

Low-energy superconducting structure in stressed thin films and implications for quantum sensors

C. W. Fink¹

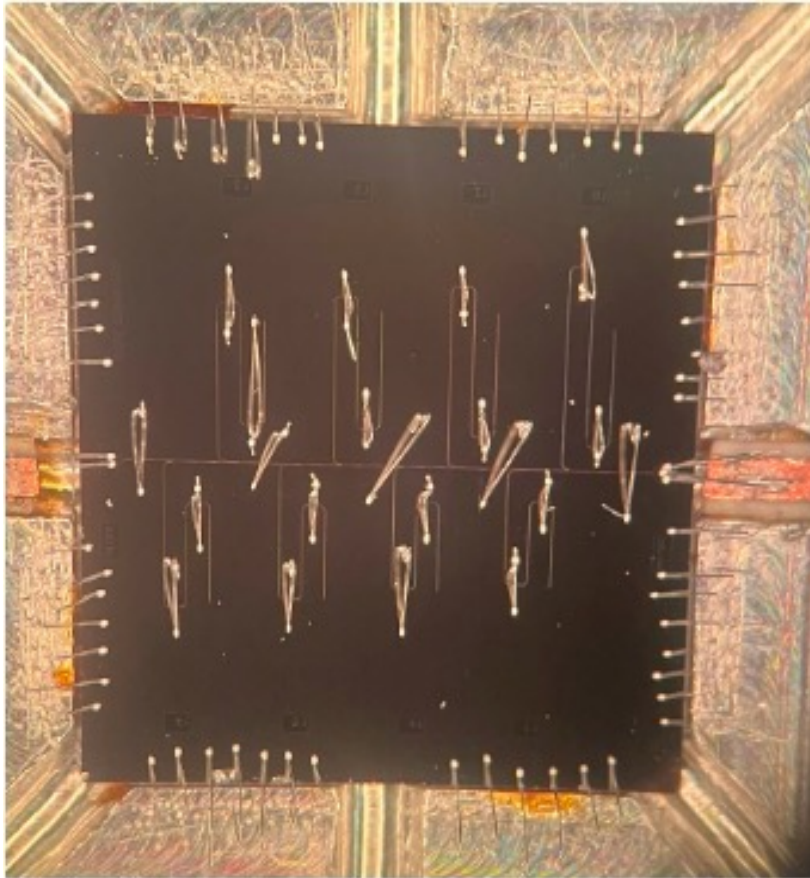
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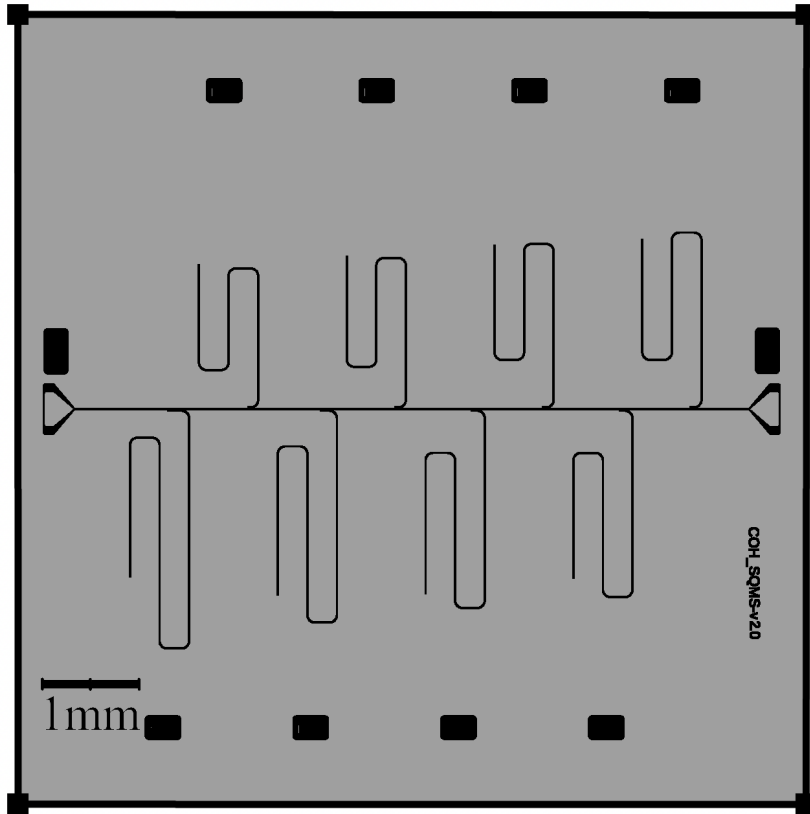
How do we know a superconducting film is good?



Superconducting devices are only as good as the films they are made from.

What should we measure to know a film is ready for a device?

Developing reliable Nb reference resonators



Evidence for a low-gap component in compressively stressed niobium thin films

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[arXiv:2609.26714](https://arxiv.org/abs/2609.26714) [quant-ph]

Goal: Develop reproducible Nb resonators for baseline reference

Approach: Five sputter recipes, identical resonator geometry, and companion wafers for materials characterization.

*note – this is about Nb, but the lessons are relevant to SC films in general

Basic transport measurements

FOUR-PROBE DC TRANSPORT, METROLOGY WAFERS

$9.0 \pm 0.2 \text{ K}$

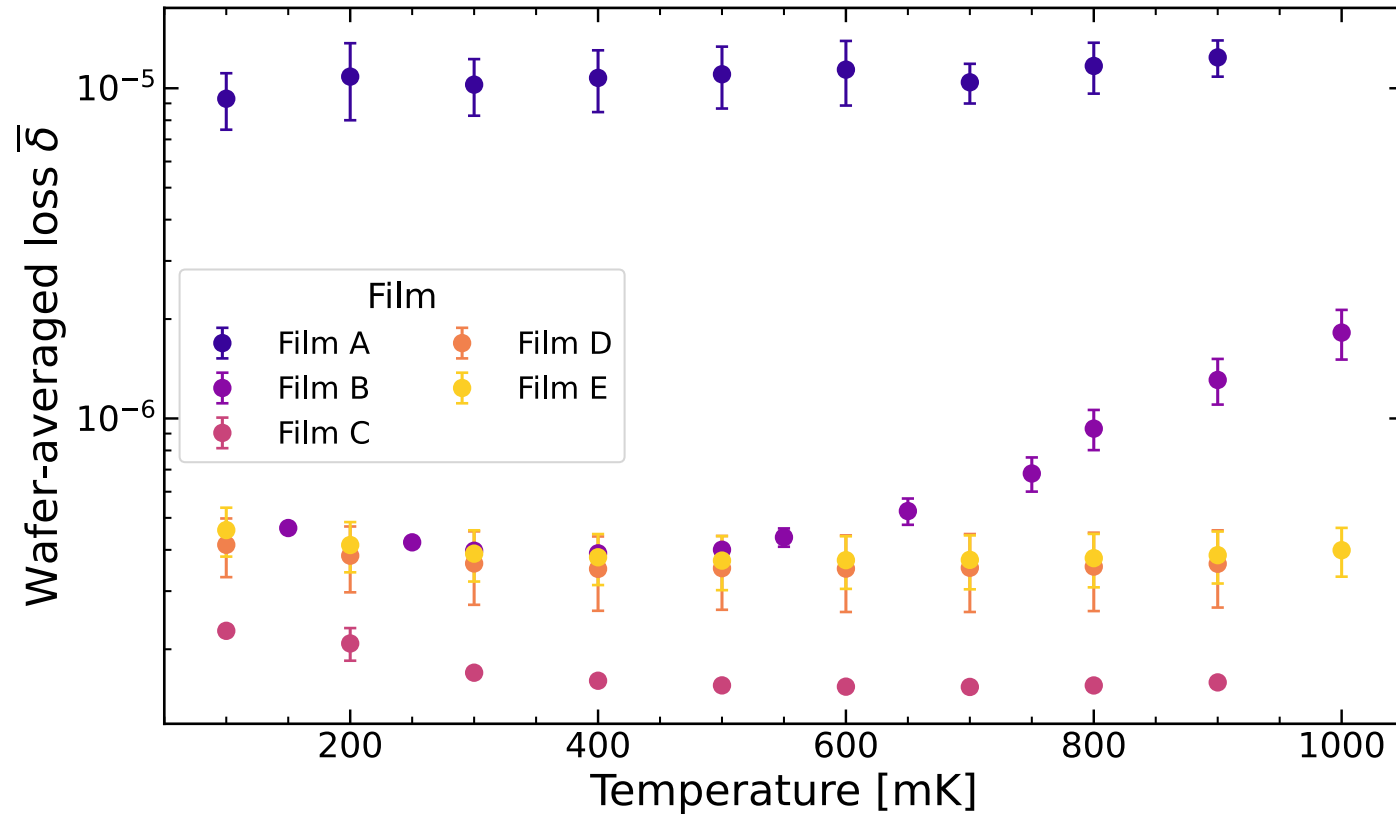
T_c across all five films, close to bulk Nb

4.0 ± 0.6

RRR across all five films

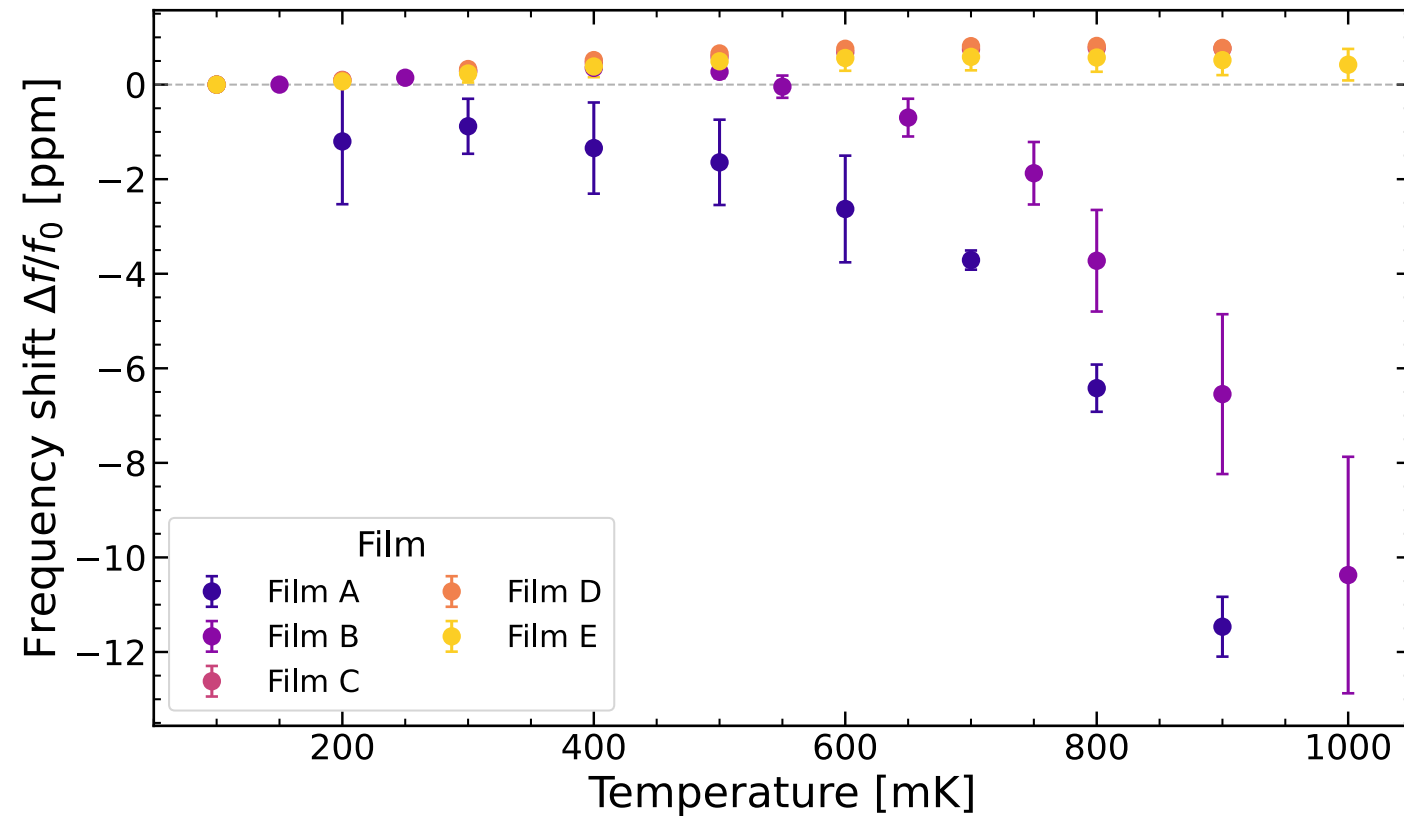
By conventional metrics, all five films would pass the same quality checks

Similar T_c and RRR conceal dramatically different microwave loss



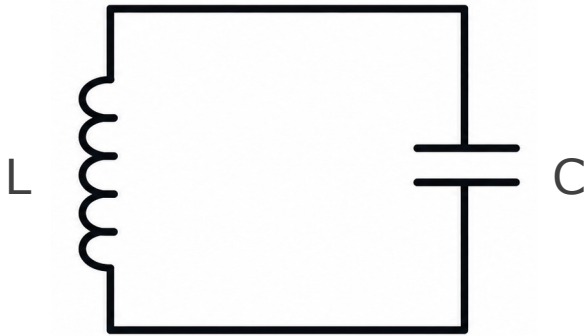
T_c and RRR alone do not predict microwave device performance

The frequency shift reveals the same anomalous electrodynamics



Both dissipative and reactive responses differ, despite similar T_c and RRR.

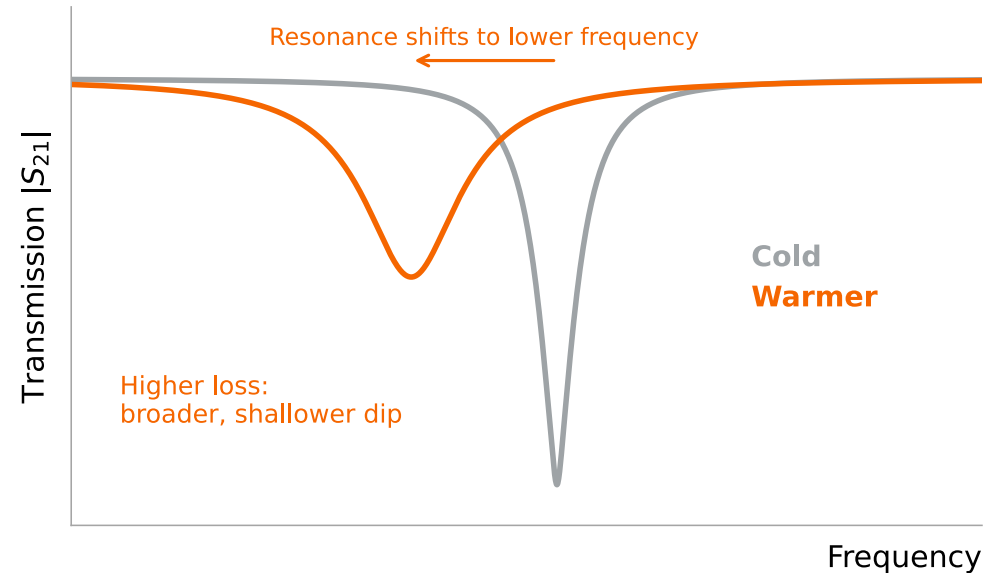
Resonator frequency and loss probe complementary material responses



Frequency shift → Reactive response

$$\frac{\Delta f}{f} \simeq -\frac{1}{2} \left(\frac{\Delta L}{L} + \frac{\Delta C}{C} \right)$$

$$\left. \frac{\Delta f}{f} \right|_{\text{SC}} \simeq \frac{\alpha}{2} \frac{\Delta \sigma_2}{\sigma_2}$$

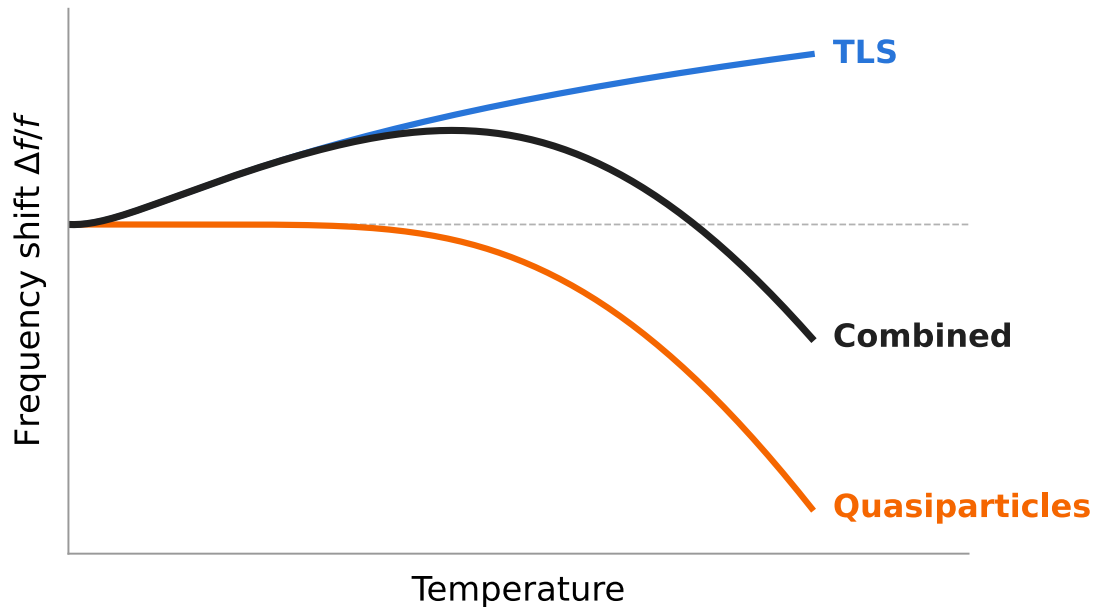


Loss → Dissipative response

$$\frac{1}{Q_i} \simeq \frac{R_{\text{eff}}}{\omega_0 L}$$

$$\frac{1}{Q_{\text{SC}}} \simeq \alpha \frac{\sigma_1}{\sigma_2}$$

Competing contributions to resonator frequency shift



Dielectric two-level systems (TLS)

$\Delta f/f \uparrow$

- Temperature-dependent dielectric susceptibility
- Typically raises the resonance frequency over this range
- Common in superconducting resonators

Superconducting quasiparticles

$\Delta f/f \downarrow$

- Thermal excitations reduce the superfluid density
- Higher kinetic inductance lowers the resonance frequency
- For conventional Nb, exponentially suppressed below 1 K

$$\frac{\Delta f(T)}{f_0} = \left(\frac{\Delta f}{f_0} \right)_{\text{TLS}} + \left(\frac{\Delta f}{f_0} \right)_{\text{QP}}$$

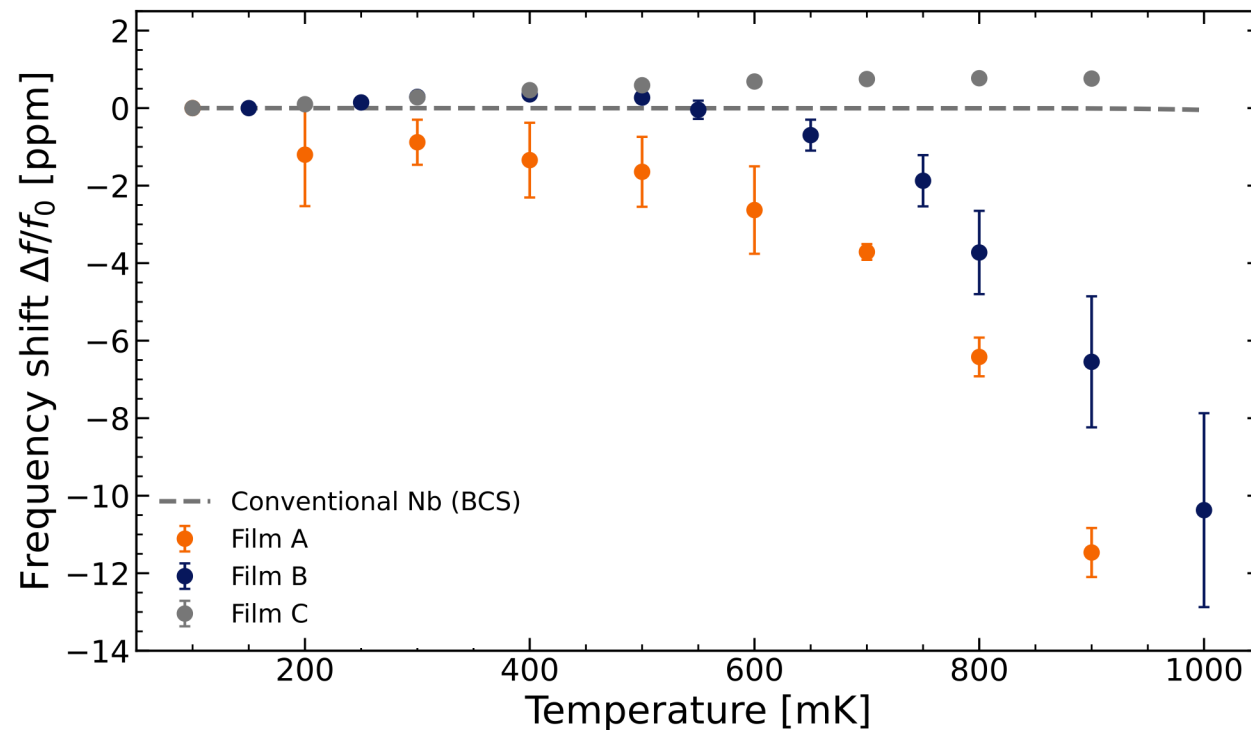
$$\left(\frac{\Delta f}{f_0} \right)_{\text{TLS}} \propto \ln T$$

$$\left| \frac{\Delta f}{f_0} \right|_{\text{QP}} \propto e^{-\Delta/k_B T}$$

Conventional Nb quasiparticles cannot explain the large negative frequency shifts below 1 K

Why is this surprising for conventional Nb?

Measured frequency shift $\Delta f/f$ vs temperature, ppm
sample average, relative to 100 mK; temperature in mK



ENERGY SCALES

$$\Delta_{\text{Nb}} \approx 1.4 \text{ meV}$$

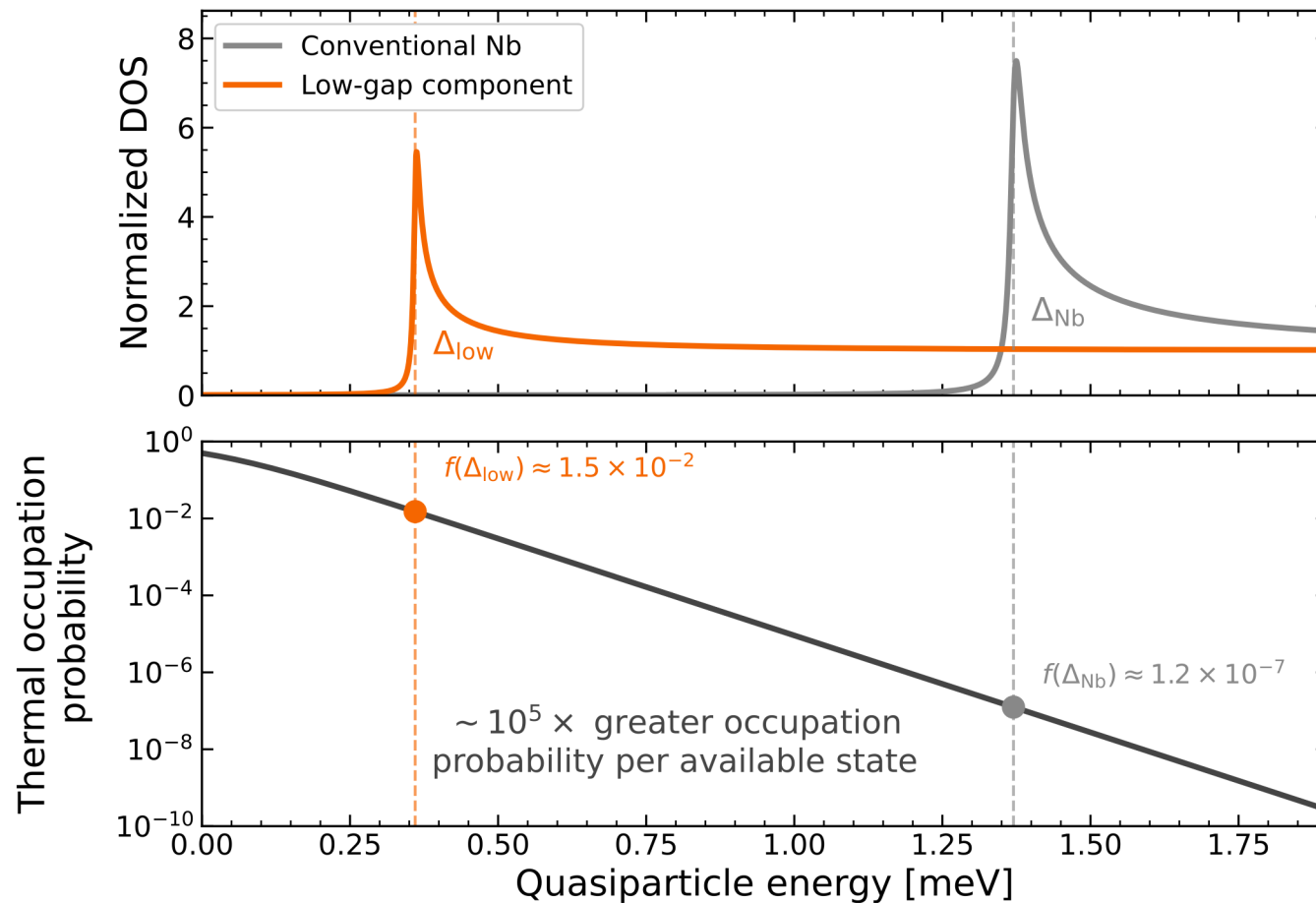
vs $k_B T \approx 0.09 \text{ meV}$ at 1 K

Thermal quasiparticles scale as $e^{-\Delta/kT}$, about 10^{-7} at 1 K.

The conventional-Nb BCS contribution should be negligible

* TLS terms are included in the analysis and do not account for the large high-temperature behavior

Possible explanation: what would a smaller gap change?

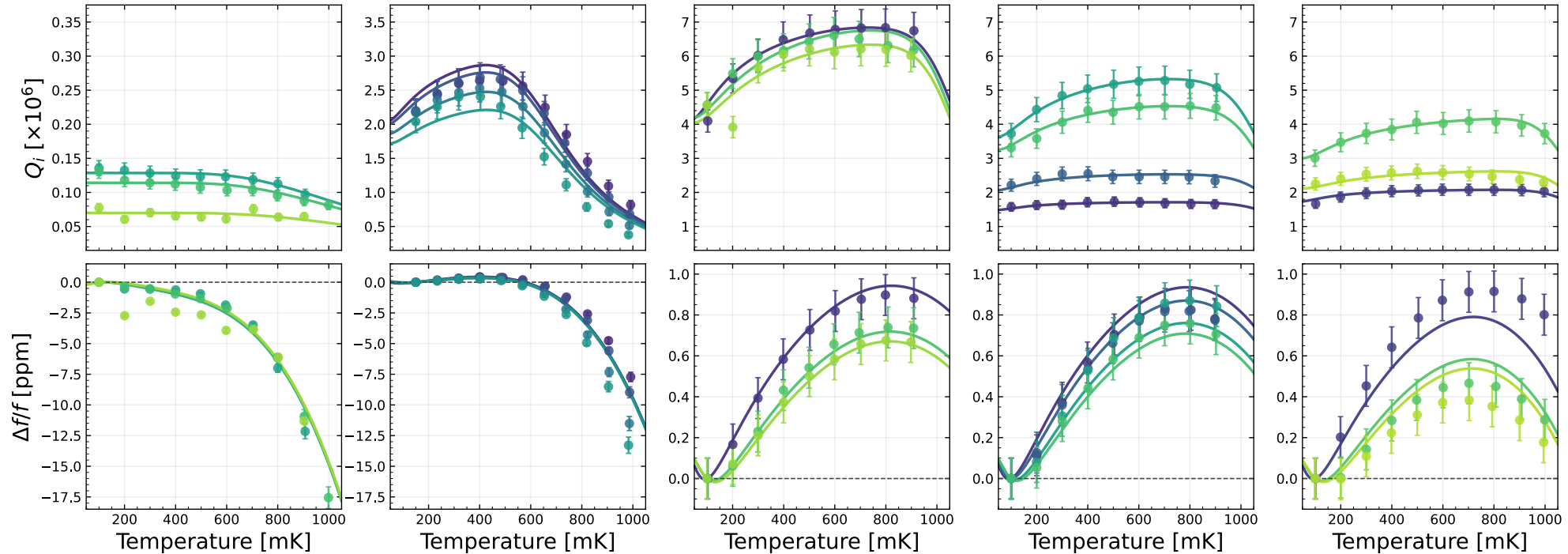


At 1 K, occupation per available state at 0.36 meV is $\sim 10^5$ times higher than at 1.37 meV.

Even a small low-gap contribution could strongly influence the thermal quasiparticle response.

*figure is only for illustrative purposes

A two-component model describes the response



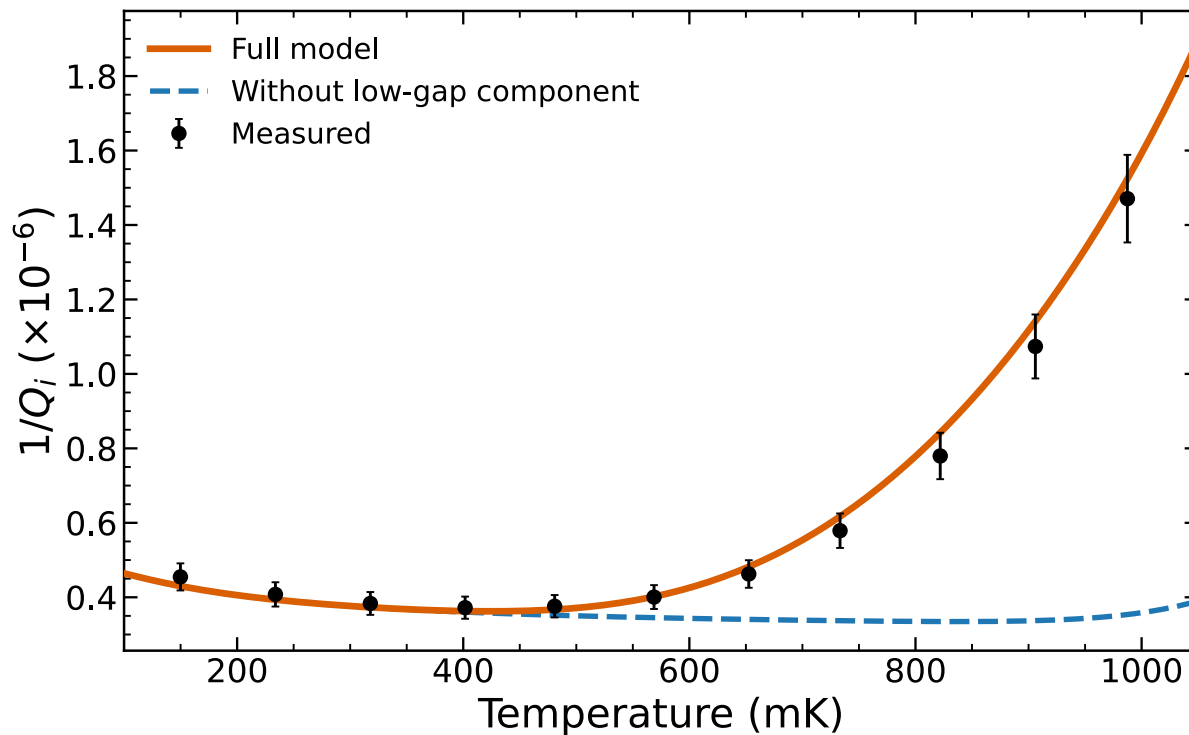
$$\frac{1}{Q_i(T)} = \delta_{\text{res}} + \delta_{\text{TLS}}(T) + \delta_{\text{Nb}}(T) + \delta_{\text{low}}(T).$$

$$\frac{\Delta f(T)}{f_0} = \Delta f_{\text{res}} + \Delta f_{\text{TLS}}(T) + \Delta f_{\text{Nb}}(T) + \Delta f_{\text{low}}(T)$$

Fit two component model to all resonators simultaneously

A two-component model describes the response

$$\frac{1}{Q_i(T)} = \delta_{\text{res}} + \delta_{\text{TLS}}(T) + \delta_{\text{Nb}}(T) + \delta_{\text{low}}(T).$$



Paustian et al., 2026, Fig. 3

- Consistent with mixture of BCC and ω -phase Nb

9.0 K

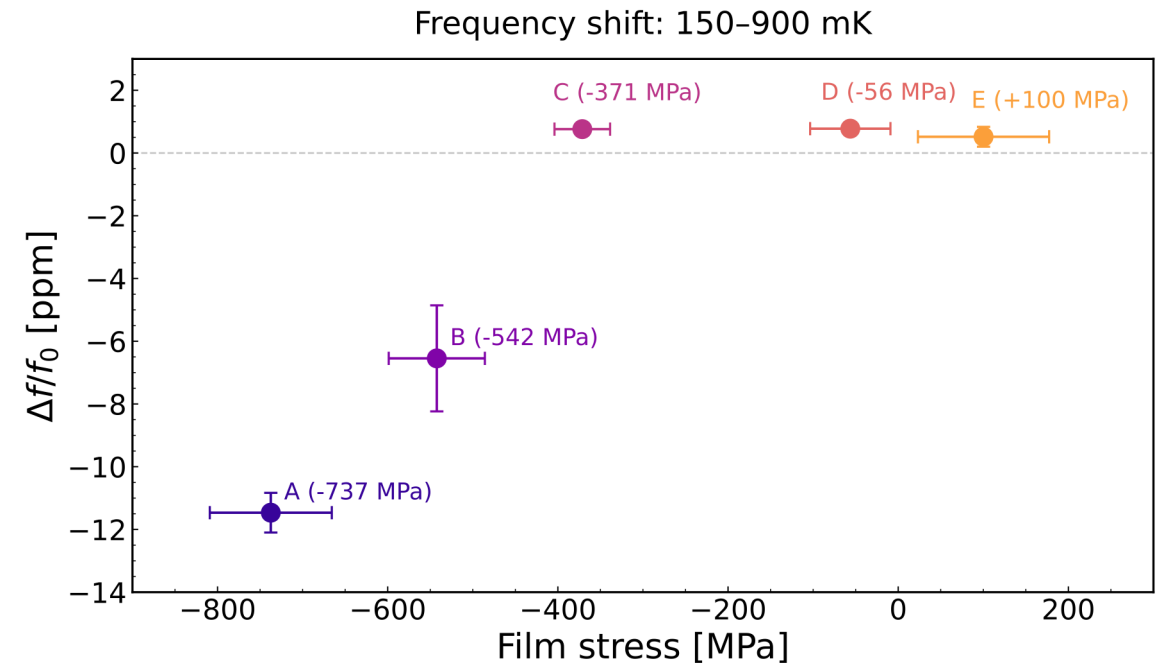
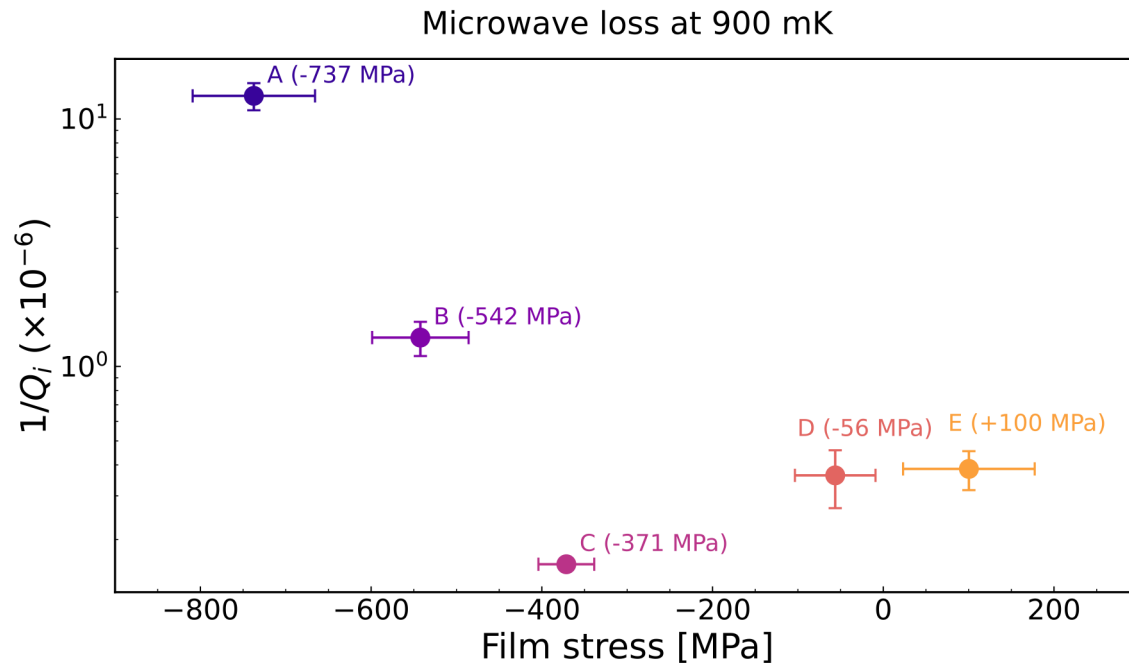
T_c from transport

2.4 ± 0.2 K

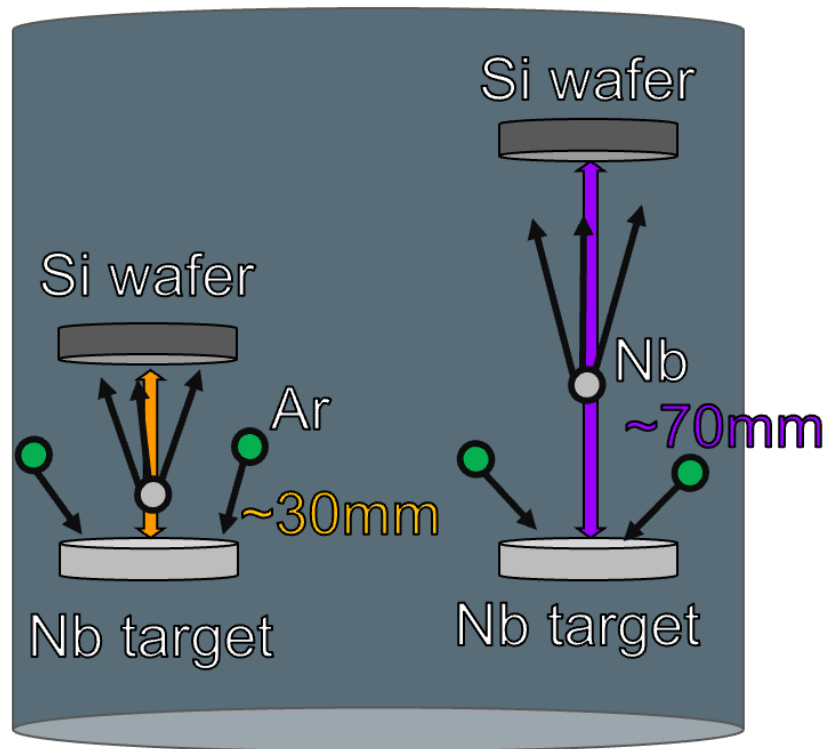
effective T_c of the added component,
from loss fits

- Low-gap contribution produces the rapid increase in loss above ~ 500 mK.
- The same effective T_c describes the frequency-shift measurements.

The strongest microwave anomalies occur in the most compressive films



How did we change the films?



Sputtering conditions: Ar pressure (2-10 mTorr) and target-to-substrate distance (~30 to 250 mm)

These set how much energy Nb atoms carry when they land, and so the as-grown film stress

Stress was not applied to finished devices. The same knobs can also change grain structure and interfaces.

Figure from J.T. Paustian

How was film stress measured?

Stylus profilometry maps the wafer before and after deposition; the film bows it

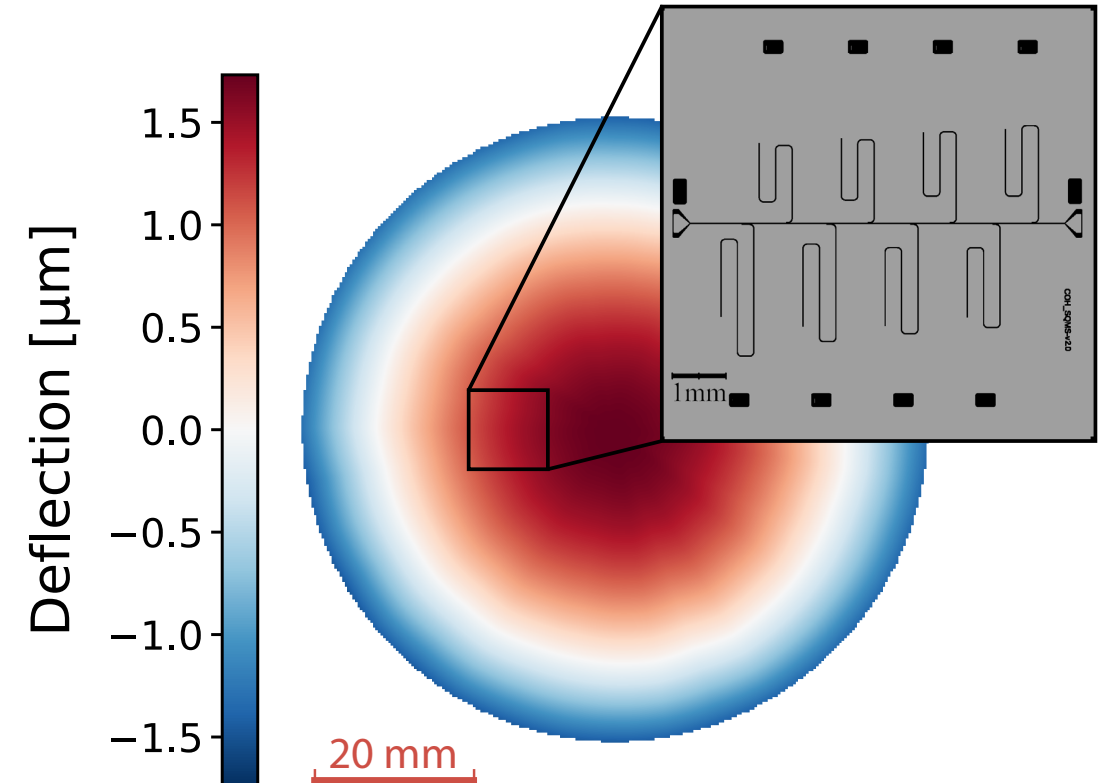


Stoney relation: $\sigma_f \propto (t_s^2 / t_f) \Delta\kappa$

t = thickness of substrate (s) and film (f); $\Delta\kappa$ = change in curvature

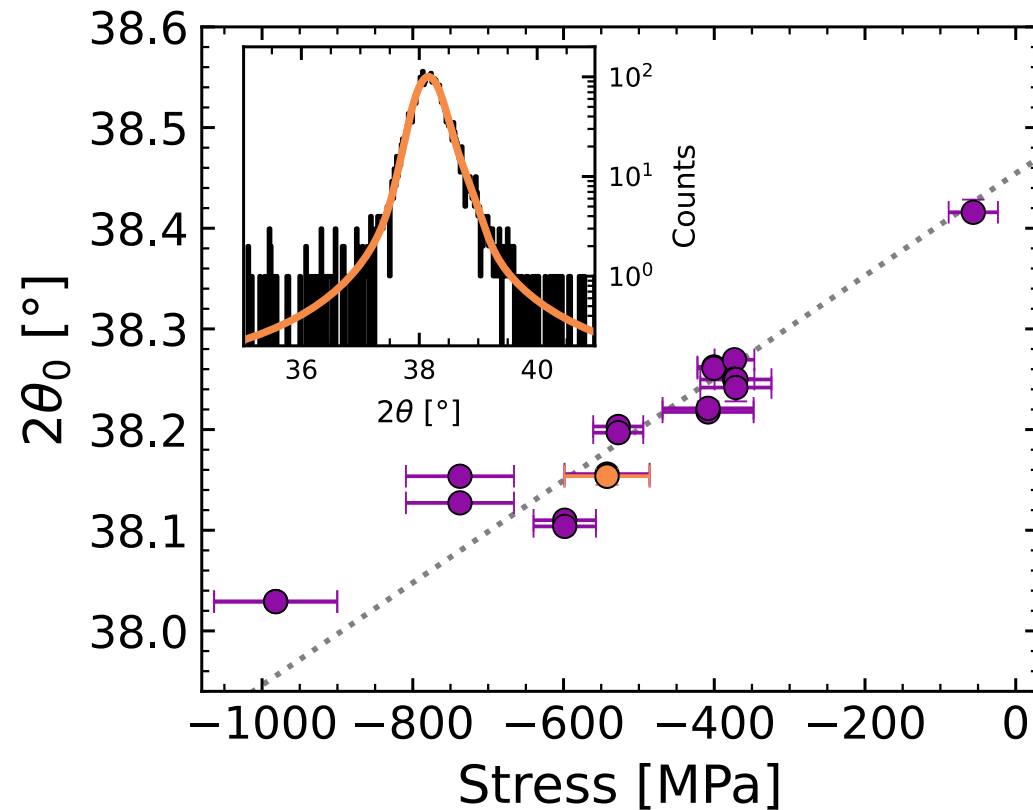
-737 to +100 MPa

measured, not assigned from the recipe; room temperature; negative = compressive



XRD shows a structural trend with stress

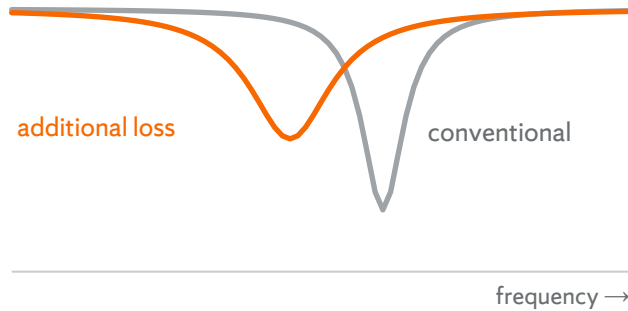
Nb(110) diffraction peak position 2θ , degrees
companion metrology wafers; ten recipes, repeat scans shown



Diffraction measures the lattice spacing.

More compressive films shift the peak to lower angle -> larger out-of-plane spacing, as expected for in-plane compression.

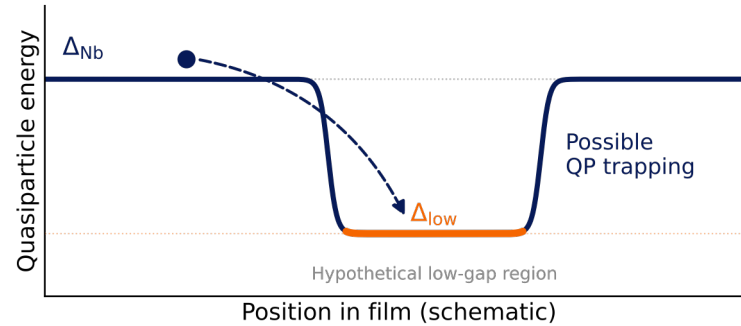
Implications for superconducting sensors



Microwave response

Low-energy excitations modify microwave loss and kinetic inductance.

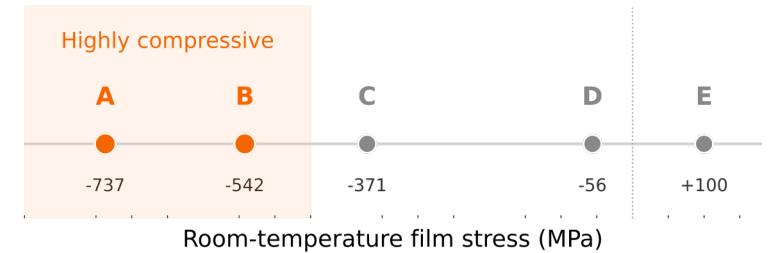
Relevant to MKIDs, resonators and superconducting readout.



Quasiparticle dynamics

Low-gap regions may alter quasiparticle populations and trapping.

Consequences for nonequilibrium backgrounds remain untested.



Detector response vs. backgrounds

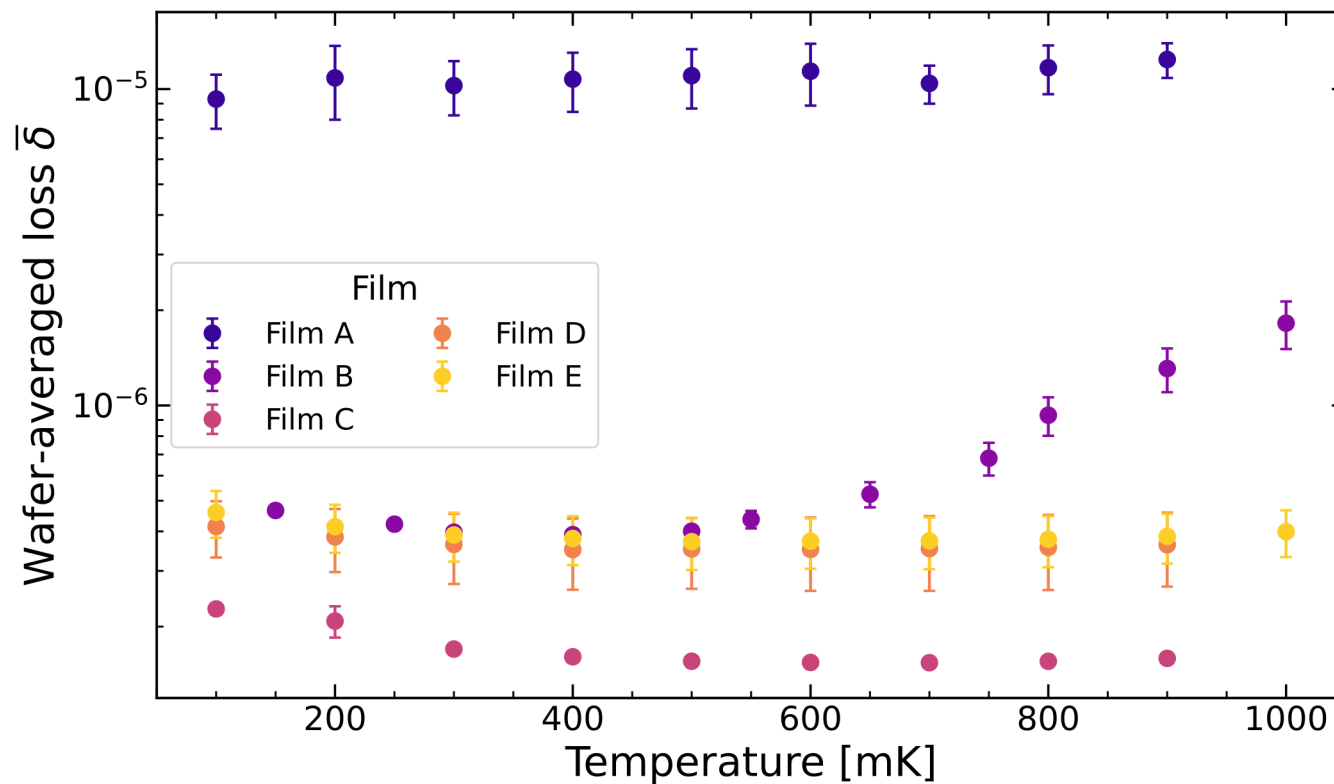
These effects must be disentangled when studying the LEE.

Controlled stress studies must account for both effects.

T_c and RRR alone cannot predict microwave device performance.

Conclusions

Five Nb films: $T_c \approx 9$ K, RRR ≈ 4

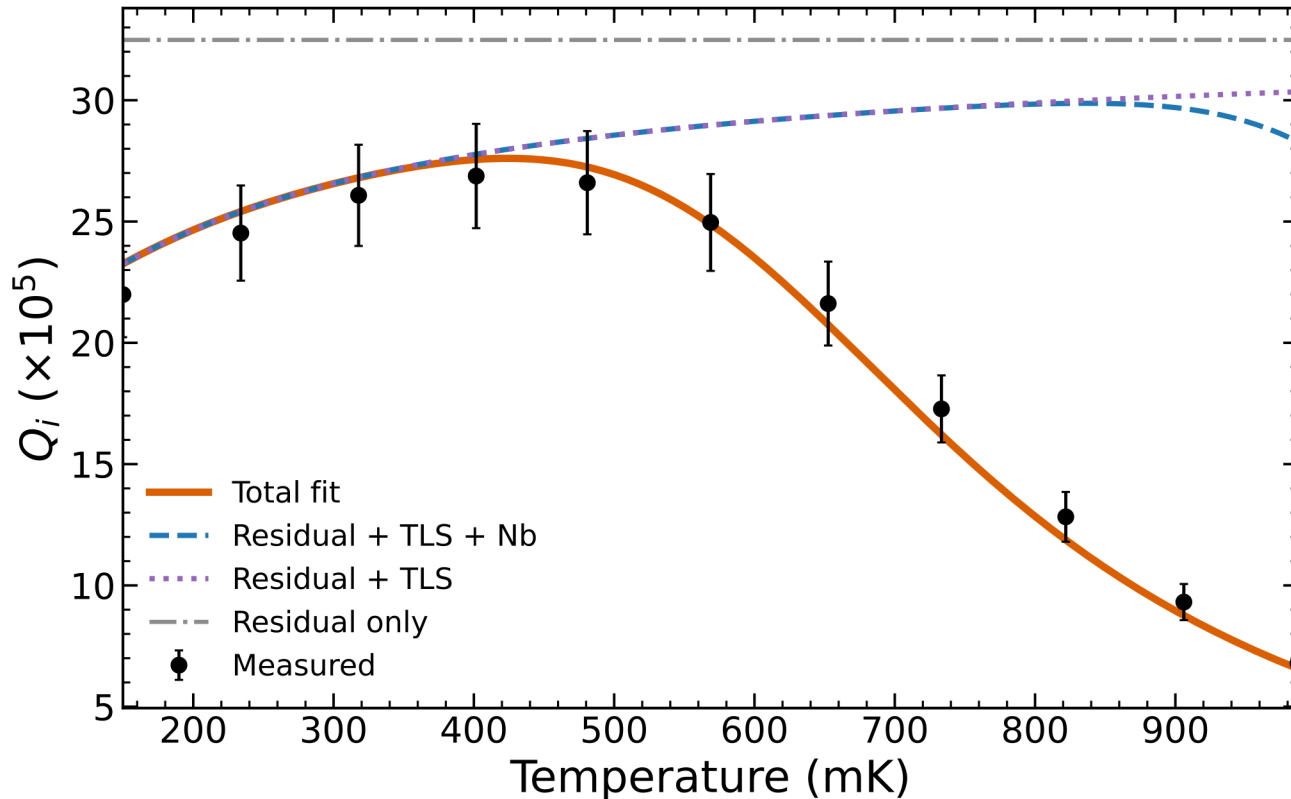


J. T. Paustian et al., "Evidence for a low-gap component in compressively stressed niobium thin films" (2026)

- T_c and RRR are insufficient to predict microwave performance.
- An additional low-energy superconducting contribution describes the anomalous response ($T_c^{\text{eff}} = 2.4 \pm 0.2$ K).
- The strongest anomalies occur in highly compressive films, motivating further studies of microstructure and quasiparticle dynamics.

Backup

A two-component model describes the response



9.0 K

T_c from transport

2.4 ± 0.2 K

effective T_c of the added component,
from loss fits

- Plot: representative loss fit; the low-gap term drives the drop above ~ 500 mK
- The same effective T_c , fixed from the loss fits, also describes the frequency-shift trends
- Its fitted contribution is about $100\times$ larger in films A and B
- Phenomenological effective low-gap component; weights are fit amplitudes, not volume fractions

Backup: two-component model and fit procedure

$$\sigma^{\text{eff}}(T, \sigma_{\text{stress}}) = [1 - p(\sigma_{\text{stress}})]\sigma^{\text{bcc}}(T) + p(\sigma_{\text{stress}})\sigma^{\text{2nd}}(T),$$

Loss

$$\frac{1}{Q_{i;s,j}(T)} = \delta_{0;s,j} + A_s^{\text{TLS}} g^{\text{TLS}}(f_{s,j}, T) + A_s^{\text{2nd}} g^{\text{QP}}(f_{s,j}, T; T_c^{\text{2nd}}),$$

$$g^{\text{TLS}}(f, T) = \tanh\left(\frac{hf}{2k_B T}\right),$$

$$g^{\text{QP}}(f, T; T_c) = \frac{\sigma_1(f, T; T_c)}{\sigma_2(f, T; T_c)}.$$

Frequency shift

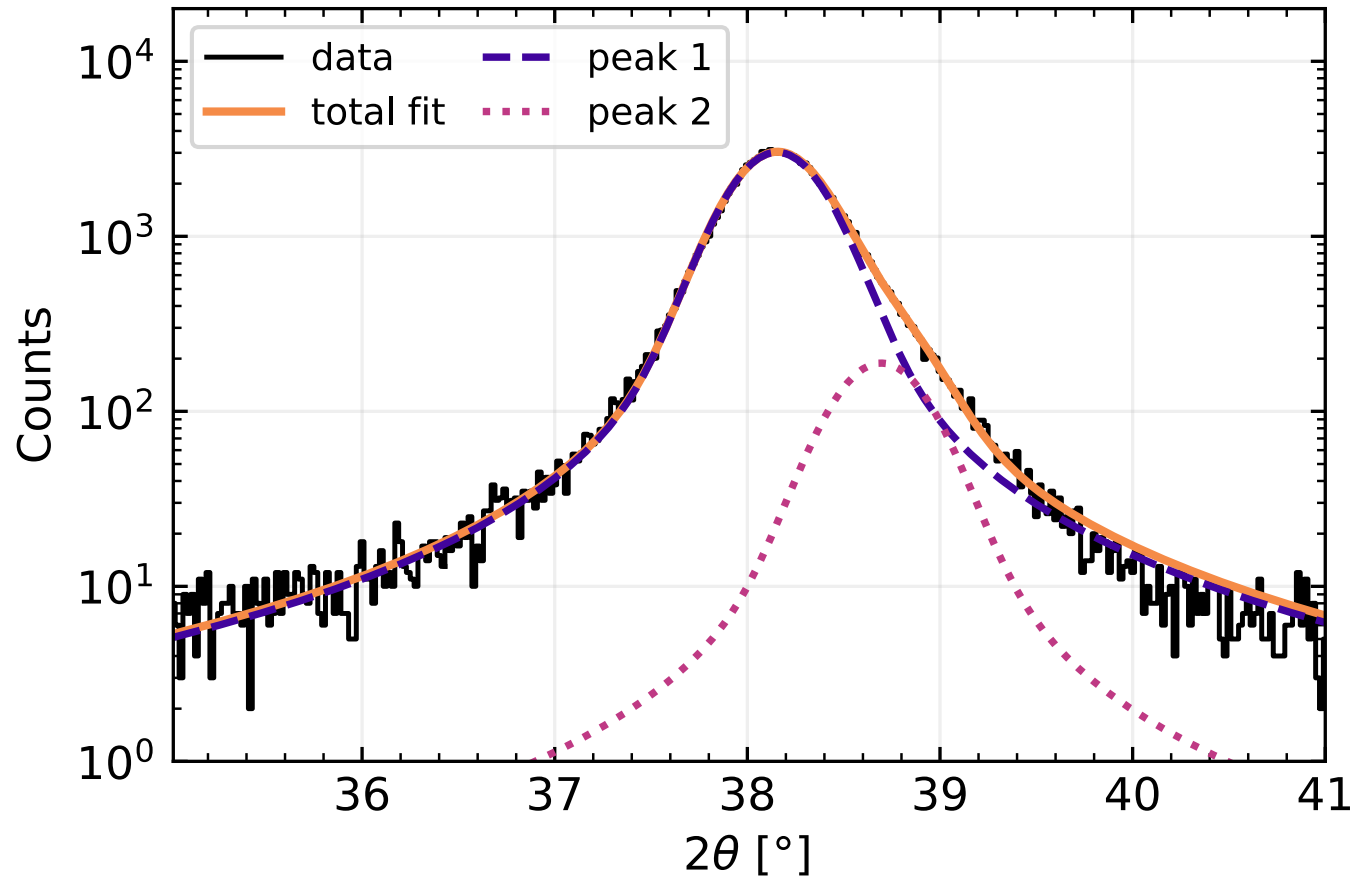
$$\frac{\Delta f_{s,j}(T)}{f_{s,j}(T_{\text{ref}})} = B_s^{\text{TLS}} \Delta h^{\text{TLS}}(f_{s,j}, T) + B_s^{\text{2nd}} k^{\text{QP}}(f_{s,j}, T; T_c^{\text{2nd}}),$$

$$\Delta h^{\text{TLS}}(f, T) = h^{\text{TLS}}(f, T) - h^{\text{TLS}}(f, T_{\text{ref}})$$

$$h^{\text{TLS}}(f, T) = \frac{1}{\pi} \left[\text{Re} \psi \left(\frac{1}{2} + \frac{hf}{2\pi i k_B T} \right) - \ln \left(\frac{hf}{2\pi k_B T} \right) \right]$$

$$k^{\text{QP}}(f, T; T_c) = \frac{1}{2} \left[\frac{\sigma_2(f, T; T_c)}{\sigma_2(f, T_{\text{ref}}; T_c)} - 1 \right].$$

Backup: XRD and candidate origin



Candidates

- ω -phase Nb: predicted $T_c \approx 2.3$ K, close to the fitted 2.4 K; a two-peak XRD fit may point to a second crystalline component
- If ω -Nb is a normal metal, the low gap could instead be proximity-induced from neighboring bcc Nb
- An inhomogeneous-gap landscape without a distinct phase

Disfavored

- Trapped vortices: cooling in 300 μ T raised low-temperature loss but left the low-gap amplitudes unchanged

TLS saturation

FIG. S6. **TLS saturation during the temperature sweeps.** (a) Average TLS saturation factor $S(\langle n \rangle) = [1 + (\langle n \rangle/n_c)^\beta]^{-1/2}$, $\beta = 0.5$, for each film in the temperature-dependent measurements. Error bars indicate the resonator-to-resonator standard deviation within each sample. Over the presented temperature range, the saturation factor remains nearly constant despite changes in resonator frequency and quality factor, indicating that the TLS power-saturation factor can be treated as approximately temperature-independent during the temperature sweeps. (b) Collapse of the normalized TLS loss measured in the power-dependent experiments onto the universal saturation functional form of Eq. (F2). Shaded bands indicate the ranges of normalized photon numbers $\langle n \rangle/n_c$ sampled for each film over the temperatures used in the fit to the model. All temperature sweeps remain within the TLS-saturated regime, where the TLS contribution is reduced to approximately 5–35% of its unsaturated value.

