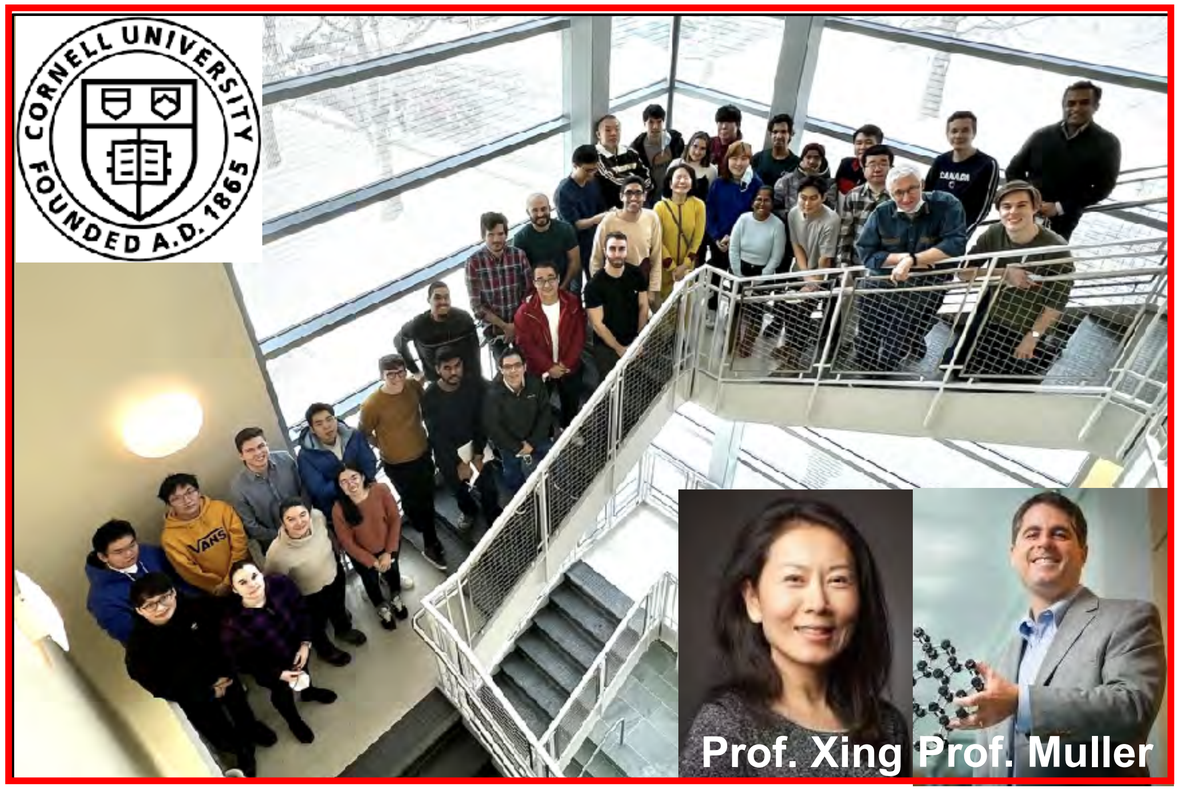
Epitaxial materials and devices for superconducting qubits

08/21/2025, NY Creates Talk

Debdeep Jena (djena@cornell.edu) with G. Xing’s group



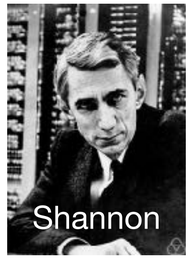
Research groups of
Debdeep Jena, Grace Xing, David Muller

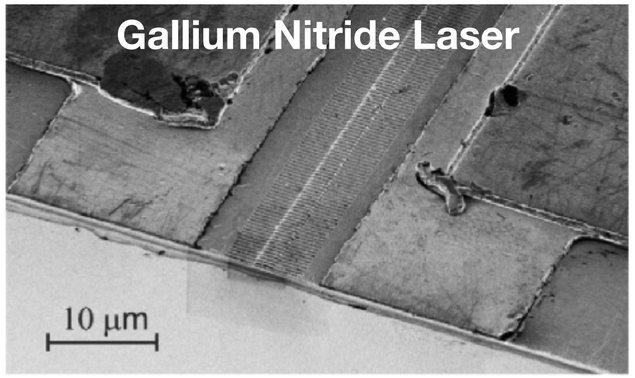
Research supported over the years by:
DoD, NSF, DOE, and SRC

Research in:
Electronics, Photonics, Quantum

Materials:
Nitrides, Oxides, 2D Crystals

Classical vs. Quantum Info Systems



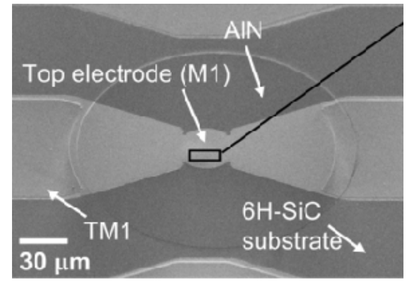


Classical
C-Bits

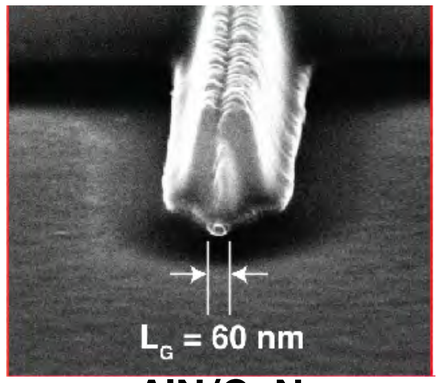
Probabilistic
P-Bits

Quantum
Qubits

	Computation	Communication	Memory
Classical	Semiconductor Transistors	Semiconductor amplifiers Semiconductor Lasers Microwaves/Photons	Semiconductors Magnets
Quantum	Superconductors Semiconductors Trapped Ions …	Superconductors Semiconductors Defect States …	Not currently known …



AlN Microwave Filter



AlN/GaN
Microwave Transistor

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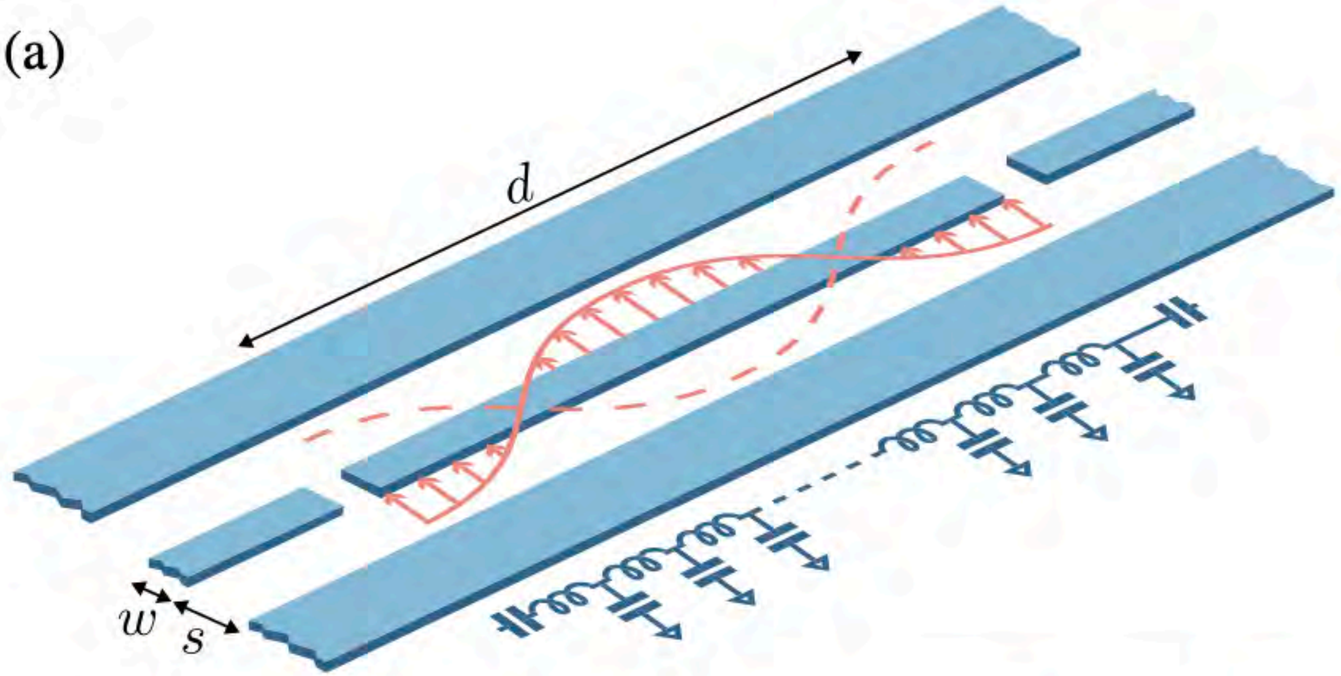
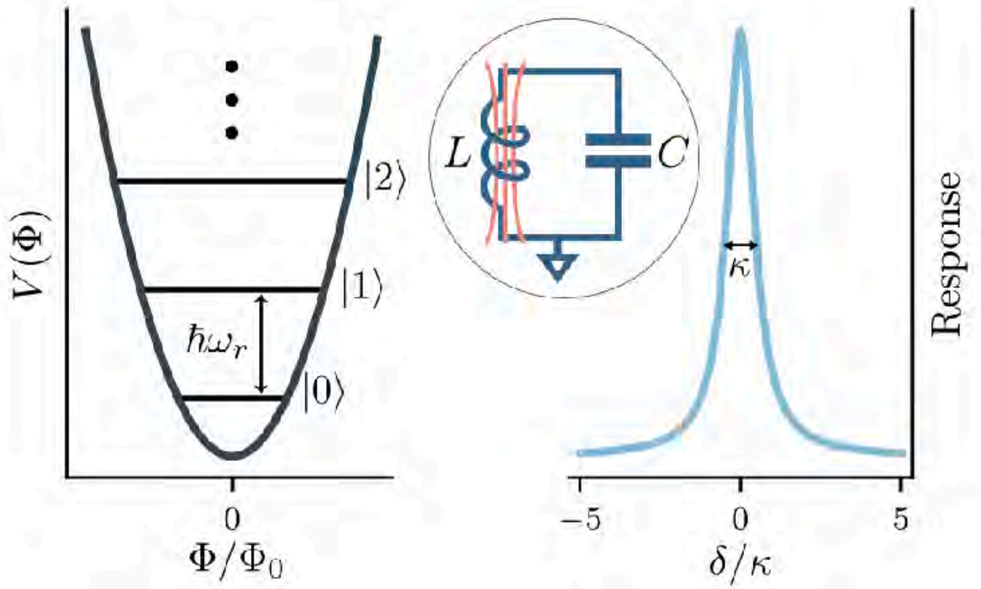
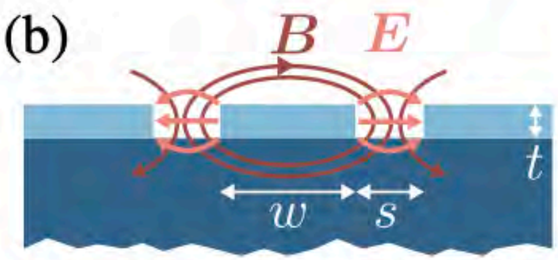
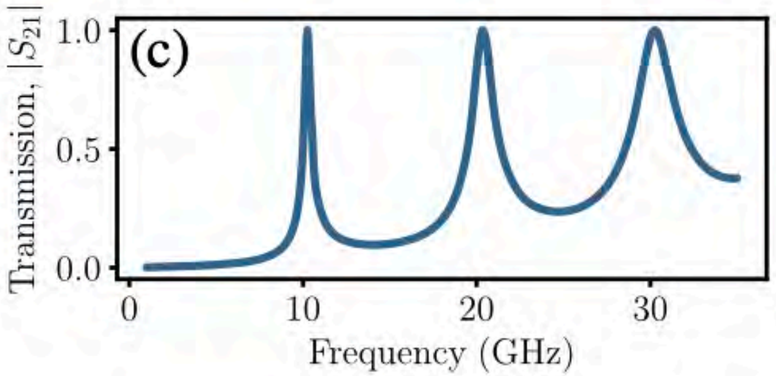
A cavity resonator









$$H_{LC} = \frac{Q^2}{2C} + \frac{\Phi^2}{2L}$$

$$\hat{H}_{LC} = \hbar\omega_r(\hat{a}^\dagger\hat{a} + 1/2)$$

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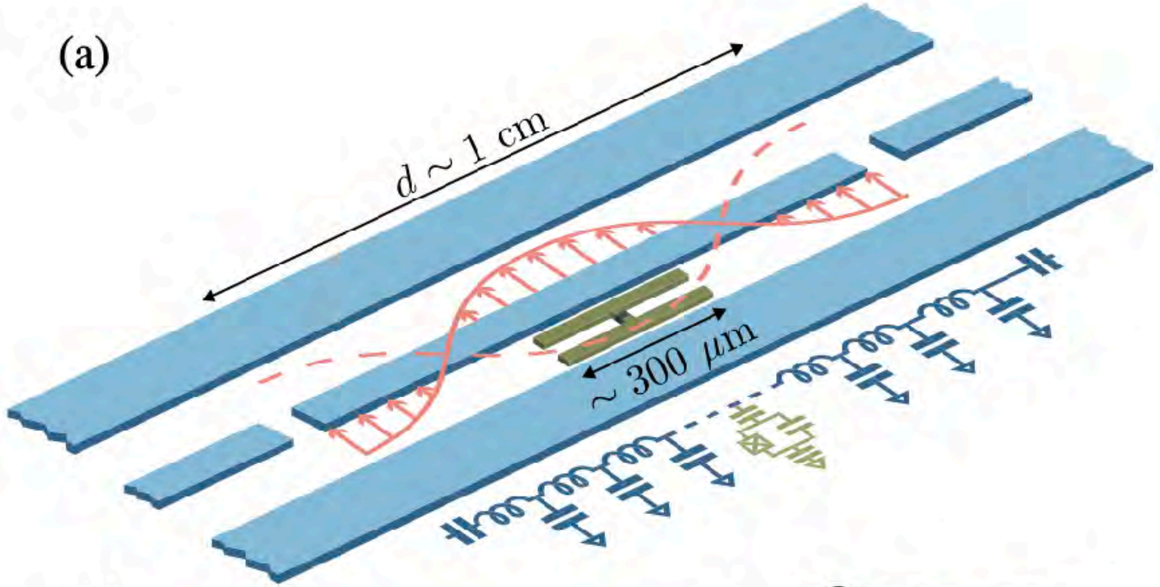
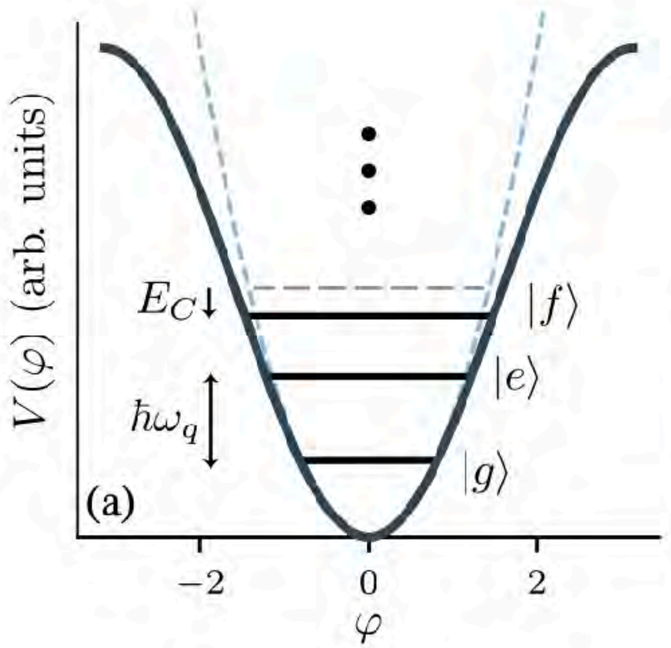
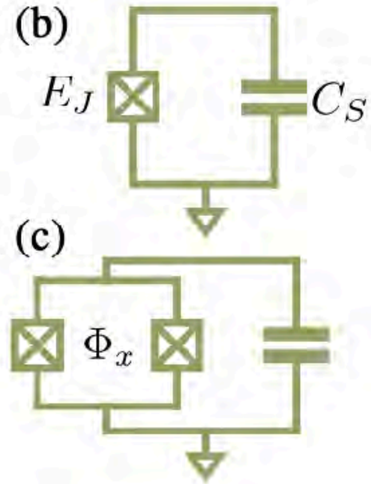
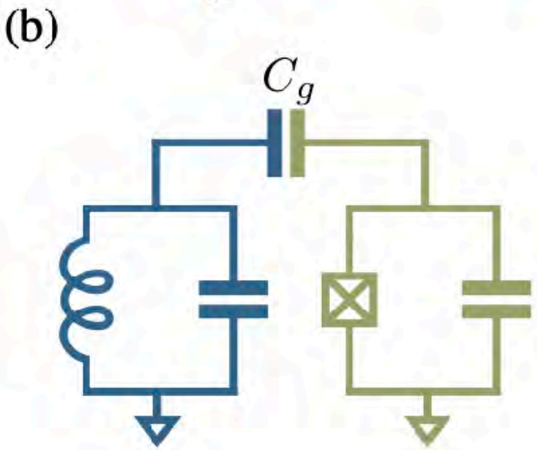
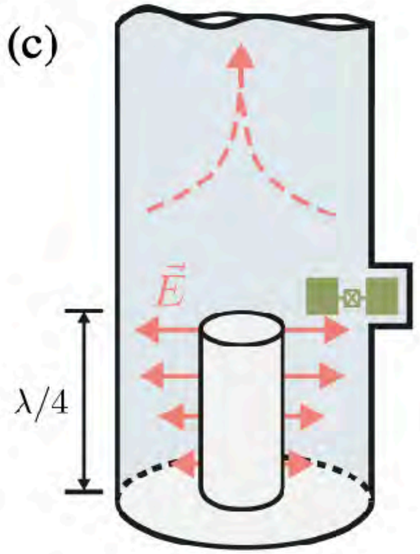
A superconducting qubit











$$\hat{H}_T = \frac{(\hat{Q} - Q_g)^2}{2C_\Sigma} - E_J \cos\left(\frac{2\pi}{\Phi_0}\hat{\Phi}\right)$$
$$= 4E_C(\hat{n} - n_g)^2 - E_J \cos\hat{\varphi}.$$

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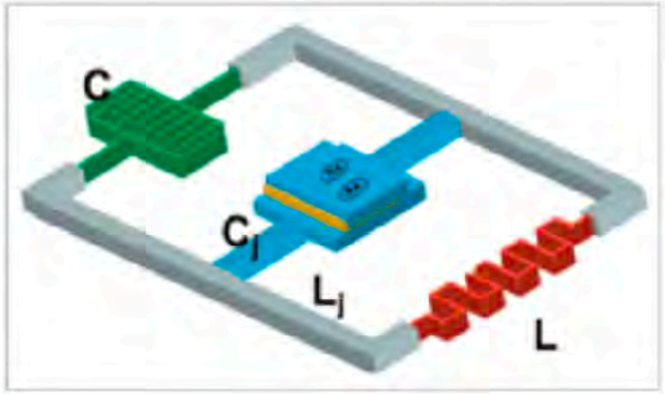
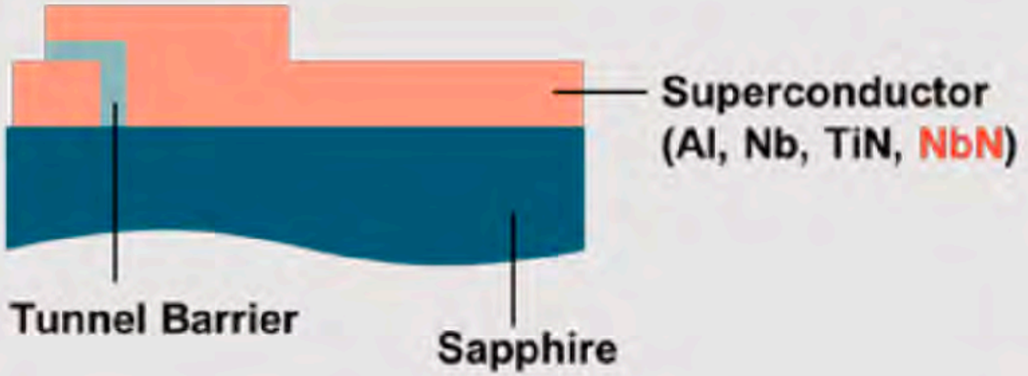
Superconducting qubits

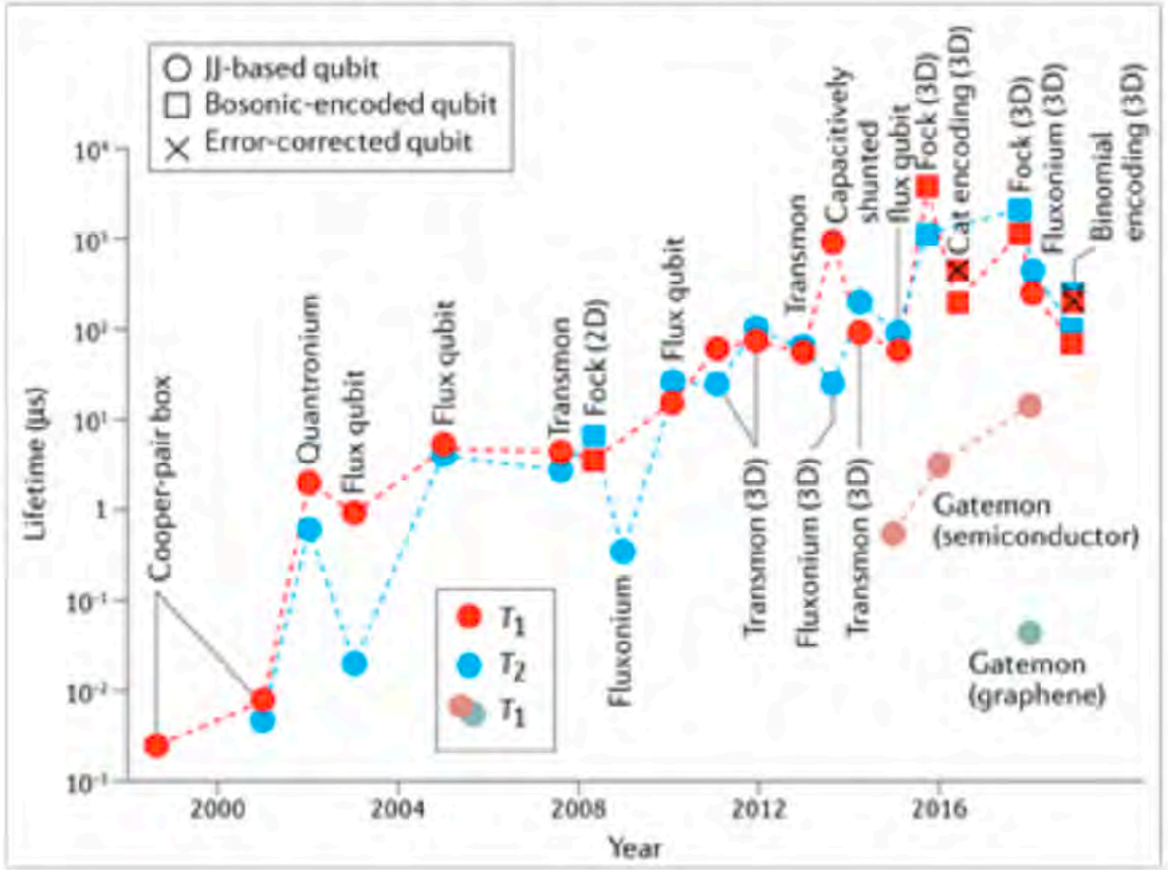
Components of a Superconducting Qubit



Material Stack of a Superconducting Resonator



Coherence Times of Various Superconducting Qubits



I. Siddiqi, Nature Reviews Materials **6**, *875–891 (2021)*
C. Müller et. al., Rep.Prog.Phys. 82 124501 (2019)

NbN/AlN/NbN JJs and Qubits

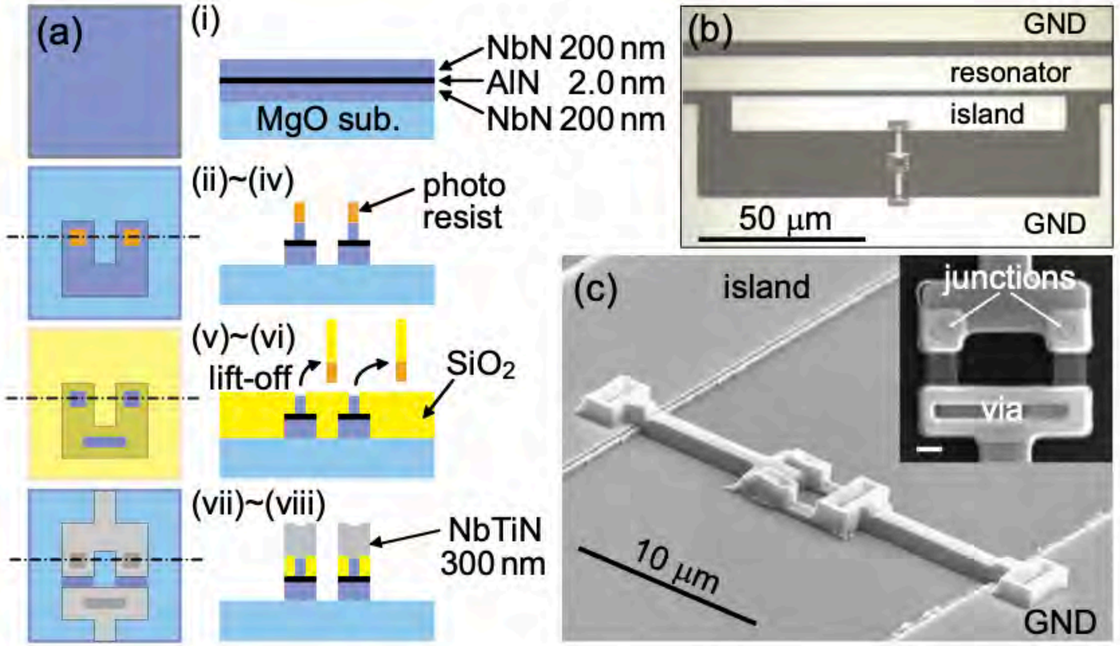


FIG. 1. (Color online) Superconducting qubits consisting of epitaxially grown NbN/AlN/NbN Josephson junctions. (a) Fabrication steps. Left: top views, right: cross-sections. (b) Micrograph of a qubit capacitively coupled to a coplanar waveguide resonator. (c) Scanning electron micrograph of the SQUID part. The inset shows magnification of the junctions and the via. The length of the white bar indicates 1 μm. A common external coil (not shown) is used to apply magnetic flux bias on the qubits.

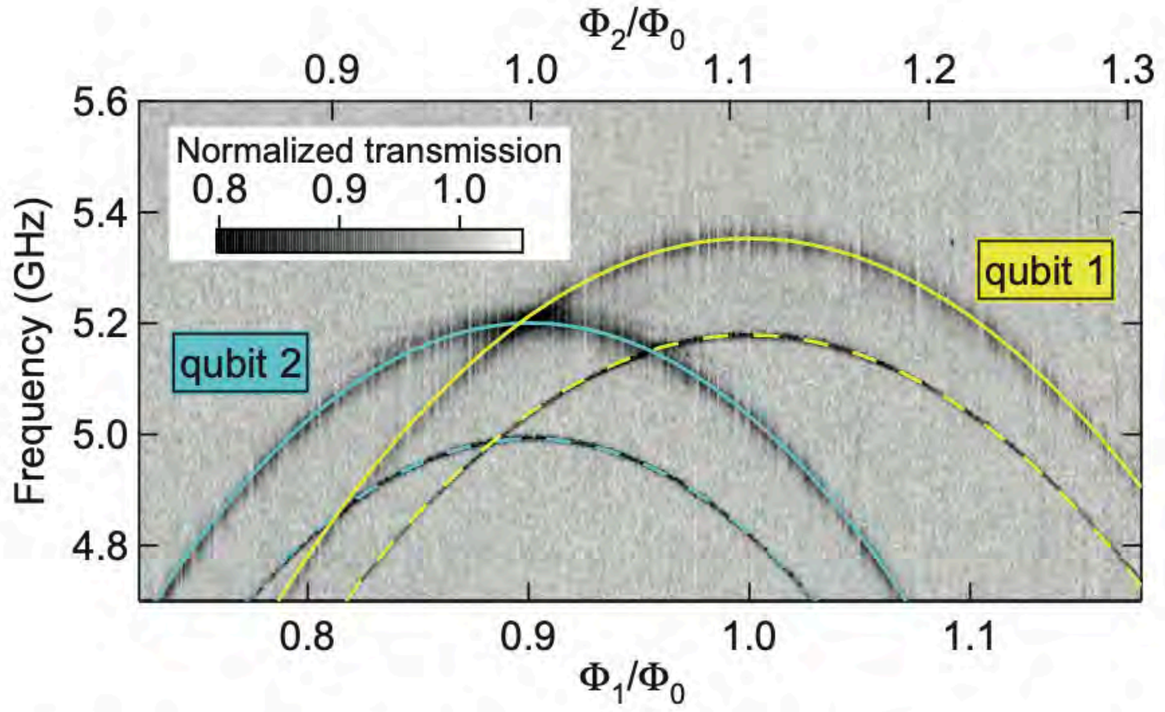


FIG. 2. (Color online) Qubit spectra measured by two-tone spectroscopy for qubit 1 (right) and qubit 2 (left) as a function of the magnetic flux bias Φ_1 and Φ_2, respectively. The curves are the fittings of the transition energies: The solid lines correspond to E_{01}/h, the single-photon excitation to the first excited state, while the dashed lines depict $E_{02}/2h$, the two-photon transition to the second excited state.

NbN/AlN/NbN JJs and Qubits

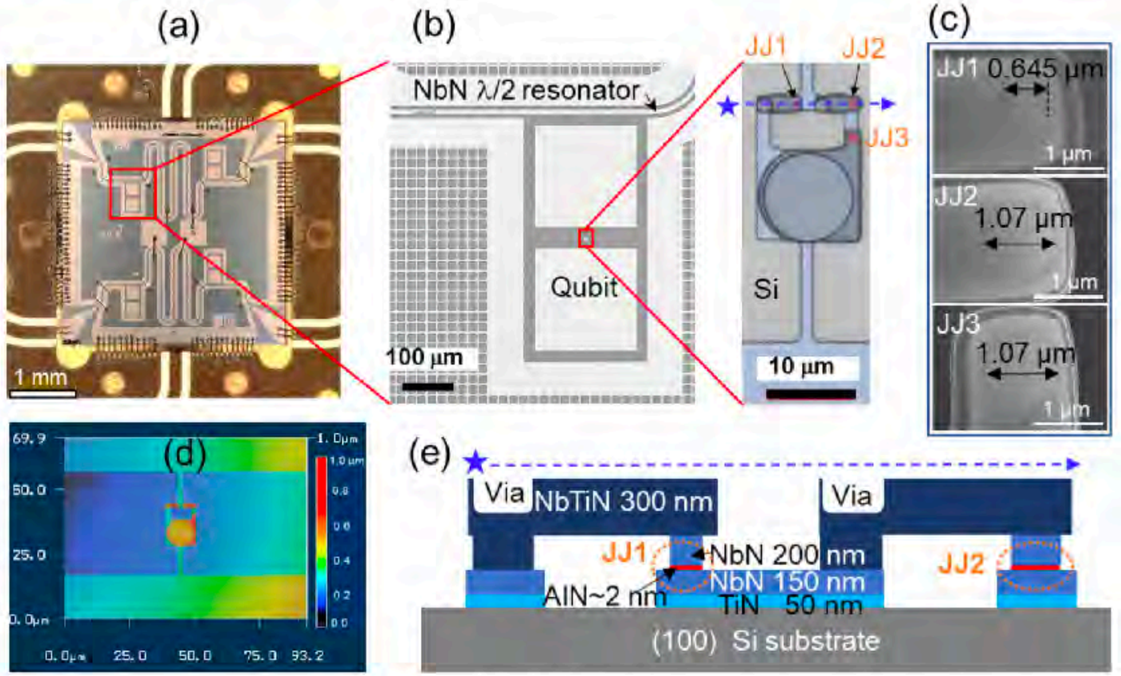


Fig. 1 All-nitride C-shunt flux qubit consisting of epitaxially grown NbN/AlN/NbN Josephson junctions on Si substrate. a a photograph of the qubit chip mounted into the sample package, **b** Laser scanning microscope image of the capacitively shunted flux qubit coupled to a half-wavelength ($\lambda/2$) CPW resonator made of NbN/TiN on a Si substrate. The inset shows a magnified image of a false-colored flux qubit structure with three NbN/AlN/NbN Josephson junctions (marked as JJ1, JJ2, and JJ3). **c** Scanning electron microscopy images corresponding to the three JJs taken after the qubit measurements. **d** The thickness profile of qubit taken from the laser scanning microscope system. The displayed scales are in μm. **e** Cross-sectional schematics of the part indicated by the blue star and dashed line in **b**. The JJ parts are marked by the orange dotted ellipses.

ARTICLE

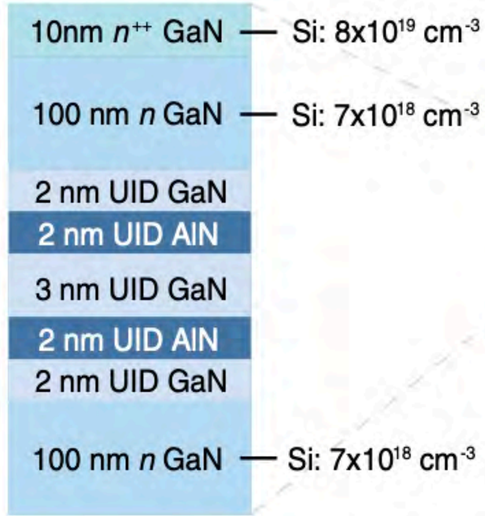
https://doi.org/10.1038/s43246-021-00204-4 OPEN

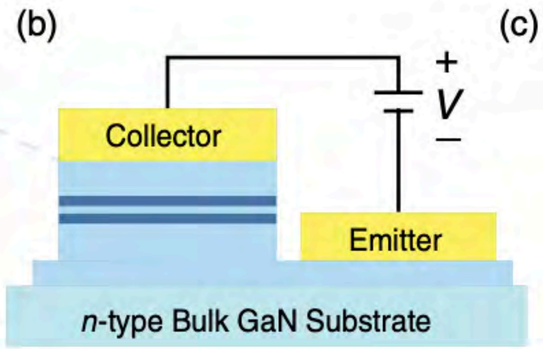
Enhanced coherence of all-nitride superconducting qubits epitaxially grown on silicon substrate

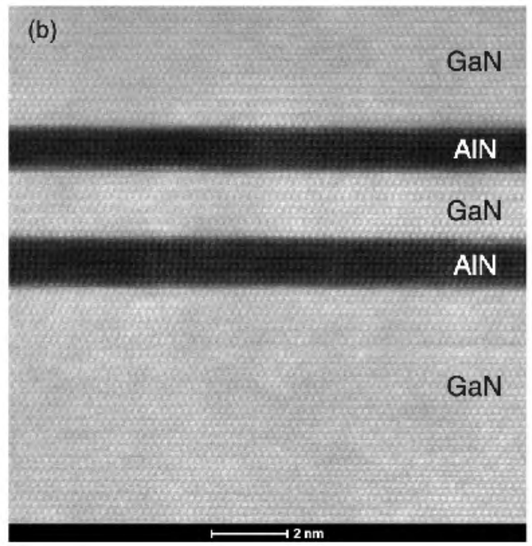
Sunmi Kim[1✉], Hirotaka Terai[2✉], Taro Yamashita[3], Wei Qiu[2], Tomoko Fuse[1], Fumiki Yoshihara[1], Sahel Ashhab[1], Kunihiro Inomata[4] & Kouichi Semba[1,5✉]

COMMUNICATIONS MATERIALS | (2021)2:98 | https://doi.org/10.1038/s43246-021-00204-4 | www.nature.com/commsmat

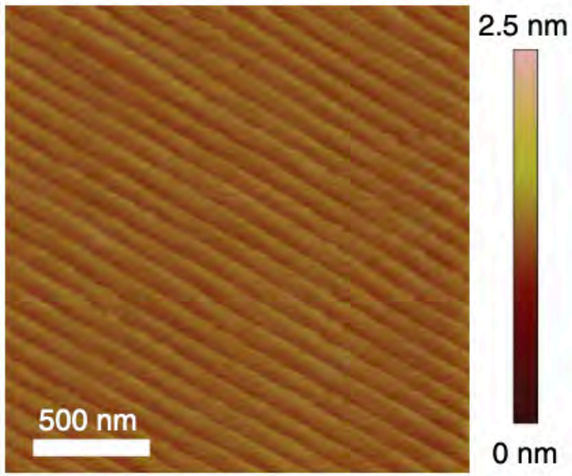
Why epitaxial qubits?

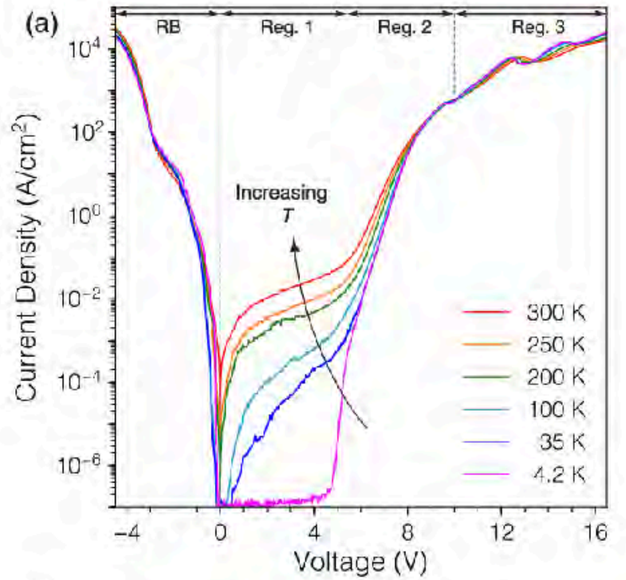


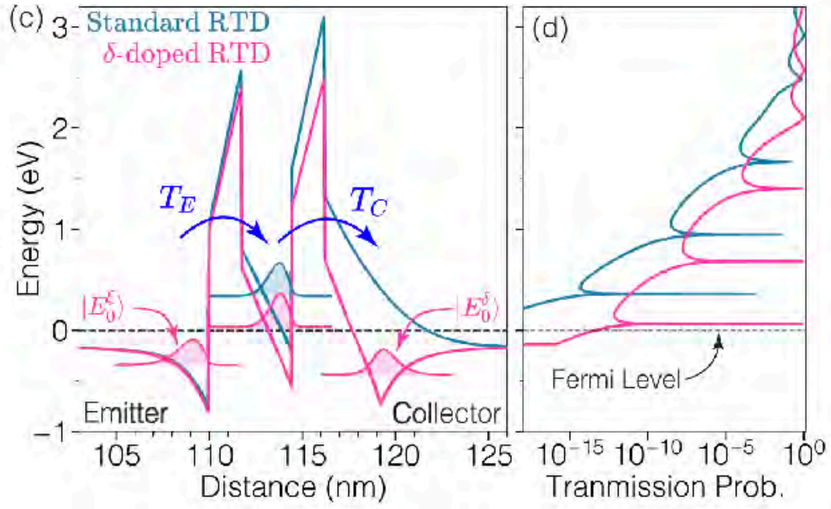


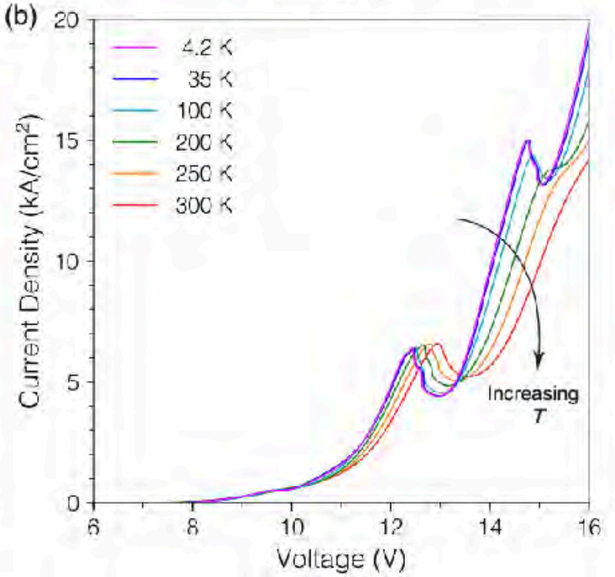


(c)









PHYSICAL REVIEW X 7, 041017 (2017)

New Tunneling Features in Polar III-Nitride Resonant Tunneling Diodes

Jimy Encomendero,[1,*] Faiza Afroz Faria,[2] S. M. Islam,[1] Vladimir Protasenko,[1] Sergei Rouvimov,[2] Berardi Sensale-Rodriguez,[3] Patrick Fay,[2] Debdeep Jena,[1,4,†] and Huili Grace Xing[1,4,5,‡]

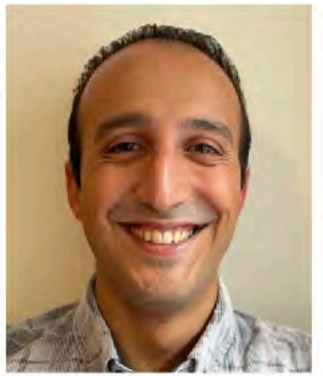
[1]*School of Electrical and Computer Engineering, Cornell University, Ithaca, New York 14853, USA*

The EpiQ Team: bridging materials and device experts

Jena

Muller

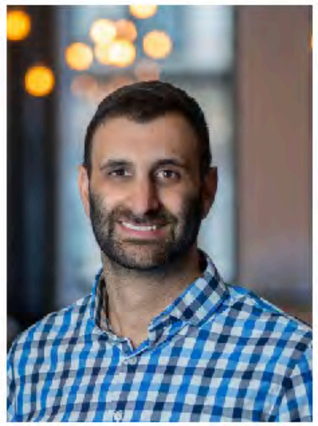
Rana



Fatemi

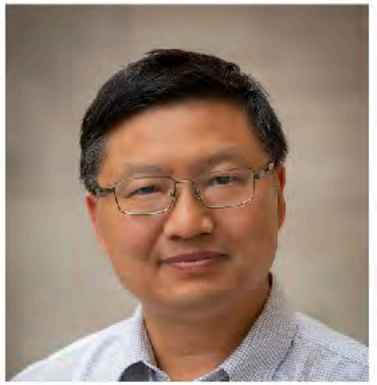
McMahon

University at Buffalo Mazumder



Stony Brook University Dreyer

NIST McRae



Yale Tang

The EpiQ Team: bridging materials and device experts


Anand Ithepalli


Arjan Singh


Danqing Wang


Naomi Pieczulewski


Manas Verma


Wenwen Zhao


Prachi Garg


John Wright


Chandu Savant

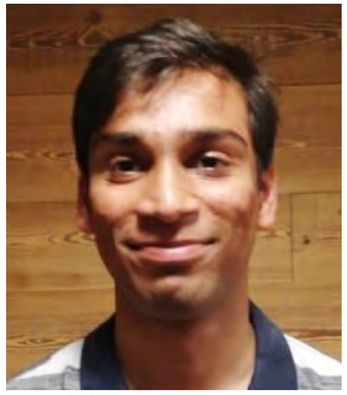

Rishabh Singh


Clara Di


Amit Rohan


Kedarsh


Haoran Lu

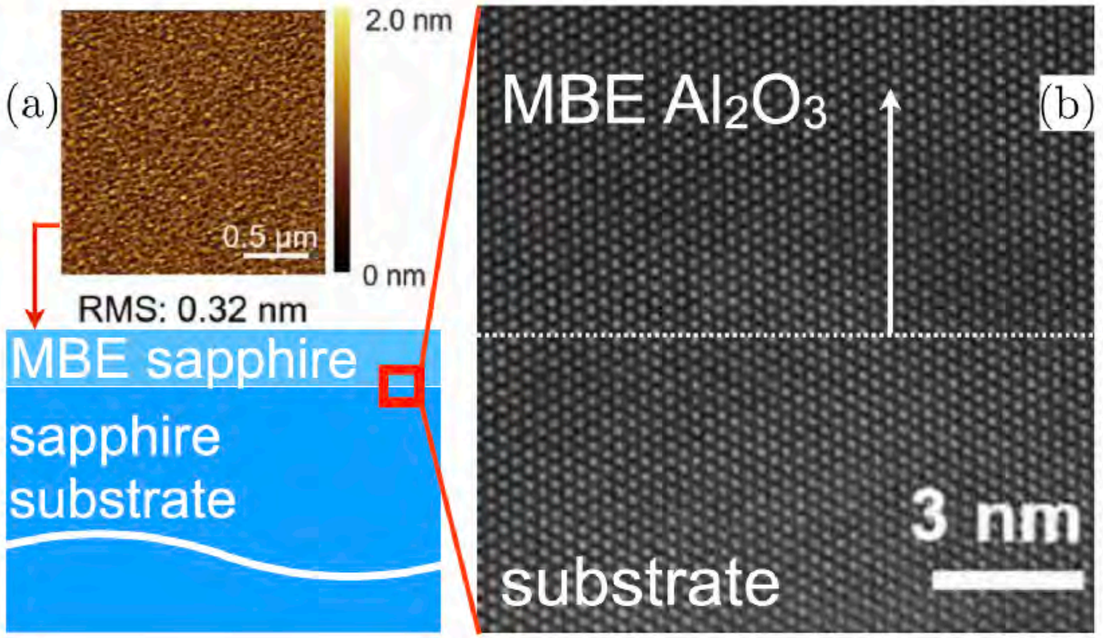

Kushagra

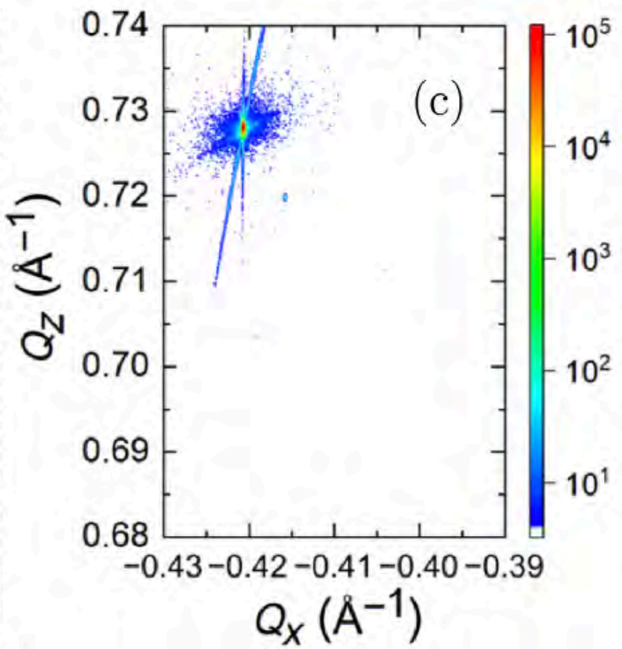

Alice Ho

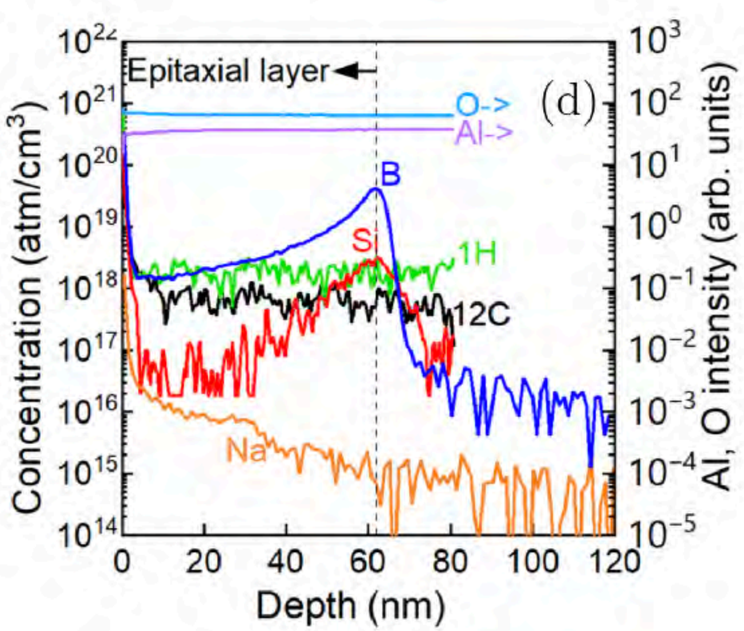

Wayne Wang


Clara Chung

Epitaxial sapphire - 21st century challenge







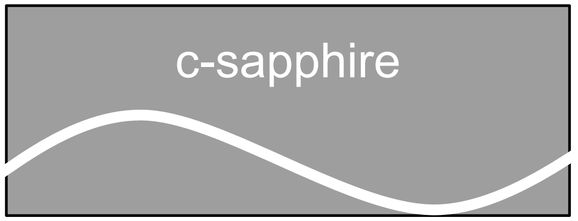
SCIENCE ADVANCES | RESEARCH ARTICLE

ENGINEERING Jinno *et al.*, *Sci. Adv.* 2021; **7** : eabd5891 8 January 2021

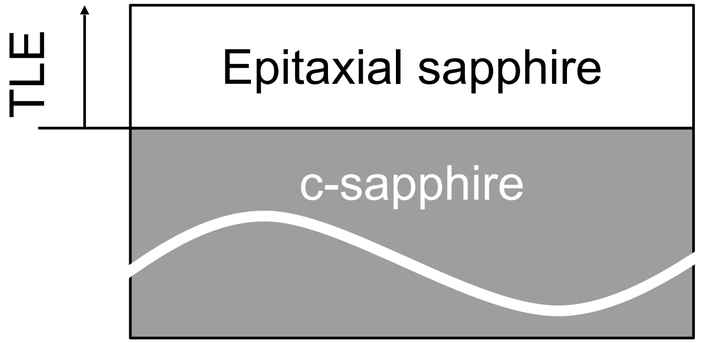
Crystal orientation dictated epitaxy of ultrawide-bandgap 5.4- to 8.6-eV α-$(AlGa)_2O_3$ on m-plane sapphire

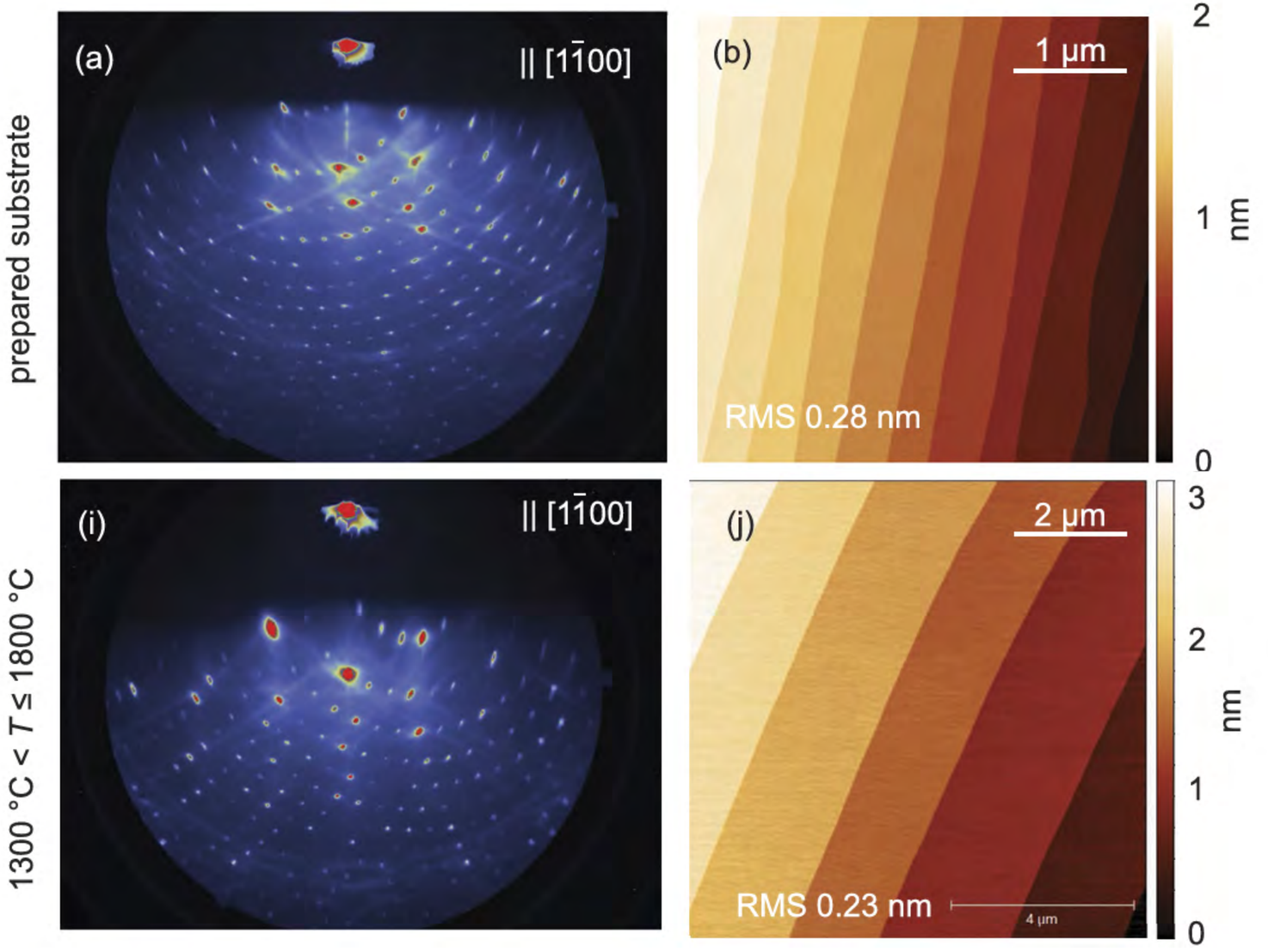
Riena Jinno[1]*†, Celesta S. Chang[2,3]*, Takeyoshi Onuma[4], Yongjin Cho[1], Shao-Ting Ho[5], Derek Rowe[1], Michael C. Cao[3], Kevin Lee[1], Vladimir Protasenko[1], Darrell G. Schlom[5,6], David A. Muller[3,6], Huili G. Xing[1,5], Debdeep Jena[1,5]‡

Epitaxial sapphire - 21st century challenge



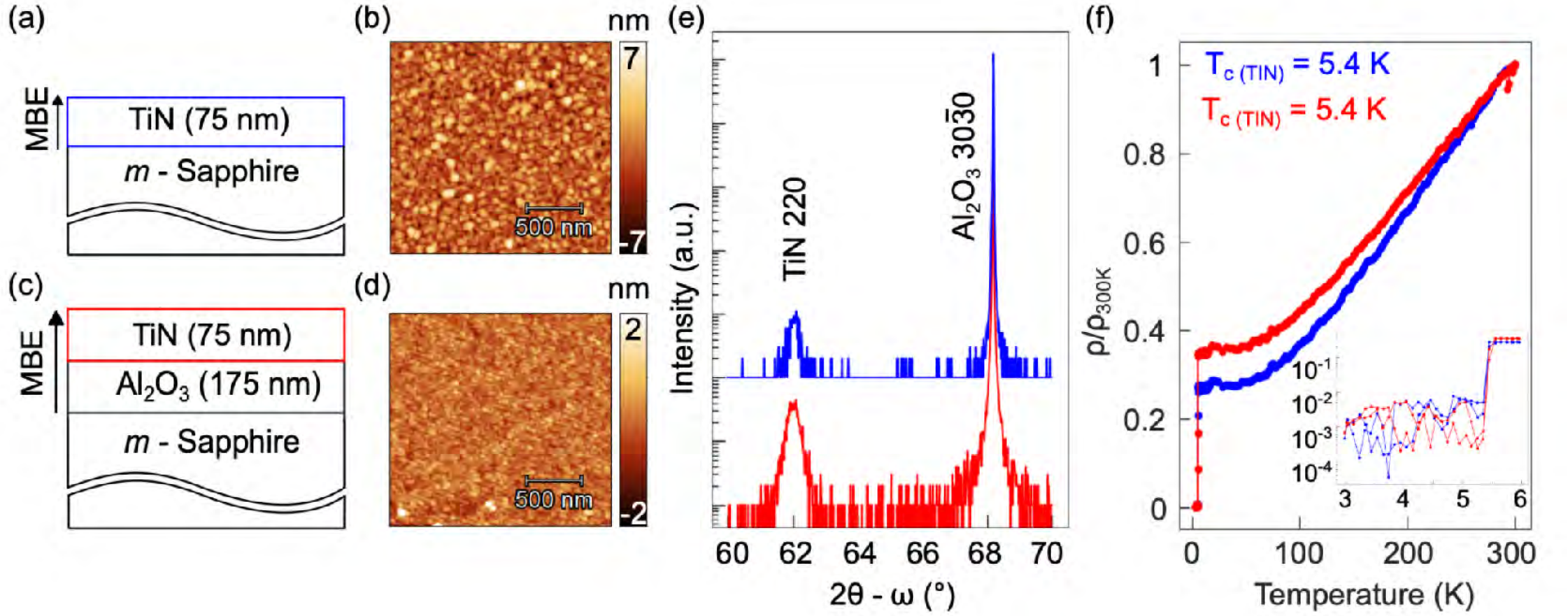
Homoepitaxial sapphire on c-plane has recently been achieved above 1300°C using laser substrate heater





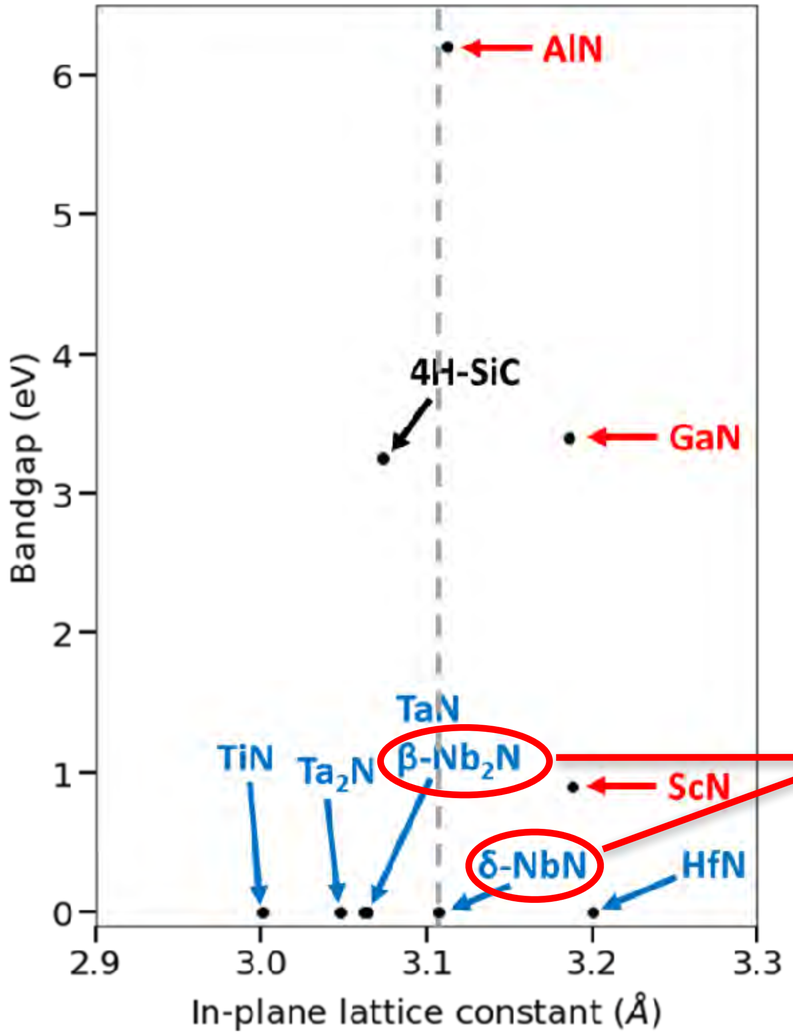
Majer et al., APL Mater. 12, 091112 (2024)

Superconductor on epitaxial sapphire

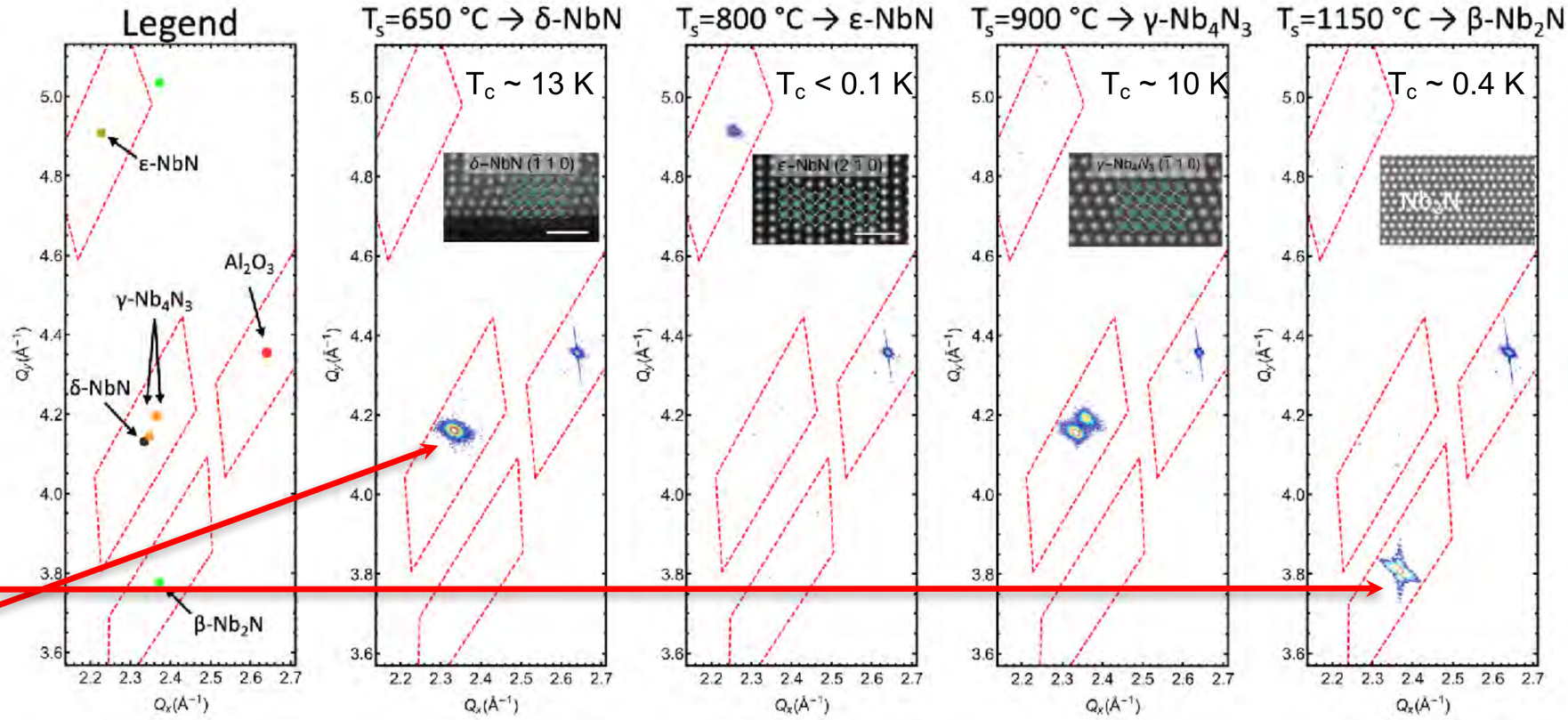


Growth and characterization of TiN on epitaxial sapphire

Epitaxial superconductors - Niobium nitride



Increasing growth temperature

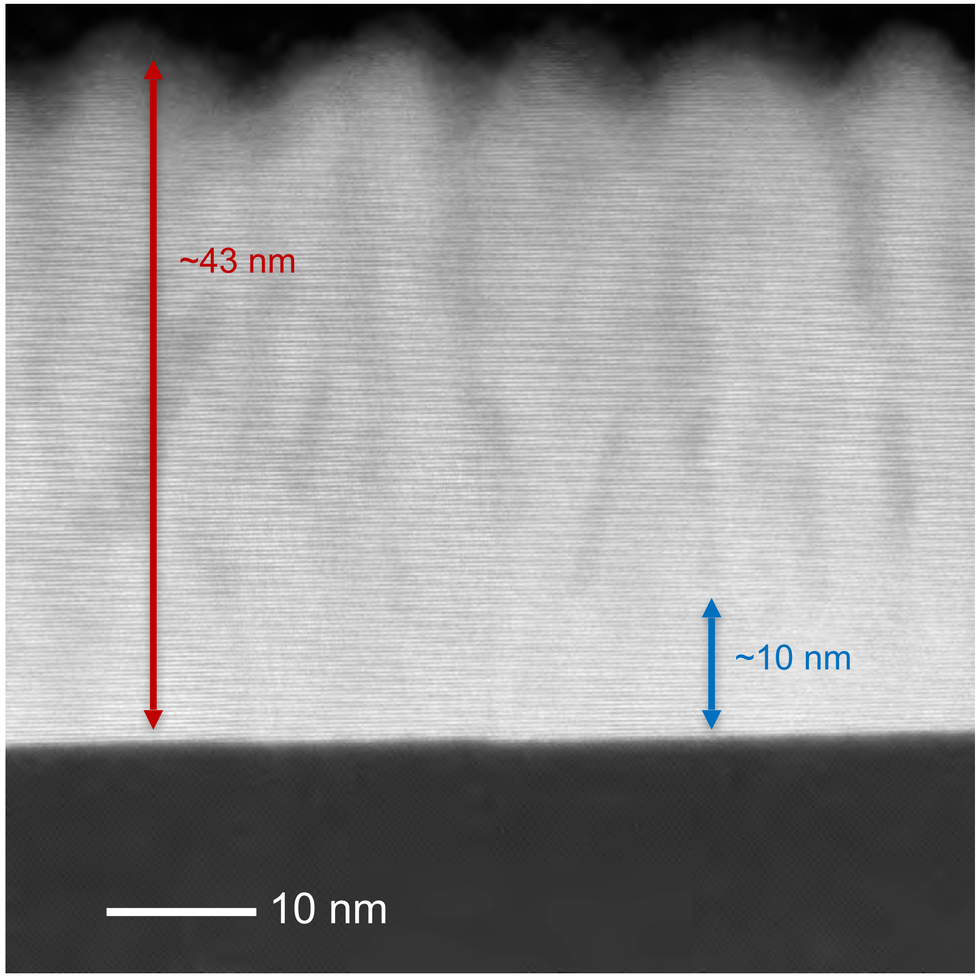


PHYSICAL REVIEW MATERIALS **7**, 074803 (2023)

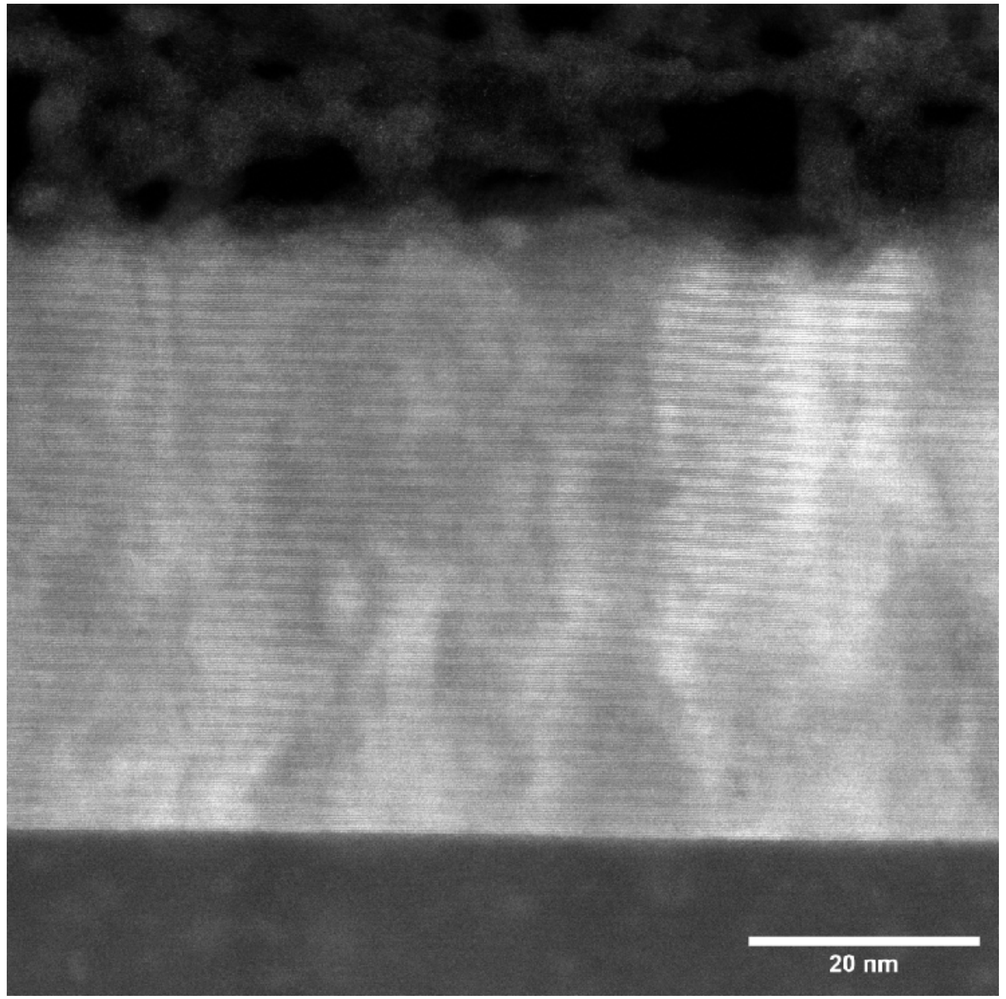
Growth windows of epitaxial NbN_x films on *c*-plane sapphire and their structural and superconducting properties

NbN and TiN share similar columnar, porous structure

NbN, $Q < 10^5$

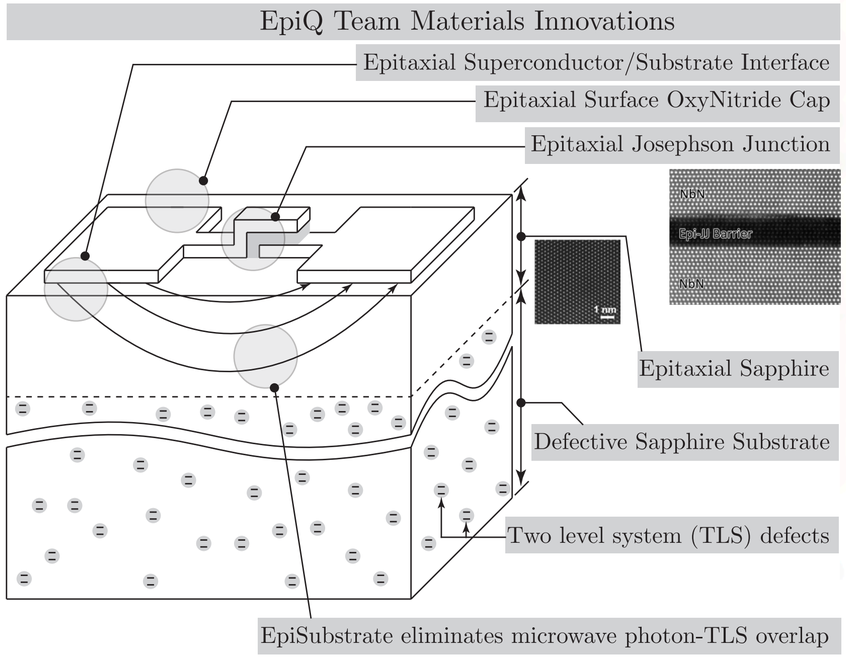


TiN , $Q \sim 10^6$



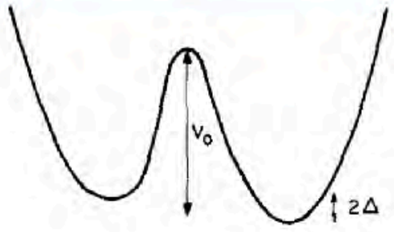
Note: 0.5 degree miscut NbN on Sapphire

Epitaxial nitride superconducting qubits



TLS loss

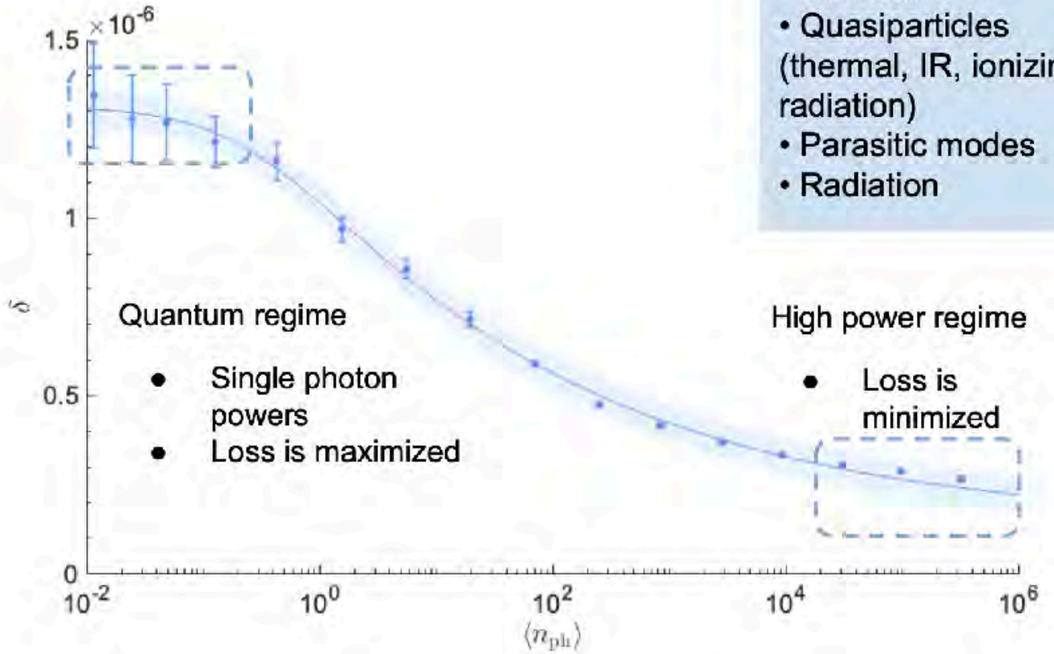
- Two-level systems (TLS)
- Dielectric loss
- Single/group of particles tunneling between two sites
- Defects, amorphous dielectrics, contaminants, impurities, lattice mismatches, etc.



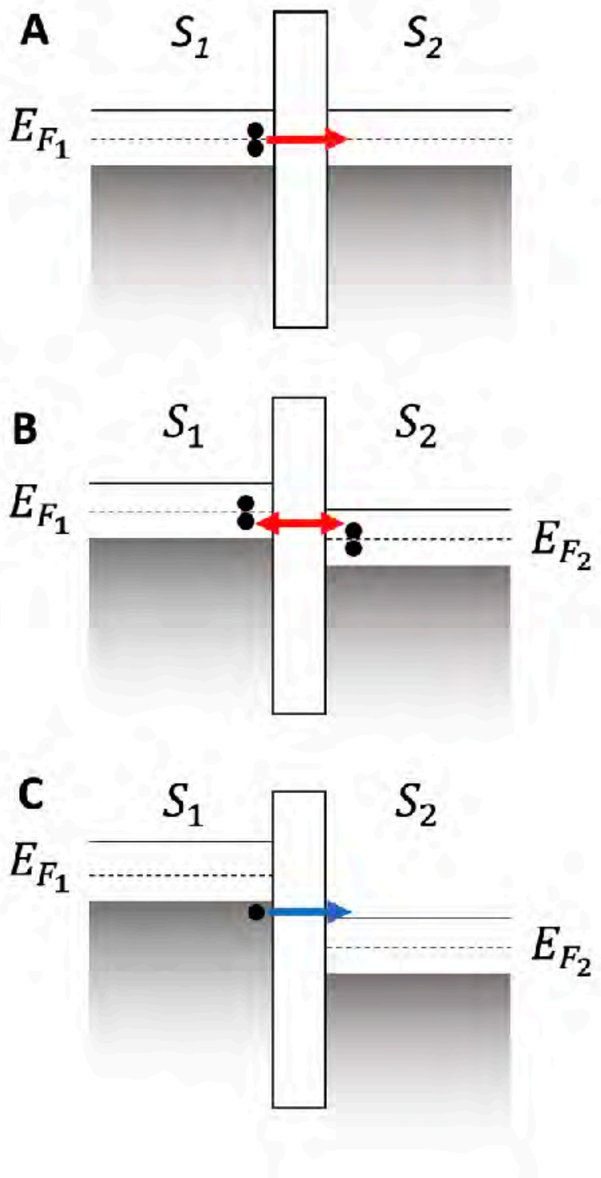
Phillips, W. A. (1972)

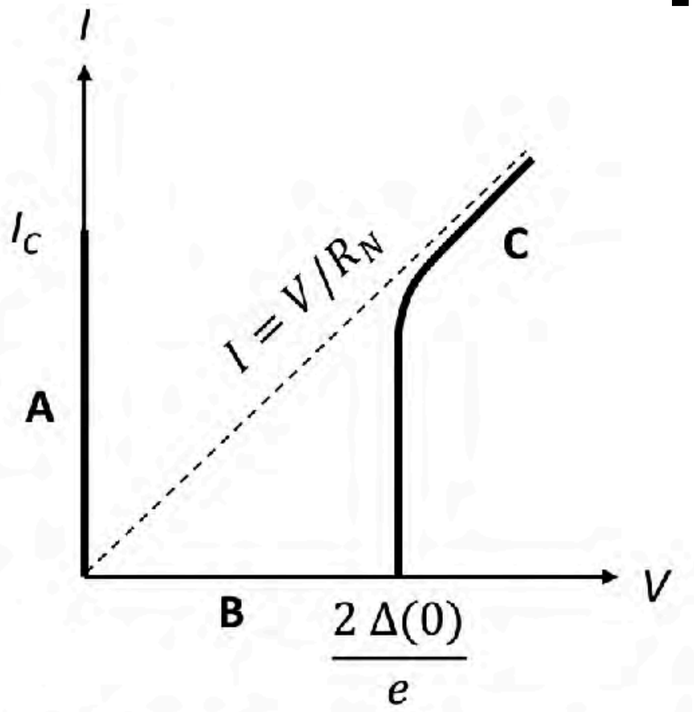
Background loss

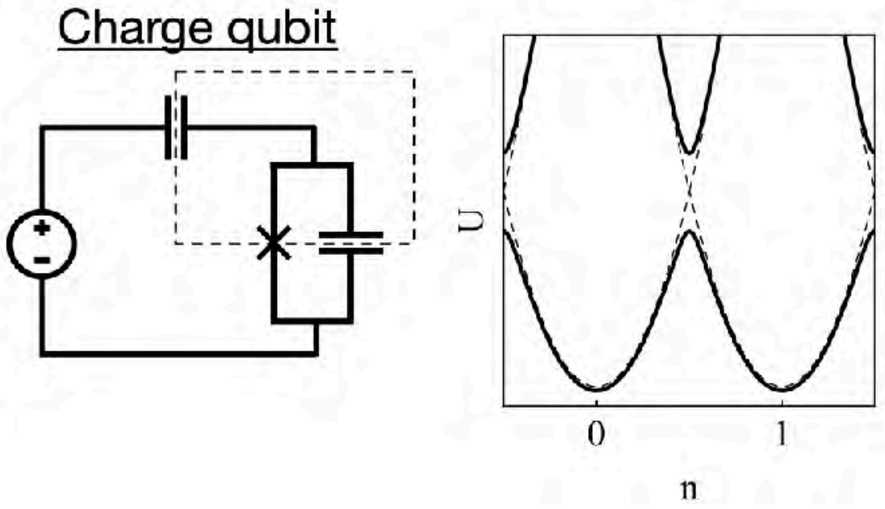
- Vortices
- Quasiparticles (thermal, IR, ionizing radiation)
- Parasitic modes
- Radiation

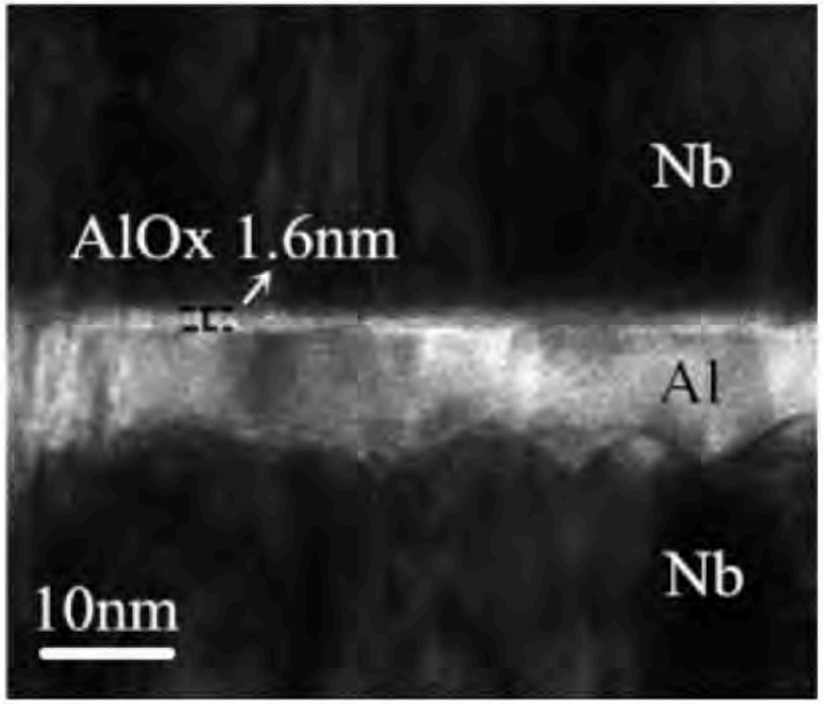


Epitaxial nitride Josephson Junctions









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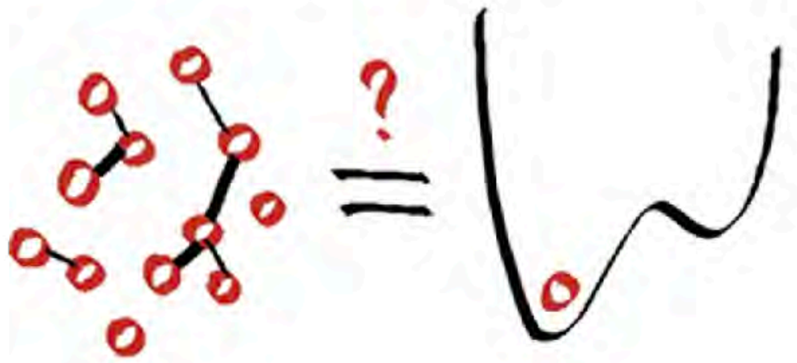

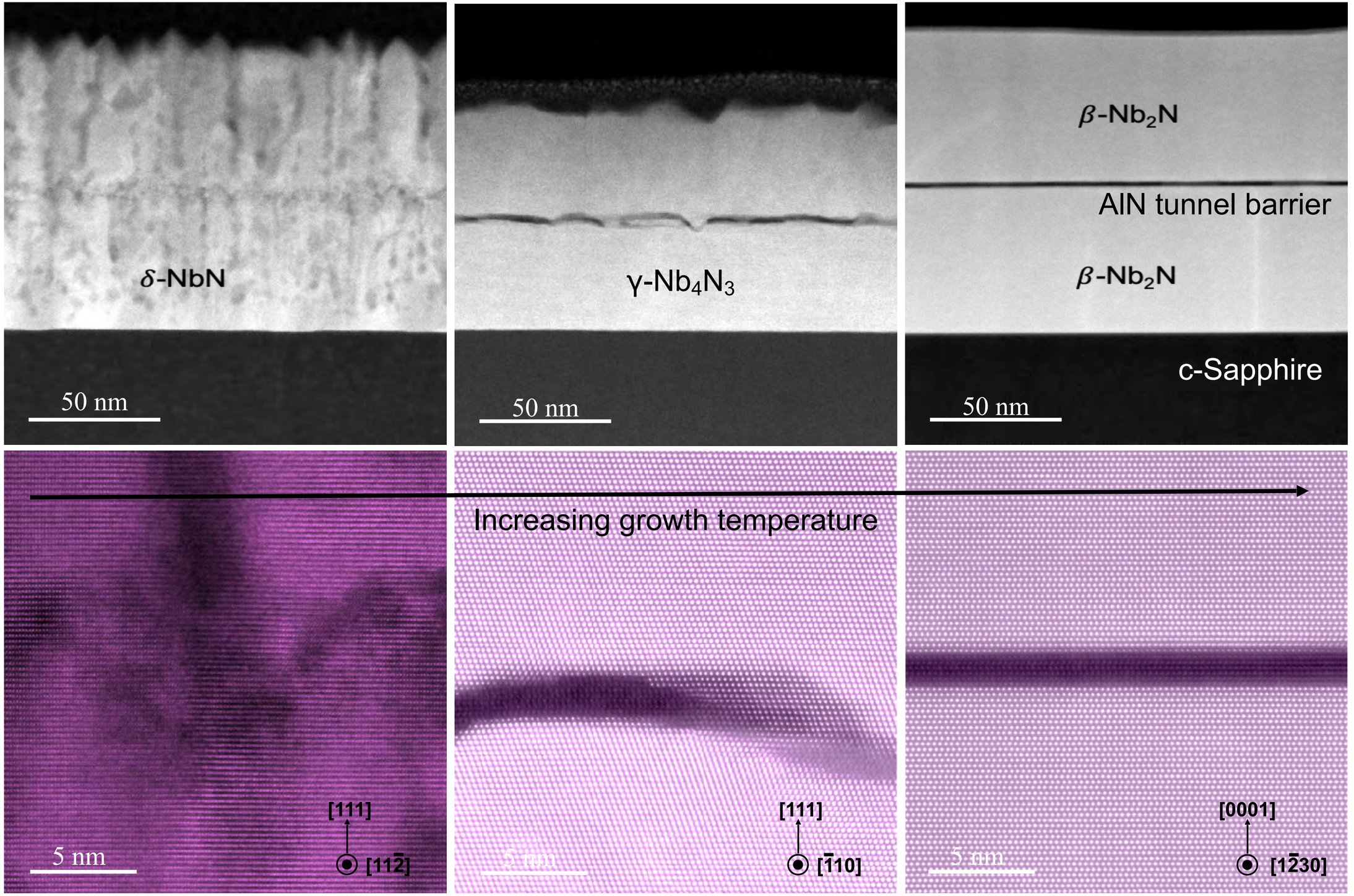
δ-NbN
50 nm
γ-Nb4N3
50 nm
β-Nb2N
AlN tunnel barrier
β-Nb2N
c-Sapphire
50 nm
Increasing growth temperature
5 nm
[111]
[11$\bar{2}$]
5 nm
[111]
[$\bar{1}$10]
5 nm
[0001]
[1$\bar{2}$30]

JJ IV temperature sweep (PPMS)