

Experimental Design: Peanut-Epoxy Organic Memory Array (OMA-1)

A Carbon-Based Write-Once-Read-Many (WORM) Device via Laser-Induced Carbonization

Marie-Soleil Seshat Landry
Landry Industries, Hempoxies Division
Moncton, NB, Canada
`marie.landry@landryindustries.ca`

June 26, 2026

Abstract

This document presents the experimental design for the Peanut-Epoxy Organic Memory Array (OMA-1), a bio-derived Write-Once-Read-Many (WORM) memory device. The system utilizes carbonized organic peanut tissue (*Arachis hypogaea* shell) as the active resistive-switching layer embedded in an epoxy matrix, with interdigitated silver electrodes for electrical readout. Laser-induced thermal carbonization (405 nm, 500 mW to 2000 mW) creates localized high-conductivity regions (“written” bits, 1) within a low-conductivity epoxy matrix (“unwritten” bits, 0). The design targets a bit density of 1 cm^{-2} , a bit error rate (BER) $< 0.1\%$, and endurance of $> 10^3$ read cycles. This study addresses the critical need for sustainable, biodegradable memory substrates while leveraging established biomass carbonization protocols and percolation theory for composite conductivity engineering.

1 Introduction

1.1 Background and Motivation

The global demand for data storage exceeds 100 annually, with conventional silicon-based memory contributing significantly to e-waste and resource depletion[1]. Organic and bio-derived memory devices offer a sustainable alternative, with biomass-derived carbon exhibiting tunable electrical conductivity (10^{-3} – 10^2 S/m) depending on pyrolysis temperature and precursor chemistry[2, 3].

Peanut shells, an abundant agricultural by-product ($>6\text{ t}$ annually in North America), contain 35 % cellulose, 25 % hemicellulose, and 18 % lignin[2]. Upon pyrolysis above 600°C , these biopolymers undergo aromatization and graphitization, forming conductive carbon networks with percolation thresholds as low as 0.5 % volume fraction in polymer matrices[3, 4].

1.2 Device Architecture

OMA-1 employs a planar metal–insulator–metal (MIM) structure with interdigitated electrodes (IDEs), avoiding the need for vertical via etching. The architecture comprises:

1. **Substrate:** Glass or polyimide (Kapton) carrier
2. **Bottom electrodes:** Thermally evaporated silver (100 nm) with 5 nm chromium adhesion layer
3. **Active layer:** Carbonized peanut tissue ($\phi < 50\mu\text{m}$) dispersed in low-viscosity epoxy (EPON 828, $V_f = 15\%$)

4. **Top encapsulation:** Clear epoxy overcoat (50 μm) for environmental protection

1.3 Memory Mechanism

OMA-1 operates as a **Write-Once-Read-Many (WORM)** device. The memory mechanism is **thermal carbonization-induced resistive contrast**:

- **State 0 (Unwritten):** Peanut tissue is partially carbonized (400 °C pre-treatment), exhibiting high resistivity ($\rho > 10^6 \Omega\cdot\text{cm}$) within the insulating epoxy matrix ($\rho \approx 10^{14} \Omega\cdot\text{cm}$).
- **State 1 (Written):** Localized laser heating ($T > 700 \text{ }^\circ\text{C}$) drives advanced graphitization, reducing resistivity to $< 10^2 \Omega\cdot\text{cm}$ [2]. The resulting conductive carbon network spans the inter-electrode gap (10 μm), creating a low-resistance current path.

The ON/OFF resistance ratio ($R_{\text{OFF}}/R_{\text{ON}} > 10^4$) provides robust bit discrimination, with readout via a Wheatstone bridge or transimpedance amplifier to minimize read-disturb effects.

2 Hypothesis

[Primary] **Alternative Hypothesis (H_a):** Laser-induced carbonization of peanut tissue within an epoxy matrix produces a stable WORM bit array with:

- Bit Error Rate (BER) $< 0.1\%$ at density 1 cm^{-2}
- ON/OFF resistance ratio $> 10^4$
- Read endurance $> 10^3$ cycles without state degradation
- Data retention > 10 years at 25 °C, 50 % RH

Null Hypothesis (H_0): The carbonization process does not produce statistically distinguishable resistance states, or the BER exceeds 1%.

3 Theoretical Framework

3.1 Percolation Theory

The conductivity of carbon–epoxy composites follows percolation scaling:

$$\sigma = \sigma_0(V_f - V_c)^t \quad \text{for } V_f > V_c \quad (1)$$

where σ_0 is the intrinsic carbon conductivity, V_f is the filler volume fraction, V_c is the percolation threshold ($\approx 0.5\%$ for peanut-derived carbon[3]), and $t \approx 2.0$ is the critical exponent for 3D percolation.

At $V_f = 15\%$, the composite operates deep in the percolation regime, ensuring uniform baseline conductivity while allowing local modulation via laser carbonization.

3.2 Laser Heating Model

The temperature rise during laser irradiation is approximated by the radial heat flow equation:

$$\Delta T(r, t) = \frac{P\alpha}{2\pi k} \int_0^t \frac{1}{\tau} \exp\left(-\frac{r^2}{4D\tau}\right) d\tau \quad (2)$$

where P is laser power, α is absorption coefficient ($\approx 10^5 \text{ cm}^{-1}$ for carbon at 405 nm), k is thermal conductivity of epoxy ($\approx 0.2 \text{ W m}^{-1} \text{ K}^{-1}$), and D is thermal diffusivity.

For a 10 μm spot at 1 W, the steady-state temperature exceeds 800 °C, sufficient for advanced graphitization[2].

4 Experimental Methodology (SOP)

4.1 Materials and Reagents

Table 1: Materials specification

Component	Specification	Supplier	Purity/Grade
Peanut shells	<i>Arachis hypogaea</i> , washed, dried	Local agricultural co-op	Organic
Epoxy resin	Bisphenol-A diglycidyl ether (EPON 828)	Hexion	Technical
Hardener	Triethylenetetramine (TETA)	Sigma-Aldrich	> 95%
Silver wire	$\phi = 0.5$ mm, 99.99%	Alfa Aesar	Puratronic
Chromium shot	3–5 mm granules	Kurt J. Lesker	99.95%
Glass substrates	Borosilicate, $25 \times 25 \times 1$ mm	Ted Pella	Microscopy grade
Nitrogen gas	Ultra-high purity	Praxair	99.999%

4.2 Equipment

- **Tube furnace:** Carbolite Gero STF 16/180, max 1800 °C, programmable PID
- **Laser system:** Omicron LuxX 405 nm diode laser,
, to
, fiber-coupled, $1/e^2$ beam waist adjustable 5 μ m to 50 μ m
- **Thermal evaporator:** Kurt J. Lesker PVD 75, base pressure $< 5 \times 10^{-7}$
- **Probe station:** Cascade Microtech Summit 12000B, micropositioners with tungsten probes ($\phi = 10$ μ m)
- **Source-measure unit:** Keithley 2450, 200 V/1 A, 5.5-digit resolution
- **Environmental chamber:** ESPEC SH-242, temperature range -40 °C to 150 °C, humidity 10 % to 95 % RH

4.3 Sample Preparation Protocol

4.3.1 Step 1: Peanut Shell Carbonization (Pre-treatment)

1. Wash peanut shells in deionized water ($18.2 \Omega \cdot \text{cm}$), dry at 105 °C for 12 h.
2. Crush and sieve to $100 < \phi < 300$ μ m using ASTM E11 standard sieves.
3. Pyrolyze in tube furnace under 200 N₂ flow:
 - Ramp: 5 °C min⁻¹ to 400 °C
 - Dwell: 2 h at 400 °C
 - Cool: Natural cooling to < 100 °C under N₂
4. Characterize: XRD (002 peak broadening), Raman (I_D/I_G ratio), BET surface area.
5. Mill to $\phi < 50$ μ m using planetary ball mill (Retsch PM 100, 400, 30 min, zirconia jars).

4.3.2 Step 2: Electrode Fabrication

1. Clean glass substrates in piranha solution ($\text{H}_2\text{SO}_4:\text{H}_2\text{O}_2 = 3:1$) for 20 min, rinse with DI water, dry under N_2 .
2. Pattern photoresist (AZ 1512, $1.2\text{ }\mu\text{m}$) via UV lithography (365 nm , 15 mJ cm^{-2}) to define IDE geometry:
 - Finger width: $w = 10\text{ }\mu\text{m}$
 - Finger gap: $g = 10\text{ }\mu\text{m}$
 - Finger length: $L = 5\text{ mm}$
 - Number of finger pairs: $N = 100$
 - Total active area: $A = 1\text{ cm}^2$
3. Thermal evaporation:
 - Cr adhesion layer: 5 nm at 0.1 nm s^{-1}
 - Ag electrode: 100 nm at 0.5 nm s^{-1}
4. Lift-off in acetone (ultrasonic bath, 5 min).
5. Verify electrode continuity via four-point probe ($R_s < 0.5\text{ }\Omega$).

4.3.3 Step 3: Composite Deposition

1. Mix pre-carbonized peanut powder ($V_f = 15\%$) with EPON 828 resin using three-roll mill (EXAKT 80E, gap $25\text{ }\mu\text{m}$, 3 passes).
2. Degas under vacuum ($< 1\text{ mbar}$) for 30 min to remove trapped air.
3. Add TETA hardener (stoichiometric ratio 13 phr), mix for 2 min at 2000 (Thinky ARE-310 planetary mixer).
4. Cast onto IDE substrate using doctor blade (gap $100\text{ }\mu\text{m}$), ensuring complete coverage of inter-electrode gaps.
5. Cure: 24 h at $25\text{ }^\circ\text{C}$ + 2 h post-cure at $80\text{ }^\circ\text{C}$.
6. Verify composite thickness via profilometry (target: $50\text{ }\mu\text{m} \pm 5\text{ }\mu\text{m}$).

4.3.4 Step 4: Laser Writing (Encoding)

1. Mount sample on motorized XY stage (Aerotech ANT130, resolution 1 nm , repeatability 50 nm).
2. Align laser to IDE grid using machine vision (Basler acA2440-75um, 5 M).
3. Set laser parameters:
 - Wavelength: 405 nm
 - Power: 1000 mW (calibrated at sample plane)
 - Spot size ($1/e^2$): $10\text{ }\mu\text{m}$
 - Pulse duration: 100 ms per bit
 - Duty cycle: 10% (100 ms on, 900 ms off for thermal relaxation)
4. Write 100×100 bit array (10) with $100\text{ }\mu\text{m}$ pitch (1 cm^{-2}).
5. For each bit, verify write success by immediate resistance measurement (**verify-after-write**).

4.4 Readout Protocol

1. Apply read voltage $V_{\text{read}} = 0.1 \text{ V}$ (AC, 1 kHz) to minimize electrochemical degradation.
2. Measure current I via transimpedance amplifier (FEMTO DLPCA-200, gain 10^6 V/A , bandwidth 50 kHz).
3. Calculate bit resistance $R = V_{\text{read}}/I$.
4. Apply threshold:

$$\text{Bit value} = \begin{cases} 0 & \text{if } R > R_{\text{th,high}} = 10^6 \Omega \\ 1 & \text{if } R < R_{\text{th,low}} = 10^4 \Omega \\ \text{Error} & \text{otherwise} \end{cases} \quad (3)$$

5. Perform $N = 1000$ read cycles per bit, logging $R(t)$ for retention analysis.

5 Data Collection and Analysis

5.1 Primary Metrics

Table 2: Measured parameters and instrumentation

Metric	Symbol	Instrument	Resolution
Resistance	R	Keithley 2450	$10 \mu\Omega$
Bit Error Rate	BER	Custom Python script	10^{-6}
ON/OFF ratio	$R_{\text{OFF}}/R_{\text{ON}}$	Keithley 2450	5.5 digits
Retention time	t_{ret}	Environmental chamber + SMU	1 s
Read endurance	N_{read}	Automated probe station	1 cycle
Topography	z	Keyence VK-X1000 confocal	0.1 nm

5.2 Statistical Analysis

1. **Bit Error Rate:** $\text{BER} = \frac{\text{Number of erroneous bits}}{\text{Total bits} \times N_{\text{read}}}$
2. **Resistance distribution:** Fit log-normal distributions to ON- and OFF-state resistances; quantify overlap via Bhattacharyya distance.
3. **Retention:** Plot $R(t)$ vs. time; fit to stretched exponential $R(t) = R_0 \exp[-(t/\tau)^\beta]$ with $\beta = 0.5\text{--}1.0$.
4. **Endurance:** Monitor R_{ON} and R_{OFF} over $10^3\text{--}10^6$ read cycles; failure defined as ON/OFF ratio $< 10^2$.
5. **ANOVA:** One-way ANOVA on $\log_{10}(R)$ grouped by (i) laser power, (ii) pulse duration, (iii) carbonization temperature, with Tukey HSD post-hoc test ($\alpha = 0.05$).

Table 3: Project phases and deliverables

Phase	Deliverables	Duration	Budget (CAD)
Phase 1: Materials	Sourcing, characterization	2 weeks	\$1,200
Phase 2: Fabrication	IDE substrates, composite optimization	3 weeks	\$3,500
Phase 3: Integration	Laser alignment, write-verify protocol	2 weeks	\$2,000
Phase 4: Testing	BER, endurance, retention	4 weeks	\$1,500
Phase 5: Analysis	Data processing, manuscript	2 weeks	\$800
Total		13 weeks	\$9,000

Table 4: Risk factors and mitigation strategies

Risk	Impact	Mitigation
Incomplete carbonization	High BER, poor ON/OFF ratio	Verify via Raman $I_D/I_G < 1.0$ before integration
Laser-induced epoxy degradation	Delamination, void formation	Use pulse mode with thermal relaxation; verify via SEM
Electrode oxidation	Increased contact resistance	Store in N ₂ glovebox; Au capping if needed
Percolation variability	Non-uniform baseline conductivity	Pre-screen composites; reject if σ CV > 5%
Moisture ingress	Ionic conduction, false ON states	Hermetic epoxy overcoat; desiccant storage

6 Project Timeline and Budget

7 Risk Assessment and Mitigation

8 Safety Protocols

- **Laser Class 3B:** Enclose optical path in interlocked housing; wear OD 5+ goggles at 405 nm; post warning signs.
- **Pyrolysis:** Operate tube furnace in fume hood; monitor CO and VOC levels; maintain < 50 CO.
- **Epoxy handling:** Use nitrile gloves and organic vapor respirator; TETA is a skin sensitizer (H317).
- **Piranha solution:** Prepare in fume hood; add peroxide to acid slowly; quench with copious water after use.

9 Expected Outcomes and Future Work

9.1 Success Criteria

- BER $< 0.1\%$ at 1 cm^{-2}
- ON/OFF ratio $> 10^4$
- Retention > 10 years (extrapolated from 1000 h accelerated aging at $85^\circ\text{C}/85\% \text{ RH}$)
- Demonstration of 10 kbit stored image (e.g., Landry Industries logo)

9.2 Future Directions

1. **Multi-level cells (MLC):** Encode 2 bits per cell via 4 resistance levels using graded laser power.
2. **Biodegradable substrate:** Replace glass with cellulose nanofiber or polylactic acid (PLA) for fully compostable memory.
3. **Neuromorphic integration:** Exploit analog conductance modulation for synaptic weight storage in bio-inspired computing.

Data Availability

All raw data, analysis scripts, and fabrication logs will be deposited in the Landry Industries Open Science Repository (<https://osf.io/landryindustries>) upon manuscript acceptance.

Conflicts of Interest

The author is the founder and CEO of Landry Industries, which holds provisional patent applications on biomass-derived memory devices (USPTO 63/XXX,XXX).

References

- [1] Mercer, T. & Chen, L. Data Storage Energy Consumption and Environmental Impact. *Nature Sustainability*, 6(4), 412–420 (2023). <https://doi.org/10.1038/s41893-023-01045-2>
- [2] Wang, H., Zhang, D., Lu, Y., et al. Peanut Shell-Derived Porous Carbon for High-Performance Supercapacitors. *Journal of Materials Chemistry A*, 8(15), 7123–7135 (2020). <https://doi.org/10.1039/C9TA13942A>
- [3] Liu, X., Kumar, R., Zhang, X., et al. Peanut Shell-Derived Carbon for Conductive Polymer Composites. *Composites Part B: Engineering*, 207, 108588 (2021). <https://doi.org/10.1016/j.compositesb.2020.108588>
- [4] Guo, S., Zhang, C., Wang, W., et al. Percolation Threshold and Electrical Conductivity of Biomass Carbon/Polymer Composites. *Carbon*, 133, 712–720 (2018). <https://doi.org/10.1016/j.carbon.2018.03.057>
- [5] Wang, L., Park, Y., Ahn, J., et al. Organic Write-Once-Read-Many Memory Devices Based on Carbon Nanomaterials. *Advanced Electronic Materials*, 7(2), 2000891 (2021). <https://doi.org/10.1002/aelm.202000891>
- [6] Kim, S., Lee, J., Park, S., et al. Resistive Switching in Organic Memory Devices: Mechanisms and Materials. *Advanced Functional Materials*, 29(26), 1900050 (2019). <https://doi.org/10.1002/adfm.201900050>
- [7] Li, Y., Wang, Z., Xu, Y., et al. Biomass-Derived Carbon Materials for Energy Storage and Conversion. *Chemical Society Reviews*, 49(9), 2813–2856 (2020). <https://doi.org/10.1039/D0CS00054C>
- [8] Song, Y., Li, X., Mackin, C., et al. Laser-Induced Graphene from Biomass: Synthesis and Applications. *ACS Nano*, 13(6), 6223–6233 (2019). <https://doi.org/10.1021/acsnano.8b09671>
- [9] Feng, Q., Zhang, Y., Zhang, F., et al. Interdigitated Electrode Arrays for Organic Memory Devices. *Organic Electronics*, 78, 105569 (2020). <https://doi.org/10.1016/j.orgel.2019.105569>
- [10] Luo, J., Wang, H., Chen, Y., et al. Epoxy-Based Composites with Biomass Carbon Fillers: Thermal and Electrical Properties. *Polymer Testing*, 108, 107528 (2022). <https://doi.org/10.1016/j.polymertesting.2022.107528>