Quantum Efficiency Study and Reflectivity Enhancement of Au/Bi Absorbers

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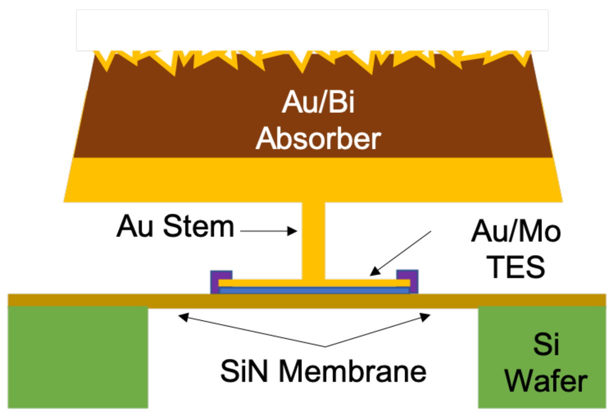
Abstract

X-ray absorbers of the X-ray Integral Field Unit (X-IFU) microcalorimeters are required to provide high quantum efficiency (QE) for incident x-rays and high reflectivity to longer wavelength radiation. The thickness of the electroplated Au and Bi layers are tuned to provide the desired pixel heat capacity and the QE. To calculate the QE precisely, in addition to filling factor, we have included the effects of surface roughness, edge profile of the absorbers and the effects of the different angles of incidence of the incoming x-rays from the X-IFU optic. Based on this analysis it is found that thickness of Bi layer needs to be adjusted by 5% to achieve the X-IFU QE requirements. To improve the reflectivity of absorbers to low energy radiation, a second thin layer of Au is sputter deposited on top of the Bi layer. Measurements in the wavelength range 300 nm - 20 microns show a significant increase in reflectivity compared to a bare Bi layer.

X-IFU TES Microcalorimeter

X-IFU [1] TES microcalorimeters [2] consist of:

- ~6 µm thick Au/Bi absorber
- Mo/Au bilayer TES sensor with $T_C \approx 90$ mK.
- 2 µm diameter and ~5 µm tall Au stems
- 0.5 µm thick SiN membrane



The absorber is a critical component to the pixel design that not only provides the stopping power for x-rays, or quantum efficiency (QE), but also dominates the total heat capacity.

Total Heat Capacity of TES microcalorimeter:

$$C_{tot}(100\%) = C_{AuMo}(8\%) + C_{SiN}(5\%) + C_{AuBi}(85\% + 2\%)$$

Quantum Efficiency of AuBi:

$$QE_{AuBi}(20\% + 70\%) = 100\% * \left(1 - \exp\left(-\frac{t_{Bi}}{\mu_{Bi}}\right)\exp\left(-\frac{t_{Au}}{\mu_{Au}}\right)\right)$$

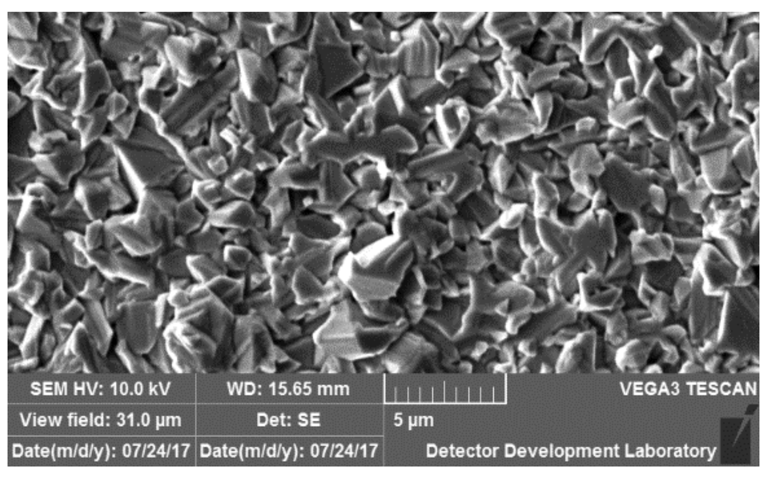
μ_{Au} = 1.7955/ 4.0034 µm @7/ 9.5keV [3]
μ_{Bi} = 3.0918/ 6.7592 µm @7/ 9.5 keV [3]

XIFU Requirements:
- ΔE_{FWHM} = 2.5 eV @ 7 keV
- QE ≥ 96% @ 0.2-1 keV
- ≥ 87% @ 7 keV
- ≥ 63% @ 9.5 keV
- Reflectivity > 40% @ 1-30 µm

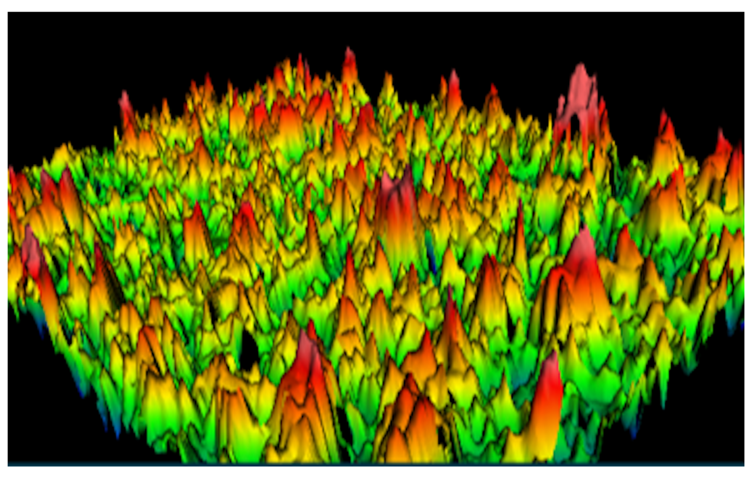
Related Parameters:
- C_{tot} = 1.1 pJ/K
- Pitch: 275 µm
- Thickness: 2 µm Au/ 3.75 µm Bi
- Filling factor: 98%

Surface Roughness of Bi

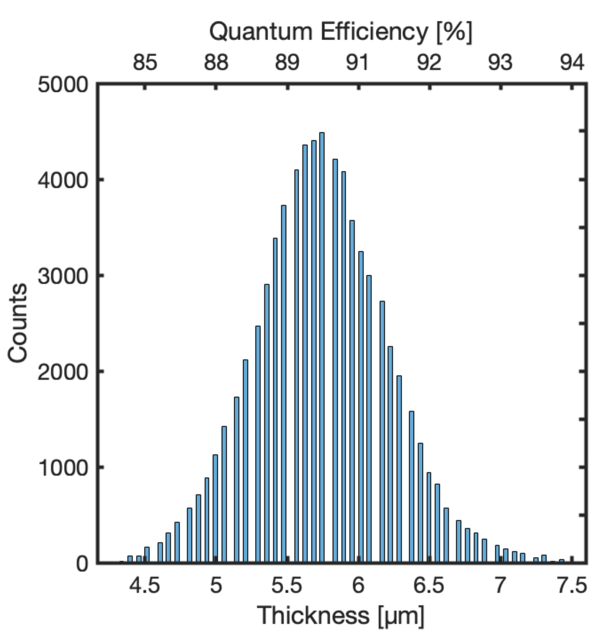
SEM image of electroplated Bi:



Surface model from interferometer:



- Electroformed Bi has gain size which is typically proportional with the thickness of the sample
- Surface roughness of 3.44 µm thick electroplated Bi sample was measured by using 3D optical profiler
- This measurement indicates that there is greater number of "valleys" than "mountains", which results in an asymmetric distribution of the thicknesses.
- Thickness variation (Δt_i) from this measurement is scaled and added to usual 2 µm thick gold and 3.75 µm Bi to obtain histogram of QE (top axis):



$$QE_i = 100\% * \left(1 - \exp\left(-\frac{t_{Bi} + \Delta t_i}{\mu_{Bi}}\right)\exp\left(-\frac{t_{Au}}{\mu_{Au}}\right)\right)$$

- Average QE is obtained by using weight of each thickness bin:

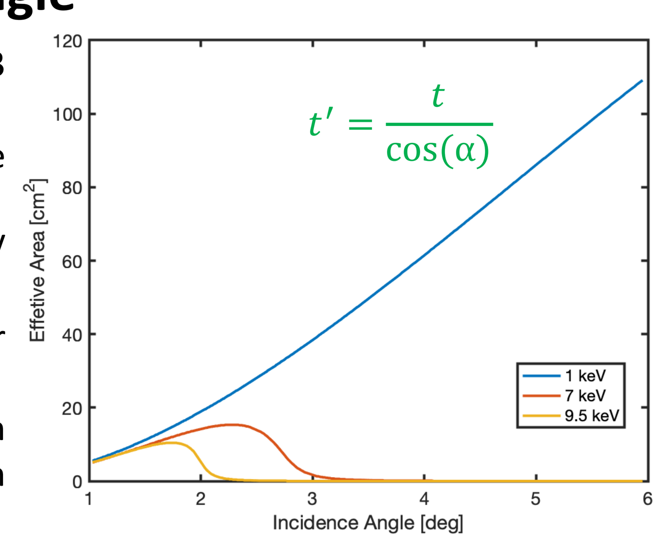
$$QE_{avg} = \frac{\sum QE_i \cdot N_i}{\sum N_i} = 90.11\%$$

- This is 0.13% less as compared to 90.24% for Au/Bi absorber without the roughness. Decrease in QE is expected because average of Δt_i is negative.

Incidence Angle

- Athena's X-ray telescope has 12 m focal length with 3 m diameter.
- Collection of X-rays is achieved by using silicon pore optics [4].
- Effective Area (EA) vs incidence angle for 1, 7, 9.5 keV x-rays are shown in the plot.
- Most of the 7 keV x-rays will hit to Au/Bi absorber with less than 3 degrees.
- Without taking into account reflection and refraction effects we estimate the effect of incidence angle on QE by taking into account the thickness increase.
- This gives a QE_{avg} which is given by:

$$QE_{avg} = \frac{\sum_i QE(\alpha_i).EA(\alpha_i)}{\sum_i EA(\alpha_i)}$$

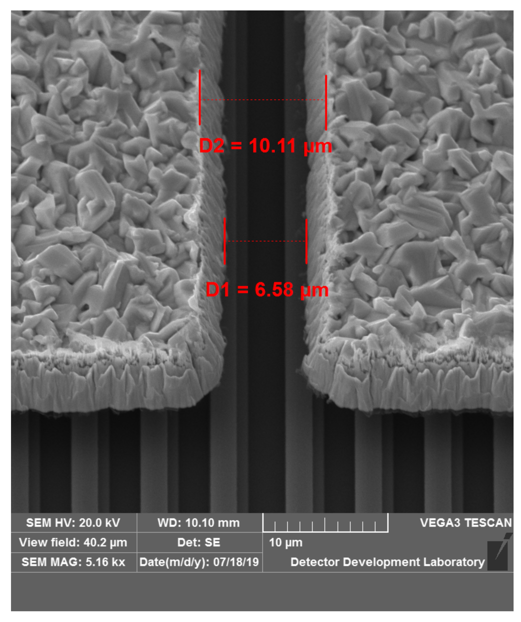


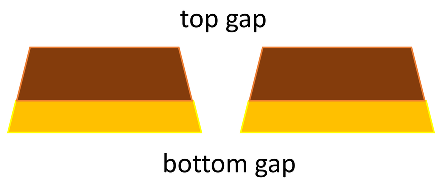
	1 keV	7 keV	9.5 keV
$QE_{\perp}$	100	90.24	65.16
QE_{avg}	100	90.25	65.17

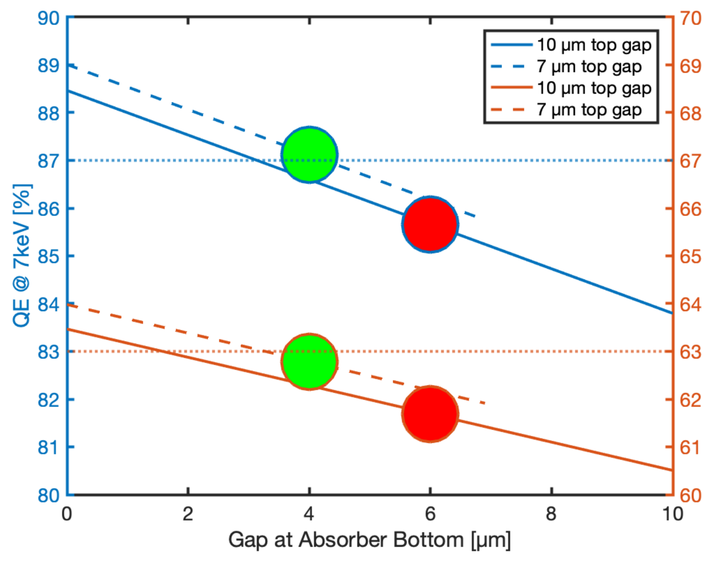
- Average QE is increased by 0.01% when we take into account the incidence angle.

Edge Profile and Filling Factor

- Au/Bi absorbers are fabricated by electroplating Au and Bi layers over the entire array and then separating the pixels by ion milling [5].
- This process leads to a trapezoidal profile where we have a narrow gap at the bottom and wider gap at top of the absorbers.
- These gaps are measured by focusing with limited depth of field to the top and bottom of the absorbers under microscope or from SEM images.



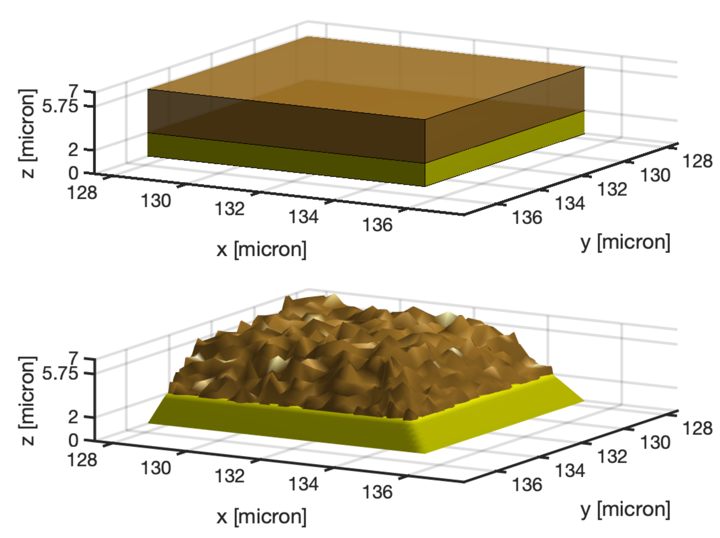


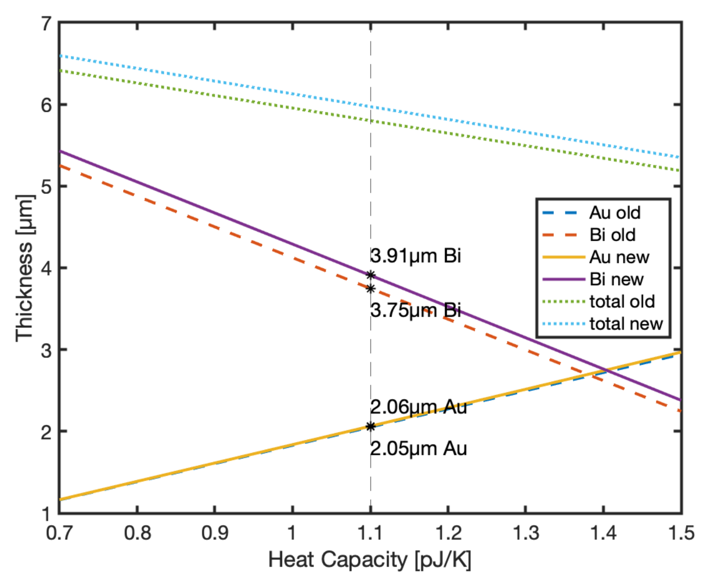


- With our current measured 10±0.5 µm top gap and 6±0.5 µm bottom gap we are at the red circles which are below requirements for both energies.
- The next iteration of AuBi absorbers are being developed with ~ 7 µm top and ~ 4 µm bottom gaps, leading to the green circles.

Au/Bi Thickness Optimization

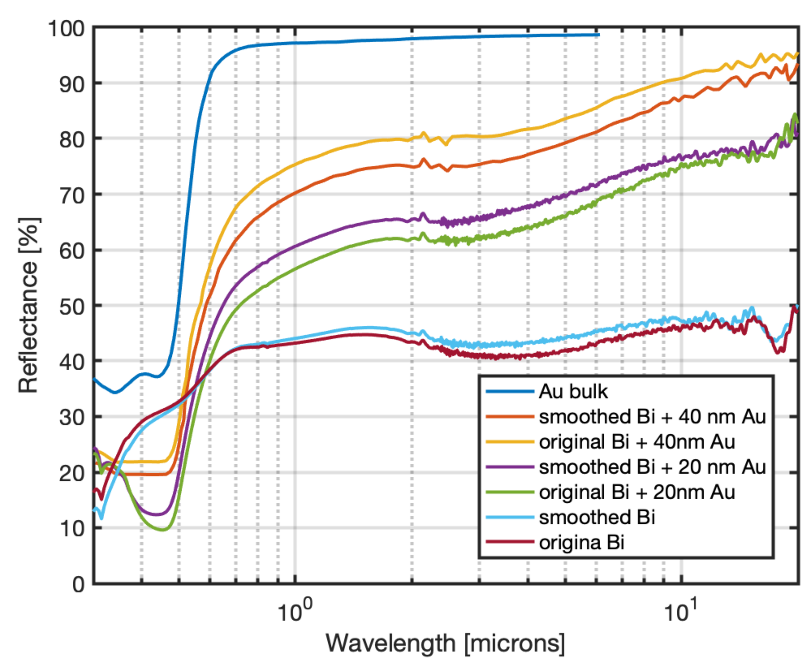
Corner of the AuBi Absorber : old model vs new model





- Target thicknesses of Au and Bi layers are optimized for new geometry model using heat capacities in 0.7-1.5 pJ/K range to achieve 63% QE at 9.5 keV.
- Old model: square absorber with 5.5 µm gap
- New model: trapezoidal absorber with 10 µm top gap, 5.5 µm bottom gap and surface roughness.
- Thickness of the Bi layer needs to be increased by 4.3% to achieve requirements.

Reflectivity Enhancement



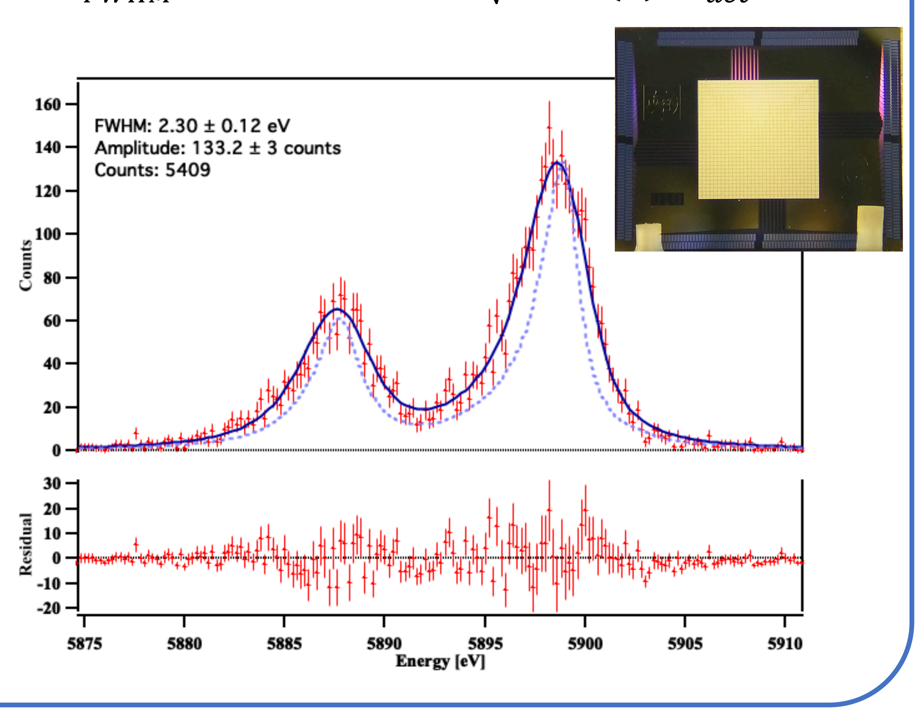
IR radiation from higher temperature stages of X-IFU cryostat can cause thermal fluctuation on detector chip, known as a shot noise, and this can lead to energy resolution degradation [6]. Noise equivalent power of IR radiation on detector:

$$NEP^2(T) = \frac{1}{N_{pixels}} \int_{\lambda_{min}}^{\lambda_{max}} 2P(\lambda, T)\frac{hc}{\lambda} d\lambda$$

Corresponding resolution degradation:

$$\Delta E_{FWHM} = 2.35 \cdot 6.24 \cdot 10^{18} \sqrt{NEP^2(T) \cdot \tau_{det}}$$

- To improve the reflectivity of absorbers to low energy radiation we have introduced an Au capping layer with Ti adhesion layer on top of the Bi layer.
- Total hemispherical reflectance of our electroplated Bi was measured to be ~ 45% at 300 K
- 20 nm thick Au/Ti capping layer increased it up to around 60-80%.
- 40 nm thick Au/Ti increased it up to 70-90%
- X-IFU TES pixel with 20 nm Ti/Au capping layer was tested in DC bias setup and had ΔE_{FWHM} = 2.3 eV at 6 keV



Summary

- TES microcalorimeters of the X-IFU instrument use ~ 6 µm thick electroplated Au/Bi bilayer absorbers
- The thickness of the Au and Bi layers are tuned to provide the desired pixel heat capacity and the QE
- We have studied effects of surface roughness, edge profile and the angle of incidence of the x-rays on average QE
  - The surface roughness of the Bi layer was found to have 0.13% effect
  - The incidence angle of x-rays found to have 0.01% effect
- We have optimized the thickness of the Au/Bi layer by taking into account the above effects and found that the thickness of only the Bi layer needs to be increased by 5%
- To enhance the reflectivity of the absorber to IR we have introduced 20 or 40 nm Au capping layer
- Reflectivity measurements on Au capped Bi samples in the wavelength range 300 nm - 20 µm show a significant increase in reflectivity compared to a bare Bi layer.

References

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