Abstract. We are developing photon-counting cameras employing cryogenic arrays of energy-resolving TES (Transition Edge Sensor) pixels. These are being tested in ground-based instruments, but will have their greatest impact when employed on space platforms, where they can cover the 10\(\mu\)m-100nm range with high time- and moderate energy-resolution. Here we summarize briefly existing device performance, current directions in array camera development and anticipated capabilities.

1. Introduction and Present UV-IR TES performance

Cryogenic energy-resolving photon detectors show considerable promise for advanced instrumentation in several wavebands. In the near-IR through UV, these devices provide noise-free photon counting with \(\leq \mu\)s time resolution at \(\delta E \approx 0.15\text{eV}\) energy resolution. Early work focused on superconducting tunnel junction devices (Perryman, Foden & Peacock 1993; Peacock, these proc.), but alternative cryogenic technologies show great promise. Our group has pursued the application of superconducting TES devices to this problem (Cabrera et al. 1998). Our detectors are pixel arrays of 40nm thick tungsten (W) films patterned on Si. When cooled below their \(\sim 100\text{mK}\) transition temperature and voltage biased to produce negative electro-thermal feedback (Irwin 1995), an absorbed photon decreases the Joule-heating current. This pulse signal is read out with a DC SQUID array (Welty & Martinis 1993). Bi-layer thin films, a variety of substrates, and multiplex schemes to read out larger arrays are also under development and TES array technology is finding interesting application from the sub-mm (SCUBA-2) to the X-ray (Con-X) regimes.

Miller et al. (2000) summarize performance of present W TES devices. We routinely achieve \(\delta E \sim 0.15\text{eV}\) at \(\sim 3\text{eV}\), absolute GPS photon times to
300ns and single-pixel count rates of $\sim 30$kHz. Energy discrimination rejects all cosmic rays and allows no ‘dark current’ above the noise floor. The intrinsic bare W quantum efficiency is $\sim 50\%$ and in astronomical systems we have achieved efficiencies on the sky as high as $\sim 20\%$.

TES resolution is given by $\Delta E_{FWHM} = 2.355[4k_BT^2C(n/2)^{1/2}/\alpha]^{1/2}$, where $T$ and $C$ are the temperature and heat capacity of the W $e^-$ system, $n = 5$ for electron-phonon conduction and $\alpha = (d\ln R/d\ln T)_{V=\text{const}}$. The pixel size sets $C$; the maximum (saturation) energy is $E_{\text{max}} \approx CT_c/\alpha$ and therefore the optimum detector design gives $\Delta E_{\text{FWHM, min}} = 2.355[4k_BT(n/2)^{1/2}E_{\text{max}}]^{1/2}$. Thus for our typical 20$\mu$m pixel and $E_{\text{max}} = 10$eV we obtain $\Delta E_{\text{FWHM, min}} \approx 0.05$eV. Somewhat higher resolution can be obtained with lower $E_{\text{max}}$ by operating in the saturation regime, measuring pulse shape rather than peak height. In the present devices on Si, 58% of the photon energy is lost from the W $e^-$ system to substrate phonons, giving an expected $\Delta E =0.088$eV; for comparison the measured resolution is 0.12eV FHWM. Interestingly, although the physics is different, these sums predict $\Delta E_{\text{FWHM, min}}$ quite similar to theoretical limits and goal resolutions for existing STJ devices. The eventual choice of detector is probably best decided on the basis of achieved performance and ease of manufacture. At low $E$ the thermodynamic fluctuation noise floor allows detection to $\sim 10\mu$m. Of course, this full sensitivity range cannot be exploited from the ground, and we have employed a variety of filtering schemes to suppress unacceptably high thermal count rates beyond 2$\mu$m.

To illustrate the astronomical utility of these detectors, we have packaged TES arrays into simple demonstration systems, based on a He dilution refrigerator used for device development, and performed some basic observations. To filter the IR background, we employ a $\sim 3$m length of high-OH optical fiber spooled at 4K in the dewar. The OH bands of this cold filter provided effective blocking at $\sim 1.7\mu$m, but allow transmission in the atmospheric windows. At the telescope, the atmosphere and optics limit us to $\sim 3.5$eV, but in the lab we detected $E > 7$eV photons. With such systems we demonstrated the first astronomical spectra taken with a cryogenic optical detector and using small telescopes have made unique, scientifically valuable, measurements of the Crab pulsar and other astronomical objects (Romani et al. 1999, Romani et al. 2001), including photon counting spectro-photopolarimetry in the optical/IR.

On small telescopes these test set-ups have achieved good efficiency, although system efficiencies of $\leq 10\%$ are typical. As we are fiber-coupled we have to date only employed a small subset of the TES array (e.g. $2 \times 3$ out of $6 \times 6$ for the McDonald 2.7m Crab observations). Also, for ease of fabrication, the present TES arrays only employ a single lithographic layer of wiring; these wiring leads are responsive to photons, which complicates the energy PSF and spectral calibration. Finally, fiber coupled schemes, while attractive for test purposes, do not match well to the eventual (space platform) imaging applications for which these TES devices should have their largest impact.

2. Current Efforts

All of these factors can be mitigated with some simple design changes, and so we are assembling a first dedicated TES system for ground-based optical/UV
astronomy. We are currently assembling an array in a compact, portable Adiabatic Demagnetization Refrigerator (ADR) with dewar windows allowing direct imaging on the focal plane array. This solution is suitable for Cassegrain or Nasmyth applications at moderate to large aperture ground-based telescopes. The system accepts a slow f/10-f/20 beam and focal reduces with a cryogenic all-reflective system to allow good coupling to the devices. At the focal plane we read out a 32 pixel array. The existing design may be run at up to $8 \times 8$ format by adding more read channels; with modest changes to the device fabrication, arrays of $4\times6$ this area could be made. With a window solution, we employ heat-absorbing filters passing primarily in the optical/UV, so the system efficiency can be increased by appropriate AR coatings. Finally, to increase the fill factor and suppress energy PSF features from the wires and substrate, we will employ a focusing mask that collects the light to the $20 \times 20\mu$ W TES pixels.

3. Future Potential from Space Platforms

As ground-based tests demonstrate, these cryogenic technologies most immediately impact faint source observations when broad features in the SED and rapid time variability encode the key physics. Compact object studies, especially spin-powered pulsars and accretion-powered CVs and black hole systems are thus the ‘killer-app’ for first generation TES systems. Some of this science can be done from the ground, but the broad (0.1-10eV) energy window accessed from space presents opportunities for uniquely powerful investigations.

The good QE and noise properties of these devices encourages application to a wider range of problems, especially in the UV. Clearly, the main driver here is array format. Imaging applications providing a low-resolution ultra-broad band spectrum of extragalactic sources (see Romani et al. 1999, Mazin & Brunner 2000) over a modest field are very appealing. However, these arrays may also be useful in different formats such as order-sorting detectors for echelle spectroscopy in the optical/UV. The ability to read out more than the modest $\sim 10^2$ simultaneous channels covered in existing cryogenic system designs is therefore quite important. One fundamental limit is the complexity and heat load of the wiring delivering the signals to room temperature. In the case of TES devices there is a demonstrated (Chervenak et al 1999) scheme for multiplex readout at moderate count rates of a number of TES pixels by a single SQUID channel. Multiplex technology development is also being driven by other TES applications and should certainly increase the useful arrays sizes by factors of $\sim 30-10^3$. There are other schemes for allowing large cryogenic pixel count without a prohibitive number of wires to low temperature (e.g. ‘kinetic inductance’ coupling; Zmuidzinas et al. 2002).

What is needed to give TES imaging arrays (or comparable cryogenic technology) an exciting science role on a space-based platform? We envision three levels of capability. The first stage is a small $\sim 8\times8-16\times16$ pixel imaging array with low ($\sim 0.1eV$) energy resolution detecting the near IR-UV band with good QE. This already provides dramatic advance on time resolved studies of Galactic compact objects, with a roughly PSF-matched format and the option for local background subtraction, polarization and similar modes. This array could also perform areal spectroscopy of small extragalactic objects reaching remarkably
faint magnitudes. It may be built as a fairly straightforward rescaling of present systems using today’s techniques. Such a (special purpose) system would enable very exciting science from a small aperture dedicated facility or a sub-orbital platform and in our opinion is should be pursued both for the science and for the demonstration of these detectors in a flight program.

A more capable facility would have 1-10 kpix format and would require some form of multiplex read-out. These read channels could be used both as an imaging array and in an elongated (order sorting) spectrographic format. It should be possible to have the same (expensive) read channels address several (cheap) array formats in a single dewar. This array appears to be a natural, near term (∼5y) extension of present programs. If such an array can be coupled with a reliable closed-cycle, space-qualified cryocooler+ADR system, a strong science case can be made for a dedicated small aperture system. Grid filtering and passive optics cooling in space could allow simultaneous access to ∼0.2-10eV and imaging and spectroscopic modes, as above.

The ultimate instrument would have ≥ 10⁵ pixels, which with the high QE, ultra-broad sensitivity range, noiseless detection and intrinsic energy resolution would exceed the capabilities of CCD/MAMA arrays for a variety of mainstream astrophysics and cosmology applications. Such an array might be dynamically addressed, reading out only an interesting pixel subset. Light travel time ensures that sub-µs timestamps are unlikely to be of interest over large areas, so cryogenic preprocessing to accumulate simple spectral images would also be desirable. Schemes to build such an array and to accomplish the required read-out and processing are presently at the cartoon stage; hence prognostication of a development time is rather pointless. However, intermediate steps are quite compelling so with sufficient resources, progress toward such ultimate astronomical detectors is likely to occur.

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