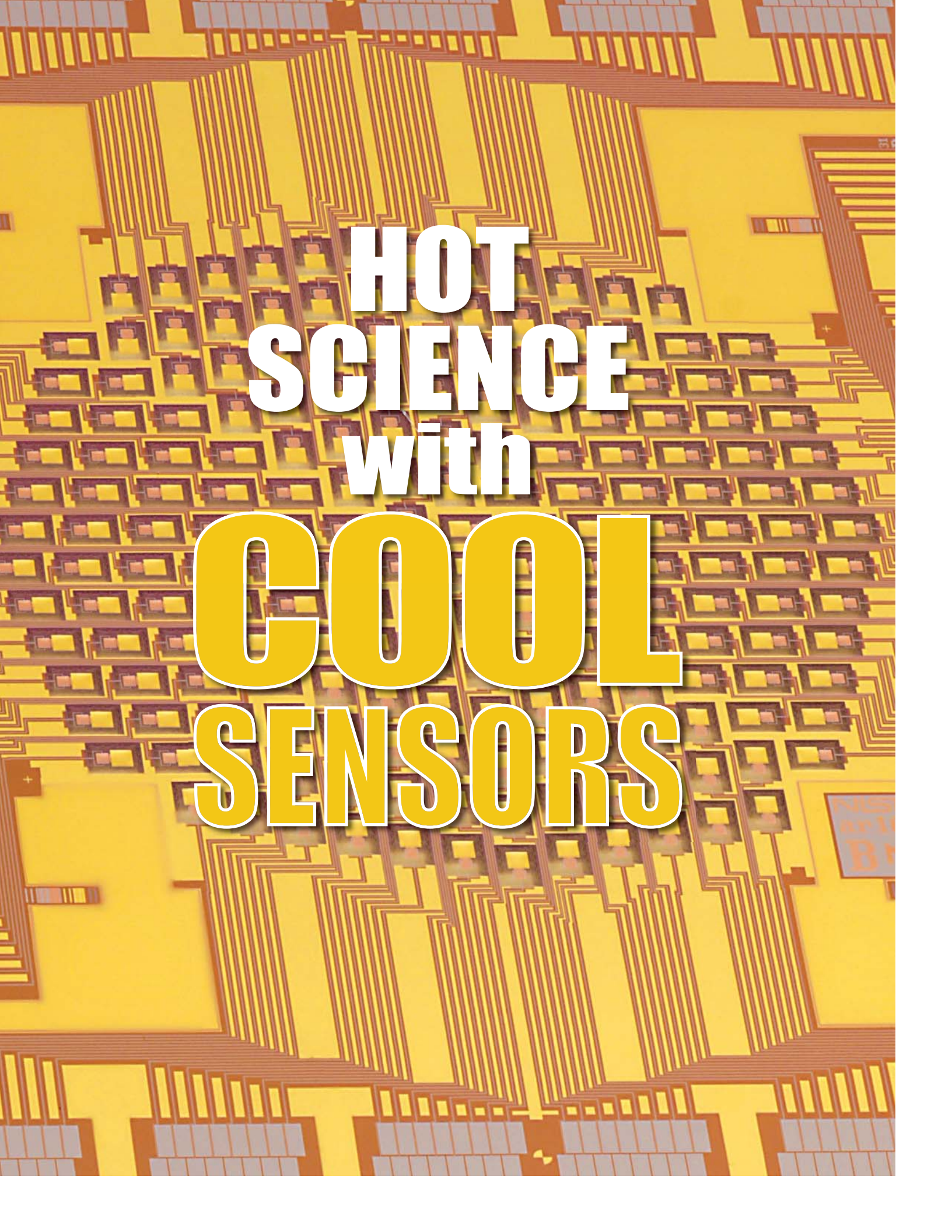


The background of the entire image is a detailed, high-magnification photograph of a microchip. It shows a complex network of reddish-brown circuit traces on a yellowish-gold substrate. Numerous small, square, reddish-brown components are arranged in a grid-like pattern across the chip. The lighting creates a sense of depth, highlighting the three-dimensional nature of the chip's surface.

HOT SCIENCE with COOL SENSORS

Kelsey Morgan is a research scientist at the University of Colorado Boulder and a member of the quantum sensors group at NIST, also in Boulder.



Kelsey M. Morgan

The superconducting transition's exquisite sensitivity to heat underlies a maturing technology for detecting photons.

A thin superconducting film on the edge of the transition between its superconducting and normal states makes an ultrasensitive thermometer, capable of measuring the energy of individual x-ray and gamma-ray photons. The transition-edge sensor (TES), like superconducting transmission lines and superconducting magnets, is not a new idea. The notion of using the superconducting transition to measure the tiny amount of heat imparted by a single photon dates back to the late 1930s. But like so many of the early ideas for applications of superconductivity, it would take decades of innovation in theory, electronics, microfabrication, and cryogenics for the TES to realize its potential.

Now the TES is used to measure radiation across the electromagnetic spectrum, from microwaves to gamma rays. By arraying hundreds or even thousands of sensors, my colleagues at NIST and elsewhere can build spectrometers with an unprecedented combination of precision and efficiency.

TES arrays are now ubiquitous in ground-based observatories that study the cosmic microwave background. A TES spectrometer is being designed for the x-ray satellite *Athena*. Planned for launch in the early 2030s, the orbiting observatory will be 100 times as sensitive as its predecessors, the *Chandra X-Ray Observatory* and *XMM-Newton*.

Today a TES array at the Stanford Synchrotron Radiation Lightsource measures the x-ray absorption spectra of delicate biological molecules as they undergo complex chemical reactions. With a TES array, many experiments that were once possible only at giant synchrotron facilities can now be conducted on a benchtop in a researcher's own lab. We have entered an era where we don't just study superconductivity; we use the superconducting phase transition as a tool for scientific discovery.

A superconducting thermometer

The TES was first proposed independently by Donald Andrews in 1938 and Alexander Goetz in 1939. The resistivity of most

metals tends to decrease slowly with temperature, but the resistive transition between superconducting and normal states is abrupt; it occurs over only a few hundredths or even thousandths of a kelvin. Andrews and Goetz realized that if a superconductor could be maintained in the transition zone, the metal's resistivity would be exceedingly sensitive to temperature. If radiation incident on the superconductor heated it, the amount of incoming radiation could be measured as a change in resistance (see figure 1).

Andrews described the results of the first TES experiments¹ in 1941. His

team at the Johns Hopkins University evaporated a thin film of lead onto a 1.5 cm × 1 mm glass ribbon. They placed the sensor on a copper block and cooled it in a liquid-helium cryostat, which reached a base temperature of around 4.2 K. Because lead becomes superconducting at a higher temperature, 7.2 K, the block was suspended on quartz fibers to isolate it from the helium bath while an attached electrical heating coil kept the lead in its superconducting transition.

The configuration was challenging to maintain because the transition region is only 0.02 K wide. Nevertheless, the researchers were able to measure a change in resistance as the lead was exposed to varying levels of IR radiation. Because the measurement was not sensitive enough to detect the heat imparted by individual photons, the sensor measured the average incident power. The measurement was termed "bolometric," in reference to earlier devices that measured radiative power through temperature-dependent changes in resistance.

Eight years later Andrews used a superconducting niobium nitride film to detect alpha particles emitted by a decaying polonium source.² Because the energy of an alpha particle is much higher than that of an IR photon, it was possible to detect the impact of single particles, a "calorimetric" measurement. Even better, Andrews realized, since the change in temperature

was proportional to the energy of the incoming alpha particle, the detector could potentially be used to measure the energy of individual particles through how much the resistance changed.

Andrews envisioned that his sensors might be used by doctors to measure the heat radiated by the human body or by physicists to make precise measurements of atomic structure. But the success of the early TESs was limited. For one thing, keeping the sensor stable was difficult. When the resistance increased as the film absorbed energy, Joule heating would tend to drive the sensor out of its transition and into the normal state. Also, the sensors were inherently low resistance. No sufficiently low-noise, low-impedance amplifiers were available to match the capability of the sensors.

Those obstacles remained for 50 years. Like so many of the early ideas for applications of superconductivity, the TES would have to wait for several important technological breakthroughs before it took off.

The modern quantum calorimeter

Although the TES would surface occasionally in the literature of the 1960s and 1970s, the field of quantum calorimetry—the thermal detection of individual quanta of energy—progressed rapidly in the 1980s. The work was motivated by the desire for better energy-resolving detectors with high quantum efficiency for astronomy and materials analysis.

The most commonly available high-efficiency alternatives to calorimeters are solid-state detectors, such as drift detectors made from high-purity germanium or silicon. The devices measure the charge produced by incoming photons when they excite electrons into the conduction band. Because the deposited energy is divided stochastically between charge and heat, the detectors' energy resolution is limited by statistical fluctuations in the number of electron-hole pairs that are instantaneously created. In silicon, for example, the fluctuations set a fundamental limit for the energy resolution of $\Delta E = 118$ eV at 6 keV.

By contrast, a thermal calorimeter is not subject to that statistical limit; all of a photon's energy is promptly converted to heat. The resolution is limited by fundamental thermal fluctuations due to the exchange of energy between the calorimeter and its bath. In 1984 Harvey Moseley, John Mather, and Dan McCammon derived an expression³ for the energy resolution of an ideal calorimeter with a resistive thermometer or thermistor (the TES is a type of thermistor):

$$\Delta E \propto \sqrt{(k_B T^2 C / \alpha)} F(T),$$

where T is the thermistor's temperature, C is its heat capacity, and α is the logarithmic derivative of resistance, $T/R \partial R / \partial T$.

For the best possible energy resolution, the sensor should be at low temperature so that the deposited energy is large compared with the thermal noise created by random transfer of heat across the link between the sensor and its surroundings. In modern sensors, temperatures are typically in the 50–100 mK range. Additionally, the sensor should have a small heat capacity so that absorption of an energy quantum creates a large temperature change. And the resistance must be a sensitive function of temperature—that is, α should be large. Lastly, it's important that the thermal link between the sensor and its heat bath, which is characterized by the function $F(T)$, should not be too strong (see figure 2). Otherwise, after a photon is

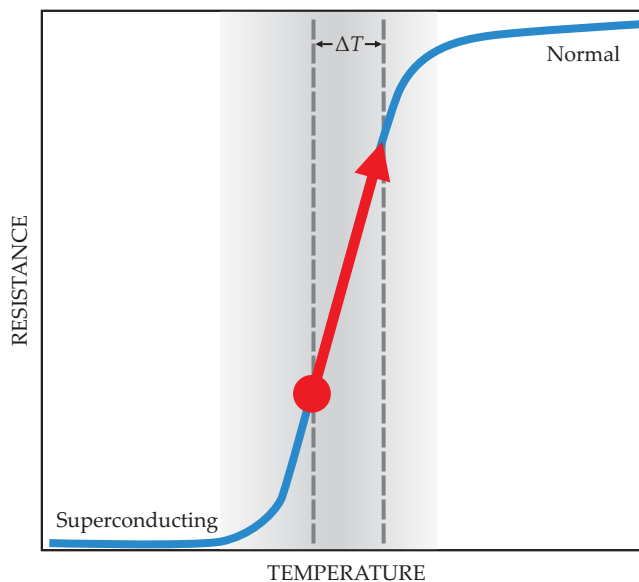


FIGURE 1. THE RESISTANCE OF A SUPERCONDUCTOR drops abruptly to zero at its critical temperature, T_c . The phenomenon can be exploited to measure small temperature changes. An electric current through the superconductor keeps it in the transition region between its normal and superconducting states (the “quiescent” or “bias” point, indicated by the red dot). When the superconductor is heated by an amount ΔT , its resistance will increase proportionally to the amount of input energy, indicated by the red arrow.

absorbed, heat will escape to the bath and thereby degrade the resolution before the device reaches thermal equilibrium. However, the weaker the link, the longer it takes for the device to return to quiescence and the lower the maximum photon count rate.

Most of the early success with quantum calorimeters was achieved with doped semiconductor thermistors made of silicon or germanium (see the article by Caroline Kilbourne, Dan McCammon, and Kent Irwin, *PHYSICS TODAY*, August 1999, page 32). However, it was soon discovered that those materials had limited sensitivity (low α) and undesirable noise properties, which drove researchers to hunt for a more sensitive thermometer. With its extremely sharp superconducting transition, the TES portended orders-of-magnitude increases in sensitivity.

Reenter the TES

Two critical innovations were necessary to take the TES from an interesting idea to a scientific instrument. The first innovation was the SQUID (superconducting quantum interference device) series array. Invented in the early 1990s by Richard Welty and John Martinis,⁴ the array met the long-standing need for a low-noise, low-impedance amplifier.

A SQUID is a magnetometer composed of a superconducting loop and one or more Josephson junctions. Although SQUIDS were first used as amplifiers in the 1970s and 1980s, the output voltage swing of a single SQUID—a few tens of microvolts—is too small for use with a TES or any other device connected to room-temperature electronics. Welty and Martinis overcame that limitation by yoking 100 or more SQUIDS in an array.

To use a SQUID as an amplifier, the TES is connected to a

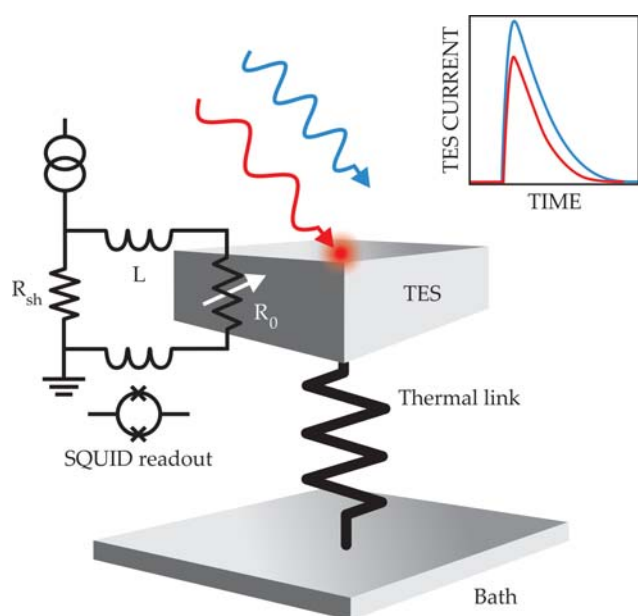


FIGURE 2. AFTER A PHOTON IS ABSORBED in the transition-edge sensor (TES), the heat flows from the sensor to the bath. The time scale for the temperature to return to equilibrium is set by the heat capacity of the TES and the strength of the thermal link between the sensor and the bath. The temperature change produces a resistance change, which is read out as a pulse in the TES current by an inductively coupled SQUID amplifier.

superconducting coil, which is then coupled to a SQUID, which is then coupled to a SQUID array. When the arrival of a photon changes the TES current, the current through the coil also changes, which in turn changes the magnetic field applied to the SQUID. The noise in a modern SQUID is orders of magnitude lower than the inherent thermal noise of the TES. Indeed, a SQUID's contribution to the total system noise of a TES is negligible.

The second enabling innovation a few years later tackled another long-standing need: ensuring thermal stability. When a TES is biased with constant current, the resulting Joule heating can cause thermal runaway. Kent Irwin realized that when a TES is biased instead with constant voltage, an increase in the TES temperature is accompanied by a drop in the TES current. That negative feedback lowers the temperature and stabilizes operation.⁵ Voltage biasing also reduces the time it takes for a TES to respond to a photon. As a result, the sensor returns to equilibrium faster than the thermalization time for the TES and its heat bath. The boost in responsiveness helps a TES handle high photon count rates.

Because of decades of advances in readout circuitry, cryogenic platforms, and fabrication techniques, the modern TES looks very different from Andrews's lead films. The critical temperature, T_c , of an elemental superconductor is an inherent property of the material. Even so, T_c can be altered by using a bilayer made up of a thin layer of a normal metal atop a film of the superconducting material. Through the proximity effect, the normal metal lowers the critical temperature of the superconductor. Lowering T_c might seem a counterintuitive thing to do. However, it's desirable in order to improve energy resolution and to tune T_c to match the available cryogenic plat-

form. Tuning is carried out by varying the relative thicknesses of the layers.

To boost the efficiency of the sensors, one adds extra absorbing structures that are customized to couple to the incoming radiation (see figure 3). The structures may be elaborate antennas designed to couple to microwaves or high-atomic-number materials like bismuth, gold, and tin that can efficiently stop x rays and gamma rays. The TES-to-bath thermal link is tuned through the choice of insulating material (typically silicon or silicon nitride) and through altering the link's structure and dimensions with advanced etch or micromachining techniques.

The wide array of materials available and the ability to precisely tune the thermal properties of a TES provide the flexibility needed to design a high-performance sensor for almost any photon wavelength. Of course, there are limitations. The TES gets its high sensitivity from operating in the narrow superconducting transition, but once the TES heats enough to reach its normal state, its sensitivity vanishes. Although it might appear that the smallest possible heat capacity plus the sharpest transition would yield the best energy resolution, we must also ensure that the highest-energy photon we are interested in measuring does not drive the TES into its normal state. The maximum energy is referred to as the saturation energy.

Even with that limitation, the TES has demonstrated excellent energy resolution. Individual TESs built at NASA's Goddard Space Flight Center⁶ have demonstrated 1.6 eV resolution at 5.9 keV. Arrays of hundreds of TESs built at NIST's Boulder campus⁷ routinely achieve 1–2 eV resolution for 0.1–1.5 keV and 3–4 eV at 6 keV. My colleagues and I have also demonstrated⁸ gamma-ray TESs capable of achieving 22 eV resolution at 97 keV.

More is more

What makes TES technology so powerful for spectrometry is the ability to use not just one sensor but arrays of hundreds or even thousands of them. TESs have achieved impressive energy resolution, but wavelength-dispersive spectrometers using gratings or crystals are able to do better: state-of-the-art instruments can achieve 0.1–0.5 eV in the 0.1–10 keV energy range.

That said, a single TES pixel, typically a few hundred micrometers on a side, can cover the same solid angle as an entire grating spectrometer, with equal or better photon detection efficiency. In practical terms, a TES array can observe more of a supernova remnant, galaxy cluster, or star-forming region at once than can a grating. Additionally, because TESs are energy dispersive rather than wavelength dispersive, the same sensor can measure the entire energy spectrum simultaneously with roughly constant energy resolution up to its saturation energy. For measurements where the eV-scale resolution of the TES is adequate, an array of several hundred TESs can cut measurement times by several orders of magnitude.⁹ Instruments with a thousand or more TES pixels are already under development (see the box on page 33), portending even larger gains.

If each TES required its own amplifier chain and set of wires running from room temperature down to 50 mK, the heating from the amplifiers' components would quickly overwhelm even the most powerful cryogenic platforms. The operation of large TES arrays therefore requires multiplexed readout.

Multiplexing has enabled the widespread use of TES

bolometers at telescopes used to study the cosmic microwave background. In that application, the signal changes slowly as the telescope slews to observe different parts of the sky. Several early multiplexing techniques could read out about 100 TESs per readout channel because of the relatively modest signal bandwidth.

By contrast, for x-ray and gamma-ray calorimetry, the energy of each incoming photon is recorded. TES response times are typically shorter than a millisecond. Multiplexers must therefore track very fast signals. The first multiplexing scheme to have widespread success in x-ray instruments is time-division multiplexing. In TDM, each TES is coupled to a SQUID, and the SQUIDs are biased on and off sequentially; one SQUID-TES pair is sampled at a time. For x-ray sensors, the bandwidth of practical TDM systems limits readout to a few dozen sensors per channel before the sampling rate per channel becomes too sparse to accurately reconstruct the current pulses.

The future of TES array readout will likely be driven by a new technology called the microwave SQUID multiplexer. Whereas TDM was highly successful for arrays with a few hundred TES pixels, microwave multiplexing provides a path toward arrays of 10 000 pixels or more. In that scheme, each TES is coupled to an RF SQUID, which is in turn coupled to a microwave resonator. When the TES current changes, the subsequent change in the SQUID inductance shifts the resonance frequency. Many resonators, each with a unique resonance frequency, are coupled to a common feed line and can be read out simultaneously by applying a comb of microwave probe tones to the feed line. The tones are amplified by a high-electron-mobility transistor, so bandwidths of several gigahertz are possible. That's much larger than the approximately 10 MHz bandwidth of existing time-division systems.

Readout of 128 TESs with a single microwave feed line has been demonstrated with the gamma-ray spectrometer known as Sledgehammer.¹⁰ Kilopixel-scale arrays read out by microwave multiplexing will arrive within the next few years. Efforts are under way to combine microwave readout with other multiplexing schemes to achieve even higher multiplexing factors, which could enable hundred-kilopixel (or even megapixel) arrays.

Less is also more

Building larger arrays isn't the only way to get more science out of a TES spectrometer. The time it takes to produce a useful spectrum can be shortened by reducing the pulse duration so that single sensors can measure more photons per unit time. Improvements in energy resolution can also shorten measure-

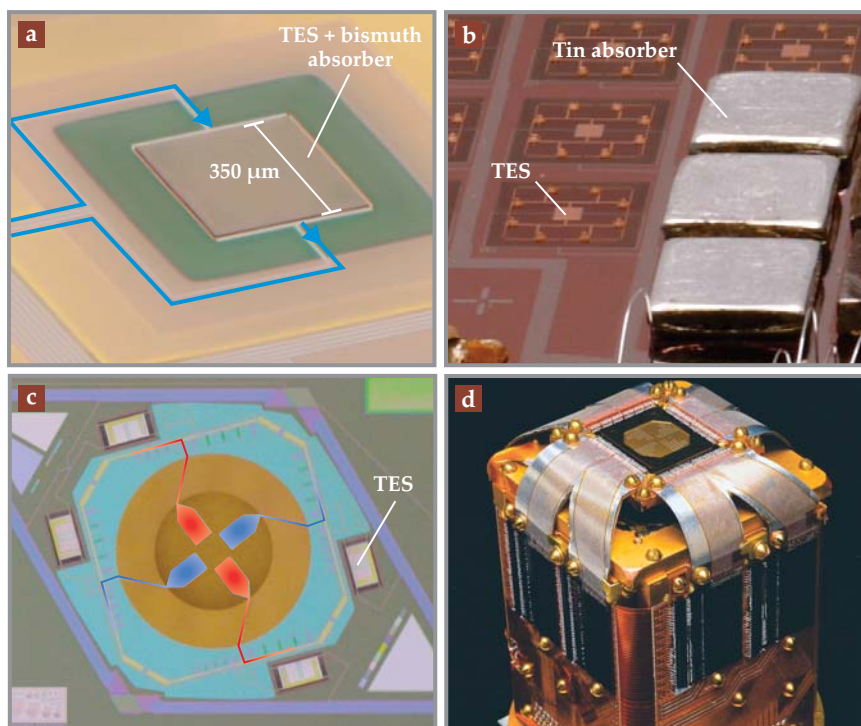


FIGURE 3. WHEN USED FOR DETECTING X RAYS, a transition-edge sensor (TES) bilayer can be topped with a thin bismuth layer to increase absorption efficiency **(a)**. The bilayer plus absorber sit on a micrometer-thick nitride membrane (green) to control the thermal link between sensor and bath. The bias current is carried on superconducting leads (the current path is highlighted in blue). **(b)** Absorbers may also be external structures, like these bulk tin pieces that are used as gamma-ray absorbers. Arrays of close-packed sensors, each corresponding to a single pixel, increase total photon count rates and can offer imaging capabilities. **(c)** For microwave wavelengths, the TES can be coupled to an antenna. In this example, an antenna designed to separate two polarizations of incoming light (red and blue) sends signals to four TESs. **(d)** Arrays of hundreds of sensors are now commonplace. Here, the array sits at the top of the assembly, facing the source to be measured. Signals are sent via flexible superconducting wiring to the readout SQUID chips that surround the side panels. (Photos by Dan Schmidt, NIST.)

ments by increasing signal-to-noise ratios. New measurements, where spectral features were previously too close in energy to be resolved, could become possible. In parallel with the development of advanced multiplexing techniques, research continues to push toward shorter TES response times and better energy resolution.

One perhaps surprising obstacle to those goals is that detailed understanding of the superconducting transition is limited. The microscopic physics of the superconducting state was successfully explained by Bardeen-Cooper-Schrieffer theory in 1957, but BCS theory doesn't tell us about how a superconductor's resistivity changes in the transition. Our current understanding suggests that at least two phenomena are involved.

The first phenomenon arises because the TES bias current is carried by superconducting leads that have a higher T_c than the sensor medium. The superconducting order parameter of the leads extends into the bilayer and decays away exponentially (the same proximity effect is exploited to lower the T_c of a superconducting-normal metal bilayer). The TES forms a weak link between the leads, which increases its critical current and changes the shape of the transition. The phenomenon has been

X-RAY SCIENCE AT LIGHT SOURCES

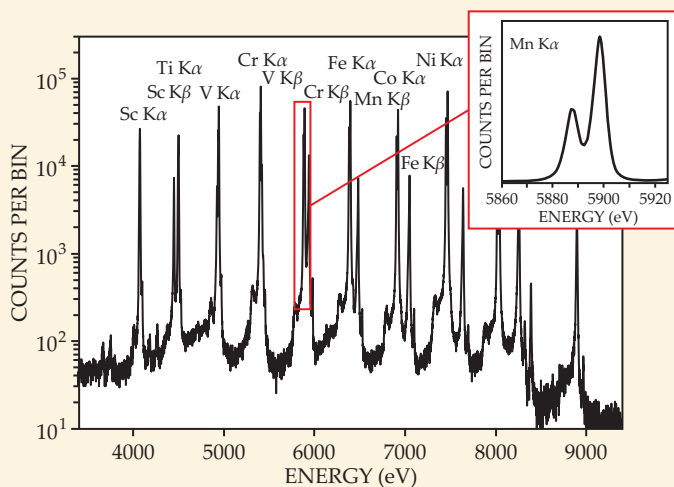
The transition-edge sensor (TES) is becoming a powerful tool for x-ray science at large user facilities such as synchrotrons and free-electron lasers (FELs). The detectors most commonly used for x-ray science have either high resolution and low efficiency (wavelength-dispersive spectrometers) or high efficiency and low resolution (solid-state detectors). A TES can provide the efficiency and broadband capability of a solid-state detector with eV-scale resolution.

For many experiments, eV resolution is perfectly adequate. Chemical shifts—that is, the shifts in an atomic nucleus's resonant frequency due to neighboring nuclei—often occur on a comparable scale.⁹ TES spectrometers can excel at measurements where the signal is inherently weak, as is the case for samples in dilute concentrations and for materials that would be damaged by prolonged exposure to an x-ray beam. Additionally, the broad spectral coverage of a TES makes it possible to measure all the emission lines from a sample simultaneously, including the elements' K_α and K_β lines. Indeed, as the insert shows, it's possible to resolve the two manganese K_α peaks, which appear as a single peak in the main figure just to the left of chromium K_β .

NIST has built TES spectrometers that have been deployed to x-ray science facilities around the world.⁷ At the National Syn-

chrotron Light Source (NSLS), a TES spectrometer performed emission spectroscopy of RDX and other explosive nitrogen-bearing compounds. The instrument will move to NSLS-II in late 2018.

A NIST-built soft x-ray spectrometer at the Stanford Synchrotron Radiation Light-



source beamline 10-1 is used to study dilute metal-centered compounds relevant to biology, chemistry, and catalysis.¹⁷ A second TES spectrometer at beamline 13-3 is used for soft-x-ray scattering studies. NIST and Argonne National Laboratory are now collaborating to build the first hard-x-ray TES beamline spectrometer for Argonne's Advanced Photon Source.

Because of its high efficiency, the TES can bring science that previously required a synchrotron to the benchtop. At a NIST laboratory in Boulder, Colorado, a tabletop UV-visible laser is used to initiate a chemi-

cal reaction in a sample. After a short, adjustable time delay, the same laser strikes a water jet to produce a burst of x rays. The x rays interact with the sample, and the emission spectrum is detected by an array of TESs. The technique is called time-resolved x-ray emission spectroscopy (TR-XES).

The NIST facility achieves timing resolution of better than 6 ps.¹⁸ The only other facilities in the world capable of TR-XES measurements with comparable energy and temporal resolution are much larger x-ray FEL facilities: SACLA in Japan, the European XFEL in Germany, and the Linac Coherent Light Source at SLAC in California.

X-ray FELs are the world's brightest x-ray sources. LCLS is receiving an upgrade (LCLS-II) that will increase its brightness by a factor of 10^4 and its

x-ray pulse rate to a million per second. NIST, the University of Colorado Boulder, SLAC, and Stanford University are collaborating to build a TES spectrometer for LCLS-II. The instrument will have 1000 high-speed TESs with 0.5 eV energy resolution below 1 keV. Experiments will target time-resolved emission spectroscopy of complex chemical and biological systems with the goal of improving solar energy conversion and photocatalysis.

As capabilities of both the x-ray facilities and the detectors continue to improve, the future of TESs at beamlines looks bright.

observed in TES devices and is probably the dominant effect when the leads are only tens of micrometers apart.¹¹

The second phenomenon arises because the superconducting coherence length for typical devices is on the order of a few micrometers, whereas TESs are often 100 micrometers or longer. As the leads get far apart, the weak-link effect diminishes and the effects on the transition become less pronounced. In that limit, the transition is better described by a phase-slip line model, where spatially localized differences in the phase of the superconducting order parameter give rise to discrete steps in the current-voltage characteristics of the TES.¹²

Modeling real-world TES geometries with a phase-slip line approach is computationally intensive and requires many assumptions. Consequently, a simplified two-fluid approach has been developed to make semiempirical predictions and provide useful scaling relations.¹³ The tools have revealed an intrinsic tension between shorter pulses and sensitivity, and they are being used to develop TES designs that mitigate it. Because

of the tools, x-ray TESs can be built to have response times faster than 100 μ s while maintaining eV-scale resolution.¹⁴

TESs around the world

Much of the early work on microcalorimeters was motivated by the desire to study astronomical objects that are faint, diffuse, or both. Arrays of TESs are used in ground-based astrophysics observatories like the Cryogenic Dark Matter Search and cosmic microwave background telescopes like BICEP, the South Pole Telescope, and the Atacama Cosmology Telescope.

X-ray astronomy is particularly challenging because it requires installing instruments on a spacecraft. Still, TES x-ray telescopes are on the way. The X-ray Imaging Field Unit (X-IFU) is a spectrometer being built for the *Athena* observatory, a mission led by the European Space Agency and planned for launch in the early 2030s. X-IFU will feature a 3840-pixel TES spectrometer with 2.5 eV energy resolution at 7 keV and will be used to study a wide range of hot, energetic systems, including

accreting neutron stars, supernova remnants, jets that shoot from the cores of some galaxies, and the thin plasma that pervades the intergalactic medium in galaxy clusters.¹⁵

Over the past decade, as TES spectrometers have grown in size and resolving power, applications outside astronomy have proliferated. NIST has developed a complete TES spectrometer package, including readout electronics and cryogenics platform, for x-ray science at light sources around the world. The same spectrometers were used last year at NIST to refine measurements of 22 x-ray L lines from lanthanide-series elements.¹⁶

A TES has been successfully used in conjunction with a scanning electron microscope to perform high-resolution materials analysis, and such instruments are now commercially available. The HOLMES collaboration, led by Italy's National Institute for Nuclear Physics and the University of Milano-Bicocca, will implant a radioactive isotope of holmium into gold absorbers coupled to TESs to derive upper limits on the mass of the neutrino. A NIST-built TES spectrometer is being used at the Japan Proton Accelerator Research Complex to probe the physics of the strong nuclear force. A collaboration between the University of Colorado Boulder, NIST, and Los Alamos National Laboratory uses gamma-ray TESs to perform nondestructive analysis of nuclear materials. The list of applications is wide-ranging and continues to grow.

In the past decade, rapid progress in high-bandwidth readout technology alongside improved theoretical understanding of the superconducting transition has enabled my fellow TES researchers and me to build faster, higher-resolution sensors. The next decade of TES development will be all about going bigger

and broader, with more pixels and more bandwidth with newly emerging applications. In a field of research that's about transitions, perhaps the most exciting one is happening now. Years of research on superconducting sensors are leading us into an era of using the TES as an instrument of scientific discovery.

Thanks to Joel Ullom, Dan Swetz, Bob Hickernell, Joe Fowler, Luis Miaja-Avila, Webster Cash, and Jerry Seidler for taking the time to read and offer valuable comments on this manuscript.

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