Touchscreen tags based on thin-film electronics for the Internet of Everything

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Capacitive touchscreens are increasingly widespread, featuring in mobile phones and tablets, as well as everyday objects such as cars and home appliances. As a result, the interfaces are uniquely placed to provide a means of communication in the era of the Internet of Everything. Here, we show that commercial touchscreens can be used as reader interfaces for capacitive coupled data transfer. The transfer of data to the touchscreen is achieved using a 12 bit thin-film capacitive radio-frequency identification tag powered by a thin-film battery or a thin-film photovoltaic cell that converts light from the screen. The thin-film integrated circuit has a 0.8 cm² on-chip monolithic antenna, employs 439 transistors and dissipates only 31 nW of power at a supply voltage of 600 mV. The chip has an asynchronous data rate of up to 36 bps, which is limited by the touchscreen readout electronics.

In the Internet of Things (IoT), millions of devices are connected to cloud-based services via different wireless communication protocols, including WiFi, Bluetooth Low Energy and 4G/5G, embedded on one or several silicon complementary metal–oxide–semiconductor (CMOS) chips. To enable the transition from the IoT to the Internet of Everything (IoE), everyday items need to be equipped with wireless communication chips that are low-cost and seamlessly integrated. Thin-film transistor (TFT) technology on plastic substrates is a promising candidate to provide these IoE communication functions. In particular, this technology can provide flexible radio-frequency identification (RFID) tags1–9 that can be concealed in numerous different objects, such as paper tickets, official letters, certified documents and payment cards.

In proposed implementations of the IoE, a device/reader serves as a hub that connects everyday items and objects via short-range communication (RFID) to the cloud. One initial potential scenario uses a TFT-based near-field communication (NFC) chip9,10, as many people have access to phones and tablets equipped with an accessible NFC reader. However, the number of connected NFC-enabled devices is still relatively small compared to the wide availability of touchscreens; thus, with the right communication technology, touchscreens could play a key role in delivering the IoE11.

Although initially unforeseen12, a capacitive touchscreen can now be considered as a data communication medium for objects equipped with an identification chip. Data transfer occurs via the capacitive antennas present on the chip and touchscreen. Capacitive communication offers many advantages, including security (due to the very short communication range13), low cost (due to the possibility of monolithically integrating antennas with no need for assembly and extra antenna substrate) and widespread compatibility (due to the presence of capacitive touchscreens in everyday devices such as cars, refrigerators and coffee machines).

Novel forms of touchscreen interaction have already been demonstrated by combining Si-CMOS chips and non-conventional off-the-shelf components such as bipolar transistors, mechanical relays and tri-state buffers15–16. Such non-conventional components are selected for the high off-state resistance required to virtually switch off a touch event, mimicking release of a finger from the screen and limiting the potential for a monolithic low-cost Si-CMOS solution. Metal–oxide TFT technologies exhibit a very low off-current leakage1, which can be translated into a substantially high off-resistance interface to the screen. In addition, the technology uses a self-aligned transistor architecture that has minimal capacitance and could provide a monolithic solution for touchscreen communication.

We recently reported monolithically integrated capacitively coupled thin-film RFID tags that use a custom-built reader17. In this Article, we report a TFT-based chip that can communicate electrically with commercial capacitive touchscreens. Our chip is a capacitive RFID tag made from indium gallium zinc oxide (IGZO) TFT technology on plastic substrates. It can be powered by a thin-film battery (TFB) that provides a continuous 1.5 V or a thin-film photovoltaic (TFPV) cell that can generate up to 600 mV from the incident light of a smartphone display. The tag system and communication method are tested using a range of different touchscreens from a variety of brands, including Apple, Samsung and Huawei.

TFT fabrication and electrical characterization

A self-aligned TFT architecture on a GEN1 (350 mm × 320 mm) plastic substrate18 was used to fabricate the capacitive touchscreen (C-touch) tags (Fig. 1). Using a temporary glass carrier with a 15 μm-thick polyimide film, a humidity barrier was deposited, then a thin layer of IGZO was d.c. sputtered and patterned to define the active semiconductor area. To create a gate dielectric, a 200 nm-thick layer of SiO₂ was deposited using plasma-enhanced chemical-vapour deposition (PECVD) at 250 °C. A 130 nm-thick layer of MoCr was added as the gate metal. The dielectric and gate metal area were selected for the high off-state resistance required to virtually switch off a touch event, mimicking release of a finger from the screen and limiting the potential for a monolithic low-cost Si-CMOS solution. Metal–oxide TFT technologies exhibit a very low off-current leakage1, which can be translated into a substantially high off-resistance interface to the screen. In addition, the technology uses a self-aligned transistor architecture that has minimal capacitance and could provide a monolithic solution for touchscreen communication.

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define the SD contacts. The stack was passivated by a thick (~2 μm) organic photo-exposable and curable interlayer/pixel definition layer material from Tokyo Ohka Kogyo Co Ltd and 130 nm-thick layer of MoCr was deposited and patterned as electrode layer. The last step in the TFT process was a final anneal at 165 °C. All process steps in the backplane process stayed below a thermal budget of 350 °C.

The transfer characteristics and gate current of 24 TFTs with width/length of 20 μm/40 μm are shown in Fig. 1b. The measurements were obtained at various locations across the 150 mm² plate. The 20/40 TFT is one most commonly used in our design and one of the smallest TFTs in the circuit blocks. The extracted average charge carrier mobility and threshold voltage distributions are shown in Fig. 1c. The median threshold voltage (\(V_T\)) is 0.65 V and the median mobility (\(\mu\)) is 10.7 cm² V⁻¹ s⁻¹. Moreover, the standard deviation of \(V_T\) is only 34 mV and that of \(\mu\) is 0.28 cm² V⁻¹ s⁻¹ across 150 mm² on the plate. Self-aligned TFTs have negligible parasitic capacitance between the gate and SD contacts, and have been shown to be compatible with capacitive RFIDs²,³. Furthermore, modifying the thickness of the gate dielectric improves the input capacitance of various TFTs across a 150 mm² wafer, showing the median and standard deviation value (top) and threshold voltage distribution (bottom) of various TFTs.

**TFPV fabrication and characterization**

Our TFPV has the following structure: glass/indium tin oxide (ITO)/poly(N,N’-bis(4-butyphenyl)-N,N’-bis(phenyl)-benzidine) (polyTPD)/perovskite/phenyl-C₆₁-butyric acid methyl ester (PCBM)/ZnO/Al (Fig. 2a), where the nominal composition (calculated from the precursor solution) of the perovskite is Cs₂,FA₂,Br₀.₃₅ where FA is formamidinium. The average power conversion efficiency (PCE) after encapsulation is 13.5 ± 0.5%. A typical current density–voltage (\(J–V\)) curve is plotted in Fig. 2b, which shows a short-circuit current (\(J_s\)) of 19.1 mA cm⁻², an open-circuit voltage of 0.97 V and a fill factor of 76% under an AM 1.5G spectrum. This device gives a steady PCE of 13.7% when operating at 0.79 V, which is the maximum power point obtained from the \(J–V\) scan (inset, Fig. 2b). The fabrication process is also compatible with flexible substrates,⁴,⁵ offering monolithic integration possibilities for the C-touch tag. A photograph of the cells is shown in Fig. 5d.

The \(I–V\) curve and power output of one individual PV cell with 12.5 mm² active area, placed on a white colour screen of a Samsung Galaxy S8 phone, are shown in Fig. 2c,d. The screen brightness was varied in three levels (25%, 50% and 100%) and the voltage was swept from 0.9 V to ~0.1 V and back, with a delay time of 0.02 s between each measurement point. For 25% screen brightness the maximum achieved power is ~400 nW at 600 mV. As expected, increasing the brightness of the screen increases the harvested power from the PV, achieving 7 μW at 100% brightness (as indicated by the phone). The phone was not fully charged, to emulate an average use case.

**System design consideration**

A detailed schematic of the flexible C-touch tag and a typical illustration of a touchscreen and its electronics are presented in Fig. 3a.
The physical structure of the interface between the touchscreen and the C-touch tag (and the main blocks) is shown in Fig. 3b. The touchscreen’s transparent metal lines are considered as the bottom plate of the capacitive coupler and the electrodes of the tag serve as the top plates. The glass of the touchscreen combined with the plastic or paper of the tag forms the dielectric of the capacitive coupler. The roughness of different materials (glass/paper/plastic) adds air to the dielectric mix, impeding the coupling of the tag to the touchscreen.

The complexity and diversity of modern touchscreens and their electronics is not captured in Fig. 3; it focuses instead on the interface between the tag and the touchscreen and illustrates its main properties. The power block of the TFT tag can be either a TFB or a TFPV. TFBs are available from 1.5 V to 4 V. Open-circuit voltages of TFPVs have recently improved, reaching 0.8 V (refs. 27,28) for organic cells or ~1.2 V for perovskite solar cells. The creation of higher voltages using only TFPV’s requires expensive and complicated fabrication methods to connect TFPV cells in series to form a module. Another option would be to implement a d.c.—d.c. up-converter to generate larger voltage levels. However, the high brightness of modern displays (>550 cd cm⁻²) delivers sufficient power to the C-touch tag at 600 mV (illustrated in Fig. 2), offering a monolithic solution for the full C-touch system.

The main blocks of the flexible integrated circuit are a clock generator, a 12 bit code generator (CG, Fig. 3b), a modulator \( T_{\text{MOD}} \) and the electrodes. The TFT dimensions of the various blocks of the tag are shown in Fig. 4b. The clock generator is a very critical block because it controls the data transmission rate to the touchscreen. Experiments indicate that the touch event readout rate (samples per second, S⁻¹) is limited to only 60 events per second. These sets of experiments (Fig. 4e) were performed on multiple touchscreens with various electrode sizes, a discrete off-the-shelf component-built lab emulator (inset, Fig. 4d) and a special touch event app. The same speed was confirmed by swiping a human finger on a touchscreen using the same touch event extraction app, setting a clock speed specification (Hz) to the clock generator, as shown in Fig. 4c. To meet the slow speed challenge, the channel length of the 19-stage ring oscillator (RO), used as a clock generator, was selected to be 200 μm and 400 μm, and a capacitor was included at the output of the RO for both battery and PV power sources. The 200 μm channel length design was selected because at 600 mV the speed of the 400 μm length was impractically slow (2.8 Hz). The power of the 200 μm RO is 7.7 nW at 600 mV.

The 12 bit code generator (CG) with hard-wired memory embedding a bit sequence 0101 0011 0110 was designed using pseudo-CMOS logic gates with single supply operation employing 439 transistors. The channel length of the logic gates was selected to be 40 μm (Fig. 4b) to reduce the total power dissipation of the tag to prolong its lifetime in the case of battery use or to reduce the foot-print of the PV cell. A typical commercially available TFB (0.5 mm thick) provided power of 1.5 mAh cm⁻² at 3 V (CP series lithium manganese primary pouch cells: high capacity (5 mm), thin (1 mm) to ultrathin (0.5 mm) non-rechargeable lithium cells; GM Battery and PowerStream, https://www.powerstream.com/thin-primary-lithium.html). The CG dissipated ~10 μW at 3 V, estimating ~450 h of continuous operation using a 1 cm² TFB. Lowering the power supply to 1 V increased the lifetime of the tag by more than an order of magnitude. At 600 mV the CG dissipated less than 23 nW of power, resulting in a total chip power dissipation of ~31 nW, leading to more than 9.5 years of continuous operation using a TFB. In addition, this low power value would enable a monolithic solution whereby a TFPV can be directly integrated on top of a thin-film integrated circuit, requiring minimum footprint. Figure 4c, d shows that the RO and CG are operational at 600 mV and that no serial connection of multiple TFPV cells nor a d.c.—d.c. converter circuit is necessary.

The modulator of the tag was a large-sized TFT connected to the output of the CG after a two-stage buffer to enhance the rise and fall times of the signal. The large W/L (1,500 μm/10 μm) was selected to improve the modulation and the distinction between a digital 0 and 1, thus facilitating identification of the code from the touchscreen and the application running on the device. As mentioned earlier, the sizes of the electrodes were evaluated using a developed lab touch emulator (inset, Fig. 4d). In Fig. 4e the need for 8 × 5 mm² electrodes is shown to achieve 24 bps data rates. Many different devices (iPad, iPhone SE, iPhone 8, Samsung S4, S8 and Note8 and Huawei Y7) were tested using 1 × 1, 2 × 2, 5 × 5 and 5 × 8 mm (x mm) electrodes. Figure 4e shows that larger-sized electrodes achieve a better data transmission rate and improve the readout of the modulator of the tag at the touchscreen. The millimetre-range size of the electrodes defines the size of the tag and provides large-area thin-film electronics with an important advantage compared to standard silicon CMOS technologies. Two electrodes were used in the developed algorithm, with one electrode permanently connected to ground and the other connected to/disconnected from the ground depending on the bit sequence 0101 0011 0110. A ‘1’ creates a swipe event on the touchscreen from the permanently grounded electrode to the other electrode.

C-touch tag experiments

Figure 4a presents the set-up used to connect the flexible TFT C-touch (tag with 0.8 cm² electrodes) to a commercially available flexible battery and Fig. 5d shows the C-touch tag connected to the developed TFPV. The interconnecting printed circuit board
(PCB) is only present to make the physical connection of the two parts; no additional electronics are present on the PCB. All the circuitry of Fig. 3 is integrated on the TFT C-touch tag. The orange horizontal and vertical lines on the touchscreen cross at the precise point of the generated touch event and are visible in Fig. 5. In Fig. 5c an enlarged view of the delaminated flexible C-touch tag without rigid support carrier is shown, with the different circuit blocks indicated.

Figure 6 shows the extracted touch event relocation data \( \Delta Y = Y - Y_0 \), obtained from three commercial phones without any change in their hardware or firmware settings, where \( Y \) is the pixel's y-axis coordinate for the first touch event and \( Y_0 \) the coordinate for a...
specific time. In Fig. 6a, the \( \Delta Y \) data were taken from experiments where the C-touch tag was driven by a 1.5 V TFB. In Fig. 6a the actual 12 bit code sequence is highlighted by a blue dotted line to assist the understanding of the \( \Delta Y \) data. The hard-wired bit sequence of the flexible tag can be detected by using the prediscussed touchscreen communication protocol. The two phones achieve similar transmission rates of 17–19 bps but differ in the maximum relocation of the touch event (\( \Delta Y_{\text{max}} \)). \( \Delta Y_{\text{max}} \) strongly depends on the resolution of the display and the touchscreen readout chip. By comparing the plots in Fig. 6, it can be concluded that the sampling rates (pink dots) of the touchscreen electronics are not similar for all phones. The same behaviour is shown in Fig. 4c, where similar experiments were performed using the lab C-touch emulator.

In a subsequent step, a gamecard paper (170\( \mu \)m thick) and a typical plastic screen protector were placed between the tag and the touchscreens, as shown in Fig. 5b for the paper case. No differences were observed either in the relocation \( \Delta Y \) or the speed of the data transmission rate to the touchscreen.

In Fig. 6c a faster data rate is achieved by driving the TFT C-touch tag at a higher supply voltage (2.2 V). The obtained relocation data are a bit less clear compared to Fig. 6d, but still more clear compared to other phones. Similar experiments with increasing data rates were performed on other phones as well, where the bit sequence was not always detectable. This implies that with the current state of touchscreen technology, a universal upper limit in data rate should be used to ensure compatibility to a wide range of phones. Obviously, one method to increase data rates with the proposed C-touch tags would be a multitouch–multiswipe event, whereby multiple electrodes can serve as input nodes. Another method already proposed in the literature modifies the firmware of the touchscreen readout hardware, obtaining up to 500 kbps data transfer, paving the way for more complex data communication to touchscreens and enabling a broader variety of applications.

Figure 6d plots the data captured by the touchscreen when the C-touch tag was powered by the TFPV. The circuit and TFPV were connected by the same interconnect PCB and wiring as for the TFB. The PV cell and tag were placed on the smartphone display as shown in Fig. 5d. The brightness of the display of the smartphone was regulated so that 610 mV was achieved by the TFPV. The tag achieved correct transmission of 12 bit code to the touchscreen. The slow speed of 4 bps is due to the RO integrated on the tag. Faster speeds can be achieved by integrating a faster RO (Fig. 4c).

Fig. 5 | Photographs of a flexible touchscreen tag connected to a flexible battery on an iPhone touchscreen. a, b, Photographs taken without (a) and with (b) paper between the tag and the touchscreen. c, An enlarged view of the delaminated flexible C-touch tag, with labels of the various parts. d, The C-touch tag, powered by a TFPV from a Samsung S8 display, in which only the top-right cell is active.

Fig. 6 | Extracted location data from experiments with the C-touch tag performed with various phones. a, b, Received data on an iPhone 8 (a) and a Huawei Y7 (b), powered by a TFB at 1.5 V. c, d, Received data for Samsung S8 touchscreens powered at 2.2 V (c) and by the TFPV at 0.61 V (d), which harvests the emitted light of the smartphone display.
Conclusions

We have reported capacitively coupled data transfer using a flexible C-touch chip (a capacitive RFID tag) based on TFT technologies and commercial touchscreens as a reader interface. The tag can be integrated with a TFB that provides continuous 1.5 V. Alternatively, it can be connected to a thin-film, foil-compatible PV cell that has an active area of only 12.5 mm²; the PV cell can generate 600 mV from the incident light of a smartphone display. The C-touch tag can achieve data transfer rates of up to 36 bps at a supply voltage of 2.2 V provided by an external power supply or battery. This is in the range of detectable sampling rates of current smartphone touchscreen readout electronics. The power consumption of the tag was four times lower than the previously reported 12 bit code generator and dissipated only 31 nW with a 600 mV supply. Our C-touch tag technology could potentially be implemented on 4.5 billion mobile phones worldwide and further touchscreen-enabled devices (cars, home appliances, smart surfaces, tablets) in the near future, without additional costs for users.

Data availability

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

N.P. and K.M. conceived, conducted and analysed the experiment(s). M.A. conceived experiments. R.G. and W.Q. conducted the TFPV analysis and fabrication. F.D. developed the apps. S.S., M.W.A.J.K and J.-L.v.d.S. conducted the fabrication. M.D. and A.M. conceived the applications. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

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