Transition Edge Sensor
Bolometers for CMB Polarimetry

Dominic Benford
NASA/GSFC

Thanks To: Jamie Bock, William Duncan, Gene Hilton, Kent Irwin, Nikhil Jethava, Adrian Lee, Harvey Moseley, Lyman Page, Bob Silverberg, Giorgio Siringo,
Status Summary

- Technology has made rapid progress in the last decade; TRL is high and trajectory is goo

- Astronomical instruments are penetrating
- Near-term balloons will mature amply
- TES bolometers represent a robust candidate technology for CMB polarimetry
TES Bolometer Theory

• Solved up to nonequilibrium, nonlinear (second order) model (see, e.g. Irwin & Hilton 2005)
  – Predictive, testable, complete

$$S_{\text{total}}(\omega) = 4k_B T_0^2 G F_{\text{thermal}} + 4k_B T_0 R_0 I_0^2 \left(1 + 2 \beta_s \right) \frac{1 + \omega^2 \tau^2}{\omega_f^2} + 4k_B T_0 R_L I_0^2 \left( \frac{\omega_f - 1}{\omega_f^2} \right) \left(1 + \omega^2 \tau^2 \right) + \frac{S_{\text{lamp}}(\omega)}{|s_f(\omega)|^2} + S_{\text{Excess}}(\omega)$$
  – Mostly well established

• Much work on “excess noise” theories
  – Some not very physically-motivated
  – All have both experimental verification and refutation.
TES Bolometer Requirements

- NEP, $P_{\text{sat}}$ known
  - Achieved!
- Speed varies, but $\approx 1\text{ms}$ satisfies most.
  - Achieved!
- Formats of $\approx 10^3$ pixels
  - Achieved! (mostly…)

2008-Aug-25

CMBPol Technology Workshop, Boulder, CO
Astronomical Applications Appearing
Positive Aspects of Progress

• Several TES-based instruments exist
  – APEX-SZ, ACT, SPT, MUSTANG, GISMO, SETA have all achieved first light in mm wavelengths

• Multiplexers work; large formats (kilopixel) have been fielded
  – NIST TDM - ACT
  – Berkeley FDM - SPT

• Sensitivity requirement achieved (sort of)
  – Record? MUSTANG, GISMO, ACT all $\approx 4 \cdot 10^{-17} \text{W}/\sqrt{\text{Hz}}$
Much Yet To Be Done…

- “Excess Noise” not understood.
  - Theory not quite there
  - Experiments disagree
- Polarimetry and TES bolometers.
  - Optical? Should be straightforward.
  - On-chip? Not even close.
- Suborbital operation; “relevant environment”
  - EBEX and Spider or something similar!
Technology Readiness Level

- My estimate: TRL=4.8
- “The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications... can be tested in a ‘simulated’ or somewhat realistic environment.”
- Why not 6? “At this level, if the only ‘relevant environment’ is the environment of space, then the model/prototype must be demonstrated in space.”
TES State-of-the-Art for CMB (1)

Figures courtesy of the ACT Collaboration
TES State-of-the-Art for CMB (2)

Images from Mehl et al. 2008; Adrian Lee
TES State-of-the-Art for CMB (3)

2 mm

220 GHz Bullet Cluster 150 GHz

960 Pixel fMUX wiring

4 mm

20 cm Mesh filters
A Big Leap Forward in TRL

“…somebody needs to operate successfully a suborbital TES-based instrument”
Advantages of TES Bolometers

• Sensitivity allows background-limited operation
• Large format arrays yield excellent mapping speed
• Response time permits many viable scan patterns and polarization modulation schemes
• Technology has matured to an acceptable level to begin directed investment in earnest
TFCMBR Technology Recommendation T1

“We recommend technology development leading to receivers that contain a thousand or more polarization sensitive detectors, and adequate support for the facilities that produce these detectors.”

“…highest priority needs to be given to the development of bolometer-based polarization sensitive receivers.”
Some Possible TES Downsides

- Dynamic range: sufficient, would like better
- Stability: adequate ($\approx 0.1$Hz), would like better
- Magnetic fields: solved by design
- Microphonics: not a challenge
- Multiplexing electronics: mature
- Foundries: several exist
TES Bolometers vs. Coherent

- Sensitivity is (probably) better in real application – at $\nu > 100\text{GHz}$
- Large arrays more feasible; multiplexing helps! HEMT multiplexing?
- Cryogenics for 0.1K system might be better
  - Kilopixel HEMT array takes $\approx 10\text{mW} \cdot 1000 = 10\text{W} @ 20\text{K}$
  - Kilopixel TES array takes $\approx 300\text{nW} @ 0.1\text{K}$
  - Scaling law for coolers: if $\text{P.E.} \propto T^2$, this gives $10\text{mW} @ 20\text{K}$!
  - Admittedly, with significant increase in complexity!

**HEMT IF ↔ TES RF**
TES vs. Semiconductor and KID

- TES is less mature than SC, more than KID
- Multiplexing much easier than SC, ≈ same as KID
- Sensitivity same as SC, slightly better than MKID
- Readout more complex but simpler than SC; KID readout simpler (?) but not mature
- *Nil nisi bonum*, KID might be competitive
TES Bolometer Instruments Common?
Conclusions

• TES bolometers are well-established.
• Several independent and interrelated groups are pushing this technology forward rapidly.
• For CMB polarimetry, will likely offer the highest performance in terms of combined sensitivity, array format, and availability.
• Directed investment could achieve TRL=6 in a few years on the entire system.
Carpe Diem!