Superconducting Transition-Edge Sensors and Superconducting Tunnel Junctions for Optical/UV Time-Energy Resolved Single-Photon Counters

Blas Cabrera - Stanford University

NHST Meeting
STScI - Baltimore
10 April 2003
**TES versus STJ Comparison**

**TES**

\[ \Delta E_{FWHM} = 2.355 \sqrt{4 k_B T_e^2 C \sqrt{\frac{n}{2}}/\alpha} \]

- \( n = 5 \) electron-phonon coupling
- \( T_e \approx T_c \)
- \( E_{sat} \approx T_c C/\alpha \)

\[ \Delta E_{FWHM} = 2.355 \sqrt{6.4 k_B T_c E_{sat}} \]

\[ \Delta E_{FWHM} \approx 15 \text{ meV} \left( \frac{E_{sat}}{1 \text{ eV}} \right)^{1/2} \left( \frac{T_c}{70 \text{ mK}} \right)^{1/2} \]

**STJ & L_K**

\[ \Delta E_{FWHM} \approx 2.355 \sqrt{E \varepsilon_0 (F + G)} \]

- \( \varepsilon_0 \approx 1.7 \Delta \approx 1.7(1.76 k T_c) = 3 k T_c \)
- \( F \approx 0.2 \) is the Fano factor
- \( G \approx 1 - 2 \) (tunneling noise)

\[ \Delta E_{FWHM} \approx 2.355 \sqrt{3.6 k T_c E} \]

\[ \Delta E_{FWHM} \approx 45 \text{ meV} \left( \frac{E}{1 \text{ eV}} \right)^{1/2} \left( \frac{T_c}{1 \text{ K}} \right)^{1/2} \]
STJ & TES Advantages

• Single photon counting
  – Time-stamping (better than 0.1 μs is possible)
  – Low resolution spectroscopy ($R \sim 100 (\lambda/100 \text{ nm})^{1/2}$)

• Broadband from near IR to far UV on up to x-rays
  – Same technologies scale through large dynamic range

• High efficiency
  – Greater than 50% in optical and UV
  – With coatings nearing 100% is possible
Optical Photon Detectors

- Demonstration of W TES sensitivity

\[ \text{Sensor Current Change} \quad [\mu \text{A}] \]

\[ \text{Bias Current} \quad [\mu \text{A}] \]

\[ \text{Time} \quad [\mu \text{sec}] \]

531 nm photon

Appl. Phys. Lett. 73, 735 (1998)
B. Cabrera, R. Romani, A. J. Miller
E. Figueroa-Feliciano, S. W. Nam
Monochromator Calibrations

[Diagram showing graph with labeled axes: Counts, Spectrum [bins], Incident Photons [eV], Bins, Energy [eV]. Annotations: rail hits, 2nd order, IR thermal background.]
Background Subtracted Energy vs Phase

Phase timing histogram

Photon energy histogram

Counts

0 100 200 300 400 500 600 700

Phase

0 0.5 1 1.5 2
Calibration Data and PSF

![Graph showing photon energy and rate](image)

**2.026 eV**

**1.000 eV**

**thermal photons**

**substrate hits**

**rail hits**

**new design**

**Al/Si mask blocks substrate and rail hits**

**W TES**

**rail hits**

**substrate hits**

**W TES**
Optical 4 X 8 Imaging Array

- W TES imaging array with 20 µm x 20 µm pixels
Reflection mask

- Reflection mask keeps photons off of wiring and reflects those that would hit rails back into TES sensors.
NIST Multiplexing Scheme for 32 X 32 array

Talk by S. W. Nam

- SQUID amps at top of columns read row that is addressed.
**TES versus STJ Comparison**

**TES**
- $\Delta E_{\text{rms}} = 15 \text{ meV} (T_c/70 \text{ mK})^{1/2}$ at 1 eV in principle
- Pixel size restricted by $C$
- Operate below 0.1 K (ADR)
- **Control of $T_c$**
- Count rates $\sim 10$ kHz
- SQUID readout
- $R \sim 20$ at 3 eV in field
- 2 X 2 fiber coupled in field
- **Multiplexing demonstrated**

**STJ**
- $\Delta E_{\text{rms}} = 45 \text{ meV} (T/1 \text{ K})^{1/2}$ at 1 eV in principle for Al
- Pixel size more flexible
- Operate below 0.3 K ($^3$He)
- Control of junction barrier
- Count rates $\sim 10$ kHz
- FET readout
- $R \sim 5$ at 3 eV in field
- 6 X 6 image array in field
- RF SET multiplexing ideas (new $L_K$ multiplexing idea)

Most important: How to get to larger arrays!!
Expected Resolution

![Graph showing the expected resolution as a function of photon wavelength. The graph has a downward sloping line indicating a decreasing resolution with increasing photon wavelength.]
Best Applications

• Point source spectrophotometers
  – Pulsars, neutron stars and black holes

• Redshifts of faintest galaxies
  – Obtain direct redshift to 28 M_v

• Excellent choice for combined x-ray, optical UV
  – Many Constellation X sources are compact or faint

• Note: cryogenics for satellites will be solved by x-ray, EUV solar and CMB missions
Simulated background subtracted spectra from one 0.1” pixel of a TES array on a 1 m aperture space passively cooled telescope, with 0.05 eV resolution and 10 hr exposure. Continuum breaks and a number of lines are well detected; broad (e.g., active galactic nucleus) lines are resolved in the blue.
Other Applications

• Order sorting spectrophotometer
  – Higher efficiency and lower read noise than MCP with dispersive optics

• Not solar blind
  – Requires filters (e.g. Woods filter) loosing efficiency
  – May have lower backgrounds than MCP
Order Sorting Scheme
STJ & TES Arrays

• Demonstrated
  – 8^2 STJ imaging array by ESA
  – 2^2 TES array by Stanford/NIST

• Under construction
  – 10^2 STG imaging array by ESA
  – 8 X 4 TES imaging array by Stanford

• In five to ten years
  – 32^2 either TES multiplexing or one FET per STJ pixel
  – 256 pixels programmable in a 1024^2 array
  – 256^2 requires new ideas and electronics advances
  – RF SET for STJ & kinetic inductance allow frequency domain multiplexing
Programmable Large Array

- For example: $1024^2$ pixels of which 256 can be selected for a particular field and then another field can be programmed in.
Conclusions

* TES Technology Ready for Initial Astronomical Application
* ‘Killer App’ Still Compact Object Spectrophotometry
* An almost Perfect Detector (But still optics for Polarization)
* Next: More Pixels and a ride to Space.
Simulate pulses including noise

- Array of pulses for 1, 2, 3, 4, and 5 eV photons which include all Johnson and phonon noise terms
- Template array of 256 energies where noise terms set to zero
Compare with Theory

Dotted red lines are theory FWHM for 1 eV and 5 eV saturation and envelope following square root of energy dependence.

The deviation of nonlinear results from square root energy dependence due to loss of high frequency information from time binning.