ELECTROCHEMICAL-MECHANICALLY TRIGGERED TRANSIENT ELECTRONICS

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ABSTRACT

Electronics, which functions for a designed time period and then degrades, holds promise in lots of areas, including medical implants, disposable electronic devices and data securing hardware. Here, we report a new type of transient electronics that is triggered through electrochemical-mechanical manner with robust and reliable mechanical design, low triggering voltage and fast transient characteristics. Such device is constructed through integrating electrochemical-mechanically triggered MEMS module with functional electronics. The electrochemical-mechanical triggering mechanism in this device opens up new vistas for transient electronics designs. Various materials and different type of electronics has been demonstrated.

INTRODUCTION

The widespread use of electronics and microchips has imposed a huge burden on data and hardware security for military, financial, corporative and personal applications. For example, a case of loss or theft equipment from armed forces could lead to endangered situations, if it is compromised by adversaries. The considerable needs in preventing loss or theft of data and hardware suggest a future direction for the development of electronics to be able to destroy themselves and even disappear physically. Recent development in an emerging class of transient electronics, which only lasts for a short period of time and then physically dissolved after its usage for certain time frame [1-8], though not exactly for these aforementioned purposes, has paved the way towards this direction. In particular, these transient electronics has profound implications in temporal medical implants, which can fulfill their medical diagnostic and therapeutic functions for a certain period of time and then disintegrate or be dissolved in biofluids without surgical removal procedure [9]. A variety of transient electronic devices has been reported, such as pH sensors, electrophysilogical ECG sensors [10], brain implants [11] for diagnosing and infection therapeutic implants [12] for therapizing, and biosensing [13]. Majority of the previous efforts has been focused on achieving the transience through submerging the device in corrosive aqueous or bio-fluid solution, which is usually associated with long period of transience yet without external control. To meet those aforementioned security needs, the devices seek for stable operation for a certain period of time and then quick transience with external control. So far, only a few literatures have reported efforts towards this direction [14-16]. Rogers and co-workers utilized thermally expandable polymers to actuate the corrosive liquids for device dissolution. Mastrangelo used heaters to melt the polymer reservoir walls to release the etching solution. Lal and coauthors reported the employment of micro-packet of rubidium (Rb) fuel to thermally activate corrosive vapors from vaporizable polycarbonate polymers to fragment the silicon nitride membrane and supported thin devices. All these approaches either involve complicated package and fabrication procedure or require specialized materials.

Here, we report a new type of transient device triggered through electrochemical-mechanical manner with robust and reliable mechanical design, low triggering voltage and fast transient characteristics. The packaged transient system is mainly composed of a triggering module with releasable solution and functional electronic components. Through electrochemical triggering, the module will mechanically burst and fragment to release the dissolving solution. We investigated programmable triggering mechanisms of this system and transience characteristics of related materials. We also investigated maximum strain and deformation of a robust Si_3N_4 membrane depending on its dimension under different pressures using finite element analysis. To demonstrate the triggered transient capabilities, Cu based resistor and indium gallium zinc oxide (IGZO) based field effect transistor as prototype electronic device were fabricated and their transience characteristics were characterized.

RESULT AND DISCUSSION

Figure 1 shows a schematic illustration of the working principle for the transient system. A packaged corrosive solution is enclosed in a reservoir that has a breakable rigid membrane, as detailed below. Upon hydrolyzing the solution, the pressure increase and eventually burst the membrane to fracture mechanically. The etching solution is therefore released from the reservoir to achieve the functional electronic devices and induce rapid dissolution by a chemical etching mechanism.

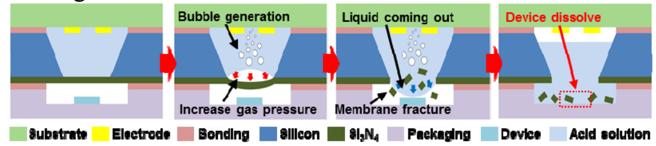

Figure 1: Schematic illustration of the working principle for transient operation.

Figure 2a shows an explored view of the construct of the electrochemical-mechanically triggered transient system, which includes a pair of electrolysis electrodes, controllable solution releasing module, etching solution, electronic devices, and packaging components. Specifically, interdigital electrolysis gold electrodes (200nm thick) were fabricated on a glass substrate by e-beam deposition and following photolithography and wet etching processes. Gold electrodes were chosen because they are inert thus intact in corrosive solution for long period (Figure 2b). Figure 2c shows a controllable solution releasing module with a free standing Si_3N_4 membrane. Such module was prepared based on low pressure chemical vapor deposition Si_3N_4 film coated Si (100) wafers.   chosen for its high stability in acidic conditions [3]. After patterning the Si_3N_4 film on one side of the Si wafer to expose the Si, anisotropic Si wet etching using potassium hydroxide (KOH) solution was performed. Suspended Si_3N_4 membrane with desired geometries can therefore be achieved.

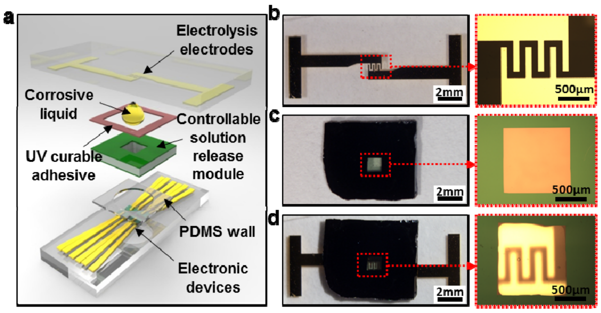

Figure 2: Schematic illustrations and optical images of the transient electronics. (a) Exploded view illustration of electrochemical-mechanically triggered transient system. Optical image of an (b) electrolysis electrode and (c) Si_3N_4 membrane. (d) The assembled module with that two components and etching solution.

The corrosive solution that was made by a mixture of Copper etchant (CE-100, Transene Co. Inc) and 10% NaCl solution (1 to 9 volume ratio). The controllable solution release module is accomplished by packaging the solution in the reservoir with the electrolysis electrode glass substrate as a seal. The reservoir and the glass substrate were bonded by UV curable adhesive (LOCTITE AA363) with 365nm of UV light exposure for 10min. The alignment was completed under an optical microscope with an accuracy of 10 µm. The assembled module with the two components and etching solution is shown in Figure 2d. The transient system was finally completed by assembling the functional electronic devices with the controllable solution release module, as shown in Figure 2a. In this study, we primarily employed Cu based resistor and indium gallium zinc oxide (IGZO) based field effect transistor as prototype functional electronic devices.

The fracture of Si_3N_4 membrane is of importance to ensure the designed operation of the transient system. The representative process of the Si_3N_4 membrane deformation, burst and fracture process is illustrated by the sequential optical images in Figure 3a. The gas (H_2 and Cl_2) were generated upon applying DC voltage bias at 5V to hydrolyze the solution. Accumulated gas will induce increased pressure within the reservoir and therefore deform the Si_3N_4 membrane. The Si_3N_4 membrane will fracture once the pressure reaches the critical value, where the strain within the membrane reaches fracture limit (1%). Due to brittle nature of the membrane, it bursts and fractures to fragments. Mechanical simulations of the membrane displacement and associated maximum strain depending on pressure were performed to facilitate the understanding of the operation of this transient electronics system. Figure 3b shows the finite element analysis result of the strain contour of the Si_3N_4 membrane (600µm x 600µm dimension and 400nm thick) deformation under 5MPa of gas pressure.

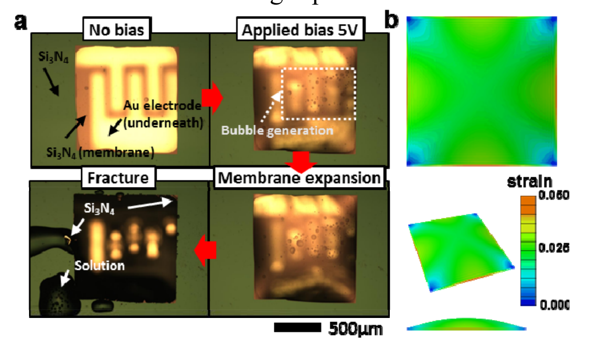

Figure 3: (a) The sequential optical microscope image of fracture process of Si_3N_4 membrane that is suspended by tetrahedrically bracing. (b) Finite element analysis result of the strain contour of the Si_3N_4 membrane deformation under 5MPa of gas pressure

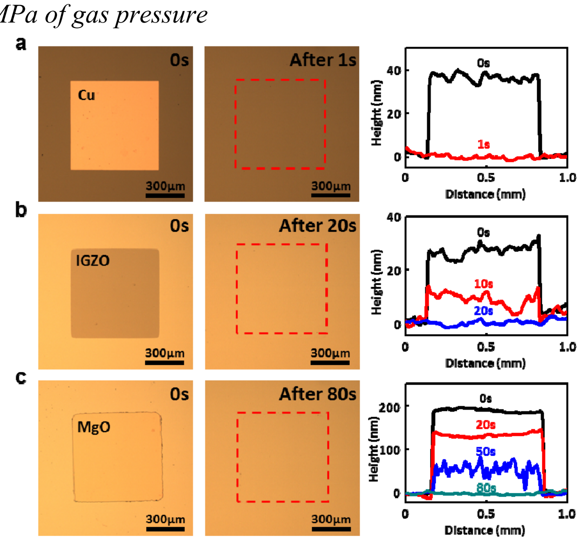

Figure 4: Optical microscope images and surface profiling results before and after etching by the corrosive solution for electronic component membrane; (a) Cu, (b) IGZO, and (c) MgO.

In order to demonstrate the feasibility of the transience system, functional electronics based on Cu, IGZO, and MgO for resistor and transistors were chosen, where the electronics can be simply attacked by acidic etching solution. We first character the transience of all three materials involved in this study. Figure 4a exhibits optical images (left and middle frames) and surface profiling results (right frame) of 40nm thick Cu membrane formed by e-beam evaporation. As shown in the middle frame of Figure 4a, it took about 1 sec to completely etch away the Cu. Thickness profiles under a profilometer before (black curve) and after (red curve) is confirmed as indicated in the right frame of Figure 4a. Similarly, we also characterize the transience of the semiconductor and dielectrics. IGZO is a promising semiconducting oxide material that has high electron mobility. DC magnetron sputtered IGZO membrane (30nm thick) was completely etched after 20 sec (Figure 4b). Optical microscope images and surface profiling results in figure 4c show that e-beam evaporated MgO dielectric also completely disappeared after etching for 80 sec.

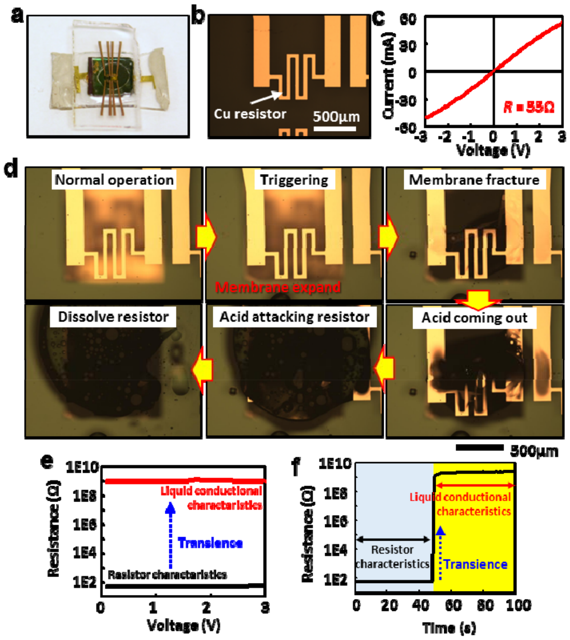

Figure 5: Transience behavior of Cu resistor with electrochemical-mechanically triggered system. (a) The Camera image of Cu resistor based transient system. (b) OM image and (c) electrical performance of Cu resistor. (d) The sequential optical microscope image of Cu resistor transience. (e and f) Electrical performance transience Transient process by triggering.

A resistor, based on 50nm thick Cu, was prepared by e-beam evaporation and patterning as one example. Figure 5a shows the transient system with a Cu resistor. Figure 5b shows an optical image of the Cu resistor, whose I-V curve indicating of electrical resistance of 55 Ω is illustrated in Figure 5c. The device transience was demonstrated by a sequence of optical images as shown in Figure 5d. The Si_3N_4 membrane is first deformed as the system is triggered via the electrolysis electrodes due to gas pressure increase. The membrane finally fractured and corrosive solution released to the Cu resistor. The attacking of corrosive solution to the resistor proceeded rapidly and complete dissolution of the resistor was achieved within less than 2 sec. Figures 5e and 5f shows static and dynamic resistance change before and after triggering the system. After triggering, the resistor dissolved immediately and the resistance increased significantly to several GΩ that matches the conductance of the liquid.

The field effect transistor as a fundamental building blocks for integrated circuits were also demonstrated in the transient system. The transistor consists of IGZO for semiconducting oxide, MgO for gate dielectrics layer, and Cu for source, drain, and gate electrodes. In order to fabricate IGZO based FETs, first the Cu layer for the source and the drain electrode was deposited by electron beam evaporation and patterned using photolithography and followed by wet etching in Cu etchant. Then 30nm thick a-IGZO, served as semiconductor channel layer, was formed by a DC magnetron sputtering under 20W of power and 4% of oxygen partial pressure to Argon using $InGaZnO_4$ target through a shadow mask. The MgO gate dielectric was deposited by electron beam evaporation through another shadow mask. Subsequently, the Cu gate electrode was deposited by electron beam evaporation directly on top of the channel region through a shadow mask.

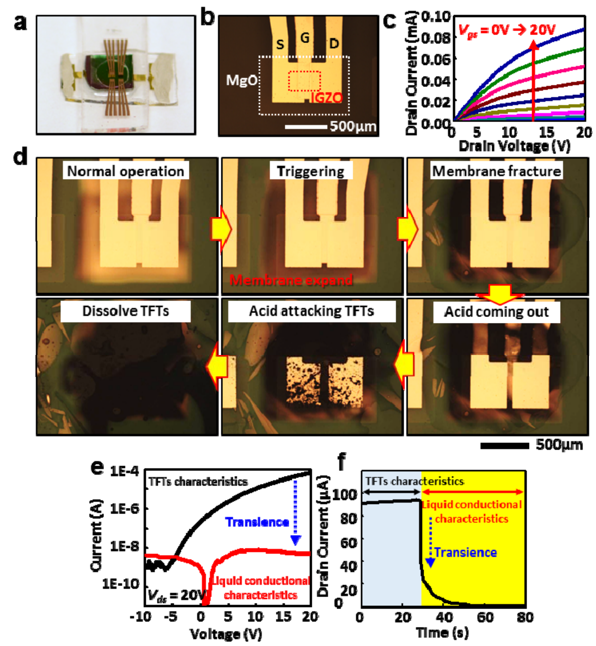

Figure 6: Transience behavior of IGZO based field effect transistor with electrochemical-mechanically triggered system. (a) The Camera image of IGZO TFTs based transient system. (b) OM image and (c) electrical performance of IGZO. (d-f) Transient process by triggering.

Figure 6a and b show the transient system and the top gated IGZO based TFTs. Figure 6c shows the output characteristic curves for the n-channel transistor with 0V to 20 V of drain voltage sweeping. The gate bias changes from 0 V to 20 V with an increment step of 2 V. Figure 6e (black line) shows its corresponding transfer characteristics with gate voltage sweeping from -10V to 20V at 20V of constant drain voltage. The extracted field effect mobility, threshold voltage, on/off current ratio, and subthreshold swing is 2.24 $cm^2/V.s$, 4.7 V, 8.36×10^4, and 2.10 V/dec, respectively. The device transience process follows the same mechanism that is described above. The triggered transience operation process of the transistor is illustrated by the images in Figure 6d. Figure 6e shows the device characteristics before and after the transient process. After triggering for about 3 sec, the transistor completely dis-functioned. The low level of the current is induced by the solution. The drain current change as a function of time is shown in Figure 6f. Although complete dissolution requires a longer period of time, approximately 60 sec, due to different dissolution rates of various materials, the device dis-functioned in a much shorter period of time.

CONCLUSION

In conclusion, the electrochemical-mechanically triggered transient device developed in this study represents a new construct of transient electronics which is featured by low voltage triggering and rapid transience. Although Cu resistors and IGZO based FETs are only demonstrated to illustrate the device transience, the transient system is applicable to other devices such as integrated circuits, memory, sensors, actuators, etc.

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