

This work was written as part of one of the author's official duties as an Employee of the United States Government and is therefore a work of the United States Government. In accordance with 17 U.S.C. 105, no copyright protection is available for such works under U.S. Law.

Public Domain Mark 1.0

<https://creativecommons.org/publicdomain/mark/1.0/>

Access to this work was provided by the University of Maryland, Baltimore County (UMBC) ScholarWorks@UMBC digital repository on the Maryland Shared Open Access (MD-SOAR) platform.

Please provide feedback

Please support the ScholarWorks@UMBC repository by emailing scholarworks-group@umbc.edu and telling us what having access to this work means to you and why it's important to you. Thank you.

Microcalorimeter Absorber Optimization for ATHENA and LEM

Edward Wassell (✉ edward.wassell@nasa.gov)

NASA Goddard Space Flight Center

Joseph Adams

University of Maryland, Baltimore County

Simon Bandler

NASA Goddard Space Flight Center

James Chervenak

NASA Goddard Space Flight Center

Renata Cumbee

NASA Goddard Space Flight Center

Fred Finkbeiner

Sigma Space Corp. / Hexagon US Federal

Joshua Fuhrman

University of Maryland, Baltimore County

Samuel Hull

University of Maryland

Richard Kelley

NASA Goddard Space Flight Center

Caroline Kilbourne

NASA Goddard Space Flight Center

Jennette Mateo

NASA Goddard Space Flight Center

Haruka Muramatsu

The Catholic University of America

Frederick Porter

NASA Goddard Space Flight Center

Asha Rani

Science Systems and Applications, Inc. (SSAI)

Kazuhiro Sakai

University of Maryland, Baltimore County

Stephen Smith

NASA Goddard Space Flight Center

Nicholas Wakeham


University of Maryland, Baltimore County
Sang Yoon
Science Systems and Applications, Inc. (SSAI)

Research Article

Keywords: Transition Edge Sensor 1, X-ray microcalorimeter 2, Superconducting Devices 3

Posted Date: November 7th, 2023

DOI: <https://doi.org/10.21203/rs.3.rs-3553841/v1>

License:  This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

High quantum efficiency (QE) x-ray absorbers are needed for future x-ray astrophysics telescopes. The Advanced Telescope for High ENergy Astrophysics (ATHENA) mission requirements for the X-ray Integral Field Unit (X-IFU) instrument dictate, at their most stringent, that the absorber achieve vertical QE > 90.6% at 7 keV and low total heat capacity, 0.731 pJ/K. The absorber we have designed is 313 μm square composed of 1.05 μm Au and 5.51 μm electroplated Bi films [1]. Overhanging the TES, the absorber is mechanically supported by 6 small legs whose 5 μm diameter is tuned to the target thermal conductance for the device. Further requirements for the absorber for X-IFU include a > 40% reflectance at wavelengths from 1–20 μm to reduce shot noise from infrared radiation from higher temperature stages in the cryostat. We meet this requirement by capping our absorbers with an evaporated Ti/Au thin film. Additionally, narrow gaps between absorbers are required for high fill fraction, as well as low levels of fine particulate remaining on the substrate and zero shorts between absorbers that may cause thermal crosstalk. The Light Element Mapper (LEM) is an X-ray probe concept optimized to explore the soft X-ray emission from 0.2–2.0 keV. These pixels for LEM require high residual resistance ratio (RRR) thin 0.5 μm Au absorbers to thermalize uniformly and narrow < 2 μm gaps between pixels for high areal fill fraction. This paper reports upon technology developments required to successfully yield arrays of pixels for both mission concepts and presents first testing results of devices with these new absorber recipes.

1 ATHENA Absorber Fabrication

X-ray absorber structures are integral to the design and performance of the microcalorimeter sensor. Their photolithographic integration enables exquisite determination of such details as thermal time constants and spectral resolution performance but can influence fabrication process flow. While many groups [2–7] have developed processes to fabricate electroplated bismuth absorbers for microcalorimeters, the requirements on x-ray absorbers for the ATHENA X-IFU instrument pose unique fabrication challenges. Specifically for X-IFU, we need to fabricate free standing absorbers with six narrow 4–5 μm diameter stems supporting a large 313 μm^2 area absorber composed of 1.05 μm Au and 5.51 μm Bi and capped by a thin Ti/Au coating[1]. The stem diameter is chosen to achieve structural and thermal needs of the absorber while being feasible to fabricate. However, small stem diameter can lead to a mechanically weak stem which may not be suitable for extended geometries and certain film thickness limits. To enhance the structural integrity of the stem, a funnel-shape photoresist mold using a proximity exposure has been developed to control the shape of the stem. Backfilling the stems with electroplated Au was also incorporated to increase the strength of thin stems in supporting the mechanical stresses applied to them from the large absorbers. Additionally, to optimize for post-patterning substrate cleanliness for absorber yield, we have developed a method of plating the thick bismuth absorbers using a photoresist mold while controlling the bismuth grain growth with a leveling process while electroplating. Finally, to separate the pixels from each other, we use an ion mill etch to remove the Ti/Au capping layer as well as the Ti/Au seed layer. Although others have backfilled stems [8] and electroplated bismuth through a photoresist mold [4, 5, 7], we are combining all of these patterning steps, requiring numerous repatterns over the

sacrificial resist layer supporting the electroplated mushroom absorber overhanging the TES. Figure 1 has a cartoon of the pixel architecture (*Left*) and a table listing our process fabrication steps (*Right*).

Historically, our calorimeter group first developed a procedure to yield overhanging mushroom shaped x-ray absorbers with electroplated gold and bismuth films suspended above a transition edge sensor on a silicon nitride membrane [9, 10]. Our NASA group has demonstrated an average 2.25 eV energy resolution in prototype arrays of spectrometer pixels with 1.5 μm Au + 3 μm Bi absorbers on 275 μm pitch [11]. Recently revised ATHENA requirements for lower heat capacity and higher quantum efficiency imposed a fabrication change to thinner Au (1.0 μm) and thicker Bi (5.5 μm) as well as an increase in absorber pixel size to 313 μm^2 [1]. Our initial attempts to yield these new absorbers resulted in absorber touches to the substrate degrading pixel performance. Further, some pixels collapse completely when the stems break near the base. SEM imaging revealed that the thinner Au stems filled with bismuth grains were not mechanically strong enough to support the larger area thicker bismuth absorbers. Figure 2 shows examples of absorber collapse (top and bottom left) and hollow stems that can break during release (top and bottom right). We measured the film stresses of the individual layers and found the titanium adhesion layer to be tensile, the gold to be mostly stress free and the bismuth to be compressive. With hollow stems from thinner electroplated Au and the additional stress from the thicker bismuth film, our traditional stem design was not mechanically strong enough to support the larger area absorbers required by ATHENA.

Our solution to making mechanically stable absorbers was threefold. First, we smoothed the shape of stems using a double exposure of the resist and a reflow bake. Next, we increased the tensile titanium in the seed layer deposition to counteract the compressive stress of the bismuth. Third, we pattern atop the seed layer and backfill the stems with electroplated Au to make them mechanically more robust.

While developing our new process to mechanically strengthen the stems supporting the overhanging absorbers, we also worked out a procedure to electroplate the absorbers through a photoresist mold. Previously, we have defined our absorbers by a long ion mill through the entire Au/Bi stack. Because the Bi grain size increases with thickness [2], we have found that after a long ion mill, a fraction of absorbers have small metal bridges thermally shorting them together, degrading badly the energy resolution in the affected pixels. Electroplating the bismuth through a photoresist mold and then following with a much shorter ion mill to clear the remaining Ti/Au from both the capping and seed layers appears to solve the problem of thermally shorted pixels. Figure 1 (*Right*) details our new fabrication flow with the additional steps highlighted in red. As will be shown later in this paper, despite the complications from the additional fabrication steps, our first delivered devices showed no degradation in energy resolution, no additional broadening in the low energy tails of the x-ray spectrum and we were still able to achieve the desired heat capacity. Figure 3 shows SEM images of an array that yielded after electroplating Bi through a photoresist mold. The absorbers are free standing and flat with 5.0 μm gaps between pixels.

2 LEM Absorber Fabrication

Absorber fabrication for LEM follows a similar flow to ATHENA without the added bismuth. The proposed LEM focal plane is a hybrid array consisting of two different pixel types. The inner array has 784 single high resolution pixels, and the outer array consists of 3184 four pixel hydras, consisting of a single transition edge sensor (TES) connected to four absorber pixels by different thermal links. Each distinct event can be separated algorithmically according to its pulse height and rise time [12]. These hydras for LEM require high residual resistance ratio (RRR) $0.5\text{ }\mu\text{m}$ Au absorbers to thermalize uniformly. Yielding flat thin Au absorbers with narrow $1.5\text{ }\mu\text{m}$ gaps between pixels poses its own fabrication challenges. Thin ($0.5\text{ }\mu\text{m}$) large area Au absorbers are difficult to yield because of film stresses in the Ti adhesion layer. While other groups have proposed corrugations in the absorber to mitigate these stresses and keep the absorbers flat [8], our solution was to reduce the Ti adhesion layer thickness and add the stem backfilling process to strengthen the mechanical support to the substrate.

The first attempt at yielding absorbers for LEM resulted in the loss of a handful of pixels during the release of the wafers. Figure 4 shows the missing absorbers after release. Photolithography was able to achieve narrow $1.5\text{ }\mu\text{m}$ gaps between absorber pixels for high areal fill factor. The SEM images in Fig. 4 highlight the success of yielding $0.5\text{ }\mu\text{m}$ thin Au absorbers with narrow gaps despite the mechanical stresses that lead to curvature in the absorber. Inspecting areas of the array where pixels were lost, we discovered cracks near the base of the stems visible in Fig. 5. Since the base of the stem is nominally $4\text{ }\mu\text{m}$ and widens considerably through our photoresist reflow process, electroplating $0.5\text{ }\mu\text{m}$ of Au will leave the stems hollow. Our initial fabrication run did not include backfilling the stems, which has been shown to eliminate the absorber loss.

After coating the shaped stem mold resist with a Ti/Au seed layer, we developed a process to backfill the hollow stem area with electroplated Au to make the absorbers mechanically robust without significantly increasing the heat capacity of the absorbers. Careful process control is needed to ensure the plating does not overfill the thin stems and form pillars on the absorbers. Figure 6 shows Keyence optical imaging of the surface of the Au coated stem photoresist mold and the depth profile of a stem before (top) and after (bottom) the stem filling electroplating procedure. The initial $4.3\text{ }\mu\text{m}$ stem height agrees with the mold resist thickness measured by a stylus profilometer. Figure 6 bottom shows three microns of the stem has been backfilled, allowing room to tune this process further.

3 ATHENA Detector Results

We tested the ATHENA detectors with the new absorber method and found no performance degradation. Eleven pixels from two wafers with the old absorber method and five pixels from one wafer with the new absorber method were examined. The Au in the absorbers is a combination of $0.2\text{ }\mu\text{m}$ evaporated Au as a seed layer for electroplating, $0.8\text{ }\mu\text{m}$ electroplated Au and then a $0.04\text{ }\mu\text{m}$ capping evaporated Au over the bismuth to increase infrared reflectivity. The pixels tested vary in width of the TES thin film but are from the same location on each wafer and are otherwise comparable. Heat capacities from both absorber methods are consistent with the predicted values from the TES and absorber dimensions. Using an Fe55

source to illuminate the detector, the energy resolution for a single pixel is found to be 1.92 eV as shown in an Mn-K α spectrum in Fig. 7.

References

1. D. Barret et al., Exp. Astron. **55**, 373–426 (2023). 10.1007/s10686-022-09880-7

2. L.M. Gades et al., IEEE Trans. Appl. Supercond. **27**, 1–5 (2017). 10.1109/TASC.2017.2662007

3. D. Yan et al., IEEE Trans. Appl. Supercond. **31**, 1–5 (2021). 10.1109/TASC.2021.3059972

4. J. Weber et al., Supercond Sci. Technol. **33**, 115002 (2020). 10.1088/1361-6668/abb206

5. P. Khosropanah et al., Proc. SPIE 106991M (2018), 10.1117/12.2313439

6. J. Chen et al., Mater. 14. 7169 (2021). 10.3390/ma14237169

7. E.J. Wassell et al., IEEE Trans. Appl. Supercond. **27**(4), 1–5 (2017). 10.1109/TASC.2016.2633783

8. C.V. Ambarish et al., IEEE Trans. on Appl. Supercond. **33**(5), 1–5 (2023). 10.1109/TASC.2023.3243156

9. C.A. Kilbourne et al., Proc. SPIE 6266, 626621 (2006), 10.1117/12.672419

10. A.D. Brown, J. Low, Temp. Phys. **151**(1), 413–417 (2008). 10.1007/s10909-007-9669-2

11. S.J. Smith et al., IEEE Trans. on Appl. Supercond **25**, 3 (2015), 10.1109/TASC.2014.2369352

12. S.J. Smith et al., IEEE Trans. Appl. Supercond. **19**, 451–455 (2009). 10.1109/TASC.2009.2019557

Figures

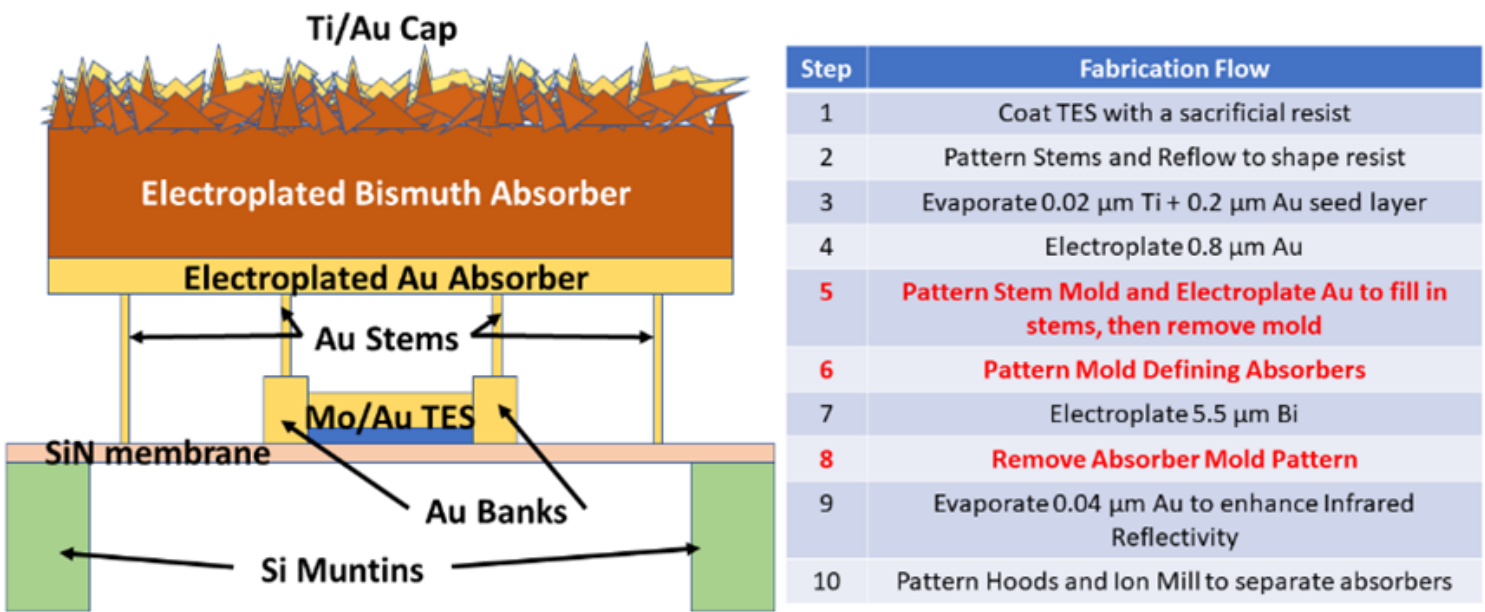


Figure 1

A cartoon of pixel architecture (*Left*) highlights an x-ray absorber overhanging but thermally linked to a TES by thin stems and suspended above a SiN membrane of low thermal conductance. Absorber

fabrication flow is listed (*Right*) with our new process additions in red. (Color figure online)

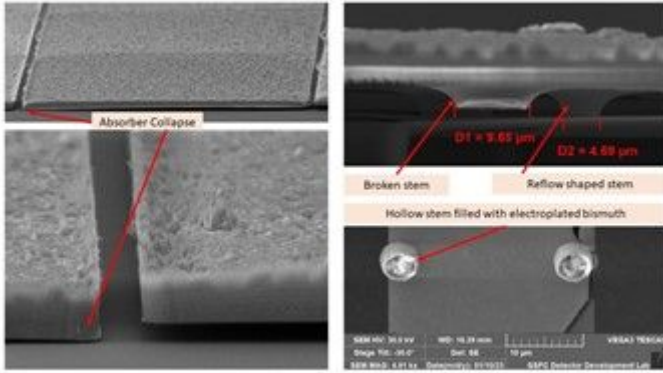


Figure 2

Initial attempts to meet new ATHENA detector requirements for larger absorbers with thicker bismuth and thinner gold resulted in absorbers touching the substrate (*Top and Bottom Left*), and broken stems (*Top and Bottom Right*). Compressive stresses in the thicker bismuth film shape the absorbers down at the corners.

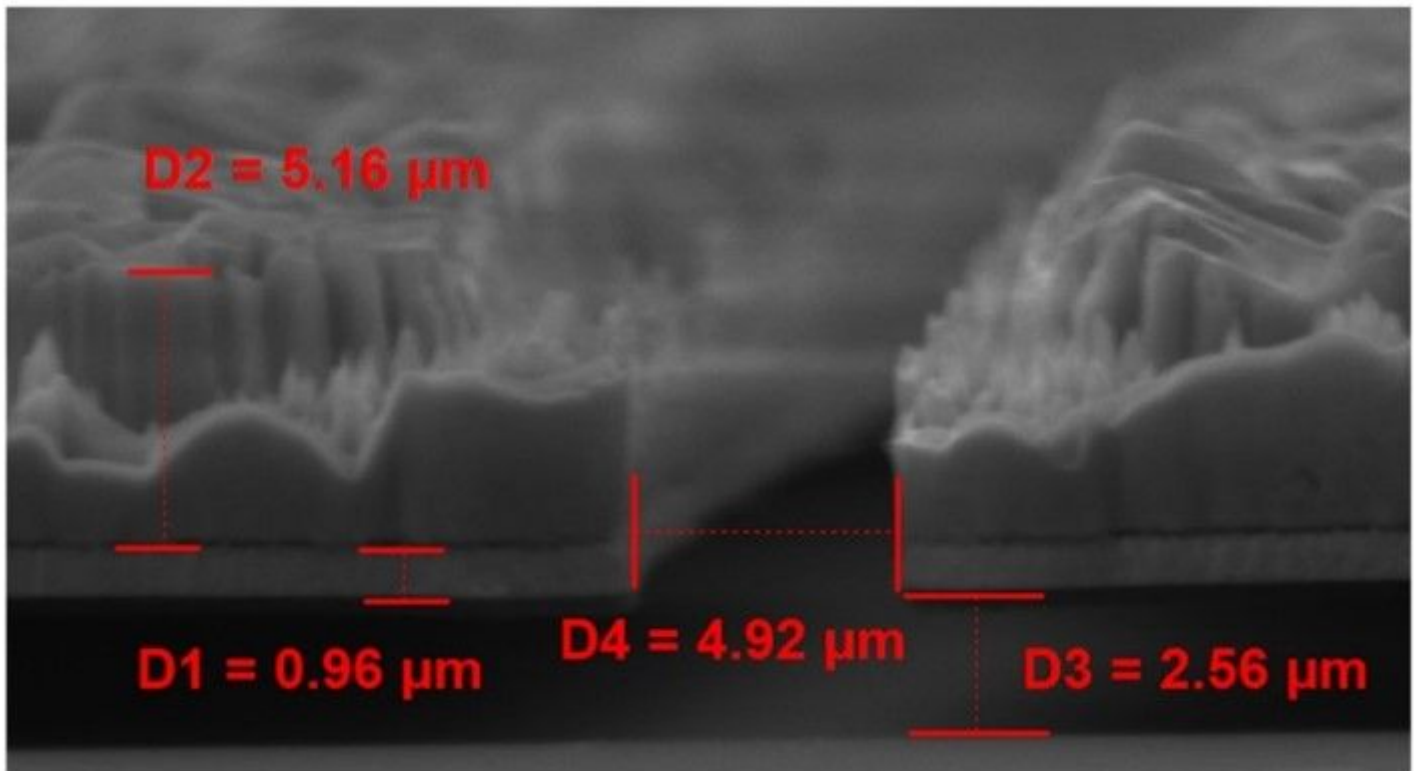


Figure 3

SEM image of a prototype ATHENA absorber incorporating electroplating Bi through a mold and backfilling the stems. We achieved flat free standing absorbers with 5.2 μm thick Bi atop 1.0 μm thin Au while preserving 5.0 μm gaps between pixels. (Color figure online)

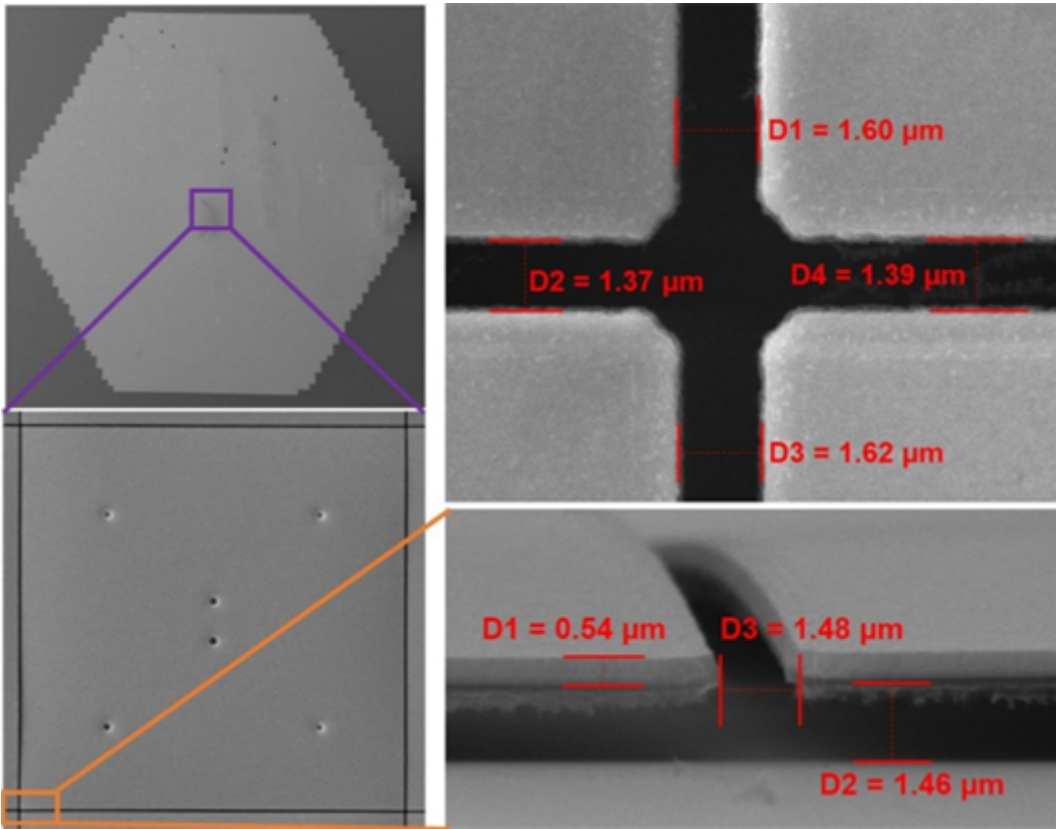


Figure 4

SEM images of LEM. *Top left* The hexagonal detector array. *Bottom left* A single pixel with six funnel shaped stems. *Top right* Yield of absorbers with under 2 μm gaps. *Bottom right* Edge view of curvature in the absorbers.

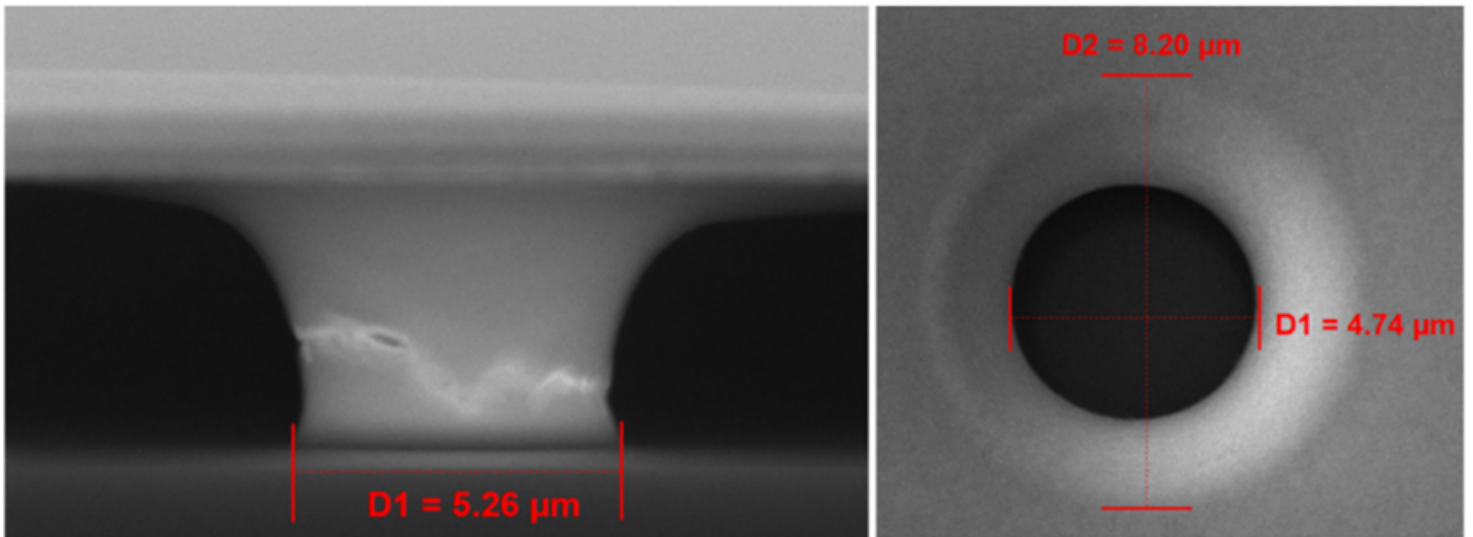


Figure 5

Edge-on SEM image (*Left*) shows a stem that cracked at the base due to high mechanical stresses from the thin absorber. Our improved photolithography with reflow (*Right*) yields a smooth funnel shaped

stem.

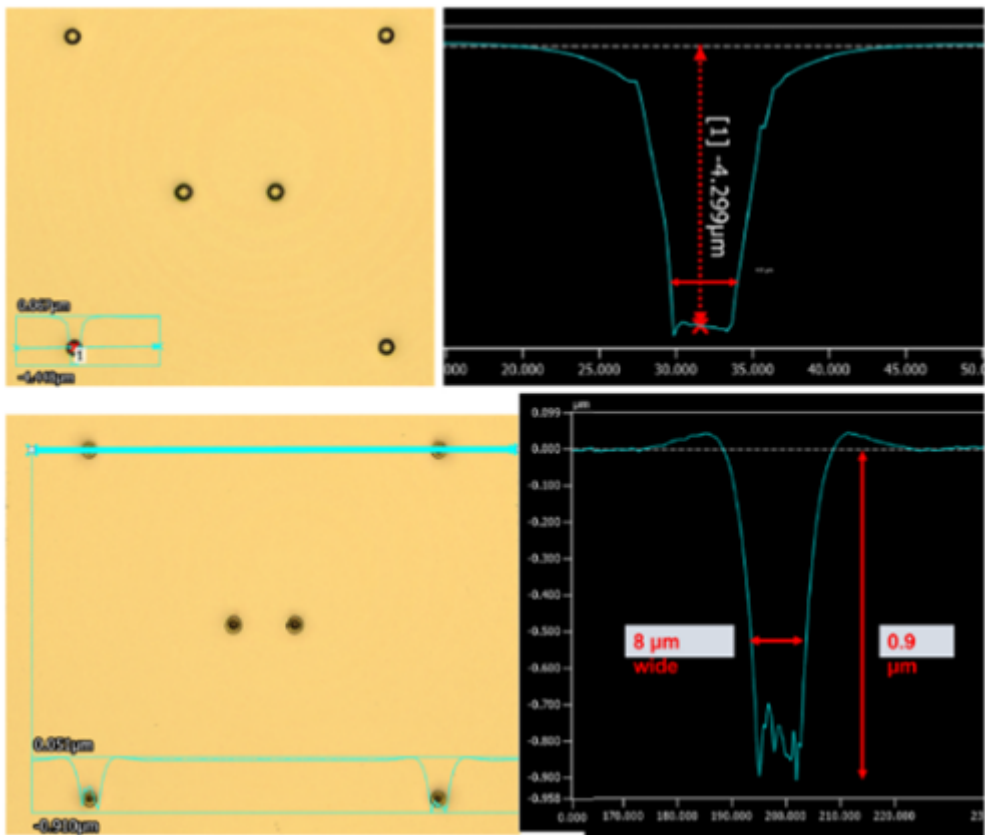


Figure 6

Keyence image and measurement of a single stem before (*Top*) and after (*Bottom*) Backfilling the stem with electroplated Au.

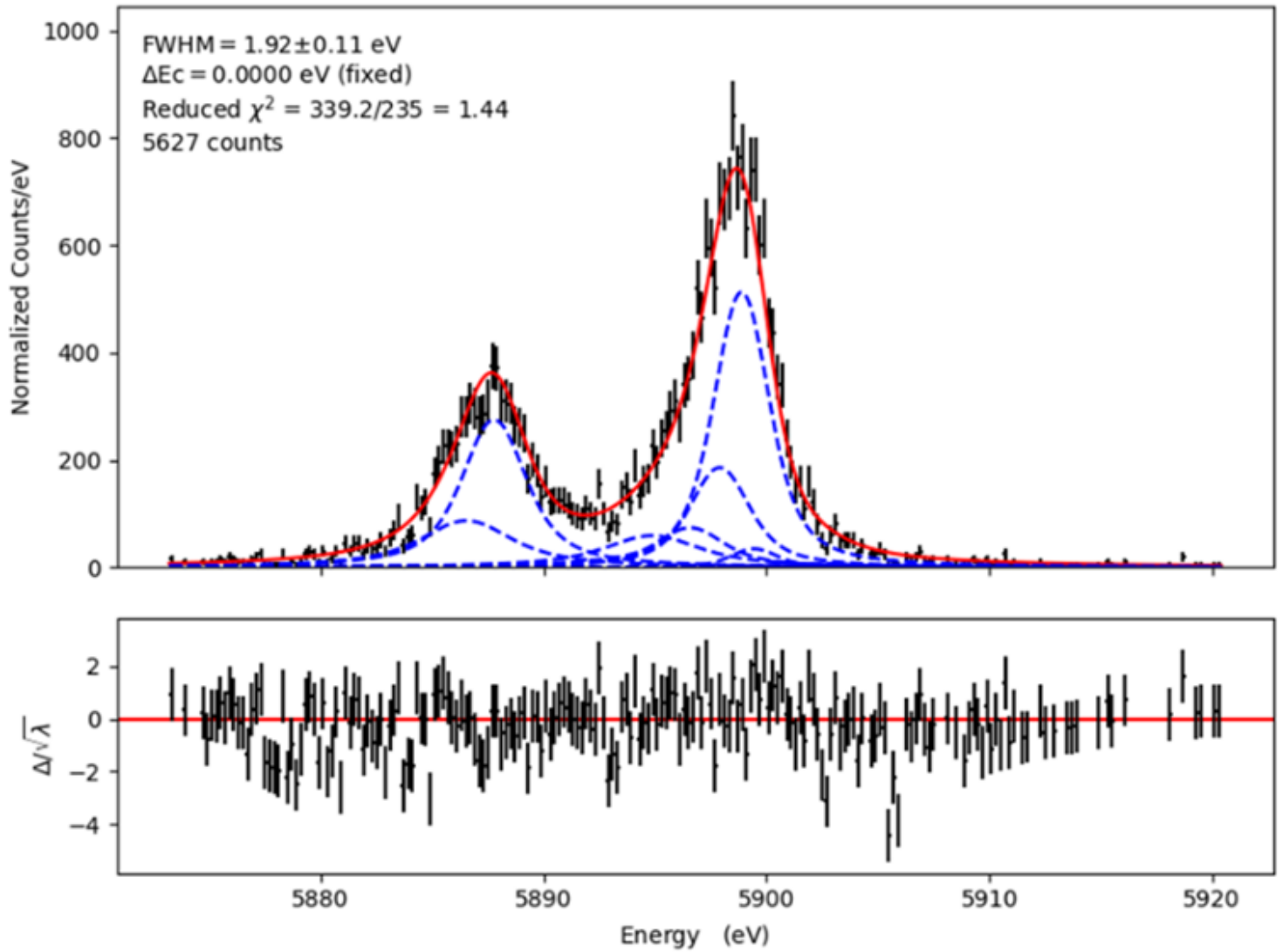


Figure 7

With the new absorber fabrication method, we have achieved sub 2eV energy resolution on a pixel from an ATHENA prototype array illuminated by an Fe55 source for the Mn-K α line in an x-ray spectrum.