Expandable Polymer Enabled Wirelessly Destructible High-Performance Solid State Electronics

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Title: Expandable Polymer Enabled Wirelessly Destructible High Performance Solid State Electronics

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Keywords: Destructible electronics, CMOS, expandable polymer.

In today's digital age, our increasing dependence on information also makes us vulnerable to potential invasion of privacy and cyber security. Consider a scenario in which a hard drive is stolen, lost or misplaced which contains secured and valuable information. In such a case, it's important to have the ability to remotely destroy the sensitive part of the device (e.g. memory or processor) if it's not possible to regain it. Many emerging materials and even some traditional materials like silicon, aluminum, zinc oxide, tungsten, magnesium, etc. which are often used for logic processor and memory, show promise to be gradually dissolved upon exposure of various liquid medium. However, often these wet processes are too slow, fully destructive and require assistance from the liquid materials and their suitable availability at the time of need. Here we show joule heating effect induced thermal expansion and stress gradient between thermally expandable advanced polymeric material and flexible bulk mono-crystalline silicon (100) to destroy high performance solid state electronics as needed and in under 10 seconds. We also show different stimuli assisted smart phone operated remote destruction of such CMOS electronics.

1. Introduction

Electronic chips that are commercially available today are durable and long-lasting. However, there is a great need for electronic systems that can lose the functionality and structure on demand, or after a certain amount of time. Transient electronics is an emerging technology field in which the functionality of a chip can be altered or completely destroyed in a controlled manner.[1-6] Application areas of transient electronics include healthcare where electronic monitoring implants that can be resorbed in the body over time, or a network of biodegradable sensors distributed in the environment that can provide a data for a certain amount of time.[1-11] A few works have been previously reported under physical transient electronics. One method is submerging electronics in their respective dissolution solutions.[2, 8, 12, 13] Another method is destroying electronics using microfluidics as chemical etchants.[14-16] There is also a recent method allowing complete destruction within 10 seconds where chip is built on strained glass and can shatter after remotely triggered with laser.[17] However, to the best of our knowledge, further details of this method has not been reported in literature till date. Also, use of laser and strained glass make the system inconvenient for on-demand destruction. Transient energy storage devices have been also developed to demonstrate fully transient systems to meet the power requirements of the systems.[18-21] Although most of current transient electronic approaches focus on polymeric and biologically-derived materials,[1, 2, 7, 8] they have limitations such as thermal instability and inherent low carrier mobility which restrict them to be used for high performance Complementary Metal Oxide Semiconductor (CMOS) for logic and memory applications. Thus, developing CMOS based transient electronic systems are important where performance is an important criteria such as in security and defense applications. For example, to protect classified information in a lost hardware, it can have the ability to be destroyed remotely with wireless integration. CMOS technology can also be integrated with commonly known fabrication techniques and with ultra-large-scale-integration densities. In this work, we show a new approach for physically transient electronics which is simple, CMOS compatible, allows on command partial or total destruction, does not limit the life cycle of electronics and can provide destruction within 10 seconds of actuation. We have demonstrated different destruction scenarios along with autonomous destruction including smartphone based operation.

The number of hardware thefts are increasing every year. According to Consumer Reports, the number of only smartphone theft nearly doubled from 2012 to 2013, affecting 3.1 million US users in 2013.[22] IDG Research reports that 10% of US smartphone users are affected by smartphone theft.[22] More than half of the respondents to the 2010 BSI Computer Theft Survey were victims of laptop theft.[23] Figure 1a shows the types of security breaches and their respective percentages.[24, 25] These security thefts cause billions of dollars in losses and millions of dollars are spent to develop various hardware and software based techniques to prevent these thefts. The software based data preventive methods such as setting passwords and data encryption are not yet completely foolproof and reliable. The ultimate method to prevent any information theft is on-demand complete destruction of the stolen, misplaced or hacked device such as laptops, mobile phones, desktops, credit cards, sim cards, hard drives and pen drives.

The reported destructible electronics system here is compatible with current state-of-the-art high performance CMOS chips and can revolutionize today's highly secure military applications that may need to self-destruct on command within seconds, if they fall in wrong hands. Moreover, instead of a complete destruction, we may also be interested in on-command partial destruction of a device, for example, in place of completely destroying a stolen laptop, we may only destroy the memory areas of the laptop to prevent any data theft. We have demonstrated both total and partial destruction of electronics in our experiments. Such hardware destructive approach comes under the domain of the emerging field of physically 'transient' electronics. Additionally, this new approach does not limit the life cycle of electronics and can provide destruction within 10 seconds of actuation.

2. Results and Discussions

Figure 1b-c shows the structure of the integrated destructible device which includes flexible polyimide substrate, heater, expandable polymer layer and 25 μm thick silicon chip. Heating of the electrodes was facilitated by Joule Heating effect. When the heater electrode was provided with a sufficient DC power supply (500-600 mW) to reach temperature values above 80 °C, the expandable polymer layer on it expanded irreversibly and increased its volume around 7 times of the original volume. Expandable polymer is composed of polymeric microspheres where small amount of liquid hydrocarbon is encapsulated by a gas tight thermoplastic shell. This shell softens when it's heated above a critical temperature and the small amount of liquid hydrocarbon inside it undergoes a phase change to gas which causes a volumetric expansion.[26] Activation temperature of the expandable polymer can be modulated by using different polymeric shells which have different glass transition temperatures (T_G). Dramatic increase in the size of the expandable polymer caused a mechanical destruction of the thin Si electronic chip placed on the expandable polymer layer. Thus, the expansion of the polymer through heating results in destruction of the top Si layer in the regions where the stress exerted is greater than the ultimate tensile strength (UTS) of Si (6.89 GPa).[27] Heat only dissipates around the electrodes and triggers the device destruction at desired places (Figure 1d). Finite Elemental Analysis (FEA) of the electrode heating behavior (Figure 1e) is in agreement with the experimental result (Figure 1d). Different electrode designs and sizes can be implemented to change the destruction size and area (Figure S1 - Supplementary Information).

We have been able to successfully demonstrate the destruction of thin Si chips upon application of a short electrical trigger. The system can be destroyed within 10 seconds from the application of the electrical trigger. It is possible to control the speed of destruction by changing the applied voltage: For example, with lower voltages (< 4V), it took longer time (up to 120 seconds with heater resistance around 10 Ω) for electrode to heat up to desired temperatures, so the destruction took longer. Figure 2a shows destruction of single Si chip on demand. Figure 2b-d presents the demonstration of modular destruction of a chip. Heat only dissipated around the predetermined locations of electrodes and caused the device destruction at desired places which transformed the functionality of the device. Three resistors were fabricated on silicon (Si) and released using "trench protect etch release" (TPER) method developed by our lab previously to get a 25 μm thin flexible Si substrate (4 cm × 3.5 cm).[28] Total resistance of the three parallel resistances was 75 Ω. Resistors were destructed sequentially on demand. After first, second and third resistor destructions, the total resistance changed to 105 Ω, 180 Ω and open circuit, respectively (Figure 2d). Figure 2e shows another demonstration of modular destruction. Two LEDs were mounted on thin Si fabric and powered up using external power source through the electrical traces on Si. Selective destruction of electrical connections caused to turn off the LEDs independently.

Using FEA, we first analyzed the bare heater temperature distribution for 2.5 V supply and found that the calculated temperature variation as shown in Figure 1d closely agrees with the corresponding experimental result as shown in Figure 1e. It can be observed that the heater was able to attain temperature values well above 80 °C, which is necessary to trigger the irreversible large expansion of the expandable polymer. Moreover, the heater is so designed that the temperature values above 80 °C are well confined over the heater area. By using different grades of expandable polymer, expansion temperature can be tuned between 80 °C to 250 °C.[29] The FEA for the study of stress and mechanical deformation was also performed for the experimental result shown in Figure 3. Two of the three heaters were activated by providing the voltage supply one at a time and calculated stress analysis and mechanical deformation are reported in Figures 3a and 3b. The ultimate tensile strength (UTS) of silicon is 6.89 GPa and the expansion of expandable polymer through heating above 80 °C results in destruction of the top Si layer in the regions where the stress exerted is greater than the UTS of Si.[27] It can be observed from the calculated stress plots that some regions of the Si layer experience stress greater than the UTS of Si and it can be stated that these regions will undergo destruction. The simulated deformation trends in Figure 3 closely agrees with the experimental deformation results in Figure 2. The maximum stress values in the plots has been limited to 7.5 GPa. Any stress value beyond this limit can be observed as removed or missing areas in the respective plots. For heater 2, zoomed in angled deformation, the desired supply voltage and resulting temperature distributions are shown in Figure 3c-e. It can be observed that the voltage supply of 5.4 V was required to produce the desired destruction, which closely agrees with the experimental results. Moreover, the calculated temperature distribution plot of the heater 2 (Figure 3e) shows that the temperature values above 80 °C (triggering temperature for irreversibly large expansion of expandable polymer) are confined over the heater area. Therefore, the region of the expandable polymer, just over the heater area undergoes the irreversibly large expansion leading to the desired destruction of the top layer electronics, while also limiting the destruction to regions over the activated heater design. Such controlled destruction can be observed in both the experimental (Figure 2c) and FEA results (Figure 3a and b) of the deformation.

We have also performed the FEA to determine the thickness beyond which the top layer Si is not destroyed by the expandable polymer. The simulation setup was the same as demonstrated in Figure S1a, however the Si thickness was varied from 20 µm in steps of 10 µm until the maximum stress induced on the Si layer was less than the UTS of Si. The resulting plot is shown in Figure 3f. It can be observed that till 90 µm of Si thickness, the maximum stress induced on the top Si layer is more than the UTS of Si and hence it would result in the destruction of the top layer. However, the 100 µm thick Si layer would not undergo destruction as the maximum stress induced in the Si is less than the UTS of Si. We believe that expansion force of the expandable polymer should be strong enough to destroy even multiple levels of devices. We envision that multilevel interconnected flexible thin silicon devices will be introduced in the future. Destruction of these systems with various kinds of materials and geometries could be a follow up study.

We further performed FEA to determine the appropriate power, temperature distribution and resulting destruction from different heater designs. We found out that the heater design and the power supply play a crucial role in achieving the desired destruction where larger electronics area can be destroyed by a larger heater designs (Figure S1 – Supplementary Information). Power can be delivered to the system using battery. Expansion time of the polymer can be changed by different power inputs. We experimentally found that ideal power values would be 500-600 mW to get an expansion (and subsequent destruction of top silicon chip) between 10-15 seconds. Lower power values (till down to 300 mW) could still induce the joule heating over 80 °C and trigger the expansion over longer time scales (more than a minute). It is to be noted that thermal expansion based current destruction may have global impact as the ultimate objective is to destroy the whole circuitry or the chip. Localized protective destruction will be possible with an intelligent combination of geometric positioning of devices, thickness of the polymeric material and silicon, heater location and thermal characteristics. Another aspect is if the chip experiences higher temperature (in this case 80 °C) that may cause auto-triggering for harsh environment applications. In such case, two options are available: (i) to restrict the device operation below 80 °C and assuming higher than that requires triggering of self-destruction or (ii) using expandable polymers which can trigger at higher temperature.

Finally, we have demonstrated the system's self-destruction capability by incorporating the system with global positioning system (GPS), light and pressure sensors. To demonstrate the autonomous destruction of the chips, a battery powered electronic system was implemented where programmable actuation of the heating element is developed upon stimulation through sensors. Electronic system details for programmable autonomous destruction experiments are given at the Supplementary Information (Figure S2). We imagined a secret device placed in the enemy teritorry. Whenever any of the incorporated sensors is activated by the enemy, it triggers the self-destruction command autonomously. Even though battery, controller circuitry, and wireless transmission circuitries will still remain, the main important parts of the device such as the memory and/or processor will be destroyed. Figure 4a shows the demonstration of autonomous destruction of the chip depending on the coordinates of the device gathered using GPS sensor. We envisioned a scenario where device will be destructed if it goes beyond a certain perimeter of coordinates. We successfully demonstrated a programmed destruction triggered by going beyond 50 meters away from the starting point (Figure 4a). In Figure 4b, we have demonstrated the self-destruction based on a light stimulus. Illumination using desk lamp triggered the destruction of the chip by exceeding the light intensity threshold assigned to the light sensor. This could be a necessary action where device needs to be kept in dark all the time in a closed box. So taking device out of the box and exposing it to a light could be a trigger for destruction as demonstrated in Figure 4b. Similarly, in Figure 4c, self-destruction of the chip based on pressure stimuli was demonstrated. During the experiment, we manually applied force to the pressure sensor which triggered the destruction. The scenario envisioned here is to mimic the event where the device box is forcefully opened which triggers the destruction of the chip. We finally demonstrated a smartphone based operation of the system (Figure 4d). An app was designed to control the operation where destruction command can be remotely activated using a smartphone. After entering a desired password, predetermined chip was destroyed on demand (Movie S1, Supplementary Information). In future versions of the device, all other sensors in the system can be also integrated with the smartphone where the status of the device can be accessed through the app.

3. Conclusions

We have introduced a new concept to deploy the high performance destructible electronics technology which can enable a number of capabilities especially in defense and security purposes. The proposed system here is easy to fabricate and operate and can destroy the electronic system within 10 seconds from the application of electrical trigger. We have demonstrated system's ability with different scenarios including modular/autonomous destruction and smartphone based operation.

4. Experimental Section

4.1 Fabrication of Destruction Device

Device design details are shown schematically in Figure 1c. We sputtered 200 nm gold on 125 µm thick flexible polyimide film (Good Fellows) and electrodes were patterned using laser 1.06 µm ytterbium-doped fiber laser (PLS6MW Multi-Wavelength Laser Platform, Universal Laser Systems). Thermally expandable polymer (Expancel, 031 DU 40, AkzoNobel) was mixed with polydimethylsiloxane (PDMS) (2:1 ratio) and spin coated on wafer to get a thin (~275 µm) sheet of expandable polymer composite and cured in an oven at 65 °C for 2 hours. It was then peeled off from the wafer using razor blade to get a thin layer of expandable polymer composite which was then placed on heating electrodes. Double sided adhesive film (30 µm thick, ARclear, Adhesive Research) was used to assemble different layers of the system. Heating of the electrodes was facilitated by Joule Heating effect. Temperature distribution of heating electrodes was analyzed using an infrared (IR) camera (Figure 1d) during activation. Temperature profile was also investigated with finite element analysis using COMSOL Multiphysics (Figure 1e).

4.2 Fabrication of Thin Silicon Chips

To fabricate thin the silicon (Si) layer (25 µm), the "trench protect etch release" (TPER) method, previously developed in our group, was used which is compatible with existing CMOS fabrication technologies.[28] In this method, patterned liftoff of 150 nm thick sputtered gold was performed to obtain the circuit design followed by deep reactive ion etching (DRIE) using the Bosch process to create numerous adjacent trenches in the Si substrate. Aluminum oxide (Al_2O_3)

was then deposited through atomic layer deposition (ALD) and reactive ion etching (RIE) was performed to remove the deposited Al_2O_3 from top surface of the substrate and bottom surfaces of the trenches. Xenon difluoride (XeF_2) gas was then used to isotropically etch the exposed Si surfaces in the trenches resulting in the release of thinned flexible Si layer. The flexible Si substrate was then removed with the help of laser etching at the edges and lifting of the substrate with the help of sharp blade.

4.3 Simulation Analysis

The software COMSOL Multiphysics 5.2 was used to perform the finite element analysis (FEA) for voltage, temperature and stress studies for different heater designs. The different layers were stacked on top of each other as detailed in the experimental section. The physics modules of heat transfer in solids, electric current shell and solid mechanics were used. Through the heat transfer in solids module, the areas of the setup exposed to air were assigned natural convection and their initial temperature was set to room temperature. In the electric current shell module, thin film was assigned to the heater design, and voltage and ground were allotted to the respective terminals of the heater. Through the solid mechanics module we constrained the bottom surface of the destructible device, since the bottom glass slab layer was used to provide rigid support the structure. To accommodate the phenomenon of thermal expansion, heat transfer in solids and solid mechanics modules were coupled to each other. Similarly for temperature coupling and boundary electromagnetic heat source phenomena, heat transfer in solids and solid mechanics; and electric current shell and heat transfer in solids modules were coupled, respectively. For creating the mesh of the structure, physics controlled mesh with normal element size was used.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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MH conceptualized the study. AG and AA equally contributed. AG led and carried the study (materials, design, processes, device, integration, characterization, data analysis). AA carried out all FEA analysis. AG, AA and AH developed all the devices. KM and IW developed all the circuitry. GTS developed the software and App. MD supported packaging. SS, SV, SA and MG assisted in characterization. Every author reviewed the manuscript independently, provided feedback and approved the final version. AG, AA and AH contributed equally.

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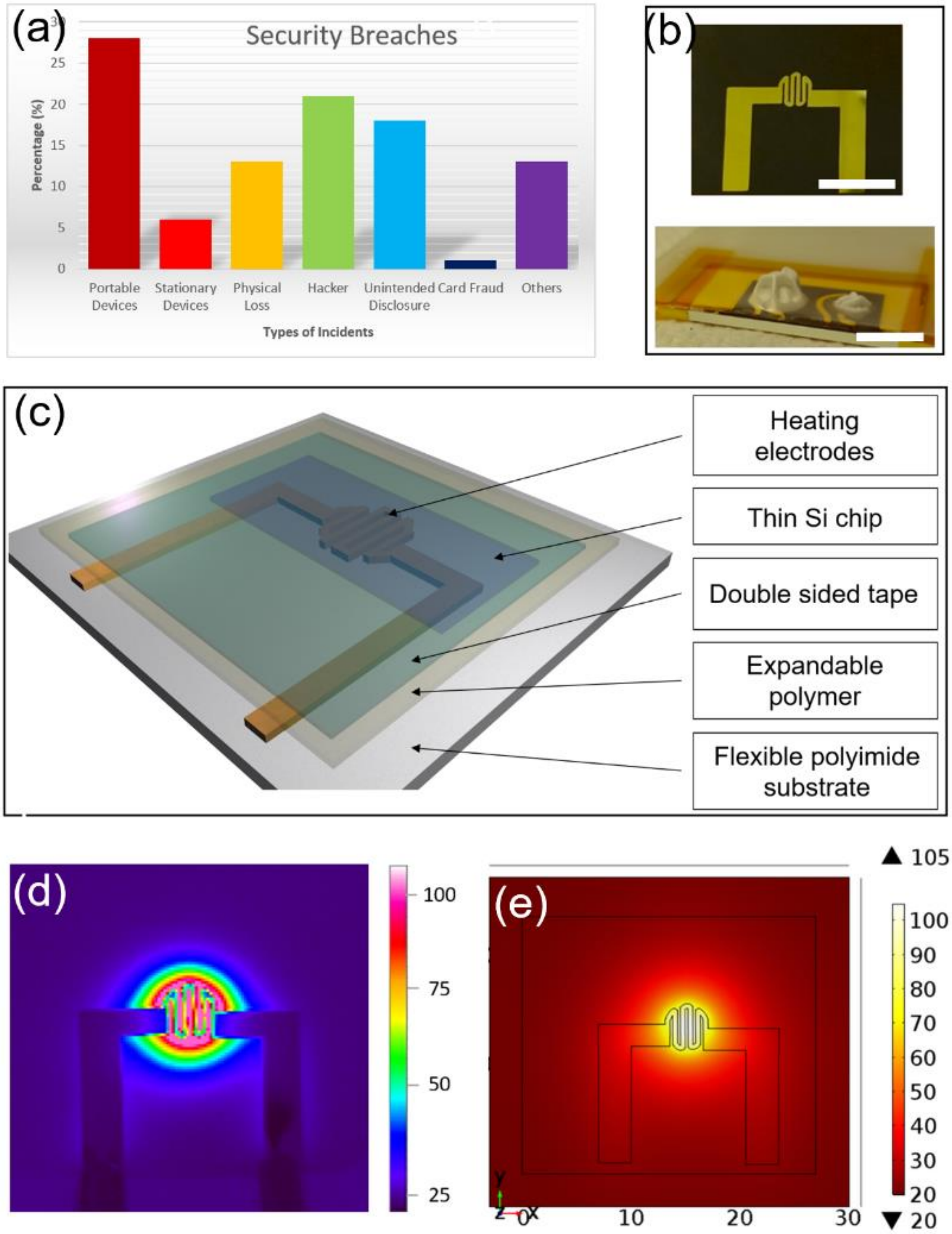

Figure 1. a) Types of cyber security breaches and their respective percentages.[24, 25] b) Heating element of the system (up), volumetric increase in the expandable polymer after triggering with heat (below) (Scale bars indicate 1 cm.) c) Structure of the integrated destructible device. d) IR image of the electrode to observe the temperature profile and distribution (ºC). e) Investigation of temperature profile with Finite Element Analysis (FEA) (ºC).

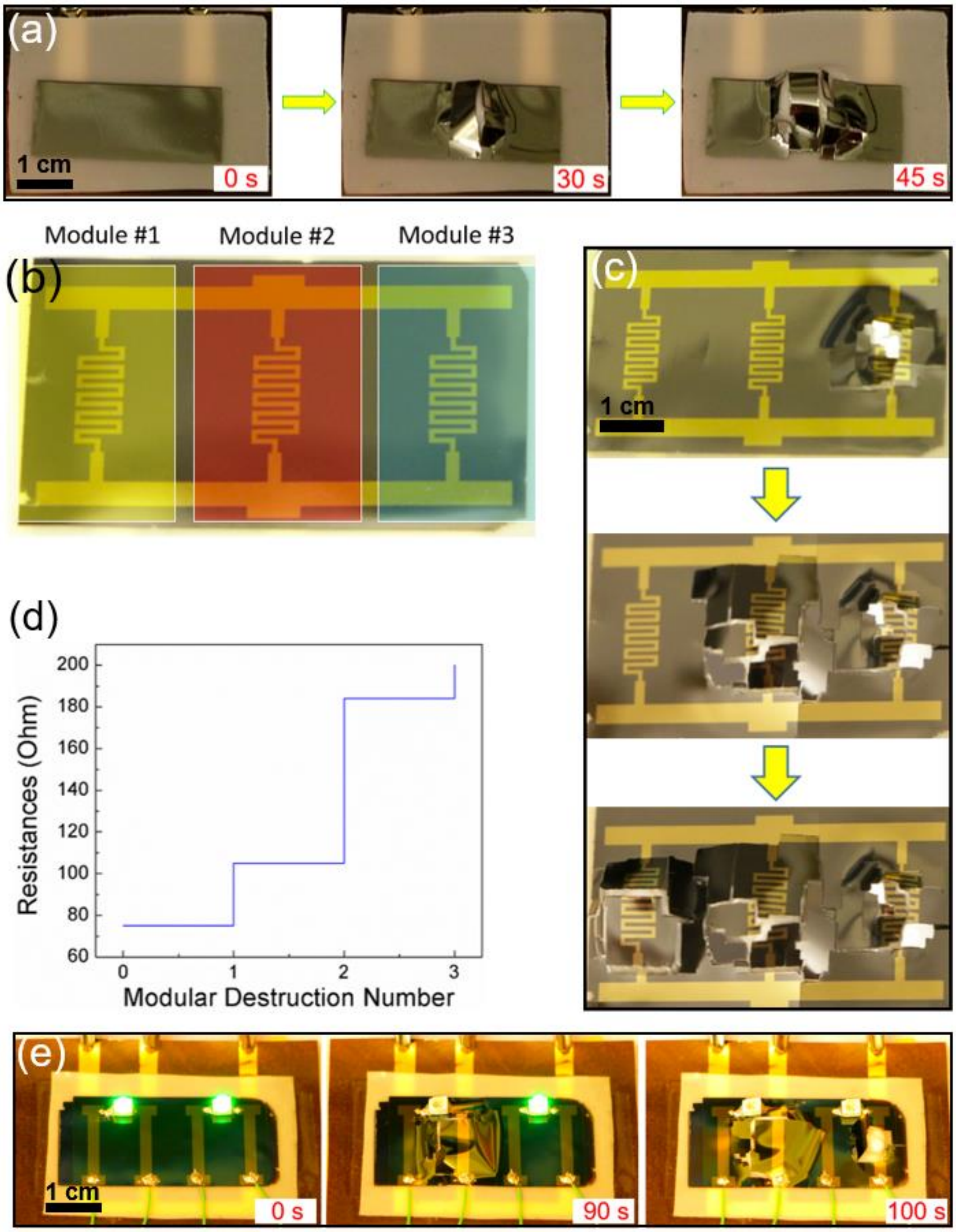

Figure 2. a) Destruction of a single silicon chip on demand. b-d) Demonstration of modular destruction of a chip. Resistors were destructed sequentially on demand. e) Another demonstration of modular destruction. Selective destruction of electrical connections caused to turn off the LEDs independently.

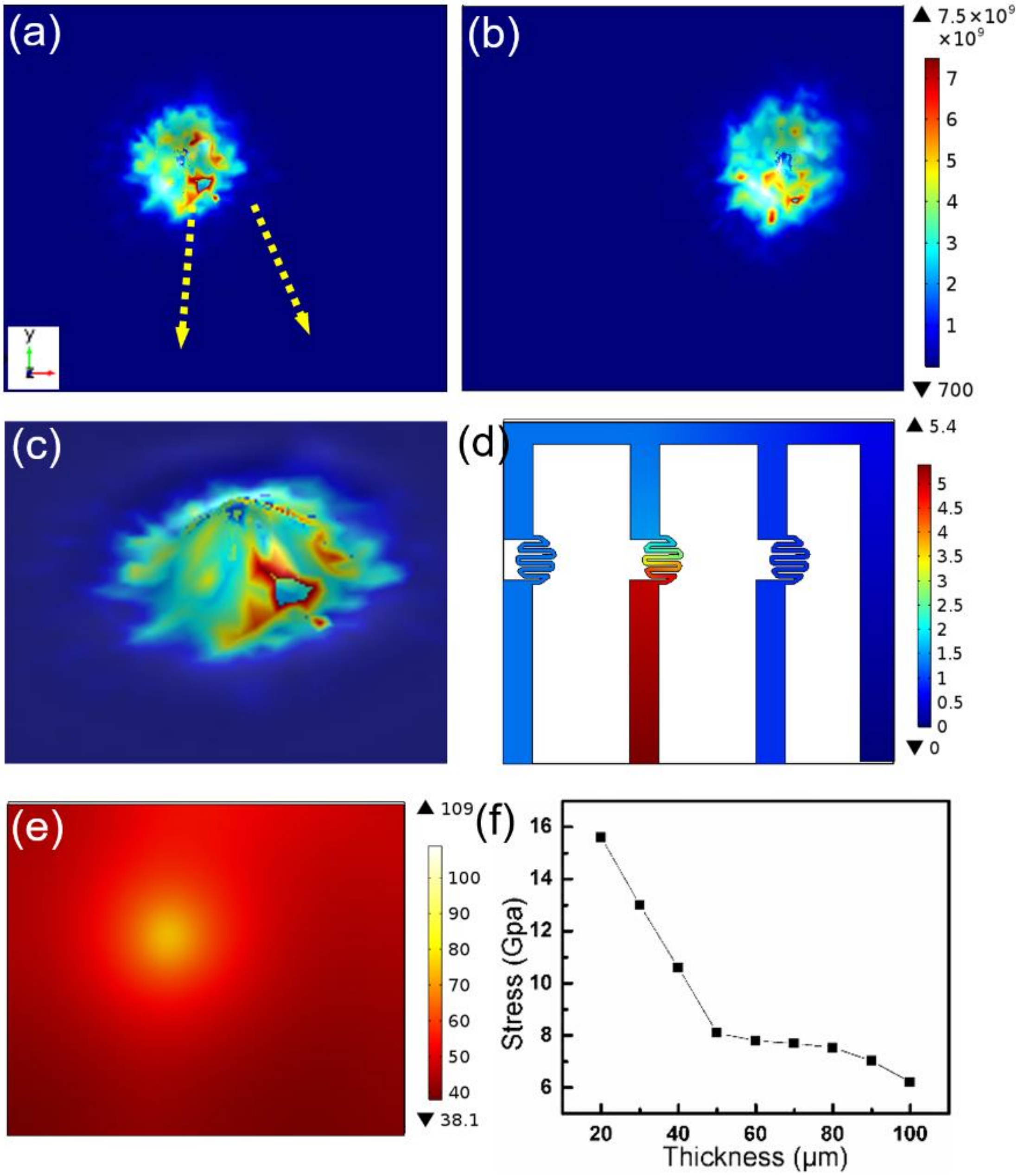

Figure 3. a-b) Activation of the heaters by providing the voltage supply one at a time and calculated stress analysis and mechanical deformation (GPa). c) Zoomed in angled deformation. d) Desired supply voltage (V) and e) calculated temperature distribution plot of heater 2 (ºC). f) FEA to determine the thickness beyond which the top layer Si is not destroyed by the expandable polymer.

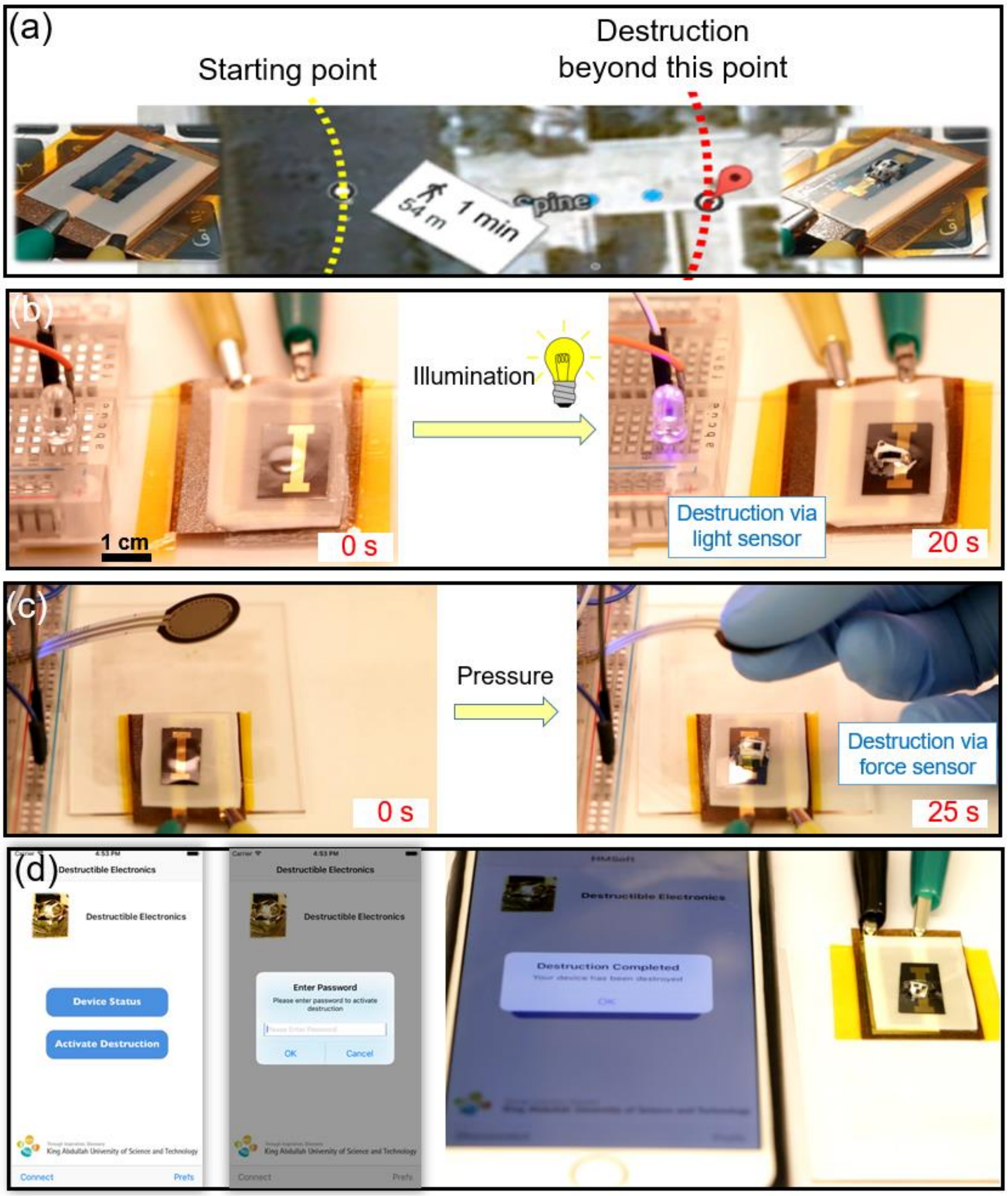

Figure 4. a) Demonstration of autonomous destruction of the chip depend on the coordinates of the device gathered using GPS sensor. Device destruction happens if it goes beyond a certain perimeter of coordinates. b) Self-destruction based on a light stimuli. Illumination using desk lamp triggers the destruction of the chip. c) Self-destruction based on a pressure stimuli to mimic the scenario where unwanted person tries to open the device box forcefully. d) Demonstration of a smartphone based operation of the system where destruction command can be remotely activated using a smartphone app.

The expandable polymer enabled destructible electronic systems presented here has the ability to wirelessly destroy the high performance solid state electronic systems.

Keywords: Destructible electronics, CMOS, expandable polymer.

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Supplementary Information

Expandable Polymer Enabled Wirelessly Destructible High Performance Solid State Electronics

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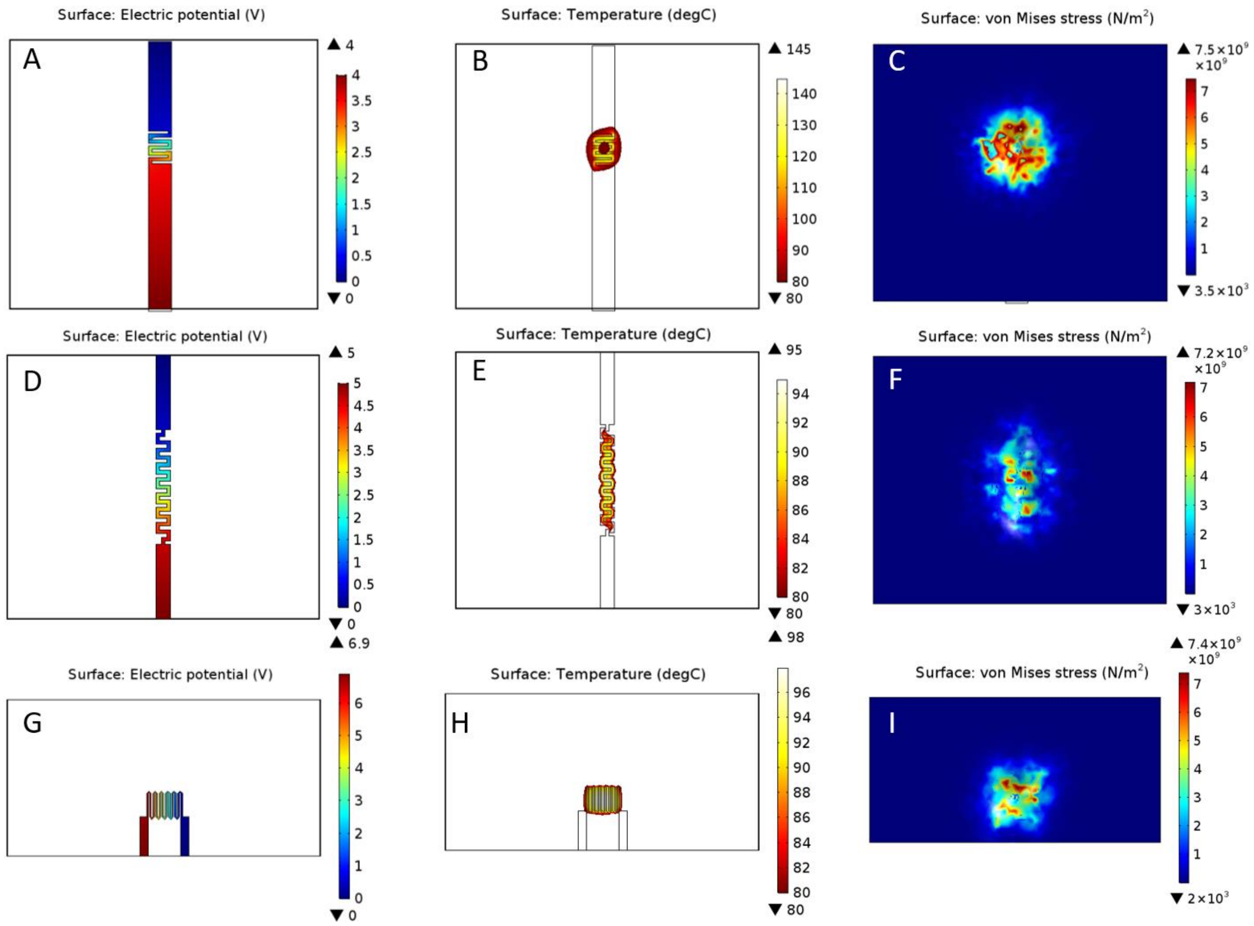

Figure S1. Finite Element Analysis (FEA) to determine voltage (A, D, G), temperature distributions (B, E, H) and resulting destruction from different heater designs (C, F, I).

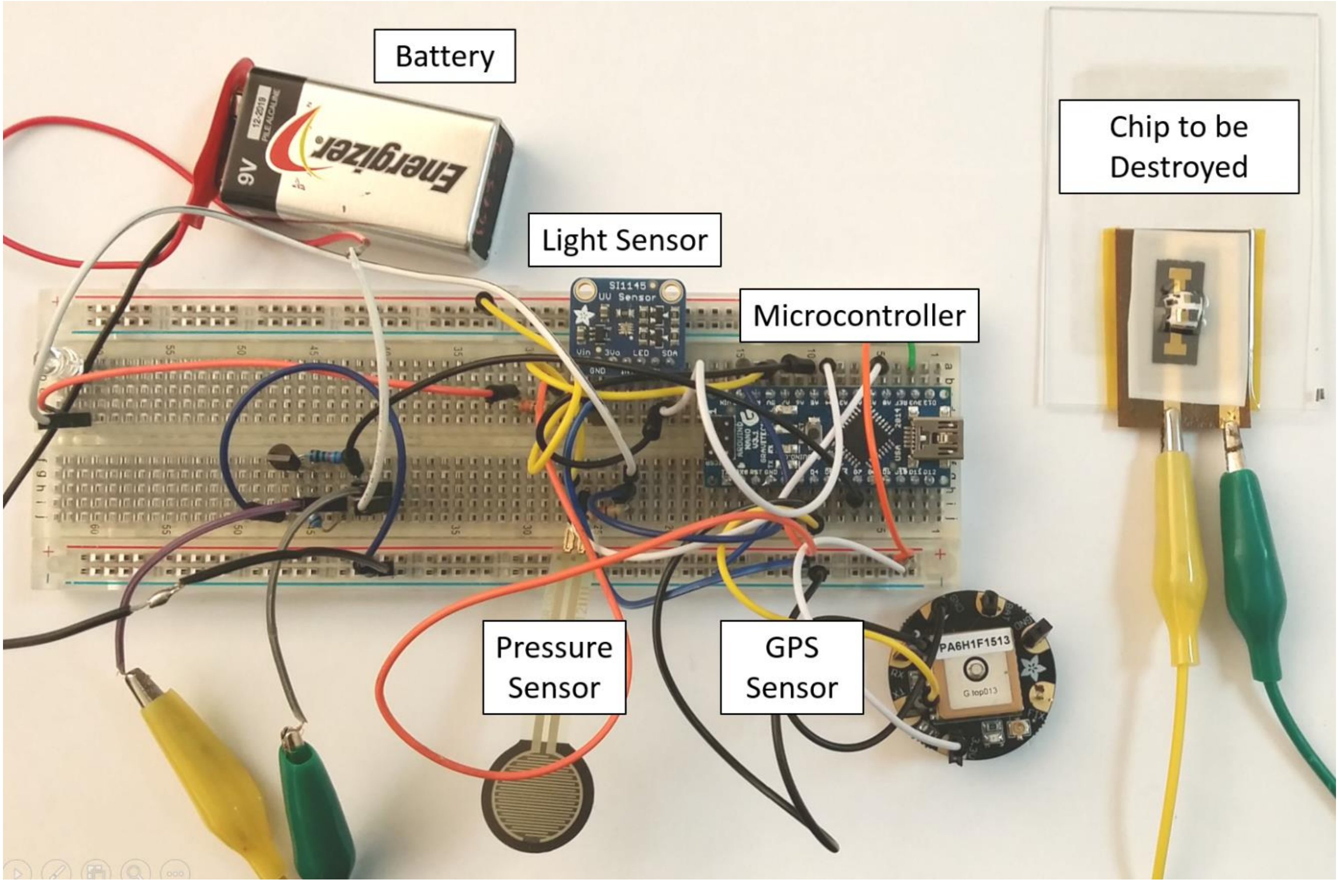

Figure S2. Battery powered electronic system for programmable autonomous destruction using light, pressure and GPS sensors.

EXTENDED EXPERIMENTAL PROCEDURES

Simulations

We performed FEA to determine the appropriate voltage, temperature distribution and resulting destruction from different heater designs. A relatively less resistive heater design, a medium resistive heater design and a relatively large resistive heater design with their respective appropriate voltage, temperature and stress distributions are shown through Fig. S1 A-I, respectively. It can be observed that the less, medium and high resistive heater designs require lower (4 V, Fig. S1A), medium (5 V, Fig. S1D) and high (6.9 V, Fig. S1G) voltage supplies, respectively, to comfortably achieve the required temperature distribution above 80 °C and stresses above the UTS of the top silicon layer and thus resulting in the desired destruction. Moreover, from the temperature distribution plots (Fig. S1B, E and H) and deformation plots (Fig. S1C, F and I) of the respective heater designs, it can be observed that the temperature values above 80 °C and stress values above UTS of silicon are limited to regions over the heater designs, respectively. Therefore, it can be concluded that the heater design and the power supply play a crucial role in achieving the desired destruction. A larger heater design can destroy larger electronics area and a smaller heater design can destroy smaller electronics area. Moreover, by controlling the power supply and heater design, our method of destructible electronics is simple to design, implement and provides the users with the flexibility to have partial or total destruction of electronics, as desired.

Electronics for Programmable Autonomous Destruction

As an effort to demonstrate the autonomous destruction of the chips, a battery powered electronic system implemented where programmable actuation of the heating element is developed upon stimulation through sensors. A current driver circuitry is constructed to provide sufficient current for heating element from battery to reach a certain temperature. A micro-controller (Arduino Nano) provides a mean to programmatically actuate the heater by turning on driver transistor. Driver circuit consists of an NPN BJT with a base resistor; the base resistor acts to limit the bias current flowing to the gate that will ultimately control the current through the collector. A current limiting resistor is also connected in series with each heating element allowing a better control of the maximum current thus temperature generated. A picture of the setup is provided in Fig. S2 with light (SI1145, Adafruit), pressure (FSR402, Interlink Electronics), and GPS (Flora wearable GPS, Adafruit) sensors. All of the sensors are connected to microcontroller and programmable actuation of the heating element happens after sensor output values exceeds a predetermined threshold values.

SI Movies Legends

Movie S1: Demonstration of autonomous destruction of the chip depend on the coordinates of the device gathered using GPS sensor.

Movie S2: Demonstration of a smartphone based operation of the system where destruction command can be remotely activated using a smartphone app.

Supporting Movie S1

Click here to access/download
Supporting Information
M7_Smartphone.mp4

Marked-up version of the revised manuscript

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Production Data

Supporting Movie.mp4