Wiring up trapped ions for quantum information processing

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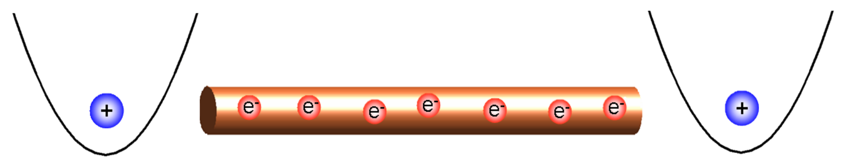
START project

Motivation

Coupling two ion traps with a wire:

The motion of a trapped ion induces an image current in the wire, which influences the motion of a second trapped ion. This interaction extends over a distance greater than that of pure Coulomb coupling.

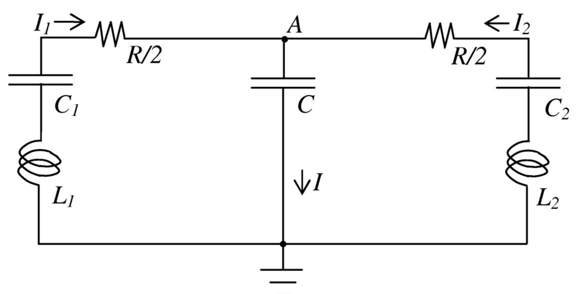


Possible applications:

- Quantum information processing
- Sympathetic cooling of ion species inaccessible by laser cooling
- Coupling ions to superconducting qubits / mesoscopic resonators
- Coulomb Force Electrometer

The coupling strength

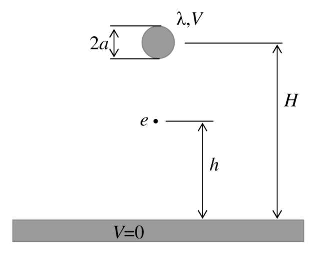
Equivalent circuit for the two ions and wire:



$$L_i = \frac{1}{\beta_i^2}\frac{m\,H^2}{e^2},\quad C_i = \frac{1}{\omega_i^2\,L_i}\,,\ i = 1,\,2$$

$$C_{1,2} \approx 4\times10^{-19}\,\mathrm{F}$$
$$L_{1,2} \approx 6\times10^{4}\mathrm{H}$$

or *equivalent Hamiltonian*:



$$H = \frac{p_1^2}{2\,m} + \frac{1}{2}m\,\omega_1^2\,z_1^2 + \frac{p_2^2}{2\,m} + \frac{1}{2}m\,\omega_2^2\,z_2^2 + \gamma\,z_1\,z_2$$

Exchange rate: $\frac{1}{t_{\mathrm{ex}}} = \frac{\gamma}{\pi\,\omega\,m} = \frac{2\,e^2\,H^2}{\pi^2\,\epsilon_0\,\alpha\,m\,\omega\,L}\cdot\frac{1}{(H^2-h_1^2)(H^2-h_2^2)}$

Current numbers:	Projected numbers:
H = 250 µm	H = 60 µm
ω =2π x 1 MHz	ω =2π x 1 MHz
h= 200 µm	h= 50 µm
L = 10 mm	L = 2 mm
t_{ex} = 190 ms	t_{ex} = 1 ms

D.J. Heinzen and D.J. Wineland, PRA **47**, 2977 (1990)

Expected decoherence

Heating of motional state from

- patch potentials – scales as D^{-4}
- Johnson noise – scales as D^{-2}

Small traps have excessive anomalous heating. Eventually one needs to use a cryostat to cool the apparatus to 4 K (see Deslauriers et al., PRL **97**, 103007 (2006), Labasciewicz et al., PRL **101**, 180602 (2008))

From the circuit model, the Johnson heating rate is:

$$\tau^{-1} = \frac{kTR}{h}\sqrt{\frac{C_i}{L_i}}$$

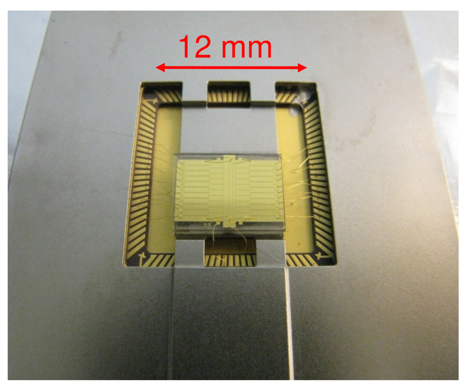
With trap & wire at 4 K this is:

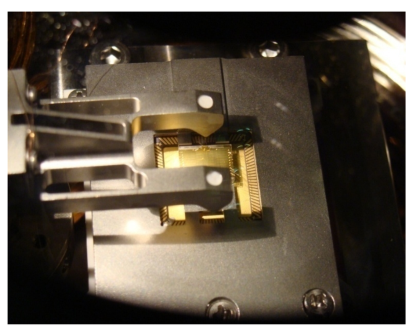
$$\tau \sim 380\ \mathrm{s/quantum}$$

Q: superconducting materials and heating rates / coherent coupling?

Experimental setup

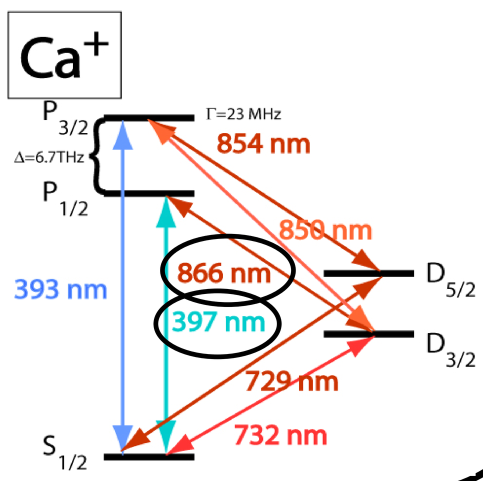
Our planar RF traps are mounted on CPGAs. For operation they reside in a vacuum vessel at approx. 10^{-11} mbar





A side view of the coupling wire on a steel/macor mount, positioned above the trap.

The level structure of $^{40}Ca^{+}$. Only the 397 nm and 866 nm lasers are needed for detection of ions.



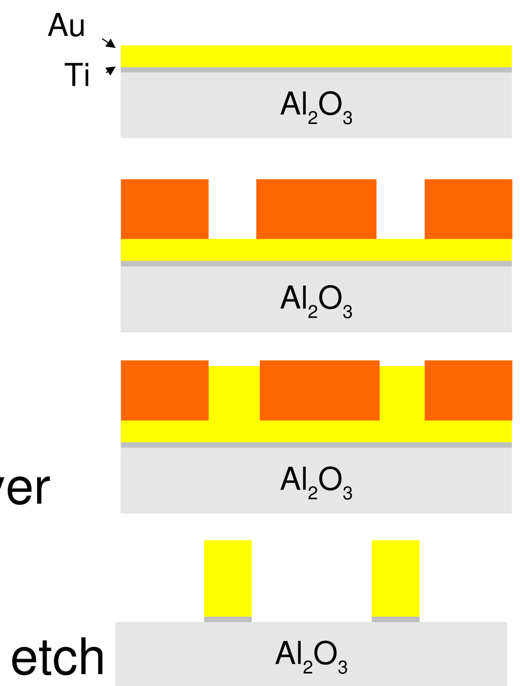
Trap fabrication

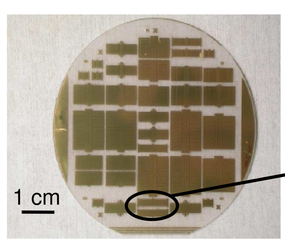
1. Evaporation
i. 5 nm Ti adhesion layer
ii. 100 nm Au seed layer

2. Lithography
~5 µm thick photoresist

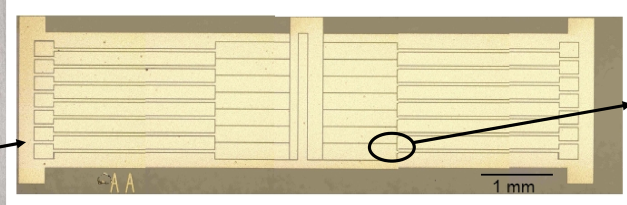
3. Electroplating
4-5 µm thick Au plated layer

4. Cleaning/Etching
Resist removal/Au etch/Ti etch

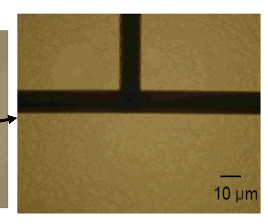




Complete wafer



Single trap

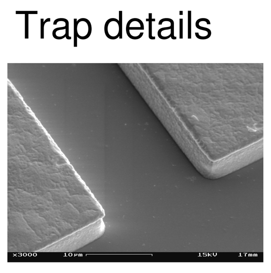


Trap details

Electrode spacing 10 µm

Surface rms roughness: 20 nm

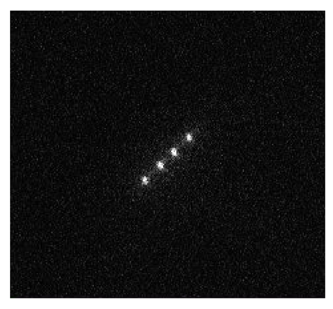
Crystallite size: 20 nm



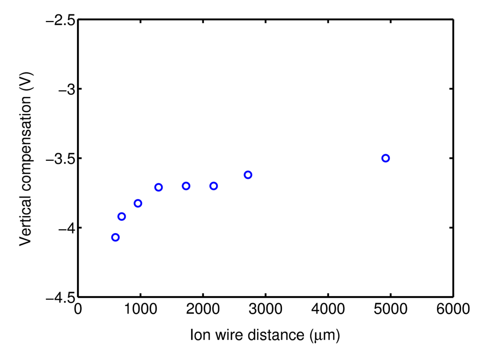
Trap operation

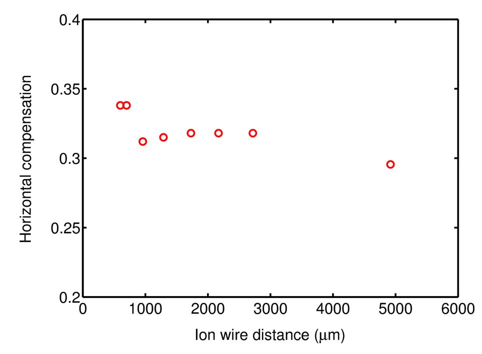
We operate with single ions in our traps

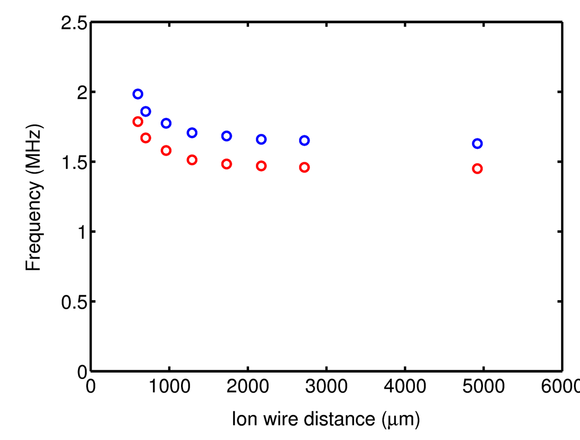
The lifetime is O(hours) at 10^{-11} mbar.



We are currently investigating changes in trap parameters as the wire is brought in.

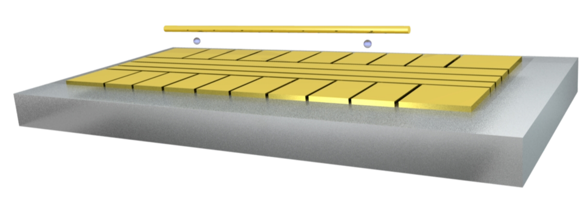


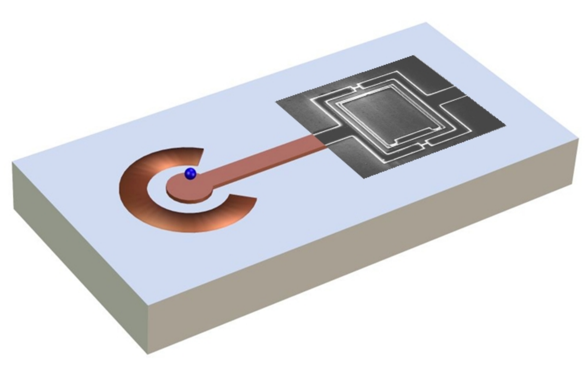




Future goals

- Observe sympathetic heating in room temperature setup.
- Trap ions in two separate traps and sympathetically cool one of the ions when the other is cooled.
- Operate traps in cryogenic environment.
- Scale down microfabricated trap sizes/ explore different fabrication methods and materials
- Transfer classical and quantum states between the ion oscillators
- Couple trapped ion to a solid state qubit, e.g. superconducting qubit.





Conclusions

- Coupling of two ions using a wire seems feasible.
- Coherent coupling expected at cryogenic temperatures.
- Preliminary experiments with room temperature apparatus in progress
- Ions have been observed, our model of the trap tested, and the first signals of ion-wire interaction observed.
- Future work will involve sympathetic Doppler cooling, and investigation of motional state exchange under different conditions and for a variety of motional states.