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Fabrication of transition edge sensor X-ray microcalorimeters for Constellation-X

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Abstract

NASA's Constellation-X (Con-X) mission is a driver for advancing low-temperature detector technologies, requiring 1000-pixel two-dimensional arrays with >95% filling fraction and quantum efficiency at 6 keV and better than 4 eV energy resolution for 1–10 keV photons. We describe a robust transition edge sensor fabrication process that can produce detector arrays with integrated absorbers approaching the specifications of Con-X. We address issues such as the methods of superconducting bilayer deposition, detector geometry definition, and absorber interface.

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1. Introduction

The application of superconducting transition edge sensors (TES) for high-resolution X-ray calorimeters is well established [1]. The calorimeter consists of superconducting wiring and bilayer, absorber structures, and a micromachined silicon substrate. Processes can be developed to produce large format arrays [2,3]. Further, TESs are coupled to cryogenic amplifiers which are low power, low noise, and scaleable to large array formats. As such, they are ideally suited to the

detector needs of NASA's Constellation-X (Con-X) mission. We report on the techniques used to fabricate functioning pixels, which can achieve suitable detector performance and array scale for Con-X. Specifically, we address the choice of bilayer deposition technique, the method of metal etching, and the interface with absorber structures.

2. Bilayer deposition

This detector fabrication first relies on a robust process for creating the superconducting films, the basic detector component. A bimetal system provides tunable critical temperature T_c , normal resistance R_N , and heat capacity for engineering detector parameters. We selected Mo–Au bilayers

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Table 1
Summary of electronic properties of bilayer films fabricated using three deposition methods

$d(\text{Mo})$ (nm)	$d(\text{Au})$ (nm)	Dep. method	$R_{\text{sq}}(\Omega)$	RRR	$T_c(\text{K})$	$\iota(\text{eff})$	$\iota(\text{int})$
50	230	e-b/e-b	0.010	6.5	0.118	0.089	0.092
50	50	e-b/e-b	0.074	3.10	0.420	0.083	0.084
50	230	sp/e-b	0.016	6.14	0.205	0.102	0.106
35	230	sp/e-b	0.015	6.40	0.095	0.083	0.085
50	400	sp/sp	0.040	2.4	0.165	0.082	0.101
58	90	sp/sp	—	1.9	0.540	0.091	0.098
50	—	e-b	1.0	1.8	0.85	—	—
50	—	sp	1.6	1.4	1.14	—	—

Properties of single Mo layers at bottom.

for the absence of intermetallic phases in Mo–Au and for corrosion resistance of Au. Successful integration of Mo-based bilayers with micromachined substrates requires control of the Mo film stress to compensate for thermal expansion of the substrate and metal. We have observed shifts in T_c as large as 50 mK in bilayers due to stress effects.

We have evaluated three different production methods for Mo/Au films and report the results in Table 1. We record the electronic properties of the deposited metals (the sheet resistance R_{sq} , the residual resistance ratio RRR between 300 and 4 K, and T_c). Further we calculate the transmission coefficient $\iota(\text{eff})$ that describes transport across the interface in the bilayer using the Martinis formulation of bilayer T_c assuming infinite RRR [5]. We also calculate $\iota(\text{int})$, which incorporates the effect of RRR of the Au toplayer on the interface.

Our Mo/Au bilayer system consists of an ultrahigh vacuum (UHV) chamber for e-beam deposition and a high vacuum sputter chamber connected by a turbo-pumped load lock. Both chambers are liquid nitrogen trapped to achieve base pressures of $5\text{e}-10$ and $5\text{e}-8$ Torr, respectively. In the e-beam/e-beam case, Mo is deposited first, 16 h elapses to cool the film and then Au is deposited via e-beam. Hydrogen gas and sometimes methane are the only species above 10^{-9} Torr in the chamber at any point after the Mo deposition. The sputtered Mo occurs in millitorr of Ar and has background gases (including water

vapor) at levels of $5\text{e}-8$ Torr. The sputtered Au is deposited after 1 min, while the e-beam Au requires transfer through the load lock, a 5 min delay before the substrate is in the UHV chamber.

Electron beam deposition of Mo results in tensile stress, which is tuned toward zero with increasing substrate temperature. At $\sim 600^\circ\text{C}$, residual film stress ranges from 400 to 600 MPa and suitable superconducting bilayers are achieved. Properties of e-beam Mo films are shown in Table 1. Sputter deposition parameters can tune the stress reproducibly in the film from compressive to tensile [4]. We choose slightly compressive ~ -100 MPa for these Mo films. Sputtering of Au metal films results in a smaller measured RRR.

The results tabulated here suggest that the range of RRRs that can be achieved by sputtering and e-beam has a profound impact on the choice of deposition technique. For sputtered Mo $\iota(\text{int}) \sim 0.1$ (which is depressed to 0.085 for thinner Mo) and the e-beam Mo has a $\iota(\text{int}) \sim 0.09$. For films with $T_c \sim 100$ mK, the low RRR of the sputtered Au significantly impacts T_c . Presumably, annealing that changes RRR would cause T_c to change after the deposition. These tests are underway. Further, the low RRR causes the Au layer to become prohibitively thick for 100 mK layers for our Con-X process. For thin, high impedance Au layers, the RRR plays a lesser role in $\iota(\text{eff})$ and thus in determining the T_c of the film. For $T_c \sim 100$ mK, the e-beam Au is recommended because its high RRR has little effect on the bilayer interface.

3. Fabrication technique

We have developed a selective etching method for the Au on Mo bilayer films. Using ion milling we achieve better than 4:1 selectivity of Au to Mo and can clear the thick Au film, etching only ~ 5 nm of the Mo underlayer. The Mo is then patterned into leads and contact pads. It is critical that the leads be integral to the detector structure to prevent variable parasitic resistances from step edge coverage of the Au films. We perform subsequent metallizations: leads, geometric boundary conditions, contact pads, and absorbers

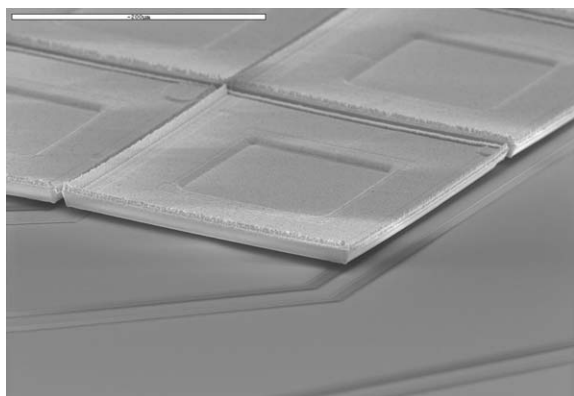


Fig. 1. TES microcalorimeter array with Bi/Cu multilayer mushroom absorber with 250 μm pitch and a 6 μm gap between neighboring pixels and between substrate and overhanging film. These pixels achieved Con-X specifications for pixel size, pitch, filling fraction, quantum efficiency, and speed in a scaleable array format.

using deposition through a patterned photoresist liftoff mask. Thermal isolation of the detectors is achieved with micromachining of the bulk silicon and SiN membrane using dry reactive ion etch processes.

4. Absorber structures

In Fig. 1, we show a detail of a 5×5 array of Bi/Cu multilayer absorbers. Eight films, alternating 2 μm Bi and 0.1 μm Cu, are successively deposited onto a photoresist mold that opens to the central portion of the detector, but protects the region surrounding each detector. When the liftoff mold is removed, the absorber film overhangs [6]. Using this “mushroom” absorber technique, we have built $244 \times 244 \mu\text{m}^2$ absorber structures with a 70 μm overhang width. The overhang maintains the thermal isolation of the detector and results in

95% filling fraction and quantum efficiency for 6 keV X-rays.

We have noted time constants associated with the Bi/Cu mushrooms and are pursuing an interfacial α -Si layer, deposited between the Au and Bi films. The thick Bi films surface roughness (~ 70 nm rms) may contribute to these effects. The energy gap in the Si film should block most of the flow of electrons from Bi to Au and allow an examination of the electron-phonon time constants in the Bi film. The deposition of Bi directly onto Au shifts T_c about 10 mK lower than that of the sample with the protective Si barrier.

5. Conclusions

We describe transition edge sensor fabrication techniques for X-ray calorimeters, focussing on the choice of bilayer deposition. Our data shows that stress-tunable Mo films can be combined with high RRR noble metal films of Au. We show integration of close-packed arrays of Con-X style pixels with absorber structures that fill 95% of a 2D focal plane.

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