ARL-TN-1175 • SEP 2023

Circuit Editing of Gold Connecting Electrodes Using a Focused Ion Beam Microscope

by Jonathan Ligda and Mary Beth Galanko

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ARL-TN-1175 ● SEP 2023

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REPORT DOCUMENTATION PAGE

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED START DATE	3. DATES COVERED END DATE
September 2023	Technical Note	2/01/2023	6/31/2023

4. TITLE AND SUBTITLE
Circuit Editing of Gold Connecting Electrodes Using a Focused Ion Beam Microscope

5a. CONTRACT NUMBER	5b. GRANT NUMBER	5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER	5e. TASK NUMBER	5f. WORK UNIT NUMBER

6. AUTHOR(S)
Jonathan Ligda and Mary Beth Galanko

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
DEVCOM Army Research Laboratory ATTN: FCDD-RLA-MB Aberdeen Proving Ground, MD 21005	ARL-TN-1175

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES
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14. ABSTRACT
The fabrication of a newly designed acoustic resonator has resulted in some faulty devices due to gold electrodes either being connected or too far apart. This has limited the number of devices available for testing. Fortunately, these devices can be edited with a focused ion beam microscope, making them functional again. This technical note describes the process of editing these gold electrodes through both subtractive and additive means.

15. SUBJECT TERMS
Energy Sciences, focused ion beam, circuit editing, gold, acoustic resonators

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	C. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UU	14

19a. NAME OF RESPONSIBLE PERSON	19b. PHONE NUMBER *(Include area code)*
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STANDARD FORM 298 (REV. 5/2020)
Prescribed by ANSI Std. Z39.18

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1. Introduction

Colleagues from the US Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL) Energy Sciences Division have designed a piezoelectric acoustic resonator for possible use in communications devices.[1] This design utilizes multiple gold electrodes deposited on a thin (5–50 µm) AT-cut quartz substrate. When an alternating voltage at the resonant frequency appears across gold pads on either side of the substrate, the quartz vibrates in thickness-shear mode resonance. Furthermore, when multiple electrode pairs are in proximity on the same quartz substrate, their motion can couple, creating a transformer that provides passive voltage gain in a radio.

To maximize performance, the electrode pairs should be a specific distance apart. However, the commercial process used for the metal deposition is not consistent and sometimes the electrodes are touching or there is too much space between them. In either case, this leaves the device unusable for system-level testing and since these custom devices are not yet mass produced, any unusable device means that less testing is completed overall.

A focused ion beam (FIB) could be used to repair these devices.[2] A FIB accelerates and focuses gallium ions at 5–30 kV at a sample surface. When the ions impact they can remove atoms from the surface, acting as a high-resolution milling machine.[3] Additionally, if certain gases are present near the sample surface, those same ions can be used to deposit metals such as platinum or tungsten.[2] This combination of machining and depositing makes the FIB an ideal tool for this type of circuit and device editing. The goal here is to use the FIB to cut the proper size gap between the electrodes or deposit metal to make the gap smaller. Hopefully these edits will make the devices usable again and allow for more testing.

2. Experiment

Pre-made devices that are known to be faulty are provided by ARL's Energy Sciences Division. The device is mounted on a printed circuit board with area 25 × 25 mm; the area of interest being a 5-mm-diameter quartz disk with gold electrodes, traces, and electrodes. Since these devices are mostly made of nonconducting material, imaging with charged particles is very difficult. Therefore, it is important to ensure a good electrical contact between the device and the microscope's stage. To achieve this, the devices are first mounted onto an aluminum stub using double-sided copper tape. A second strip of copper tape is used to join metal connectors on the top of the device to that same stub. Once loaded onto the FIB, a quick check with a multimeter shows a low resistance (<10 Ω) between the device and stage.

This gives the best chance for reducing charging and therefore drifting during machining.

A ThermoFisher Helios G4 UX dual-beam FIB is used for editing the circuits. This is a dual-beam system, meaning there are two separate beams. The first is a traditional electron beam that is used for imaging and the second is the gallium-based ion column used for machining. The combination of these two columns makes it possible to machine/deposit with the ion beam but also image with the electron beam at the same time, allowing for higher control of the process.

Secondary and backscatter scanning electron microscope (SEM) images are captured at 5 kV, 0.8 nA and are taken both before and after machining/deposition.

For electrodes that are touching, a 25- to 30-µm gap is machined at ion beam conditions of 30 kV, 1.4 nA. It is important to stop milling once the gold layer has been removed. To know when to stop, an end point monitor is used. This monitors the gray scale levels of a live image during machining. At the start, the contrast is adjusted so that the gray scale of the image is the highest (i.e., white). As the gold is machined away the gray scale level drops, eventually reaching its minimum (i.e., black). Once the gray scale reaches this level the machining is stopped to ensure that the quartz material underneath is not also machined away. For these devices, the machining typically takes around 2.5 min. To confirm that the gold layer is completely removed, electron dispersion spectroscopy (EDS) is done on the machined gap. An EDAX Octane elite EDS detector is used, and line scans are performed across the gap using a 15-kV electron beam. For electrodes that are too far apart, a combination of platinum deposition and FIB milling are used to create the proper sized gap. First, the entire space between the two electrodes is filled with a 100-nm-thick platinum layer, deposited at 30 kV, 9.4 nA. To ensure good electrical contact, there is a slight overlap of the gold and platinum. This takes between 10 and 15 min depending on the size of the initial gap. Then a 25- to 30-µm gap is machined into the platinum layer using the same beam conditions: 30 kV, 9.4 nA. The different beam current is used because the devices with a large gap were much bigger. Increasing the beam current to 9.4 nA deposits and machines much faster.

3. Results

Figure 1a shows an SEM image of a faulty device where electrodes are touching. The size of the electrodes depends on the frequency the device is designed for, but typically are rectangular and range from 350 × 550 µm or 200 × 200 µm. Clearly seen in Fig. 1a, there is a roughly 300-µm-long section in the middle that connects both electrodes. At the top and bottom of those electrodes there are sections separated by roughly 40 µm. Figure 1b shows the same gold electrodes as seen in Fig. 1a but now they are no longer touching. The FIB milling has successfully cut through the gold layer leaving a gap width of 24 µm. Figure 2a is a higher magnification image of that gap region showing no gold is present. The bright areas observed in the gap are charging due to the nonconductive quartz substrate. The charging is encouraging, as it helps confirm that there is no conductive pathway between the two electrodes. Figure 2b shows results from the EDS line scan across the gap overlaid on this same SEM image. The plot shows the intensity of gold and silicon EDS peaks across the machined gap while the red dashed line shows the start and end of the scan. The scan starts and ends on a gold electrode and as such there are high levels of gold in these regions. There is still some intensity from the silicon peak because the gold layer is only 100 nm thick. The incident electron beam is able to penetrate though the gold and excite some X-rays from the quartz underneath. However, once the line scan reaches the gap, the gold intensity drops to zero and the silicon intensity rises. This is due to the signal only coming from the quartz disk. There is one spike in the gold intensity, suggesting that there still might be small particles or islands of gold, but not enough to create a continuous electrical pathway.

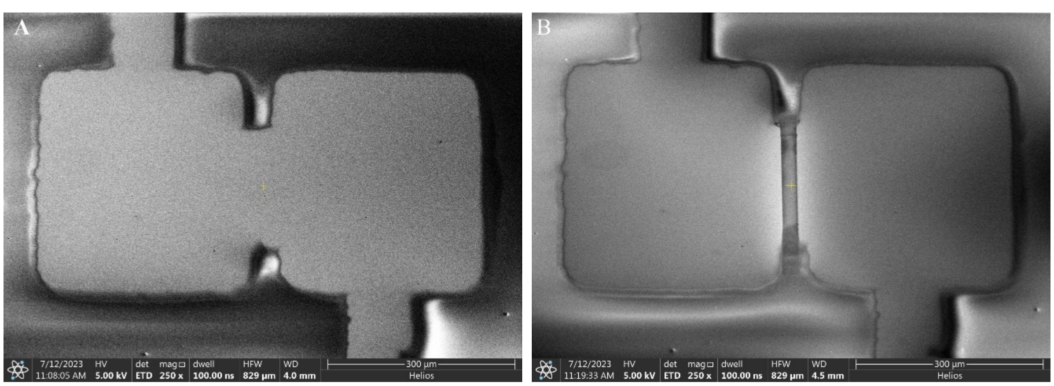

Fig. 1 SEM images showing examples of defective devices with (A) electrodes touching and (B) electrodes cut free and no longer touching

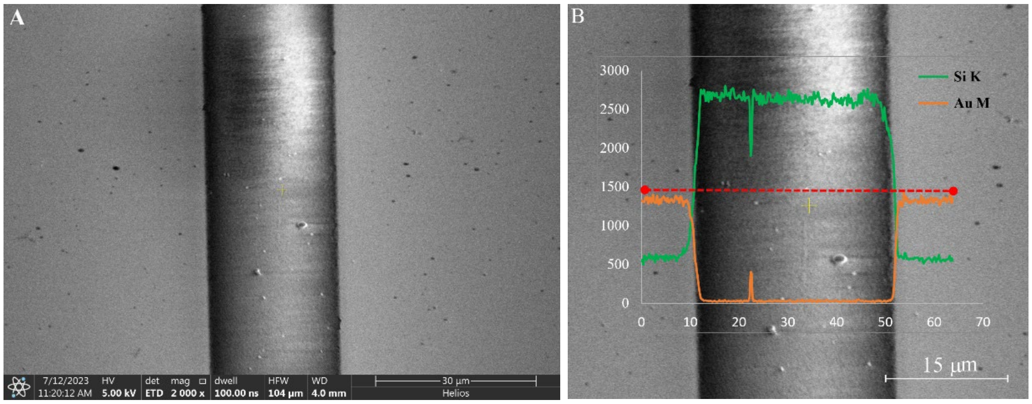

Fig. 2 **SEM images showing a machined gap in gold electrodes that were once touching. (A) Shows the gap is now completely separating the electrodes while (B) is a higher magnification image showing no gold present in the gap region.**

Figure 3 shows the results of a set of electrodes that are too far apart. Figure 3a shows an initial sample with the electrodes too far apart. In this case they are separated by roughly 140 µm. Figure 3b shows the results of filling this space with platinum and FIB milling the gap. This is a backscatter image, which makes the difference between the gold and platinum easier to see. Measurements give the gap width for this device as 27 µm.

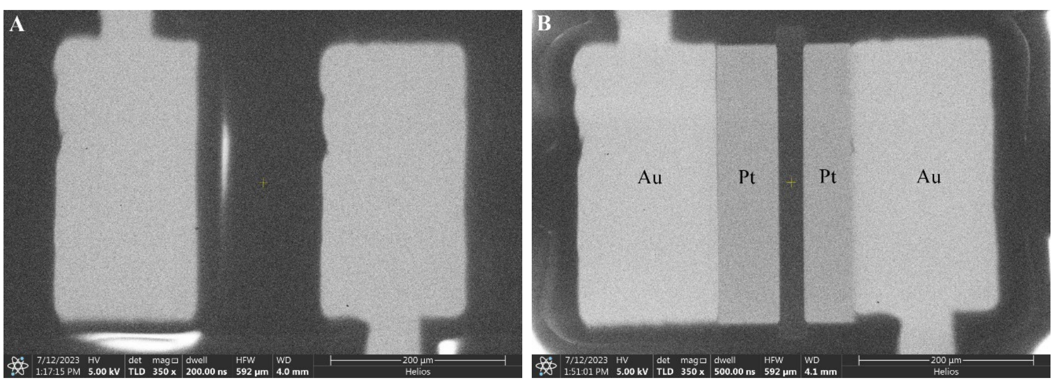

Fig. 3 **Results from an EDS line scan across the machined gap. This line scan shows how the intensity of the gold peak drops to zero inside the gap while the intensity for the silicon rises.**

4. Conclusion

The FIB is used to perform circuit editing on a newly designed acoustic resonator since the commercial metallization process is not consistent. The inconsistency in the process leads to some devices being defective due to gold electrodes either touching or being too far apart. Using both the machining and deposition capabilities of a FIB, gaps with a consistent 25- to 30-μm width are achieved in these faulty devices. These devices that were defective can now be tested and improve the statistics of the data being gathered about the new design.

5. References

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2. Giannuzzi LA, Fred AS. Introduction to focused ion beams. Springer Science+Business Media Inc.; 2005.

3. Volkert CA, Minor AM. Focused ion beam microscopy and micromachining. MRS Bull. 2007:389–395.

List of Symbols, Abbreviations, and Acronyms

ARL	Army Research Laboratory
DEVCOM	US Army Combat Capabilities Development Command
EDS	electron dispersion spectroscopy
FIB	focused ion beam
SEM	scanning electron microscope

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