Cold-Blooded Circuits: Transient Electronics that Require Constant Heat Input to Prevent Dissolution

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The majority of electronics are used for applications that exploit the invariance of the materials used to form the circuitry. Recently, however, there has been a push to expand electronic architectures to include materials that can be easily induced to disintegrate and vanish. Current efforts in the field of transient electronics have demonstrated silicon-based microelectronic circuits that dissolve in aqueous solutions with predetermined timeframes. These systems are promising in many applications, such as therapeutic systems, secure "self-destructing" electronics that may contain classified or other high value information, or zero-waste vanishing environmental sensors.[1] There are applications, however, that may require more sophisticated mechanisms for transience. To produce novel circuitry that requires constant heat input to *prevent* irreversible dissolution and loss of function, we have combined thermoresponsive polymers that exhibit a lower critical solution temperature (LCST) behavior with patterned conductive nanowire networks.[2]

To form conductive traces, we use a patterned parylene mask to pattern networks of silver nanowires at densities above the percolation threshold. We then spin-coat the LCST polymer (e.g. methylcellulose) over the nanowire networks. Upon drying, the polymer film (with embedded nanowires) can be peeled off and serves as the circuit's substrate. Figure 1 illustrates this fabrication process.

When the thermoresponsive transient circuit is placed in a warm water bath above the LCST, the polymer remains hydrophobic and holds the nanowire networks together, enabling an electrically conductive path (Figure 2A). Upon cooling below the LCST, the polymer quickly becomes hydrophilic and dissolves, releasing the nanowires into solution and destroying the conductive path. By patterning electrodes on both sides of the polymer film, a transient capacitor can be formed (Figure 2B). Thus, by forming a composite of conductive nanowires and thermoresponsive polymer binder, we are able to achieve a unique transient circuit that requires heat input to prevent irreversible disintegration. Such systems have potential for use in applications such implantable circuitry that dissolves upon loss of life or removal from host tissue.

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[1] S.-W. Hwang, H. Tao, D.-H. Kim, H. Cheng, J.-K. Song, E. Rill, M. A. Brenckle, B. Panilaitis, S. M. Won, Y.-S. Kim, Y. M. Song, K. J. Yu, A. Ameen, R. Li, Y. Su, M. Yang, D. L. Kaplan, M. R. Zakin, M. J. Slepian, Y. Huang, F. G. Omenetto, and J. A. Rogers, Science **337**, 1640 (2012).

[2] X. Zhang and L. M. Bellan, ACS Appl. Mater. Interfaces **9**, 21991 (2017).

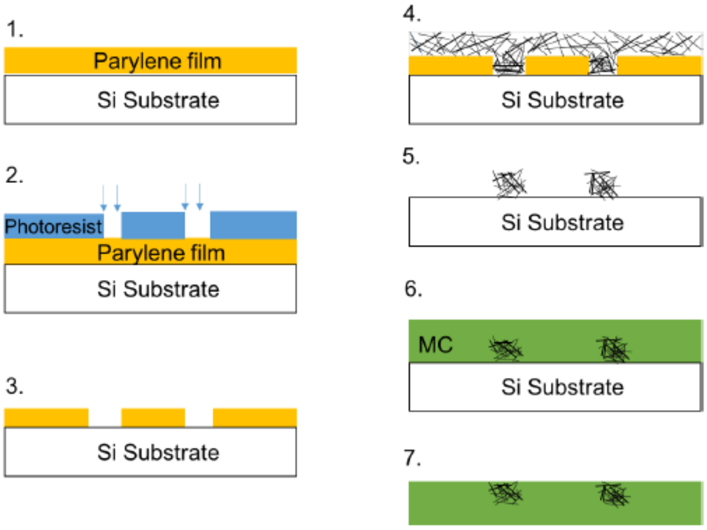

Figure 1: Illustration of fabrication steps. (1) Parylene is deposited onto a silicon wafer, (2) patterned with photoresist, and (3) etched to open windows. (4) A solution of silver nanowires is spun onto the patterned parylene and allowed to dry. (5) The parylene is removed, leaving the patterned network of nanowires. (6) An LCST polymer (methylcellulose, in this case) is spun onto the nanowires and allowed to dry. (7) The nanowire-embedded polymer film is peeled off the wafer.

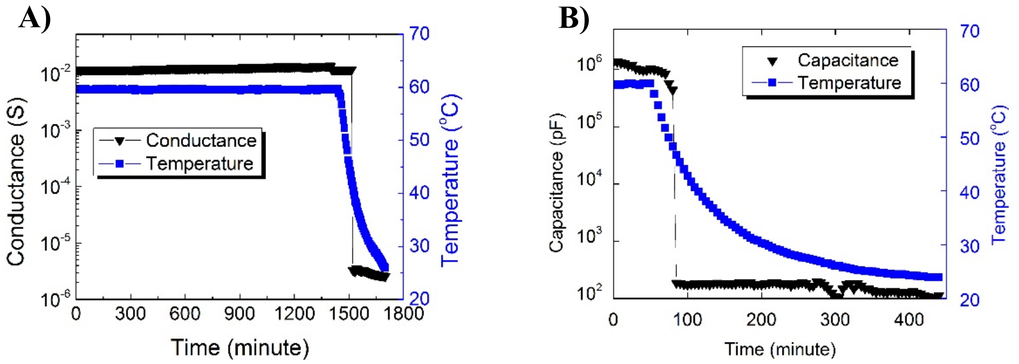

Figure 2. Transient response of (A) a conductive trace and (B) a capacitor. Devices are placed in a water bath at a temperature above the LCST (~45 °C for methylcellulose). (A) Measurements indicate that the conductivity of the nanowire network is stable for at least 24 hours in the warm bath. When the heater is turned off, the bath starts to cool. Upon cooling below the LCST, the polymeric binder dissolves and the nanowire network disintegrates, resulting in a dramatic loss of conductivity. (B) In the case of the capacitor, the disintegration of the electrodes results in dramatic loss of capacitance.