Fabrication of MEMS 4H-SiC Gyroscopes

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Introduction – What is MEMS?

Micro-**E**lectro-**M**echanical **S**ystem

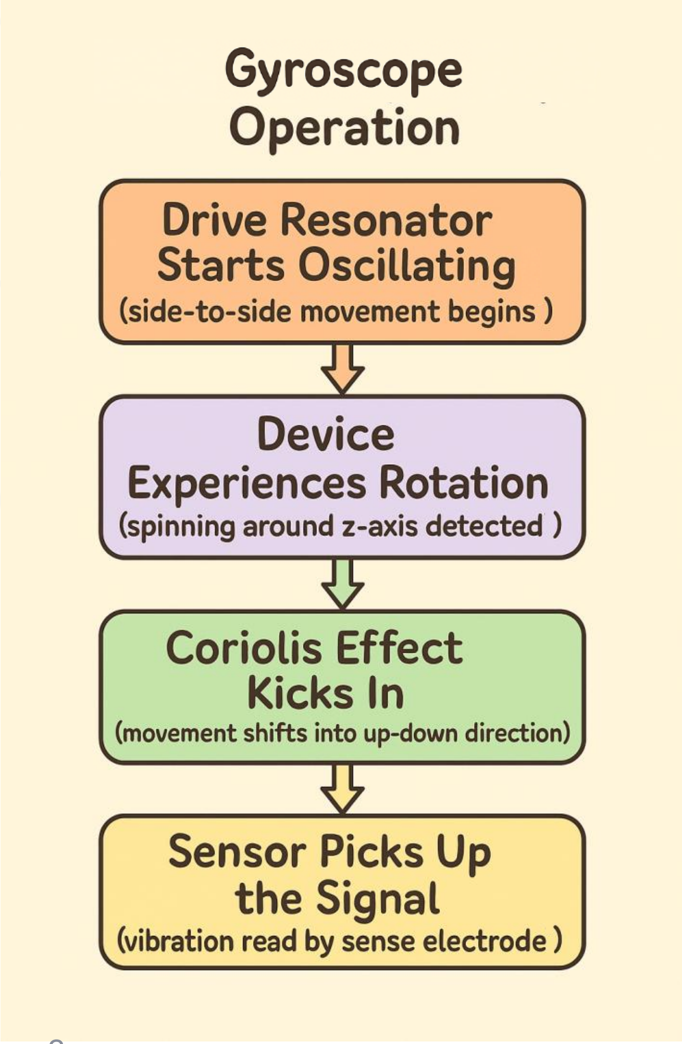
Micro – It’s small!

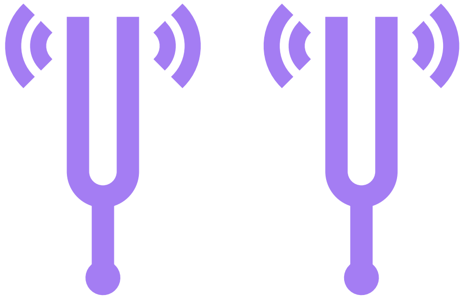
Electro – Uses electrical signals

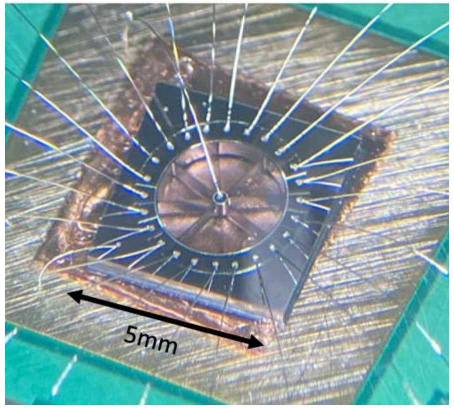
Mechanical – Has moving parts

System – A singular device

What is a MEMS Gyroscope?







[1]

MEMS Resonator

- A tiny silicon structure (often tuning-fork or ring shaped) that's driven to vibrate at a steady frequency by on-chip electrodes.

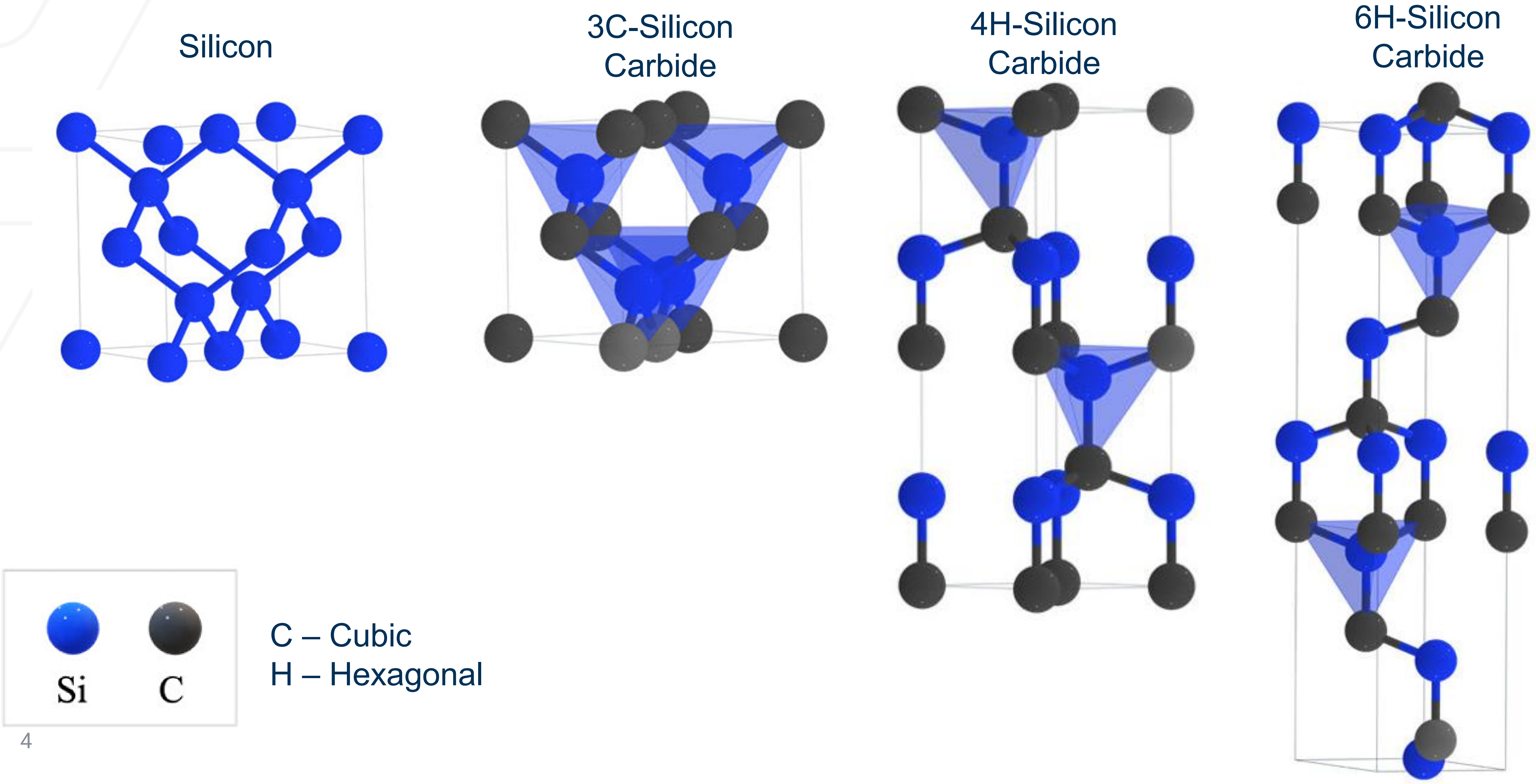
Drive vs. Sense Modes

- Drive: Electrodes keep the resonator oscillating along one axis
- Sense: When you rotate the device, Coriolis forces transfer a bit of that motion into a perpendicular axis

Coriolis Coupling

- Rotation "kicks" the vibrating mass sideways; the size of that kick is directly proportional to the angular rate

Why 4H-SiC?



C – Cubic
H – Hexagonal

[1]

Why 4H-SiC?

- Bandgap: The energy difference between the valence band (where electrons are tightly bound to atoms) and the conduction band (where electrons can move freely and conduct electricity).

- F·Q Limit: **F** is the pitch (frequency), **Q** is how long it rings

- Melting Temperature/ Thermal Expansion: How material reacts to heat

[1]

Material	Crystal Structure	Bandgap (eV)	F·Q Limit (10^{13} Hz)	Melting Temperature (°C)	Thermal Expansion (ppm/°C)
Si	Cubic	1.1 (Low)	2-3	1412	2.6
3C-SiC	Cubic	2.4 (Medium)	10-50	2830	2.4
4H-SiC	Hexagonal	3.2 (High)	20-60	2830	4.1
6H-SiC	Hexagonal	3.0 (High)	20-60	2830	3.4

Why 4H-SiC?

Mechanical and Electrical Properties Comparison [1]

Property	Unit	(100) Si	(111) Si	(100) 3C-SiC	(0001) 6H-SiC	(0001) 4H-SiC
Density	Kg /m^3	2230	2230	3166	3211	3210
Young's Modulus	GPa	130	174	314	450	481
Fracture Strength	MPa	47.1	31.8	800	--*	200
Yield Strength	GPa	2.7	2.7	12.0	14.3	11.8
Poisson's Ratio	1	0.28	0.26	0.237	0.207	0.205
Volumetric Heat Capacity	10^6 J/ (m^3K)	1.58	1.58	2.24	2.22	1.92
Thermal Conductivity	W/cm /°C	1.3	1.48	3.6	3.5	3.7
Thermal Expansion	ppm °C^{-1}	2.6	2.6	2.4	3.4	4.1
Melting Temperature	°C	1412	1412	2830	2830	2830
Acoustic velocity	10^3 m/s	9.1	9.1	11.9	11.9	11.9
Piezoelectric Coefficient e_{33}	10^{-5} C/ cm^2	N/A	N/A	4.0**	4.0	3.4
Bandgap	eV	1.1	1.7	2.4	3.0	3.3
f.Q$_{AKE}$	10^{13} Hz	2 - 3	2 - 3	10 - 50	20 - 60	20 - 60

Fabrication Process of a Bulk Acoustic Wave (BAW) Gyroscope

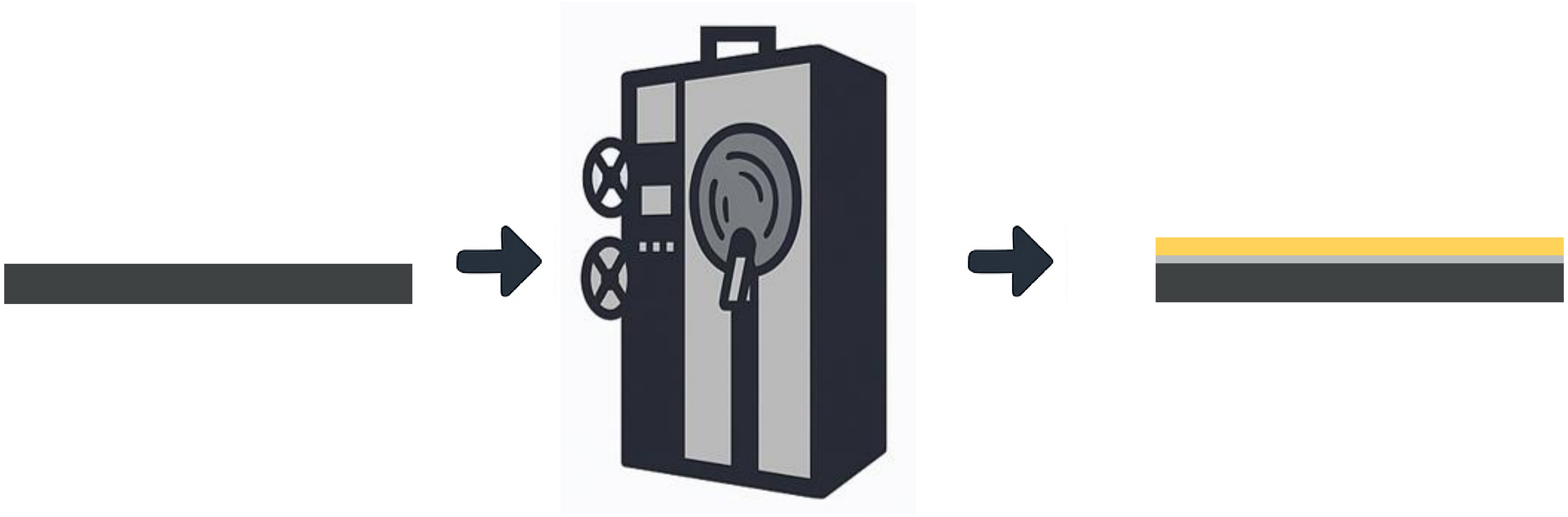
Objective: Explore the fabrication process using SiC

Gold

Chromium

SiC

1. Deposit a layer of chromium followed by a layer of gold onto SiC wafer (Seed Layer)



- Chromium: 20 nm
- Gold: 100nm

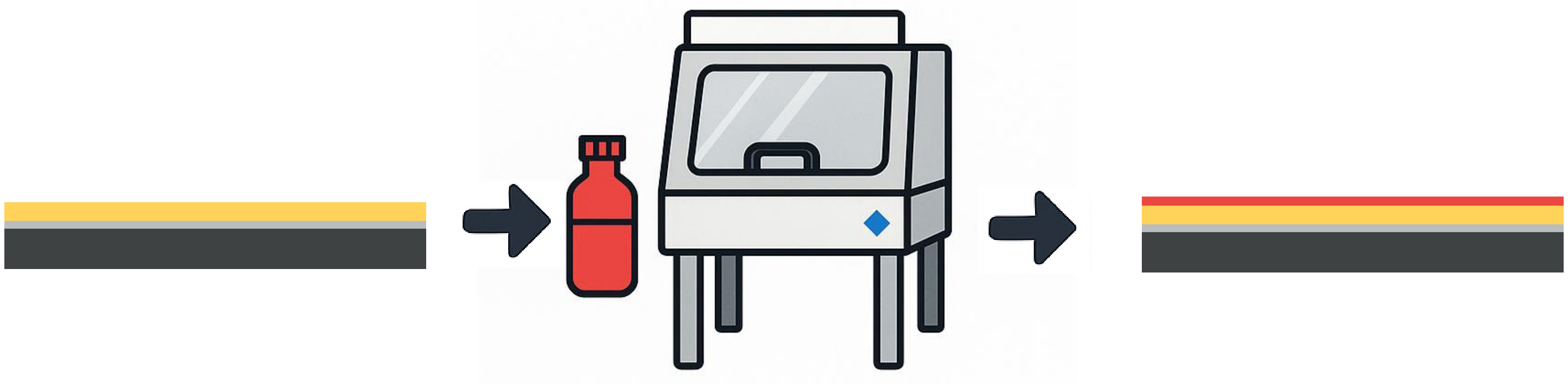
2. Apply a layer of photoresist on it… then soft-bake the wafer

Photoresist

Gold

Chromium

SiC



Photoresist:

- AZ-10XT
  - 500rpm for 5 sec; 1400 rpm for 40 sec

Soft-Bake:

- 110°C for 3 min

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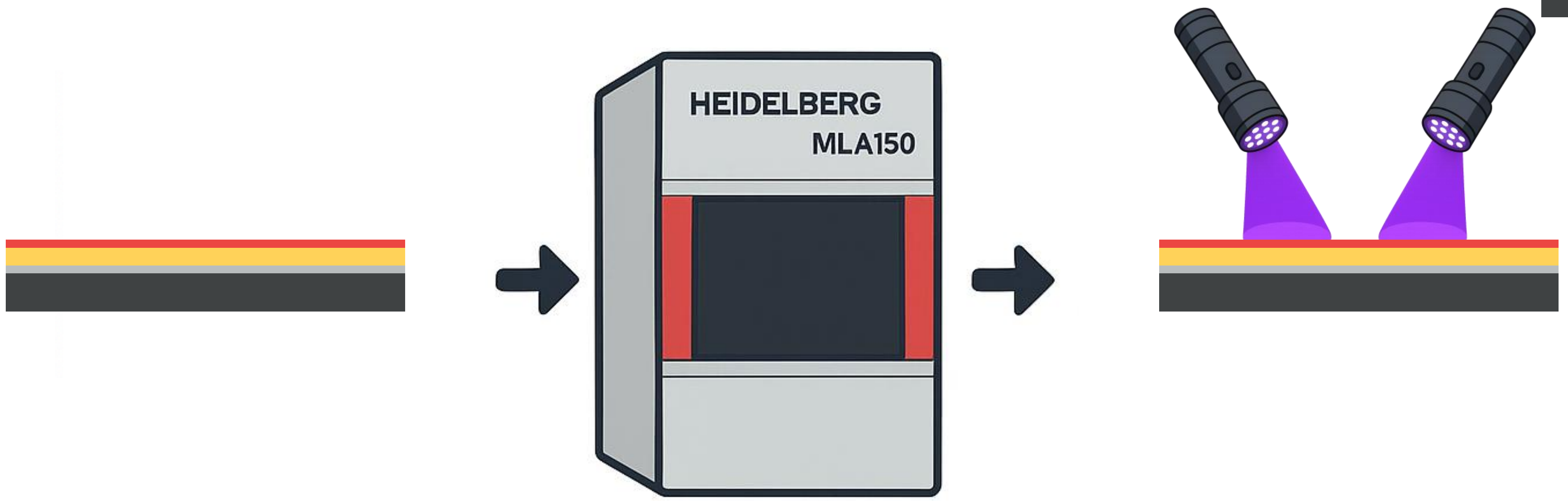
3. Using Maskless Aligner, transfer a predetermined pattern to your wafer

Photoresist
Gold
Chromium
SiC



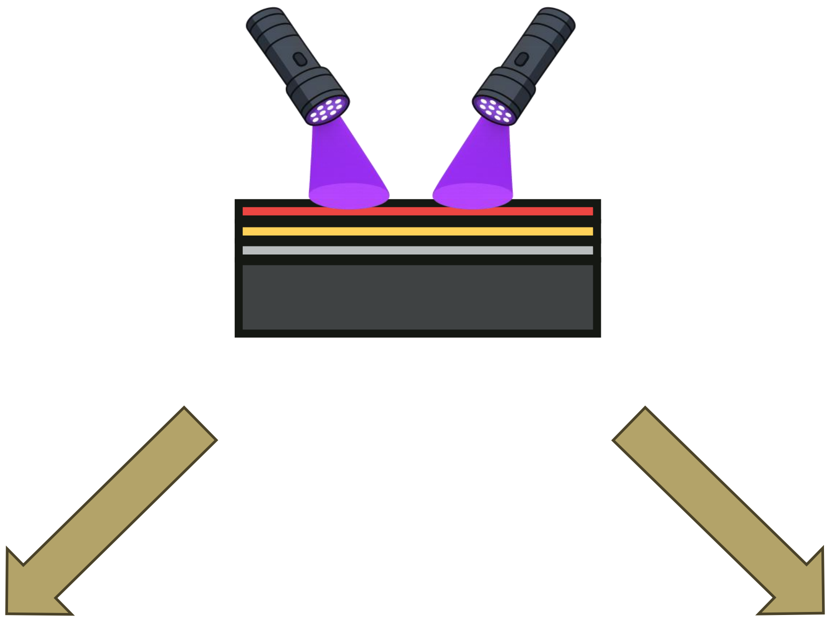
Exposure:

- λ = 375 nm, dose: 430 for MLA1

Positive vs Negative Photoresist

Positive Resist:

- Exposed PR gets removed
- Non-Exposed PR stays



Negative Resist:

- Exposed PR stays
- Non-Exposed PR gets removed

Positive Resist Effect

Negative Resist Effect

Non-inverted vs Inverted (Positive Photoresist)

The black will be exposed to the UV light. Depending one whether your design is inverted or not will determine what is removed from the wafer.

- The pattern is black so it will come off when being developed.

Non-inverted Mask

- Everything except the pattern is black so everything aside from the pattern will come off when being developed.

Inverted Mask

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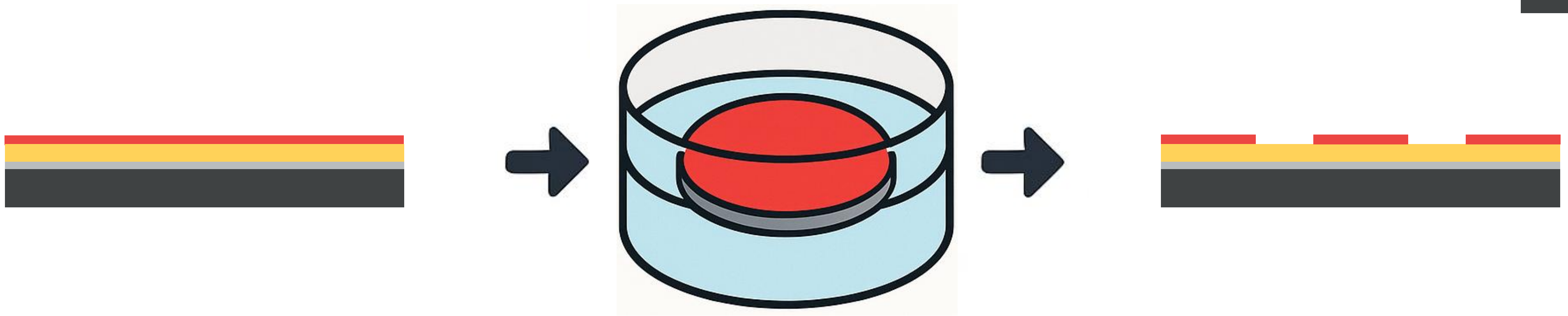
4. Develop the pattern… then hard-bake the wafer

Photoresist

Gold

Chromium

SiC



Developer:

- AZ400K

Hard-Bake:

- 110°C for 10 min

Nickel

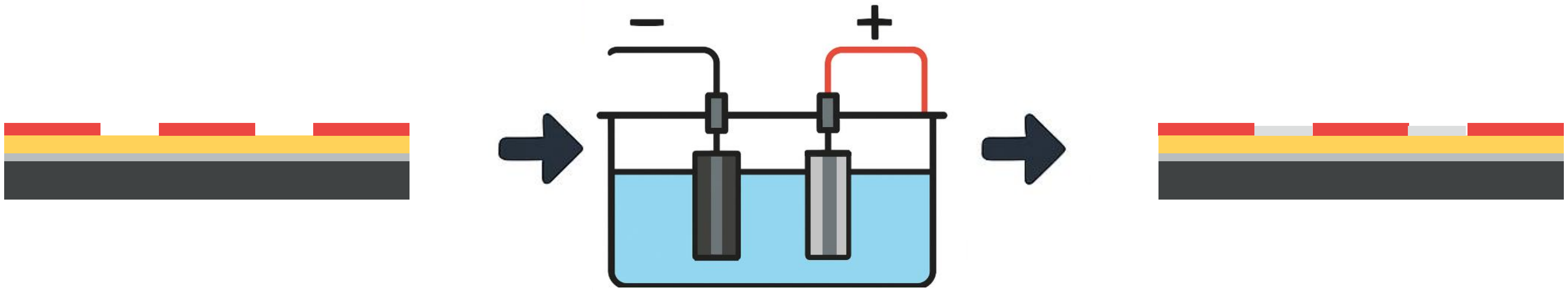
Photoresist

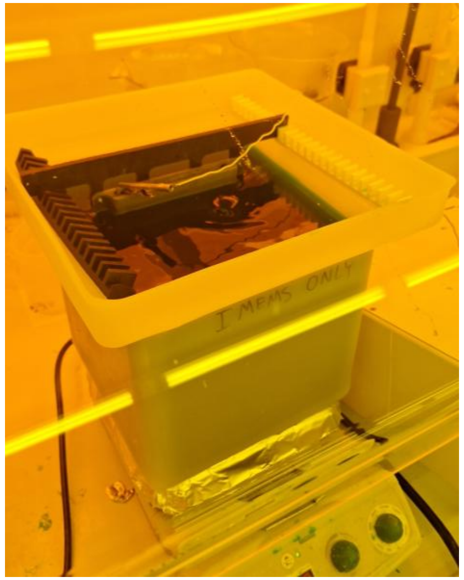
Gold

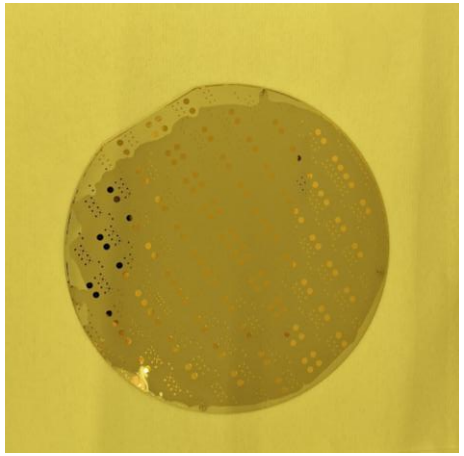
Chromium

SiC

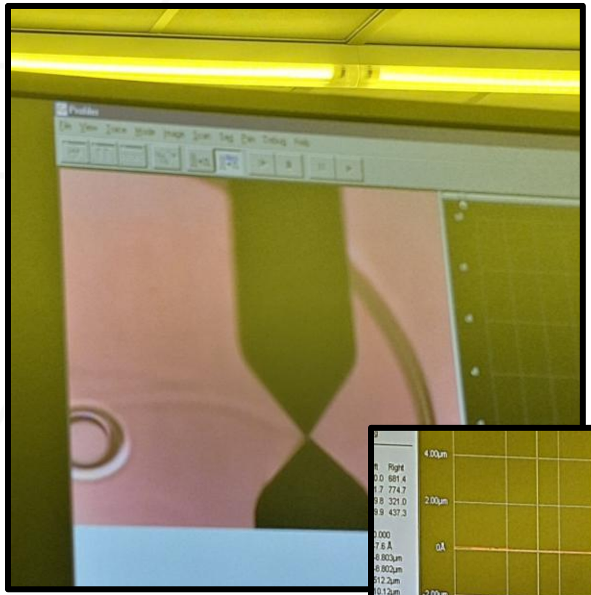
5. Transfer a nickel mask to the wafer by electroplating

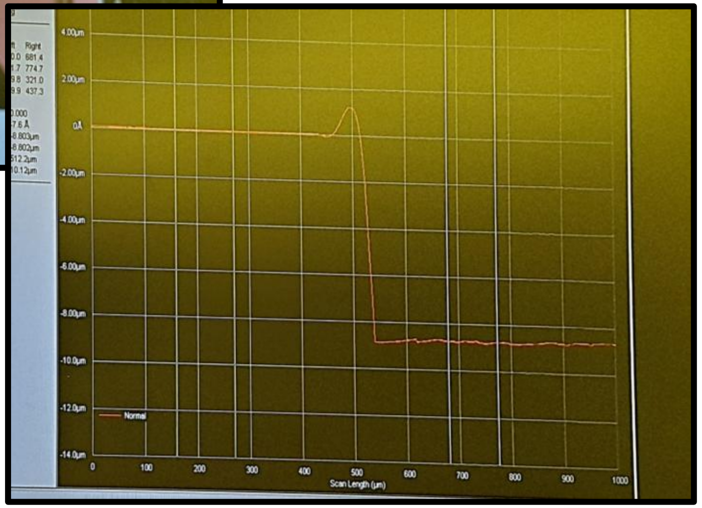






6. Using the profilometer to measure the nickel mask





Wafer	Location	Before Depositing Ni (µm)	After Depositing Ni (µm)
UJ7231-01-EV	T	10.12	5.101
	B	10.11	4.346
	C	10.12	5.472
	L	10.11	5.282
	R	10.12	4.171
UI2954-03-EV	T	10.25	4.034
	B	10.06	4.067
	C	10.25	5.15
	L	10.08	4.113
	R	10.26	4.378

Why use a Nickel Mask?

Durability Against Etching Gases

Nickel withstands reactive ion etching gases like SF_6 much better than photoresist, ensuring the integrity of the mask during the etching process and leading to higher-quality patterns.

Resistance to Burning and Erosion

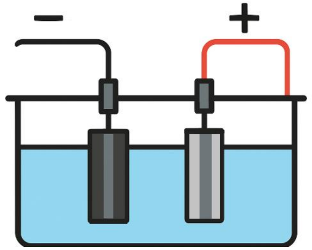
Unlike photoresist, which can burn or erode during long etches, nickel maintains its structure, allowing for consistent etching results throughout prolonged fabrication processes.

Maintaining Sharp Features

Nickel masks retain **sharp pattern features** even during deep etches, which is crucial for achieving precise microfabrication results, thereby enhancing device performance and reliability.

Easy to Electroplate onto Gold

Nickel can be deposited on gold seed layers, providing versatility in microfabrication by enabling tailored mask applications and improving overall process efficiency.



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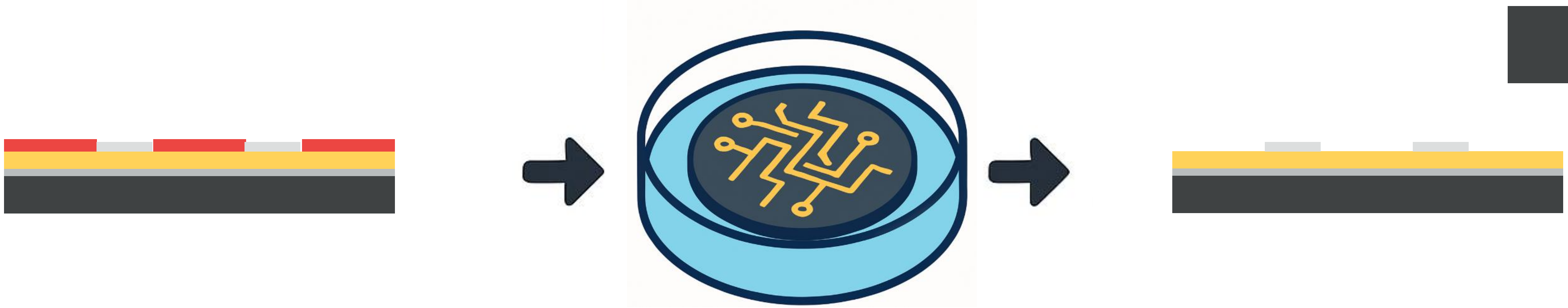
7. Soak in acetone over night to remove photoresist

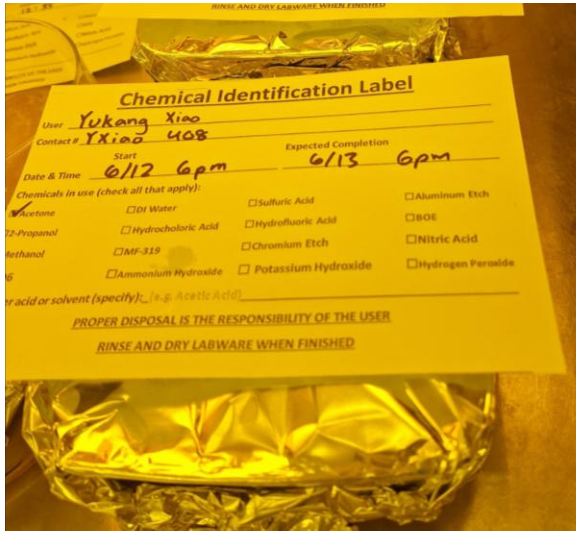
Nickel

Gold

Chromium

SiC

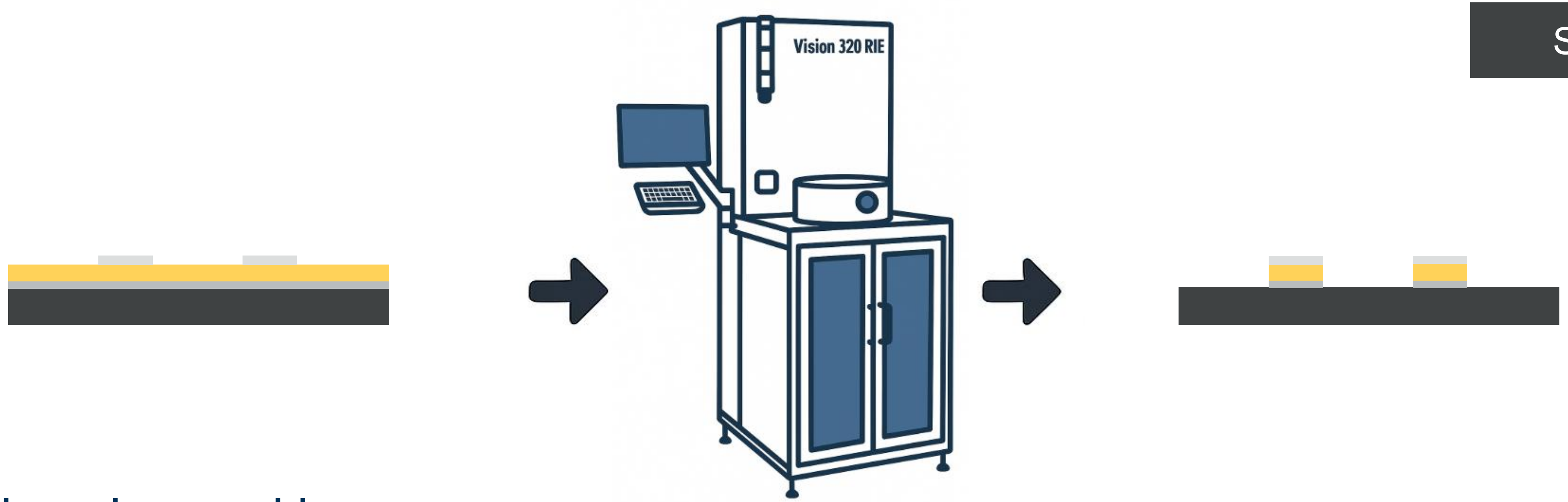




- Usually, piranha is used to remove the photoresist in just a few minutes

8. Now we can begin etching the wafer using the Vision RIE machine

Nickel
Gold
Chromium
SiC



- Etches the seed layer

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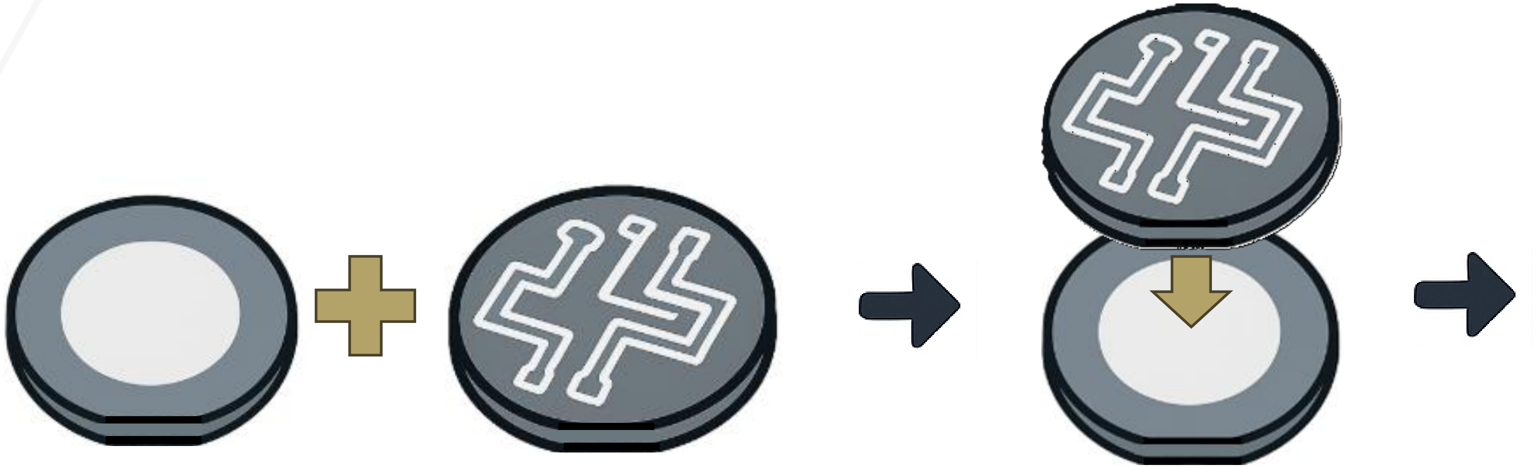
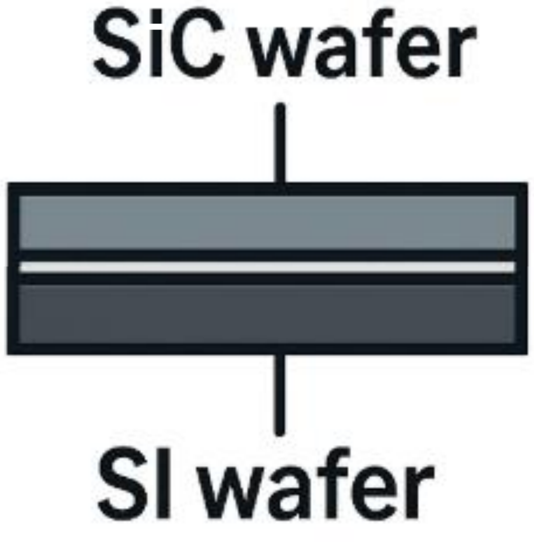
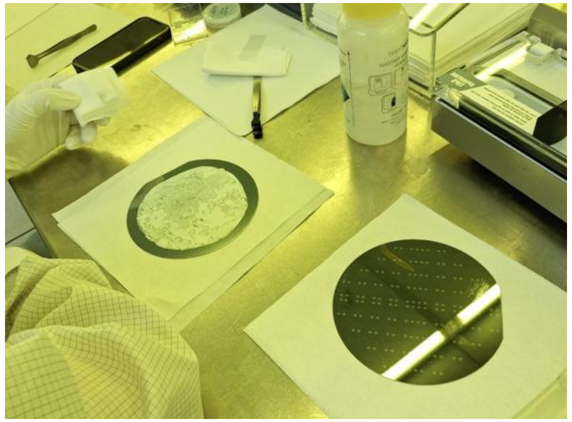
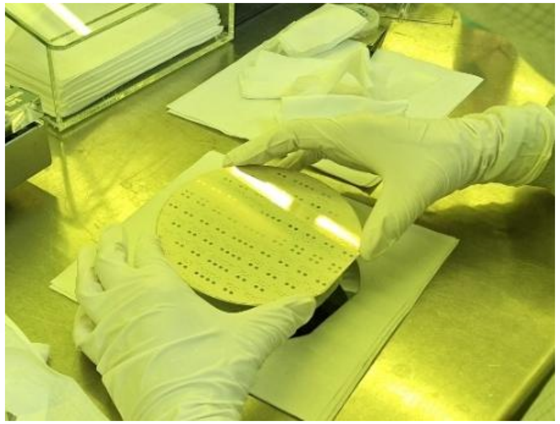
9. Bond wafer to a regular silicon wafer using thermal paste



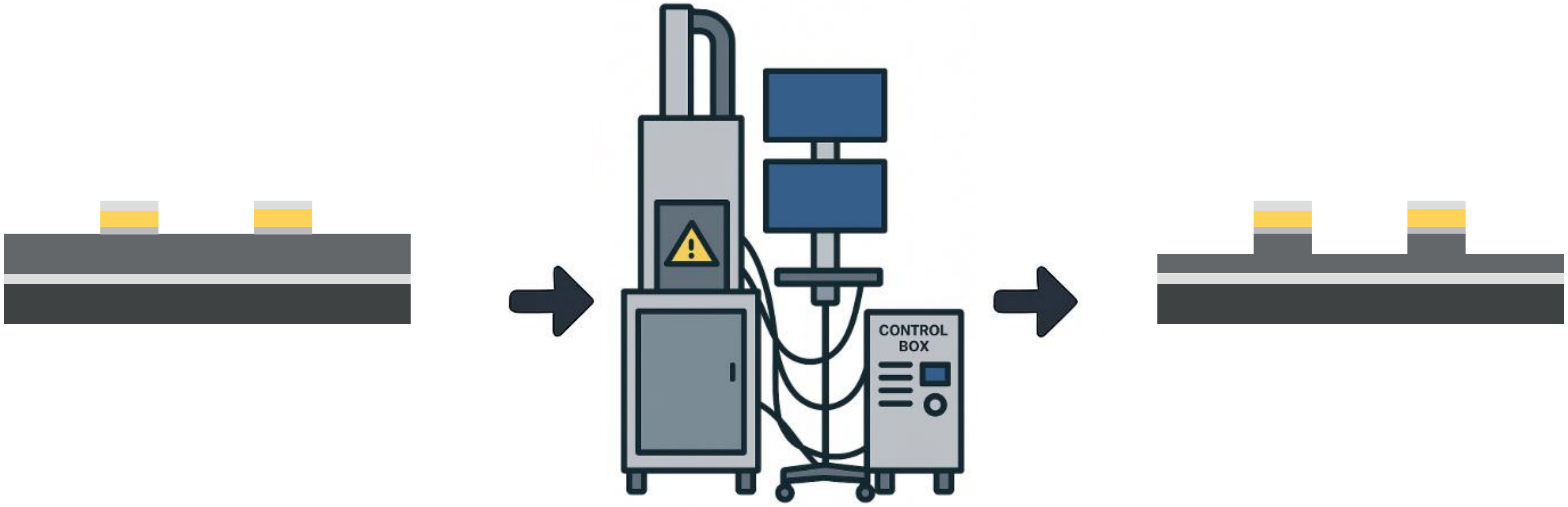






10. Etch the SiC wafer using the Versaline ICP

Nickel
Gold
Chromium
SiC
Thermal Paste
Si



- Etches the actual SiC wafer

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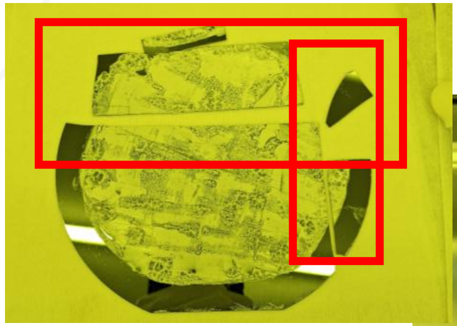
11. Remove the Carrier Wafer (Si Wafer)

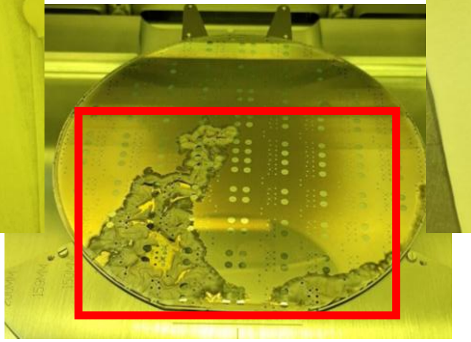
- Nickel
- Gold
- Chromium
- SiC
- Thermal Paste
- Si

Process Tests – Changing the temperature

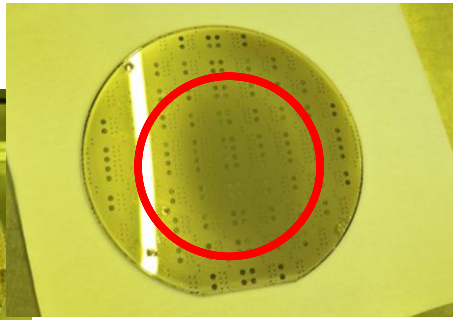
Temperature	Immediate Observations (Naked Eye)	Results Under a Microscope
10°C	Slight Discoloration	Few, small potholes
20°C	No discoloration or burning	Typical pothole count; size within normal range
30°C	Seed Layer / Ni Mask shows burn marks	Fewer potholes; no unusual size deviations
40°C	Mild SiC discoloration; Si shattered	Increased potholes; noticeably larger size
60°C	Slight Discoloration	Few, small potholes



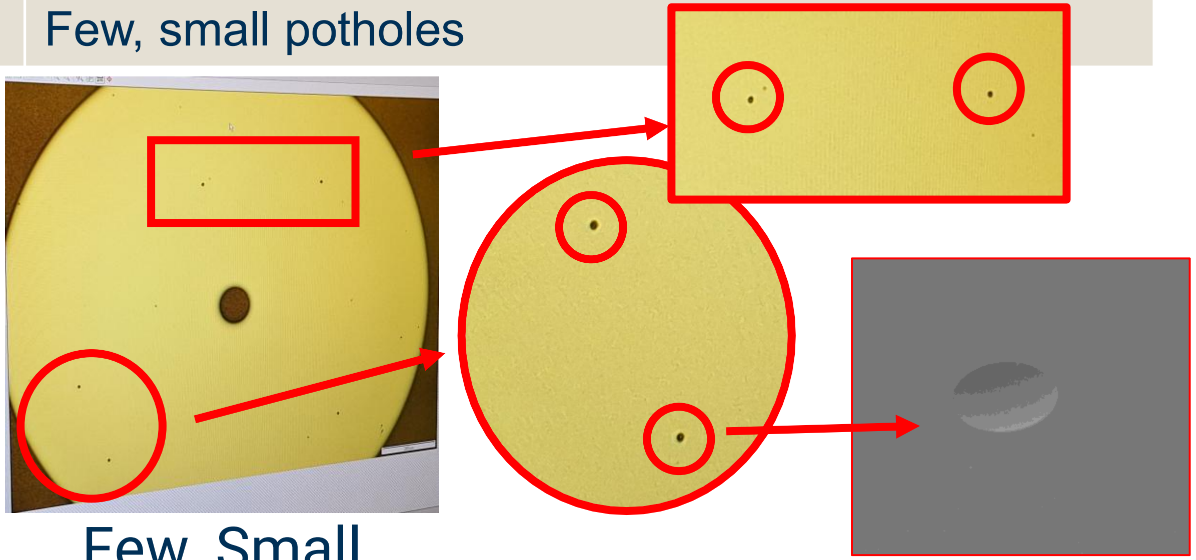
Shattered Si Wafer



Burnt Seed Layer & Ni Mask



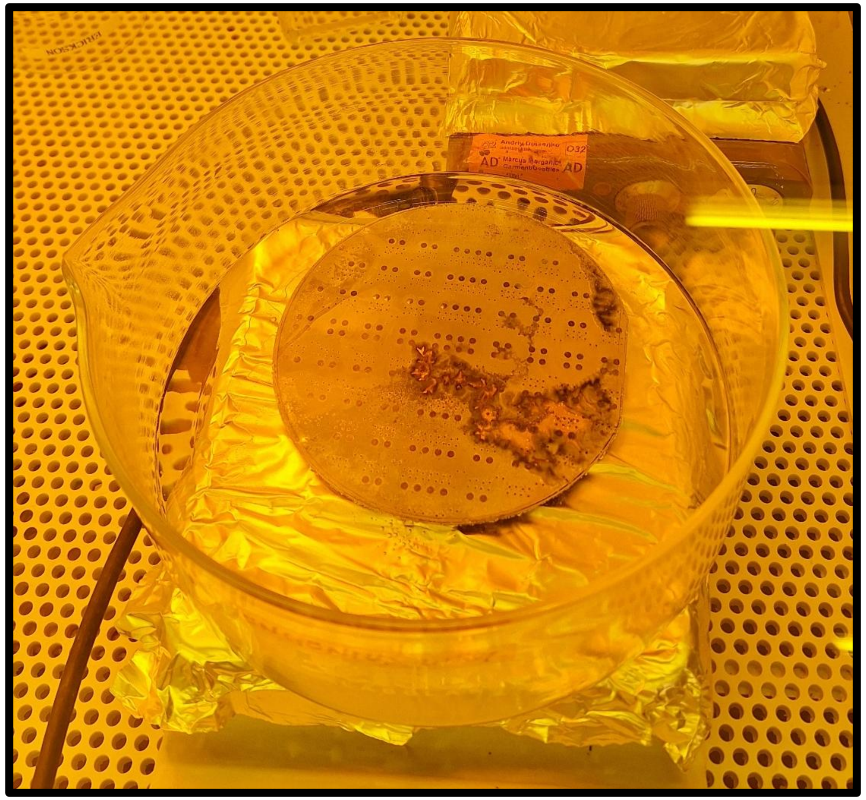
Slight Discoloration



Few, Small Potholes

Xiao et al., 2025

12. Removing Particles



Nickel

Gold

Chromium

SiC

Solution consists of 3:1:

- Sulfuric Acid
- Hydrogen Peroxide

Hotplate: ~80°C

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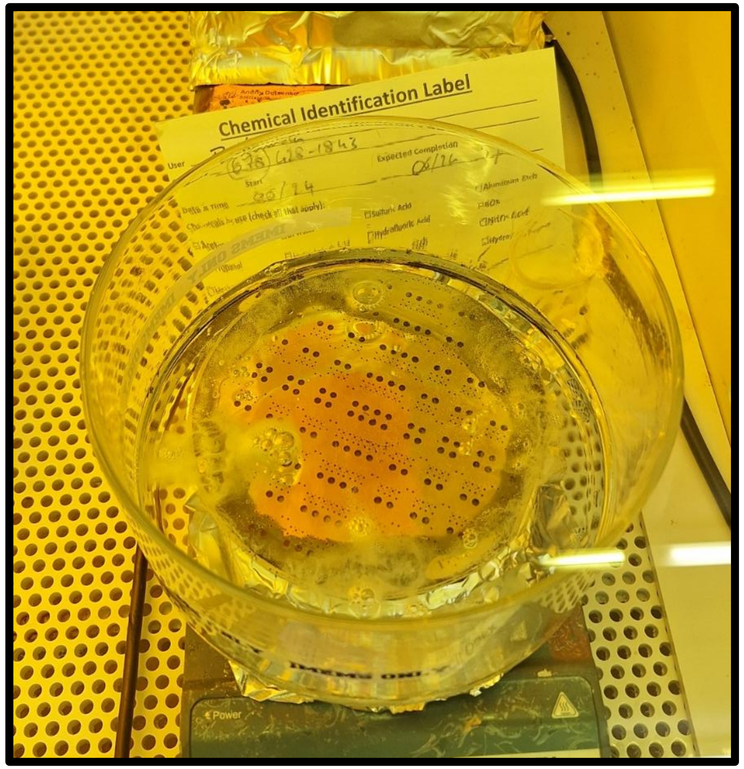
13. Removing the Ni Mask

Solution consists of 3:1:

- Nitric Acid
- Hydrogen Peroxide

Hotplate: ~80°C

Until nickel appears gone



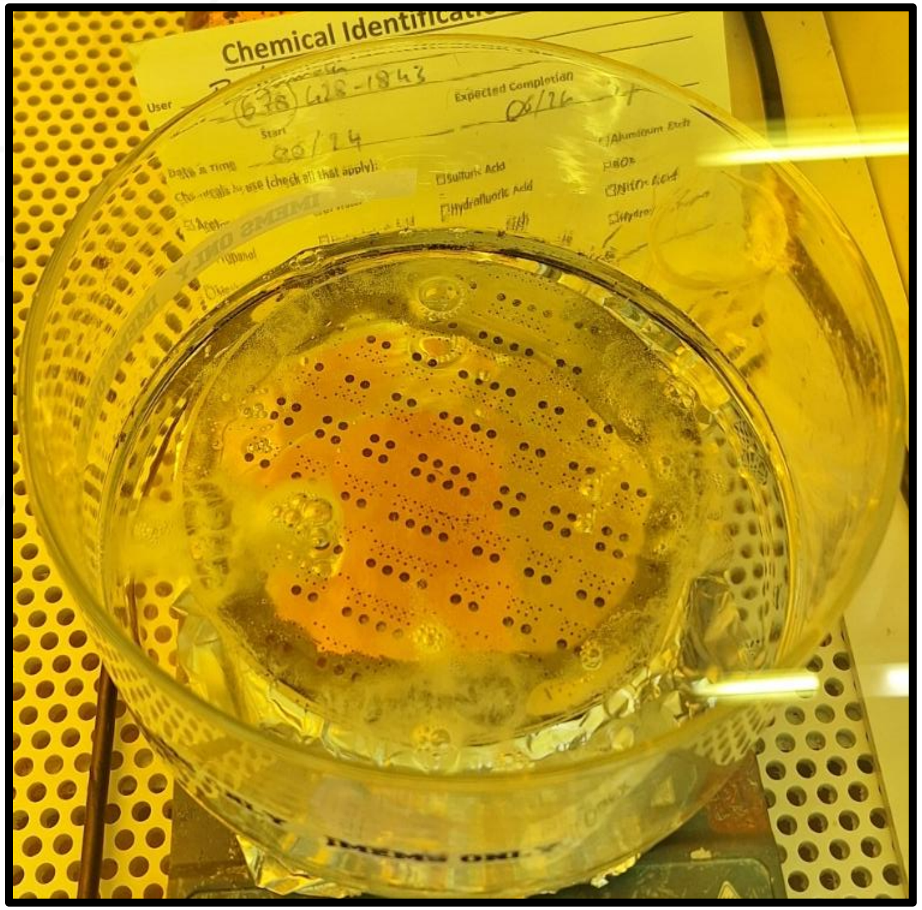
Nickel

Gold

Chromium

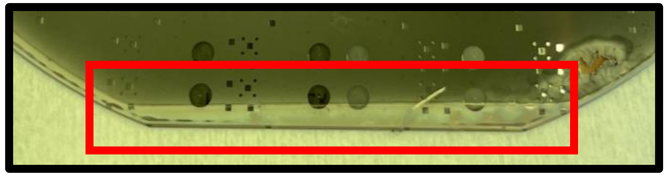
SiC

Why is Nickel hard to remove around the edges of the wafer?



Thermal Effects:

- Si carrier wafer is slightly smaller → exposed SiC edges overheat
- More heat = nickel bakes in more = harder to etch off



14. Removing the Gold Layer

Gold

Chromium

SiC

Solution consists of 3:1:

- Hydrochloric Acid
- Nitric Acid

Hotplate: 80°C

Until gold appears gone

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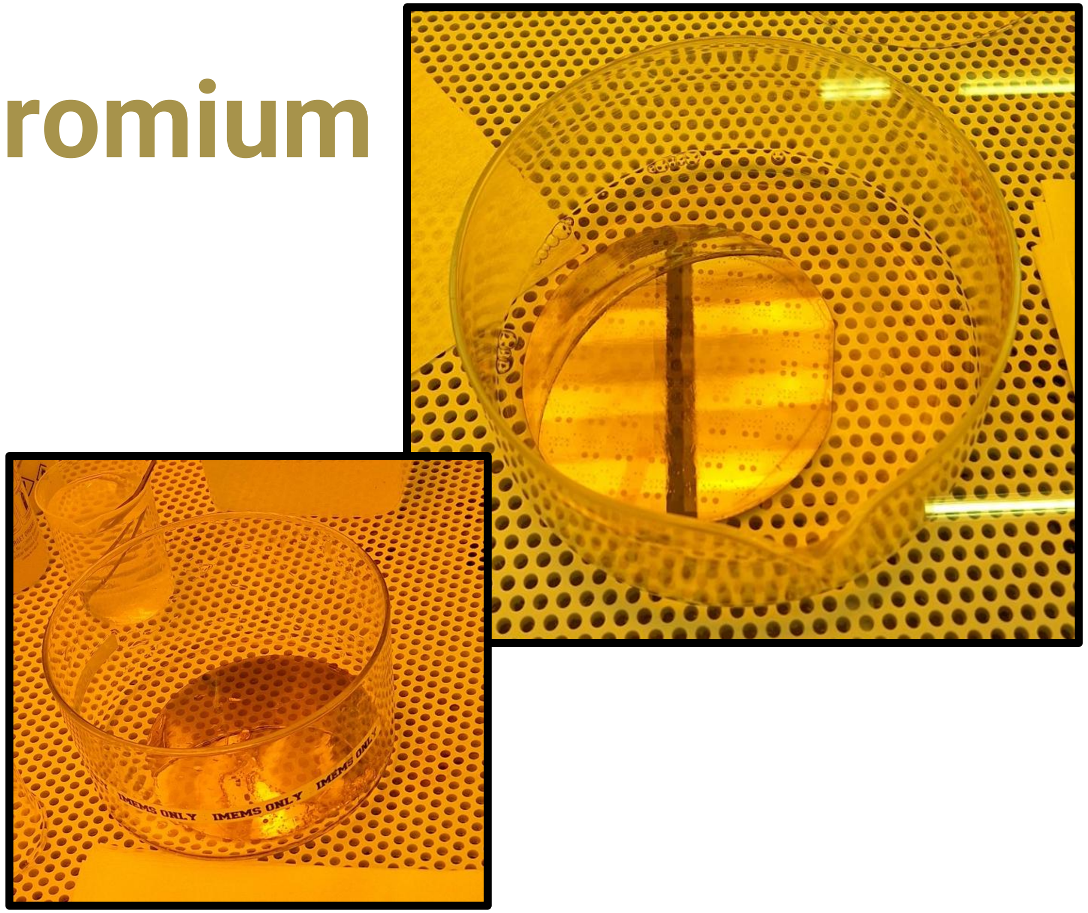
15. Removing the Chromium Layer

Solution consists of:

- Chromium Etch

No hotplate!

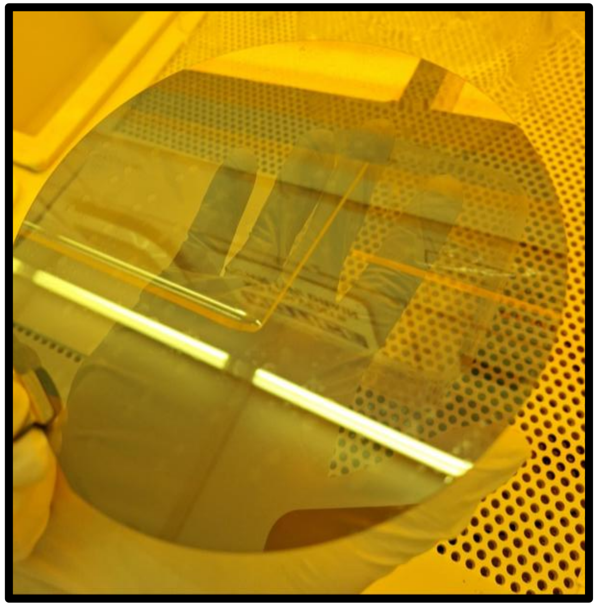
Until chromium appears gone

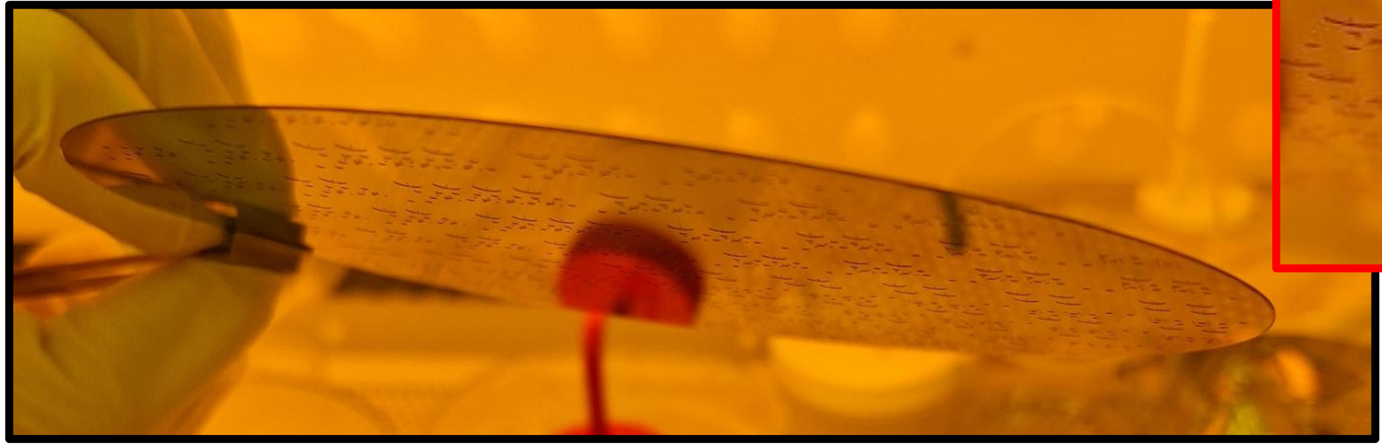


Chromium

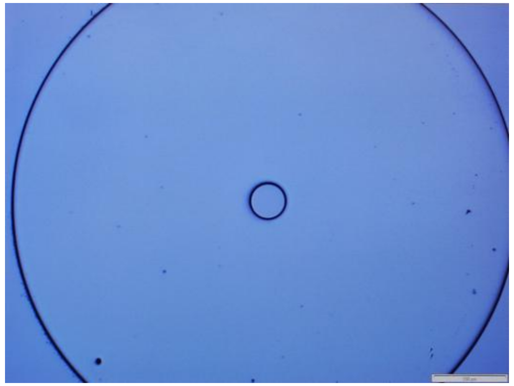
SiC

Results:

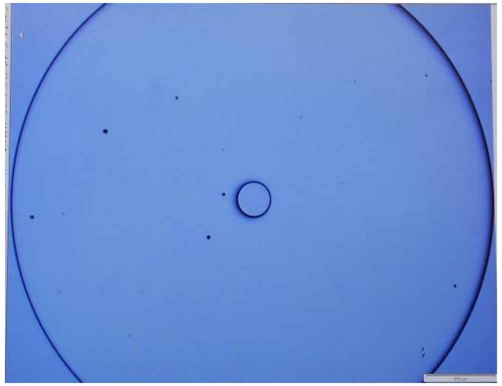


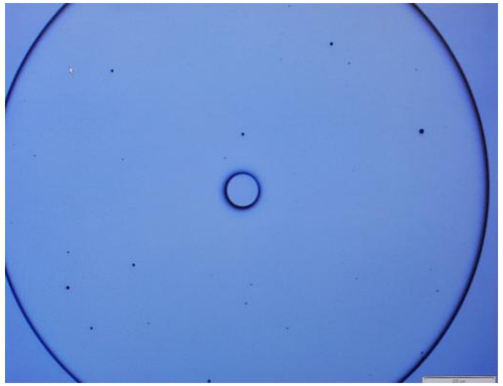


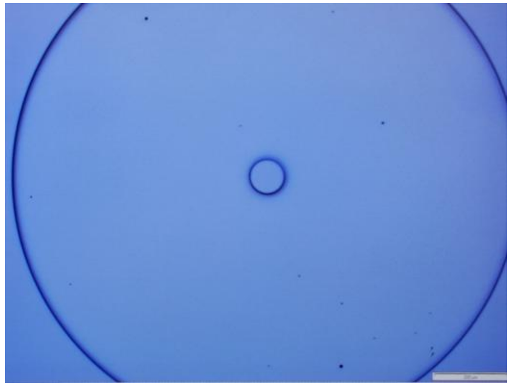
Under the Microscope: 10°C

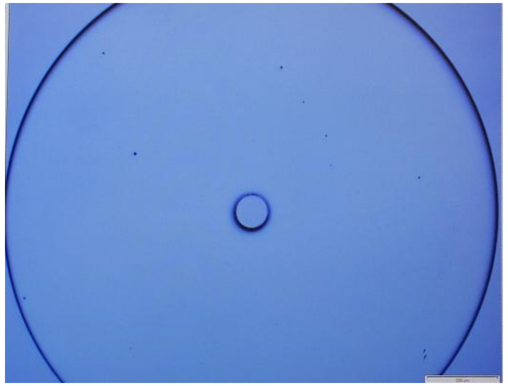


- Very few and small potholes

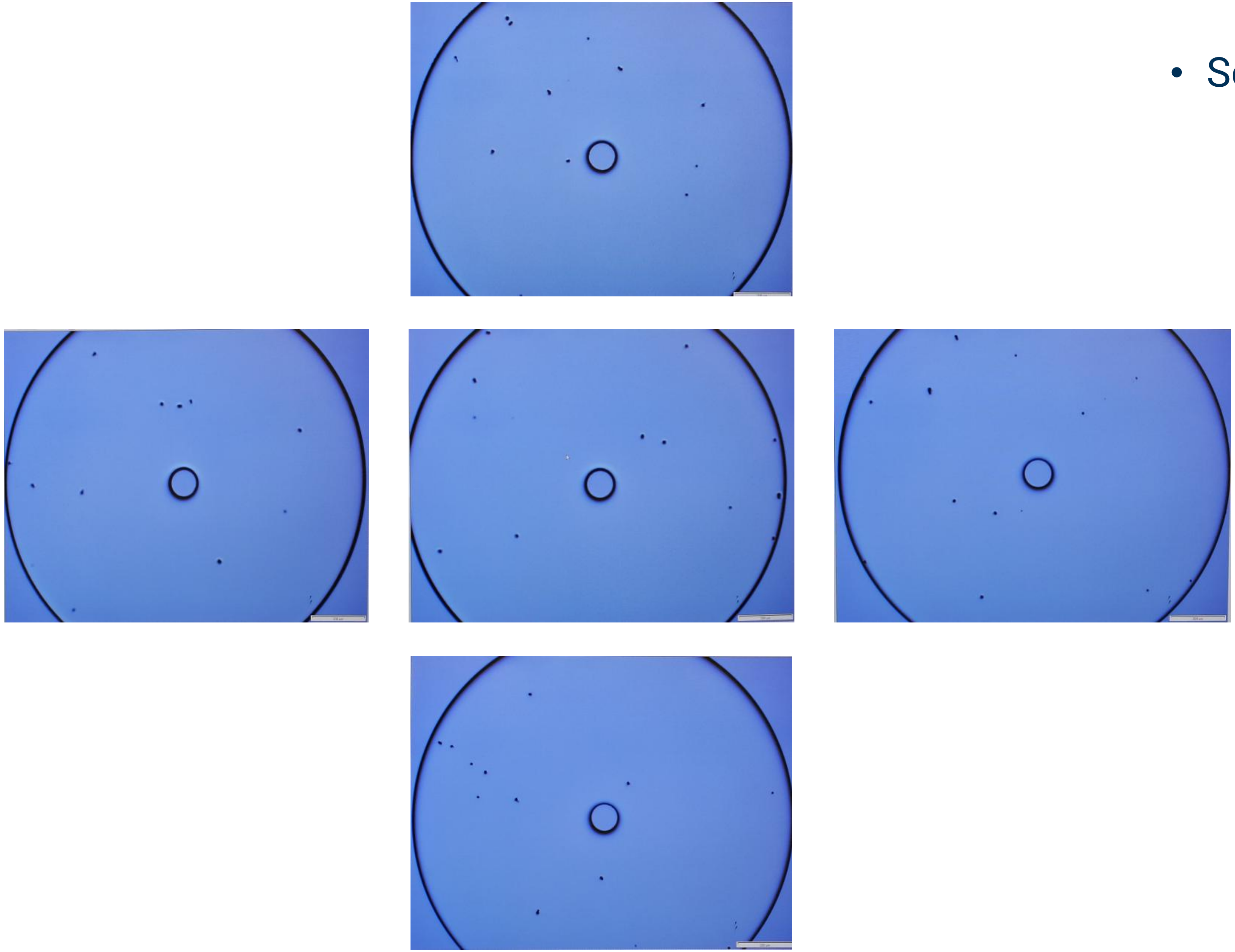






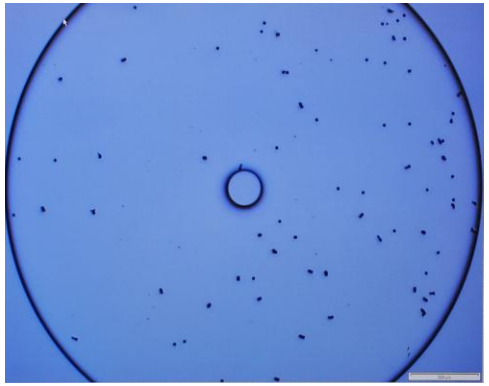


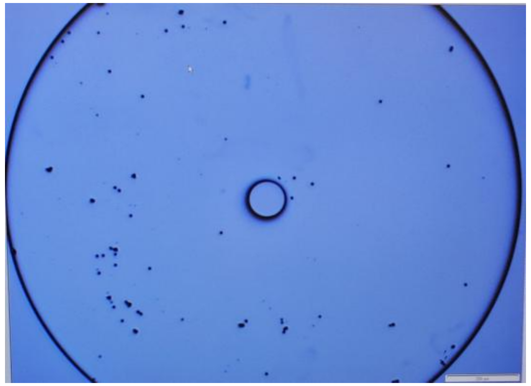
Under the Microscope: 20°C

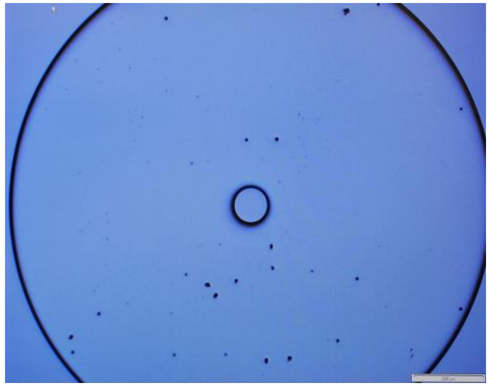


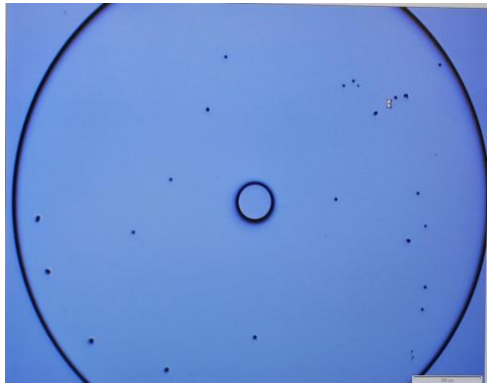
- Some potholes

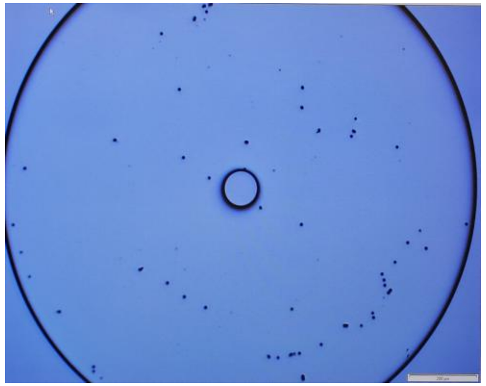
Under the Microscope: 40°C





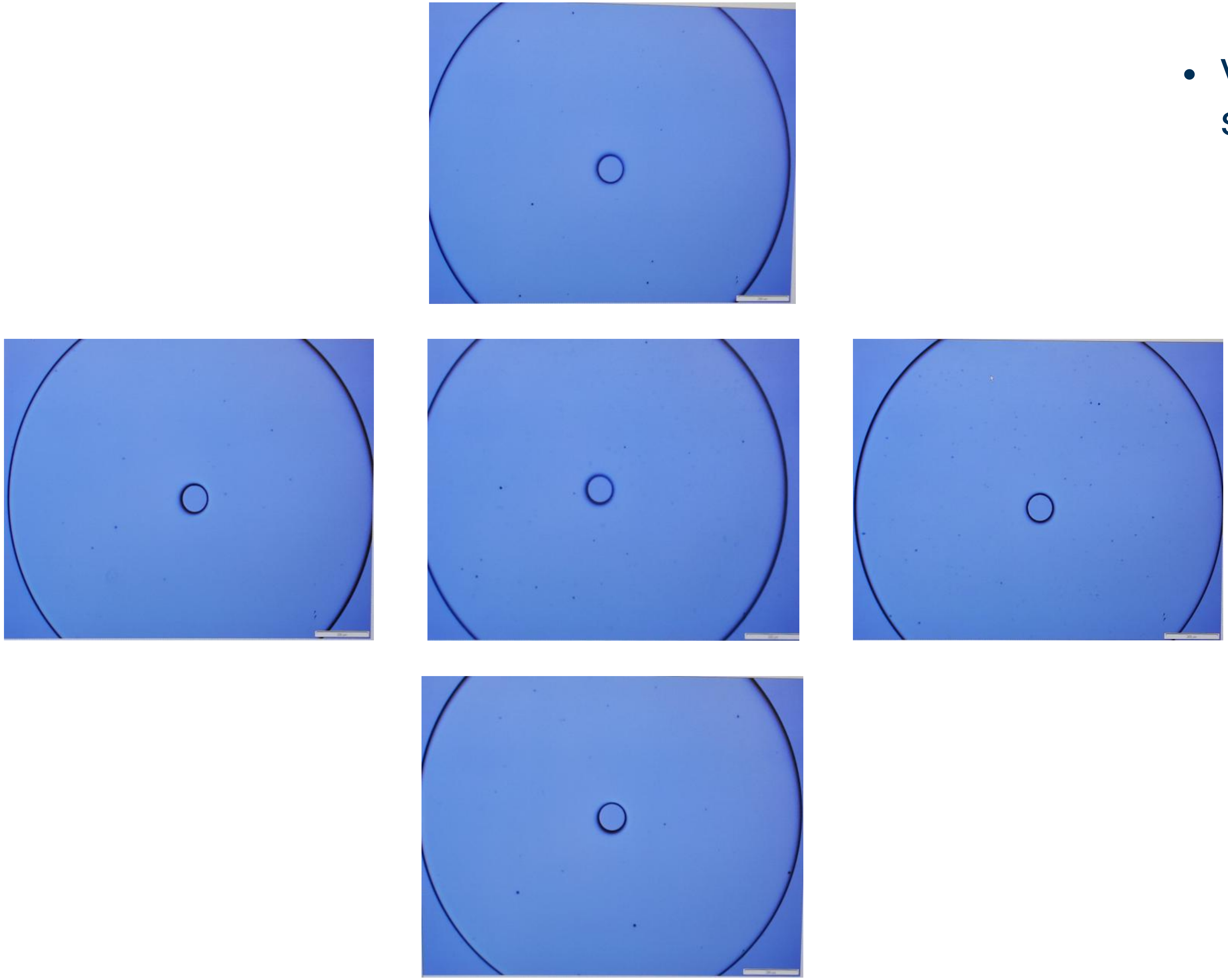






- Numerous and large Potholes

Under the Microscope: 60°C

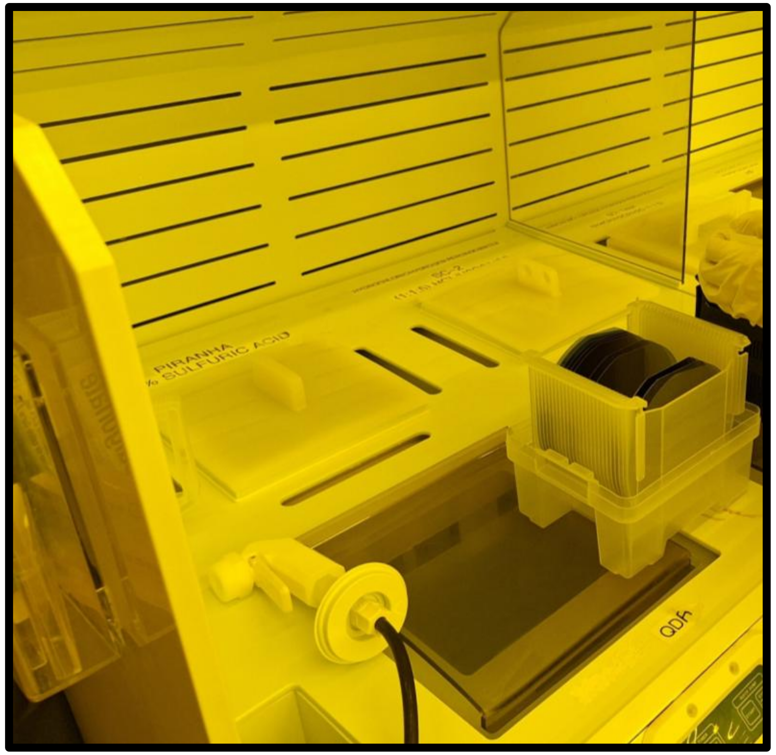


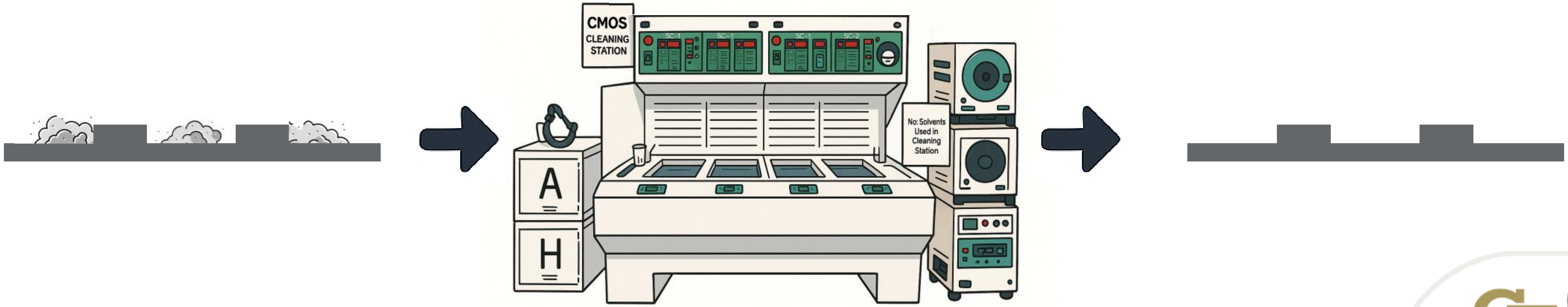
- Very few and small potholes

16. Prep for TEOS

Piranha (3:1 Hydrogen Peroxide & Sulfuric Acid)

- 120°C
- 10 minutes

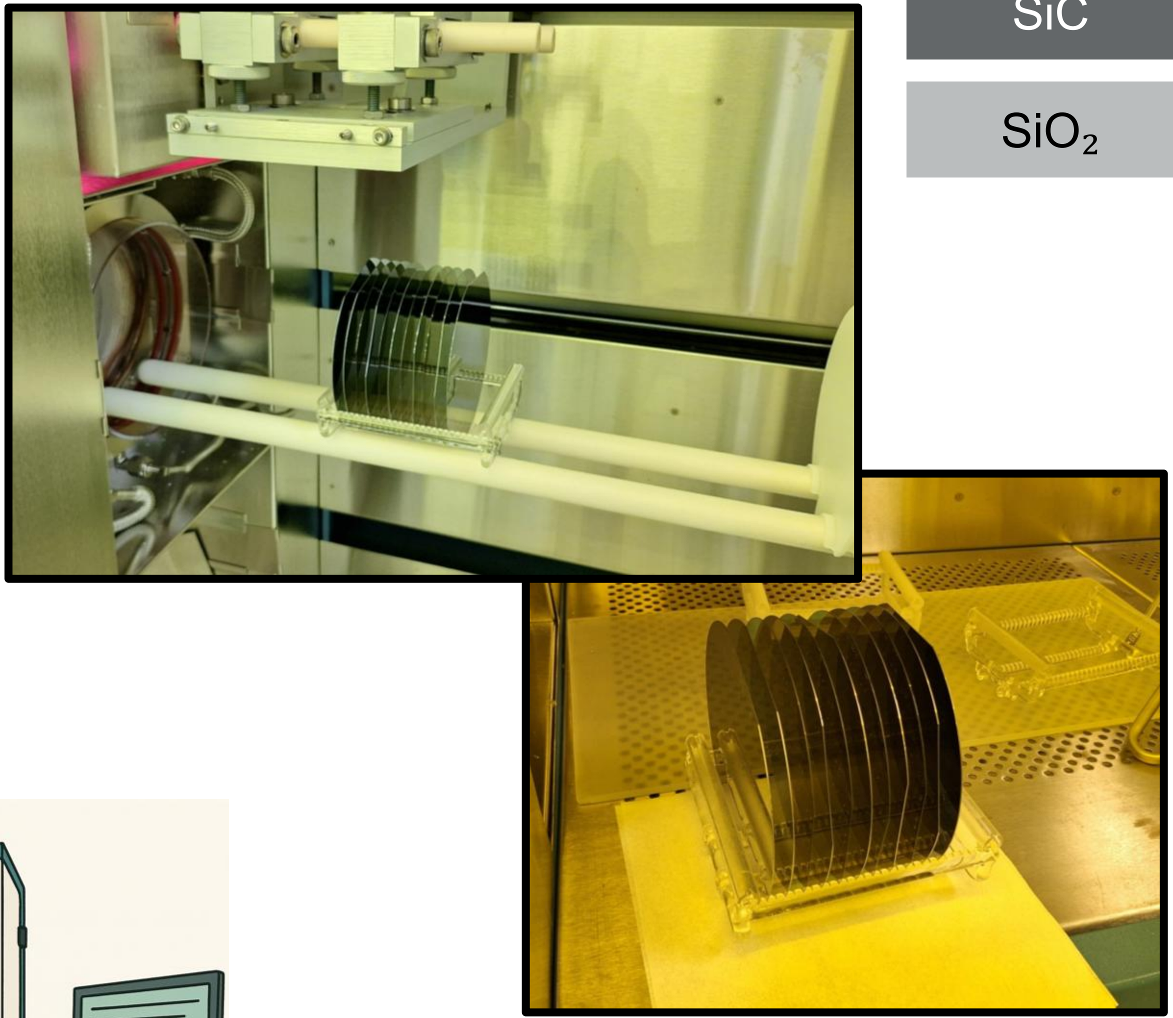


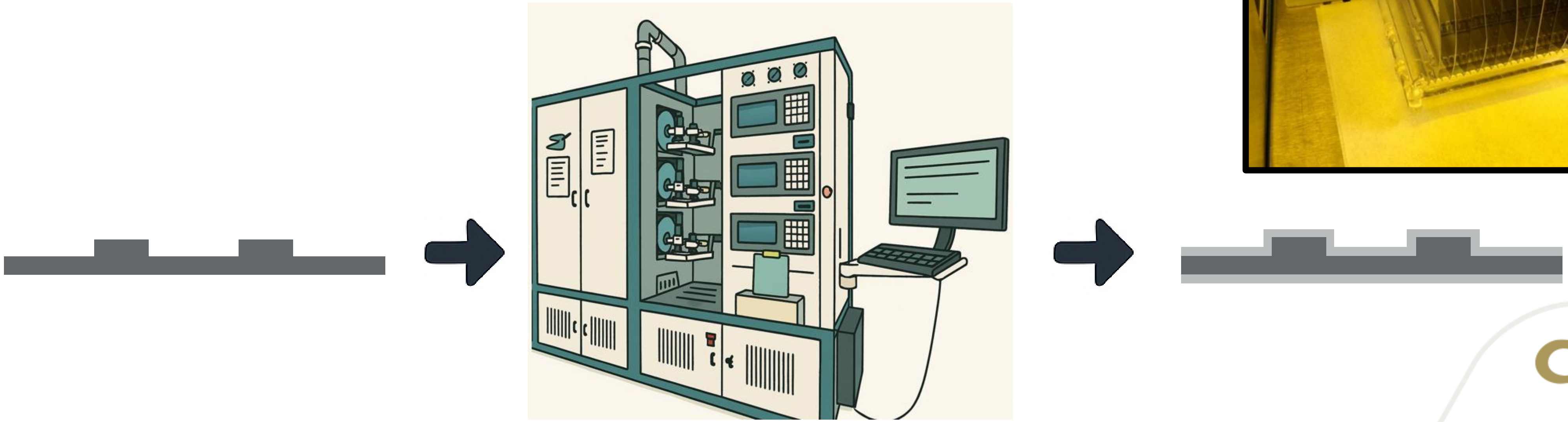


17. TEOS Deposition 5×

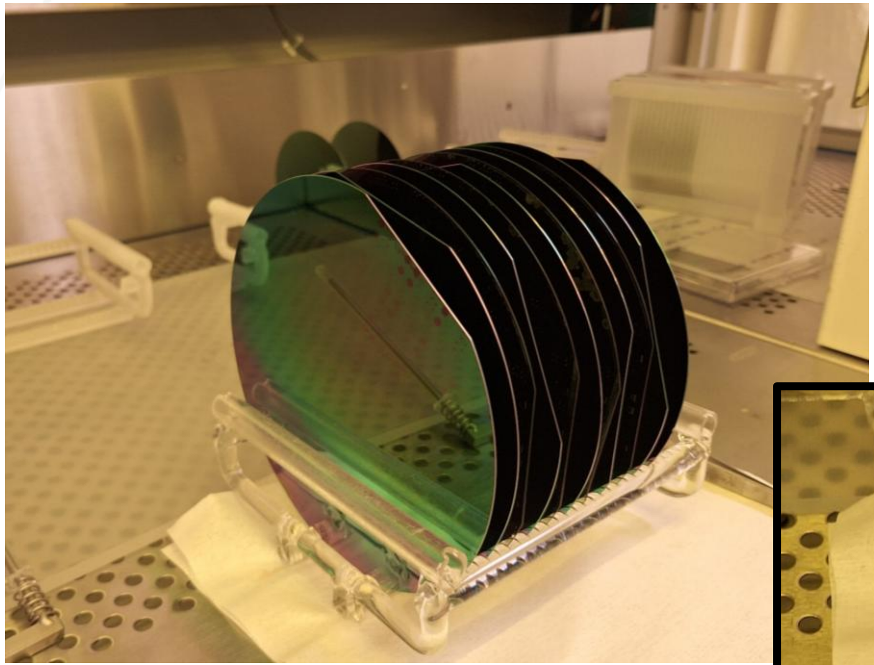
SiC
SiO_2

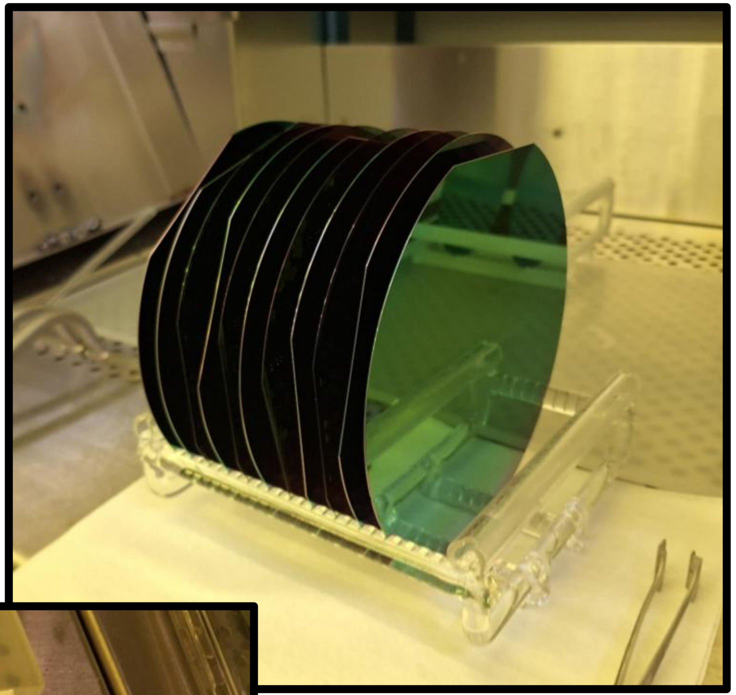
- Used to deposit silicon dioxide (SiO_2) (.8μm)
- Annealing is carried out after each deposition iteration to reduce film stress

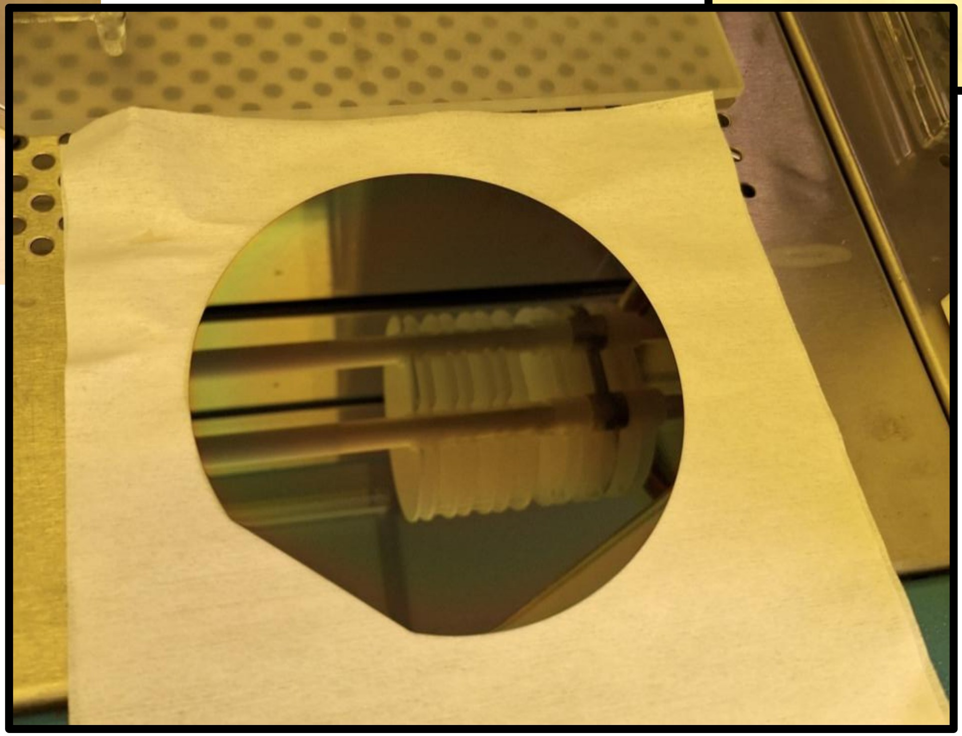




TEOS Deposition



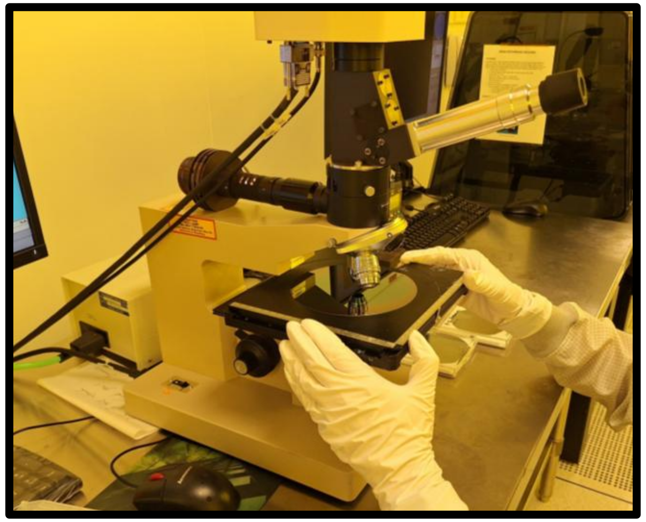


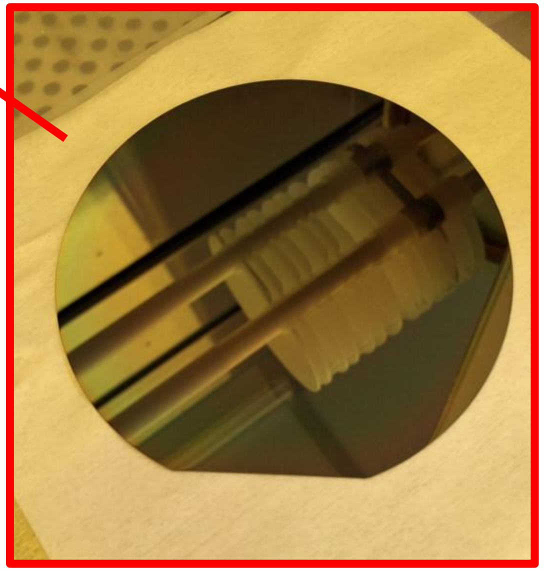


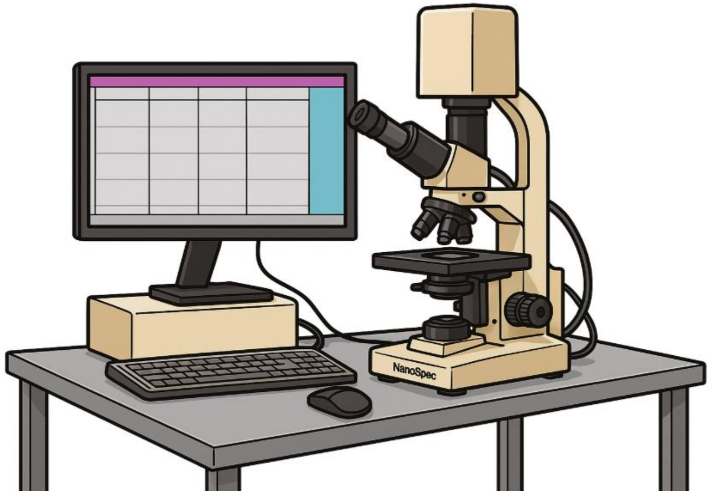
18. Measuring the SiO_2 Layer

- Use a reflectometer
- Use the Si wafers to measure the film thickness.
- Thickness should increase by ~.8μm per iteration

After 2nd Iteration	
Position	Thickness
C	1.6940μm
T	1.7464μm
L	1.7866μm
R	1.7538μm
B	1.7765μm



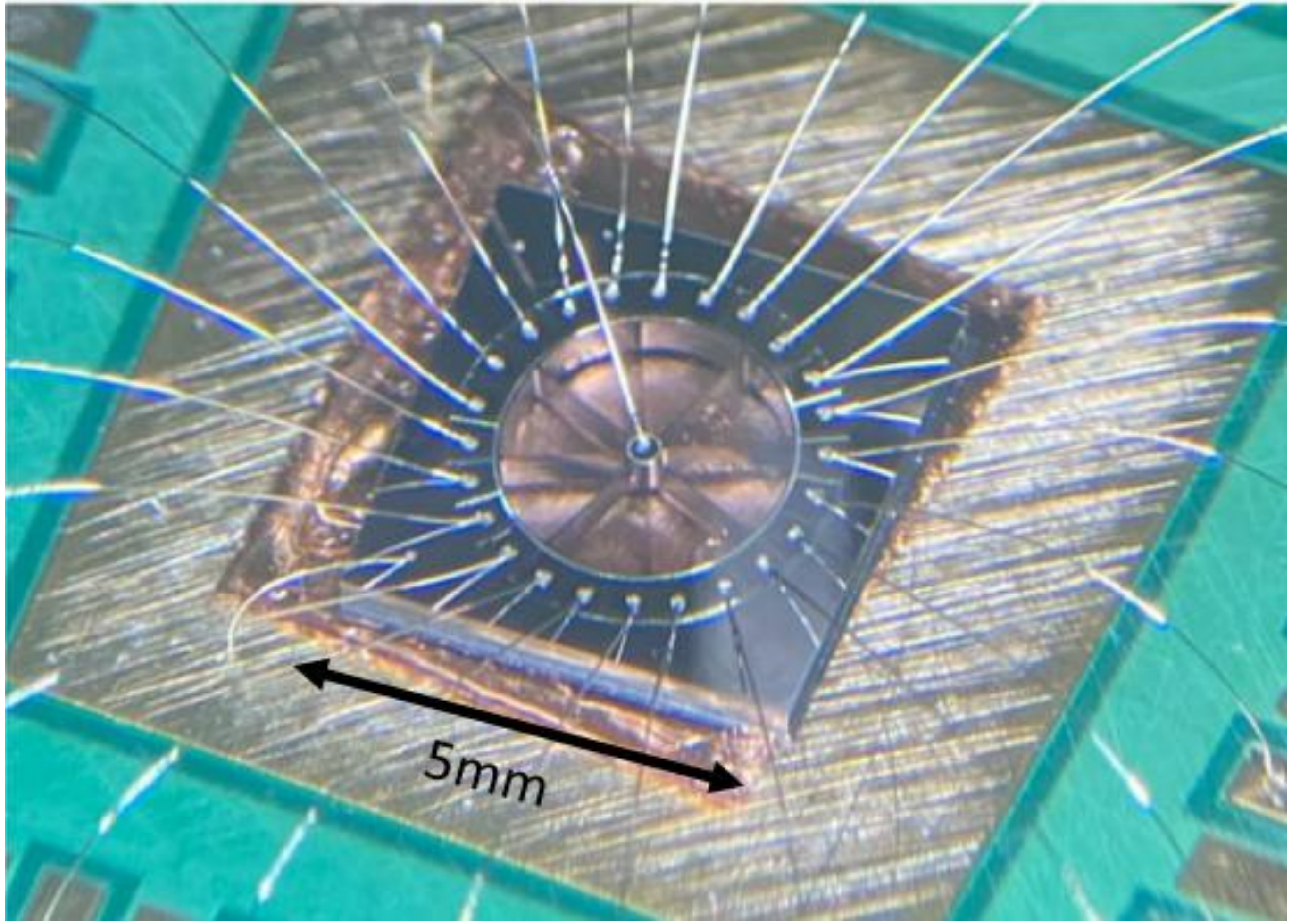




Overall Results

The gyroscope will ultimately have performance levels suitable for navigation when a GPS signal is not available.

https://www.nature.com/articles/s44172-024-00234-z



A diced 4H-SiC BAW gyroscope mounted on PCB with all 24 electrodes and center post wire-bonded. [1]

Georgia Tech

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Georgia Tech Institute for Matter and Systems

NSF

STATE

IMEMS

National Nanotechnology Coordinated Infrastructure

SENIC Southeastern Nanotechnology Infrastructure Corridor

References

[1] Long Y, Liu Z, Ayazi F. 4H-Silicon Carbide as an Acoustic Material for MEMS. IEEE Trans Ultrason Ferroelectr Freq Control. 2023 Oct;70(10):1189-1200. doi: 10.1109/TUFFC.2023.3282920. Epub 2023 Oct 17. PMID: 37276110.

[2] N. Li et al., "Advances in High-Aspect-Ratio Deep Reactive Ion Etching of 4H-Silicon Carbide Wafers," in Journal of Microelectromechanical Systems, vol. 33, no. 6, pp. 776-784, Dec. 2024, doi: 10.1109/JMEMS.2024.3466769.

[3] Liu, Z., Long, Y., Wehner, C. et al. 4H silicon carbide bulk acoustic wave gyroscope with ultra-high Q-factor for on-chip inertial navigation. Commun Eng 3, 87 (2024).

[4] J. Yang, B. Hamelin, F. Ayazi, "Investigating Elastic Anisotropy of 4H-SiC using Ultra-High *Q* Bulk Acoustic Wave Resonators," *Journal of Microelectromechanical Systems*.