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Paper-Based, Capacitive Touch Pads

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This paper describes low-cost, thin, and pliable touch pads constructed from a commercially available, metallized paper commonly used as packaging material for beverages and book covers. The associated electronics with the individual keys in the touch pads detect changes in capacitance or contact with fingers by using the effective capacitance of the human body and the electrical impedance across the tip of a finger. To create the individual keys, a laser cutter ablates lines through the film of evaporated aluminum on the metallized paper to pattern distinct, conductive regions. This work includes the experimental characterization of two types of capacitive buttons and illustrates their use with applications in a keypad with 10 individually addressable keys, a keypad that conforms to a cube, and a keypad on an alarmed cardboard box. With their easily arrayed keys, environmentally benign material, and low cost, the touch pads have the potential to contribute to future developments in disposable, flexible electronics, active, "smart" packaging, user interfaces for biomedical instrumentation, biomedical devices for the developing world, applications for monitoring animal and plant health, food and water quality, and disposable games (e.g., providers of content for consumer products).

There is no simple method of integrating buttons with structures on single-use or throw-away devices. Current commercial buttons are not thin enough, inexpensive enough, or easy enough to array seamlessly with paper-based products for disposable applications. The touch pads in this work are thin (~60 μm in some cases), simple to array, fabricated by etching patterns into metallized paper, low-cost (<\$0.25 m^{-2} for the thin grade of metallized paper we use in this work), and lightweight (100s of g m^{-2}). The individual keys measure changes in capacitance when touched by a user, and the buttons require no physical displacement of conductive elements. Even though the individual keys on the touch pads detect changes in capacitance, the paper-based keypads are still functional when touched by fingers in nitrile gloves.

Developments in paper-based electronics include ring oscillators with organic electronics,[1] transistors,[2–4] methods for patterning conductive traces,[5–7] speakers,[8] supercapacitors,[9] batteries,[10] MEMS,[11] and solar cells.[12] Each of these developments focuses on a single technological advance that would enable new types of consumer products. Many types of new consumer products will require some form of user interface or input. In order to gather key strokes from end users with polymer-based or textile-based flexible electronics, it is possible to use changes in resistance[13] or capacitance.[14–17] Obviously, technology being developed commercially–Samsung, 3M, Displax, Elo TouchSystems, and other companies are pursuing technology for transparent touch-based systems–for use with glass-based displays on mobile phones or computer screens might also be applicable to future developments in one-time use, paper-based electronics. Conventional capacitive touch screens detect changes in capacitance through a piece of glass with a thickness much greater than that of the polymeric coatings on top of the metallized paper. Thus, instead of detecting changes in capacitance of 10s or 100s of pF, they use optimized electronics to detect changes closer to 1 pF. Besides a patent for capacitive buttons on posters,[18] there are no descriptions for simple methods of receiving input/key strokes on paper-based substrates.

Metallized paper is a commodity. It is easy to ablate or cut the metal film with a laser or razor blade, and paper is both durable (i.e., documents can last for years) and disposable. Touch pads made from metallized paper may fill a niche between displays with touch screens and conventional commercial keypads. The metallized paper (A-238 and A-550 from Vacumet Corporation) consists of cellulose, polymeric coatings, and evaporated aluminum (see Supporting Information (SI) **Figure 1**). The cellulose serves primarily as structural support for a ~10-nm thick, conductive layer of evaporated aluminum. The metallized layer without structural support would not have sufficient strength for manual handling or use. The polymer-based portions of the paper assist in adhering the metallized layer to the cellulose and protect the thin, metallized layer from scraping or other environmental damage. The uncoated side of the metallized paper has exposed cellulose-based paper, which can absorb moisture, while the polymeric coating on the opposite side of the paper blocks moisture. Nevertheless, using the laser cutter to ablate through the polymeric coating can make the metallized paper more susceptible to moisture on the coated side. Experiments have also shown

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DOI: 10.1002/adma.201200137

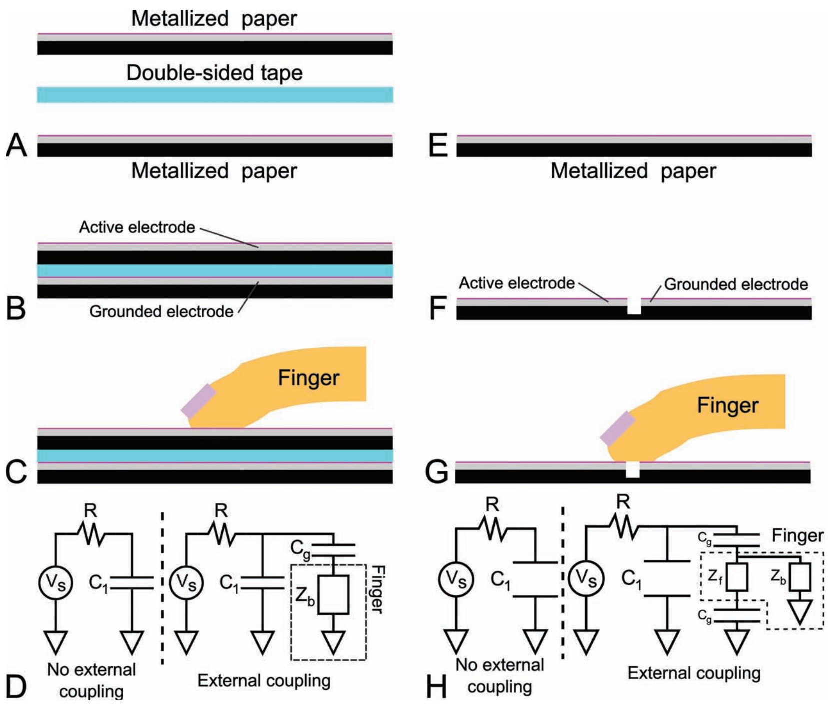

Figure 1. Schematic layouts for two types (A-D and E-H) of capacitive keys made with metallized paper. (A) Components for a two-layer key based on capacitive coupling between a finger and an active electrode. (B) Assembled capacitor from components shown in A. (C) A finger serves as an external, electrical coupling to the active electrode. (D) Description of the electrical circuits without (left) and with (right) the coupling of the finger to the active electrode. *R* is the value of the resistor placed in series with an untouched button with effective capacitance of C_1. The source of electric potential (V_s) applies a stepped, repeating pattern to the circuit. (E) Metallized paper used for single-layer touch pads. (F) Etched or ablated lines through the conductive portion of the metallized paper designate regions or traces of conductance. (G) A finger bridges the gap between an active electrode and a grounded electrode to cause a measurable change in capacitance. (H) Description of the electrical circuits without (left) and with (right) the coupling of the finger to the electrodes.

that a paper-based button exposed to moisture can exhibit a change in effective capacitance (see SI).

A button or key on a touch pad is a physical device that signals a single, binary change in state when touched by a user, and returns to its original state when no longer touched. To array buttons on metallized paper, we used a laser cutter (VersaLaser from Universal Laser Systems) to ablate lines through the aluminized layer of the paper to create discrete, conductive regions. These conductive regions served as both electrodes for the buttons and conducting traces that lead to external electronics.

Each button on the touch pads described in this work is a capacitor. The individual capacitors, or buttons, have a capacitance–the ratio of storable charge to the applied electric potential–that changes when touched with a finger. Between parallel plates, capacitance (C) scales with the inverse of the gap (Equation 1), where ε is the dielectric constant of the material separating the plates, ε_o is the permittivity of free space (8.854×10^{-12} F/m), A is the cross-sectional area of the plates, and d is the distance between plates.

$$C = \varepsilon \varepsilon_o A/d \quad (1)$$

In the case of capacitive coupling of a finger to a parallel-plate capacitor, we consider the finger to contribute electrical impedance (Z_b) (see Figure 1A-D). This electrical impedance acts as a "body capacitor" with an approximate capacitance of 100 pF and an approximate resistance of 1.5 kΩ.[19] Because of the polymer coated on the top surface of the metallized paper, the finger does not make direct, conductive contact with the top plate of the capacitor. As the finger approaches the polymeric coating above the metallized layer, the capacitance between the finger and the top plate of the button (C_g) increases. When the finger makes contact with the button, the body capacitor then makes a significant, detectable contribution to increasing the effective capacitance measured at the button.

Buttons using parallel-plate capacitors require two sheets of metallized paper. The bottom sheet (not touched with a finger) serves as a grounded electrode, while the top sheet (touched with a finger) carries an applied potential and is electrically active. To create buttons on a single sheet of metallized paper, we patterned active and grounded electrodes adjacent to each other (Figure 1F). A finger can bridge between the active electrode and grounded electrode on a single side of metallized paper (Figure 1G). For a single button with a single sheet of metallized paper, assigning either of the electrodes to ground would not make a difference provided the areas of the electrodes are comparable. Nevertheless, a single sheet of multiple buttons benefits from having a single grounded electrode that surrounds all of the buttons without the need for individually grounded traces running to each button.

The change in electrical impedance with a finger bridging between the grounded and active electrodes is a result of the skin acting as a dielectric material and the ionic solution within or on the surface of the finger acting as a conductive material. The dominant electrical path from one metallized electrode to an adjacent electrode goes from a metallized electrode, through the insulating coating on the metallized paper, through or along the surface of the finger, through the insulating coating above the adjacent electrode, to the metallized layer on the adjacent electrode. The electrical impedance through or along the surface of the human finger (Z_f) acts in parallel with the impedance (Z_b) through the finger and the body of the person. Given our objective and microprocessor-based method of detecting on/off touches, we model the variable impedance of each key as having an effective capacitance or time constant associated with an "RC-circuit" (see SI Figure 3).

To aid our understanding of the interaction of a finger with our capacitive buttons, we have detected touches successfully with gloved human fingers and non-human finger-portions of nitrile gloves filled with aqueous solutions. Human fingers in gloves (Sterling nitrile powder-free examination gloves from Kimberly-Clark) caused smaller changes in capacitance than those observed with bare human fingers, but the changes in capacitance with human fingers in gloves were still measurable. The layer of rubber between the finger and the conductive layer of the metallized paper increased the distance between the finger and the electrodes (relative to a bare finger touching a button) and thus, caused a reduction in the overall measured capacitance. The finger-portion of a glove filled with an aqueous solution (deionized water in one case and ~150 mM NaCl in another) also registered responses with the system shown in SI Video 1. For both cases (glove filled with deionized water and glove filled salt water), the apparent change in capacitance was less than that with a gloved finger. The reduced change in capacitance may have been from the effective thickness of the glove being greater than that of human skin, reduced conductivity of the aqueous solution, or increased resistance in the path to electrical ground through the liquid-filled portion of the glove. In contrast to a liquid-filled glove, an air-filled glove registered almost no observable change in capacitance when pressed against a key (i.e., capacitive buttons would rarely trigger a response by lighting an LED). We attribute these spurious readings to the accumulation of surface charge on the outer surface of the glove.

Vacumet Corporation evaporates approximately 0.05 g/m^2 of aluminum onto papers of different thicknesses. Assuming a density of 2700 kg/m^3 for aluminum, the thickness of the layer of evaporated aluminum is less than 20 nm. The two grades of metallized paper used in this work have specified average thicknesses and ranges of 56 ± 6 µm and 137 ± 5 µm. These specified thicknesses include paper, coatings of polymer, and evaporated aluminum (see SI Figure 1). By measuring the electrical resistance of different cut sheets of metallized paper, we estimate the average thickness and standard deviation of the evaporated aluminum to be 13 ± 2 nm (see SI Figure 2).

Figure 1A-D show the configuration for keys based on coupling between a finger and a parallel-plate capacitor with two layers of metallized paper. To fabricate two-layered buttons, we etched the traces and cut out the overall dimensions of the sheets of metallized paper using a laser cutter. Once cut, we used double-sided tape (Indoor Carpet Tape from 3M) to hold the pieces of metallized paper together. We brushed on silver conductive adhesive (Silver Conductive Adhesive 503 from Electron Microscopy Sciences) to connect traces or tabs on the metallized paper electrically with external electronics through conductive pads or wired leads

To measure the changing effective capacitance of the buttons and demonstrate interactive applications using paper-based touch pads, we used the Arduino platform (UNO and MEGA 2560). Arduino is a microprocessor-based system with open-source hardware and software for signal processing and computation (see http://www.arduino.cc/). The Arduino platform has also demonstrated its utility for applications with flexible or wearable electronics.[20] The Arduino is capable of applying a step input to a resistor and capacitor in series and measuring the time required for the potential on the capacitor to reach 2 V (see an example at http://arduino.cc/it/Tutorial/CapacitanceMeter and the Supporting Information for code used in SI Video 1). Using this measured time, it is possible to estimate an "RC" time constant and calculate an effective capacitance for a circuit with a known resistance (see SI Figure 3). The typical resistance for the resistor placed in series with a button was 100 kΩ or 1 MΩ. To buffer the potential across the capacitor against the impedance of the inputs leading to the Arduino, we used an operational amplifier (LM324) with unity gain. We also used a demultiplexing chip (TI CD4067BE 1:16) addressed with four binary outputs to measure the responses of 10 to 48 individual buttons with only one to three electrical inputs. The Arduino-based system and accompanying electronics required about 0.4 W, even though an estimate for the power required for an individual button of 100 pF is 250 nW (see SI for both estimates).

At this point, the electronics for detecting changes in capacitance are neither mechanically compliant nor inexpensive enough to be considered disposable after a single use. The packaged electronics might plausibly be multiple-use with only the paper-based system being disposable. It is also conceivable that the electronics could be made inexpensive enough through mass-production and conventional techniques for fabricating semiconductor-based circuits (e.g., disposable RFID tags and cell phones are representative efforts to produce low-cost, complex electronic systems). To make the required circuits flexible, DuPont™ Pyralux® or the metallized paper itself might serve as a flexible substrate. Nevertheless, we envision applications, which might use reusable electronics for interfacing the disposable touch pads with standard protocols for communication with personal computers or commercial electronic databases (e.g., a small box with reusable electronics for sensing and wireless transfer of data might ship multiple times with distinct disposable touch pads and packaging).

To test our touch pads, we constructed single buttons (**Figure 2**). One button consisted of parallel plates (Figure 2A and B), while the other button consisted of a single layer of metallized paper with etched traces to form inter-digitated electrodes, or macroscopic buttons that were easy to touch (Figure 2D and E). We mounted the buttons to a manila folder with double-sided tape, connected the electrical leads of the buttons to an Arduino-based system, and used the serial output from the Arduino to log data on a laptop computer. Figure 2C and F show the measured effective capacitances in a box plot–based on the time required for the potential across the capacitive button in series with a resistor of 1.01 MΩ to reach 2 V with a step input of 5 V–measured over five seconds of sampling for seven untouched buttons and seven touched buttons with an index finger from a single user. The touch button with a single sheet of metallized paper was more sensitive than the touch button with two sheets (see SI for more details). Touch buttons in a single sheet are also easier to construct than touch buttons in a two-layer configuration (i.e., no need to align and bond two layers of metallized paper to each other).

To demonstrate the functionality of the touch button in Figure 2D, we pressed the button shown over 2000 times, and it continued to function reproducibly without exhibiting drift (i.e., it was not necessary to adjust the threshold of detection. That said, we have implemented a scheme for other touch pads with moving averages for the thresholds on the Arduino to ensure proper responses over extended periods of time (see http://www.arduino.cc/en/Tutorial/Smoothing and included code for SI Video 1 in the Supporting Information). We also measured the response of the button to hundreds of presses with a bare

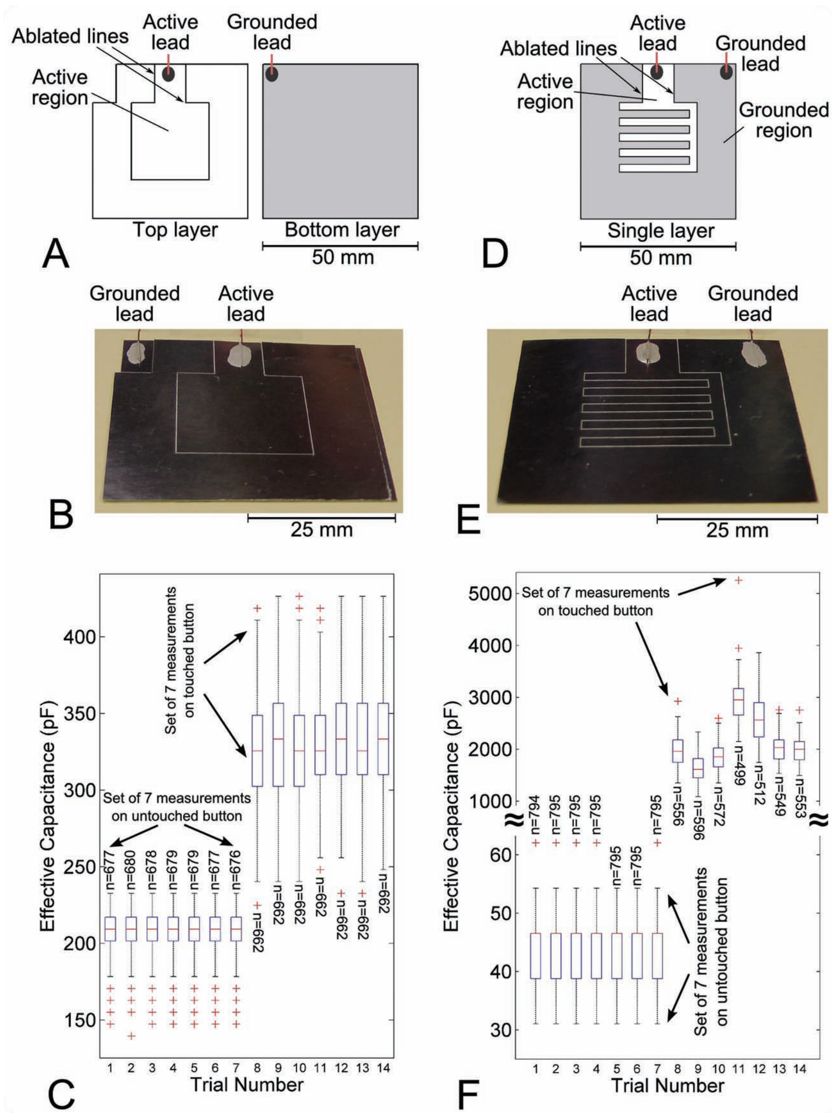

Figure 2. Capacitive buttons fabricated with metallized paper. (A) The top piece was Vacumet A-238 (thickness of 56 μm) with etched lines outlining the touched, active region, and the bottom piece (grey) was Vacumet A-550 (thickness of 137 μm) and served as an electrical ground. Manually cut pieces of double-sided tape bound the two pieces of metallized paper together. (B) Photo of the button shown in A. (C) Box plots for the effective capacitance of the button shown in B for two sets (touched with a bare finger and untouched) of seven measurements, each lasting five seconds and having more than 660 sampled points ($n > 660$). The whiskers extend 1.5 X the interquartile length dictated by the distance between the top (75^{th} percentile) and bottom (25^{th} percentile) of the boxes. The horizontal line in the box shows the median, and the crosses represent outliers. (D) A single piece of Vacumet A–238 etched with inter-digitated fingers forming a button. The greyed region served as electrical ground. (E) Photo of the tested button shown in D. (F) Box plot for the effective capacitance of the button shown in E for two sets (touched and untouched) of seven measurements, each lasting five seconds and having more than 490 points ($n > 490$). The attributes of the box plot are the same as those in C, except the median is at the top of the box for the untouched cases.

finger and a gloved finger (nitrile-based glove from Kimberly-Clark). **Figure 3** shows some of the measurements taken with the Arduino-based system after the button had already received more than 1000 presses. The red crosses shown in Figure 3A and B indicate when the Arduino-based system detected a change in the state of the button relative to a fixed threshold of an effective capacitance of 78 pF. Figure 3C and D show the distribution of peak values in measured capacitance during each press. The touches with a finger in a gloved hand elicited a much smaller change in capacitance than that observed with a bare finger, and future improvements in electronics might improve sensitivity to gloved fingers.

To make a keypad with ten buttons (**Figure 4**), we ablated lines in a piece of Vacumet A-238 (thickness of 60 μm) to form conductive traces and inter-digitated regions for ten separate keys. After ablating the lines in the metallized paper, we attached the keypad to a manila folder with double-sided tape. To connect the keypad to external electronics, we attached 30-gauge wire to each of the contact pads (ten contact pads for the keys and one contact pad for the ground) with conductive paste. To address the separate keys, we used an input and five outputs (one output supplied a stepped signal to the RC circuits and the other four addressed a demultiplexer) on the Arduino. The stepped signal from the Arduino went through the same resistor for all ten keys but went through a separate capacitive region as dictated by a 1:16 demultiplexer (TI CD4067BE). Figure 4C shows measurements taken when a gloved finger touched each key individually, touched keys "0" and "1" simultaneously, and touched keys "1" and "2" simultaneously. With another 10-button keypad mounted to a piece of plastic (see SI Video 1), more than 25 different people were all able to trigger the appropriate LEDs to respond with the touch of their bare fingers.

To demonstrate the fabrication of a three-dimensional keypad from a two-dimensional patterned piece of metallized paper, we ablated lines in a piece of Vacumet A-550 (thickness of 140 μm) and created traces for six individual buttons as shown in **Figure 5**A. Then, we gently folded (sharp creases could cause a break in electrical conductivity) the two-dimensional pattern around a cube to form the three-dimensional keypad shown in Figure 5B and C. Using the Arduino-based electronics and the same demultiplexer used for the keypad with 10 buttons, the three-dimensional keypad detected touches with either bare or gloved fingers and lit corresponding LEDs (see SI Video 2).

The paper-based touch pads described in this work may be useful as active packaging to prevent theft of the contents of containers. To demonstrate a possible implementation (see **Figure 6** and SI Video 3), we attached a piece of metallized paper (thickness of 60 μm) with a 10-button keypad and two LEDs to a cardboard box with double-sided tape (Figure 6A and

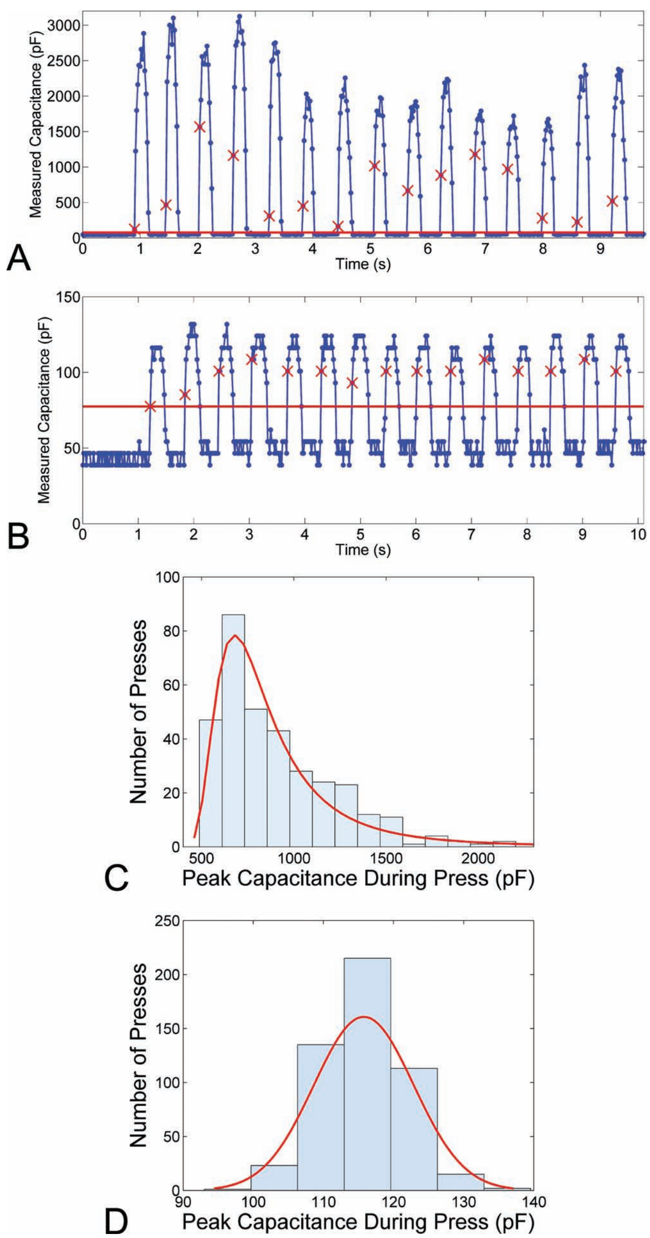

Figure 3. Measured changes in capacitance for the capacitive button shown in Figure 2D after the button had already experienced more than 1000 touches. (A) Measurements taken with a bare finger touching the button. The ticks show when the electronic system registered a capacitance greater than or equal to the threshold of 78 pF. The red baseline shows the threshold set at 78 pF. (B) Measurements taken with a gloved finger and the same threshold (red baseline) shown in A. (C) The distribution (general extreme value) of peak capacitances measured during 335 presses of the button with a bare finger. The data had a minimum measured peak at 490 pF. (D) The distribution (normal) of peak capacitances measured during 504 presses of the button with a gloved finger. The mean was 120 ± 7 pF (± 1 standard deviation) for 504 presses, and the minimum peak measured was at 93 pF.

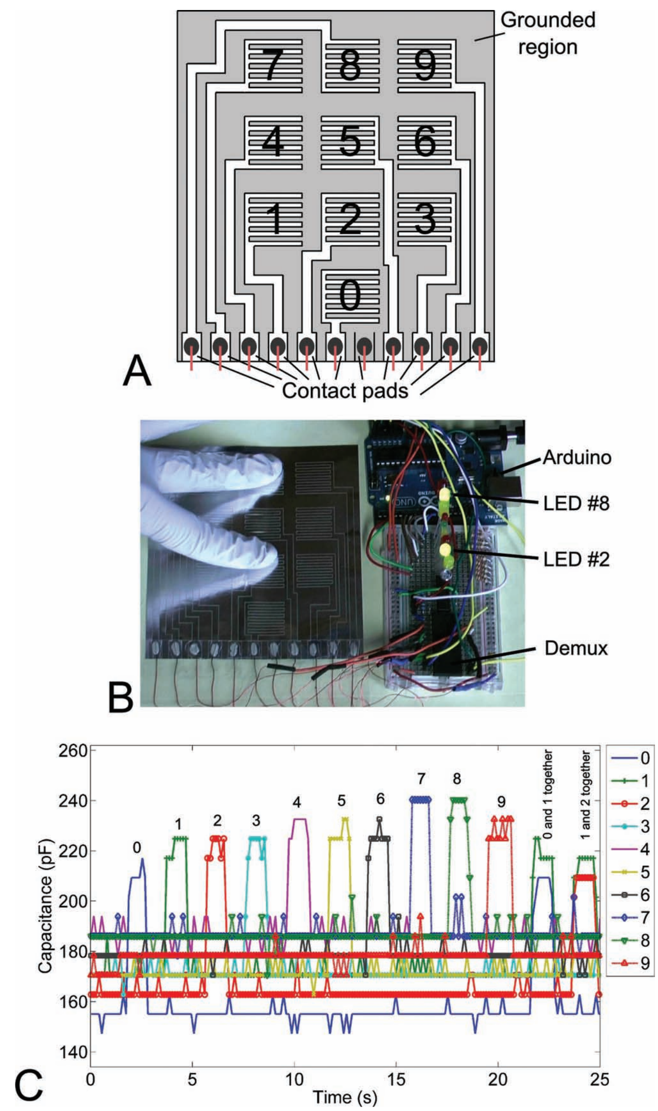

Figure 4. Touch pad with 10 keys that produced measurable changes in capacitance when touched with a bare or gloved finger. (A) The single layer (105 mm × 116 mm) comprises discrete keys (17 mm × 19 mm) with metallized traces leading to contact pads for connection to the Arduino-based system. (B) Photo of the completed keypad being touched with two gloved fingers on key "2" and key "8". (C) Measured responses at each of the 10 buttons to touches with a gloved finger. The change in capacitance was greater with a bare finger than that measured with a gloved finger.

B). The keypad served as the user interface to arm or disarm an alarm "built" into the box.

When armed, the LEDs were off. Opening the top lids on the box caused a decrease in the capacitance between the two pieces of metallized paper taped to the lids (capacitive switch). This decrease in capacitance, unlike the increases experienced by the buttons when touched with a finger, triggered the alarm, sounded a buzzer, and lit up both LEDs on the metallized paper. For purposes of demonstration, closing the lids caused the alarm to stop sounding.

To disarm the alarm, the user entered a numeric code by touching the keys on the keypad. With every press of one of the keys, the blue LED would flash to provide visual feedback to the user. To demonstrate the functionality of all the keys in SI Video 3, we set the password to "0,1,2,3,4,5,6,7,8,9". When disarmed,

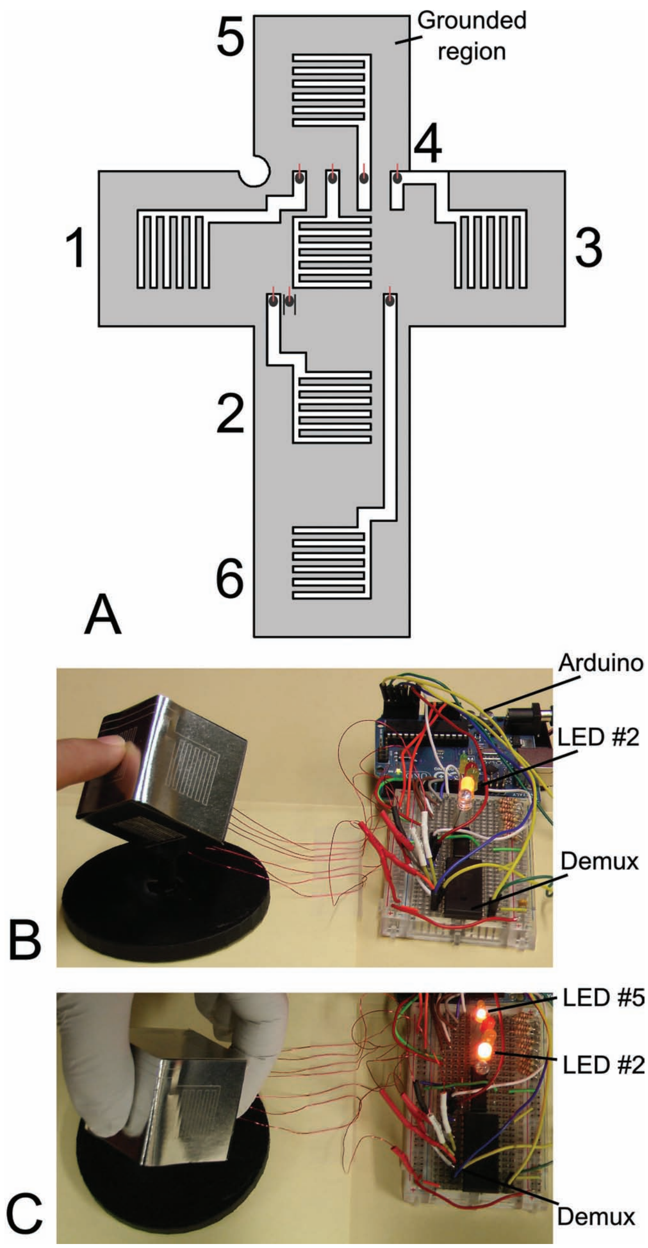

Figure 5. Paper-based touch pad fixed to a cube. (A) Layout for six buttons—one button for each face. Each edge of the cube has a length of 38 mm. (B) Image and associated output for a bare finger touching the button on face number "2". (C) Image and associated output for a gloved thumb and index finger making simultaneous contact with buttons number "5 and "2".

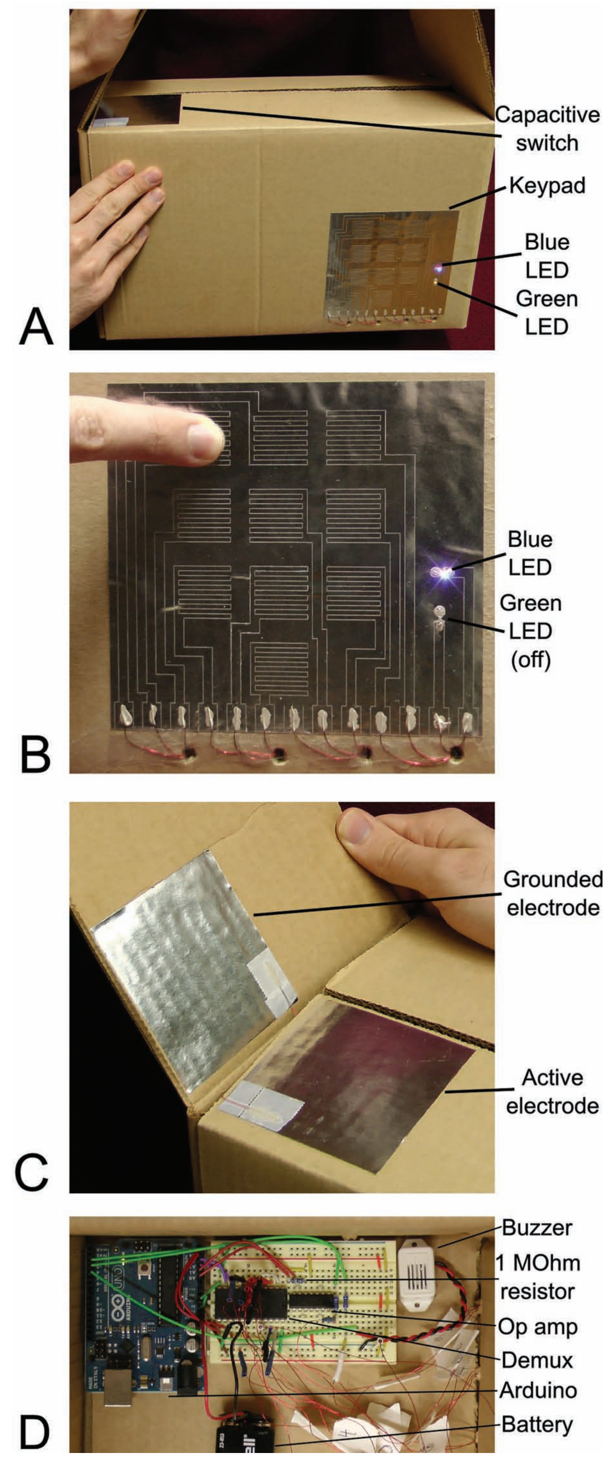

Figure 6. An alarmed cardboard box with a paper-based touch pad. (A) On an outside face of the box, the paper-based touch pad had accompanying LEDs to provide feedback to the user. Both LEDs turned on when the alarm went off. In the upper left region, there was a capacitive switch to detect whether or not the box was open. (B) The keypad and accompanying LEDs. The keypad had to receive the appropriate code to disable the alarm. The blue LED flashed whenever a button was pushed. (C) Close-up photo of the capacitive switch. (D) All the required electronics inside the box for operating the alarm. The buzzer sounded when the alarm went off.

the electronics lit the green LED, and opening the box did not trigger the alarm. To arm the alarm from the disarmed state, a user hit any button on the keypad, and the LEDs returned to an unlit state.

Capacitive sensing and metallized paper provide a low-cost solution for integrating electronic interfaces with paper-based products. The paper-based keypads in this work are disposable, are as a thin as 60 µm, are simple to etch in a single layer of metallized paper, and can consist of arrays of button. The keypads respond to both bare and gloved fingers, but performance is more reliable with bare fingers. Paper that serves as a structural support for very thin layers of metal (approximate thickness of 10 nm) has the potential to provide solutions for future developments in sensors and flexible electronics.

Supporting Information

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

Acknowledgements

This work was supported by Defense Advanced Research Projects Agency (DARPA) N/MEMS S&T Fundamentals Program under grant no. N66001-1-4003 issued by the Space and Naval Warfare Systems Center Pacific (SPAWAR) to the Micro/nano Fluidics Fundamentals Focus (MF3) Center, the Gates Foundation, and DARPA Transient Electronics grant no. W911NF-11-1-0254. In addition, we would like to thank Steven A. Morin, Sam Liss, Adam A. Stokes, Jabulani R. Barber, Robert F. Shepherd, and Courtney Hilliard for helpful discussions. We would also like to thank Joe Formosa and Vacumet Corporation for providing samples of metallized paper.

Received: January 11, 2012
Published online: April 27, 2012

[1] F. Eder, H. Klauk, M. Halik, U. Zschieschang, G. Schmid, C. Dehm, *Appl. Phys. Lett.* **2004**, *84*, 2673.
[2] R. Martins, A. Nathan, R. Barros, L. Pereira, P. Barquinha, N. Correia, R. Costa, A. Ahnood, I. Ferreira, E. Fortunato, *Adv. Mater.* **2011**, *23*, 4491.
[3] S. Yun, S. D. Jang, G. Y. Yun, J. H. Kim, J. Kim, *Appl. Phys. Lett.* **2009**, *95*.
[4] R. Martins, P. Barquinha, L. Pereira, N. Correia, G. Goncalves, I. Ferreira, E. Fortunato, *Appl. Phys. Lett.* **2008**, *93*.
[5] A. Russo, B. Y. Ahn, J. J. Adams, E. B. Duoss, J. T. Bernhard, J. A. Lewis, *Adv. Mater.* **2011**, *23*, 3426.
[6] A. C. Siegel, S. T. Phillips, M. D. Dickey, N. S. Lu, Z. G. Suo, G. M. Whitesides, *Adv. Funct. Mater.* **2010**, *20*, 28.
[7] D.-H. Kim, Y.-S. Kim, J. Wu, Z. Liu, J. Song, H.-S. Kim, Y. Y. Huang, K.-C. Hwang, J. A. Rogers, *Adv. Mater.* **2009**, *21*, 3703.
[8] H. Tian, T. L. Ren, D. Xie, Y. F. Wang, C. J. Zhou, T. T. Feng, D. Fu, Y. Yang, P. G. Peng, L. G. Wang, L. T. Liu, *ACS Nano* **2011**, *5*, 4878.
[9] Z. Weng, Y. Su, D. W. Wang, F. Li, J. H. Du, H. M. Cheng, *Adv. Energy Mater.* **2011**, *1*, 917.
[10] L. B. Hu, H. Wu, F. La Mantia, Y. A. Yang, Y. Cui, *ACS Nano* **2010**, *4*, 5843.
[11] X. Liu, M. Mwangi, X. Li, M. O'Brien, G. M. Whitesides, *Lab on a Chip* **2011**, *11*, 2189.
[12] M. C. Barr, J. A. Rowehl, R. R. Lunt, J. J. Xu, A. N. Wang, C. M. Boyce, S. G. Im, V. Bulovic, K. K. Gleason, *Adv. Mater.* **2011**, *23*.
[13] R. K. Kramer, C. Majidi, R. J. Wood, presented at 2011 IEEE International Conference on Robotics and Automation (ICRA), Shanghai, China, May, 2011
[14] D. Cotton, I. M. Graz, S. P. Lacour, *Sensors Journal, IEEE* **2009**, *9*, 2008.
[15] A. R. Deangelis, D. B. Wilson, B. A. Mazzeo, US Patent 7,578,195, 2009.
[16] A. R. Deangelis, B. D. Wilson, B. A. Mazzeo, US Patent 7,395,717, 2008.
[17] A. R. Deangelis, B. D. Wilson, B. A. Mazzeo, US Patent 7,301,351, 2007.
[18] R. Hagglund, T. Unander, A. From, P. Wagberg, US Patent App. 2007/0018998 A1, 2007.
[19] *ESD Fundamentals*, ESD Association, Rome, NY 2010.
[20] L. Buechley, M. Eisenberg, *Pervasive Computing, IEEE* **2008**, *7*, 12.