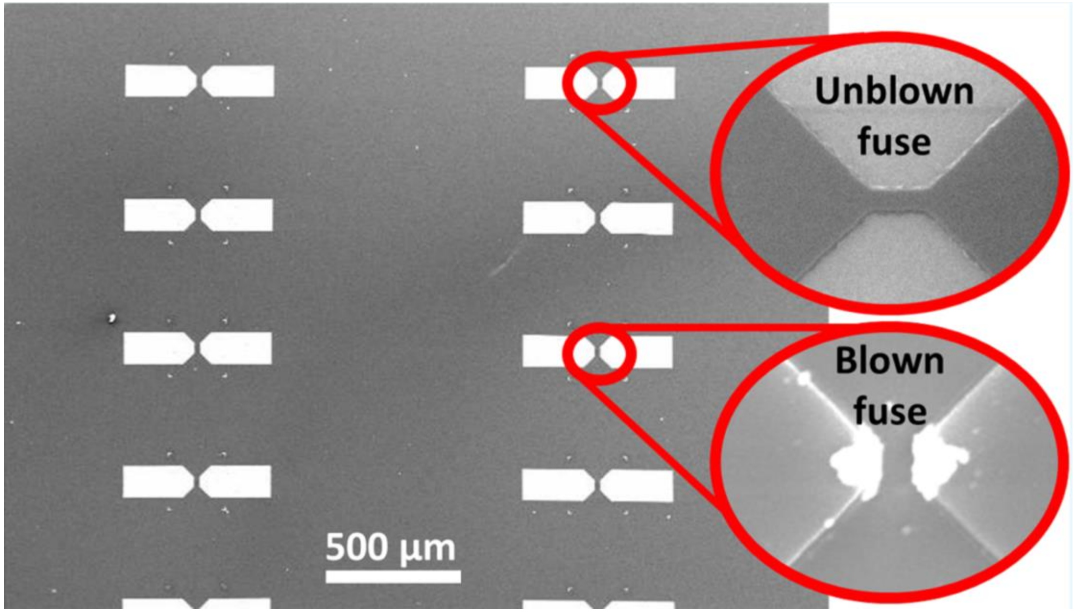
Permanent Digital Data Storage: An Overview and Report



Barry M. Lunt, Eric Christie,
Shiuh-hua Wood Chiang, Robert C. Davis, Matthew R. Linford

Brigham Young University, Provo, Utah, USA

Micropower Circuits Laboratory

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Outline

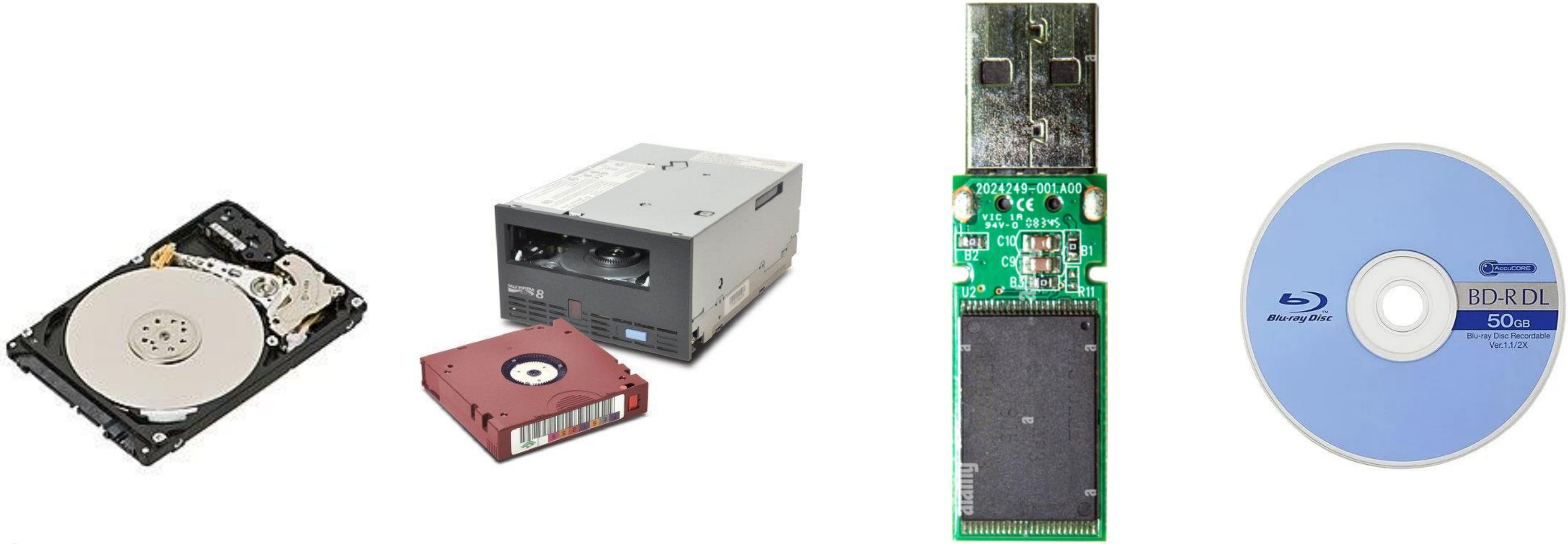
- “Long-Term” Storage Devices
- Metal Fuse vs Carbon Fuse
- Thin-Film Carbon Nanofuses for Permanent Data Storage
- Current Research
  - Fabrication and Characterization
  - Deposition Error
- Advanced Aging for Device Life Expectancy Testing

14 Factors for Digital Storage

1. Sticker Price
2. Active Power Requirement
3. Standby Power Requirement
4. Deep Archival Power Requirement
5. Life Expectancy (LE) of Medium
6. LE of Data
7. Expandability
8. Media Transportability
9. Store and Forget
10. Cost of Medium
11. Relative Capacity
12. Near-line Access Time
13. Time Extensibility
14. Data Remastering

“Long-Term” Storage Options

- Hard Drive Disks (HDD’s)
- Magnetic Tape
- Solid-State (Flash)
- Recordable Optical Disks



14 Factor Comparison

Factor	HDDs	Magnetic Tape	Solid-State (flash)	Recordable Optical Discs
Sticker Price	Low	High	Medium	Low
Active Power	High	High	Low	Medium
Standby Power	High	Very Low	Very Low	Low
Deep Archival Power	NA	Zero	Zero	Zero
LE of medium	3-5 yrs	20-30 yrs	>100 yrs	>100 yrs
LE of data	20-30 yrs	5-10 yrs	8-10 yrs	5-10 yrs
Expandability	High	High	High	High
Transportability	Medium	Medium	High	High
Store & Forget	NA	Good	Good	Good
Media cost	Low	Medium	Medium	Low
Relative capacity	High	High	High	Low
Near-line Access Time	m seconds	seconds	μ seconds	m seconds
Time Extensibility	Good	Good	Good	Good
Data Remastering	Good	Good	Good	Good

14 Factor Comparison

Factor	HDDs	Magnetic Tape	Solid-State (flash)	Recordable Optical Discs
LE of medium	3-5 yrs	20-30 yrs	>100 yrs	>100 yrs
LE of data	20-30 yrs	5-10 yrs	8-10 yrs	5-10 yrs

Long-Term Storage means the LE of Data is >100 years. No current storage method meets that criteria.

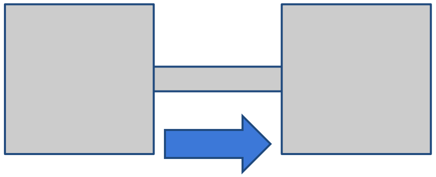
To increase LE of Data, the data writing process should be irreversible.

Our lab has been developing a “write once, read mostly” (WORM) storage scheme to reach these long-term storage goals.

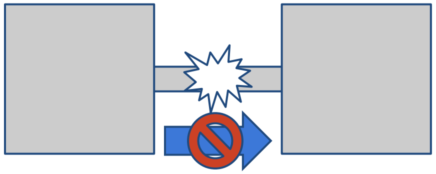
Metal Fuses vs Carbon Fuses

A decades-old structural-based digital memory device utilized metal fuse PROM. Its write process applies a voltage to irreversibly destroy the fuse structure.

The silicide material is susceptible to data corruption.



Intact Fuse: current flows, digital “1”

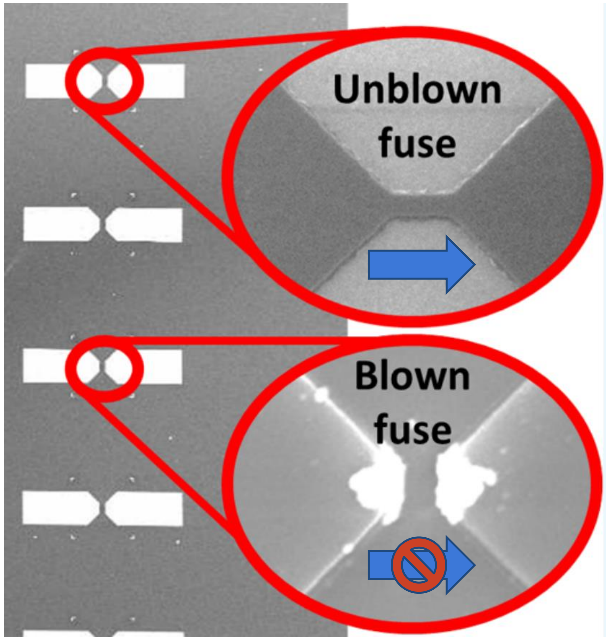


Blown Fuse: no current flow, digital “0”

Under applied electric fields, dendrites can reform conductive paths causing data corruption

Metal Fuses vs Carbon Fuses

By substituting thin-film amorphous carbon for silicide, the same programming scheme can be used with higher structural integrity. These fuses may last up to 1000 years.

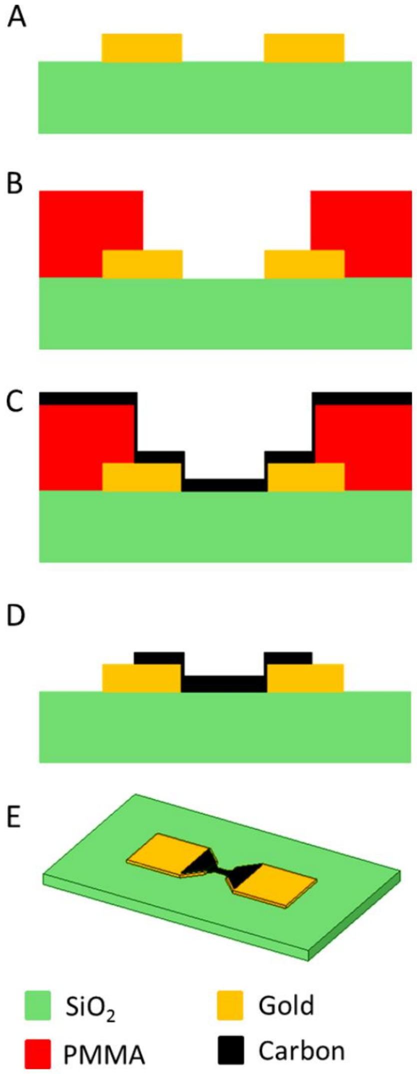


Intact Fuse: current flows, digital “1”

Blown Fuse: no current flow, digital “0”

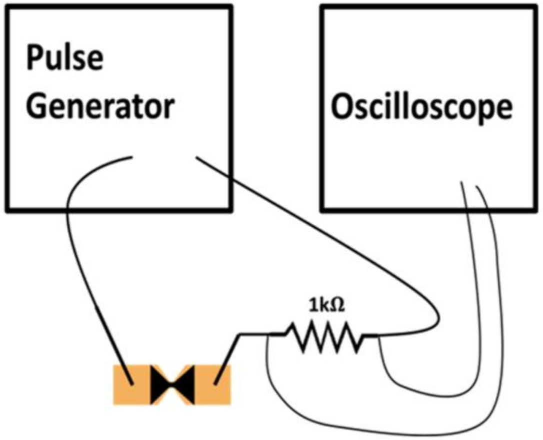
Amorphous carbon has high local bond strength and doesn’t readily oxidize below 300C, making the fuse resistant to degradation.

Thin-Film Carbon Nanofuses for Permanent Data Storage



In 2017, these fuses were fabricated and tested by Kevin Laughlin. Arc deposition was used to deposit amorphous carbon with low resistivity over gold contact pads.

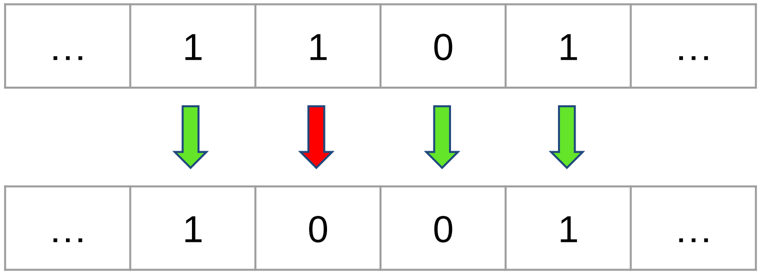
A pulse generator and oscilloscope were used to characterize the programming process. A 1.8v, 1mW pulse was sufficient to program most fuses.



Life Expectancy Metrics

Device and data life expectancy depend on device failures when accessing and storing data. Two types of errors are considered here:

- Read Disturb (RD) errors occur during a data retrieval event where the accessed bit is changed.
- Data Retention (DR) errors occur outside of data accessing events and may be caused for various reasons, such as physical degradation of components.



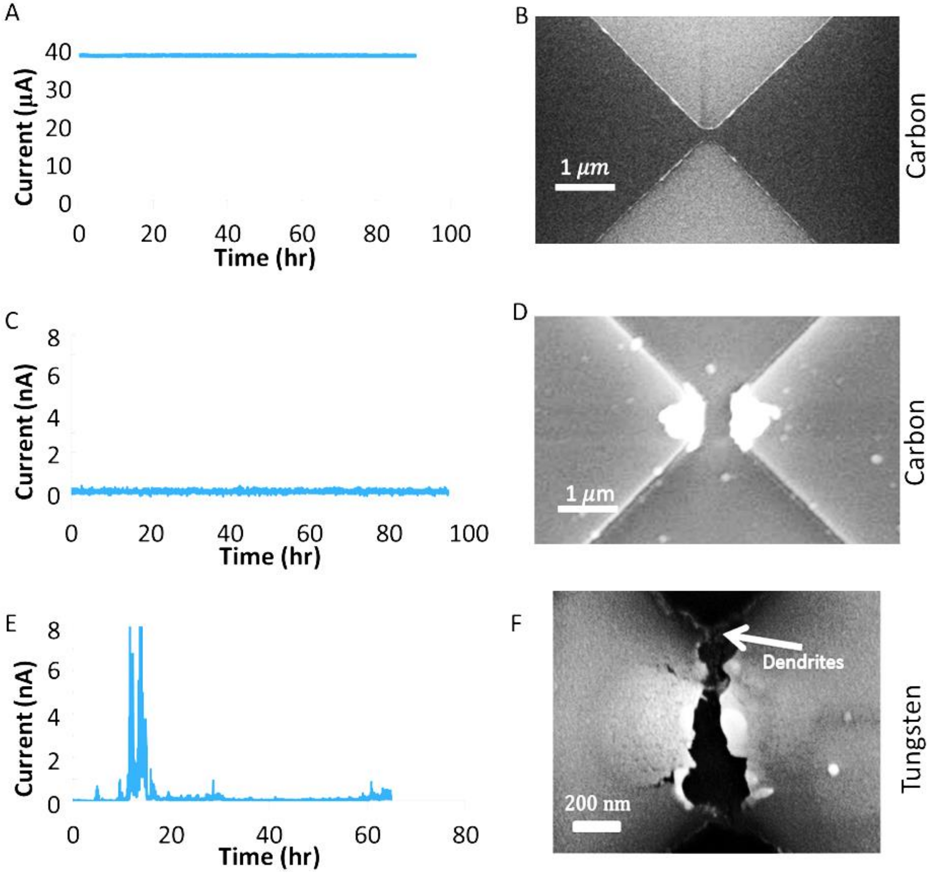
…	1	1	0	1	…

…	1	0	0	1	…

Thin-Film Carbon Nanofuses for Permanent Data Storage

The fuses were subjected to a 90 hour continuous-read test to understand RD errors. This simulated 10^{12} read events.

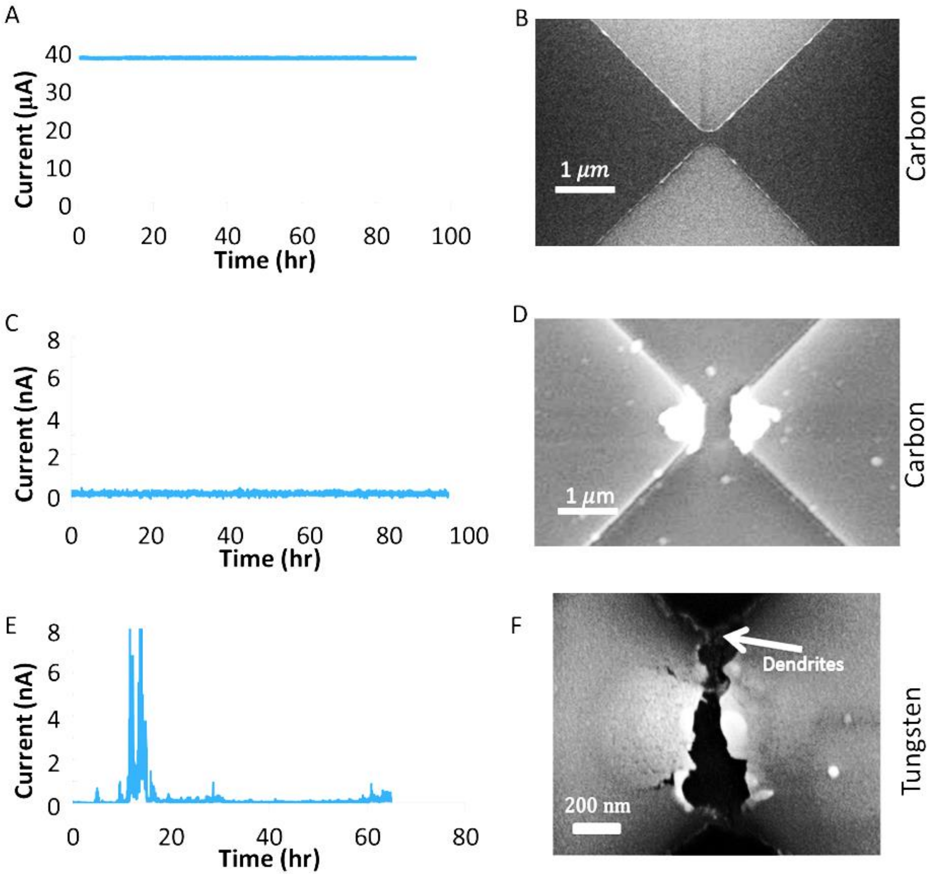
A 1v read voltage was applied to the intact carbon fuse, while 10v was applied to both blown fuses to induce potential failures.



Thin-Film Carbon Nanofuses for Permanent Data Storage

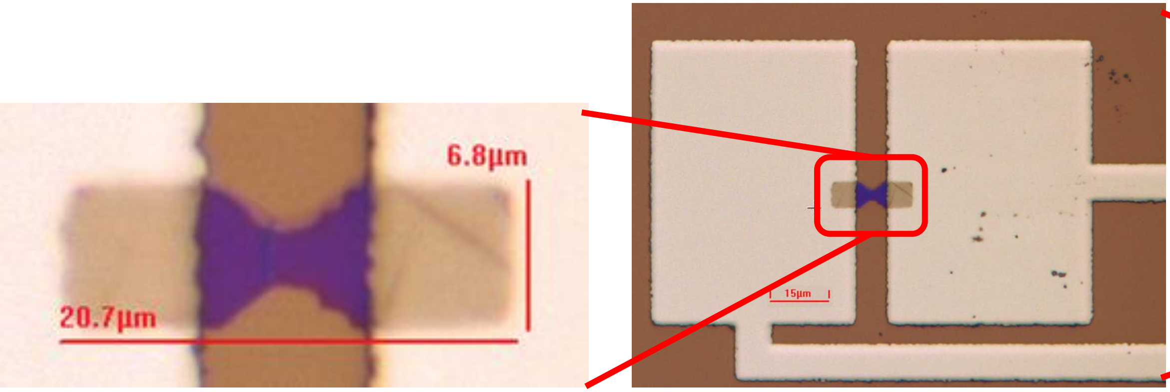
Both carbon fuses showed remarkable stability over the course of the test. The tungsten fuse exhibited RD errors due to dendritic growth.

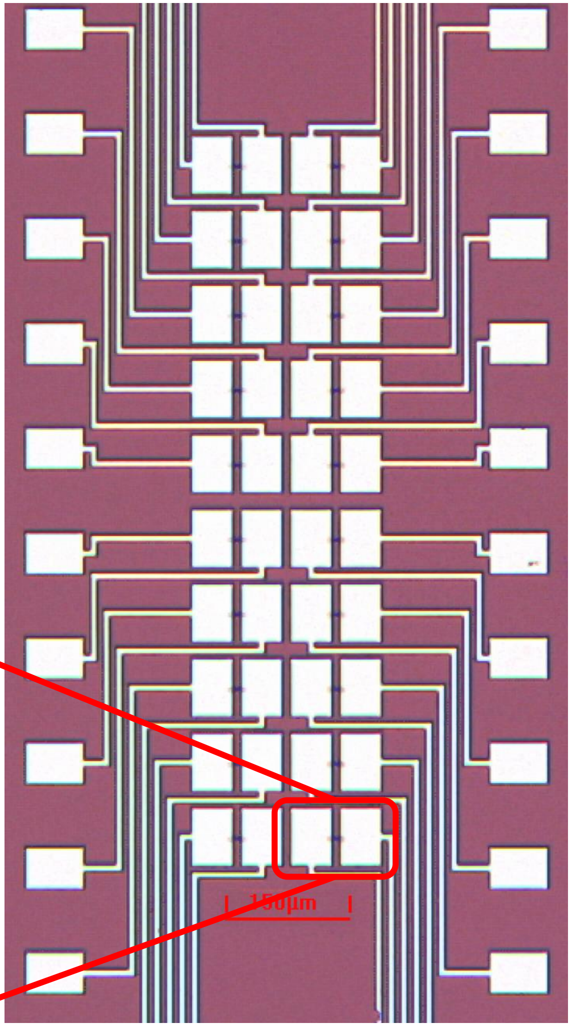
DR errors were not tested in this paper.



Current Research

1. Recreate carbon fuses with available fabrication steps
2. Verify electrical characteristics compared to past fuses
3. Analyze DR errors with advanced aging





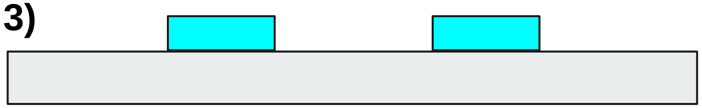
Fabrication Process

Tungsten is deposited by Sputter PVD and patterned with photoresist.

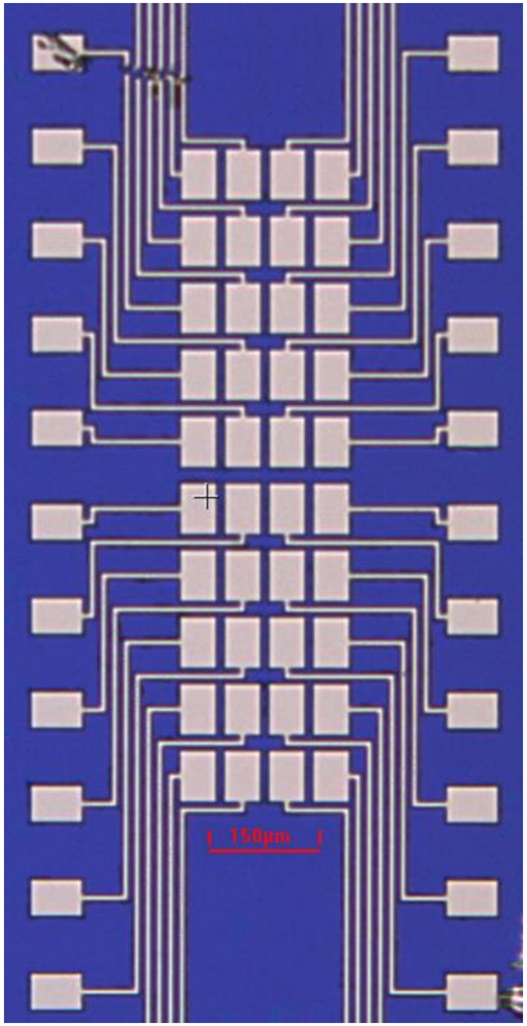
1)

2)

3)



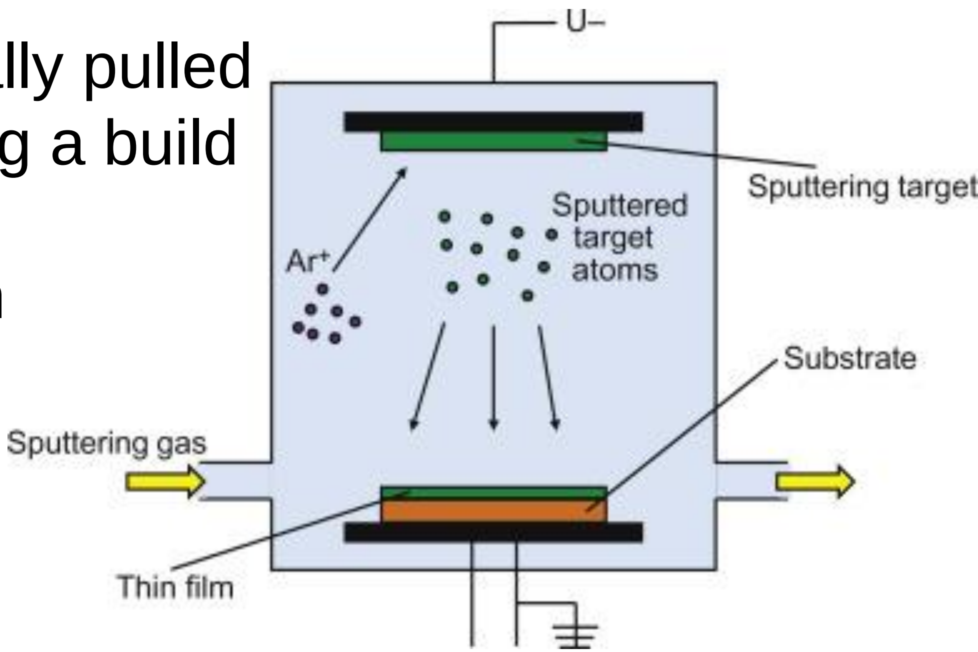
SiO2
Tungsten
Carbon
Photoresist



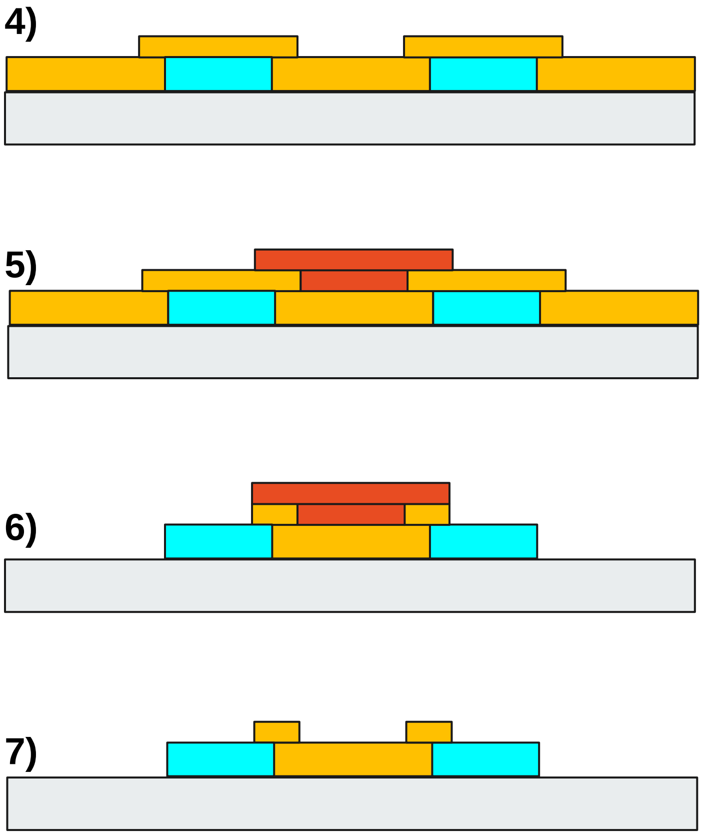
Sputter PVD

Sputter PVD is used in place of Arc Deposition to deposit thin-films of Tungsten and Carbon.

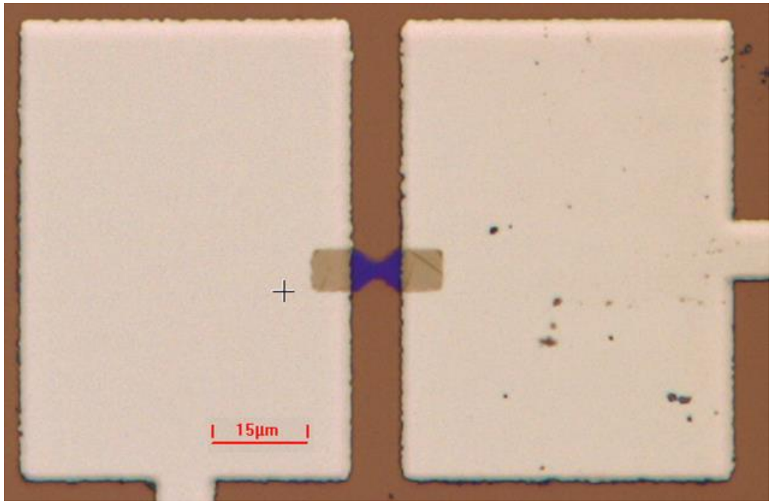
1. Charged argon atoms collide with deposition material, knocking loose atoms.
2. Loose atoms are electrically pulled towards the wafer, causing a build up of the material.
1. Thin-film layers are grown nanometers at a time.



Fabrication Process



Carbon is deposited across the whole substrate. Photoresist protects the fuse structure while excess is removed through oxygen etching.



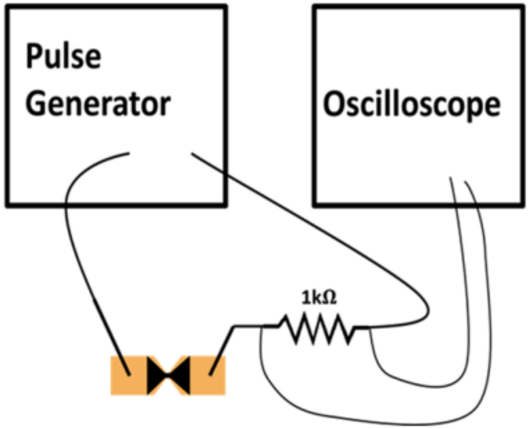
SiO2
Tungsten
Carbon
Photoresist

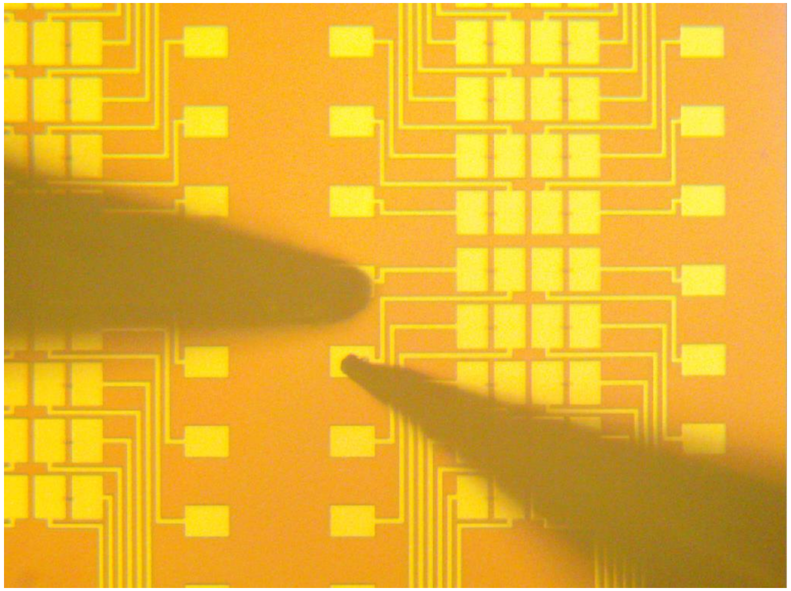
Characterization of Fuses

The same programming scheme is used to test these fuses.

Fabrication steps are adjusted based on results to ensure new fuses are as close as possible to those used in the publication.

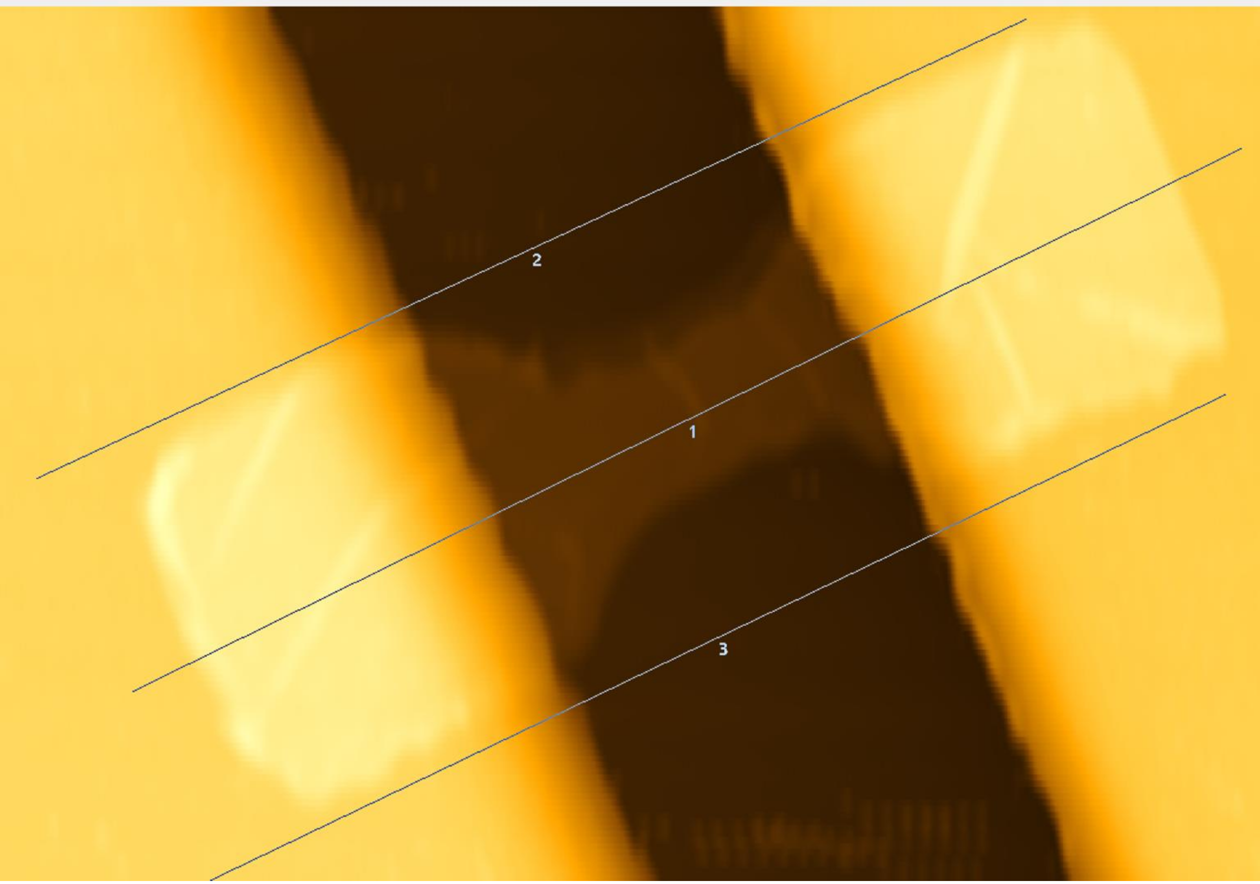
First results showed errors in material deposition.



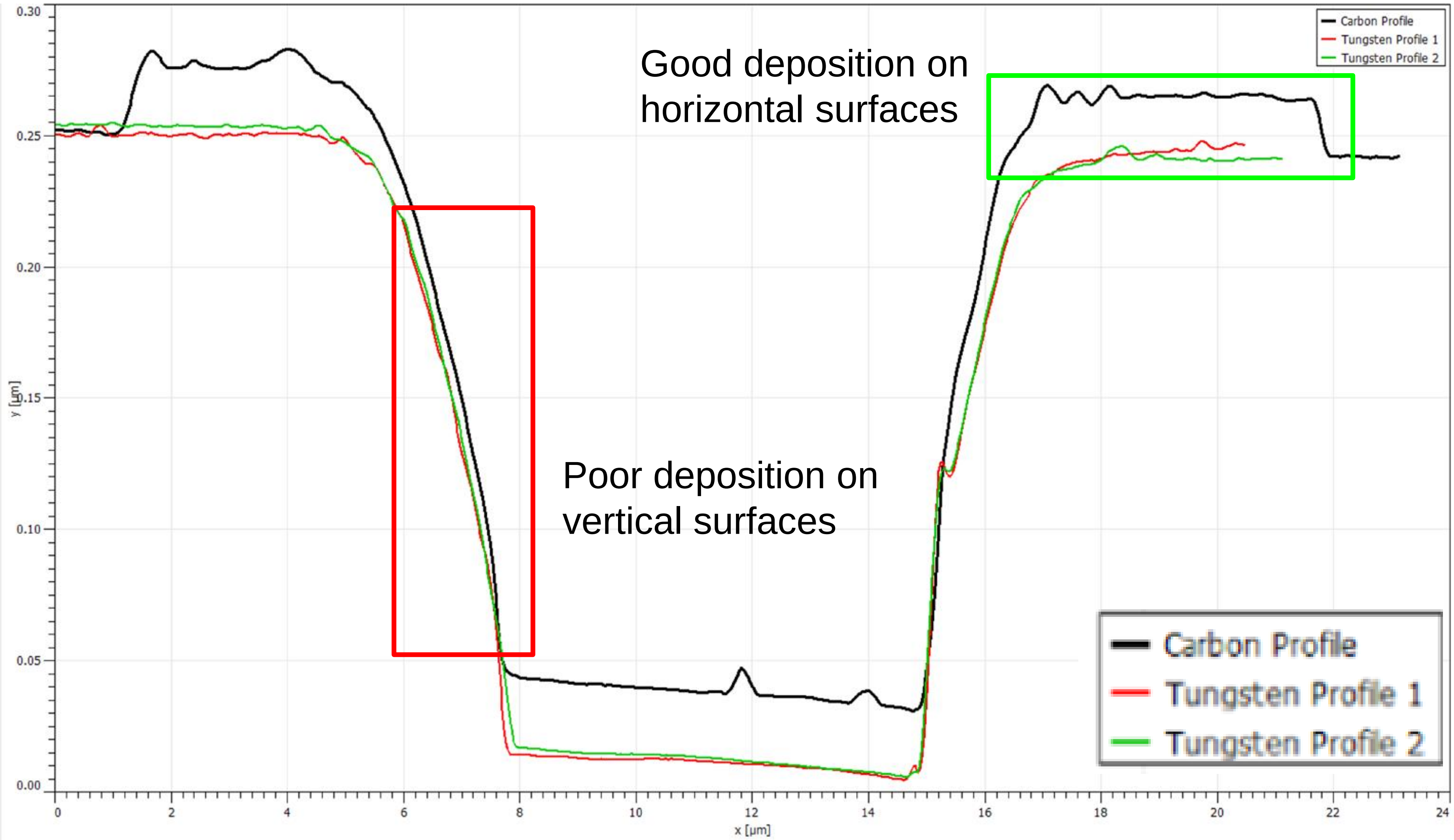


Deposition Error

Atomic Force Microscopy (AFM) was used to analyze deposition quality. The profile of the carbon fuse was analyzed compared to the surrounding tungsten.



Deposition Error



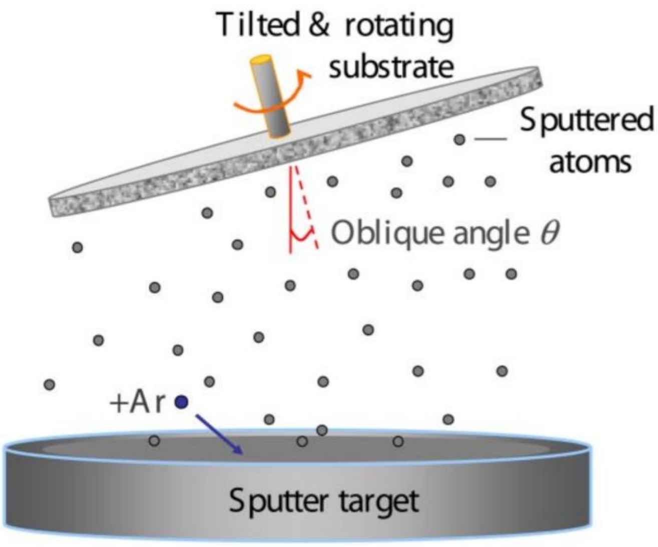
Good deposition on horizontal surfaces

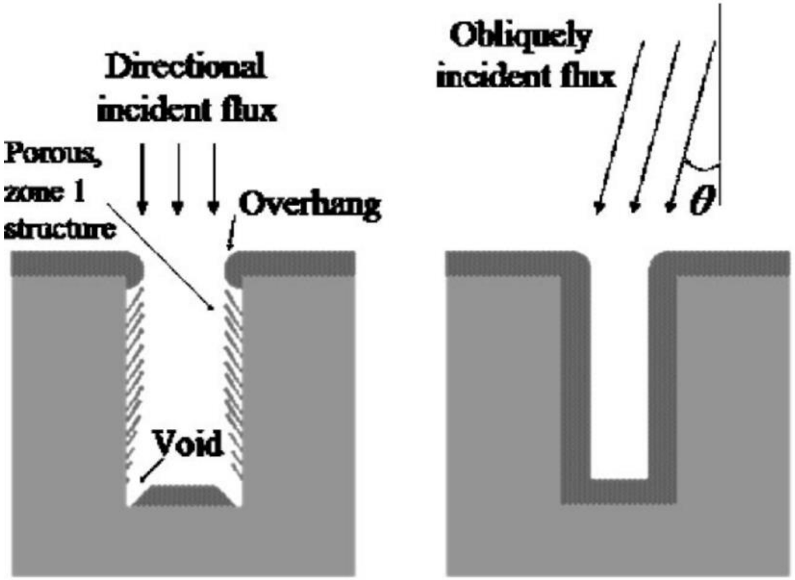
Poor deposition on vertical surfaces

Deposition Error

A 2004 paper *Enhanced step coverage by oblique angle physical vapor deposition (T. Karabacak, T. Lu)* addresses the anisotropic nature of Sputter PVD.

Rotating the substrate feature at an angle exposes vertical surfaces to the direction of deposition.

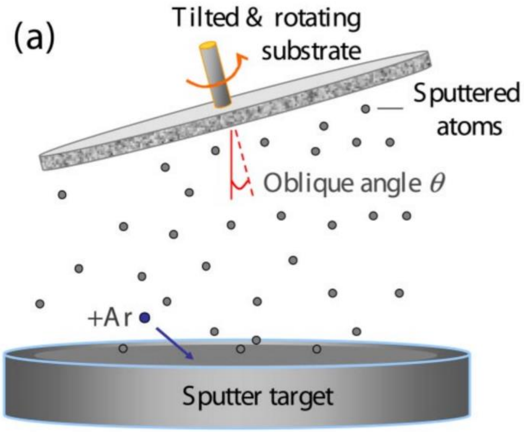


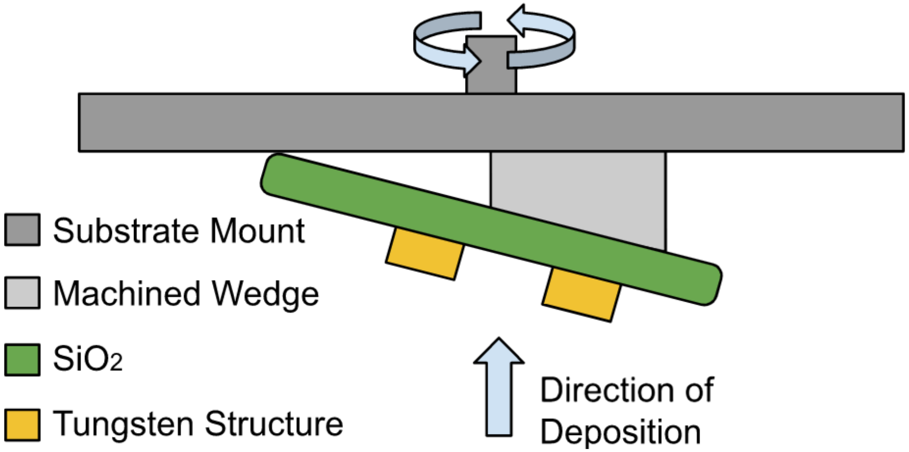


Deposition Error

The rotating substrate mount inside our PVD chamber is not able to be tilted, so a 15° wedge was machined. Only one side of the tungsten pad is able to be exposed in this fashion, so the wafer is rotated 180° halfway through the deposition.

Tests are still ongoing, but appear promising.





Accelerated Aging for Device Life Expectancy

By baking the devices in a heat- and humidity-controlled environment, we can simulate years of aging.

Both intact and blown fuses will be aged to analyze Data Retention (DR) errors. Physical characteristics and electrical performance will be measured to understand how they degrade over time.

We believe these devices can last up to 1000 years!

Conclusion

We believe that our thin film amorphous carbon fuses fill a void in true long-term data storage. Publications have already shown this structure to be highly resistant to Read Disturb (RD) errors.

Current efforts focus on reproducing those fuses with commonly available processes in a large-scale form. Data Retention (DR) tests through Advanced Aging will complete our knowledge of the Life Expectancy (LE) of the devices and data. Models predict LE as long as 1000 years.