New material platform for superconducting transmon qubits with T1 > 0.3ms

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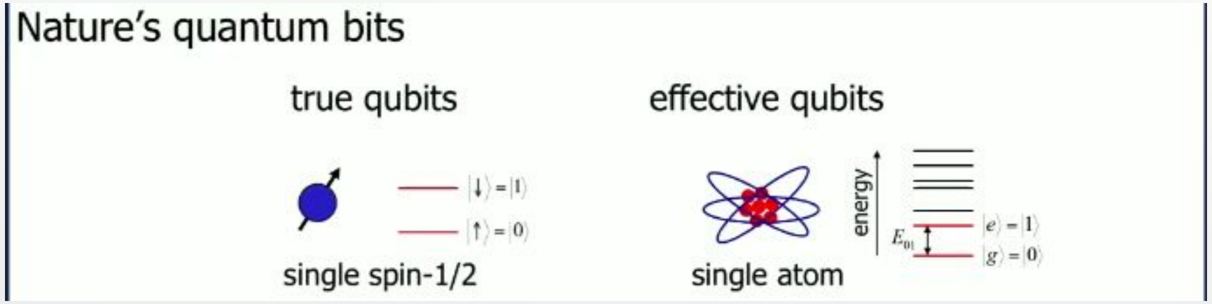
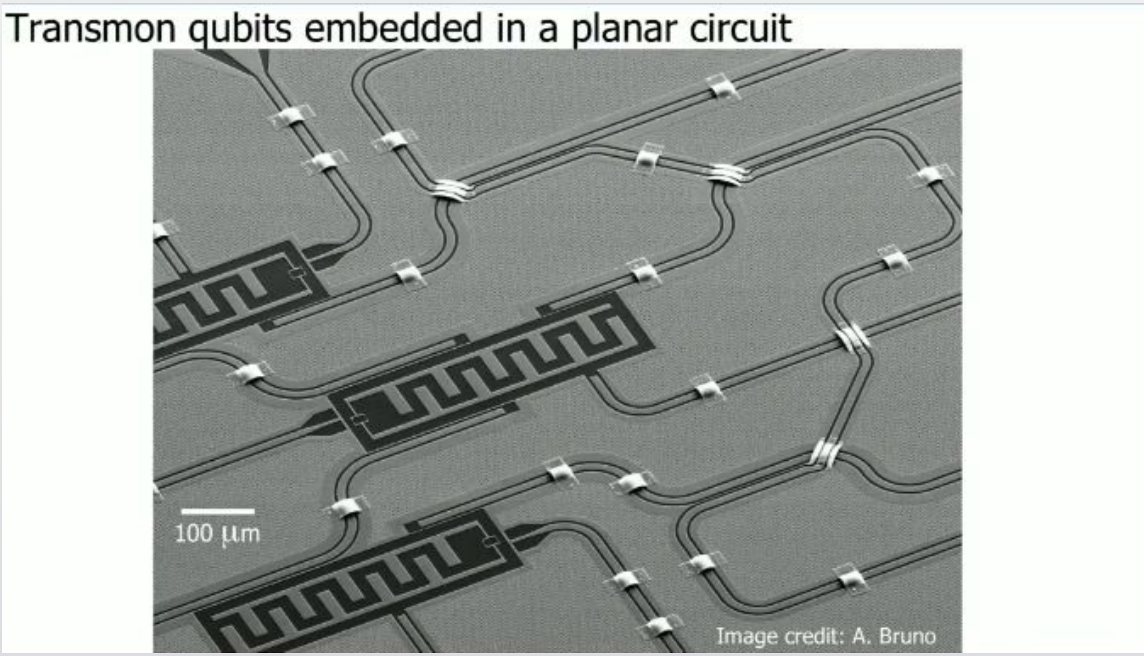
Summary

- **2d transmon qubits with lifetimes(T_1) and coherence times > 0.3ms**
    1. 2d transmon qubits: basic introduction and theoretical lifetime
    2. replacing niobium with tantalum
    3. observation and data
- **8 qubit fabrication data**
- **23 geometrically different qubits fabrication data**
- **Conclusion and future prospects**

2D transmon qubit

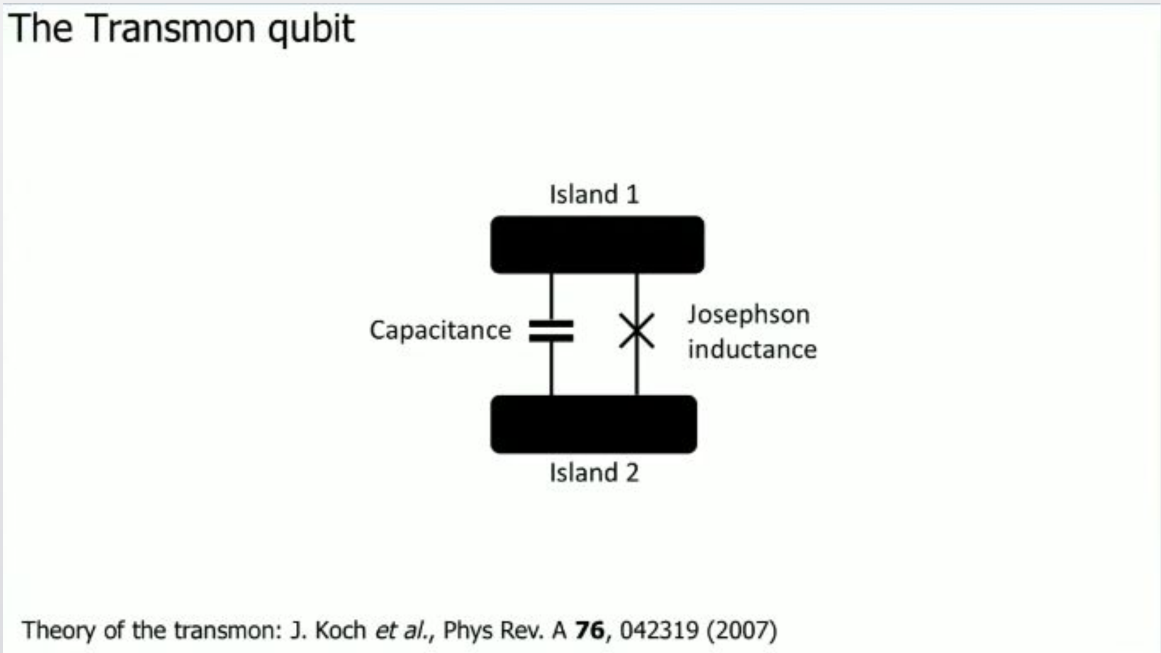


Nature's quantum bits



Transmon qubits embedded in a planar circuit

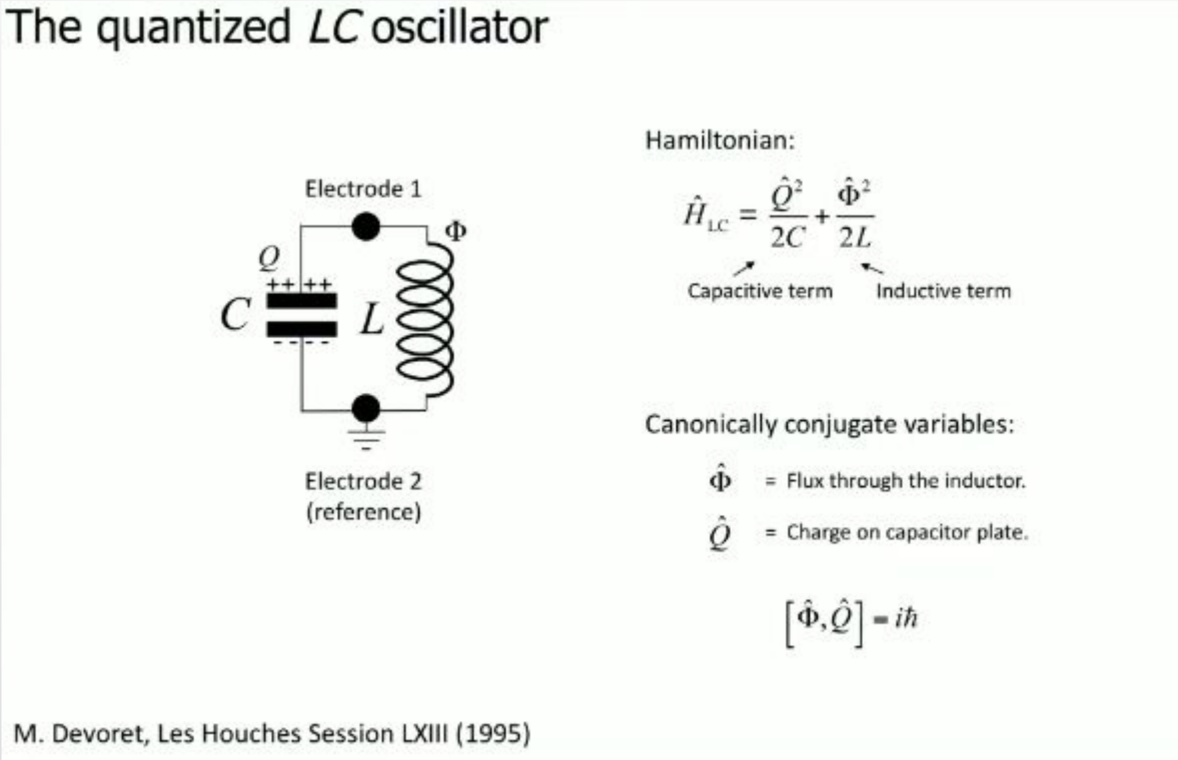
Image credit: A. Bruno



The Transmon qubit

Theory of the transmon: J. Koch *et al.*, Phys Rev. A **76**, 042319 (2007)

2D transmon qubit



The quantized *LC* oscillator

Hamiltonian:

$$\hat{H}_{\mathrm{LC}} = \frac{\hat{Q}^2}{2C} + \frac{\hat{\Phi}^2}{2L}$$

Capacitive term

Inductive term

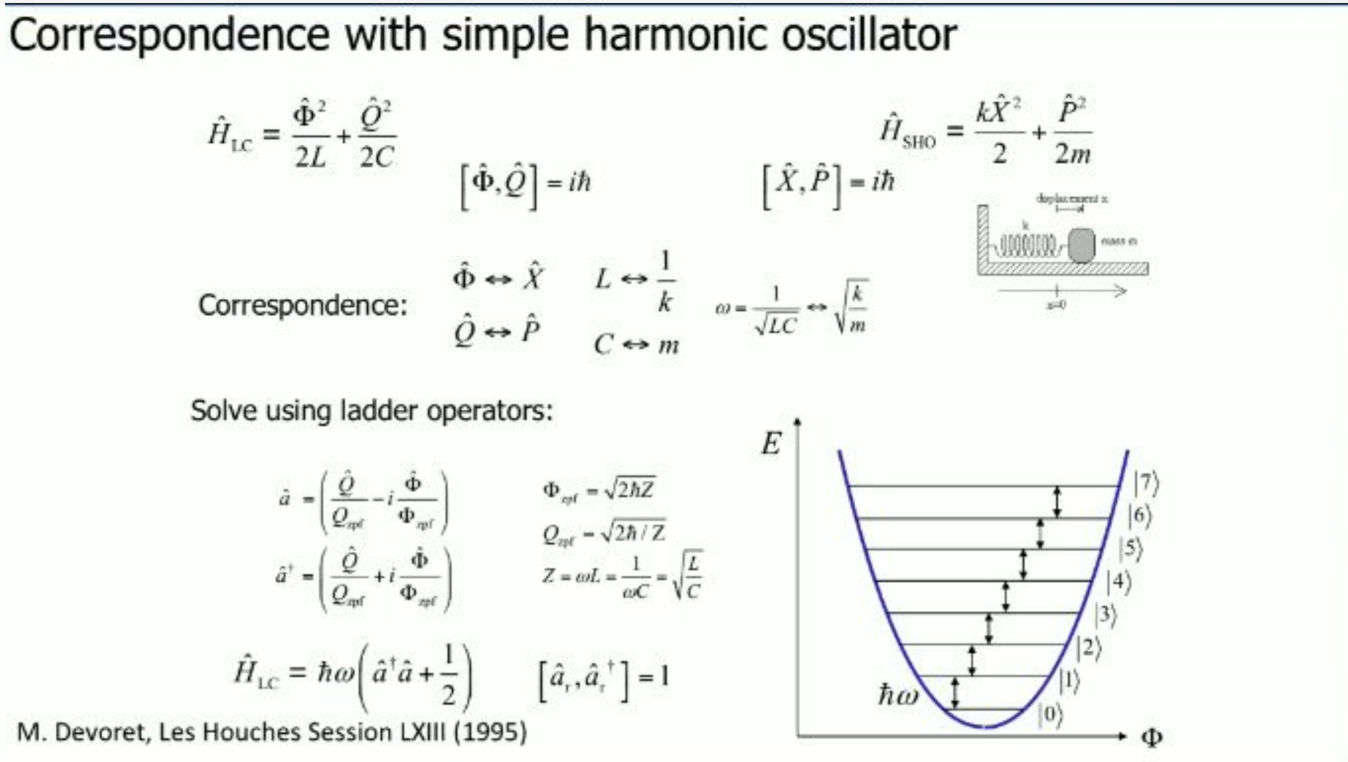
Canonically conjugate variables:

$\hat{\Phi}$ = Flux through the inductor.

$\hat{Q}$ = Charge on capacitor plate.

$$\left[\hat{\Phi}, \hat{Q}\right] = i\hbar$$

M. Devoret, Les Houches Session LXIII (1995)



Correspondence with simple harmonic oscillator

$$\hat{H}_{\mathrm{LC}} = \frac{\hat{\Phi}^2}{2L} + \frac{\hat{Q}^2}{2C} \qquad \left[\hat{\Phi}, \hat{Q}\right] = i\hbar$$

$$\hat{H}_{\mathrm{SHO}} = \frac{k\hat{X}^2}{2} + \frac{\hat{P}^2}{2m} \qquad \left[\hat{X}, \hat{P}\right] = i\hbar$$

Correspondence:

$$\hat{\Phi} \leftrightarrow \hat{X} \qquad L \leftrightarrow \frac{1}{k} \qquad \omega = \frac{1}{\sqrt{LC}} \leftrightarrow \sqrt{\frac{k}{m}}$$

$$\hat{Q} \leftrightarrow \hat{P} \qquad C \leftrightarrow m$$

Solve using ladder operators:

$$\hat{a} = \left(\frac{\hat{Q}}{Q_{zpf}} - i\frac{\hat{\Phi}}{\Phi_{zpf}}\right) \qquad \Phi_{zpf} = \sqrt{2\hbar Z}$$

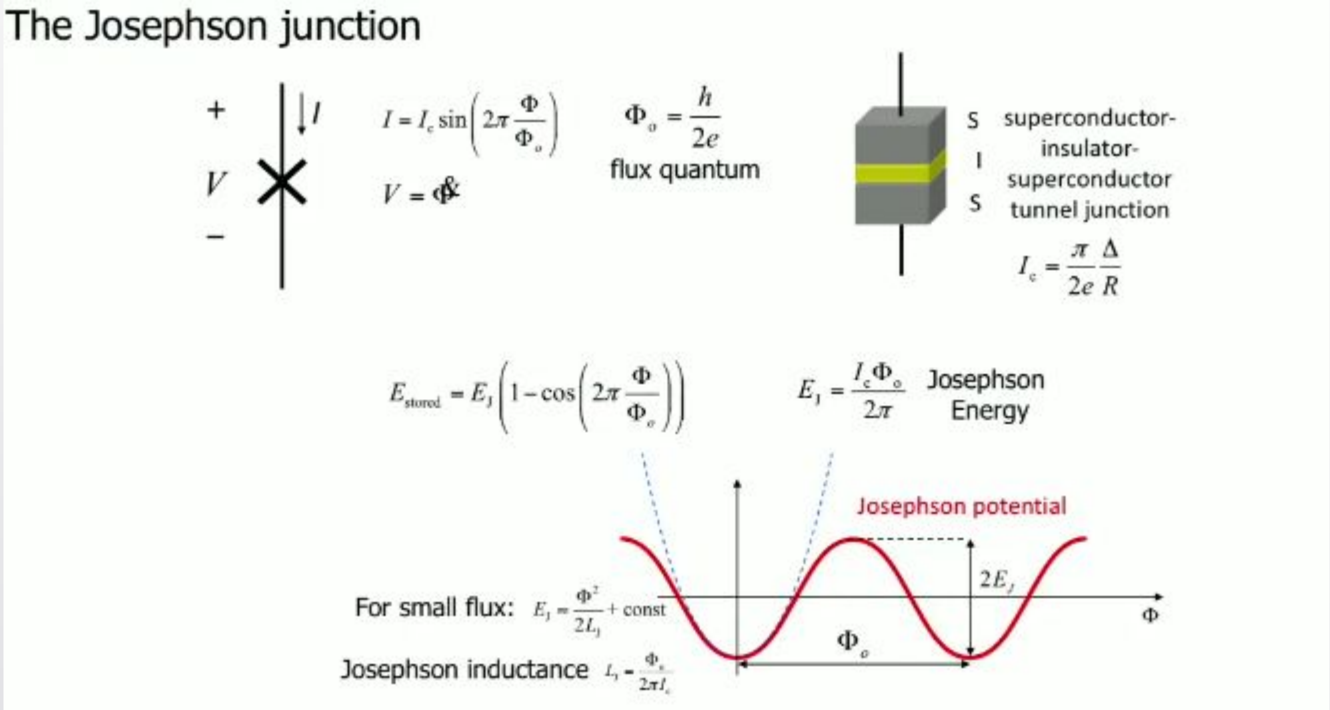
$$\hat{a}^\dagger = \left(\frac{\hat{Q}}{Q_{zpf}} + i\frac{\hat{\Phi}}{\Phi_{zpf}}\right) \qquad Q_{zpf} = \sqrt{2\hbar / Z}$$

$$Z = \omega L = \frac{1}{\omega C} = \sqrt{\frac{L}{C}}$$

$$\hat{H}_{\mathrm{LC}} = \hbar\omega\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right) \qquad \left[\hat{a}_r, \hat{a}_r^\dagger\right] = 1$$

M. Devoret, Les Houches Session LXIII (1995)

2D transmon qubit cont.



The Josephson junction

$I = I_c \sin\left(2\pi \frac{\Phi}{\Phi_o}\right)$

$V = \dot{\Phi}$

$\Phi_o = \frac{h}{2e}$

flux quantum

superconductor-insulator-superconductor tunnel junction

$I_c = \frac{\pi}{2e}\frac{\Delta}{R}$

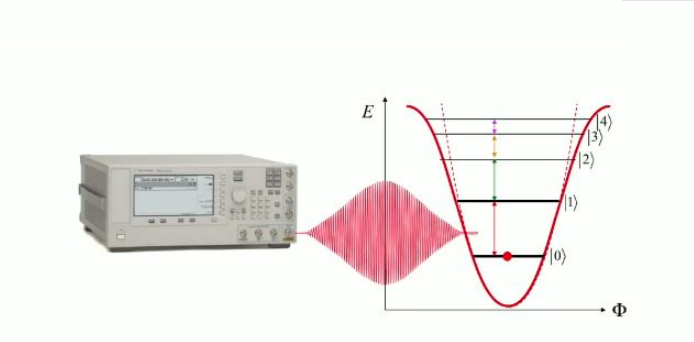
$E_{\text{stored}} = E_J\left(1-\cos\left(2\pi\frac{\Phi}{\Phi_o}\right)\right)$

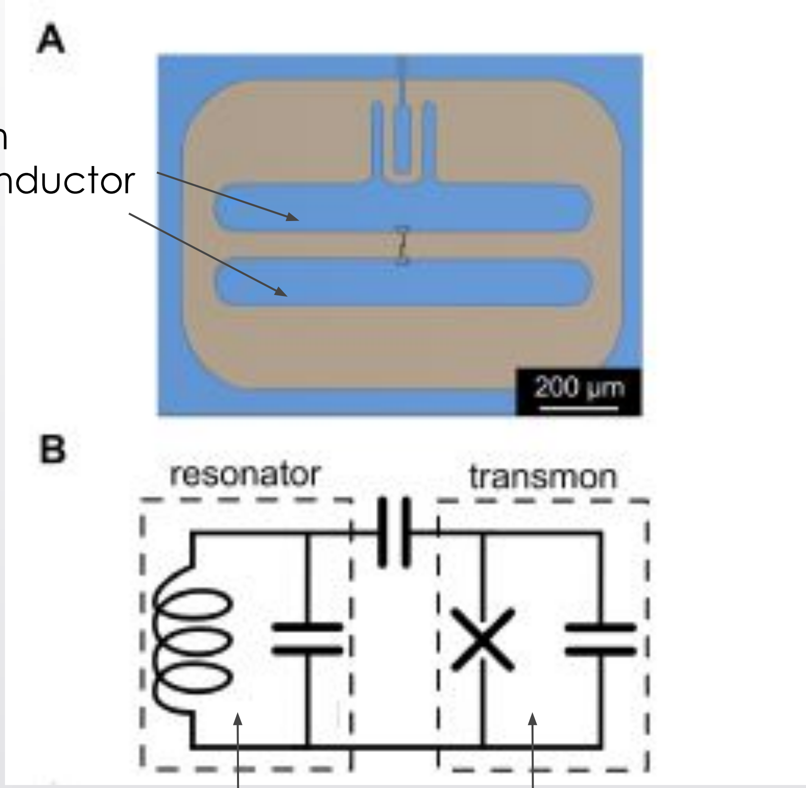
$E_J = \frac{I_c \Phi_o}{2\pi}$ Josephson Energy

For small flux: $E_J \approx \frac{\Phi^2}{2L_J} + \text{const}$

Josephson inductance $L_J = \frac{\Phi_o}{2\pi I_c}$

M. Devoret, Les Houches Session LXIII (1995)





tantalum superconductor

lithographically-defined cavity

LC circuit

Lifetime (T_1) of 2D transmon qubit

- **~ 100μs since 2012 with 114μs top**
- **limited by microwave dielectric losses (微波介電損失)**
  1. theoretical (T_1) > 30ms
  2. hypothesized losses are dominated by uncontrolled defects at surfaces/interfaces/material contaminants

- **Replacing Niobium by Tantalum as superconductor**
  3. complicated stoichiometry of oxides at niobium surface increases loss
  4. insulating oxide of tantalum reduces loss

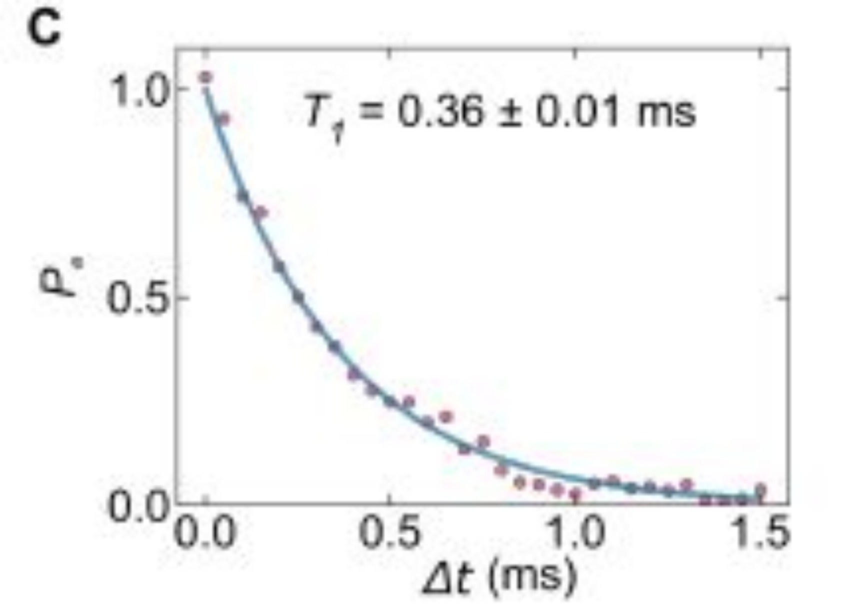
Lifetime (T_1) of 2D transmon qubit cont.

- **T_1 Measurement method**
  1. excite qubit with a π-pulse
  2. measure qubit decay over time at 9-20mK

- **Peak T_1 measurement**

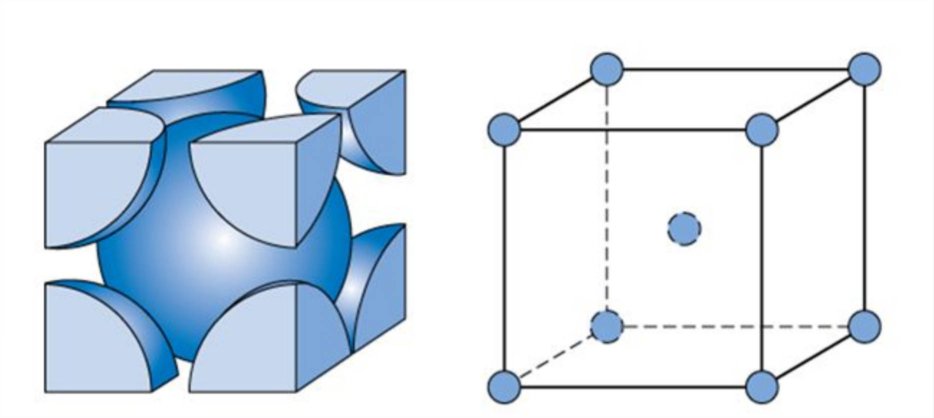
  showing the excited state population P_e as a function of delay time t.

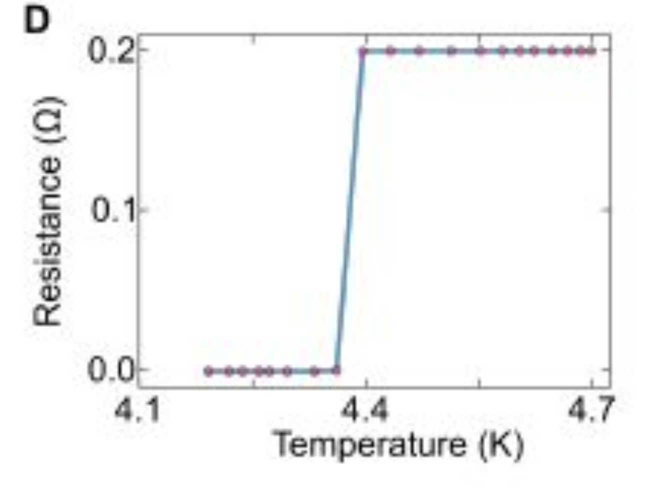
  Line represents a single exponential fit with a characteristic T_1 time of 0.36 ± 0.01 ms.



Lifetime (T_1) of 2D transmon qubit cont.

- **Verify the deposited tantalum film is in BCC a-phase**
    - measuring resistance as a function of temp.
    - Four-probe resistance measurement tantalum film showing Tc = 4.38 ± 0.02 K, consistent with the critical temperature of a-tantalum.

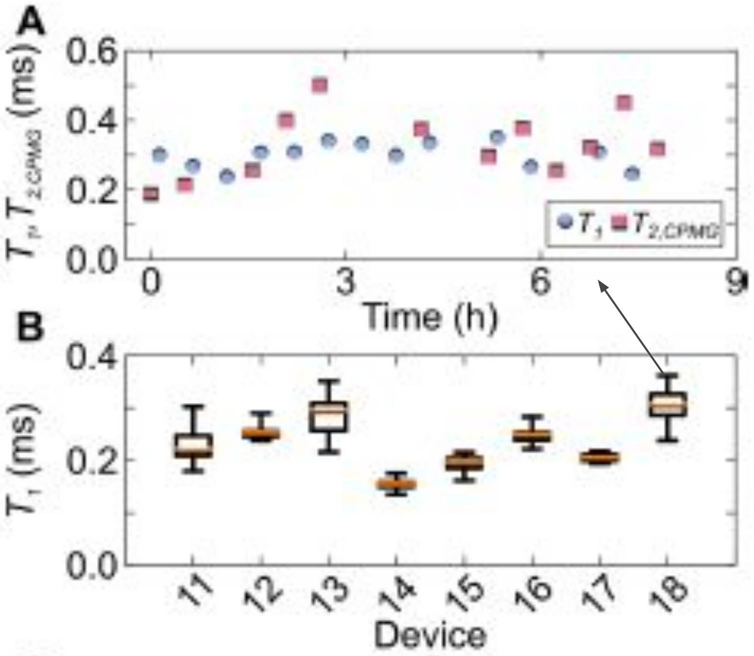




8 qubits fabrication data

- **The lifetime of a given qubit fluctuates over time, with a standard deviation of around 7% of the mean**

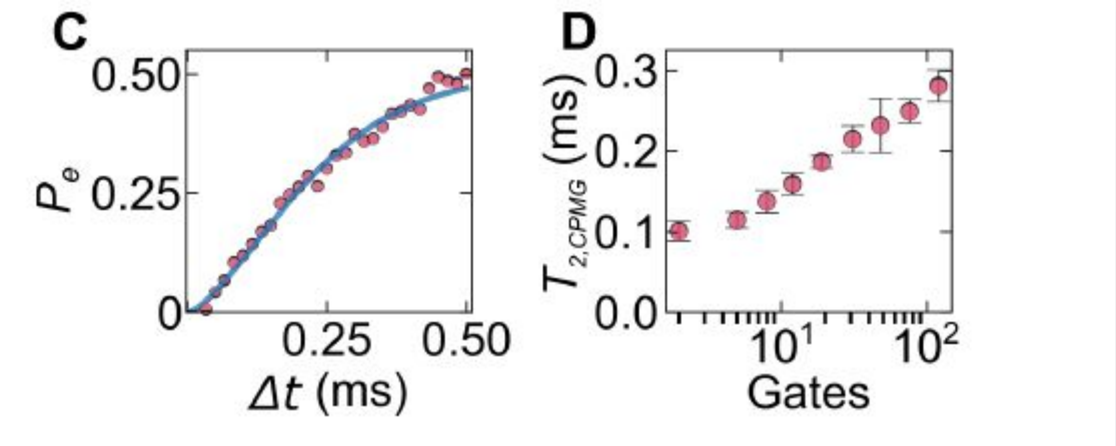
- **Results for eight devices are presented in Fig. 2B, with the time-averaged T_1 ranging from 0.15 ms to 0.30 ms, and an average T_1 of 0.23 ms across all devices**



The yellow line shows the median, while the box spans the middle two quartiles of the data. The whiskers show the extremal measurements.

8 qubits fabrication data cont.

- The time-averaged coherence time, $T_{2;Echo}$, in our best device is 0.20±0.03 ms (a trace is shown in Fig. 2C).
- The coherence time can be further increased using a Carr-Purcell-Meiboom-Gill (CPMG) pulse sequence (Fig. 2D)
- Achieved a time-averaged $T_{2;CPMG}$ of 0.38±0.11 ms in our best device (Fig. 2A)



(C) A $T_{2;Echo}$ measurement of Device 18a, fit with a stretched exponential. The fit gives $T_{2;Echo}$ = 249±4μs.

(D) $T_{2;CPMG}$ of Device 11c as a function of the number of gates in a CPMG pulse sequence.

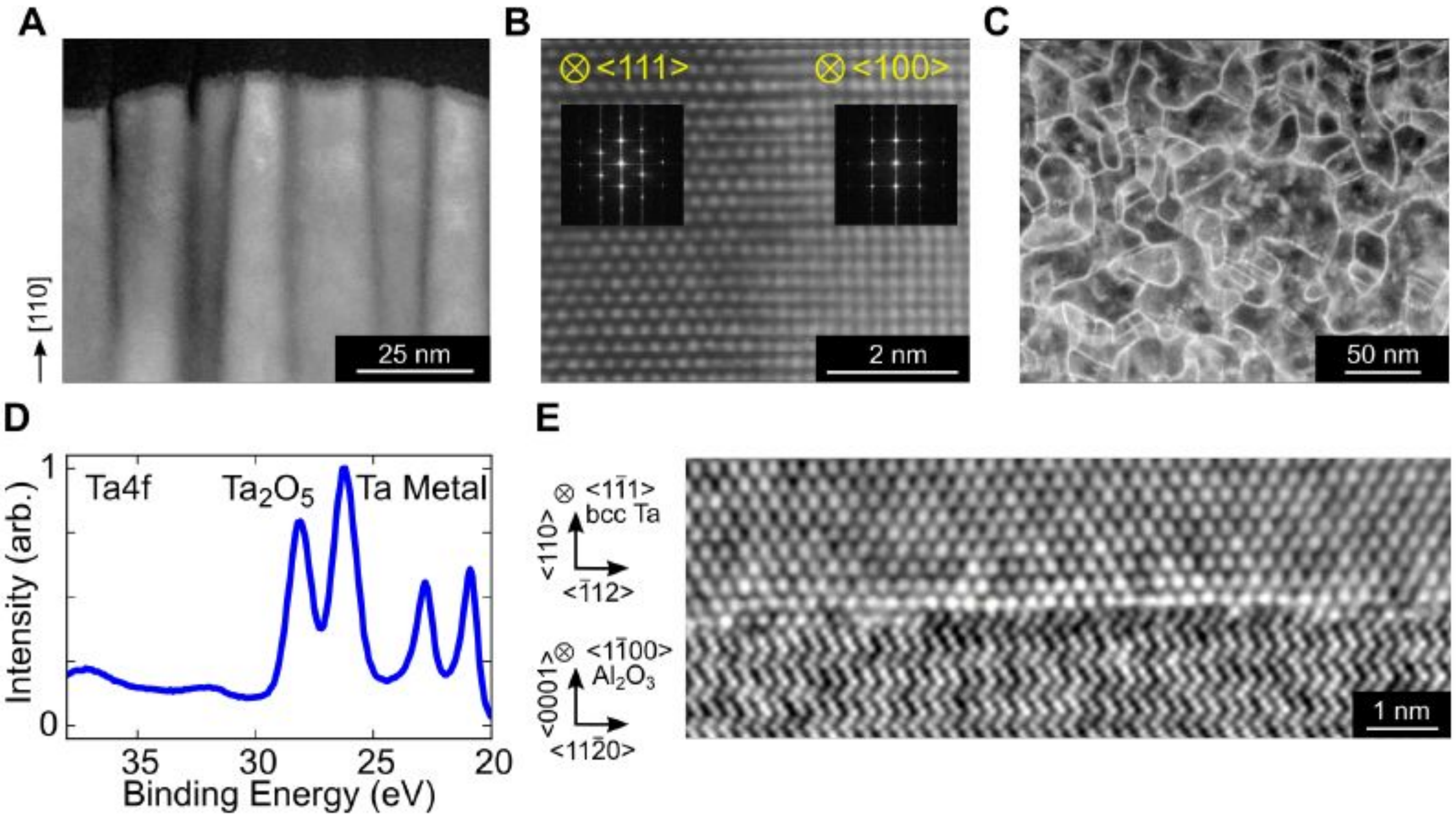
23 Geometrically different transmon qubits fabrication data

- **Swapping Niobium with Tantalum**
- **Heating the substrate during deposition (500°C) improved T1 to 79±1μs**
- **Iterative improvements to processing**
  a. wet etching to pattern tantalum layer (<200μs): improved edge morphology
  b. introduction to extra cleaning: Pirahna cleaning process - substrate surface
  c. data 11-18 (a+b processes) >200μs

23 Geometrically different transmon qubits fabrication data cont.

- **Observation methods:**
  a. Microscopy and spectroscopy of tantalum deposits confirm BCC structure and high orientation
  b. Scanning Transmission electron microscopy (STEM) - columnar structure
  c. Energy dispersive spectroscopy (EDS) - no oxide growth between grains
  d. Photoelectron spectroscopy - imaging oxide layer
  e. integrated differential phase contrast imaging (iDPC) of STEM

     shows an atomically sharp boundary with clear evidence of epitaxial growth, in which the tantalum atomic layer is directly grown on top of the oxygen atomic layer in the sapphire



A) STEM image of tantalum film
B) Atomic resolution STEM image between two columns
C) STEM image of horizontal cross section, grain boundries
D) XPS spectrum of the device
E) High-resolution STEM with integrated differential phase contrast imaging of the interface between the sapphire and tantalum showing epitaxial growth.

Conclusion and future prospects

- **Conclusion**
  a. demonstrated that tantalum 2D transmon qubits exhibit longer T_1 and T_2 than the previous state of the art with remarkable consistency
- **Future prospects**
  b. First, $T_{2;Echo}$ is shorter than T_1 for all tantalum devices measured. Could help exploring microscopic mechanisms for decoherence.
  c. Exploring the impact of tantalum grain size, oxide thickness, and heteroepitaxial (磊晶)growth interface quality on T_1 and T_2
  d. Explore how particular material choices quantitatively affect variations between qubits
  e. Explore how judicious material choice can narrow the distribution of device properties
  f. Explore the role of contamination and interfaces in the coherence of all-aluminum qubits
  g. Explore possibility of fabricating all-tantalum qubits

THANK YOU FOR YOUR ATTENTION