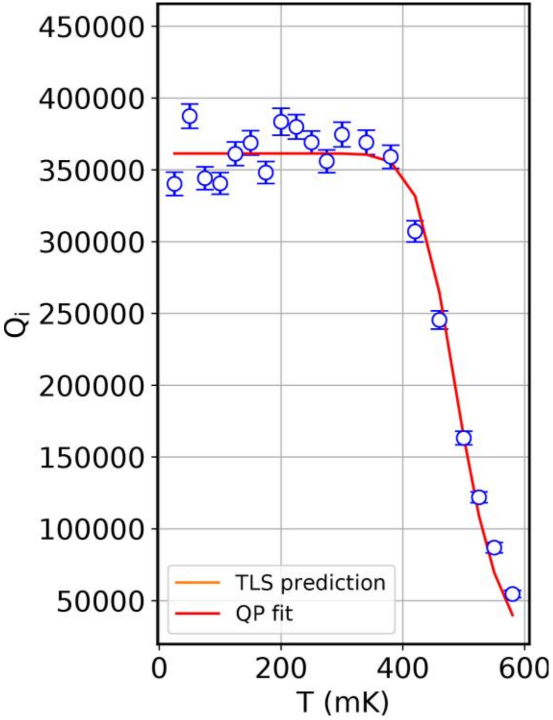
Fitting parameters:

β, γ (linked to QP dynamics and interaction with photons)

Q_i possibly limited by quasiparticles

Temperature dependence of Qi





Thermally induced QP

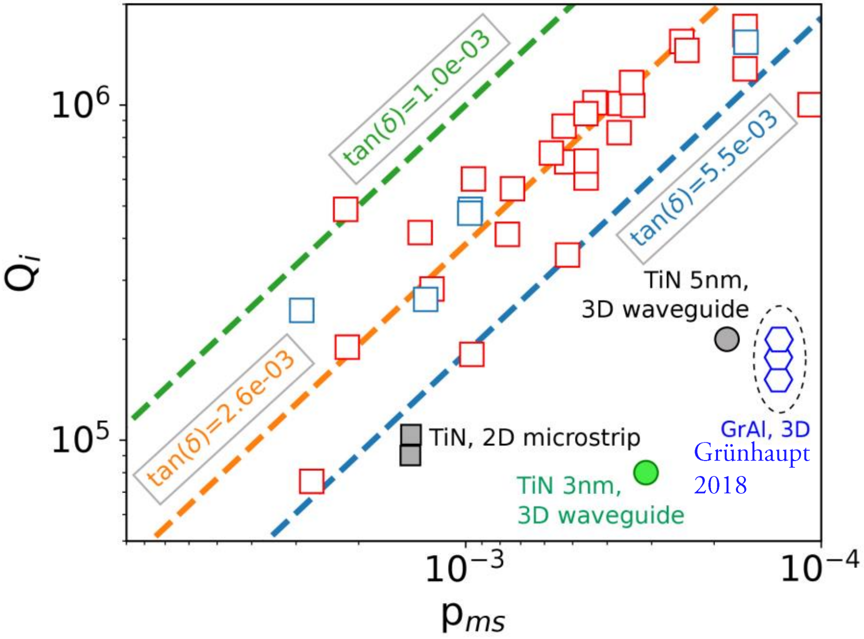
$$\frac{1}{Qi} = 2\alpha\sqrt{\frac{k_B T}{\pi h f_R}}\exp\left(-\frac{\Delta}{k_B T}\right)+\frac{1}{Q_a}$$

α: kinetic inductance fraction

Q_a: other losses than thermally induced QP

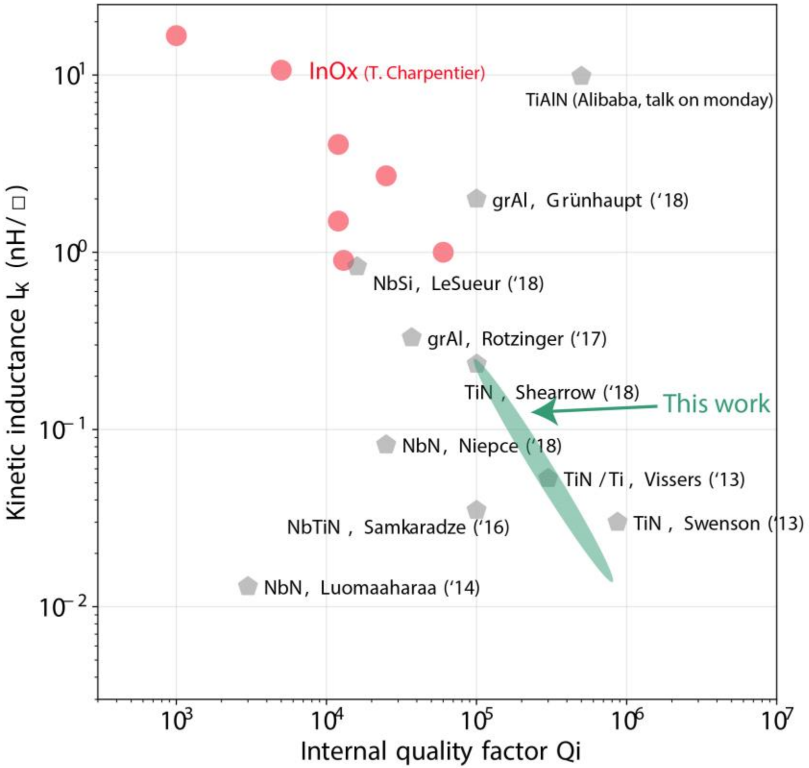
No sign of TLS limited internal Q

Internal quality factor and TLS effect dilution

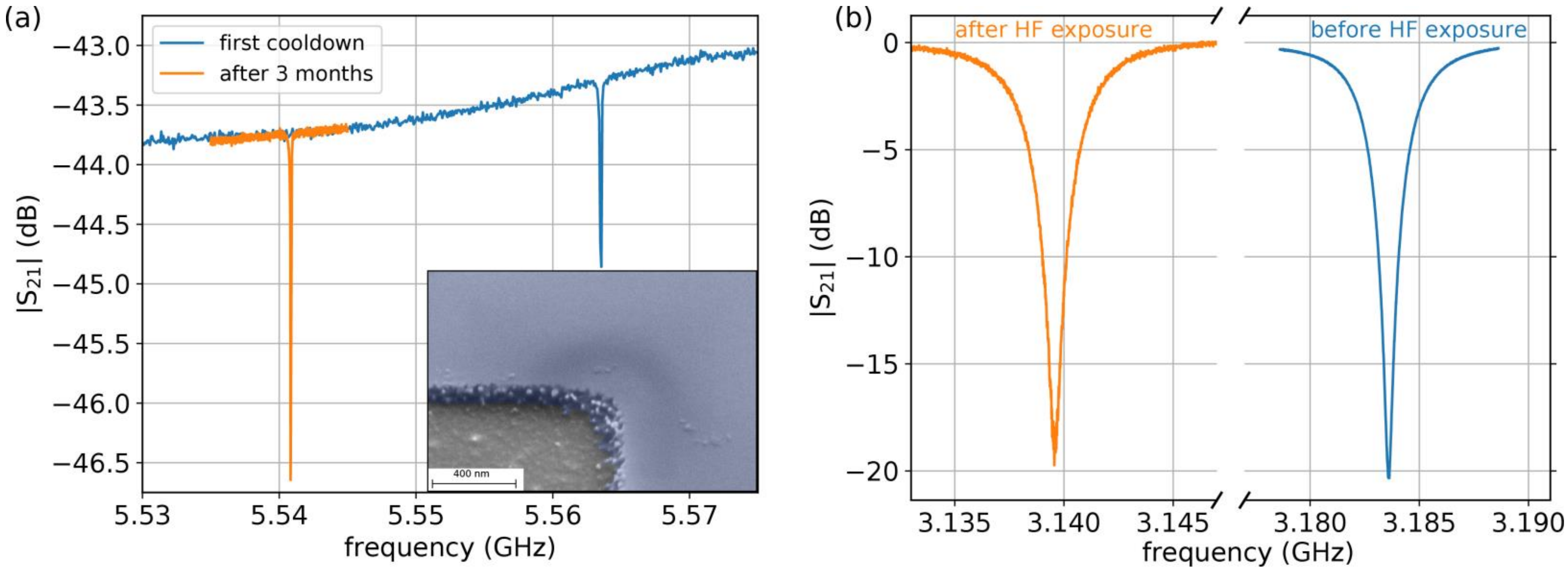


Importance of QP in high L_K materials

Summary on internal Q



Stability of TiN?

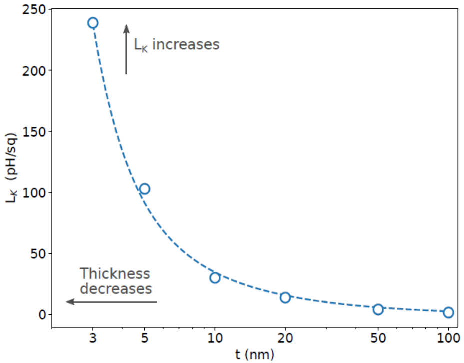


Very minimal aging (3nm thin film!) and resilient to HF

Outline

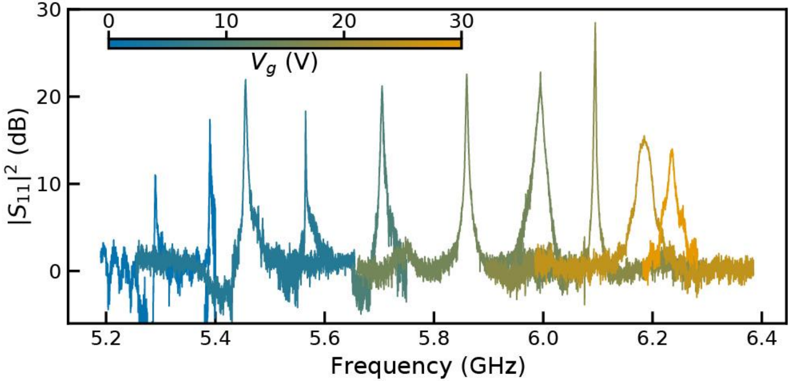
TiN high impedance superconducting circuits

K. Rafsanjani Amin et al Appl. Phys. Lett (2022)



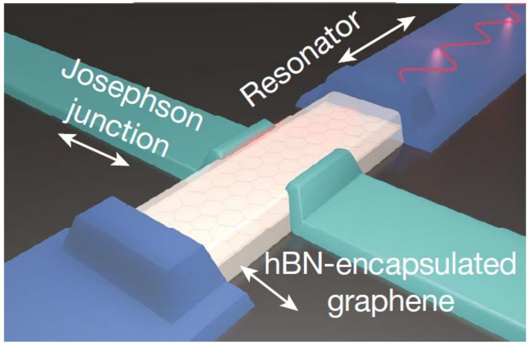
Graphene based superconducting quantum circuits

G. Butseraen et al Nature Nano (2022)



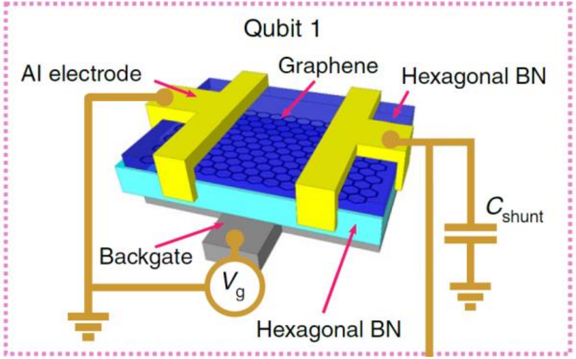
2D materials for superconducting circuits

Microwave bolometers



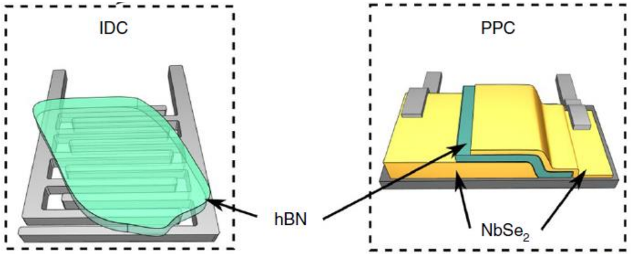
G.H. Lee et al Nature (2020)
R. Kokkoniemi et al Nature (2020)

Quantum bit



J.I.J. Wang et al Nature Nano (2019)

h-BN (low losses)

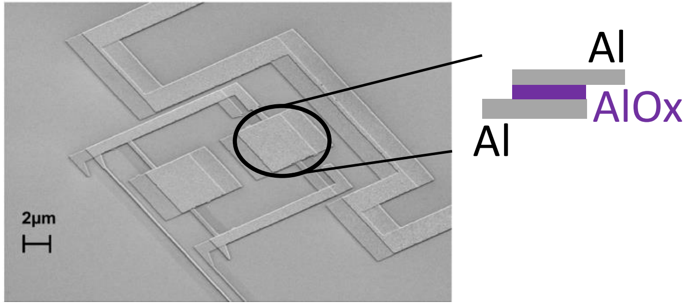


J.I.J. Wang et al Nature Mater (2022)

Large variety of applications in superconducting quantum technologies

Gate tunable superconducting quantum circuits

« Standard » tunnel JJ

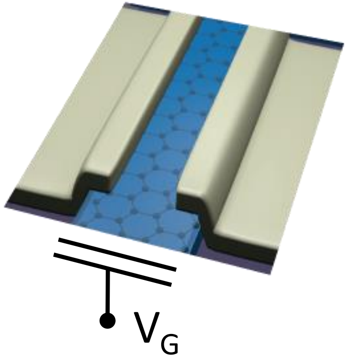


F. Lecocq PhD thesis, I. Néel

- Large number of channels with low transmission
- Josephson energy tunable with a magnetic field

$E_J(\phi)$

Graphene (semiconductor) weak link

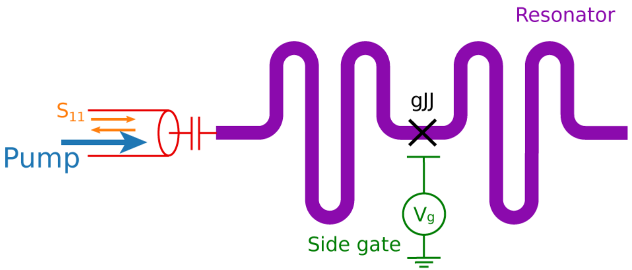


- Small number of channels with high transmission
- Josephson energy tunable with an electric field

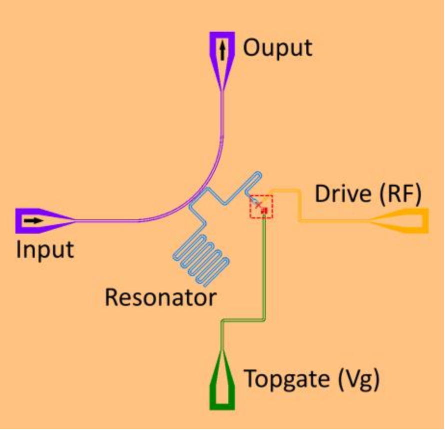
$E_J(V_G)$

(Sub)Outline

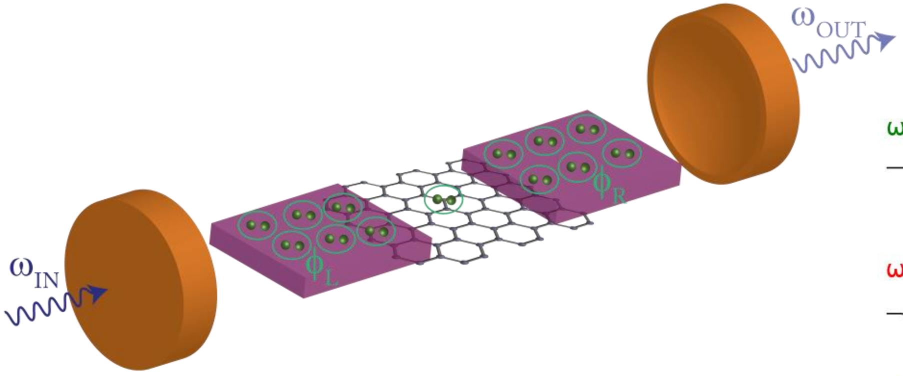
Gate-tunable Josephson parametric amplifier

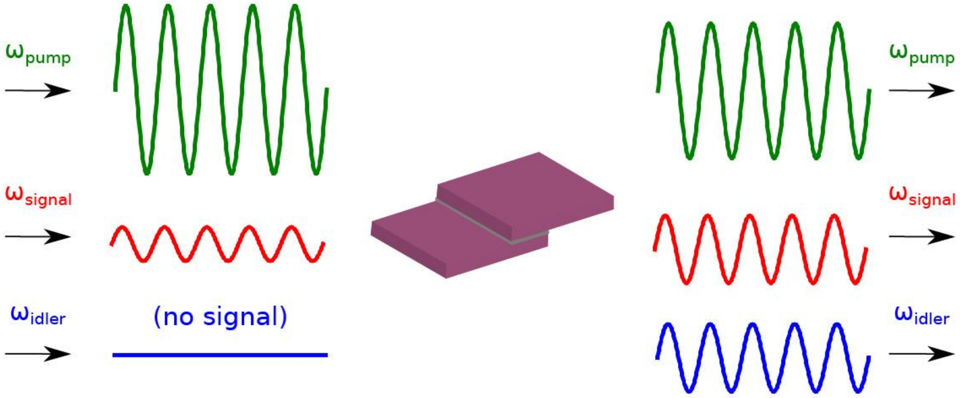


Qubit with a gate-tunable anharmonicity



(Resonant) parametric amplifier



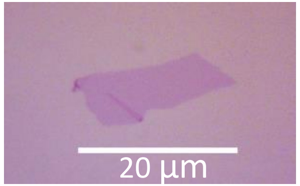


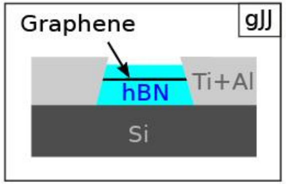
$$\omega_{signal} + \omega_{idler} = 2\omega_{pump}$$

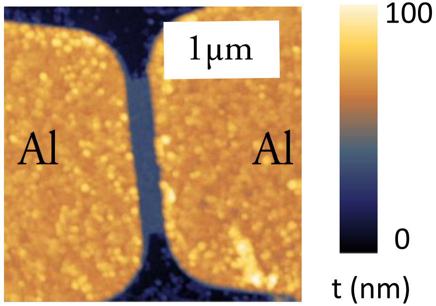
$$H=\hbar\omega\, a^{\dagger}a + \hbar g\, a^{\dagger}a^{\dagger}aa$$

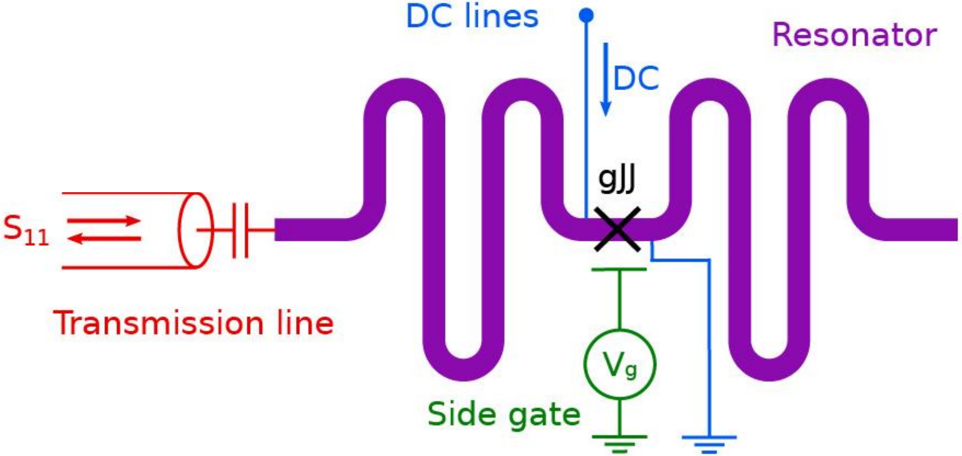
Non-linearity introduced by the Josephson junction

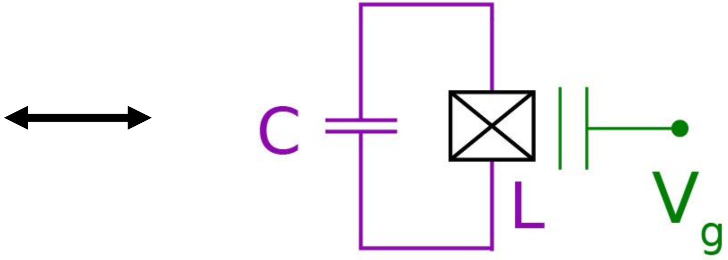
Device layout





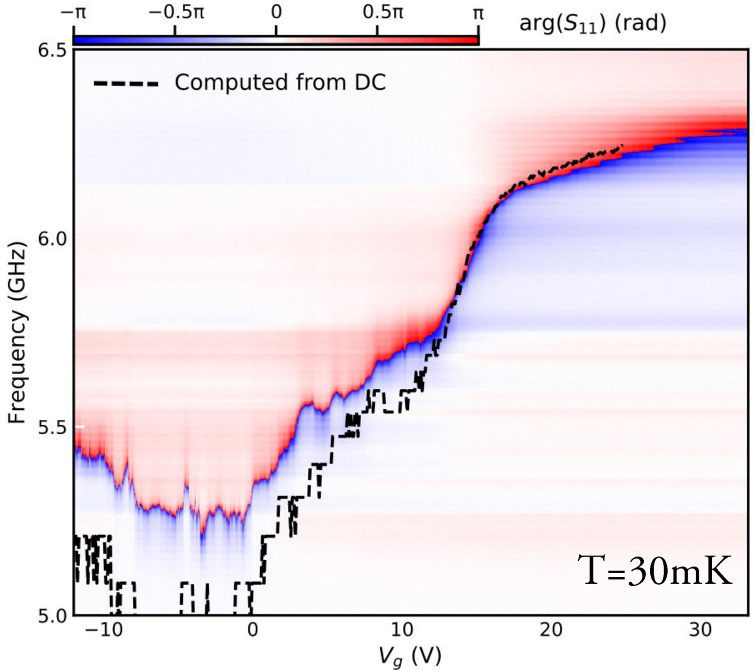






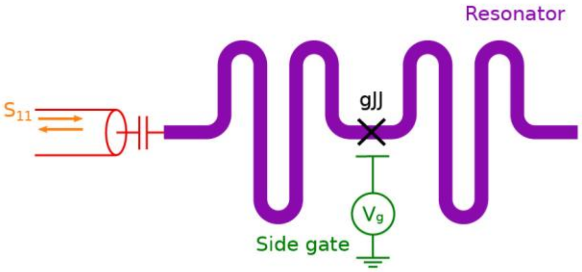
Microwave resonator with an embedded graphene Josephson junction

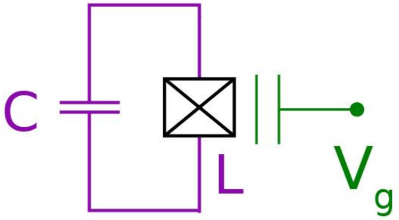
Tunable microwave properties



$$L_J = \frac{\Phi_0}{2\pi \mathbf{I_c}(\mathbf{V_g})}$$

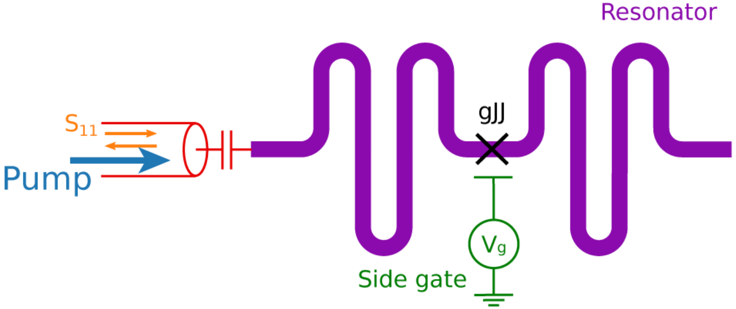
$$\omega_0 = \frac{1}{\sqrt{(L+\mathbf{L_J}(\mathbf{V_g}))C}}$$

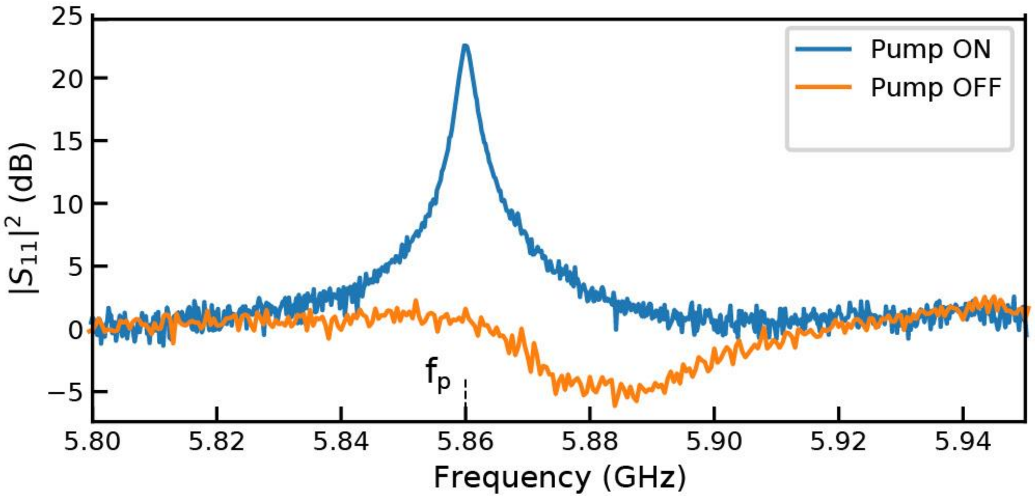




Gate-tunable resonance frequency (>1GHz)

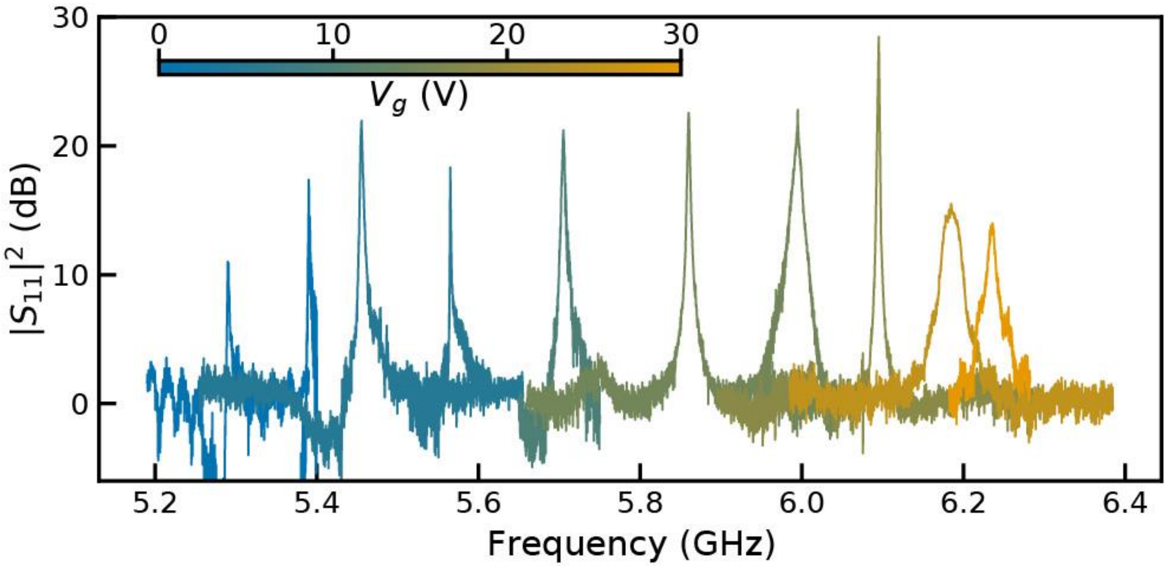
Parametric amplification

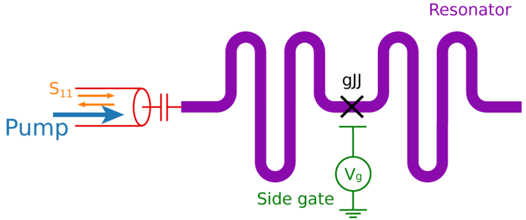




Gain >20 dB thanks to the nonlinearity of the graphene junction

Gate tunability of the amplifier



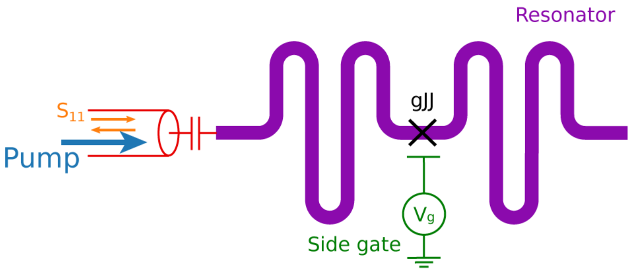


G. Butseraen et al Nature Nano. 2022
(see also J. Sarkar et al Nature Nano. 2022)

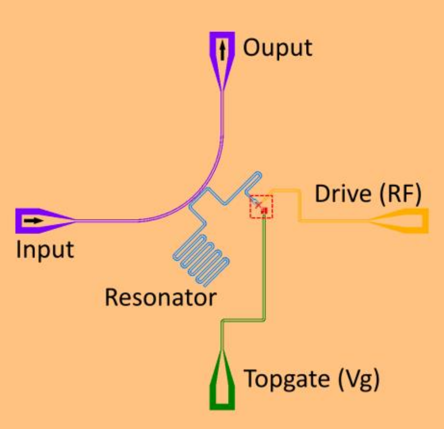
First gate-tunable Josephson parametric amplifier

(Sub)Outline

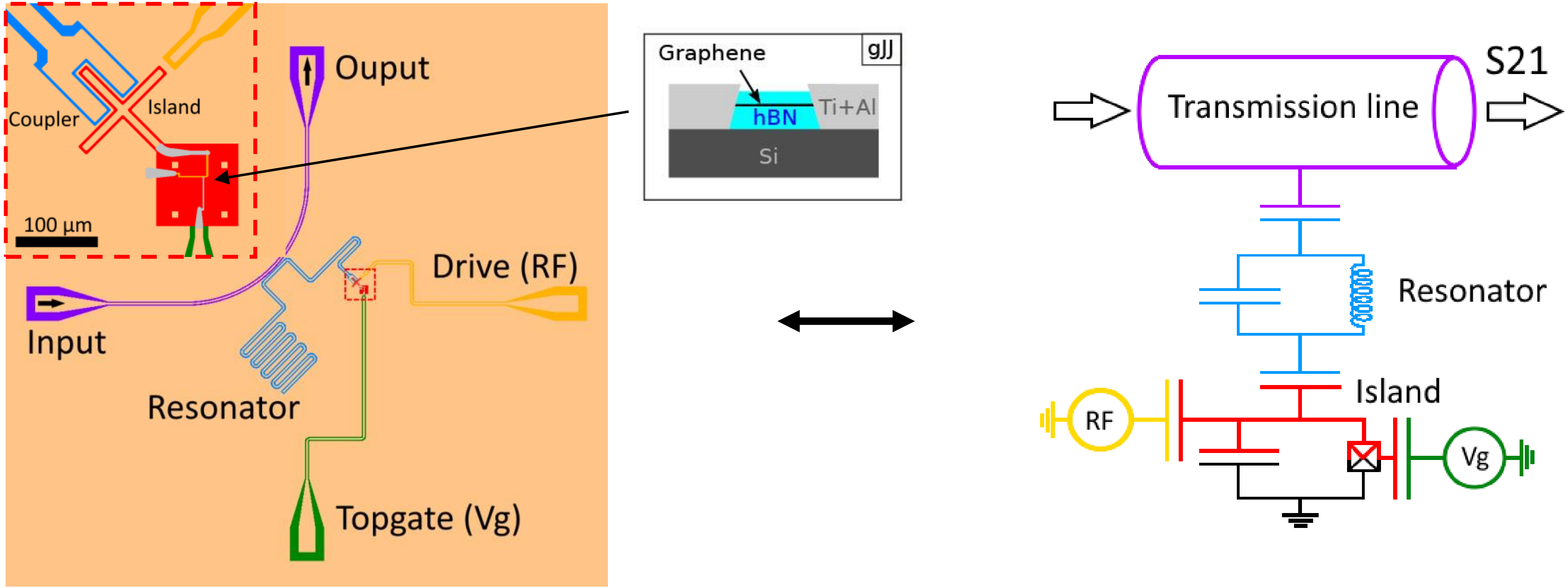
Gate-tunable Josephson parametric amplifier



Qubit with a gate-tunable anharmonicity



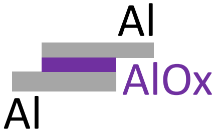
Device layout



Gate-tunable superconducting Qubit

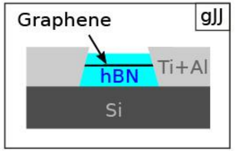
Qubit with a high transmission junction

Tunnel junction (τ → 0)



$$H = 4E_c n^2 - E_J(B)\cos\phi$$

Graphene junction



$$H = 4E_c n^2 - \frac{4E_J(V_g)}{\tau}\sqrt{1 - \tau\sin\frac{\phi^2}{2}}$$

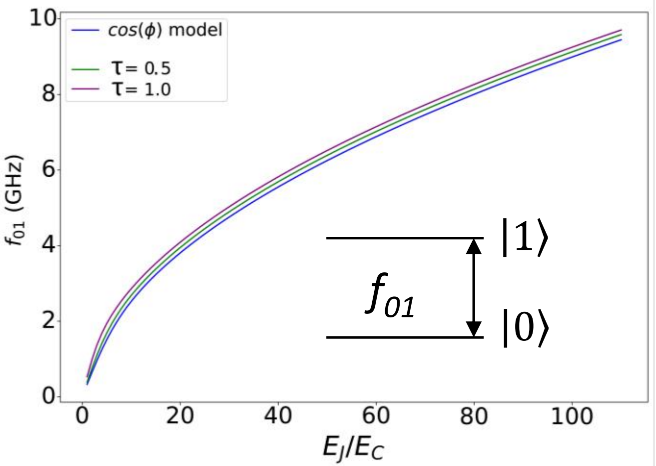
E_c: charging energy (geometry) ~ 400 MHz

n : charge

E_J: Josephson energy

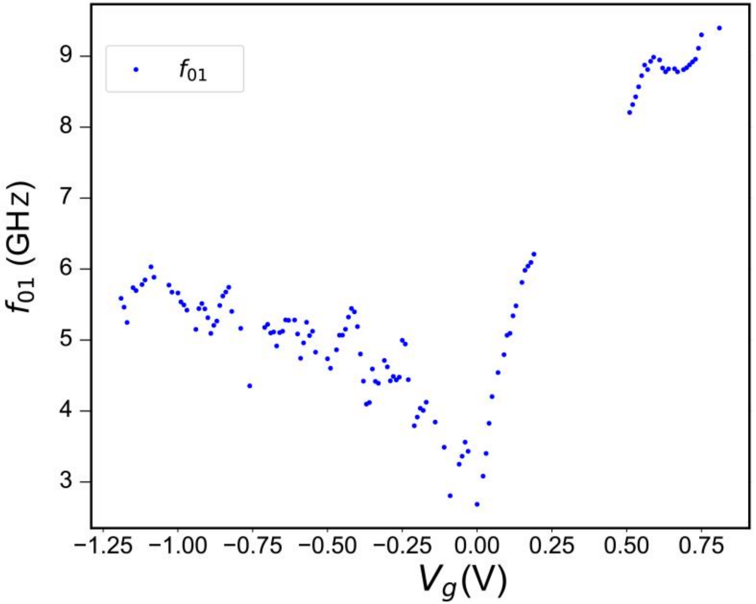
ϕ : phase

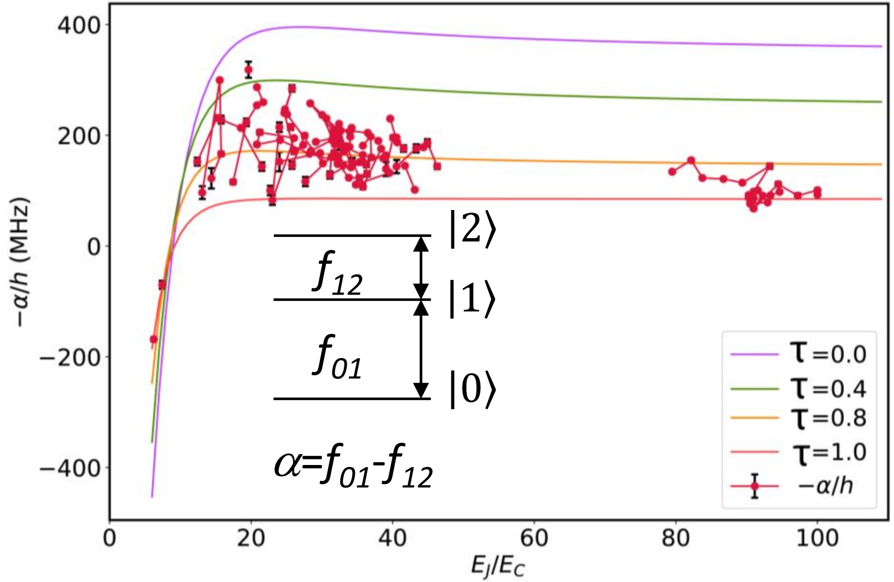
τ : transmission



Gate-tunable Qubit spectrum

Gate-tunable qubit





Gate-tunable frequency (2-10 GHz) and anharmonicity (α)

Acknowledgments

- High kinetic inductance in TiN thin films

K. Rafsanjani Amin, N. Roch (Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel)
C. Ladner, G. Jourdan, S. Hentz (Univ. Grenoble Alpes, CEA, LETI)

- Graphene superconducting quantum circuits

G. Butseraen, A. Ranadive, N. Aparicio, K. Rafsanjani Amin, A. Juyal, M. Esposito, E. De Seze, N. Zhurbina, S. Messelot,
J. Coraux, N. Roch (Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel)
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