



# Microwave Kinetic Inductance Detectors (MKIDs): Background and First Results on Photon Detection

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# Superconducting Kinetic Inductance Detectors



<u>SQUID readout</u> :

McDonald and Sauvageau (IEEE Trans. Magn. 25, 1331 (1989)).

Near Tc operation.

Grossman, McDonald and Sauvageau (IEEE Trans. Magn. 27, 2677 (1991)).

Equilibrium and non-equilibrium response.

Bluzer (PRB 44, 10222 (1991), JAP 78, 7340 (1995)).

Sergeev and Rizer (Int. J Mod. Phys. 10, 635 (1996)); Sergeev, Mitin and Karasik (APL 80, 817 (2002)).

Advantages of T<<Tc operation

Microwave readout :

VanVechten et. al. (Nucl. Instrum. Meth. A370, 34 (1996)).

Non-resonant, transmission loss

# **Pair-Breaking Detectors**



• Finite gap energy

-Quasiparticle lifetime  $t_{qp} \sim 1/n_{qp} = 10^{-6} - 10^{-3}$  sec –Thermal quasiparticle density scales as  $n_{qp} \sim exp(-D/kT)$ -Fundamental sensitivity set by quasiparticle generationrecombination noise, scales as  $(n_{qp}/t_{qp})^{1/2} \sim exp(-D/kT)$ quasiparticles (N ~  $h\nu/\triangle$ )  $N_s(E)$ photon Cooper pair



# Kinetic Inductance and Surface Impedance

- For AC currents:
  - Accelerative response of supercurrent:  $\Lambda \partial \vec{J}_{s} / \partial t = \vec{E}$
  - Allows kinetic energy storage in supercurrent
  - B penetrates a distance | into the surface
     → magnetic energy storage.
  - "kinetic inductance" effect: surface inductance  $L_s = m_0 I$
  - Surface impedance Zs = Rs + i Xs = Rs + iwLs
    - $Xs \gg Rs$ , for  $T \ll Tc$

# Surface Impedance vs. Quasiparticle Density



- $\delta X_s$ ,  $R_s$ ,  $n_{qp}$  all decrease exponentially with temperatures
- $\delta X_s$ ,  $R_s$  have nearly constant response to changes in  $n_{ap}$



# Measurement of Surface Impedance with a Microwave Resonator

- Quarter wave resonator
  - resonance 'dip'
- Response scales with Q





$$f_{0} = 4\overline{c} / l, \quad \overline{c} = (LC)^{-1/2}$$

$$L_{tot} = L_{geom} + L_{k}$$

$$\alpha \equiv L_{k} / L_{tot} \quad (K.I. \text{ fraction})$$

$$\delta f / f_{0} = -\frac{1}{2} \alpha \, \delta L_{s} / L_{s}$$

$$\delta \theta = \frac{Q\alpha}{f_{0}} \, \delta L_{s} / L_{s}$$

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# Multiplexing



Frequency domain muliplexing

Excite with a 'comb'

Can use single cryogenic amplifier

Multiplexing factor determined by Q, cross talk, lithographic precision

See talk Y02



#### A Test Device



#### CPW 0.2mm aluminum on sapphire $L = 3mm \rightarrow 10 GHz$ А Q = 55,000; a = 0.04;**28** µm V=2000mm<sup>3</sup> В 7 μm Strip conductor Ground planes Dر εr Substrate

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# Rough Estimate of Responsivity



$$\delta L_{s} / L_{s} \sim \delta n_{qp} / N_{0} \Delta$$
$$|\delta f| / f_{0} = \frac{\alpha}{2} \delta L_{s} / L_{s}$$
$$\alpha \approx 0.04, \quad V = 2000 \,\mu \text{m}^{3}, \quad \Delta \approx 0.171 \text{meV}$$

For a 5.9 keV photon

$$\rightarrow |\delta f| / f_0 \sim 3 \times 10^{-5} > 1/Q = 2 \times 10^{-5}$$

• Large frequency shifts expected

#### Readout Circuit





#### X-Ray Events



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I-Q trajectory





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# **Decay Times**





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#### **Decay Times**





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# 'Thermal' Calibration of Responsivity



- Measure response to temperature changes
- thermally excited quasiparticles



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Noise Measurements

- Amplifer noise can be measured off resonance
- On resonance noise exceeds the readout noise





#### Noise Measurements







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# Coupling



- Use absorbers with higher D
- Quasiparticle diffusion / trapping





• Antenna coupling

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# Ultimate Sensitivity

- Assume amplifier limited noise (with  $T_N = 5K$ )
- Assume readout power scales inversely with a Q / V



# Conclusions



- MKIDs appear to be very interesting for large-format detector arrays (10<sup>3</sup>-10<sup>4</sup> pixels, or larger ?)
- Basic detector physics has been demonstrated
- Observed single-photon X-ray pulses with high SNR
- Much work remains to be done !