The properties of MKID made of crystal Al films and amorphous Al films

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Outline

• Sub-millimeter camera developments at NAOJ
  - lens, double slot antenna
• Motivation
• Epitaxial Al films using by MBE
• Results
Long-term Goal

- Pixel: 10000 (2015)
- Frequency 100 GHz (3mm) – 3 THz (100 um)
- NEP $\sim 10^{-19}$ W/Hz$^{1/2}$
- Dynamic Range $> 10^5$
- Simple, compact and low cost instrument as well as high performance
### Millimeter Camera Development at NAOJ ATC

**Collaborator**
- Satellite for B-Mode Polarization of CMB, LiteBIRD
  - KEK, RIKEN, Okayama Univ.
- mm-wave Telescope in Antarctica
  - Univ. of Tsukuba

### Short-time Schedule

<table>
<thead>
<tr>
<th>year</th>
<th>pixel</th>
<th>MKID + optics</th>
<th>Other task</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>120</td>
<td>9 pixel</td>
<td>multiplex readout</td>
</tr>
<tr>
<td>2011</td>
<td>400</td>
<td>102 pixel</td>
<td>$10^{-17}$ (W/Hz$^{1/2}$)</td>
</tr>
<tr>
<td>2012</td>
<td>1000</td>
<td>1024 pixel</td>
<td>System</td>
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</table>
Overview of the camera design

- Microwave Kinetic Inductance Detector (Day, 2003)
- Lens coupled double slot antenna (Fillipovic, 1993)

MKID

Double Slot Antenna 500 um

9 pixel @ 220 GHz

102 pixel @ 440 GHz
Overview of the camera design

- Microwave Kinetic Inductance Detector (Day, 2003)
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102 pixel @ 440 GHz

Double Slot Antenna 500 um

9 pixel @ 220 GHz
Fabrication of Lens Array

Machining by High-speed spindle

- Prototype Silicon Lens Array
  - 3 x 3 array
  - Lens diameter: D = 4.09 mm → 3 x 1.36 mm (= 220GHz)
  - Extension thickness: L = 0.35 mm → good beam quality

P-V: 20 um

completed 9 pixel silicon lens array
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Origins of Noise

Generation-Recombination Noise (Barends, 2009)

$$\text{NEP} \propto \left( \frac{N_{qp}}{\tau_{GR}} \right)^{1/2}$$

$$N_{qp} \rightarrow \text{low temperature} \quad (< Tc/10)$$

Gap energy vs $T$

Number of quasi-particle vs $T$

$$\text{NEP} = \frac{1}{N_{q}N_{q}^{*}V_{eff}} \int_{\Delta}^{\hbar} \frac{1 - 2 f(E)}{\sqrt{E^2 - \Delta^2}} dE$$

$$n_{qp} = 2N_{q}^{*}(0) \int_{\Delta}^{\infty} N(E)f(E)dE$$
Improvement of Sensitivity

Generation-Recombination Noise (Barends, 2009)

\[ \text{NEP} \propto \frac{N_{qp}}{\tau_{\text{GR}}} \]

- \( N_{qp} \rightarrow \text{low temperature} \quad (\textcolor{red}{<} \text{Tc/10}) \)
- \( \tau_{\text{GR}} \rightarrow \text{weak electron-phonon coupling (Al, Ta, TiN)} \)

- \( \text{T dependence of Quasiparticle lifetime} \)

\[ \text{Generation-Recombination diagram of cooper pair} \]

\[ \text{quasi-particle} \quad \text{phonon} \]

\[ \text{cooper pairs} \quad \text{N(E)} \]
Is Film Quality Important?

Barends, 2009
Epitaxial Aluminum films

<table>
<thead>
<tr>
<th>Metal</th>
<th>Dielectric</th>
<th>W (µm)</th>
<th>tanδ_eff</th>
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<tbody>
<tr>
<td>Nb (poly)</td>
<td>“wet” SiO₂/Si</td>
<td>10</td>
<td>2.4e-5</td>
</tr>
<tr>
<td>Nb (poly)</td>
<td>Si</td>
<td>10</td>
<td>1.5e-5</td>
</tr>
<tr>
<td>Nb (poly)</td>
<td>Sapphire</td>
<td>10</td>
<td>1.8e-5</td>
</tr>
<tr>
<td>Al (poly)</td>
<td>“dry” SiO₂/Si</td>
<td>10</td>
<td>2.0e-5</td>
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<tr>
<td>Al (poly)</td>
<td>Si</td>
<td>10</td>
<td>1.5e-6</td>
</tr>
<tr>
<td>Al (poly)</td>
<td>Sapphire</td>
<td>10</td>
<td>1.6e-6</td>
</tr>
<tr>
<td>Al (epi)</td>
<td>Sapphire</td>
<td>10</td>
<td>1.8e-6</td>
</tr>
<tr>
<td>Re (epi)</td>
<td>Sapphire</td>
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<tr>
<td>TiN (poly)</td>
<td>Si</td>
<td>10</td>
<td>9.6e-7</td>
</tr>
</tbody>
</table>

Only Q measurements!

(Sage, 2011)
What is a good quality film?

- Decreasing defects and impurities, smooth surface
- Reduce the probabilities of scattering and resistivity
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Molecular Beam Epitaxy

Cartoon of MBE chamber

Cartoon of crystal growth
Crystal Aluminum on Si wafers

Molecular Beam Epitaxy

Al on Si (111) wafer
Thickness 160nm
Cleaning: BHF + 650 deg. (20 min)
Back ground: 2×10^-8 Pa
Wafer: 75 deg.
XRD and AFM measurements

X-ray diffraction pattern

Picture of Al surface with AFM
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Measurement Set-up

Block diagram

- Signal generator (4-8 GHz)
- KIDs
- CLNA
- Coaxial Cable
- 0.1 K Cryostat
- Re[S21]
- Im[S21]

0.1 K Stage

- KIDs
- MW

0.1 K dilution refrigerator

lab
NEP Calculations (Baselmans, 2008)

Eq. (1) \[ \text{NEP}^2 = S_x \left( \frac{\pi \tau}{\Delta} \left( \frac{\partial x}{\partial N_{qp}} \right) \right)^{-2} (1 + \omega^2 \tau^2)(1 + \omega^2 \tau_{res}^2) \]

Eq. (2) \[ \frac{\partial \theta}{\partial N_{qp}} = \frac{\partial R}{\partial F} \frac{\partial N_{qp}}{\partial N_{qp}} = \frac{\partial R}{\partial \theta} \frac{\partial \theta}{\partial N_{qp}} = \frac{4}{F_0} - \text{noise responsibility lifetime} \]

Eq. (3) \[ \frac{\partial R}{\partial N_{qp}} = \frac{\partial R}{\partial \theta} \frac{\partial \theta}{\partial N_{qp}} = 0.26 \frac{\partial \theta}{\partial N_{qp}} \]
Noise Measurements

S21 spectrum @140 mK

IQ spectrum and fluctuation

Noise Spectrum
$F_0$ vs $N_{qp}$

$N_{qp}$/volume ($\text{um}^3$) vs $T$

$f_0$ vs $N_{qp}$

0.1-0.55 K

EB-Al

$f_0$ vs $T$

$\delta f_0/f_0$ vs Temperature (K)
Relaxation Measurements

MBE-Al on Si(100) @230mK
LED pulse duration 50 us
Electrical NEP of MKID
Why NEP is Equivalent?

- Good vs Poor

- NEP (W/Hz^{1/2})
  - MBE 140 nm Bad
  - Sputter 100 nm

- RRR vs Temperature (K)

- Quasiparticle Lifetime (s)
  - MBE–Al (7.08 GHz)
  - EB–Al (4.52 GHz)
  - Theory (Kaplan)
Why NEP is Equivalent?

- Limited by the measurement system?
- The film quality is not enough?
Light-tight Set-up

Life time vs T

Low pass coax filter (Milliken, 2007)

Baselmans, 2008
Background Pressure

$2 \times 10^{-8} \text{ Pa} \rightarrow < 10^{-9} \text{ Pa}$

Ion pump + TSP  TMP  chamber

AVC inc.
Summary

- MKID camera @ NAOJ.
- The properties of the epitaxial Al film is so far equivalent to that of amorphous one.
- Improving the set-up and vacuum system.