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A Physically Transient Form of Silicon Electronics, With Integrated Sensors, Actuators and Power Supply

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Abstract

A remarkable feature of modern silicon electronics is its ability to remain functionally and physically invariant, almost indefinitely for many practical purposes. Here, we introduce a silicon-based technology that offers the opposite behavior: it gradually vanishes over time, in a well-controlled, programmed manner. Devices that are ‘transient’ in this sense create application possibilities that cannot be addressed with conventional electronics, such as active implants that exist for medically useful timeframes, but then completely dissolve and disappear via resorption by the body. We report a comprehensive set of materials, manufacturing schemes, device components and theoretical design tools for a complementary metal oxide semiconductor (CMOS) electronics of this type, together with four different classes of sensors and actuators in addressable

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arrays, two options for power supply and a wireless control strategy. A transient silicon device capable of delivering thermal therapy in an implantable mode and its demonstration in animal models illustrate a system-level example of this technology.

An overarching goal in the development of nearly any new class of electronics is to achieve high performance operation in physical forms that undergo negligible change with time. Active and passive materials, device and circuit layouts and packaging strategies are each carefully formulated individually and then configured collectively to accomplish this outcome. The transient electronics technology introduced here involves similar attention to engineering design, but in the context of systems that physically disappear, in whole or in part, at prescribed times and with well-defined rates. Use scenarios range from integration with living hosts (human/animal/insect/plant; on-dwelling or in-dwelling) to indoor/outdoor environments such as buildings, roadways or materiel. Enabled devices include medical monitors that fully resorb when implanted into the human body (“bio-resorbable”) to avoid adverse long-term effects, or communications systems that dissolve when exposed to water (“eco-resorbable”) to prevent unwanted discovery. Other concepts involve circuits that incorporate strategic regions with timed transience, to affect controlled transformation in function.

In this following, we present (1) a complete collection of transient electronic building blocks, including n- and p-channel silicon nanomembrane (NM) metal oxide field effect transistors (MOSFETs), and their integration into circuits that disappear or functionally transform, (2) sensors of light, temperature and strain, each of which uses functional materials and formats common to those for the electronics, (3) photovoltaic and inductive devices for power supply, (4) experimentally validated, analytical models of transience, suitable as design tools for engineered behaviours and (5) integrated examples in wirelessly controlled, bio-resorbable devices that provide thermal therapy in an implantable form. Because this technology is based on silicon, it can exploit many modern, established aspects of device and circuit design, with operational characteristics that can match those of non-transient counterparts formed in the usual way on wafer substrates. This result, taken together with supporting technologies in sensors, power supply and wireless control, provides access to qualitatively more sophisticated capabilities than those available with recently reported forms of organic electronics in which certain constituent materials are water soluble [1–3] or simple non-transient transistors formed on bio-resorbable substrates [4].

Figure 1a, b and S1 provide images and schematic diagrams of a demonstration platform for the technology. All of the components shown here, ranging from the inductors, capacitors, resistors, diodes, transistors, interconnects and crossovers, to the substrate and encapsulation layers disappear completely, through reactive dissolution by hydrolysis, as illustrated in the time sequence of images in Fig. 1c. This example of transient electronics uses magnesium (Mg) for the conductors, magnesium oxide (MgO) and silicon dioxide (SiO₂) for the dielectrics, monocrystalline silicon (Si) NMs for the semiconductors, and silk (not only water soluble but also enzymatically degradable [4, 5]), for the substrate and packaging material. The fabrication involves a combination of transfer printing (Si NMs), physical vapour deposition through fine-line stencil masks (Mg, MgO, SiO₂) and solution casting (silk). (See Methods and SI for details. In some cases, we used minute amounts of titanium to promote adhesion of Mg. Device fabrication was possible without this layer, although with somewhat lower yields in certain cases.)

The chemical reactions responsible for dissolution of each material appear in Fig. 1d. The Si NMs and layers of SiO₂ are particularly important, due to their essential roles in high performance transistors, diodes, photodetectors, solar cells, temperature sensors, strain

gauges and other semiconductor devices, as described subsequently. For both, hydrolysis forms ortho-silicic acid ($\text{Si}(\text{OH})_4$), whose water solubility is ~ 0.10 g/L at room temperature, as determined from studies of nanoporous silicon bodies [6–8]. The NM geometry is important because it enables high performance devices and planar architectures, minimizes the amount of material that must be consumed during the transient step, and provides mechanics and processing options that are favourable for heterogeneous integration onto substrates such as silk [4]. The second characteristic allows access to high rates of transience while avoiding solubility limits and potentially adverse biological responses, for applications where bio-compatibility is important. A typical transistor described here involves less than ~ 1 μg of Si, which can be dissolved as $\text{Si}(\text{OH})_4$ in as little as 30 μL of water (or bio-fluid) [8]. Straightforward reductions in the dimensions of the devices could decrease even further the required amount of Si. For example, the mass of Si in the active region of a conventional MOSFET built on an ultrathin silicon-on-insulator wafer is ~ 10 fg, which corresponds to solubility in as little as ~ 300 fL [9].

Figure 2a presents atomic force micrographs of a Si NM (3×3 μm) with thickness of 70 nm, collected at different stages of dissolution in phosphate buffer solution (PBS; pH of 7.4) at a physiologically relevant temperature (37 °C), to simulate transience by bio-resorption (See Fig. S2 for different thicknesses of Si NM). The kinetics can be captured analytically using models of reactive diffusion (Fig. 2b; SI for details) [10–12] in which the rate limiting step is defined by diffusion of water and hydroxyl ions into the Si and reaction throughout the

thickness direction y , according to $D \frac{\partial^2 w}{\partial y^2} - kw = \frac{\partial w}{\partial t}$ [13–15], where D and k are the diffusivity for water and the reaction constant between silicon and PBS, respectively, and w is the concentration of water. Upon dissolution, the following equilibrium is formulated: $\text{Si} + 4\text{H}_2\text{O} \leftrightarrow \text{Si}(\text{OH})_4 + 2\text{H}_2$, where the neutral silicic acid leaves the silicon surface by diffusion. In this model, the thickness of the Si NM (h), normalized by its initial thickness (h_0), depends on the normalized time Dt/h_0^2 and reaction constant kh_0^2/D according to

$$\frac{h}{h_0} = f\left(\frac{Dt}{h_0^2}, \frac{kh_0^2}{D}, \frac{w_0}{\rho_{\text{Si}}}\right) = 1 - \frac{w_0 A_r(\text{Si})}{4\rho_{\text{Si}} A_r(\text{water})} \frac{kh_0^2}{D} \left[\frac{Dt}{h_0^2} \cdot \frac{\tanh \sqrt{\frac{kh_0^2}{D}}}{\sqrt{\frac{kh_0^2}{D}}} - 2 \sum_{n=1}^{\infty} \frac{1 - e^{-\frac{Dt}{h_0^2} \left[\frac{kh_0^2}{D} + \left(n - \frac{1}{2}\right)^2 \pi^2 \right]}}{\left[\frac{kh_0^2}{D} + \left(n - \frac{1}{2}\right)^2 \pi^2 \right]^2} \right], \quad (1)$$

where $A_r(\text{water})$ and $A_r(\text{Si})$ are the respective atomic weights, w_0 is the initial water concentration, and $\rho_{\text{Si}} = 2.329$ g/cm³ is the mass density of Si. This expression captures the experimental observations for $h_0 = 35, 70$ and 100 nm at body temperature (37 °C) (Fig. 2c) for $k = 5.0 \times 10^{-6}$ s⁻¹ and $D = 4.5 \times 10^{-16}$ cm²/s and at room temperature (25 °C, Fig. S3a) when $k = 2.8 \times 10^{-6}$ s⁻¹ and $D = 3.4 \times 10^{-16}$ cm²/s, consistent with Arrhenius scaling. The critical time for the thickness to reach zero is approximately given by (see SI for details)

$$t_c = \frac{4\rho_{\text{Si}} A_r(\text{water})}{k w_0 A_r(\text{Si})} \frac{\sqrt{\frac{kh_0^2}{D}}}{\tanh \sqrt{\frac{kh_0^2}{D}}}. \quad (2)$$

The results are $t = 14, 16$, and 19 days for $h_0 = 35, 70$ and 100 nm, respectively, at body temperature, consistent with experiment.

Similar calculations quantitatively capture related behaviours in other materials for transient electronics, including those in Fig. 1 (See SI for other examples). Figure 2d presents an example of a meander trace of Mg (150 nm) on a thin film of MgO (10 nm; adhesion promoter), in which the measured changes in resistance correlate well to those expected

based on computed changes in thickness (Fig. 2e, Fig. S4a and b, and see SI for details), where the resistance is given by $R_0 \times (h/h_0)^{-1}$, and R_0 is the initial resistance. (Other examples appear in Fig. S5.) This result connects a key electrical property to models of reactive diffusion, thereby suggesting the capacity to use such analytics in conjunction with established circuit simulators as a comprehensive design approach for transient electronics.

The predictive use of these models highlights the importance of NMs and thin film device designs. In particular, the time for hydrolytic dissolution of a piece of silicon with dimensions comparable to those of a diced integrated circuit ($\sim 12 \text{ mm} \times \sim 12 \text{ mm} \times \sim 700 \text{ }\mu\text{m}$) is estimated to be more than ~ 600 years, and would require nearly $\sim 8 \text{ L}$ of water to avoid solubility limits [8]. By comparison, the dissolution time for a Si NM with similar lateral dimensions and a thickness of 35 nm is less than ~ 10 days, and can occur in as little as $\sim 0.4 \text{ mL}$ of water. The timescales for NM-based electronic components can be extended, in controlled amounts, by adding transient encapsulating layers and packaging materials; they can be reduced by decreasing the critical dimensions or by physically structuring the materials in a way that accelerates dissolution by disintegration (Fig. S6). Figure 2e and S4 show results of measured transience in a serpentine resistor of Mg, encapsulated with different thicknesses of MgO, and with combinations of MgO and overcoats of silk. Corresponding modeling results are also shown (See SI for details), all of which agree well with experiments and general expectation. Silk is attractive for this purpose because its solubility in water can be programmed, over several orders of magnitude, through control of crystallinity [5, 16]. Other biodegradable polymers can also be used, as shown in Fig. S7.

These materials, fabrication techniques and modelling tools can yield component devices for almost any type of transient electronic system, in CMOS designs. Figure 3 presents several examples. For both n- and p-channel MOSFETs, Mg electrodes (thickness $\sim 250 \text{ nm}$) serve as the source, drain and gate; MgO and/or SiO₂ provide the gate dielectrics (thicknesses between 100 and 150 nm); and Si NMs (thickness 300 nm) act as the semiconductor. The resulting electrical properties for a typical n-channel device with $L = 20 \text{ }\mu\text{m}$ and $W = 900 \text{ }\mu\text{m}$, include saturation and linear regime mobilities of $560 \text{ cm}^2/\text{Vs}$ and $660 \text{ cm}^2/\text{Vs}$, respectively, on/off ratios of $> 10^5$, subthreshold slopes of 160 mV/dec (at $V_d = 0.1 \text{ V}$) and width-normalized current outputs of 0.34 mA/mm (at $V_g = 5 \text{ V}$). These properties, and those of p-channel devices, compare favourably to those of counterparts with similar critical dimensions formed on silicon wafers. (For the range of channel lengths investigated, contact resistances do not limit performance. See Fig. S8.)

In addition to MOSFETs, many other classes of semiconductor devices and passive components are possible. Images and electrical characteristics of some examples appear in Fig. 3, Fig. S9, and S10. The resistors and diodes can serve as temperature sensors; the latter can also be used in photodetectors and solar cells, as shown in Fig. 3 and Fig. S10e – g. The Si NM diode and Mg resistive temperature sensors show sensitivities of $-2.23 \text{ mV}/^\circ\text{C}$ (change in voltage for a given current output) and $0.23\%/^\circ\text{C}$ (percentage change in resistance) both of which are consistent with the behavior of conventional, non-transient devices [17]. With current designs and standard measurement systems, changes in temperature of $\sim 0.5 \text{ }^\circ\text{C}$ can be resolved easily. Ultrathin silicon solar cells ($\sim 3 \text{ }\mu\text{m}$ thick) provide fill factors of 66% and overall power conversion efficiencies of $\sim 3 \%$, even without light trapping structures, backside reflectors or anti-reflection coatings. Doped Si NMs with Mg contacts can serve as strain gauges (Fig. 3e, left), with gauge factors of nearly ~ 40 (Fig. 3f, left, and Fig. S10f), comparable to those of state-of-the art devices [18]. The technologies and fabrication schemes presented here are sufficiently well developed to enable functional, interconnected arrays of sensors. As an example, we built a transient digital imaging device, consisting of collections of Si NM photodiodes with blocking diodes for passive matrix addressing (Fig. 3e, right), capable of capturing pictures when operated in a scanned mode

(Fig. 3f, right). (See more details on device dimensions in Fig. S11.) Many other possibilities can be realized.

The transience times of various elements in an integrated system can be the same or different. The latter can be achieved by use of varied thicknesses and/or stack compositions, or even via combination with non-transient materials. The last possibility is shown in a logic gate (inverter) in the right hand frames Fig. 3c and 3d, where a non-transient metal (Au) serves as source, drain and gate electrodes for two transistors joined by a transient Mg interconnects. In this case, transience in the Mg converts the system from an inverter to two isolated transistors. Variable dissolution rates in purely transient systems can be similarly exploited to transform function over time. Disappearance of Mg shunt resistors or interconnects in systems that are otherwise encapsulated in MgO can affect the functional addition or subtraction, respectively, of selected components in a transient integrated circuit. Figure 3g and 3h illustrate the latter possibility, in a Si NM MOSFET logic gate that transforms from NOR to NAND operation due to disappearance of an interconnect. Examples of transient shunts appear in Fig. S12, where the effects are to change function from of a resistor to a diode, from a NAND gate to an inverter, and from a NOR gate to independent transistors.

This broad variety of device components, sensors and actuators enables integrated systems with useful levels of functionality. One option for power supply is to exploit silicon solar cells such as those shown in Fig. S10e. Another uses inductors and capacitors like those in Fig. 1a, 3a and b, and S9 as wireless antennas for near-field mutual inductance coupling to a separately powered, external primary coil. A compelling application of transient electronic systems is in implantable devices [4], made possible by the bio-compatibility of the constituent materials introduced here (Fig. 1). In particular, Mg is already used as structural material in certain types of intravascular stents [19]. Silk is FDA approved for use in sutures, and tissue engineering [5]. A 1 μg transient Si NM device dissolved in 3L of blood plasma yields a concentration of 0.33 $\mu\text{g/L}$, which falls below physiological concentrations [20]. The boron and phosphorous doping needed to achieve n and p channel MOSFETs with Si NMs represent concentrations ~ 1 ng/L for phosphorous and ~ 11 pg/L for boron, both of which are well below physiological levels (400 mg/L for phosphorous, 24 mg/L for boron in blood), even at minimum volumes necessary to avoid solubility limits for Si (90 $\mu\text{g/L}$ for phosphorous and 1 $\mu\text{g/L}$ for boron in 0.03 mL). The total amounts of ~ 3 ng for phosphorous and ~ 33 pg for boron reported here are orders of magnitude smaller than the suggested daily intake (~ 1500 mg for phosphorous and 1 ~ 13 mg for boron) from a normal diet [21–24].

To demonstrate bio-resorption and bio-compatibility, we conducted a series of *in vivo* experiments. Various representative transient devices (e.g. Fig. 1 and others) were fabricated, sealed in silk packages, sterilized with ethylene oxide, and then implanted in the sub-dermal region of BALB/c mice in accordance with Institutional Animal Care and Use Committee (IACUC) protocols. Figure 4a (shows the case of the demonstration platform presented in Fig. 1. Examination after 3 weeks (Fig. 4b) revealed only faint residues, with evidence of slow reintegration into the subdermal layers along with apparent revascularization. The tissue is then sectioned and examined for inflammatory reactions. The histological section is presented in figure 4c that shows the subdermal layer (A), the silk film (B) and the muscle layer (C).

Inductive coils of Mg combined with resistive microheaters of doped Si NMs, integrated on silk substrates and housed in silk packages, provide transient thermal therapy systems for potential use in infection mitigation and disease management, where localized heating can facilitate bacterial suppression and provide localized pain relief [25–27]. Figure 4c shows an image of a device formed on glass, that includes two coils with different resonance

frequencies (70 MHz and 140 MHz) and three separate heaters. Wirelessly operating either or both of these coils with appropriate frequencies and power levels applied to a separate primary coil enables full control of the system, as illustrated in the thermal images of Fig. 4d. (See Fig. S13, S14 and S15 for other examples) Incorporating additional coils and heaters can allow full control over more complex temperature distributions. Similar approaches can be used for spatially and temporally programmed electrical stimulation. To demonstrate *in vivo* functionality, a single-coil, single-heater, fully transient version of this device was implanted under the skin of a Sprague-Dawley rat (Fig. 4e, left). Inductive coupling through the skin generates a localized temperature increase of $\Delta T \sim 5^\circ\text{C}$ (Fig. 4e, right), coincident with the position of the heater. The complete device is transient, with a timescale of 15 days. The silk package determines the transience time, which is adjustable via the degree of crystallinity in the silk.

The concepts reported here establish a comprehensive baseline of materials, modelling approaches, manufacturing schemes and device designs for transient electronic systems, sensors, actuators and power supply. The Si NMs, with or without SiO_2 , are critically important elements because their use immediately enables sophisticated semiconductor components with both active and passive functionality. For the dielectrics and conductors, additional possibilities range from collagen to poly(lactic-co-glycolic acid) and from iron to zinc, respectively. Alternative modes of transience include absorption, corrosion, depolymerization and others. The rates for these processes could, conceivably, be adjustable in real-time, triggered, and/or sensitive to the properties of the surrounding environment, determined by chemical or biological events, or changes in temperature, pressure, or light. Exploring these options, developing advanced fabrication methods and alternative device designs represent promising avenues for future work, particularly when coupled closely to clinically relevant modes of use or other applications.

METHODS SUMMARY

Fabrication of devices

Doped single crystalline silicon nanomembranes (NMs) were prepared from silicon-on-insulator (SOI) wafers (top silicon thickness ~ 300 nm, p-type, SOITEC, France). Undercut etching of the buried oxide with hydrofluoric (HF, 49% Electronic grade, ScienceLab, USA) acid, formed isolated silicon NMs that were transfer printed onto silk film substrates. Gate and interlayer dielectrics (MgO , or SiO_2), as well as electrodes and interconnects (Mg) were deposited by electron-beam evaporation through high resolution stencil masks. For the latter, MgO layers served as an adhesion promoter, except for the Mg/Si contacts needed for the transistors, where Mg was either deposited directly or, for improved yields and adhesion strength, with an 5 nm layer of Ti. More details on fabrication processes appear in the supplementary information.

Preparation of substrates, encapsulation layers and packages

B. mori silkworm cocoons were cut and boiled in a 0.02 M Na_2CO_3 solution to extract the glue-like sericin proteins. The remaining silk fibroin was rinsed in Milli-Q water and dissolved in a LiBr solution at 60°C for 4 h and then dialyzed with distilled water using dialysis cassettes for a couple of days to remove LiBr. After centrifugation and filtration to remove insoluble remnants, the silk solution was diluted to 5 to 7 wt % with ion-free distilled water and cast onto silicon substrates or glass slide to form ~ 20 μm thick films and kept drying out in air to form silk films.

Silk fibroin packaging scheme

Two ~100 μm silk fibroin films, cut into areas of ~5 cm $\times$ 5 cm, were cross-linked via lamination at 120 $^{\circ}\text{C}$ for 60s, to achieve maximum β -sheet crystallinity and complete adhesion of the silk layers. The films were stacked, and then one edge was sealed by re-lamination with 10 μL of ~6 % silk fibroin solution as an adhesion layer. The silk substrate for the functional device was left uncrosslinked, and placed in between the two cross-linked films. Finally, the other three sides were sealed by the same method, fully encapsulating the sample in between the two films. Excess film was trimmed from the edges to minimize the size of the encapsulated sample for implantation.

Animal model evaluations

Female BALB/c mice (6 – 8 weeks old) and female albino Sprague-Dawley rats were anesthetized with an intraperitoneal injection of a ketamine/xylazine mix. The depth of anesthesia was monitored by palpebral and withdrawal reflexes to confirm that the animal had reached “stage 3” of anesthesia. The back was shaved and cleaned at the incision site with 70 % ethanol, followed by a betadine surgical scrub. Once stage 3 was confirmed, a small longitudinal incision was made through the skin and the sterile implants (ethylene oxide sterilized) were inserted. The incision was closed with a Dexon 5-0 suture. The animal was monitored until ambulatory and given a dose of analgesia (Buprenorphine subcutaneously) as soon as surgery was completed.

Wireless operation, and testing THIS SECTION GETS MOVED TO THE SOM IF WE GO WITH THE PROPOSED VERSION OF FIG. 4

The antenna structure was designed to exhibit a resonant frequency at ~1.6 GHz when formed on an untreated/water-dissolvable silk film and encapsulated in the same fashion described above. The silk package was treated to be water insoluble and sealed along the edges using a few drops of silk solution as the glue. The antenna was examined by measuring the resonant responses with a network analyzer (HP 8753D) before and after the encapsulation process in prior to implantation. *In vivo* responses of the antenna were recorded on day 0 (right after the implantation), day 4, day 8 and day 15 (when the resonance of antenna was undetectable), as shown in Fig. 4f. The device was retrieved thereafter showing signs of broken Mg traces indicative of the degradation of embedded antenna through the diffusion of the bio-fluids through the silk pocket when implanted.

Transient electronic systems with wireless power supply for thermal therapy

The device consists of silicon resistors, inductive coils and interconnection lines, formed on a silk substrate, with a separate silk package. Transfer printing doped silicon NMs was followed by deposition and patterning of a first metal layer (Ti/Mg, 5/250 nm), and interlayer dielectric (MgO, 400 nm) and a second metal layer (Ti/Mg, 10/800 nm). The device was then packaged with silk, as described previously. The coupling frequency for wireless power transmission was ~ 100 MHz.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1. Demonstration platform for transient electronics, with key materials, device structures, and reaction mechanisms

a, Image of a transient electronic platform that includes all essential materials and several representative device components -- transistors, diodes, inductors, capacitors and resistors, with interconnects and interlayer dielectrics, all on a thin silk substrate. **b**, Exploded view schematic illustration of this device, with a top view in the lower right inset. All of the materials -- silicon nanomembranes (Si NMs; semiconductor) and thin films of magnesium (Mg, conductor), magnesium oxide (MgO, dielectric) silicon dioxide (SiO_2 , dielectric) and silk (substrate and packaging material) -- are transient, in the sense that they disappear by hydrolysis and/or simple dissolution in water. **c**, Images showing the time sequence of this type of physical transience, induced by complete immersion in water. **d**, Chemical reactions for each of the constituent materials with water.

Figure 2. Experimental study of transient electronic materials and corresponding theoretical analysis

a. Atomic force microscope (AFM) topographical images of a single crystalline silicon nanomembrane (Si NM; initial dimensions: $3 \mu\text{m} \times 3 \mu\text{m} \times 70 \text{ nm}$), at various stages of dissolution by hydrolysis in phosphate buffered saline (PBS). **b.** Diagram of the processes of transport, adsorption, diffusion, reaction and desorption used in theoretical models of the transience. **c.** Experimental results (symbols) and simulations (lines) for the time dependent dissolution of Si NMs with different thicknesses, 35 nm (black), 70 nm (blue), 100 nm (red) in PBS at 37 °C. **d.** Optical microscope images of the dissolution of a serpentine trace of Mg (150 nm thick) trace on top of a layer of MgO (10 nm thick). **e.** Experimental (symbols) and

simulation (lines) results showing the ability to tune the dissolution time of similar traces of Mg (300 nm thick) by use of different encapsulation layers of different materials. Here, measurements of length-normalized resistance show that the transience times increase progressively with encapsulation layers of MgO (400 nm, red; 800 nm, blue) and silk (condition i, cyan; condition ii, purple). With these simple schemes, the transience times can be adjusted in a range from minutes to several days. Silk packaging strategies can further extend these times.

Figure 3. Images and electrical properties of transient electronic components, circuits and sensors, including simple integrated circuits and sensor arrays

a, Image of LC (inductor-capacitor) oscillator fabricated with Mg electrodes and MgO dielectric layers (left) and silicon diodes with serpentine Mg resistors (right). **b**, Measurements of the S21 scattering parameter of an inductor (blue), capacitor (black), and LC oscillator (red) at frequencies up to 3 GHz. **c**, Images of an array of p-channel (left) metal-oxide semiconductor field effect transistors (MOSFETs) and a logic gate (inverter; right) comprised of n-channel MOSFETs. Each MOSFET consists of Mg source, drain, gate electrodes, MgO gate dielectrics and Si NM semiconductors. The inverter uses Mg for interconnects, and Au for source, drain, gate electrodes, in a circuit configuration shown in the diagram. **d**, Current-voltage (I-V) characteristics of a representative n-channel MOSFET (left, channel length (L) and width (W) are 20 μm and 900 μm , respectively). The threshold voltage, mobility and on/off ratio are -0.2 V, 660 $\text{cm}^2/\text{V}\cdot\text{s}$, and $> 10^5$, respectively. Transfer characteristic for the inverter (right, L and W are 20 μm and 700 μm for input transistor and 500 μm and 40 μm for load transistor, respectively). The voltage gain is ~ 8 . **e**, Image of a collection of strain sensors based on Si NM resistors (left) and matrix of Si NM photodetectors with blocking diodes. In both cases, Mg serves as contact and interconnection electrodes and MgO as dielectric layers. **f**, Fractional change in resistance of a representative strain gauge as a function of time during cyclic loading (left). Bending induces tensile (red) and compressive (blue) strains, uniaxially up to ~ 0.2 %. Image collected with the photodetector array (right). Inset shows the original image taken by the photodetector array. **g**, Images of logic gates in which controlled transience affects functional transformation, in this case from NOR (left) to NAND (right) operation, by selective dissolution of an unencapsulated Mg interconnect. **h**, Output voltage characteristics

of the circuits before (NOR, left) and after (NAND, right) transformation. V_a and V_b represent voltage inputs.

Figure 4. *In vivo* evaluations and example of a transient bio-resorbable device for thermal therapy

a, Image of implantation of a demonstration platform for transient electronics in the dorsal region of a BALB-c mouse (left). Implant site after 3 weeks (right). **b**, Histological section of tissue at the implant site, excised after 3 weeks, showing the remainder of the silk film. (A, subcutaneous tissue; B, silk film; C, muscle layer). **c**, Transient wireless device for thermal therapy, consisting of two resistors (red outline) connected to a first wireless coil (70 MHz; outer coil) and a second, independently addressable, wireless coil (140 MHz; inner coil). **d**, Thermal image of this device coupled with a primary coil driven on resonance with the outer coil. Here, the two outer resistors (Re) are powered, to generate local heating (left). The thermal image on the right shows the case where the primary is operated at two frequencies, to drive both the inner and outer coils simultaneously. **e**, Primary coil next to a sutured implant site for a transient thermal therapy device (left). Inset shows the image of a device. Thermal image

collected while wirelessly powering the device through the skin; the results show a hot spot (5 °C above background) at the expected location (right), with magnified view in the inset.