

Supplementary Materials

Thermally switchable gauge-factor bits for multilevel gain coding in reversible shape-memory strain sensor arrays

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Supplementary Table 1. Comparison of representative sensitivity-regulation strategies for flexible strain sensors and the GF-bit strategy developed in this work.

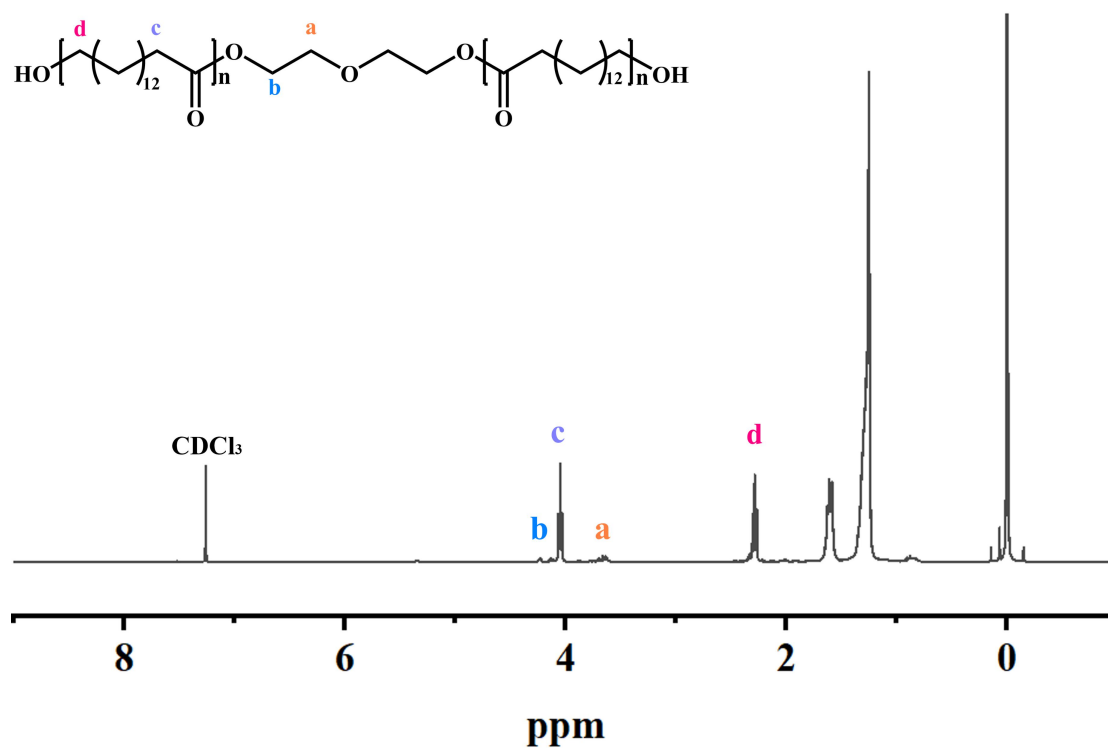
Strategy	Post-fabrication GF regulation	Mechanical reprogramming	Operation-stage switching	Discrete GF states / array coding	References
Conventional fixed-GF sensors	No	—	No	No / No	Refs. [1–3]
Post-tunable sensitivity sensors	Yes	Strategy-dependent	Limited	Usually no / ND	Refs. [4, 5]
Shape-reconfigurable sensors	Yes	Often required	Strategy-dependent	Usually no / ND	Ref. [6]
Mechanically programmed sensitivity	Yes	Yes	Limited	No / ND	Refs. [7, 8]
GF-bit system, this work	Yes	Not required during readout	Yes	Yes, binary 0/1 / Yes	This work

Note: The comparison is based on representative studies rather than an exhaustive survey of the field. “ND” denotes that the corresponding function was not demonstrated in the cited representative studies.

Supplementary Table 2. Recovery of the two GF states after thermomechanical reprogramming.

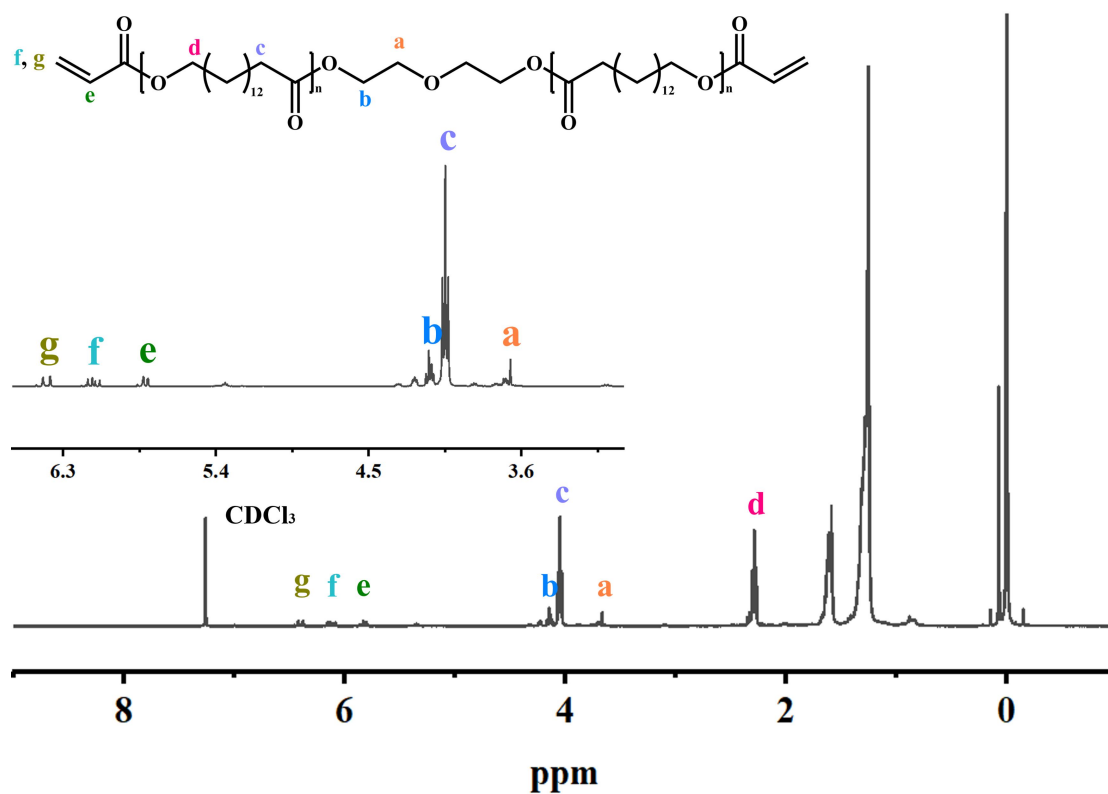
State	Initial programmed GF	GF after reset and reprogramming
Low-GF state (54 °C)	3.30	3.35
High-GF state (22 °C)	72.1	73.9
High-/low-GF contrast	≈21.8-fold	≈22.1-fold

The post-reprogramming GF values were measured immediately after one 140 °C erase-and-reprogram operation applied to a representative sensor following the 50-cycle evaluation.



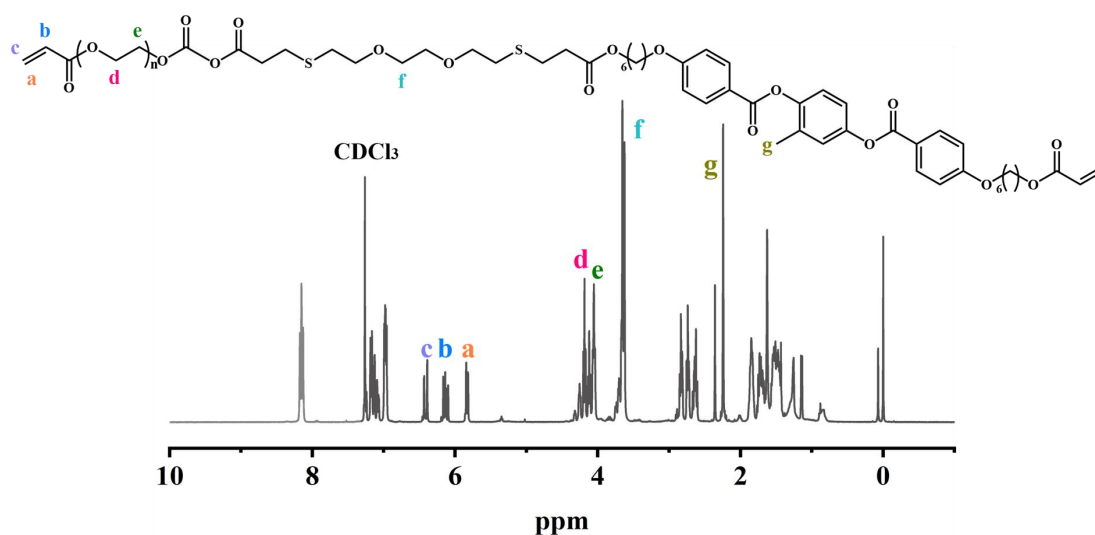
Supplementary Figure 1. ¹H NMR characterization of PPDL.

Chemical structure and ¹H NMR spectrum of poly(pentadecanolide) (PPDL) in CDCl₃. The characteristic proton resonances of the PPDL backbone are assigned as labeled in the spectrum.



Supplementary Figure 2. ¹H NMR characterization of PPDL-DA.

Chemical structure and ¹H NMR spectrum of poly(pentadecanolide) diacrylate (PPDL-DA) in CDCl₃. The labeled proton signals, including the terminal acrylate vinyl protons, verify the end-functionalization of PPDL.



Supplementary Figure 3. ^1H NMR spectrum of the liquid-crystalline oligomer.

Chemical structure and ^1H NMR spectrum of the liquid-crystalline oligomer (LCO) recorded in CDCl_3 . The labeled proton resonances correspond to the acrylate, aliphatic, ether, and aromatic segments in the LCO structure, confirming the formation of the designed liquid-crystalline oligomer.

Supplementary Note 1. Exact circuit model for the effective GF of coded GF-bit arrays

To quantitatively describe the electromechanical response of coded GF-bit arrays, an exact circuit model was established based on the measured initial resistance, local GF state, and electrical connection topology of the constituent sensing units. The following expressions were derived in this work from the conventional definition of gauge factor^[9–11] and standard series/parallel circuit relations.

In the GF-bit array, each sensing unit can be thermally addressed into either a low-GF or a high-GF state. The array-level response therefore depends not only on the GF state of each unit but also on its initial resistance and electrical connection topology. For quantitative comparison with experiment, the exact strain-dependent array resistance was calculated over the same 0–10% strain range used experimentally, and the calculated effective GF was obtained from the slope of the corresponding $\Delta R_{\text{array}}/R_{\text{array},0}$ –strain curve using the same origin-constrained linear-fitting procedure as for the experimental data.

S1.1 Unit-level resistance response

For an individual GF-bit unit (i,j), the resistance under an applied tensile strain ε can be written as

$$R_{ij}(\varepsilon) = R_{ij,0}(1 + \text{GF}_{ij}\varepsilon)$$

where $R_{ij,0}$ is the initial resistance of unit (i,j), GF_{ij} is the gauge factor of this unit, and ε is the applied strain. Here, GF_{ij} can take either a low-GF or high-GF value depending on the thermal state of the unit.

The relative resistance change of a single unit is therefore

$$\frac{\Delta R_{ij}}{R_{ij,0}} = \frac{R_{ij}(\varepsilon) - R_{ij,0}}{R_{ij,0}} = \text{GF}_{ij}\varepsilon$$

and the unit GF is defined as

$$GF_{ij} = \frac{\Delta R_{ij}/R_{ij,0}}{\varepsilon}$$

The individual sensing units exhibit an approximately linear $\Delta R/R_0$ –strain response over the experimentally selected 0–10% strain range. Accordingly, the fitted unit-level GF is used in the following circuit calculation over the same strain interval.

S1.2 Series-connected branch model

For a branch j containing three GF-bit units connected in series, the total branch resistance is the sum of the resistance of each unit:

$$R_j^{\text{branch}}(\varepsilon) = \sum_{i=1}^3 R_{ij}(\varepsilon)$$

Substituting the unit-level resistance response gives

$$\begin{aligned} R_j^{\text{branch}}(\varepsilon) &= \sum_{i=1}^3 R_{ij,0} (1 + GF_{ij} \varepsilon) \\ &= \sum_{i=1}^3 R_{ij,0} + \varepsilon \sum_{i=1}^3 R_{ij,0} GF_{ij} \end{aligned}$$

The initial resistance of branch j is

$$R_{j,0}^{\text{branch}} = \sum_{i=1}^3 R_{ij,0}$$

Therefore, the branch resistance change is

$$\Delta R_j^{\text{branch}} = R_j^{\text{branch}}(\varepsilon) - R_{j,0}^{\text{branch}} = \varepsilon \sum_{i=1}^3 R_{ij,0} GF_{ij}$$

The relative resistance change of branch j is then

$$\frac{\Delta R_j^{\text{branch}}}{R_{j,0}^{\text{branch}}} = \frac{\varepsilon \sum_{i=1}^3 R_{ij,0} GF_{ij}}{\sum_{i=1}^3 R_{ij,0}}$$

Accordingly, the effective GF of branch j is

$$GF_j^{\text{branch}} = \frac{\Delta R_j^{\text{branch}} / R_{j,0}^{\text{branch}}}{\varepsilon} = \frac{\sum_{i=1}^3 R_{ij,0} GF_{ij}}{\sum_{i=1}^3 R_{ij,0}}$$

This equation indicates that the GF of a series-connected branch is a resistance-weighted average of the GF values of the individual units. Because the constituent unit responses are treated as linear over 0–10% strain, the series-branch response remains linear over this interval.

S1.3 Exact parallel-branch model for the 3×3 array

For the 3×3 GF-bit array, each row is treated as a series-connected branch, and the three branches are connected in parallel. The initial resistance and conductance of branch j are

$$R_j^{\text{branch}} = \sum_{i=1}^3 R_{ij,0}$$

and

$$G_{j,0} = \frac{1}{R_{j,0}^{\text{branch}}}$$

Based on the series-branch result derived above, the resistance of branch under an applied strain ε is

$$R_j^{\text{branch}}(\varepsilon) = R_{j,0}^{\text{branch}}(1 + GF_j^{\text{branch}} \varepsilon)$$

Therefore, the exact conductance of branch j is

$$G_j(\varepsilon) = \frac{1}{R_j^{\text{branch}}(\varepsilon)} = \frac{G_{j,0}}{1 + GF_j^{\text{branch}} \varepsilon}$$

Because the three branches are connected in parallel, the total strain-dependent resistance of the 3×3 array is

$$R_{\text{array}}(\varepsilon) = \left[\sum_{j=1}^3 \frac{G_{j,0}}{(1 + GF_j^{\text{branch}} \varepsilon)} \right]^{-1}$$

At zero strain,

$$R_{\text{array},0} = \left(\sum_{j=1}^3 G_{j,0} \right)^{-1}$$

The exact relative resistance change of the array can therefore be expressed as

$$\frac{\Delta R_{\text{array}}}{R_{\text{array},0}} = \frac{\sum_{j=1}^3 G_{j,0}}{\sum_{j=1}^3 \frac{G_{j,0}}{(1 + GF_j^{\text{branch}} \varepsilon)}} - 1$$

This expression is evaluated directly without applying a first-order expansion. Because the parallel-connected array response can become nonlinear at finite strain even when the constituent sensing units exhibit approximately linear responses, a strain-independent closed-form effective GF is not imposed on the array response.

For quantitative comparison with experiment, $R_{\text{array}}(\varepsilon)$ and $\Delta R_{\text{array}}/R_{\text{array},0}$ were calculated over the same 0–10% strain range used experimentally. The calculated effective GF was then obtained from the slope of an origin-constrained linear fit to the calculated $\Delta R_{\text{array}}/R_{\text{array},0}$ –strain response over 0–10% strain.

$$GF_{\text{eff}}^{\text{calc}} = \text{slope} \left[\frac{\Delta R_{\text{array}}}{R_{\text{array},0}} \text{ vs. } \varepsilon \right]_{\varepsilon=0-0.10}$$

S1.4 General expressions for series- and parallel-connected arrays

For a purely series-connected array containing n sensing units, the total strain-dependent resistance is

$$R_{\text{series}}(\varepsilon) = \sum_{i=1}^n R_{i,0} (1 + GF_i \varepsilon)$$

Therefore, the effective GF of the series-connected array is exactly

$$GF_{\text{series}} = \frac{\sum_{i=1}^n R_{i,0} GF_i}{\sum_{i=1}^n R_{i,0}}$$

For a purely parallel-connected array containing n sensing branches, the exact strain-dependent resistance is

$$R_{\text{parallel}}(\varepsilon) = \left[\sum_{i=1}^n \frac{1}{R_{i,0}(1 + GF_i \varepsilon)} \right]^{-1}$$

or equivalently,

$$R_{\text{parallel}}(\varepsilon) = \left[\sum_{i=1}^n \frac{G_{i,0}}{(1 + GF_i \varepsilon)} \right]^{-1},$$

where

$$G_{i,0} = \frac{1}{R_{i,0}}$$

The corresponding exact normalized resistance response is

$$\frac{\Delta R_{\text{parallel}}}{R_{\text{parallel},0}} = \frac{\sum_{j=1}^n G_{j,0}}{\sum_{j=1}^n \frac{G_{j,0}}{(1 + GF_j \varepsilon)}} - 1$$

In contrast to the series case, this parallel response is generally nonlinear at finite strain. Therefore, the calculated effective GF of a parallel-connected array is obtained from the slope of an origin-constrained linear fit to the exact normalized resistance response over the same 0–10% strain range used experimentally.

S1.5 Near-zero-strain limit and ideal equal-resistance approximation

Although the exact finite-strain expressions described above were used for all quantitative calculations, a simplified analytical relation can be obtained in the differential limit of $\varepsilon \rightarrow 0$. Differentiating the exact parallel-array response at zero strain gives

$$GF_{eff}^0 = \frac{d}{d\varepsilon} \left(\frac{\Delta R_{array}}{R_{array,0}} \right) \bigg|_{\varepsilon=0} = \frac{\sum_j G_{j,0} GF_j^{branch}}{\sum_j G_{j,0}}$$

Thus, the conductance-weighted GF expression represents the differential or near-zero-strain limit of the exact circuit response, rather than the finite-strain effective GF over the experimental 0–10% interval.

If the initial resistance of all GF-bit units is approximately identical, namely

$$R_{high,0} \approx R_{low,0}$$

then the resistance-weighted and conductance-weighted expressions can be simplified. Under this ideal equal-resistance condition, the effective GF mainly depends on the fraction of high-GF units in the array:

$$GF_{eff} = (1 - f_{high})GF_{low} + f_{high}GF_{high}$$

where

$$f_{high} = \frac{N_{high}}{N_{total}}$$

Here, N_{high} is the number of high-GF units, and N_{total} is the total number of sensing units in the array.

For an ideal equal-resistance illustration, the low-GF and high-GF values can be represented by GF_{low} and GF_{high} , respectively.

$$GF_{low} = 3.3$$

$$GF_{high} = 72.1$$

Thus,

$$\begin{aligned} GF_{eff} &= 3.3 + (72.1 - 3.3)f_{high} \\ &= 3.3 + 68.8f_{high} \end{aligned}$$

This simplified relation is included only as an intuitive design rule for the dependence of effective GF on the high-GF fraction and is not used for the quantitative calculations

in Figure 4G; those values are obtained from the exact finite-strain circuit response over 0–10% strain.

S1.6 Model assumptions and sources of deviation

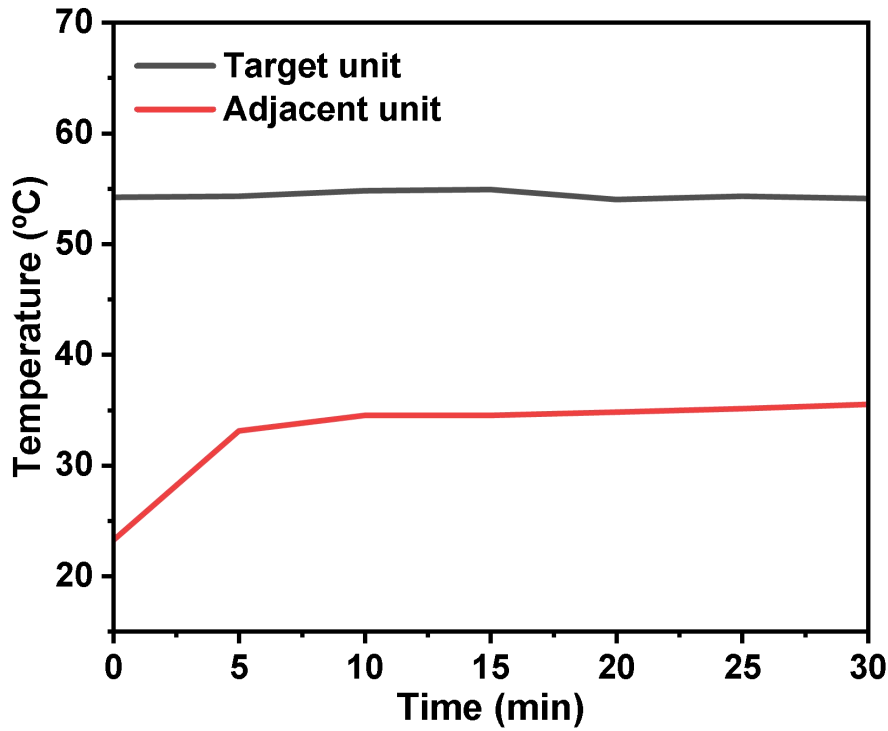
The exact circuit model calculates the strain-dependent electrical response of the coded array from the measured initial resistance, fitted GF state, and electrical connection topology of the constituent sensing units. For quantitative comparison with experiment, the calculated array response is evaluated over the same 0–10% strain interval used experimentally, and the calculated effective GF is extracted using the same origin-constrained linear-fitting procedure as used for the experimental data.

The model assumes that:

- (i) each individual GF-bit unit exhibits an approximately linear $\Delta R/R_0$ –strain response over the selected 0–10% strain range;
- (ii) the fitted unit-level GF and initial resistance are representative of the unit during array operation;
- (iii) the applied deformation is transferred reproducibly to the sensing units; and
- (iv) electrode and interconnect resistances remain sufficiently stable during measurement.

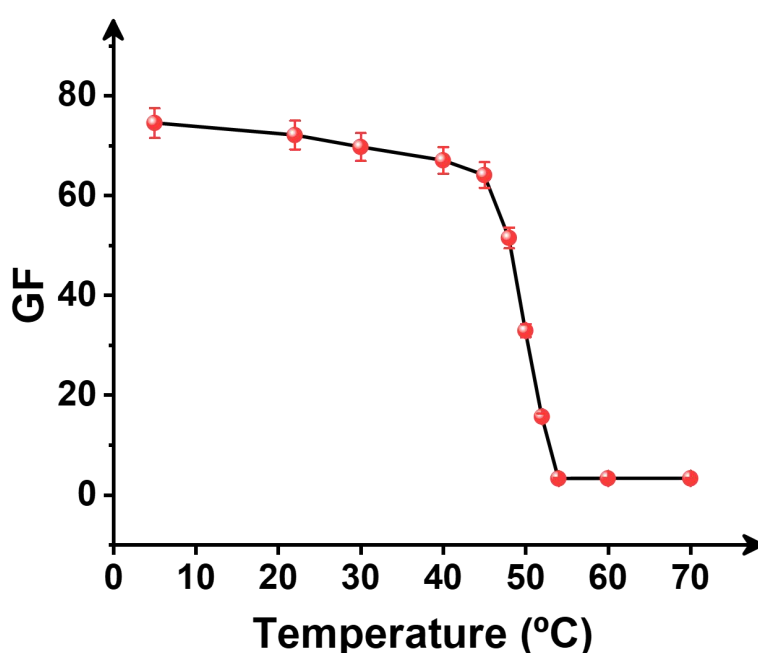
Deviations between calculated and measured effective GF values can arise from unit-to-unit resistance variation, electrode/contact resistance, nonuniform strain transfer, current redistribution among parallel branches, local thermal gradients, incomplete thermal switching, and thermal crosstalk between neighboring GF-bit units.

The exact circuit model is therefore intended to rationalize the array-level electrical response using experimentally measurable unit-level parameters while preserving the finite-strain response of the parallel network.

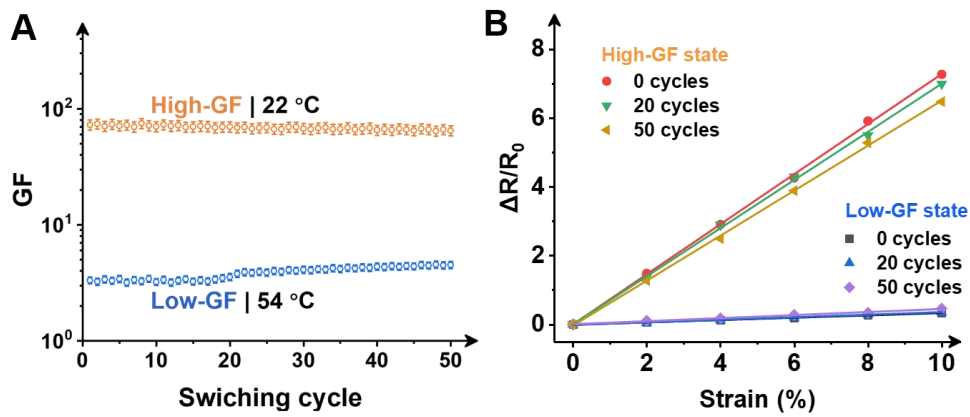


Supplementary Figure 4. Thermal-crosstalk characterization between neighboring GF-bit units. In a separate extended local-heating test, the directly irradiated target unit was maintained at approximately 54 °C for 30 min, while the temperature of the nearest adjacent unit sharing a common edge with the target unit was monitored. The adjacent-unit temperature increased from room temperature but remained below the experimentally identified principal GF-switching region. This 30-min crosstalk test was conducted separately from the approximately 43 s required for the active sensing layer to first reach 54 °C during the routine IR-heating experiment.

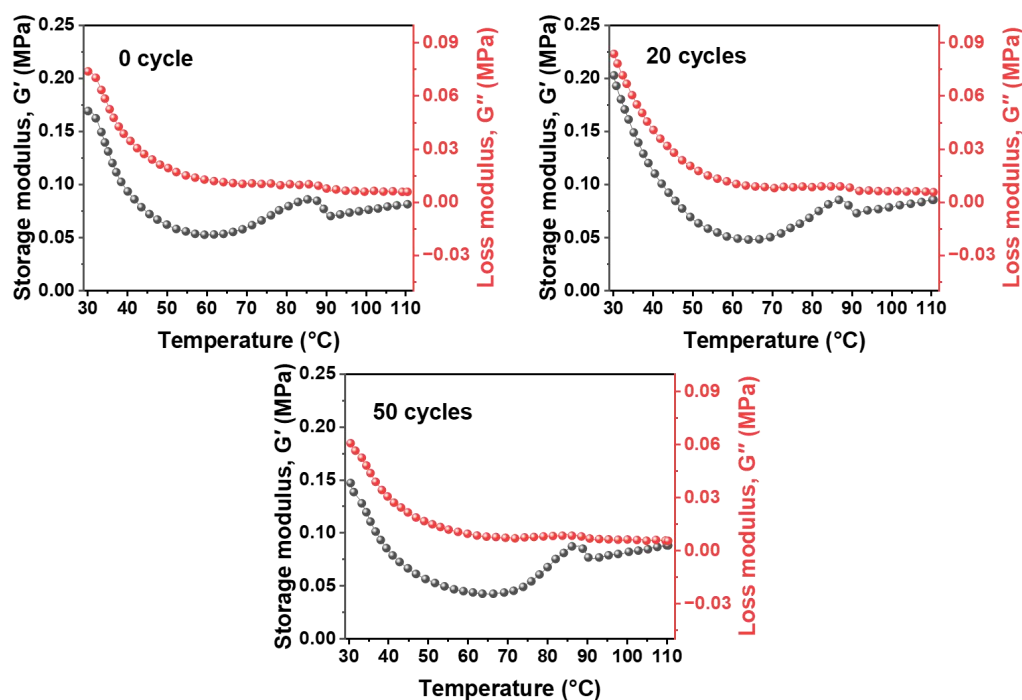
The modest decrease in GF below the principal switching region is consistent with progressive temperature-dependent changes reported in related responsive material systems. In liquid-crystalline elastomers, the nematic order parameter and the associated strain can evolve continuously with temperature rather than changing only at a single sharp transition.^[12] In conductive polymer nanocomposites, temperature can also modify electrical transport and piezoresistive sensitivity through changes in the conductive/percolative network.^[13] These coupled effects provide a plausible basis for the gradual GF variation observed below approximately 45 °C.



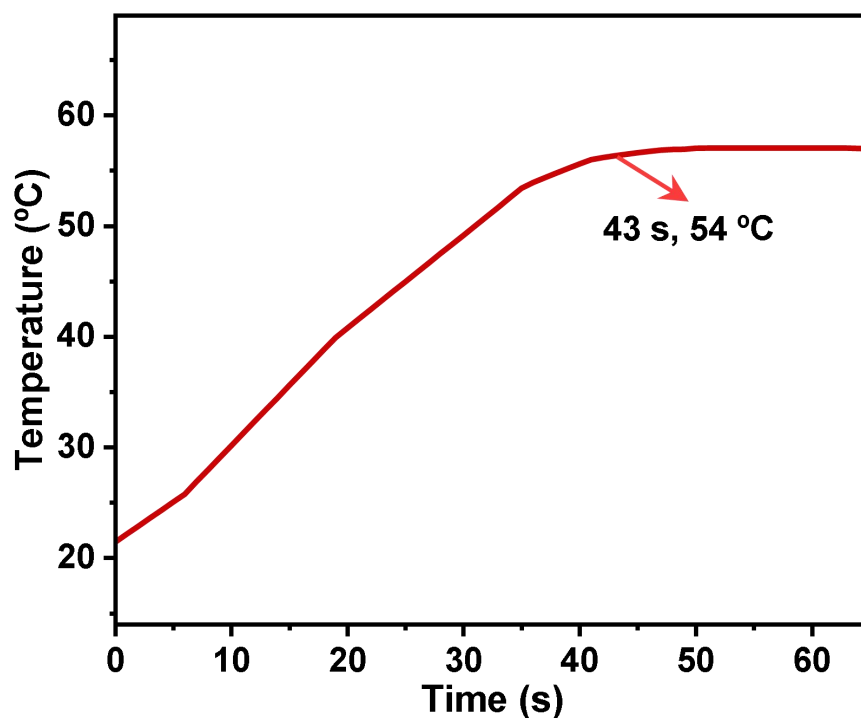
Supplementary Figure 5. Temperature dependence of the gauge factor of the rSMP/CB sensor. GF values were measured from 5 to 70 °C, with denser temperature sampling around the principal switching region. The sensor remained in a high-GF regime over the tested range of 5–45 °C, although a modest decrease in GF was observed with increasing temperature. A substantially steeper decrease occurred over approximately 45–54 °C, identifying this interval as the principal GF-switching region. A low-GF plateau was observed over the tested range of 54–70 °C. The 22 and 54 °C conditions represent the selected high- and low-GF readout temperatures, respectively. Data are presented as mean $\pm$ SD from three independently prepared sensors ($n = 3$).



Supplementary Figure 6. Electromechanical response retention and GF-state evolution of the rSMP/CB GF-bit sensor over 50 thermal switching cycles. (A) GF values measured during repeated switching between the high-GF state at 22 °C and the low-GF state at 54 °C. The two measured GF-state ranges remained nonoverlapping over the tested 50-cycle interval, although a modest downward shift of the high-GF state and a small upward shift of the low-GF state were observed during the later cycles. Data are presented as mean $\pm$ SD from three independently prepared sensors ($n = 3$). (B) Representative $\Delta R/R_0$ –strain responses of the high- and low-GF states before thermal cycling and after 20 and 50 heating–cooling cycles. The symbols represent experimental data, and the solid lines represent origin-constrained linear fits over the 0–10% strain range. Both states retained measurable and approximately linear electromechanical responses after 50 cycles, while the cycle-dependent changes in slope were consistent with the corresponding GF evolution shown in (A). The response slopes of the high- and low-GF states remained clearly distinguishable after 50 cycles.

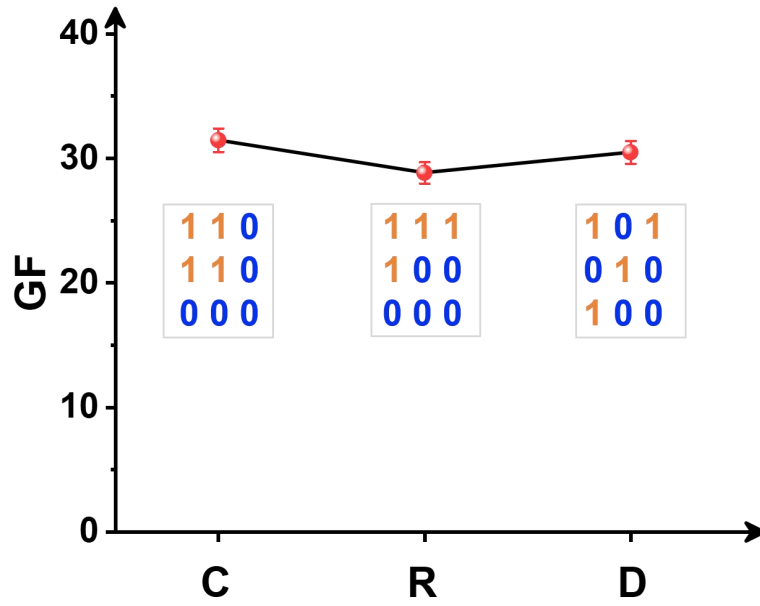


Supplementary Figure 7. Temperature-sweep rheological response of rSMP/CB specimens after different prior thermal switching histories. Storage modulus (G') and loss modulus (G'') were measured during heating from approximately 30 to 110 °C for specimens subjected to 0, 20, and 50 prior GF-switching cycles between 22 and 54 °C. The three profiles exhibited broadly comparable temperature-dependent G' and G'' evolution over the investigated heating range, suggesting that the characteristic bulk viscoelastic response was retained after the tested switching histories. Each profile was obtained from a separately preconditioned specimen measured under identical conditions.



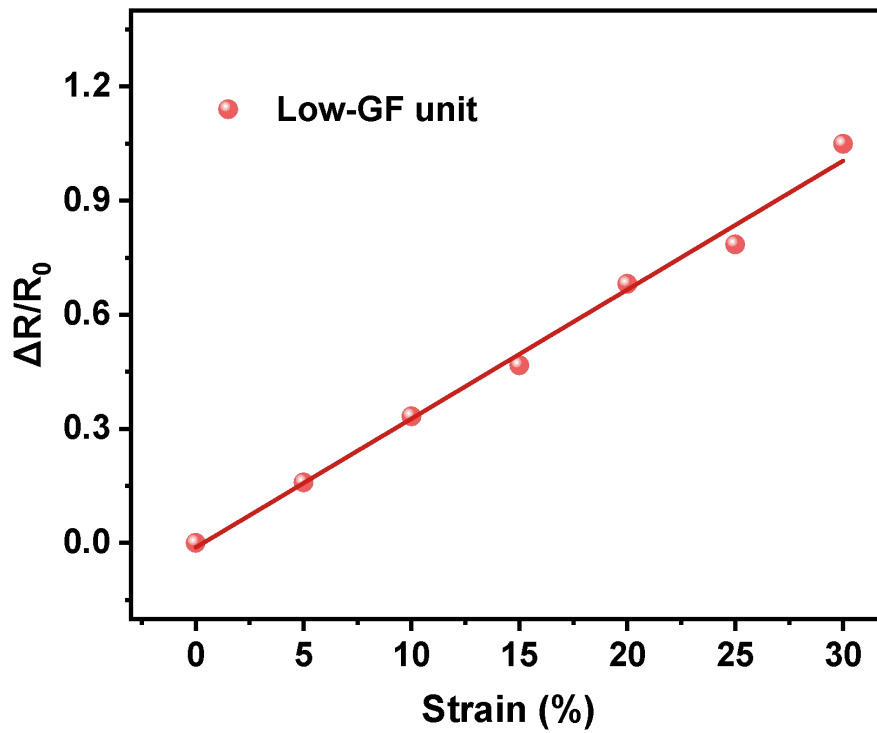
Supplementary Figure 8. Temperature evolution of the rSMP/CB sensing layer during IR photothermal heating.

Under IR irradiation, the local sensor-layer temperature increased from room temperature to approximately 54 °C within 43 s and subsequently stabilized. This temperature plateau corresponds to the representative low-GF readout condition used in this study and maintains the sensor in the low-GF state.



Supplementary Figure 9. Effect of spatial GF-bit distribution at a fixed high-GF fraction.

Effective GF values of 3×3 GF-bit arrays with the same high-GF fraction ($f_{\text{high}} = 4/9$) but different spatial arrangements. C, R, and D denote clustered, row-concentrated, and dispersed distributions, respectively. Orange and blue numbers represent high-GF (1) and low-GF (0) units, respectively. The three layouts exhibit only small differences in effective GF, indicating that the high-GF fraction is the primary determinant of the array-level gain, while spatial arrangement provides a secondary contribution. Data are presented as mean $\pm$ SD ($n = 3$ independently prepared arrays).



Supplementary Figure 10. Strain response of a low-GF unit over an extended strain range.

Relative resistance change of a representative low-GF sensing unit under tensile strain from 0 to 30%. The low-GF state maintains a low but stable resistance response over the tested strain range, supporting its use for stronger-input or larger-deformation readout.

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