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SUPERCONDUCTING X-RAY SENSORS FOR TOMOGRAPHY OF MICROELECTRONICS

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INTRODUCTION

Integrated circuits (ICs) are highly complex manufactured devices. They contain billions of 3D structures covering a wide range of size scales and are composed of multiple metallic, semiconducting, and dielectric materials. Individual transistor gates and their wiring can be as small as a few nanometers, while a complete die can exceed a centimeter across. To determine the internal structure and composition of an IC after it is manufactured is an important and extremely challenging problem.

Many kinds of users could benefit from tomographic analysis of microelectronic devices. Manufacturers with an eye on process control and improvement could use 3D imaging, especially for new processes still in the development or research stage. Imaging could also help researchers to connect functional failures of ICs to the physical defects that caused them. ICs are often designed and manufactured by different organizations in different countries, which raises questions of hardware security assurance. A tomographic imaging system could help to detect disabled features, hardware trojans, counterfeit designs, or other deliberate design changes introduced just before the fabrication stage.

Several technical challenges hinder tomographic x-ray imaging at the sub-micrometer length scales required to analyze an IC. An intense x-ray source must be confined to a spot not much larger than the desired resolution, while its position relative to an IC sample must be both measured and controlled with similar precision. Tomographic imaging at fine spatial resolutions also demands the detection of a very large number of x-ray photons, a requirement that grows rapidly with improving resolution. Specifically, a 3D measurement of x-ray attenuation through an optically thin sample of fixed total volume requires detection of total photons scaling as the inverse fourth power of the voxels' linear dimensions. Two powers come from the increased number of narrower voxels across any fixed cross-section, and two more arise from the reduced attenuation signal in each, thinner voxel. At the same time, making x-ray sources smaller tends to decrease the photon production rate by at least the square of the resolution scale unless the intensity can be made to grow as the source shrinks. In short, even modest improvements in

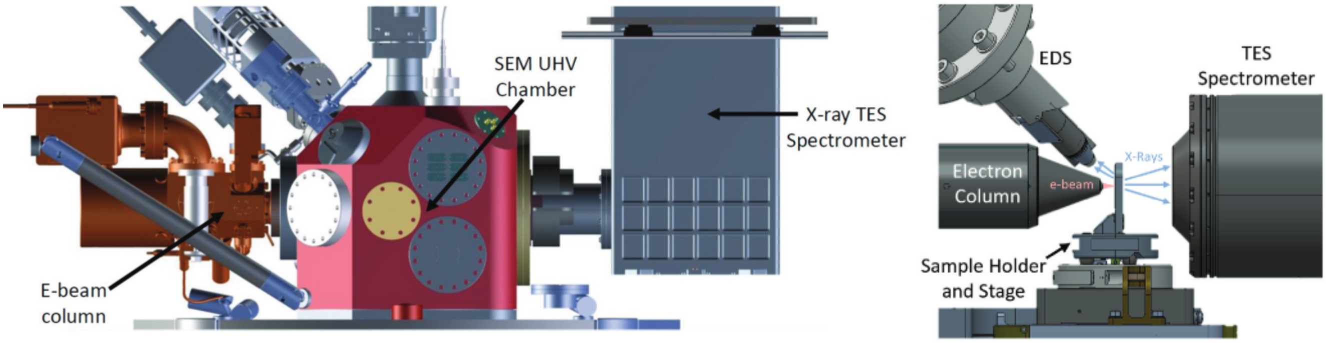


Fig. 1 **Design of the Tomcat instrument, shown from the outside, left, and inside the vacuum chamber, right. Right-hand figure reprinted from Ref. 3 with permission.**

spatial resolution require producing and detecting vastly more x-ray photons and confining them to an ever-smaller, resolution-sized spot.

The extreme demands for x-ray intensity mean that published 3D analysis of ICs at nanoscales has generally been the province of research based at synchrotron beamlines. Since the first IC imaging at a synchrotron by absorption contrast in 1999,[1] the technique has been further refined. The complementary technique of x-ray ptychography further exploits both the high x-ray intensity available at synchrotrons and the coherent nature of their radiation.

Valuable as they are, synchrotrons are scarce resources that cannot be moved into industrial or other typical research settings. There remains a strong interest in the development of laboratory instruments that can also tomographically analyze semiconductor devices. Some promising work applies a focused-ion beam to delaminate layers of a microelectronic device, alternating with acquisition of 2D surface images from a scanning-electron microscope (SEM).[2] The accurate synthesis of many thousands of such images into the full 3D reconstruction is a challenging mathematical problem, however. The process also destroys the IC, preventing follow-up measurements by spectroscopic or other analytic techniques.

We have lately been exploring whether nondestructive tomography of ICs can be accomplished by harnessing the extremely high energy-resolving power of superconducting x-ray detectors. This power can dramatically reduce unwanted x-ray backgrounds to achieve the most efficient possible use of the limited supply of x-ray photons. It also opens the door for discrimination among multiple chemical elements in a sample.

In our approach (Fig. 1), a small x-ray spot is achieved by focusing a SEM beam onto a platinum film only 100 nm thick. The sub-micrometer features of an IC are magnified onto an imaging x-ray spectrometer by generating the x-rays in the thin-film target mere micrometers from the layers of interest in the IC. By placing the electron-to-photon converter so close to the attenuating sample, we can perform the measurement in a compact instrument only a few meters across. It is the size not of a synchrotron facility, but of a typical laboratory instrument based on a vacuum chamber. Discrimination of the signal x-rays from a large background is aided by good energy resolution. This is where superconducting sensors enter the picture.

TRANSITION-EDGE SENSORS: SUPERCONDUCTING X-RAY MICROCALORIMETERS

Microcalorimeters are energy-resolving sensors that detect x-ray photons, or in fact, photons all the way from the optical band to gamma-ray energies. Like any calorimeter detector, they convert photon energy to heat, then take advantage of some temperature-dependent property to measure that thermal energy electrically. In order to make precision measurements of each x-ray photon's energy, the sensors generally must be made small and kept cryogenically cold. Many designs harness the unusual properties of cryogenic materials: the metallic magnetic calorimeter uses the temperature-dependent magnetization of a metallic paramagnet, while the superconducting tunnel junction uses the quantum tunneling of electrons freed by the absorbed energy.

One of the most fully developed and widely used types of microcalorimeter is the superconducting transition-edge sensor (TES),[4] such as those shown in Fig. 2. In a TES, the temperature is sensed by a material held in the transition between its superconducting and normal states. At temperatures in the narrow range of this superconducting phase transition, the material's electrical resistivity is extremely sensitive to tiny temperature changes. The desired temperature can be reached by placing a constant electrical potential (typically, a few microvolts) across a

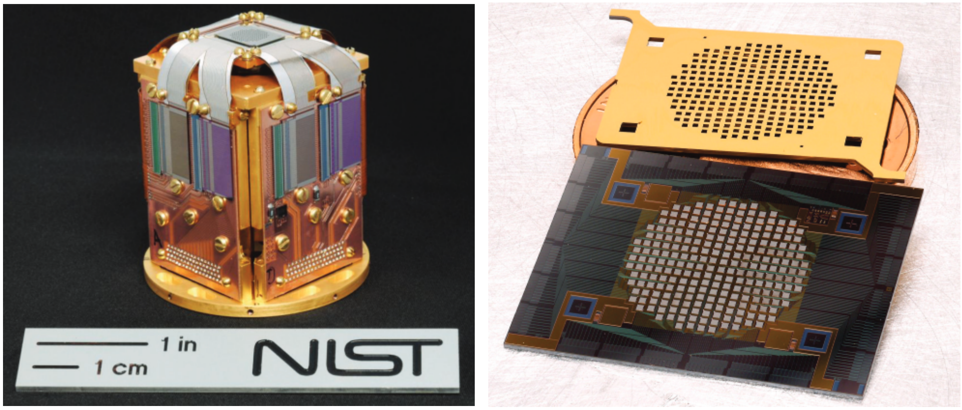


Fig. 2 **Left: A TES array "snout." The sensors (top), the multiplexing SQUID amplifiers (4 of 8 are shown below the flexible wiring runs), and other support electronics are cryogenically cooled in this assembly. Right: An array approximately 9 mm in diameter containing 240 TES detectors (bottom), similar to the array used in the first version of Tomcat. Courtesy of Daniel Schmidt.**

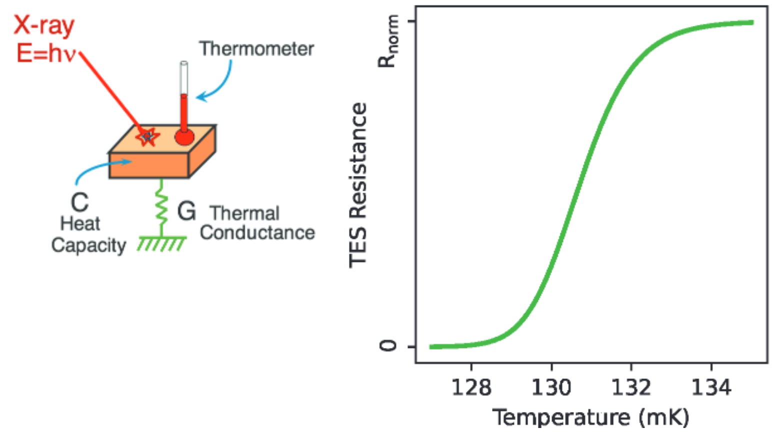
TES. Negative electrical-thermal feedback then balances the device at the desired point on the superconducting transition. A heating event such as the absorption of an x-ray photon causes a brief reduction in the electrical current through the device, lasting typically a few milliseconds or less. Figure 3 shows the operating concept of a TES. Pulses in the TES current are the signatures of a photon detection; the amplitude of the pulse indicates the photon's energy. TESs with energy-resolving powers of 2000 and higher have been demonstrated at x-ray energies from near 1 keV[5] up to at least 12 keV,[6] as well as for gamma rays in the range of 100 keV[7] and even for alpha particles with energies of several MeV.[8] (An energy resolving power of 2000 implies a relative uncertainty of 0.05 %.)

Once fabricated, a TES operates only at a specific temperature, that of its superconducting phase transition. Thanks to the properties of metallic thin films, it is possible to select the transition temperature of materials that combine a superconductor with a normal metal. Thin-film bilayers of molybdenum with either gold or copper can be produced having a range of transition temperatures up to 1K (the transition temperature of bulk Mo), with the temperature engineered to match the available cryogenic cooling system. A layer of high-Z material such as gold or bismuth is often placed near (and thermally connected to) the TES to improve the calorimeter's efficiency for absorption of x-ray photons. Thermal fluctuations are the dominant source of noise in a well-designed TES, so the energy resolution is optimized by designing them for the coldest achievable operating temperature. We typically work with detectors in the range of 20 to 140 mK, temperatures accessible to some commercial refrigerators that offer automated operation without using liquid cryogens.

The fundamental advantage of a microcalorimeter such as the TES over other technologies for x-ray detection is its extremely high energy resolution. The resolution is as good as that of any but the best diffraction-based wavelength-dispersive spectrometers. In addition, the ability to measure the entire spectral band at once means that measurement throughput exceeds that of most high-resolution analyzers. TESs must be made small, however, to minimize their heat capacity and maximize their resolving power.

To accelerate measurements with TESs, we employ arrays of hundreds of sensors (Fig. 2, right). Considerations of both thermal loading and system complexity mean we cannot realistically connect thousands of wires from room temperature directly to a sensor array at sub-Kelvin temperatures. Instead, multiplexing readout systems must be used. Many TES applications have used time-division multiplexing: an amplifier chain based on superconducting quantum interference devices (SQUIDs),[9] Fig. 2, left, cycles through dozens of sensors in a time-shared manner. In a more recent development, a frequency-domain multiplexing system built upon microwave SQUIDs delivers even higher multiplexing factors and/or wider readout bandwidth for each detector. Such systems have been demonstrated to multiplex 250 TESs onto a single radio-frequency transmission line.[10]

Arrays of TES microcalorimeters have been developed



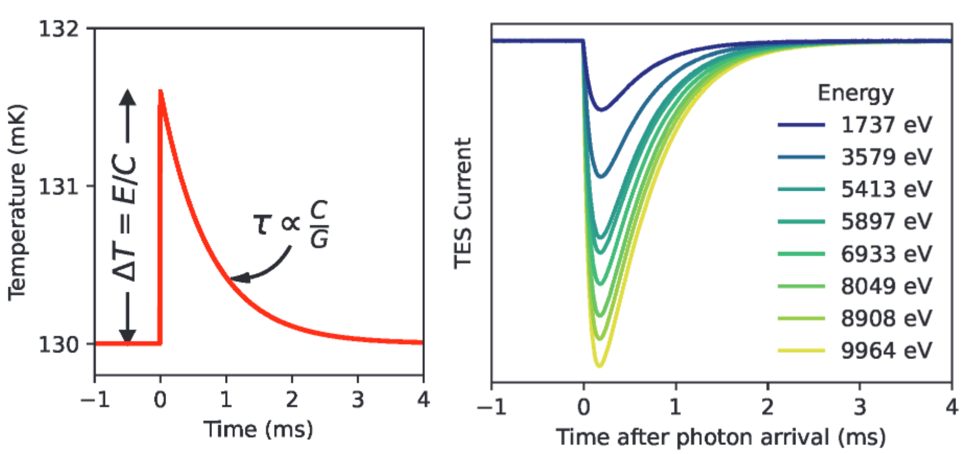


Fig. 3 **The TES detection concept. Top left: Photons are absorbed on a microcalorimeter, a small island of low heat capacity containing the TES thermometer. Top right: In the transition, the TES resistance is a very steep function of its temperature. Bottom left: Absorption of a photon causes a transient pulse in the temperature and a corresponding reduction in the bias current. Bottom right: This dip in current is the signal; the size of the pulse indicates the x-ray energy.**

for many analytic purposes. Several have been installed at synchrotron beamlines for diverse energy bands and scientific goals.[11] They are also used for analysis of radioactive materials in the nuclear fuel cycle[12] and to study the decay-energy spectrum of isotopes such as ^{163}Ho that are sensitive to the mass of the electron neutrino. TES spectrometers are planned for multiple orbiting x-ray telescopes and will analyze samples returned from an asteroid.

TES arrays are also excellent tools for the analysis of more usual, earth-bound materials. In one recent example, we used the emission spectra of several lanthanide-series elements to improve our understanding of certain x-ray fundamental parameters, including the energies and line shapes[13] and relative intensities[14] of the elements' L-series emission lines (Fig. 4). While TESs do not directly register photon energies, energy calibration to one part in 10^4 is possible if enough reference materials—such as the 3d transition metals—are measured along with the unknown samples. The sensitivity and high resolution of the TES also enables the discrimination of distinct chemical states, such as Kα and Kβ emission of titanium (Fig. 5).[15]

X-RAY NANO-CT DEMONSTRATED WITH TES ARRAYS

The energy resolution of a TES spectrometer can also serve as a powerful tool to distinguish signal photons from backgrounds. A new research instrument called the tomographic circuit analysis tool (Tomcat) is the first to use this property of TESs in an x-ray computed tomography (CT) measurement. It recently imaged a small region of an IC and resolved wiring features as small as 160 nm.[16] In future research, the spectrometer will also be able to analyze the elemental composition of the sample, taking advantage of the element-dependent nature of x-ray transmission as a function of energy.

The Tomcat instrument uses the tiny electron beam of a SEM to generate a concentrated source of x-rays for a measurement of x-ray transmission through the IC sample (Fig. 1). The SEM focuses electrons to a spot approximately 100 nm in diameter while accelerating them with a 25 kV potential. A thin-film target, 100 nm of platinum, converts many of the electrons to x-ray photons. The conversion happens in two ways: through broadband

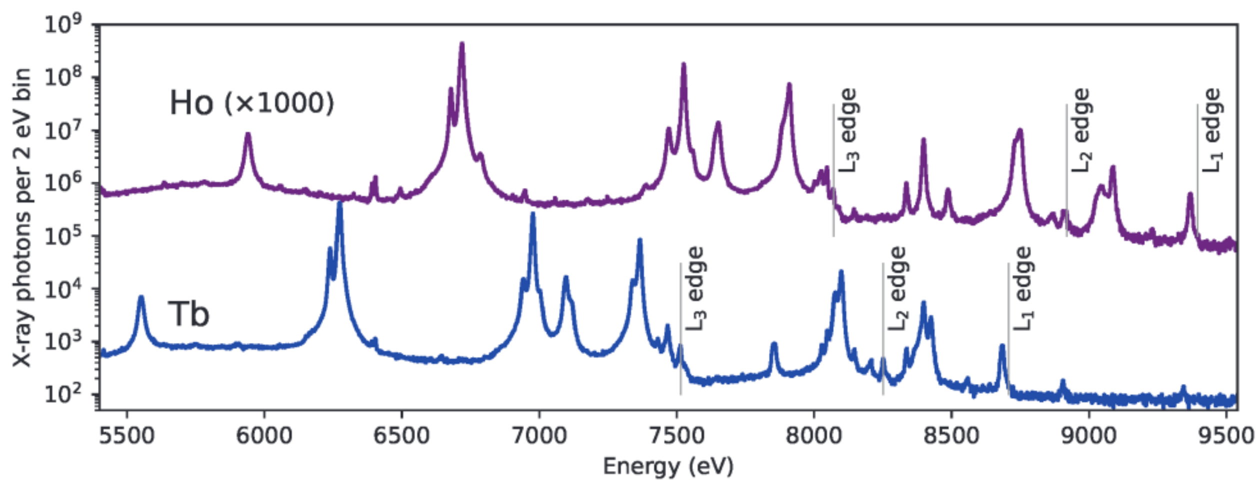


Fig. 4 **Emission spectra of two lanthanide-series metals, a demonstration of the energy resolution and the wide range of energies and intensities the TES can measure.[13] For clarity, the holmium spectrum is scaled up by a factor of 1000.**

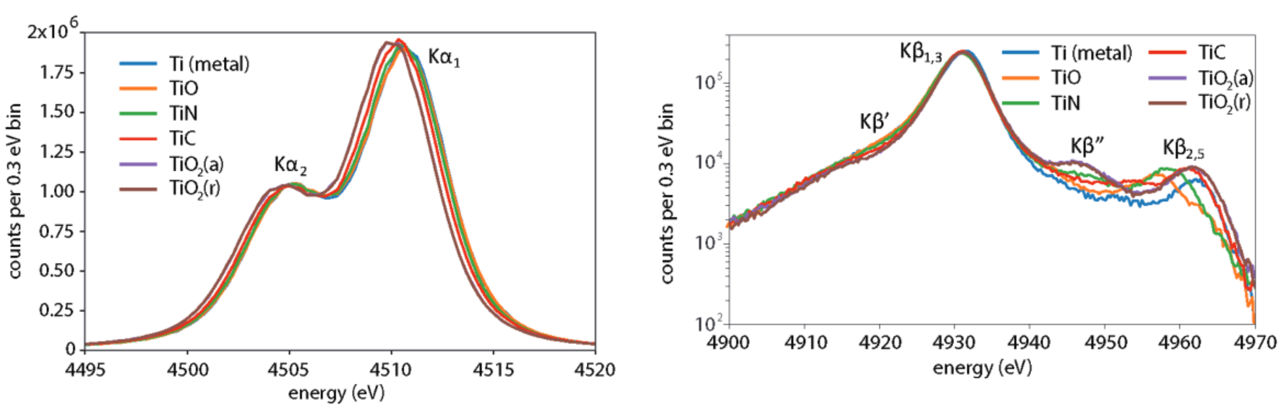


Fig. 5 **TES-measured Kα and Kβ emission spectra of titanium in various oxidation states.**

bremsstrahlung radiation and through inelastic scattering that excites atomic electrons, which then relax by emitting characteristic fluorescence radiation. Any x-rays emitted in the forward direction pass through a narrow spacer layer of silicon and then through the IC of interest, to be imaged by the TES array. Two-dimensional images over larger areas are generated by moving the sample laterally relative to the source and detector array, while the third (depth) dimension is explored by rotating the sample so that x-rays cross it at a variety of angles.

The Tomcat CT instrument requires specially prepared—but reusable—IC samples. For the first demonstration, we removed the circuit's largest, back-end-of-line wiring layers by spin-milling the IC in a plasma focused ion beam. Tomcat would still work with the larger wiring layers intact, but their presence would have slowed down imaging of the smallest features that were of primary interest in the initial demonstration. After the thinning step, three wiring and three dielectric layers of silicon dioxide remained in the sample circuit. A carbon wafer transparent to x-rays was then epoxied to the sample to stiffen it for the remaining preparation work.

One critical design challenge that Tomcat faces is that of achieving high resolution in a compact, laboratory-sized system. The smallest features of interest, only 160 nm wide, must be magnified onto the surface of the imaging detector so that they are larger than the typical spacing of the pixels, which is 500 µm in the TES array. The magnification requirement could have been met by placing the detectors very far from the sample, but this choice would strain the limits of a "compact" system and also reduce the all-important photon yield. To achieve a lab-scale and high-efficiency instrument, we instead chose to locate the conversion target very close to the sample.

IC wafers are far too thick to meet this requirement without further processing—the platinum thin-film electron-conversion target must be placed within micrometers of the transistor layers, in the middle of the wafer itself. Thus, the next step in preparation was to thin the carrier wafer. The great majority of the wafer was removed by lapping and polishing, leaving a spacer layer of silicon only 8.5 µm thick behind the transistor region of the circuit. The 100 nm film of platinum, the conversion target, was then deposited on the remaining spacer. This step fixed the system geometry with a high and, importantly, a constant optical magnification. The spacer thickness was chosen because the imaging array could be no closer than 75 mm from the sample, and because of the minimum feature sizes of this specific IC sample. The choice of platinum as a target material involved several factors; most critically, platinum efficiently emits fluorescence lines at energies that maximize the x-ray absorption contrast between the copper wiring and dielectric in the IC.

For CT measurements, the prepared sample is held in a complex stack of positioning instruments that enable 3D placement with 10 nm precision, as well as rotation about a vertical axis. The IC region of interest (ROI) is measured in a raster-scan pattern across a rectangular area, with discrete steps no more than a fraction of the roughly 1 µm viewable by the TES array at any one instant. The ROI is then rotated about the vertical axis and scanned again to access information about the third, depth, dimension.

The two 3D-reconstruction algorithms used are based on Bayesian and maximum-entropy methods. We adopt a Bayesian prior that penalizes absolute gradients in the reconstructed image, favoring smoother reconstructions. Maximum-entropy methods are well suited to a problem where we have a set of measurements covering only a limited range of angles. In contrast, filtered backprojection, which reigned in medical tomography for four decades,[17] requires that the data be collected in a complete and regular array of angles, then Fourier transformed. Relying on fast Fourier transforms, filtered backprojection is indeed very fast. The speeds of algorithms are becoming less of a concern, however, and the focus today is on obtaining the best reconstructed images for any given data collection.

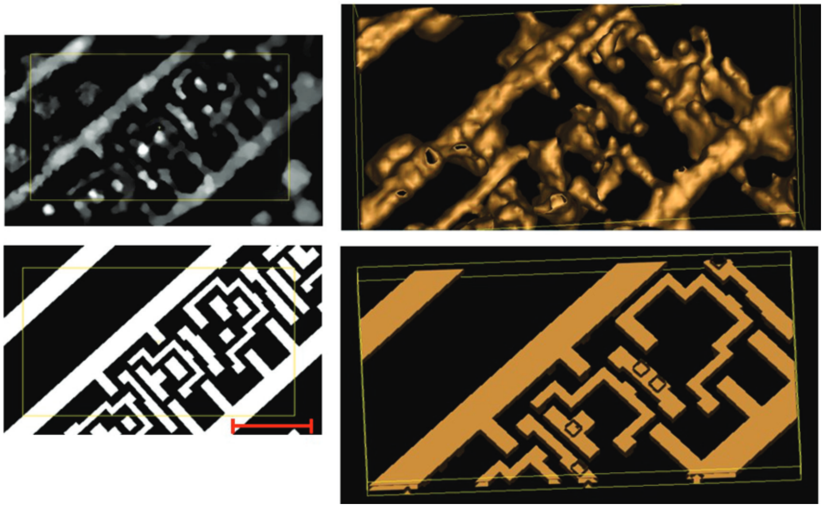


Fig. 6 **Comparison of reconstructions (top) and the design file (bottom). The left images show a single slice; the right images show a 3D view. The finest lines are 160 nm wide and the scale bar is 2 µm. Figure reprinted from Ref. 16 with permission.**

We have found it essential for the reconstruction to model the x-ray source accurately. During the research, we improved the CT spatial resolution by a factor of two simply by starting from a better estimate of the mean transmission through the sample. Detailed radiation-transport modeling of the 3D shape of the x-ray source (and its changes as the source was tilted through various angles) improved the resolution by another factor of two. Both analytical steps were needed to produce the high-quality reconstruction results we obtained with a mere 100 photons detected per voxel. In addition to the shape of the source, the x-ray energy spectrum is also incorporated into the analysis. Again, we use radiation-transport modeling to learn the form of the spectrum. Our TES detectors report the energy of each transmitted photon, allowing our reconstruction algorithm to weight each photon according to its measured energy. This weighting eliminates "beam-hardening artifacts," a class of bias often present when imaging with energy-integrating detectors.

Maximum-likelihood and Bayesian methods have an additional advantage: users can obtain confidence intervals for the reconstruction. It is possible in principle to give a probability that two adjacent pieces of metal are connected or not, or a confidence interval for the width of a given metal line.

The first full IC measurement with Tomcat was made in early 2022 over the course of 300 hours. X-ray transmission scanning at a single angle was repeated for twelve to sixteen hours in a day, then the sample was rotated about the vertical axis to a new angle for the next day, until the sample was imaged many times each over a full range of ±45° in 12 steps. This sample IC was designed and fabricated by colleagues who shared the GDS circuit-design files. The data were used to reconstruct some 100 μm^2 of the sample IC, an IC known to have wiring features as narrow as 160 nm. Comparison of the reconstructed data to the GDS file shows that Tomcat successfully identified and resolved all features in field of view (Fig. 6). We are not aware of any similar, published, structure-by-structure verification of a laboratory CT reconstruction based on the circuit's design file.

FUTURE DIRECTIONS

We are now pursuing improvements to the existing Tomcat instrument. The first is to install TES arrays with smaller supporting electronics, which allows us to operate many more cryogenic detectors. This change will improve the system's imaging speed, which has been limited so far by the small x-ray detection area. Figure 7 shows one of the "microsnouts" now being installed in Tomcat. These small structures will allow us to pack 3000 TESs in 12 arrays close to the IC sample.[18] Coupled with higher-transmission x-ray vacuum windows, the new design should measure x-ray photons at twenty times the rate possible with the single array of 240 TESs used in the first design (Fig. 2).

Tomcat uses the energy resolution of the TES to distinguish signal photons from background. Many electrons from the SEM beam penetrate the platinum target layer, and the bremsstrahlung they create beyond the target could come from practically anywhere, smearing the images badly. The Pt fluorescence photons, on the other hand, are guaranteed to be emitted in the target and thus confined to a 100 nm spot. This was the initial reason to use high-resolution spectroscopy in the instrument.

With our experience and modeling to date, and with the platinum target film roughly 100 nm thick, we have found that even the bremsstrahlung can be mostly confined to a small region—small enough to be a useful signal for tomography at the desired spatial resolution. In this limit, the energy-resolving power of a TES is less critical. Recent

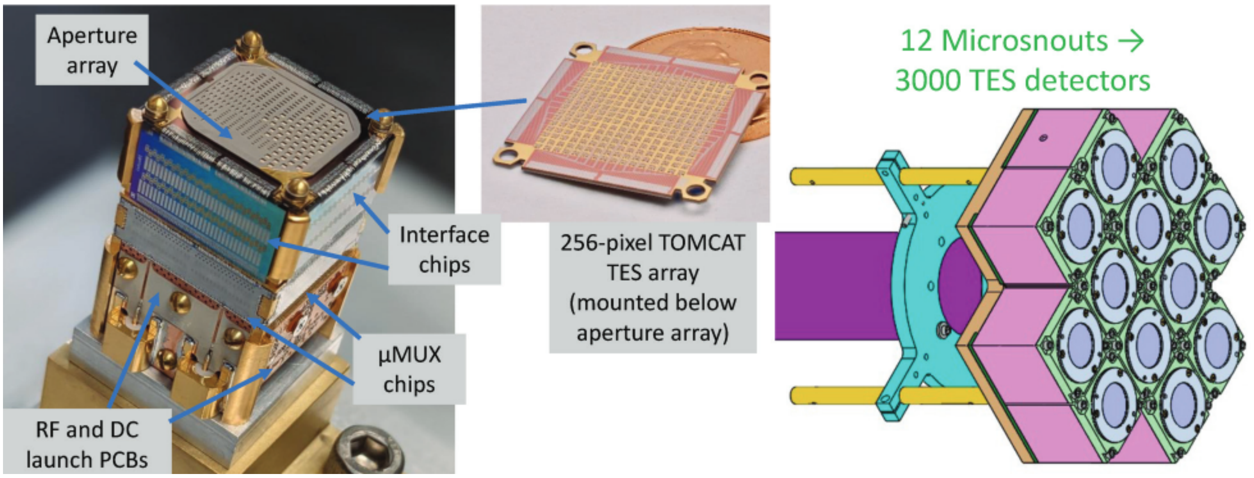


Fig. 7 **The "microsnout" now replacing its much larger predecessor.**

developments in pixelated, hybrid photon-counting x-ray cameras enable an interesting possibility. We will replace the TES detectors with a commercial detector of this type. This camera is in some ways the opposite of the cryogenic microcalorimeter camera: it gives up the energy resolution of the TESs in favor of large collecting area. It should increase the overall photon-counting rate by a factor of 1000 for signal photons, though the exact penalty that comes with the higher background rate remains difficult to assess through modeling.

We expect to find that the optimal approach would blend the virtues of these two contrasting detection techniques. The best instrument might combine them; it might employ both a large-area camera for fast imaging and a camera based on TESs with excellent energy resolution that could exclude the more diffuse bremsstrahlung emission, allowing accurate measurement of the smallest features in a sample. Another reason to use the energy-resolving TES camera along with a large-area camera is to enable pan-chromatic imaging. This possibility would mean using the energy spectrum of transmitted x-rays to determine the elemental composition of wiring and other features inside an IC sample. The TES spectrometer would disentangle elements by their characteristic absorption edges, identifying multiple materials and determining their distinctive distributions across an IC.

Peering inside the complex 3D structures that make up a modern IC with x-ray tomography is not easy. It requires exquisite control over positioning, intense and tiny x-ray sources, and efficient detection of transmitted photons over large areas. Making the measurements in a laboratory rather than a synchrotron only amplifies the challenges. Superconducting detectors can play an important role with their ability to identify fluorescence emission and to distinguish multiple materials in a sample according to their x-ray transmission. We expect the continued refinement of sources, detectors, and positioning equipment to bring practical tomographic imaging of nanoscale structures to the laboratory in the very near future.

ACKNOWLEDGMENTS

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Zachary Levine is a physicist at NIST in Gaithersburg, Maryland. He obtained undergraduate degrees in math and physics from MIT in 1976 and a Ph.D. in physics from the University of Pennsylvania in 1983. A computational physicist by training, he has been doing tomography on and off since about 1997 when he led a team which made the first tomographic reconstruction of an integrated circuit interconnect. Recently, he led a joint experimental-theoretical team which demonstrated an efficient and accurate treatment of diffraction in microtomography with application to an optical fiber.

Paul Szypryt is a research associate and NASA Nancy Grace Roman Technology Fellow (RTF) at the University of Colorado and the NIST Boulder Labs. He completed his Ph.D. in physics at the University of California, Santa Barbara in 2017 and B.S. in applied and engineering physics at Cornell University in 2011. As a graduate student and NASA Space Technology Research Fellow (NSTRF), he helped to develop the first superconducting microwave kinetic inductance detector (MKID) instruments for optical astronomy with a focus on the direct imaging of exoplanets.

Daniel Swetz is a research physicist and leader of the Quantum Calorimeters Group at NIST. He received his B.S. from the University of Wisconsin in 2003 and his Ph.D. in physics from the University of Pennsylvania in 2009. He joined NIST as a National Research Council Postdoctoral Fellow in 2010. His research at NIST focuses on developing superconducting sensors into arrays of x-ray detectors capable of measuring the energy of individual photons and particle decays in ways that are difficult or impossible with conventional detector techniques. He has authored over 100 publications, and has received several awards, including Department of Commerce Gold, Silver, and Bronze medals, and R&D100 award.