Kinetic Inductance Detectors for X-ray Science

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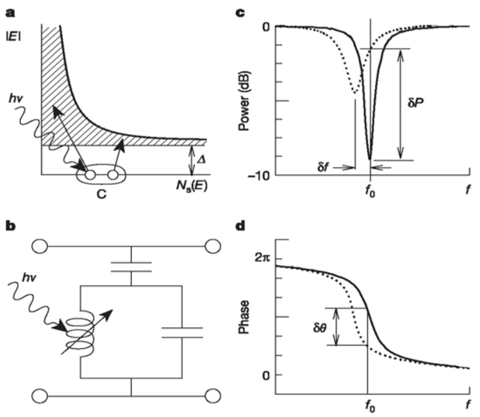
Overview

The lack of efficient X-ray detectors is often the main factor limiting the effective use of ever more powerful synchrotron light sources. The current state-of-the-art spectroscopic X-ray detectors are semiconductor devices, and their energy resolutions are approaching their theoretical limit of about 100eV at 6 keV. We describe a detector research and development program to develop the next-generation of high-resolution spectroscopic X-ray detectors using superconducting Microwave Kinetic Inductance Detectors (MKIDs). MKIDs offer up to two orders of magnitude increase in energy resolution and can be optimized for detection of photons ranging in energy from hard X-ray to IR.

MKID Operation

Superconducting kinetic inductance detectors detect the change in quasi-particle density due to an absorbed photon through the change in kinetic inductance. The change in kinetic inductance can be read out by forming the superconductor into a high Q resonator



(a) **Photons break Cooper pairs in a superconductor, creating quasiparticles.**
(b) Quasiparticles change the inductance of a resonant circuit.
(c) The resonance shifts to lower frequency and becomes broader and shallower.
(d) The density of quasiparticles, which reflects the absorbed energy, can be monitored by measuring the shift in phase of a microwave signal sent through the resonator.

Detector Design

To readout the change in kinetic inductance the superconductor is patterned into a high quality factor (~10^6) resonant circuit

¼ λ CPW resonator with Absorber

Advantages
- Thin CPW resonator = high sensitivity
- Thick absorber = high stopping power
- Strip detector enables position sensitivity

Disadvantages
- Additional fabrication steps with two layers
- Resonator-absorber interface issues
- Absorber requires large diffusion length
- Non-uniform pixel spacing

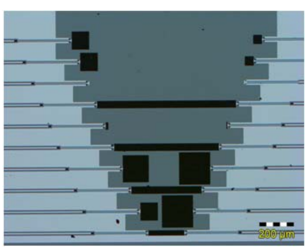
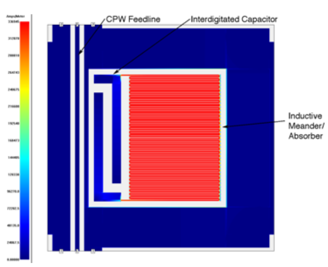


Photo of Al CPW MKID with Sn absorber fabricated at ANL

Lumped Element LC resonator

Advantages
- Single layer for easy fabrication
- Does not require large diffusion length
- Easy to create uniformly spaced pixels

Disadvantages
- Trade off between sensitivity and stopping power
- Complex RF design – current in inductor must be uniform to prevent spatial variation in sensitivity



SONNET simulation of current density in a 100um pixel

Instrumentation

Superconducting: How Cold?
- Operating Temperature < 10% of T_C
- Lower T_C gives better resolution
- Tantalum absorber (with Al MKID)
  - T_C = 4.3K
  - Theoretical Resolution: 2.8eV at 6keV
  - Operates at 100mK

Adiabatic Demagnetization Cryostat
- Cryogen free cryostat
- Pulse tube cooler with adiabatic demagnetization salt pills
- 50mK base temperature
- 150 hours at 100mK (no heat load)
- Ports for use on SEM (snout for use at beamlines)

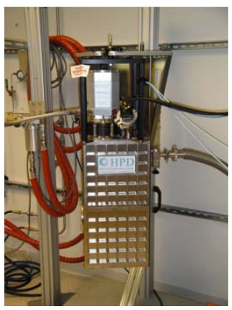
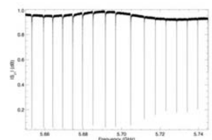


Photo of ADP cryostat and stand from HPD @ APS

Frequency Multiplexing
- High quality factor allows passive frequency domain multiplexing
- Arrays of several thousand pixels using a single LNA and coax cable
- Transfer complexity from cryogenic electronics to room temperature RF electronics.



Insertion Loss (S21) of an array of MKIDs

ROACH Board
- Reconfigurable Open Architecture Computing Hardware (developed by the Radio Astronomy community)
- Xilinx Virtex 5 FPGA board with 10 Gbe interface
- Configurable with ADC and DAC boards for signal synthesis and analysis

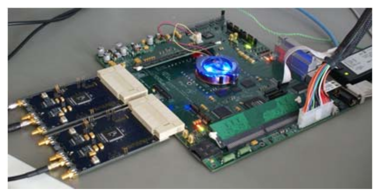
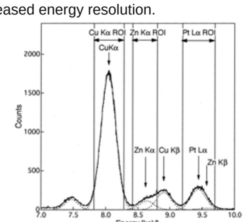


Photo of ROACH board with two ADC boards

Applications

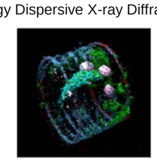
Silicon-based energy dispersive detectors have almost reached their theoretical energy resolution (i.e., Fano noise) of ~100eV at 6 keV.

X-ray Fluorescence Microscopy
- Requires wideband energy resolving detectors with sufficient energy resolution, count rate capabilities and solid angle coverage.
- MKIDs can be multiplexed to give large count rate throughput and large solid angle with increased energy resolution.



XRD spectrum of a cancer cell with uptake of platinum anticancer agents; there is considerable overlap of fluorescence lines.
(P. Ilinski, et al 2003)

Pixelated Detectors with Energy Resolution
- There are few larger area /pixelated detectors with energy resolution
- MKID are a path towards pixelated detectors with energy resolution
- Some applications include:
  - X-ray Fluorescence Tomography
  - X-ray Powder Diffraction
  - Energy Dispersive X-ray Diffraction



3D distributions of the elements (Si, P, S, Cl, K, Ca, Mn, Fe, Cu, and Zn) in the freshwater diatom *Cyclotella meneghiniana*
(de Jonge, et al 2010)