Microwave Kinetic Inductance Detectors for visible to near infrared astronomy

Mazin Lab
All of the wavelengths
All of the times
mazinlab.org

Grégoire Coiffard
On behalf of Mazin Lab

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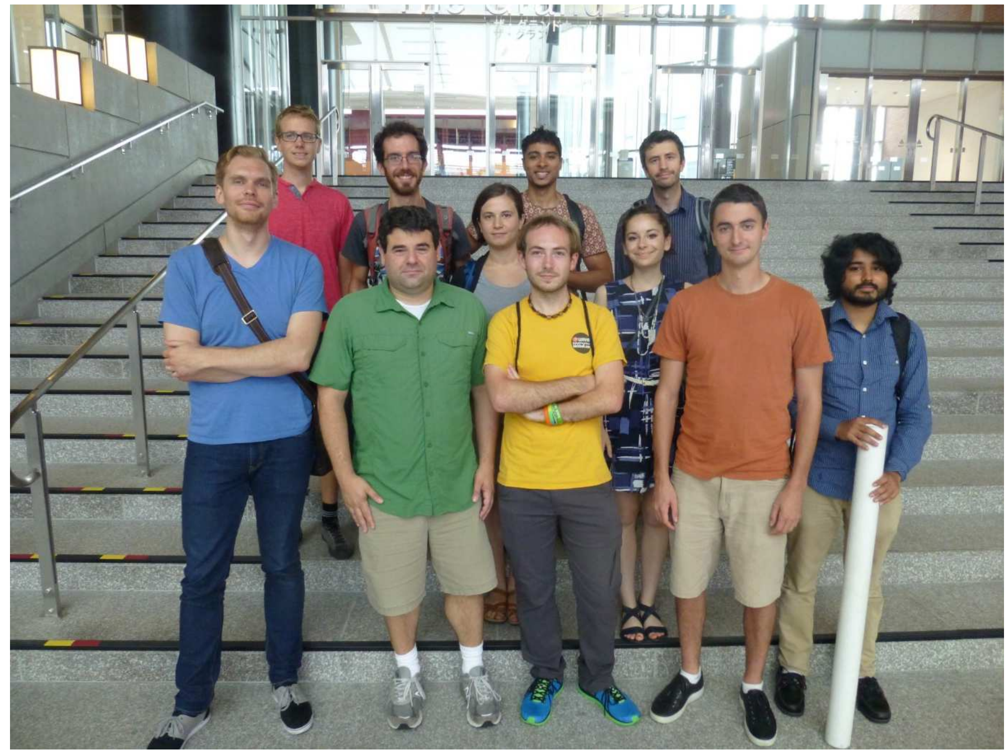
Subaru: Olivier Guyon, Julian Lozi
Caltech: Dimitri Mawet, Nem J.
JPL/IPAC: Bruce Bumble, Gautam Vashisht, Mike Bottom
Oxford: Kieran O'Brien, Rupert Dodkins
Fermilab: Juan Estrada, Gustavo Cancelo, Chris Stoughton



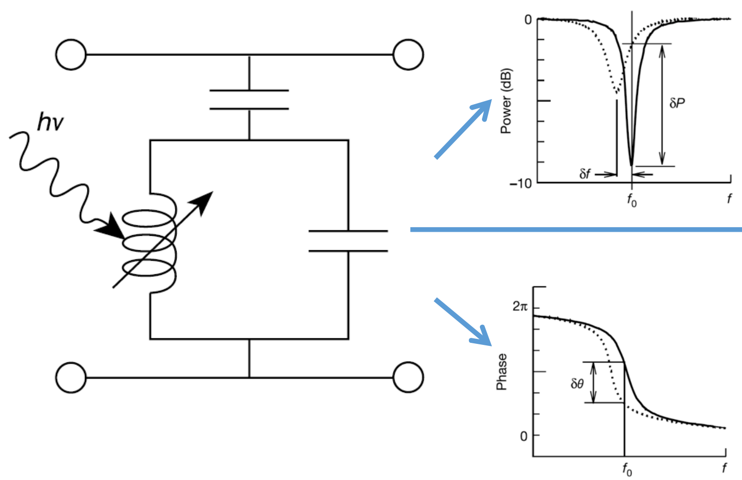
KIDs: The Next Generation - workshop DIAS Sept. 2017

Outline

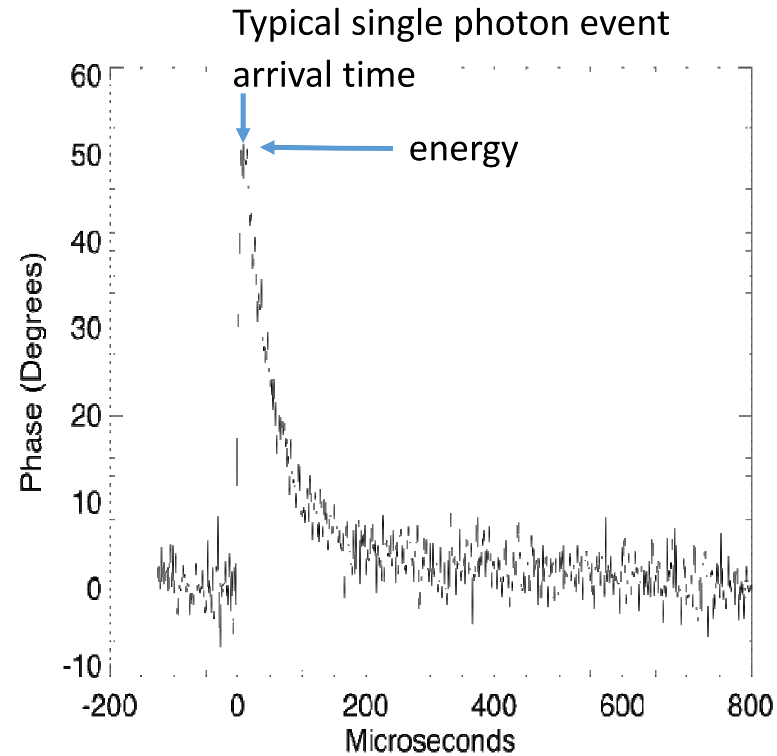
- MKIDs for single photon detection
- Fabrication of kilopixels MKIDs arrays
- New MKIDs development

Single photon detector

MKID equivalent circuit

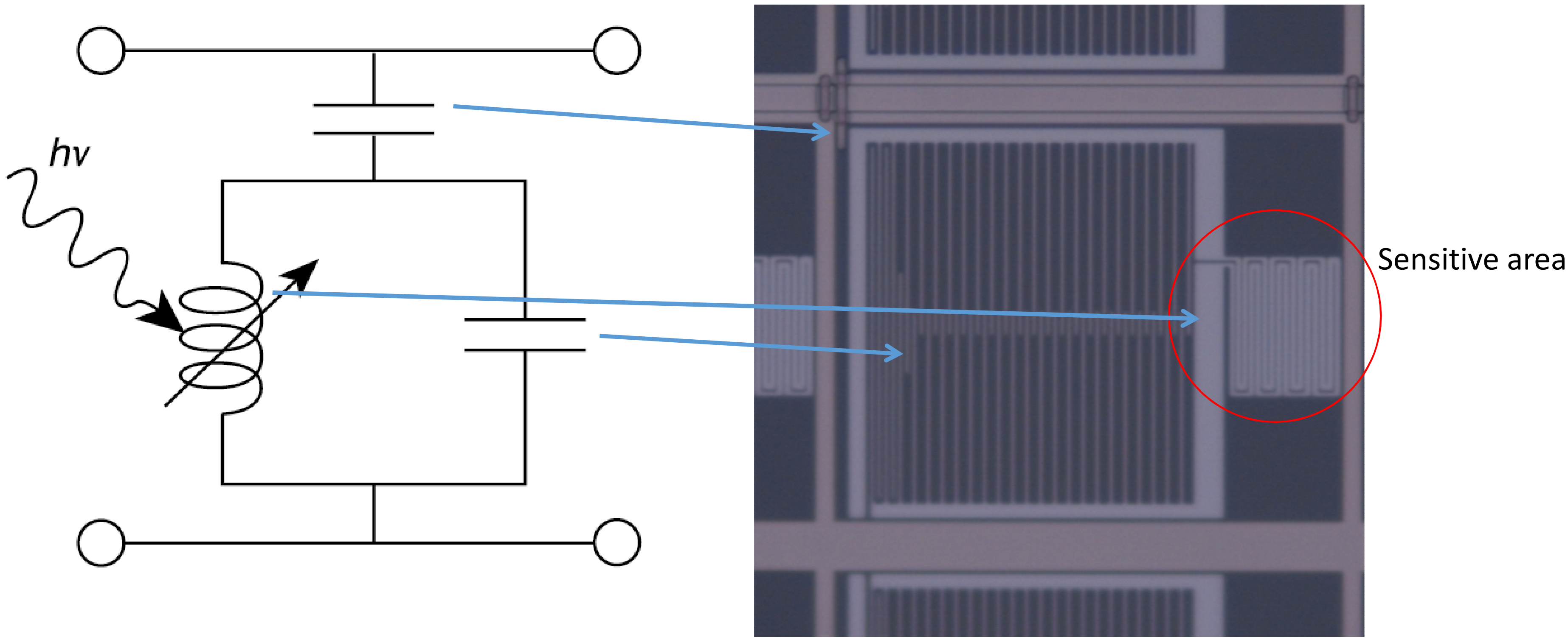


We monitor the phase shift



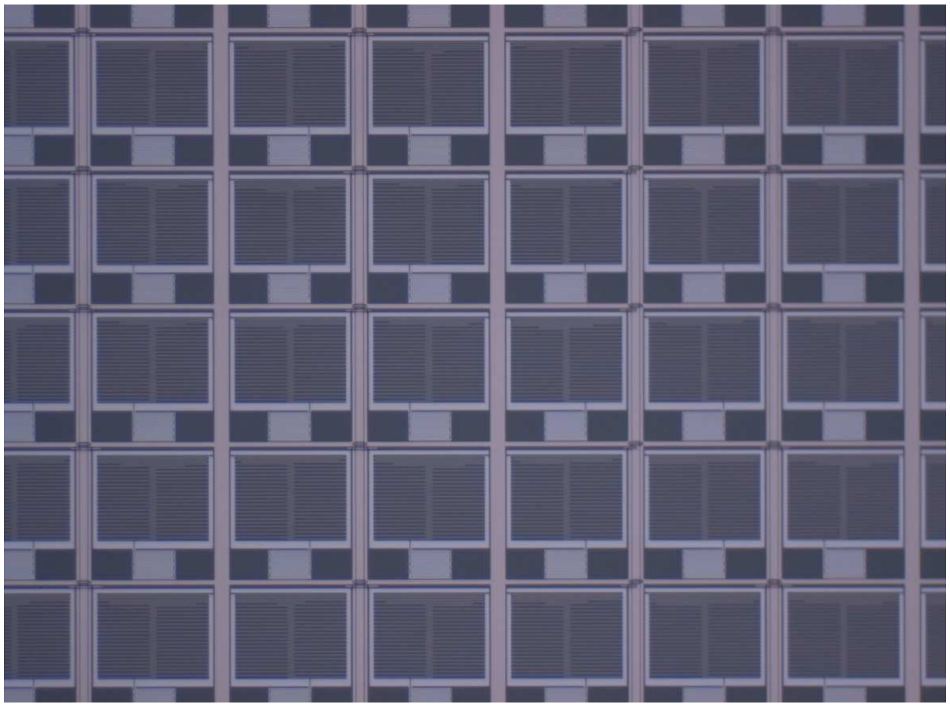
- Single photon counting with ~ 100 microsec timing
- Energy resolving R~10

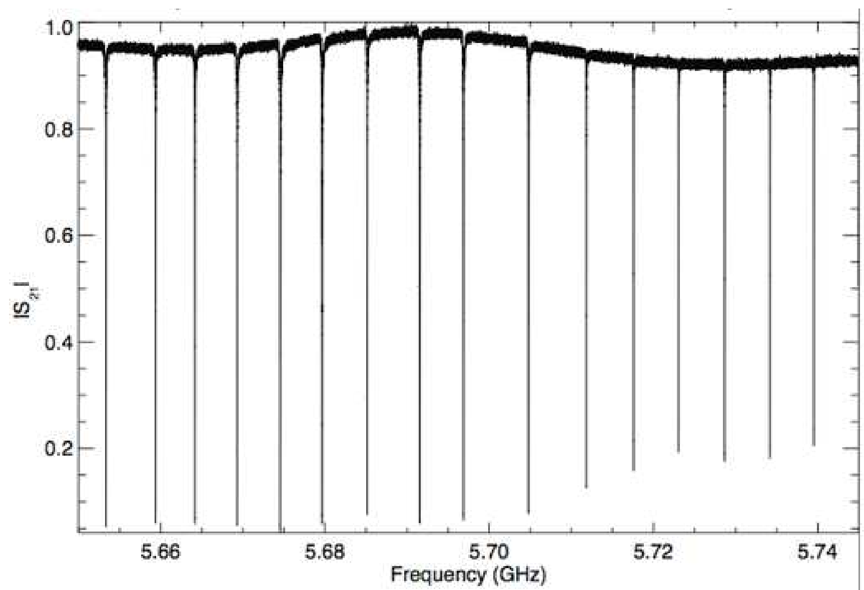
Microwave Kinetic Inductance Detectors



We use a microlens array to improve effective fill factor to ~92%

Multiplexing



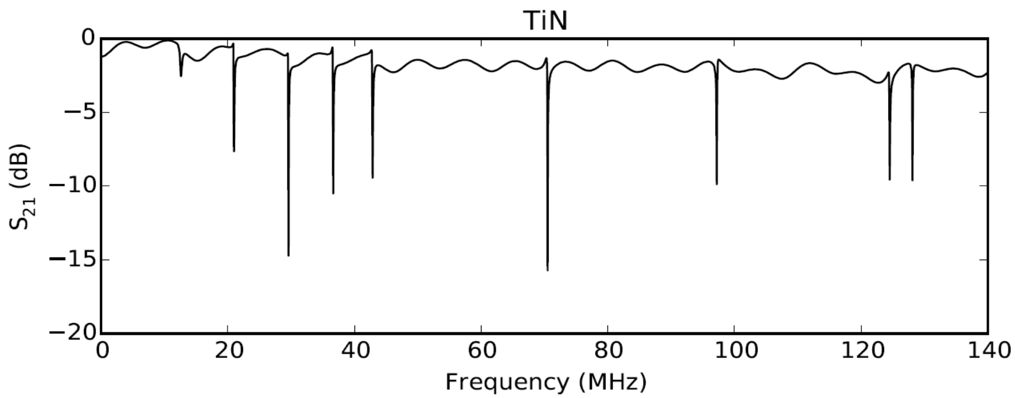


10 to 20k pixels arrays

Which material for the MKIDs?

TiN : Strongly non uniform in nitrogen content over a wafer – poor control of f_0 position

→ Looking for an alternative material



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Platinum Silicide: PtSi

- Resistivity: 50 μΩ.cm
- $T_c \approx 940$ mK
- We aim for 60 nm films with ~10 pH/sq inductance

Deposition of Pt and Si on sapphire substrate + anneal in-situ

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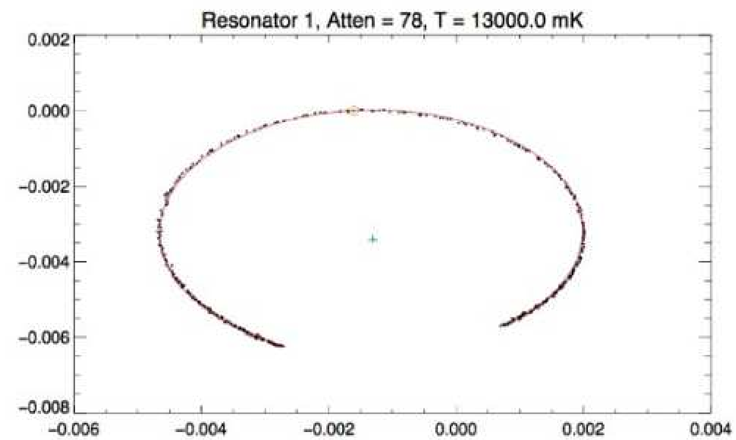
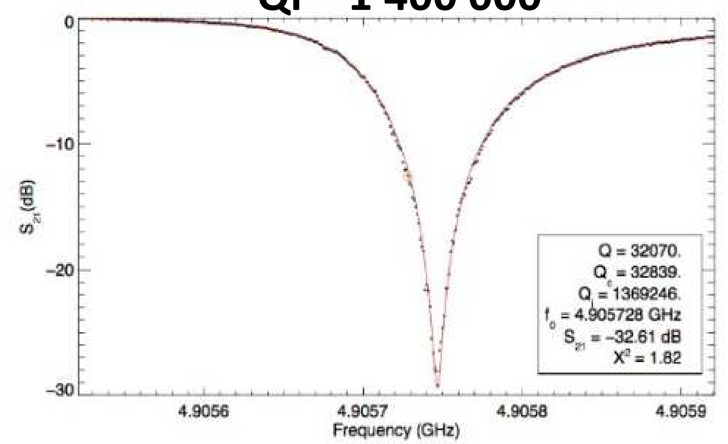
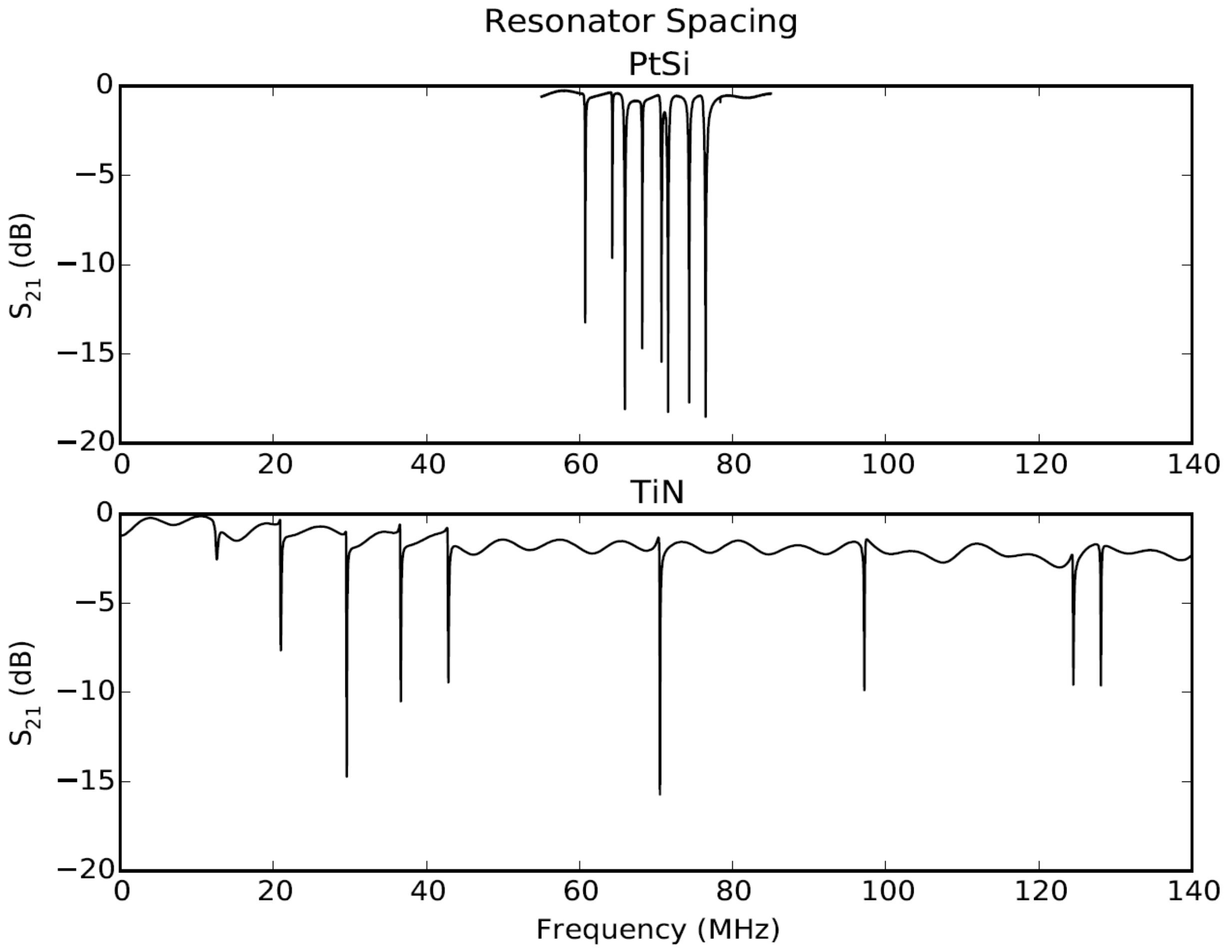
→ Qi of 1 millions!! (on single layer test device)



Qi ~ 1 400 000



TiN vs. PtSi

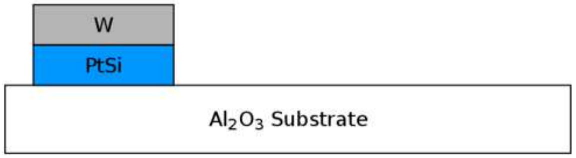


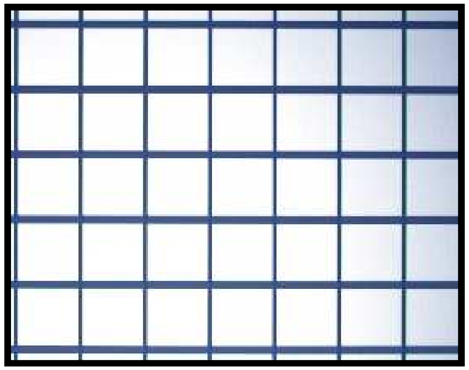
Szypryt et al. 2016

Fabrication process

1) PtSi Resonator Outline

- PtSi deposition and annealing + W done in-situ using AJA ATC sputter system.
- ICP etching of the W (SF6) + PtSi (Cl2 + CF4 + Ar)





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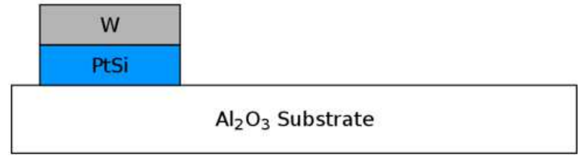
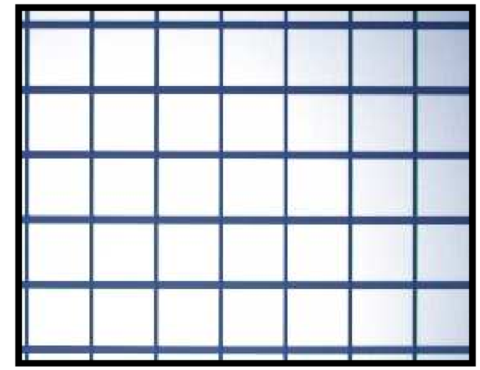
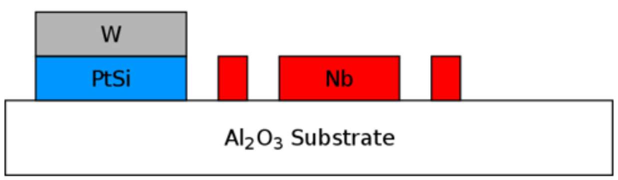
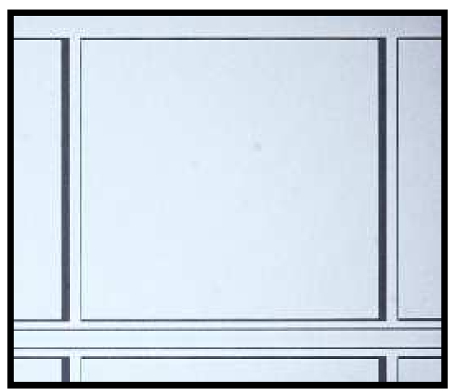




2) Nb Feedline and Ground Plane (lift-off)

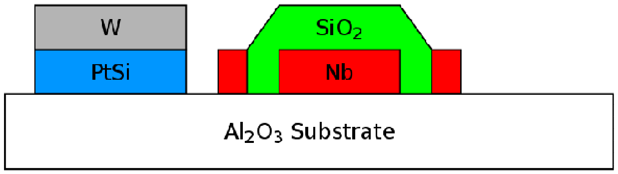


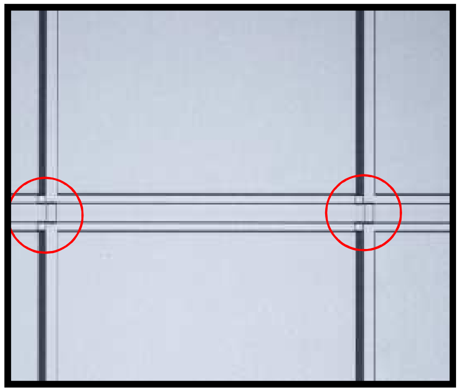


Fabrication process

3) SiO2 insulating pads

- Insulating pads over the feedline used to connect ground plane segments
- Reactive sputtering of SiO2 (alternative recently tried : aSi:H – similar performances but much easiest to deposit! 3 min vs. 3 hours!)





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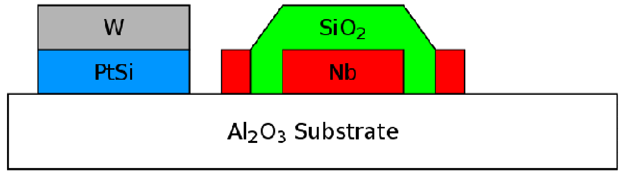
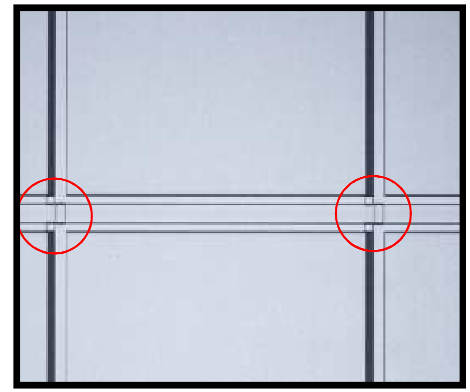
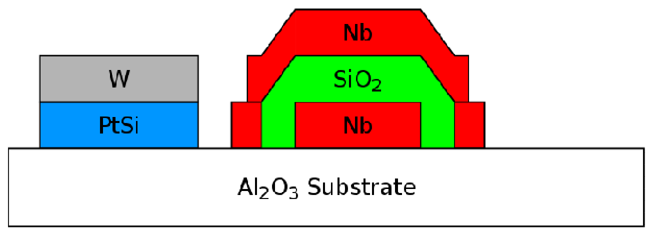
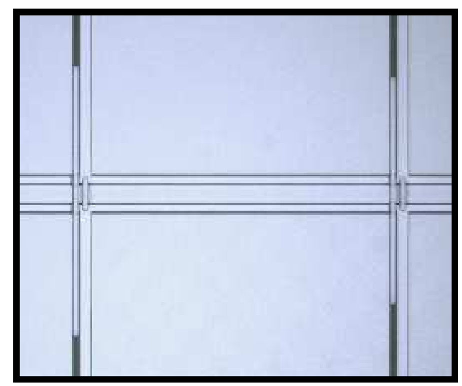




4) Nb Crossovers and Coupling Bars

- Crossovers to connect ground plane segments and connections of the feedline to couplers

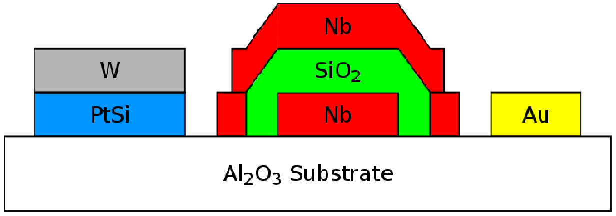


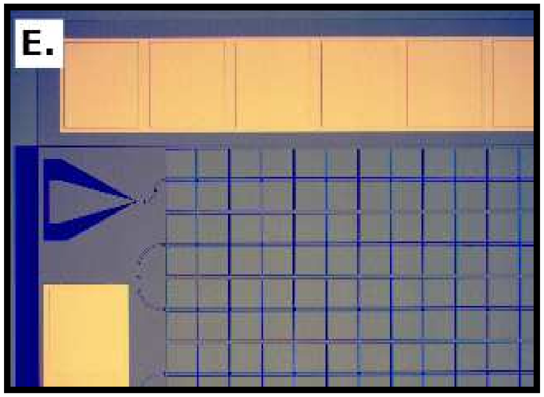


Fabrication process

5) Gold Bond Pads

- Gold bond pads used for gold wire bonding (reduce heat excess)





Fabrication process

5) Gold Bond Pads

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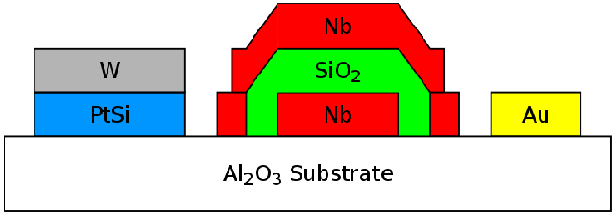
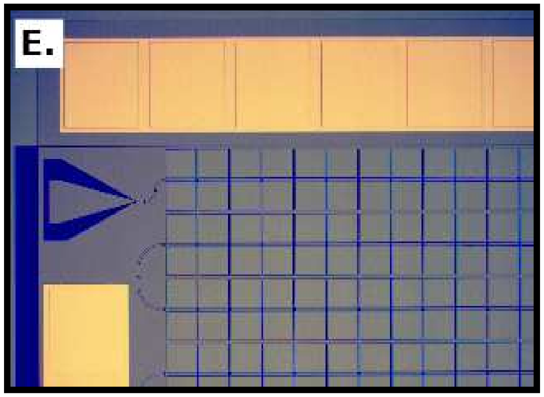
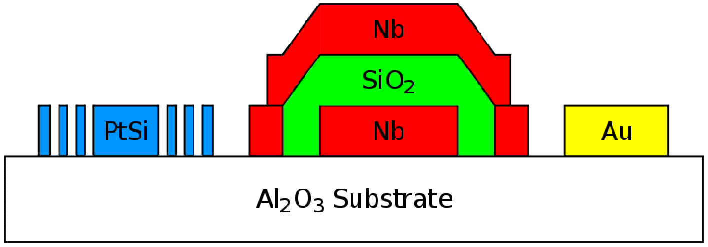
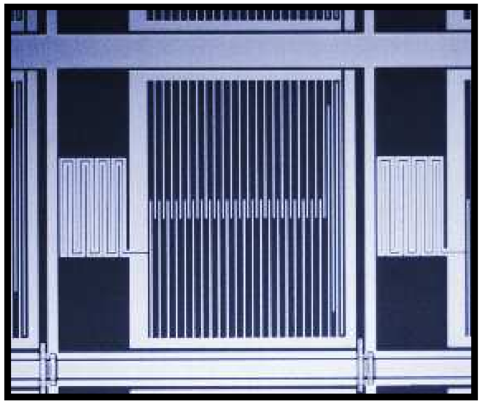




6) PtSi Resonator Etch

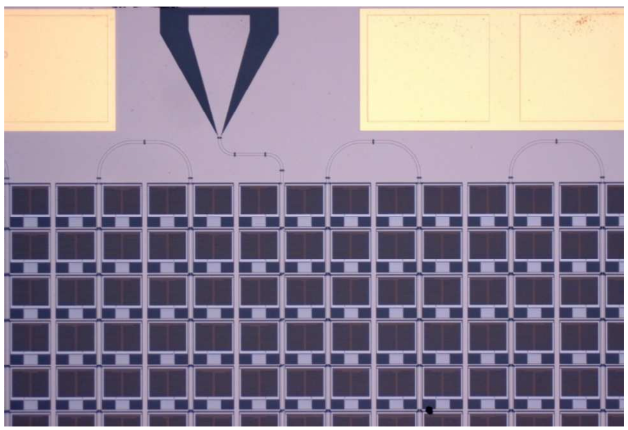
- W and PtSi Etched with ICP etcher
- Protect layer removed in heated H2O2

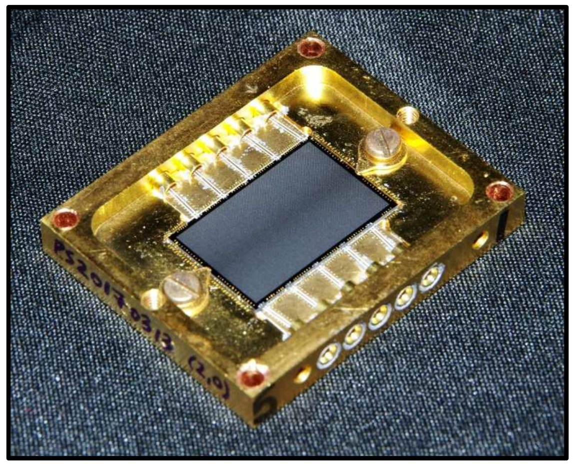


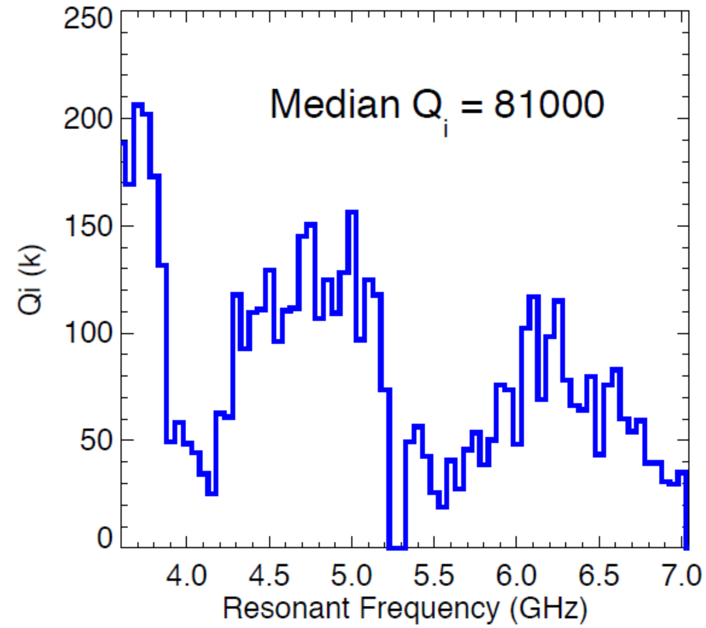


Dark-speckle Near-IR Energy-resolved Superconducting Spectrophotometer (DARKNESS)

Large-Format Platinum Silicide Microwave Kinetic Inductance Detectors for Optical to Near-IR Astronomy
Paul Szypryt, submitted to Optic Express (last week)





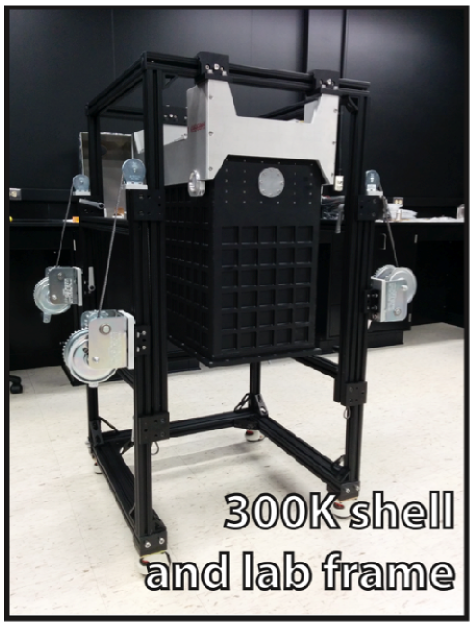


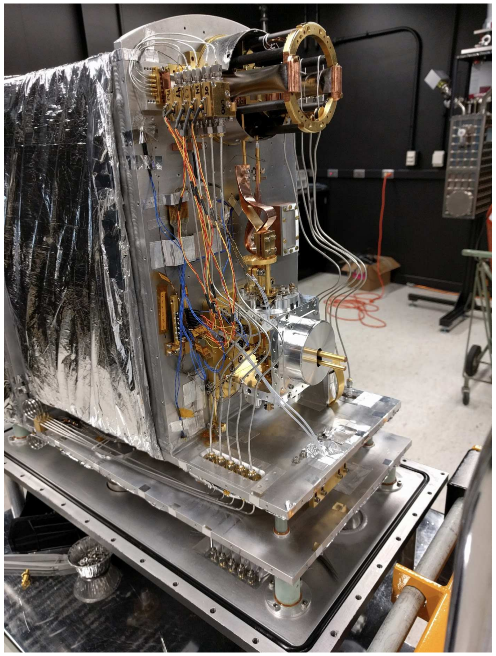
- Qi Lower than expected (~80,000), R~8 at 1 micron
- Great sensitivity to photons in instrument's wavelength band
- Low yield due to roll off of Qi toward higher frequency
- On par or better than the best 10,000 pixel TiN arrays

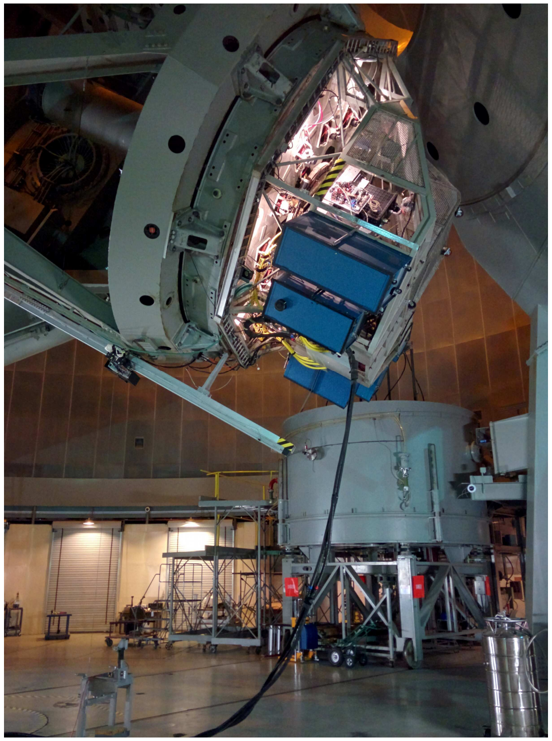
DARKNESS

DARKNESS is commissioned and science runs are ongoing… (Palomar)

DARKNESS: A Microwave Kinetic Inductance Detector Integral Field Spectrograph for high-contrast Astronomy
- Seth R. Meeker, submitted to PASP (last week)



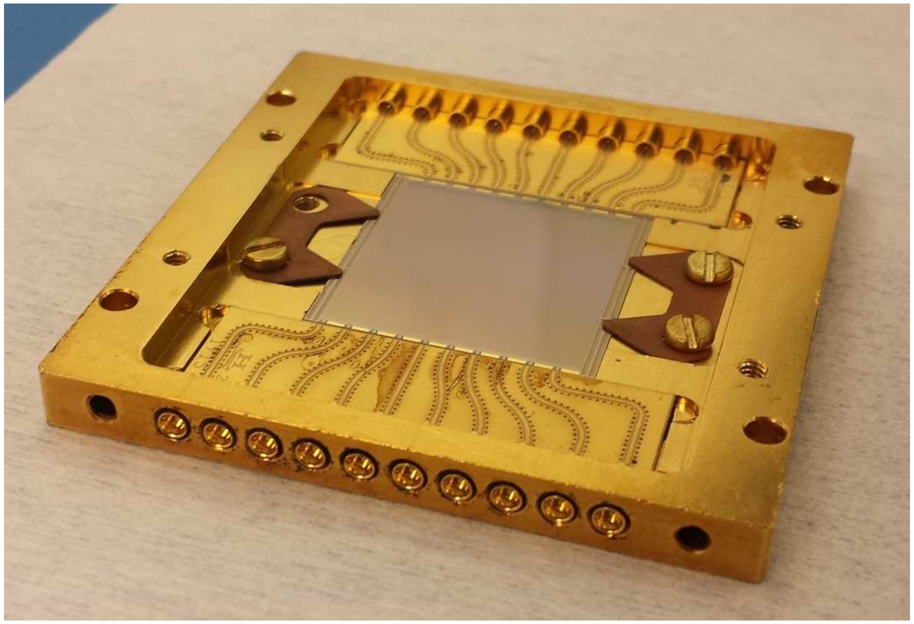




MKID Exoplanet Camera (MEC)

- 20,440 (140x146) pixels split between 10 feedlines (14x146)
- 150 um pixel pitch
- 22x22 mm imaging area
- 20 ROACH2 readout boards

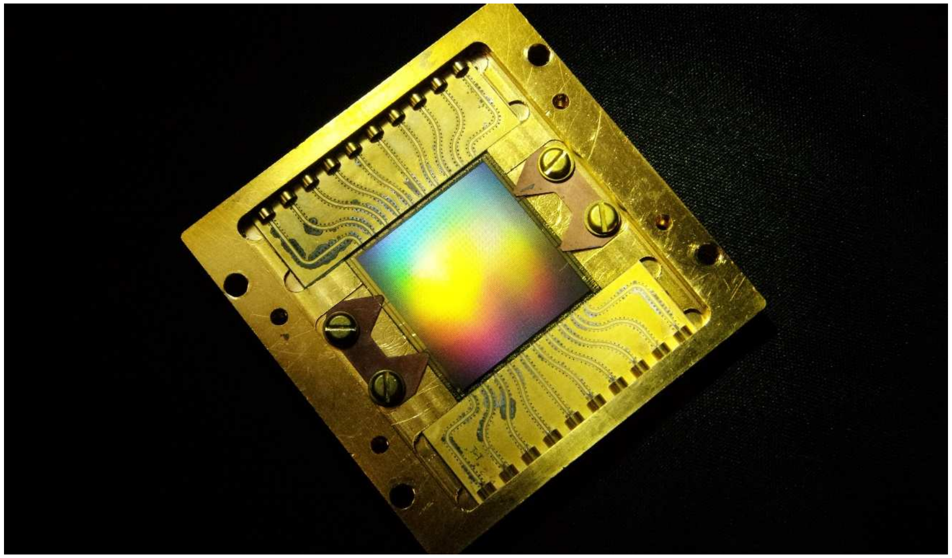
Large-Format Platinum Silicide Microwave Kinetic Inductance Detectors for Optical to Near-IR Astronomy
Paul Szypryt, submitted to Optic Express (last week)

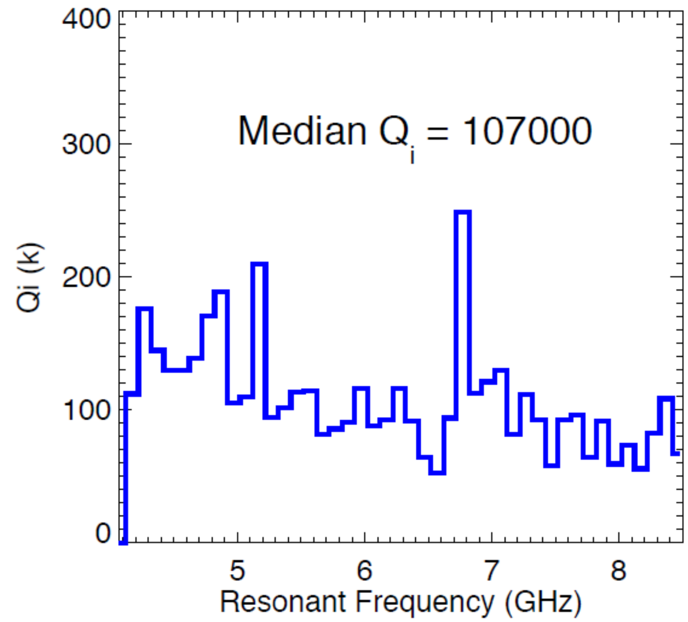


Improvements from DARKNESS array:

- 500 nm inductor gaps as opposed to 300 nm gaps used in DARKNESS
- 1 crossover every 10 pixels (~λ/8)
- Optimized Sonnet simulations for better control of designed resonator placing and 2 MHz spacing (capacitor shrinking)

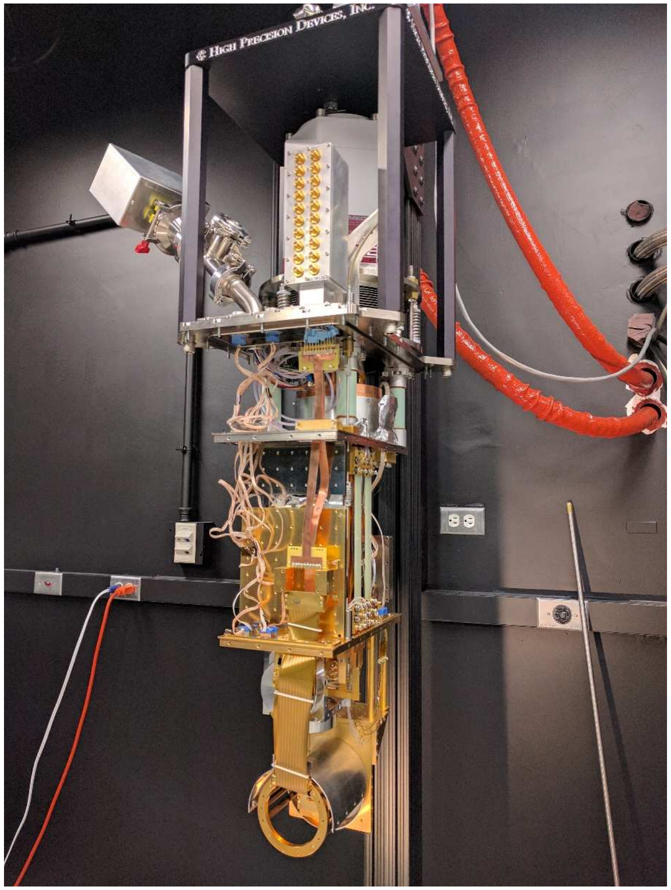
MEC results





- Our best array has Qi values of ~ 100,000
- Less variation of Qi with frequency, no significant dips
- Energy resolution of 8 at 1 micron
- Pixel yield approaching 90% (fitted resonators). *Still need more work to determine how many of those are actually photosensitive*
- Generally very good sensitivity to photons in the 700-1400 nm band

MEC results



Laminated NbTi on Kapton Microstrip Cables for
Flexible Sub-Kelvin RF Electronics – *A. B. Walter in preparation*

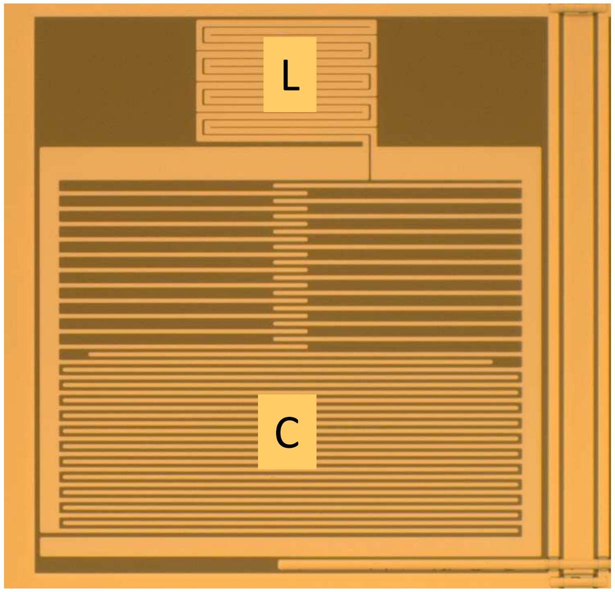
New UVOIR MKID development

- Parallel plate capacitor MKIDs
- Low Tc material

Parallel Plate Capacitor MKIDs

Classical LEKID design

High meandered inductance



Small interdigitated capacitance

f_0 dominated by L

$$f_0 \propto \frac{1}{\sqrt{LC}}$$

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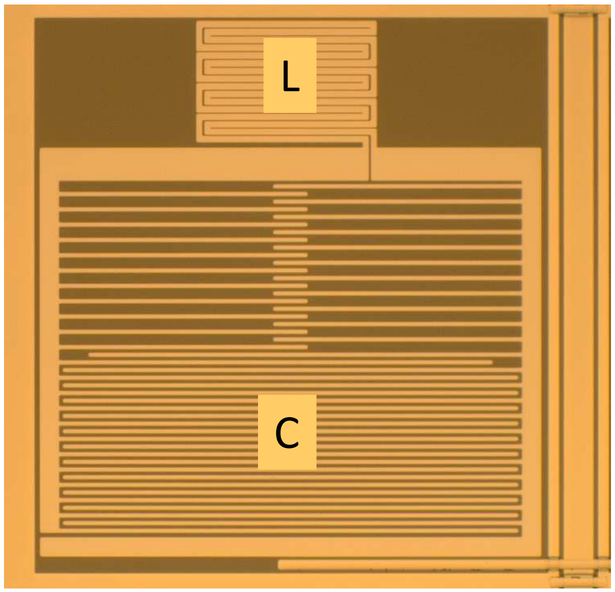

Small interdigitated capacitance

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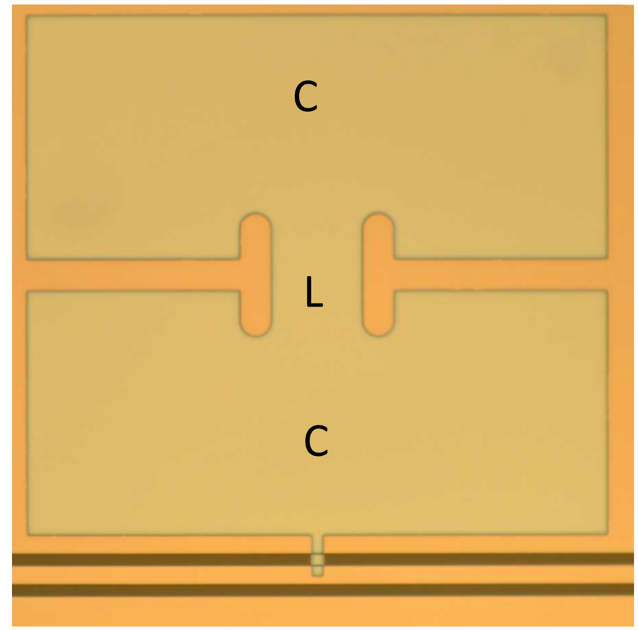
$$f_0 \propto \frac{1}{\sqrt{LC}}$$

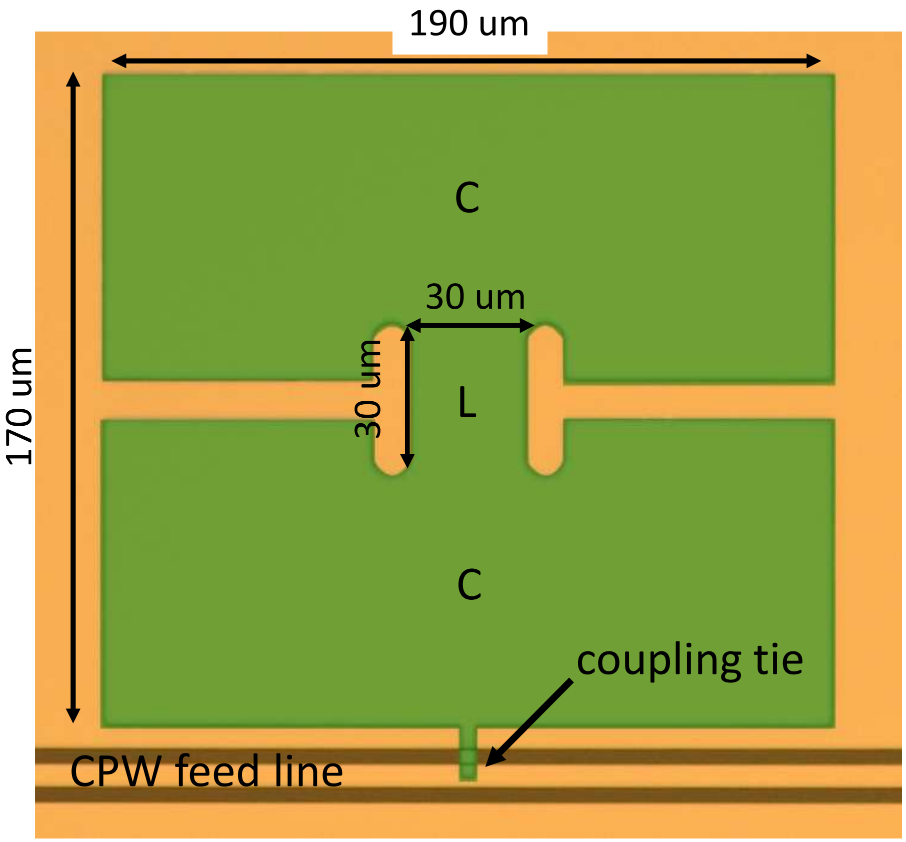
Parallel plate design



Major change = two large parallel plate capacitors and small square inductance

f_0 dominated by C

Parallel Plate Capacitor MKIDs



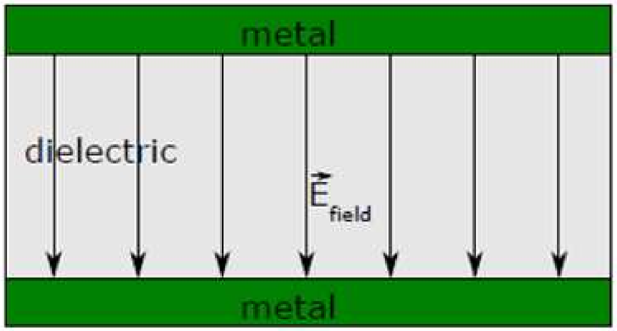
(color added for clarity – Insulator not shown)

- Maximize the readout power before nonlinear effects thanks to the low current density in the wide inductor (30umx30um)
- Improvement in signal-to-noise ratio due to the saturation of TLS (drive at high power)
- Inductor geometrically more uniform than a classical meandered inductor → increase energy resolution

Parallel Plate Capacitor MKIDs

$$S_{TLS}(\nu) = \kappa(\nu,\omega,T) \times \frac{\int_{V_{TLS}} \left|\vec{E}(\vec{r})\right|^3 d^3\vec{r}}{4\left(\int_V \left|\varepsilon(\vec{r})\vec{E}(\vec{r})\right|^2 d^3\vec{r}\right)^2}$$

J. Gao et al. Applied Physics Letters 92, 212504 (2008)



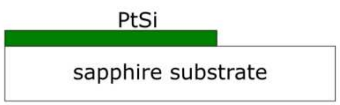
For a parallel plate capacitor: $V_{TLS} = V$

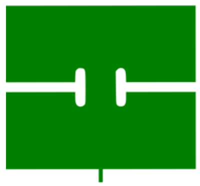
$$S_{TLS} \propto \frac{E^3 V}{4\varepsilon^2 E^4 V^2} \propto \frac{1}{\varepsilon^2 E V}$$

Lower TLS noise by:

- Using a high ε material
- Maximizing the electric field in the capacitor (driving the MKID at high power)
- Making the volume of the capacitor as large as possible

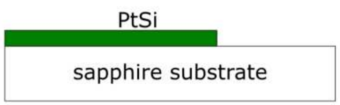
Micro-fabrication process

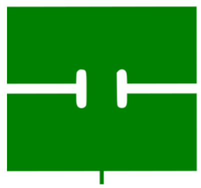




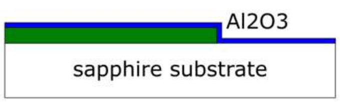
Sputtering of Pt and Si + annealing at 300C = 55nm thick PtSi film → Patterning of the inductor, the coupling tie and the first side of the parallel plate capacitor

Micro-fabrication process



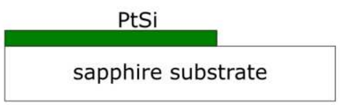


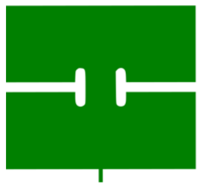
Sputtering of Pt and Si + annealing at 300C = 55nm thick PtSi film
→ Patterning of the inductor, the coupling tie and the first side of the parallel plate capacitor



Atomic layer deposition of 10 nm of Al_2O_3 over the entire wafer (thickness uniformity of 98% over a 4inch wafer)

Micro-fabrication process





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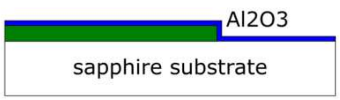

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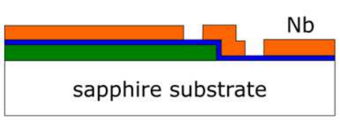
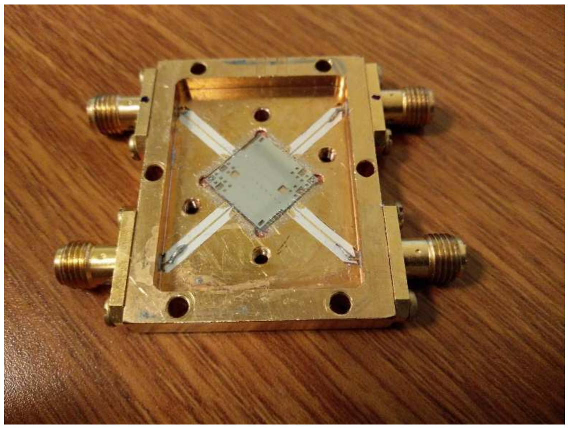
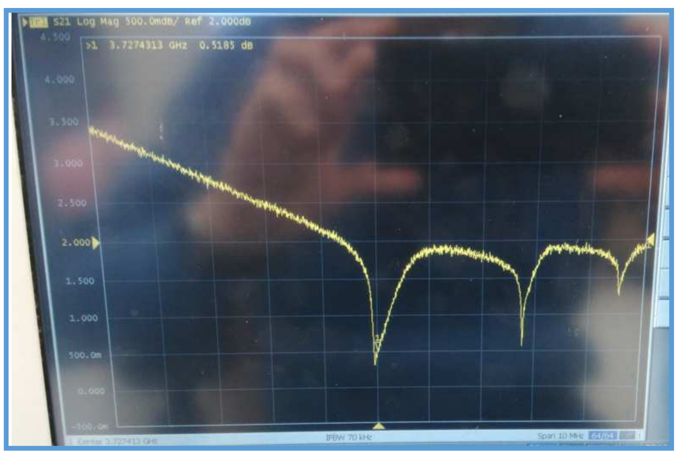


Sputtering of 80 nm of Nb
→ CPW feedline and second side of the capacitor

Characterization



Parallel plate MKIDs resonate

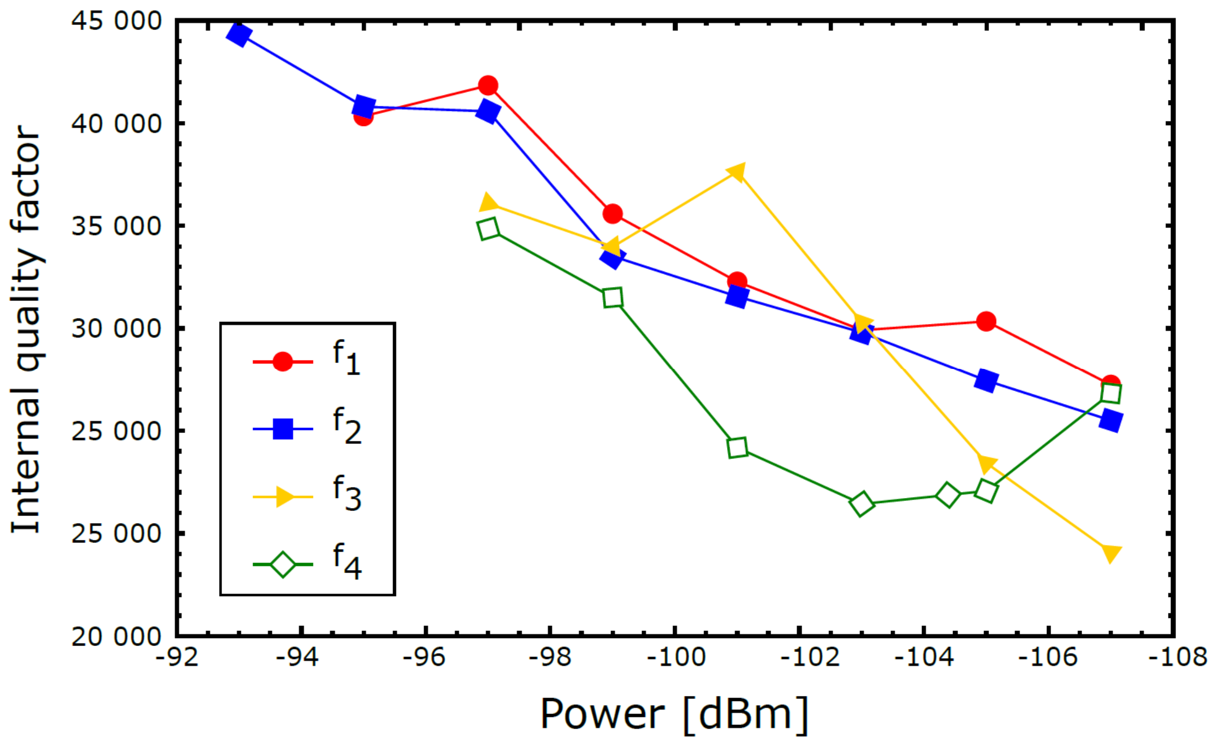


Test device:

- 2 feedlines (different inductor dimensions)
- 18 resonators, 3x6 centered on 4 GHz, 6 GHz and 8 GHz

- Resonances located around their design frequencies
- 13 resonances out of 18 were identified
- Few dB deep, best resonances Qi ≈ 35 000 – 40 000

Characterization



Qi increases as the power is increased
→ We tend to saturate TLS loss

Parallel plate MKIDs become nonlinear at high power: A factor of 4 compared to lumped element design

→ Qi are a bit low and we are missing photons data

Try next: crystalline Al2O3 annealing / ebeam deposition (pinholes?), new tri-layer insitu design Hf/HfO2/Hf

Low Tc material

Why lower T_C?

- Sensitivity $\propto \frac{1}{{T_C}^2}$

- Energy resolution $R \propto \sqrt{\frac{1}{T_C}}$

Low Tc material

Why lower T_C?

- Sensitivity $\propto \frac{1}{T_C^{\,2}}$

- Energy resolution $R \propto \sqrt{\frac{1}{T_C}}$

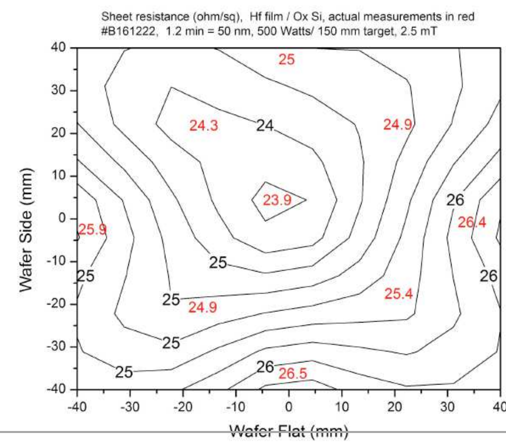
Why Hafnium?

- elemental material (easy to deposit)

- T_C ~ 400mK (Δ~eV)

- High normal state resistivity

- Good uniformity over a 3inch substrate



~ 5% variation (pretty much the same than our PtSi films)

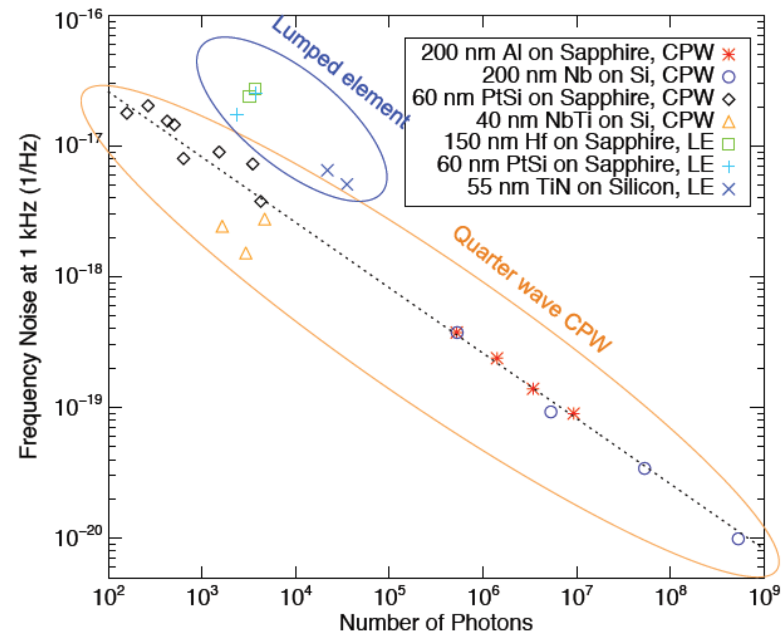
Resonator characterization

We fabricated several Hf test devices:

- Different substrate orientation (a-place, c-place, r-plane sapphire)
- Various sputtering parameter (try to further reduce T_C)
- Annealing of the Hf in-situ

125 nm of Hf sputtered on a-plane sapphire gave good preliminary results!

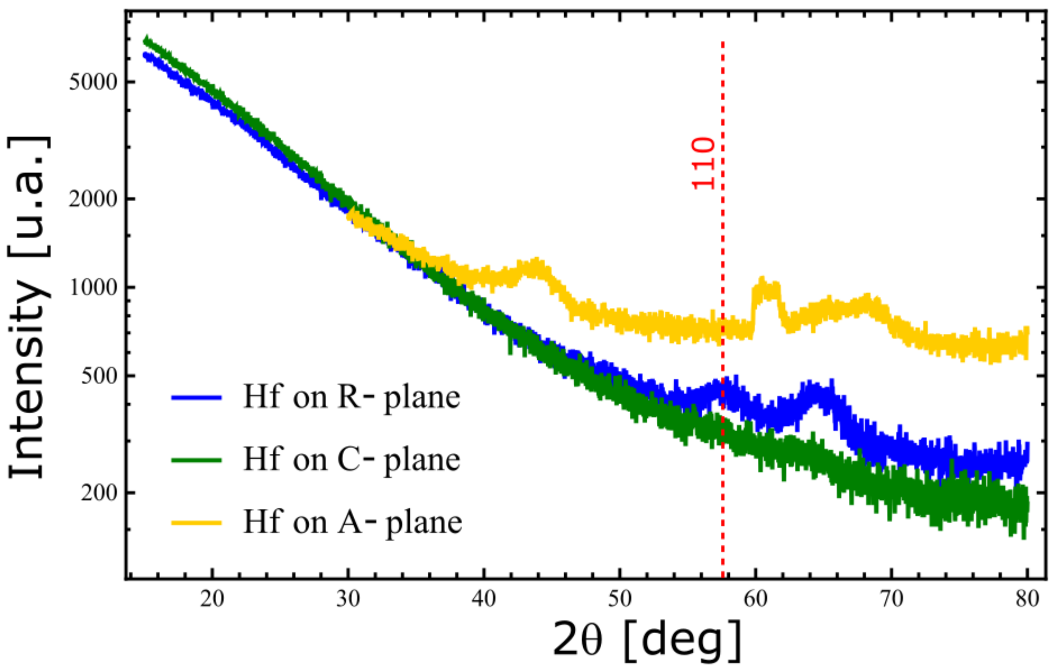
- Qi up to 500 000
- R ~ 9 @ 808nm
- First τ_{qp} on Hf ever measured ~ 30 μsec



Any correlation between crystal structures and performances?

→ It seems that the performances of our test device are substrate dependent

X-ray spectra for Hf deposited on different substrate



We saw :

- Nothing on C-plane
- low Qi resonators (~10k) on R-plane
- High Qi (~100k) on A-plane

Hard to find a correlation from XRD data?

Need to identify theses peaks

Perspective on low Tc materials

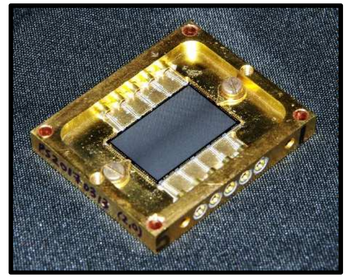
Hafnium:

- Try to further reduce Tc with reducing the stress in the films
- Improving uniformity?
- Improve heat sinking (very low temperature measurement! Tc/8 ~ 56mK)

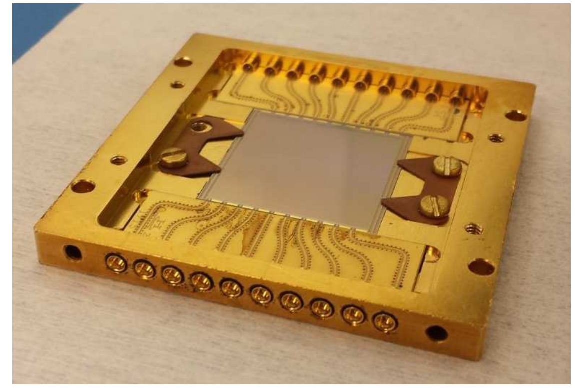
Other materials?

Conclusions

- We make large arrays of single photon detectors
- We achieved high performances (Qi~100 000, R~8)



DARKNESS
10 000 pixels



MEC
20 000 pixels

Conclusions

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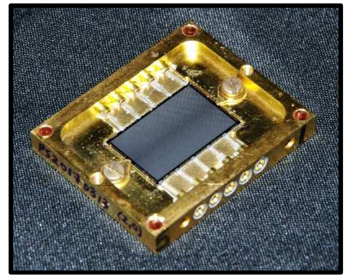
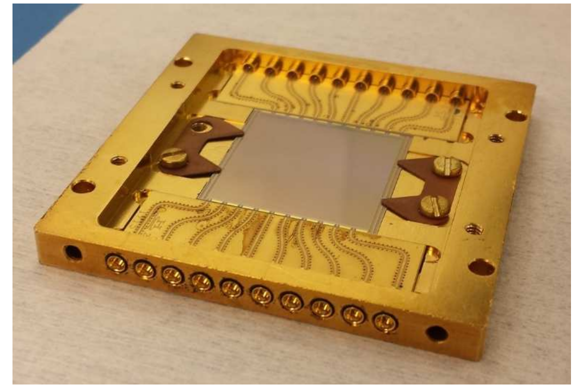
- We achieved high performances (Qi~100 000, R~8)

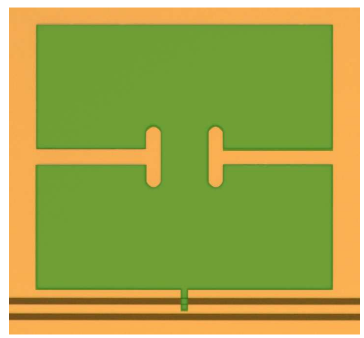


DARKNESS
10 000 pixels



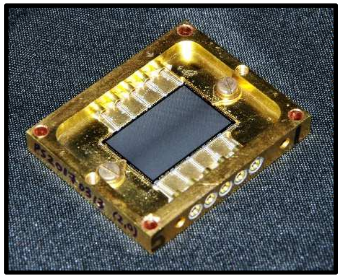
MEC
20 000 pixels

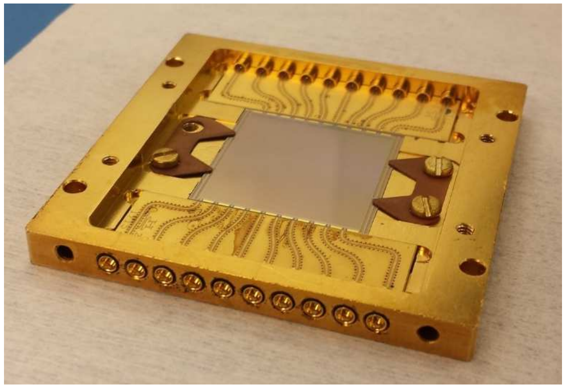
- Development of parallel plates MKIDs : We demonstrate high readout power by a factor of 4 compared to classical MKIDs



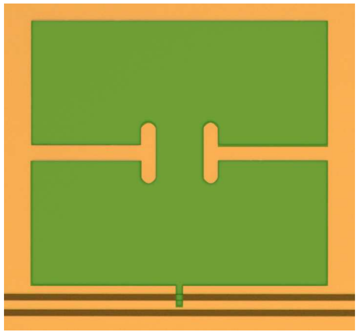
Conclusions

- We make large arrays of single photon detectors
- We achieved high performances (Qi~100 000, R~8)


DARKNESS
10 000 pixels

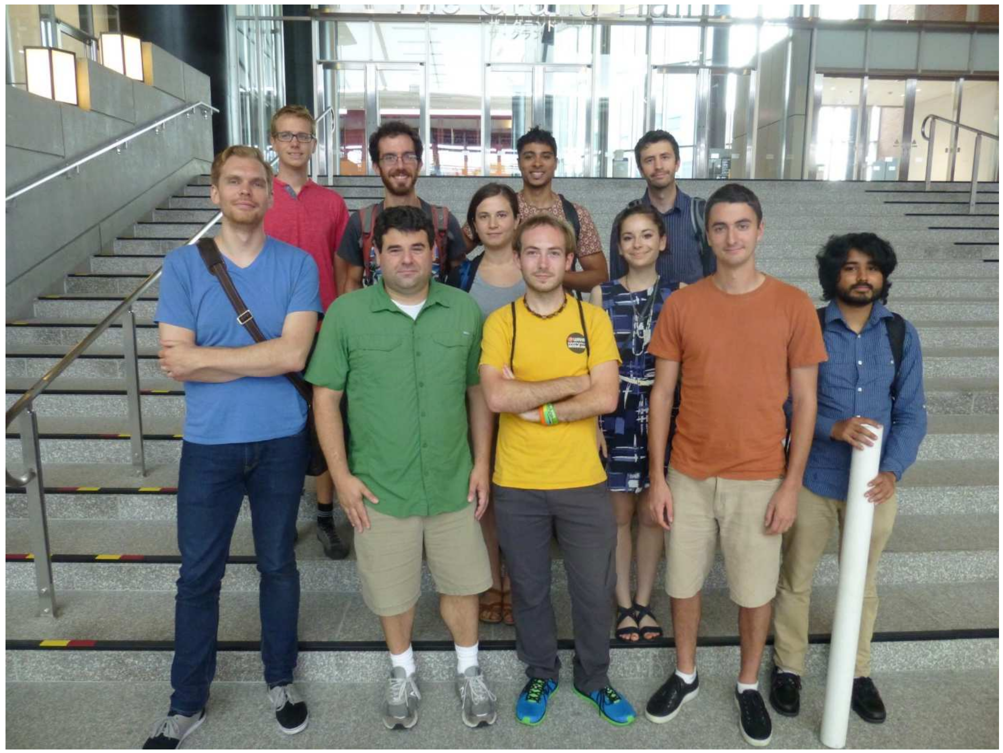

MEC
20 000 pixels

- Development of parallel plates MKIDs : We demonstrate high readout power by a factor of 4 compared to classical MKIDs



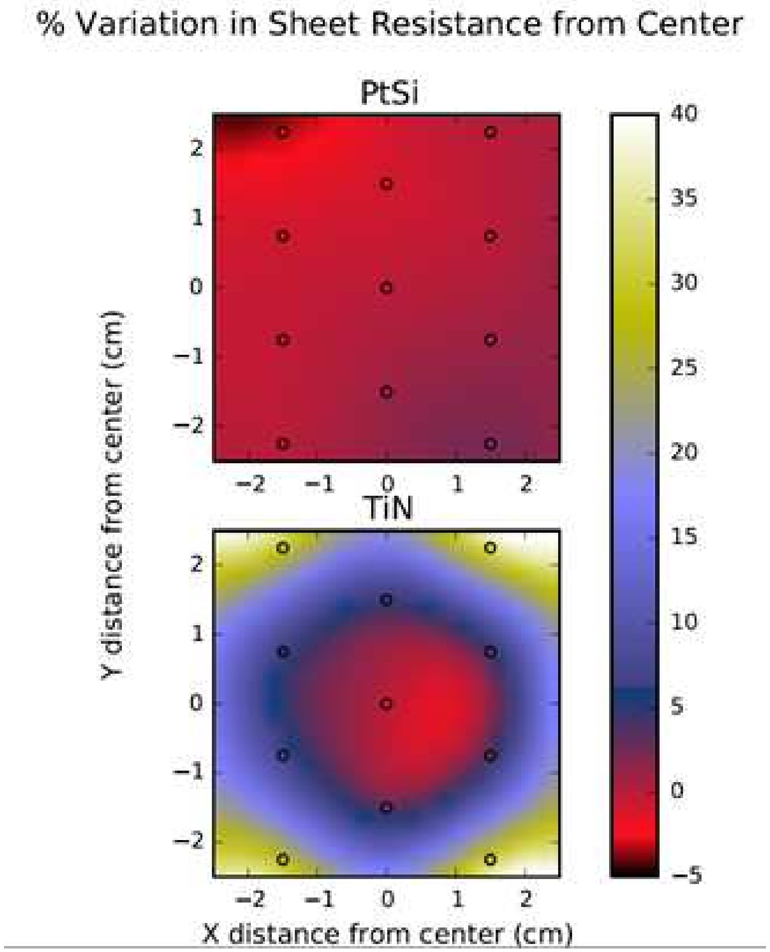
- Hafnium resonators are promising! We already have good Qi (>100 000) and energy resolution (R~9 @ 808nm) after only a few tests

Thanks!



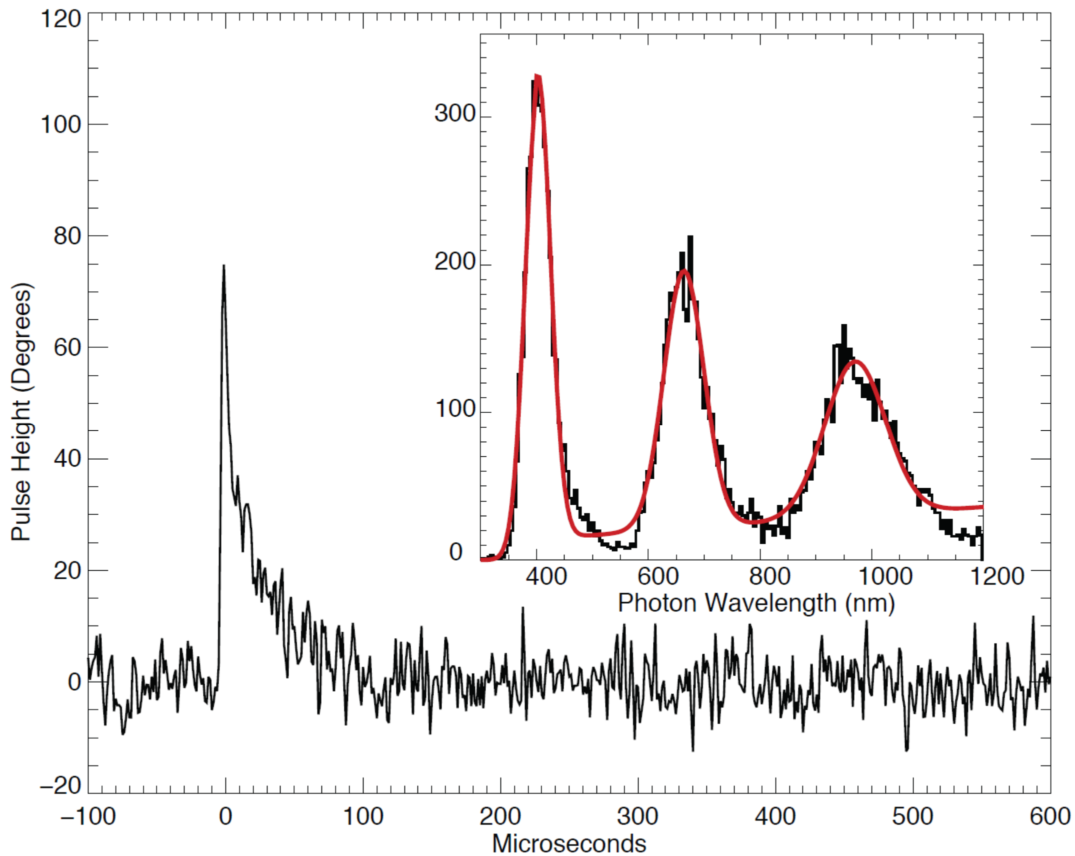
Uniformity

- Measured sheet resistance across full 4” wafers. Early estimates show PtSi to be roughly an order of magnitude more uniform than TiN.
- For 1K T_C films, PtSi is annealed to it’s thermally stable stoichiometry, whereas TiN requires precise control of the N_2 flow rate during Ti sputtering in a region where the TC is very sensitive to this Ti/N ratio.



Szypryt et al. 2016

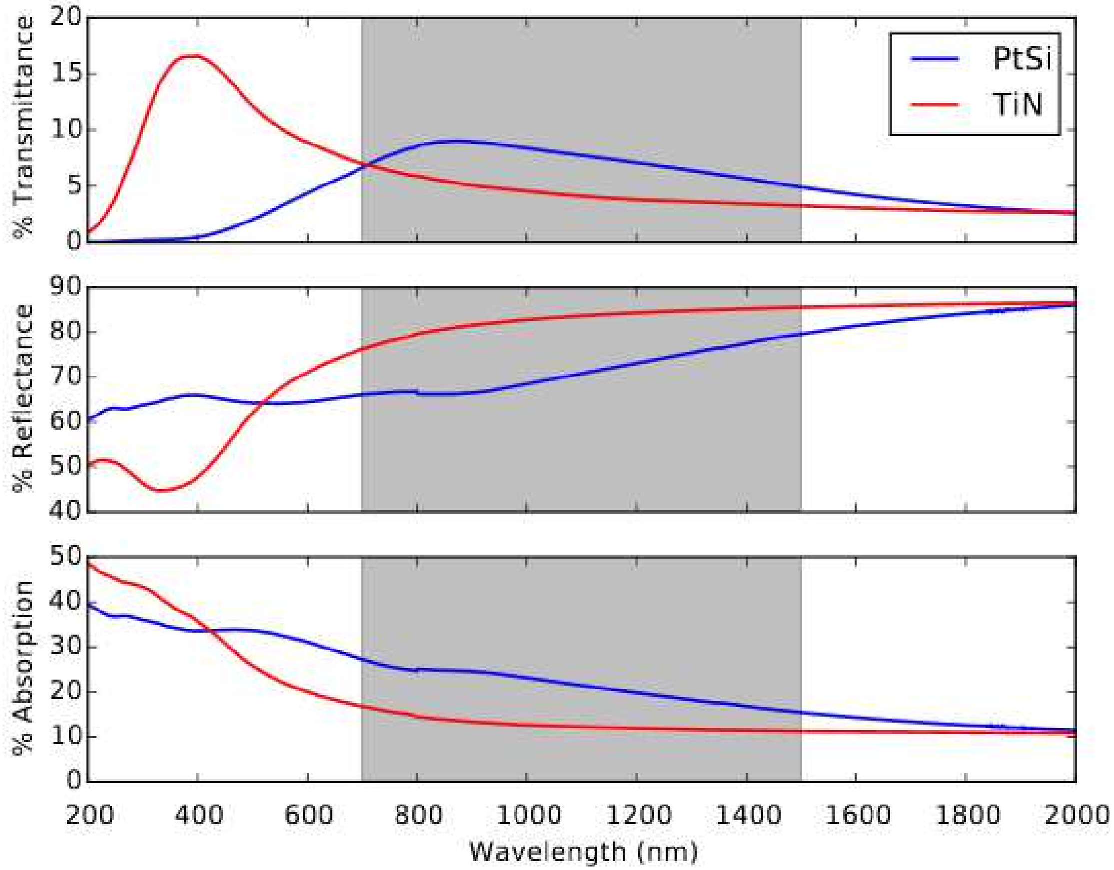
PtSi Pulses



Szypryt et al. 2016

- Measured quasiparticle lifetimes of 30-40 us.
- Fairly flat energy resolution of R=8 across observable wavelength band.

Quantum



Szypryt et al. 2016

- Shaded region represents wavelength band of DARKNESS instrument.