Microwave Kinetic Inductance Detectors for visible to near infrared astronomy

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On behalf of Mazin Lab
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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)
TiN vs. PtSi

Grégoire Coiffard – MKIDs workshop DIAS

Szypryt et al. 2016
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)
3) SiO$_2$ insulating pads

- Insulating pads over the feedline used to connect ground plane segments
- Reactive sputtering of SiO$_2$ (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
5) Gold Bond Pads

- Gold bond pads used for gold wire bonding (reduce heat excess)
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6) PtSi Resonator Etch
   - W and PtSi Etched with ICP etcher
   - Protect layer removed in heated H2O2
• 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

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)

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

\[ f_0 \propto \frac{1}{\sqrt{LC}} \]

\( f_0 \) dominated by \( L \)
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Parallel plate design

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

\( f_0 \) dominated by \( C \)
Parallel Plate Capacitor MKIDs

- 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

(color added for clarity – Insulator not shown)
Parallel Plate Capacitor MKIDs

\[
S_{TLS}(V) = \kappa(v, \omega, T) \times \frac{\int |\vec{E}(\vec{r})|^3 d^3 \vec{r}}{V_{TLS}} \times \frac{1}{4 \int |\epsilon(\vec{r}) \vec{E}(\vec{r})|^2 d^3 \vec{r}}^2
\]


For a parallel plate capacitor: \( V_{TLS} = V \)

\[
S_{TLS} \propto \frac{E^3 V}{4 \epsilon^2 E^4 V^2} \propto \frac{1}{\epsilon^2 EV}
\]

Lower TLS noise by:

- Using a high \( \epsilon \) 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
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Atomic layer deposition of 10 nm of Al₂O₃ over the entire wafer (thickness uniformity of 98% over a 4 inch wafer)
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Atomic layer deposition of 10 nm of Al₂O₃ over the entire wafer (thickness uniformity of 98% over a 4inch wafer)

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

Test device:
• 2 feedlines (different inductor dimensions)
• 18 resonators, 3x6 centered on 4 GHz, 6 GHz and 8 GHz

Parallel plate MKIDs resonate

• Resonances located around their design frequencies
• 13 resonances out of 18 were identified
• Few dB deep, best resonances $Q_i \approx 35\,000 – 40\,000$
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 $R \propto \sqrt{\frac{1}{T_C}}$
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Why Hafnium?

- Elemental material (easy to deposit)
- $T_C \sim 400\text{mK ($\Delta$~eV})$
- 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!
- $Q_i$ up to 500 000
- $R \sim 9$ @ 808nm
- First $\tau_{qp}$ on Hf ever measured $\sim 30$ µsec
Any correlation between crystal structures and performances?

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

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 these 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 ($Q_i \approx 100,000$, $R \approx 8$)

DARKNESS
10 000 pixels

MEC
20 000 pixels
Conclusions

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- Development of parallel plates MKIDs: We demonstrate high readout power by a factor of 4 compared to classical MKIDs
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• We make large arrays of single photon detectors
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• 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 its 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

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

Szypryt et al. 2016
Quantum

Shaded region represents wavelength band of DARKNESS instrument.

Szypryt et al. 2016

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