Membrane materials in superconducting electromechanical circuits

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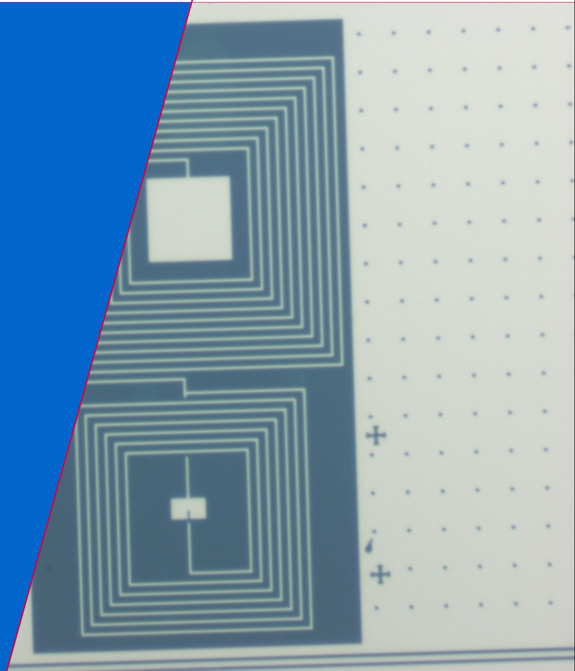


May 30, 2017

Research area and motivation

Motivation

- Study of graphene and $NbSe_2$ as membrane mechanical elements in high frequency circuits
- Manipulation of the motion of a 2D crystal with microwave photons in LC cavity
- Perform quantum-limited measurements of position
- Use relatively large zero-point motion of 2D materials for stronger coupling
- Can a superconducting 2D crystal improve performance?

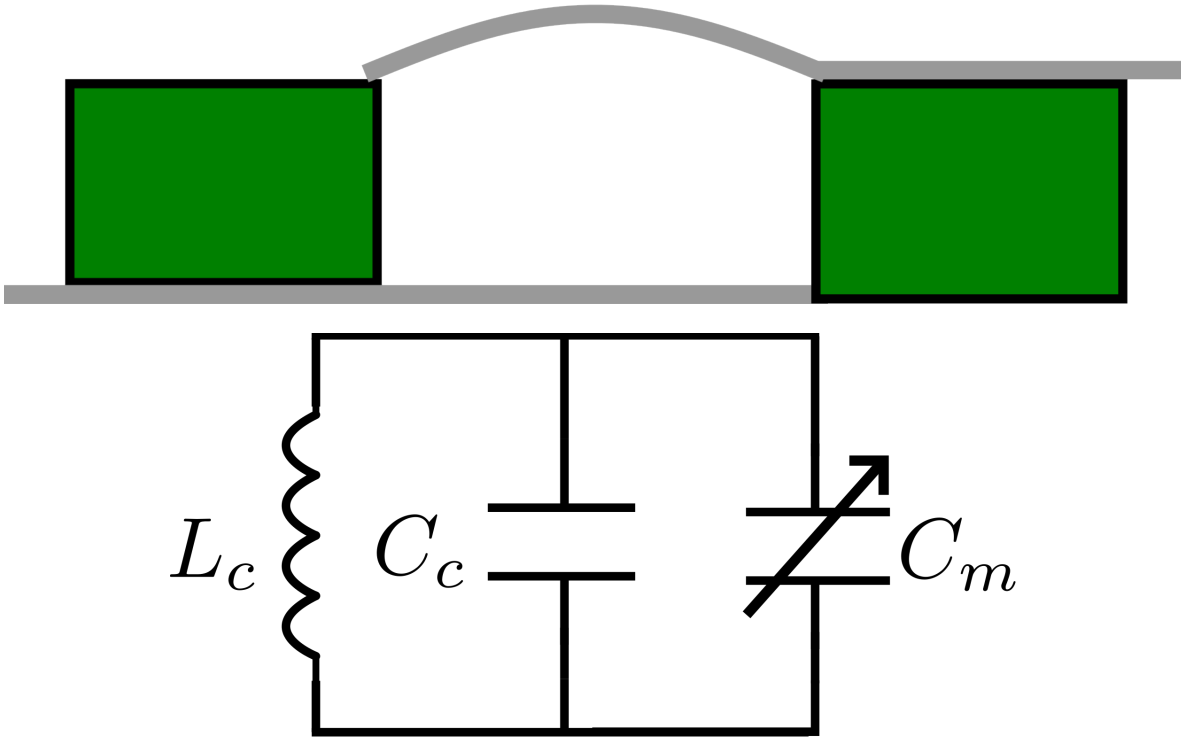
Some capabilities

- Cooling to the ground state of motion, quantum-limited position detector[a]
- Use of MEMS as bridge between microwave and optical photons[b]

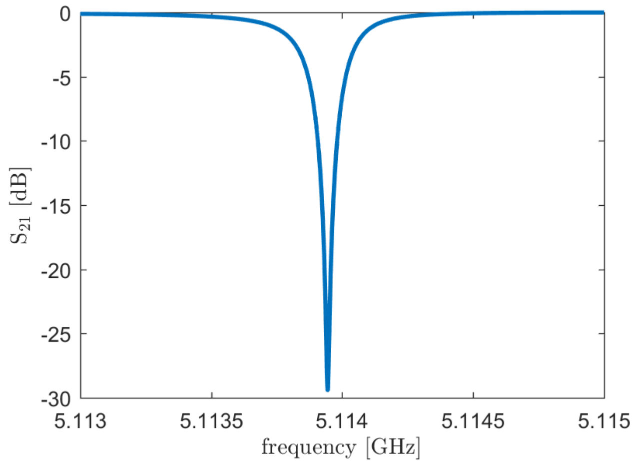
[a] J. D. Teufel et al. In: Nature (June 2011). DOI: 10.1038/nature10261.
[b] T. Bagci et al. In: Nature (2014). DOI: 10.1038/nature13029.

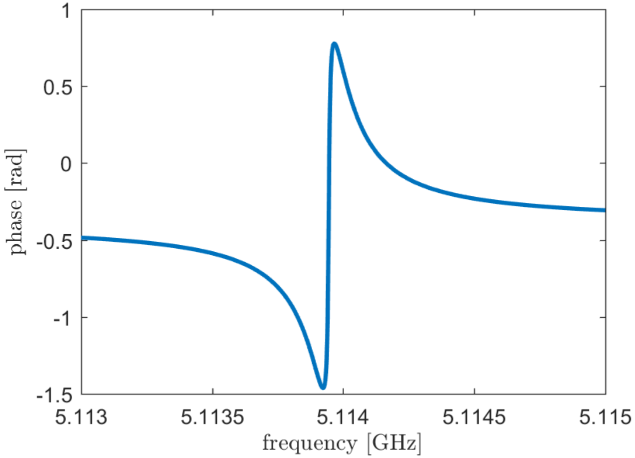
2D crystals as mechanical oscillators

- Variable capacitance measured in resonant LC circuit, with resonance frequency $\omega_c = \frac{1}{\sqrt{L(C+C_m)}}$

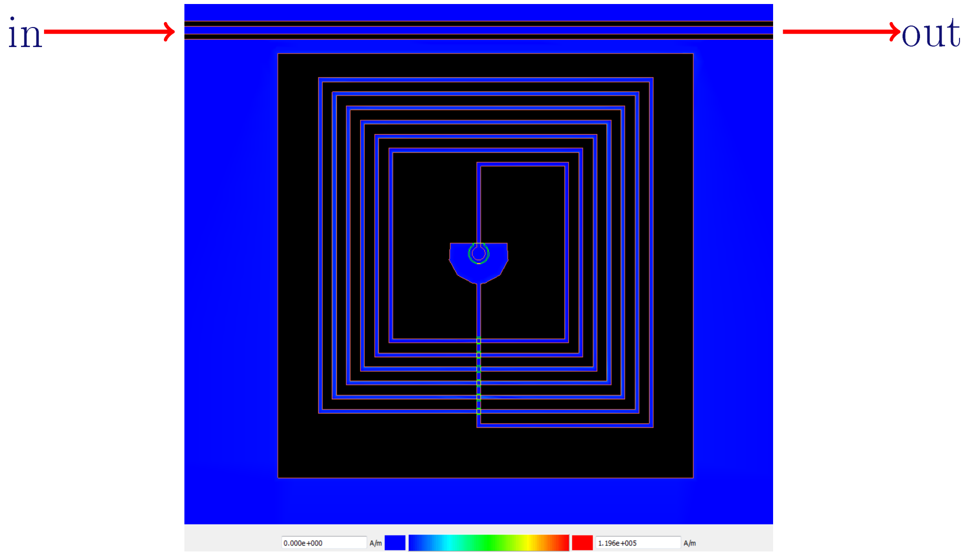


Superconducting microwave resonators





Simulation of suface current density (colour scale) at 5.11 GHz



Quantum mechanical picture

Undriven Hamiltonian

$$\hat{H} = \hbar\omega_c(\hat{x})\hat{a}^\dagger\hat{a} + \hbar\omega_m\hat{b}^\dagger\hat{b}$$

$$\hat{H} = \hbar\left(\omega_c(0) + \frac{\partial\omega_c}{\partial x}\hat{x} + \frac{1}{2}\frac{\partial^2\omega_c}{\partial x^2}\hat{x}^2 + \cdots\right)\hat{a}^\dagger\hat{a} + \hbar\omega_m\hat{b}^\dagger\hat{b}$$

$$\hat{H} \approx \hbar\omega_c\hat{a}^\dagger\hat{a} + \hbar\omega_m\hat{b}^\dagger\hat{b} + \hbar\frac{\partial\omega_c}{\partial x}x_{zp}\left(\hat{b}^\dagger + \hat{b}\right)\hat{a}^\dagger\hat{a}$$

Coupling can be increased by an increase in the zero point motion:

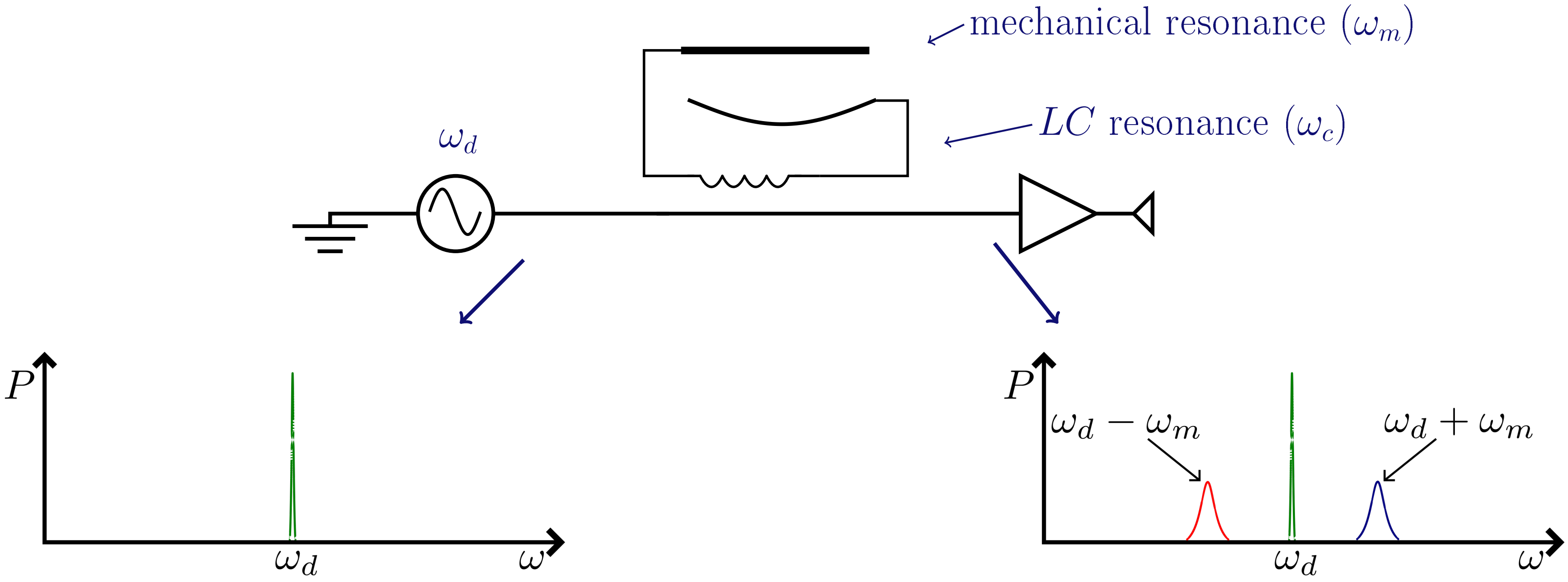
- Coupling rate: $g = x_{zp}\partial\omega_c/\partial x$
- $\omega_c = \frac{1}{\sqrt{LC(x)}}$ and $x_{zp} = \sqrt{\frac{\hbar}{2m\omega_m}}$
- For 10 MHz $NbSe_2$ resonator (10 layers), estimated $g/2\pi \approx 280$ Hz
- For a single layer, estimated $g/2\pi \approx 880$ Hz
- Similar to graphene electromechanical resonator results[a,b]

[a] X. Song et al. In: Physical Review Letters (2014). DOI: 10.1103/PhysRevLett.113.027404.

[b] V. Singh et al. In: Nature Nanotechnology (2014). DOI: 10.1038/NNANO.2014.168.

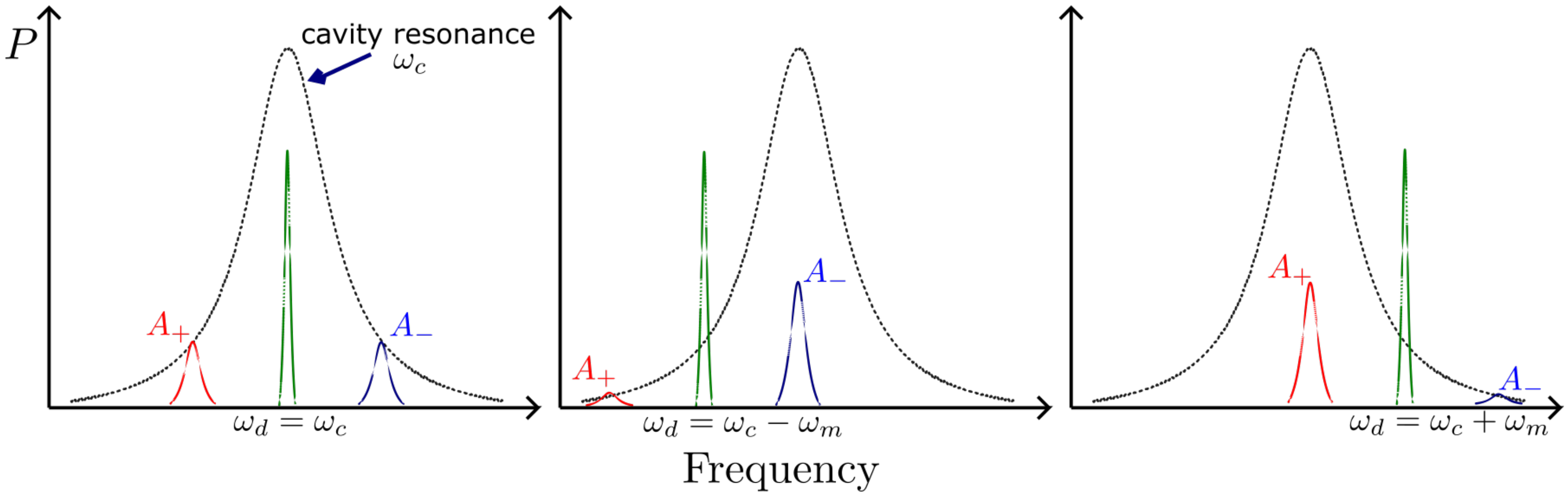
Measuring and manipulating

Imprint of motion on drive tone at ω_d

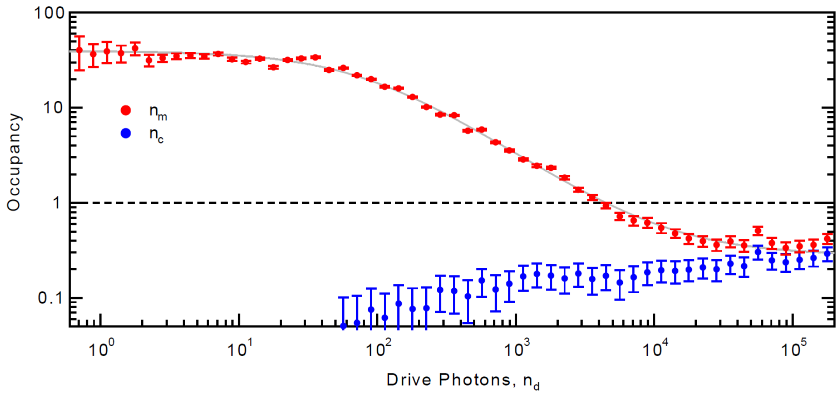


$$P_{out}(\omega_c) = 2P_{in}\left\langle x^2\right\rangle \frac{\kappa_{ext}^2}{\kappa^2 + 4\left(\omega_c - \omega_d\right)^2}\left(\frac{1}{\kappa}\frac{\partial \omega_c}{\partial x}\right)^2$$

Sideband scattering and detuning



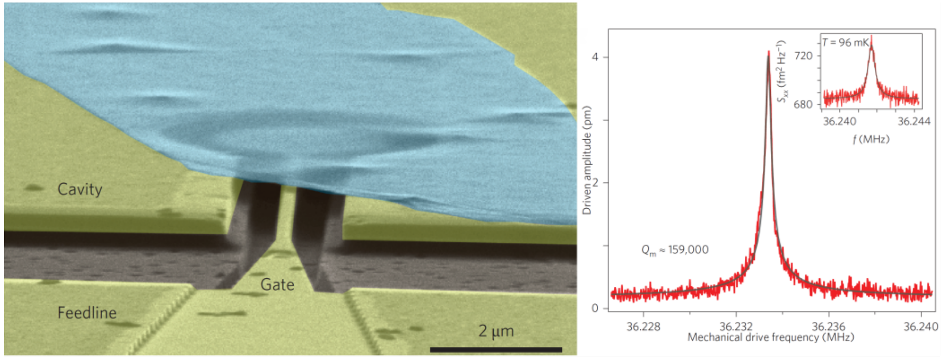
- Scattering rates equal with no detuning[a]
- Scattering preferential to A_- with red detuning
- Scattering preferential to A_+ with blue detuning
- Demonstrated by Teufel et al. with Al resonator[b]

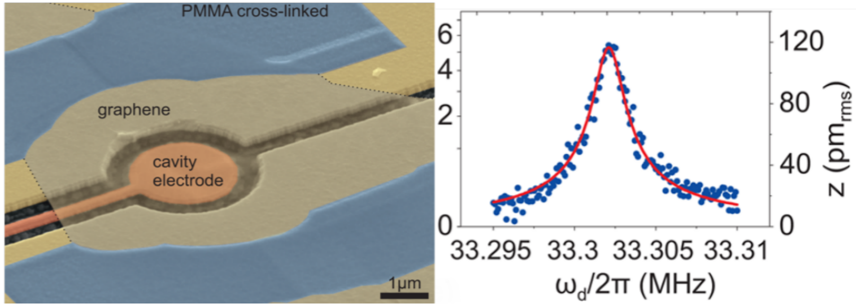


[a]Simon Gröblacher. PhD thesis. University of Vienna, 2012.
[b]J. D. Teufel et al. In: Nature (June 2011). DOI: 10.1038/nature10261.

Graphene in microwave resonators

- Work has been done integrating graphene with microwave resonators[a,b]
- In the sideband-resolved regime
- A large limitation is resistance in graphene relative to superconductor



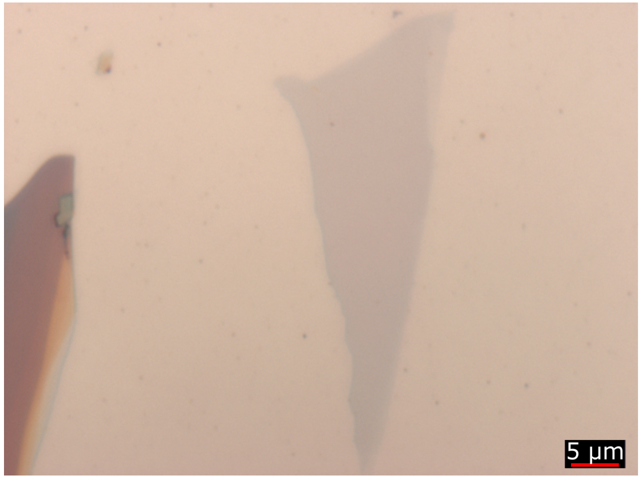


[a]V. Singh et al. In: Nature Nanotechnology (2014). DOI: 10.1038/NNANO.2014.168.
[b]P. Weber et al. In: Nano Letters (2014). DOI: 10.1021/nl500879k.

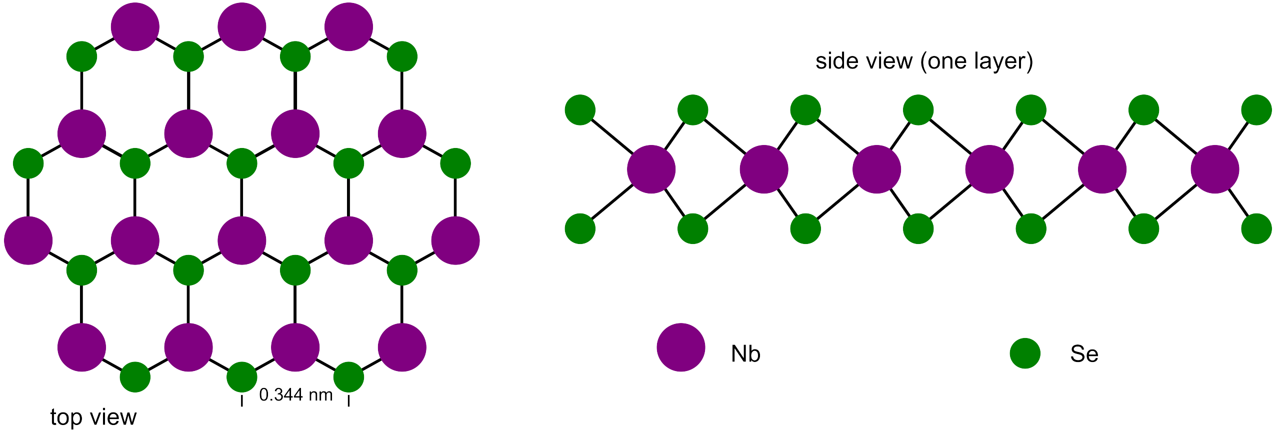
2D crystal materials

2D crystal materials are compatible with a parallel plate geometry

- Graphene, $NbSe_2$, BSCCO (among others)
- Must be conducting, with low resistivity
- Thin nature allows for rich non-linear response

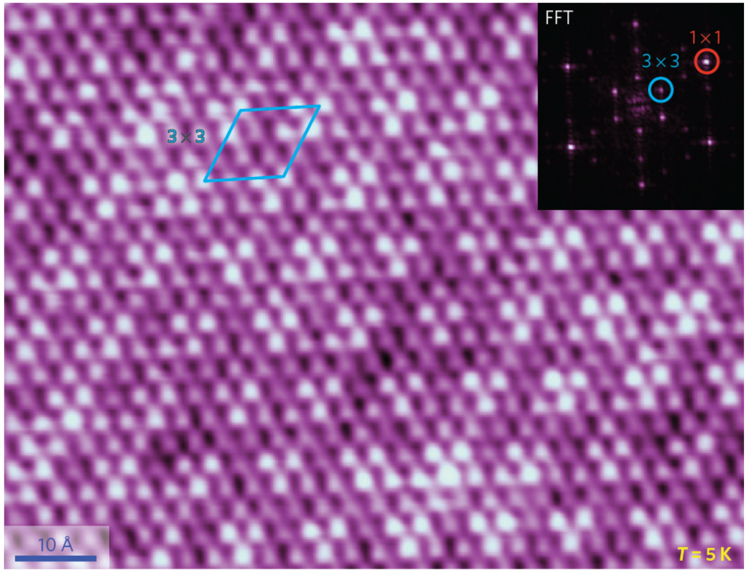


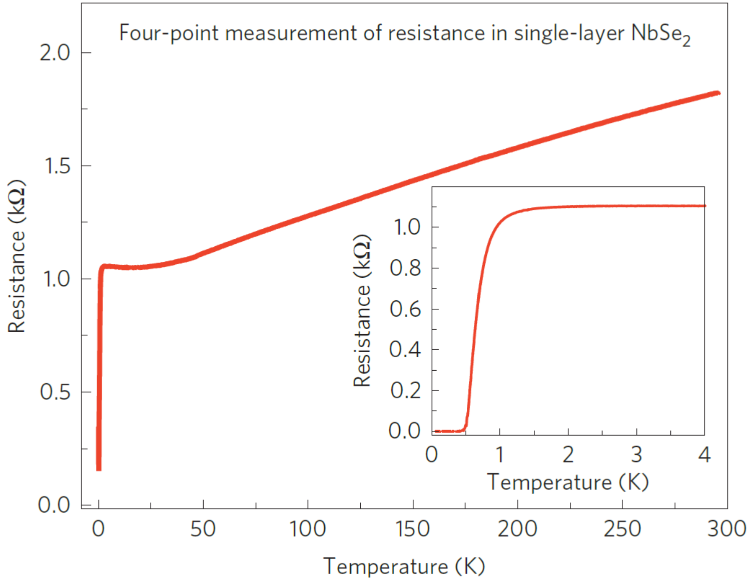
Niobium diselenide



Niobium Diselenide

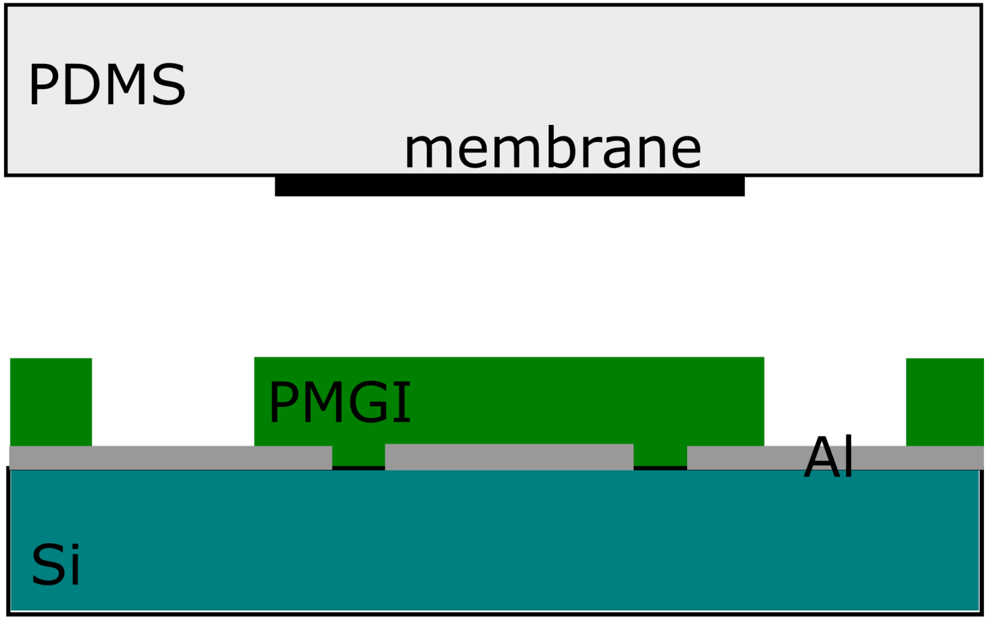
- Transition metal dichalcogenide showing metallic properties
- Exhibits superconductivity even down to a single crystal layer[a]
- Charge density wave phase transition viewed in mechanical measurement[b]





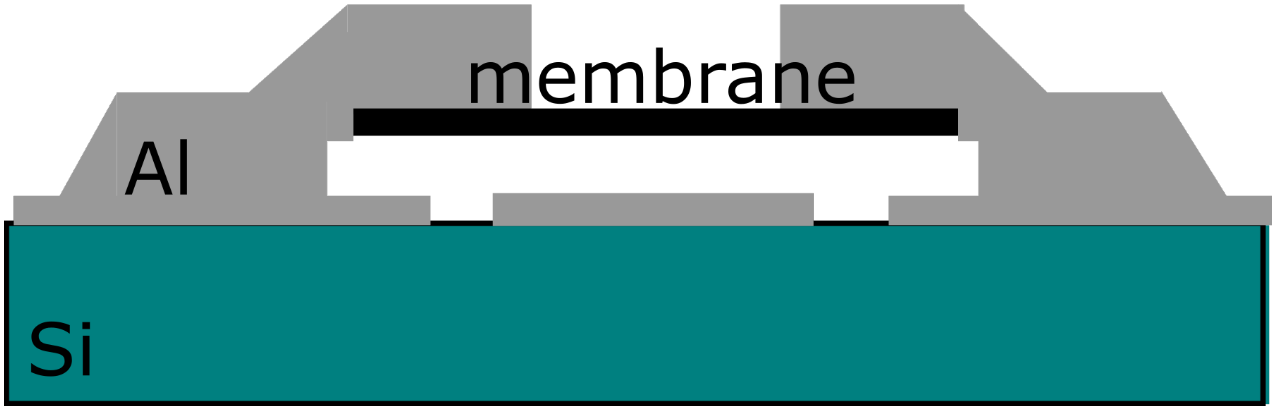
[a] Miguel M. Ugeda et al. In: Nature Physics (2015). DOI: 10.1038/NPHYS3527.
[b] Shamashis Sengupta et al. In: Physical Review B (2010). DOI: 10.1103/PhysRevB.82.155432.

Fabrication - membrane placing



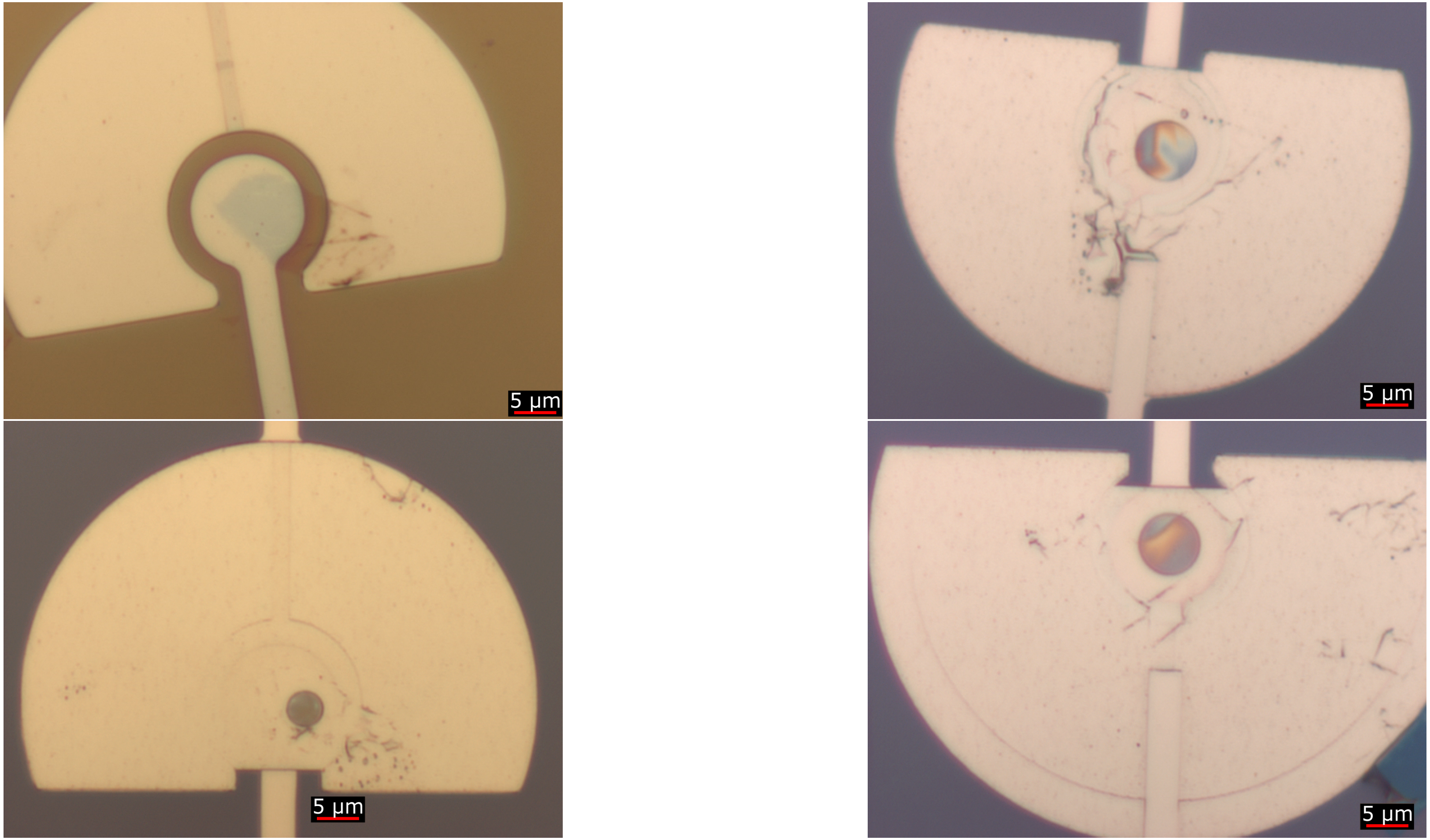
- Suspend membrane above another electrode with ∼100 nm spacing
- Thin membranes through exfoliation, place on polydimethylsiloxane (PDMS) elastomer
- Use photomask aligner to position and stamp the membrane onto polymethylglutarimide (PMGI), over an Al electrode

Fabrication - clamp with aluminum



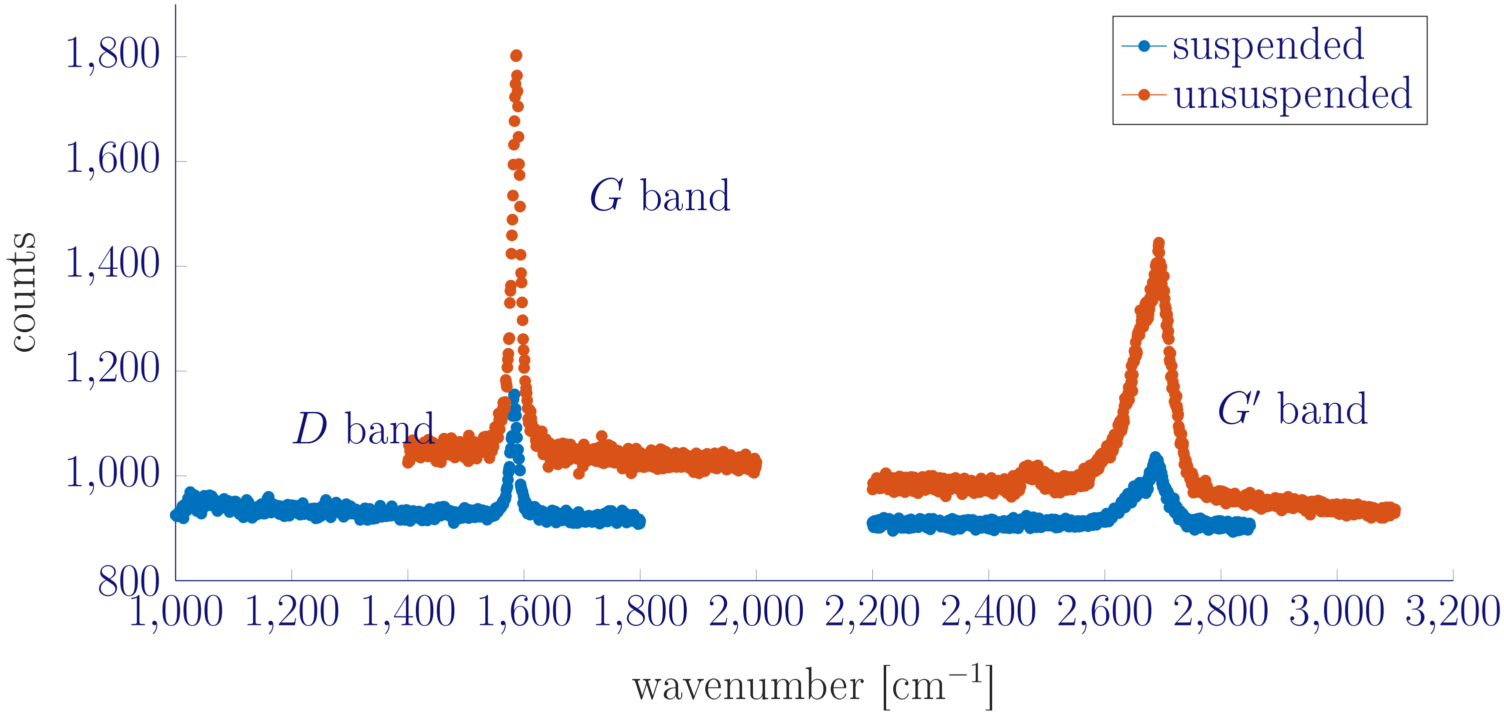
- Use electron beam lithography to define clamps and evaporate Al
- Dissolve PMGI and use critical point drying
- From top down, membrane-air-aluminum path forms a (poor) optical microcavity

Current progress - graphene devices



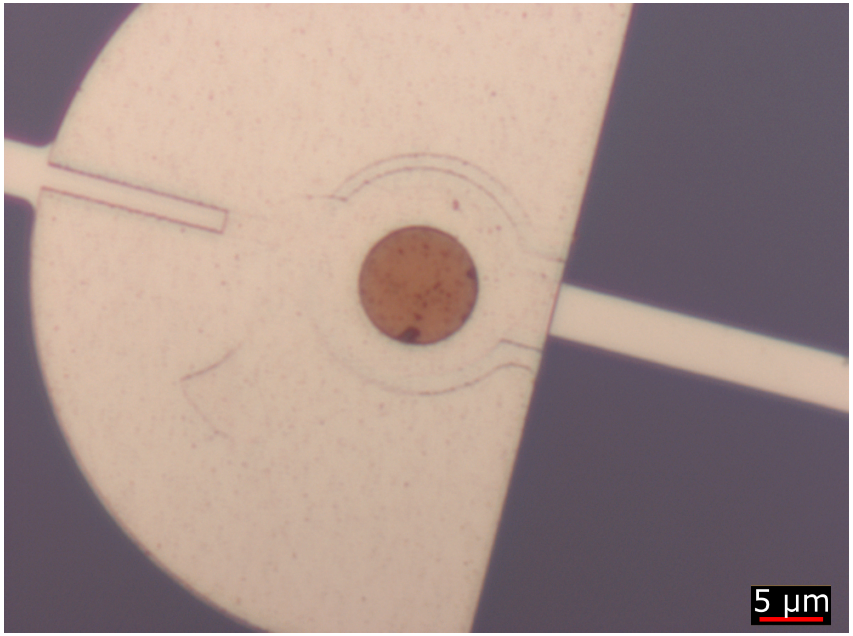
Current progress - graphene devices

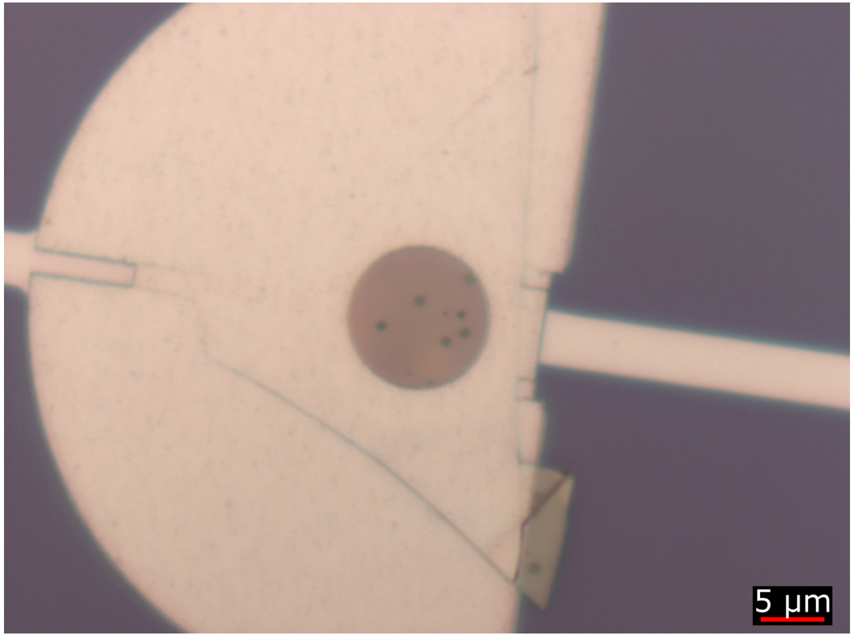
- Raman spectra show exfoliated graphene is low defect (no visible D band)
- $G > G'$ (peaks) shows multilayer graphene



Current progress - NbSe2 devices

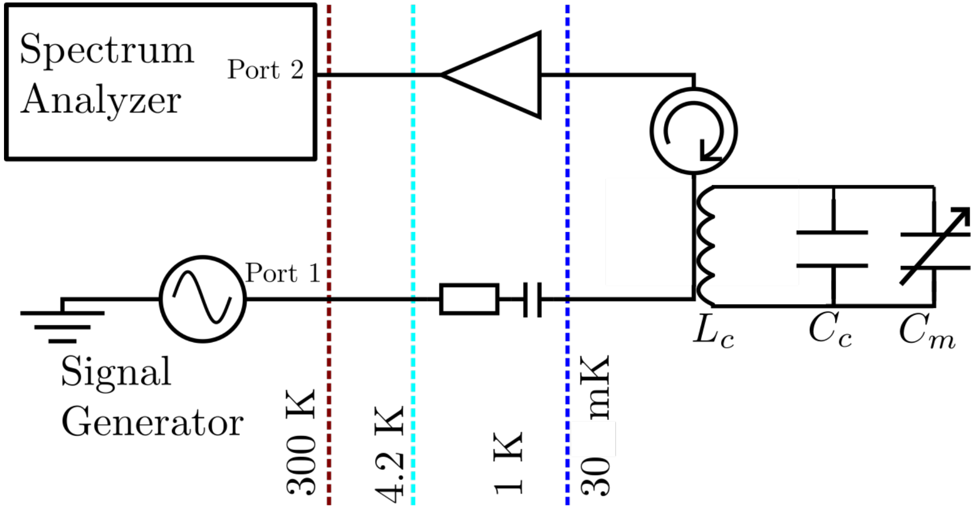
- Contamination after processing
- Switching to nitrogen glove box for processing, changing baking conditions

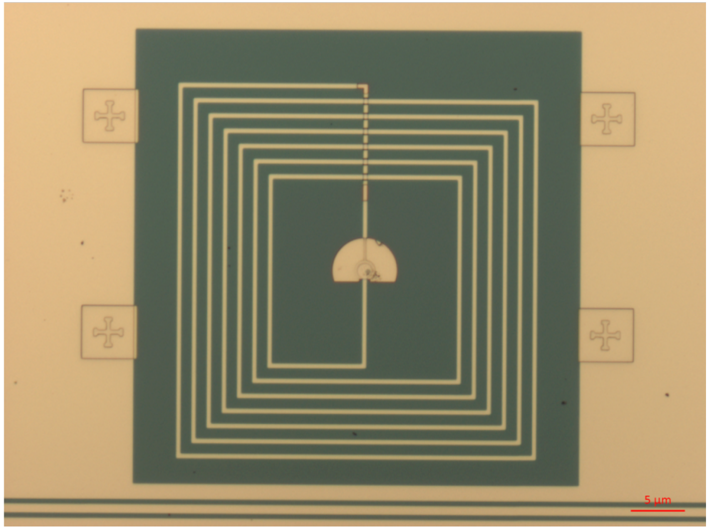




Summary and outlook

- We are looking at graphene and $NbSe_2$ as mechanical elements in microwave circuits
- Allows the study of material properties and quantum mechanics of motion
- Can $NbSe_2$ improve upon graphene in such systems?
- 30 mK cryogenic tests are set to begin this summer





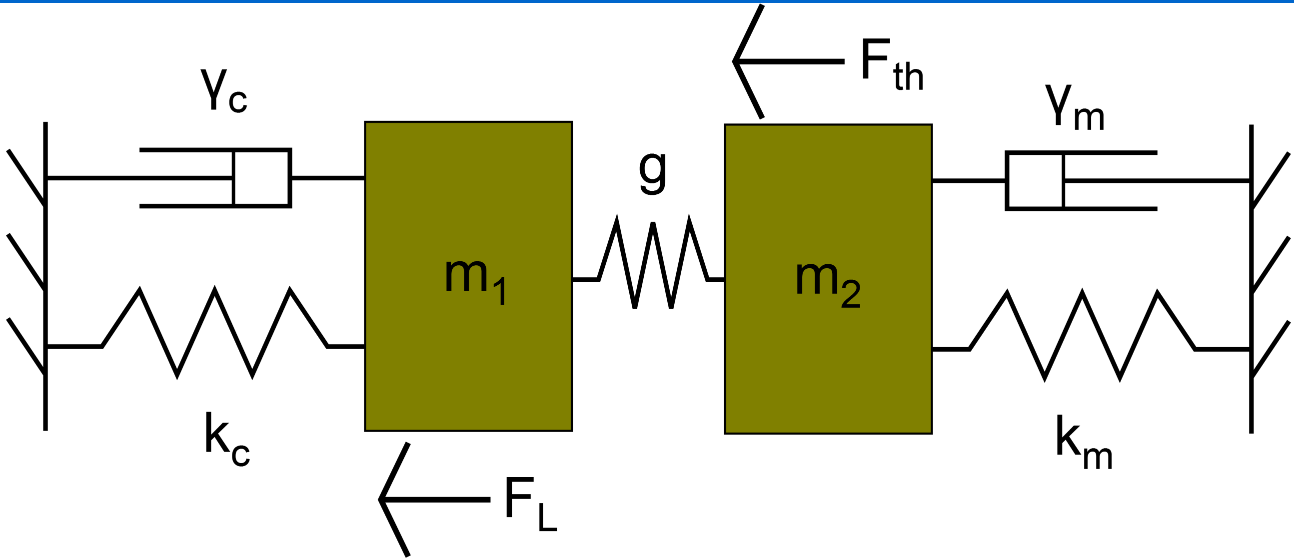
Thank you

Acknowledgements

NSERC
CRSNG

CMC
MICROSYSTEMS

Classical model



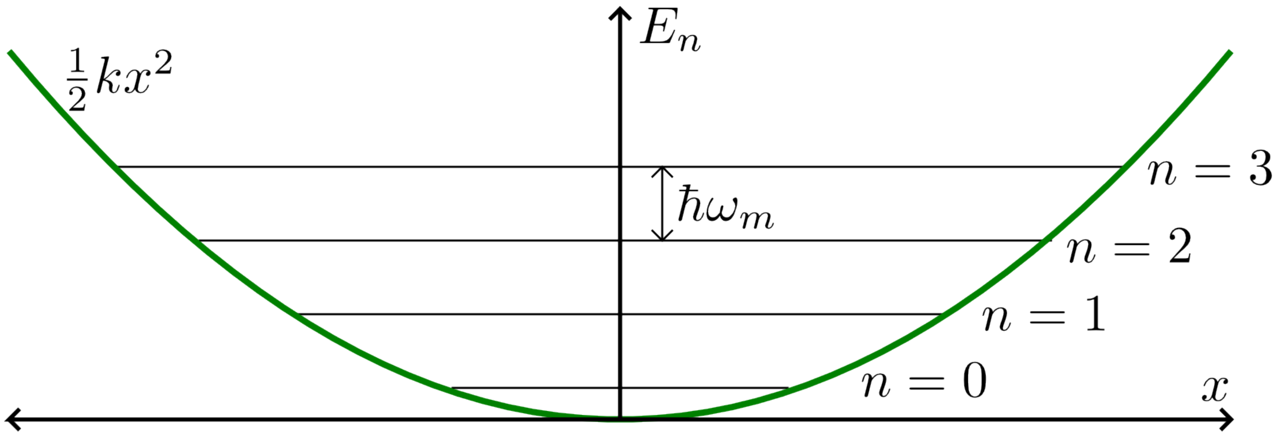
- Two harmonic oscillators, $g = x_{zp}\partial C/\partial x$
- Driven by Brownian thermal force, F_{th}, and signal input, F_l
- Simplify by just looking at the mechanical oscillator ($g = F_r$)

$$\ddot{x} + \gamma_m \dot{x} + \omega_m x = \frac{F_r(x(t)) + F_{th}(t)}{m}$$

Quantum harmonic oscillator

When does a harmonic oscillator become "quantum"?

- Quantum harmonic oscillator has energy levels $E_n = \hbar\omega_m(n + 1/2)$
- In a thermal bath of temperature T, if $k_B T < \hbar\omega_m$, start to enter quantum regime
- Zero-point motion [a]
  - $\sigma_x(n) = \sqrt{\langle n|\hat{x}^2|n\rangle - (\langle n|\hat{x}|n\rangle)^2} = \sqrt{\frac{\hbar}{2m\omega_m}(2n+1)}$
  - Fluctuations in position, even when $n = 0$
  - $x_{zp} = \sqrt{\frac{\hbar}{2m\omega_m}}$

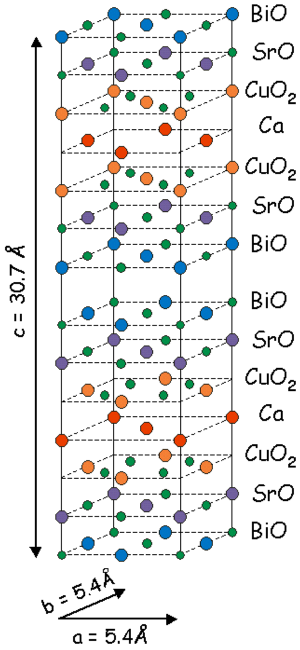


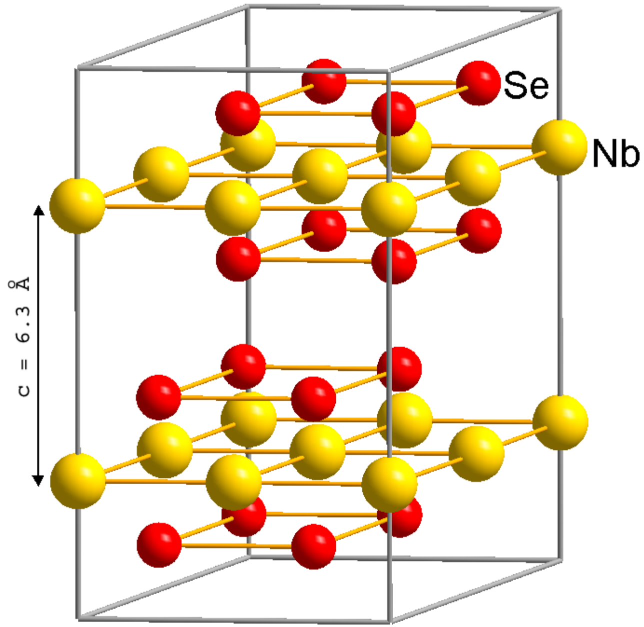
[a] $\hat{x}(t) = x_{zp}\left(\hat{b}e^{-i\omega_m t} + \hat{b}^\dagger e^{i\omega_m t}\right)$

2D crystal materials

2D crystal materials can be compatible with a parallel plate geometry

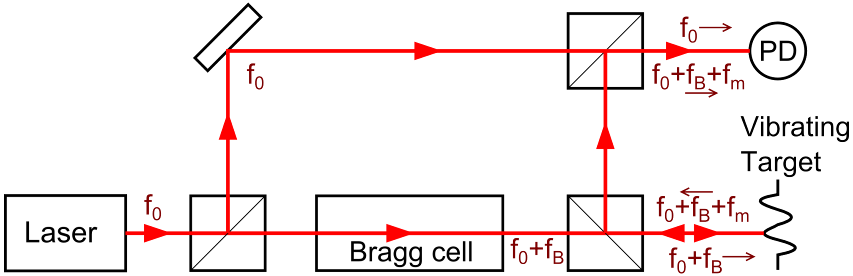
- $NbSe_2$ has a T_c as low as 4.6 K for two layers[a]
- Bismuth strontium calcium copper oxide has $T_c = 95K$ to 108K
- MoS_2 has been shown to be piezoelectric with 1, 3, 5 layers[b]

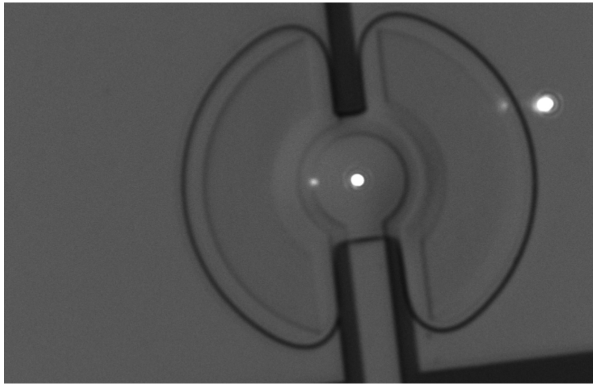




[a]R. F. Frindt. In: Physical Review Letters (1972).

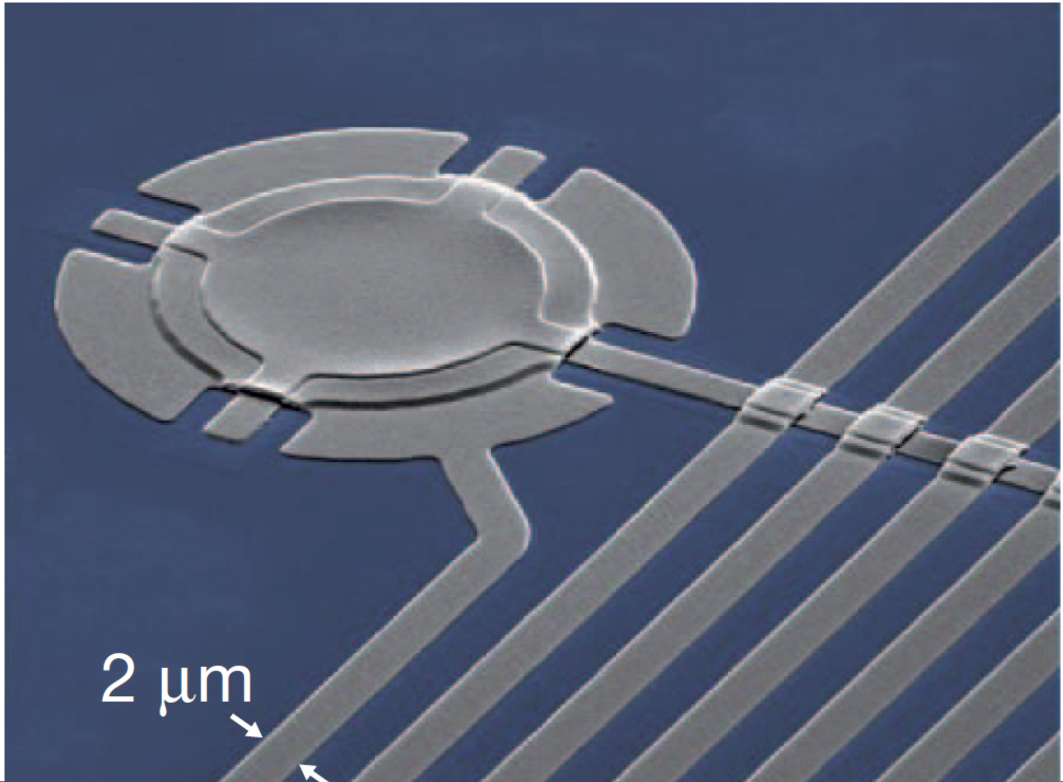
Laser doppler vibrometer



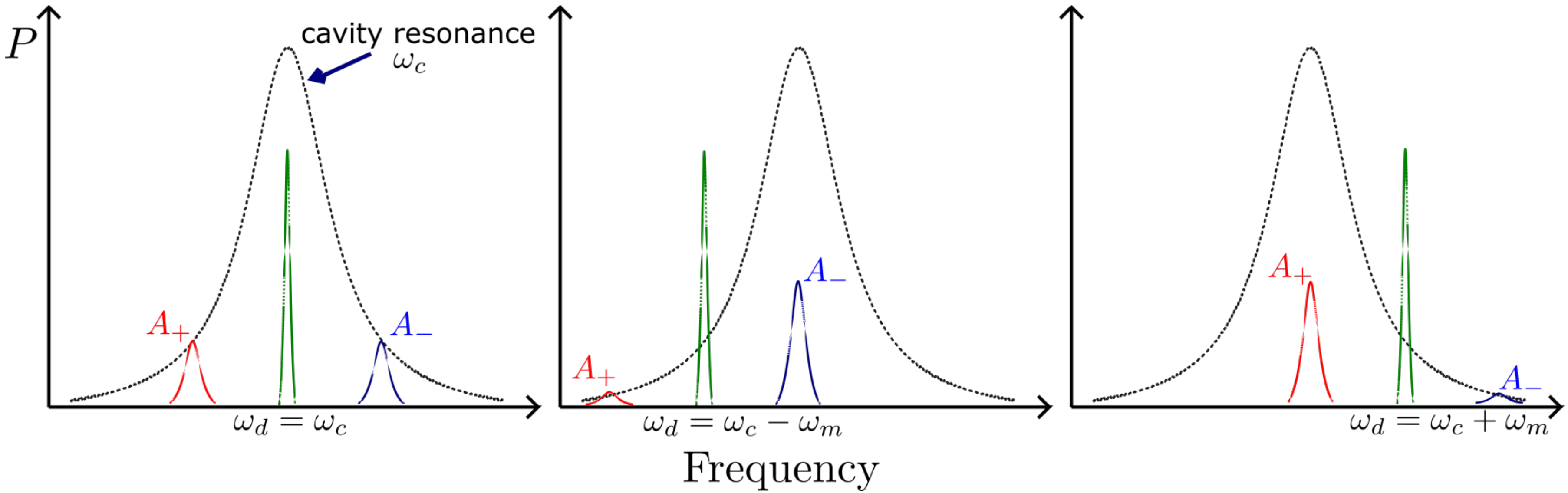


Sideband heating and cooling

- Reached phonon occupation of 0.34 ± 0.05 quanta[a]
- Used Al membrane with $\sim 10^{12}$ atoms
- Photon drive was 2×10^{5} quanta



Sideband scattering and detuning



- Scattering rates equal with no detuning[a]
- Scattering preferential to A_- with red detuning
- Scattering preferential to A_+ with blue detuning

[a]Simon Gröblacher. PhD thesis. University of Vienna, 2012.

The system Hamiltonian

$$\hat{H} = \hbar\omega_c \hat{a}^\dagger \hat{a} - \hbar\omega_d \hat{a}^\dagger \hat{a} + \hbar\omega_m \hat{b}^\dagger \hat{b} + \hbar g \left(\hat{b}^\dagger + \hat{b}\right) \hat{a}^\dagger \hat{a} + i\hbar P \left(\hat{a} - \hat{a}^\dagger\right)$$

- Coupling rate: $g = x_{zp} \partial\omega_c / \partial x$
- $\omega_c = \frac{1}{\sqrt{LC(x)}}$
- Includes terms for signal drive power

Quantum Langevin equations

Harmonic oscillators coupled to lossy universe...

- $\partial\hat{O}/\partial t = (i/\hbar)[\hat{H},\hat{O}] + \hat{N}$
  - $\hat{N}$ represents noise operator for $\hat{O}$
- Gain a system of coupled differential equations (simplified)

$$\dot{\hat{x}} = \omega_m \hat{p}$$
$$\dot{\hat{p}} = -\omega_m \hat{x} - \gamma_m \hat{p} + g\hat{a}^\dagger\hat{a} + \hat{\xi}$$
$$\dot{\hat{a}} = -\left(\gamma_c + i\Delta\right)\hat{a} + ig\hat{a}\hat{x} + \sqrt{\frac{2P\gamma_c}{\hbar\omega_\ell}} + \sqrt{2\gamma_c}\hat{a}_{in}$$

- Rather nasty to solve
- Steady-state, strongly driven, linearized approximation

Coupling, damping, scattering

Results from the coupled operator equations[a]

- Field-dependent coupling

$$g_{eff} = \alpha_s g$$

- Detuning-dependent damping

$$\gamma_{eff}(\omega) = \gamma_m + \frac{g_{eff}^2 \Delta_{eff} \omega_m \gamma_c}{\left[\gamma_c^2 + (\omega - \Delta_{eff})^2\right]\left[\gamma_c^2 + (\omega + \Delta_{eff})^2\right]}$$

- Detuning-dependent scattering rates

$$A_{\pm} = \frac{g_{eff}^2 \gamma_c}{2\left(\gamma_c^2 + \left[\Delta_{eff} \pm \omega_m\right]^2\right)}$$

[a] C. Genes et al. In: Physical Review A (2008).

Experimental schematic