NSENSE: Non-destructive Statistical Estimation of Nanoscale Structures and Electronics


National Institute of Standards and Technology (NIST), Boulder, CO

Collaboration between BAE Systems, NIST Quantum Sensors Group, and Orsay Physics
Project Goals

• State of the art integrated circuits (ICs) have been getting increasingly complex with extremely small feature sizes (~10 nm) and many fabrication layers.

• Although patterning these features can be done with advanced lithography techniques, imaging embedded features can be much more difficult.

• Advanced x-ray imaging techniques must be developed to map 10 nm scale features in a timely manner.

• Ideally, such techniques would be non-destructive to the IC and can be performed with a tabletop instrument.
How do TES calorimeters fit into all of this?

**NSENSE approach**: perform tomography on IC under test using a tightly focused SEM electron beam as the source and a TES microcalorimeter array for x-ray detection.

1. **Pixelated array** – Simultaneously probe multiple x-ray paths through sample, large active area.
2. **High x-ray collection efficiency** – maximize count rate, reduce time needed for a tomographic scan.
3. **High resolving power over a broad (~10 keV) energy range** - maximize SNR at emission lines used for tomography.
Phased Approach

• **Phase 1**: Prototype 240 pixel TES instrument, prioritize achieving best spatial resolution (~10 nm) over imaging speed.

• **Phase 2**: Scaled up 3,000 pixel TES instrument using microwave SQUID multiplexing, expected throughput increase of 1000x, main goal of increasing imaging speed while maintaining spatial resolution.

• **Phase 3**: Full scale instrument with 10,000 or more TES microcalorimeters, further increase imaging speed.
Phase 1 TES Optimization

• Unlike NIST’s typical X-ray TES spectrometers, optimizing for energy resolution at extremely high count rates.

Issues at high detection rates

Detector Array:
Increase speed of detectors in standard 240-TES to meet 200 cps/pixel target.

Multiplexing Chips:
Increase slew rate limit by decreasing the coupling by 2.5x.
Fast TES Design

\[ \frac{2}{\tau_{\pm}} = \frac{R_{sh} + R(1 + \beta)}{L} + \frac{1 - \frac{\alpha}{n}(1 - \left(\frac{T_{bath}}{T}\right)^n)}{C/G} \]

1. Decrease thermal time constant: \( C/G \)
   - Decrease heat capacity by adjusting material type or mass of structures on TES island
   - Increase perimeter of TES
   - Fewer/smaller membrane perforations
   - Increase TES critical temperature

2. Change TES \( R(T,I) \) transition shape

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     - Increase TES critical temperature \(T_c = 130\) mK

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NSENSE Array Measured Au L-line Pulses

**TES Current vs. Time**

- Au L3M5, 9.713 keV
- Au L2M4, 11.443 keV
- Au L3N5, 11.587 keV

Pulse duration (dead time): 710-740 μs

**Slew Rate vs. Time**

Max ~0.7 A/sec

Maximum measured slew rate below ~0.9 A/sec NSENSE TDM limit
Energy Resolution Scaling

200 cps/pixel Cu Kα Spectrum

Cu Kα

FWHM: 12 eV

200 cps

Energy resolution meets high rate NSENSE goal of 20 eV!
TES Spectrometer Integration
First Light Spectrum!

- Au from 50 nm target layer
- Ti from 2, 10nm adhesion layers
- Fe, Ni, and Cr from stainless steel, likely from both the sample holder and UHV chamber walls.
- Cu from mounting clips and wiring.

15 kV
10 nA
20 cps/pixel
Expected Scaling Relations:

- **Count rate**: increases linearly with beam current and target thickness (eventually saturates), also increases with acceleration voltage.

- **Beam spot size**: decreases with acceleration voltage, but increases with beam current and target thickness.

- **SNR**: Depends on line energy, expect best efficiency when beam energy is 2-3x the line energy.

**Results:**

- 20-25 kV optimal range for beam spot size and Au Lα SNR.
- Beam current trade-off between flux and spatial resolution.
System Characterization Example

Spectra from sample 102: 50 nm Au, 5 nm Ti

Counts per 4 eV bin, normalized

2000 4000 6000 8000 10000 12000
Photon Energy (eV)

- TiKAlpha
- CrKAlpha
- FeKAlpha
- AuLAlpha1
- AuLAlpha2
- AuLBeta1
- AuLBeta2

LTD-18, July 26, 2019
System Characterization Example
Contrast Tests and Initial Scans

**Sample:** 150 nm thick Au structures.

**Target:** 1 um Al spacer, 75 nm Au, 125 nm Ti.

Measured contrast ratios of ~25-30%
Contrast Tests and Initial Scans

- Bar widths 550 nm.
- 20x20 dwell locations, 100 nm steps, 30 s dwells, 2.5 s step times.
- Essentially 20 line scans at different vertical positions.
- Coadded across all detectors, averages across ~130 nm.
Continuous operation and increased cooling power, allowing for larger arrays of lower $T_C$ detectors.

Increased readout bandwidth (4 GHz) to facilitate larger and faster TES arrays, common microwave transmission line also reduces wiring complexity.

Scaling array size and detector speed

Modular “micro-snout” design, simplifies scaling to large numbers of pixels. Generation 2 instrument would house 12 micro-snouts = 3000 TESs

- Will increase detector speed by a factor of 10 in a similar fashion as was done for optimizing the Phase 1 RAVEN detectors.
  - The increased bandwidth of µMUX readout allows us to make much faster detectors that would have been unusable with our current TDM architecture due to slew rate limitations.
  - Throughput improvement will depend on being able to increase the source strength

\[
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\]

Talk by Abby Wessels on Friday, 9:15 am
Improvements from lowering $T_C$

Ignoring $\beta$ dependence

$$\Delta E \approx \sqrt{\frac{CT_c^2}{\alpha} \sqrt{\frac{1}{1 - (T_b/T_c)^n}}}$$

$$E_{max} \approx \frac{CT_c}{\alpha}$$

Linear TES model with constant dynamic range

$$\Delta E \approx \sqrt{E_{max}} \sqrt{\frac{T_c}{\sqrt{1 - (T_b/T_c)^n}}}$$

$T_b$ sufficiently low

$$\Delta E \propto \sqrt{T_c}$$

Potential for up to a factor of 2 improvement in resolution, increasing the SNR of spectral features used for tomography

Also allows us to increase detector size, ~2-4x collection area improvement
Thicker Bi absorber (~2x improvement)

Current Bi absorbers, 4.4 um thick

Electroplated Bi absorbers, 15 um thick

Talk by Joel Weber on Wednesday, 12:15 pm
Next Steps

• Continue scans on 2 dimensional structures. Reduce system vibrations/noise sources and determine best achievable spatial resolution.

• Begin scans of more complicated ICs with varying numbers of structural layers and feature sizes.

• Begin design of 2\textsuperscript{nd} generation instrument cryostat, readout, and detectors.
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