Progress Toward Development of All-Printed RFID Tags: Materials, Processes, and Devices

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Invited Paper

Printed electronics provides a promising potential pathway toward the realization of ultralow-cost RFID tags for item-level tracking of consumer goods. Here, we report on our progress in developing materials, processes, and devices for the realization of ultralow-cost printed RFID tags. Using printed nanoparticle patterns that are subsequently sintered at plastic-compatible temperatures, low-resistance interconnects and passive components have been realized. Simultaneously, printed transistors with mobilities $> 10^{-1}$ cm^2/V*-s have been realized using novel pentacene and oligothiophene precursors for pMOS and ZnO nanoparticles for nMOS. AC performance of these devices is adequate for 135-kHz RFID, though significant work remains to be done to achieve 13.56-MHz operation.*

Keywords—*Organic electronics, printed electronics, RFID, thin-film transistor (TFT).*

I. INTRODUCTION

In recent years, there has been great interest in the development of RFID tags for item-level tracking of individual consumer goods [1]. Such tags are expected to dramatically improve automation, inventory control, and checkout/purchasing operations. Most cost models indicate that individual tags must cost less than one to two cents to be economically viable for these applications. To realize this low cost, emphasis has been placed on the development of printed electronics technologies with performance suitable for RFID applications. This has been driven by the fact that printed electronics is generally expected to be one to three orders of magnitude cheaper than silicon technology per unit area. In this paper, we briefly review the basic cost assumptions driving the development of printed RFID tags, explore the various approaches being pursued, and describe our progress toward realizing the component technologies required to realize ultralow-cost all-printed RFID.

A. Regulatory and Economic Constraints

Given the strong economic interests driving the development of printed RFID, it is worthwhile to briefly summarize the economic imperatives in this regard. Item-level RFID is intended to produce an electronic replacement for the ubiquitous UPC barcode. Based on current standards, this “electronic barcode” will likely consist of at least 96 bits of information [2]. The precise code length is still unclear, since item-level electronic product code standards are still developing. By implementing the barcode in electronic form, it is expected that item-level RFID will enable automated inventory control in supermarkets and department stores, will facilitate rapid checkout, and will also allow more efficient product flow from the manufacturer to the consumer with reduced overall wastage and idle inventory. Individually tagged items typically have a price floor in the range of a few cents to few tens of cents. Given typical price margins, it will therefore be necessary to deliver a tag with a total price perturbation of less than two cents (and perhaps less than one cent) to allow widespread deployment. In contrast, pallet-level tracking solutions that are currently being deployed have price-points > ten cents.

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RFID devices are generally being deployed in four main communication bands, as allowed by the FCC and its global counterparts [3]. These bands are: 1) the low-frequency range up to 135 kHz; 2) a band at 13.56 MHz; 3) a band at 900 MHz; and 4) a band at 2.4 GHz. Each band has its own advantages and disadvantages. For item-level RFID, typical read-range requirements are expected to be in the range of < 1 m. Operating range of most low-cost RFID technologies is likely to be limited by power delivery from the reader to the passive tag. At the short distances required for item-level RFID, more power can be delivered to the tag at the lower frequencies that at the higher frequencies, since they lie within the near-field coupling region. Based on this consideration, it would be expected that the lower frequencies would typically be advantageous for power coupling. However, this is complicated by the fact that inductors at low frequencies are substantially larger and have significantly lower quality factor (Q). Therefore, in general, in practice, the range of RFID tags is typically larger at higher frequencies, and thus, most pallet-level RFID solutions make use of 900 MHz or 2.4 GHz [4]. Furthermore, since the passive components (both inductors and capacitors) are smaller at these higher frequencies, total tag size can be reduced at these frequencies, reducing cost.

For item-level tracking, unfortunately, the situation is complicated by the fact that these systems must function in the presence of substantial amounts of metal (for example, soup cans, etc), and RF-absorbing fluids (water, milk, etc.). Therefore, at this time, it appears that 13.56 MHz or lower is attractive from this perspective, since absorption is reduced at these frequencies. The net consequence of these opposing frequency trends suggests that the sweet spot for item-level RFID will likely exist at 13.56 MHz, though there is currently a push for developing 900-MHz solutions as well.

B. *Current Trends in Item-Level RFID Development*

In general, three main approaches are currently being pursued to realize item-level RFID. In the most conventional approach, low-cost silicon RFID tags will be used. The cost of silicon itself is miniscule, since typical tags (excluding the antenna) are less than 1 mm on a side. Using various attachment technologies (including conventional pick-and-place [5] and lower cost technologies such as fluidic self assembly [6]), the tags are added to a paper or plastic strip containing the external antenna. Unfortunately, costs for this attachment operation do not appear to scale well at this time, and it seems unlikely that a silicon-based approach will realize sub-one-cent RFID in the foreseeable future. Additionally, to realize low silicon cost while maximizing range, manufacturers are pushing toward higher operating frequencies (900 MHz and 2.4 GHz) to drive down the size of the chip and increase antenna Q. As mentioned above, while these high frequencies work well for pallet-level tracking, they do not work well in water- and metal-contaminated environments and therefore are likely not as attractive for item-level RFID.

A more aggressive approach is to eliminate the silicon and make use of alternative flexible electronics technologies. The highest performance technologies in this area are, in order of decreasing performance, polysilicon TFTs on plastic, vacuum-sublimated small-molecule TFTs on plastic, amorphous silicon TFTs on plastic, and printed organic TFTs on plastic. The costs associated with polysilicon TFTs are generally considered too high to realize item-level RFID, since they require all the major cost points associated with conventional silicon technology, namely, lithography, vacuum processing, and subtractive process steps. This is similarly true for amorphous silicon TFTs. Therefore, currently, several groups have placed major emphasis on the development of organic-based RFID technologies [7].

Using vacuum sublimation, excellent performance has been achieved using small-molecule organic materials, particularly pentacene. Carrier mobilities $> 10\ \text{cm}^2/\text{V-s}$ have been realized, resulting in circuits operating at several megahertz [8]. Unfortunately, all high-performance pentacene devices realized to date have made use of extremely slow deposition processes (deposition rates of less than 1 nm/min for 50 nm thick layers), which will either reduce throughput to economically unacceptable levels or will necessitate the use of unrealistically large reel-to-reel deposition systems. Correspondingly, the use of shadow-masking (required to achieve patterning in these circuits) is economically uncertain at this time. If progress is made toward realizing high-performance with flash deposition technologies and if the economic risks associated with shadow masking are resolved, vacuum-sublimated organic TFTs may represent a disruptive path toward the realization of item-level RFID.

The final approach being considered for the realization of item-level RFID is all-printed organic electronics [9]. In this process, an entirely additive printing process is used to realize printed devices and circuits, thus eliminating the need for lithography, vacuum processing, and subtractive process steps. Printing is also potentially an extremely high throughput technology. Thus, the costs associated with this technology are expected to be substantially lower than silicon-based techniques, per unit area. It is important to note that the cost-per-transistor will likely be substantially larger than silicon; however, at 13.56 MHz (and at 135 kHz), the area of the circuit is largely determined by the passive components, and therefore the circuit becomes area constrained rather than transistor constrained. To date, performance of printed devices is generally substantially lower than the aforementioned vacuum-based technologies. However, progress is this field has been rapid, and within this paper we will describe the results obtained in our group that will hopefully allow performance to be improved to the point where all-printed item-level RFID will be technically and economically feasible.

II. TECHNOLOGY STATUS

A. *Antenna and Interconnection Technology*

The technology used to realize the antenna inductor is perhaps the most important technology in RFID development.

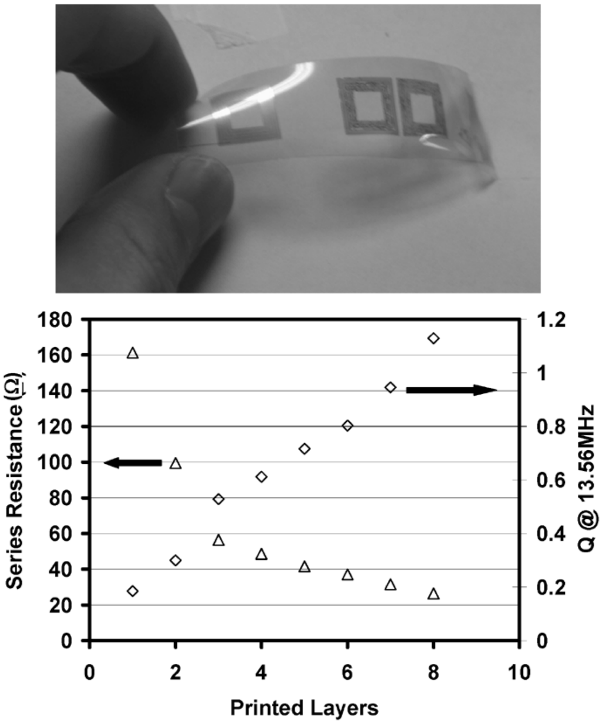

Fig. 1. Inductors on plastic produced from ink-jetted nanoparticles. Q for a given inductance is limited by ability to increase pitch due to ink-jet instability, resulting in long signal paths for a given inductance, with an associated increase in series resistance.

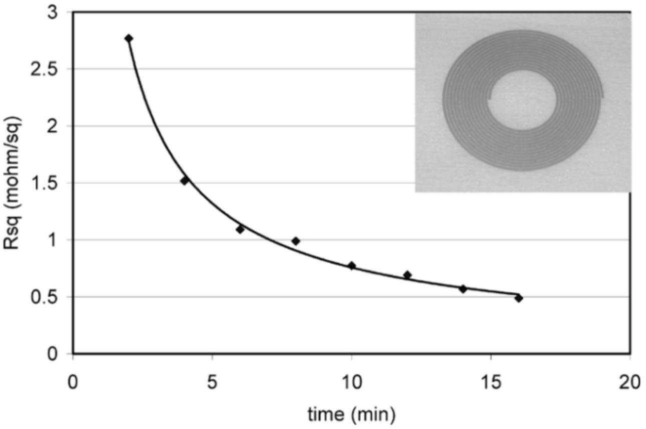

Fig. 2. Reduction in sheet resistance through a combined printing/plating process. A 100× reduction in sheet resistance is achieved, resulting in a corresponding boost in inductor Q (inset: a plated inductor with a measured Q of ~ 30).

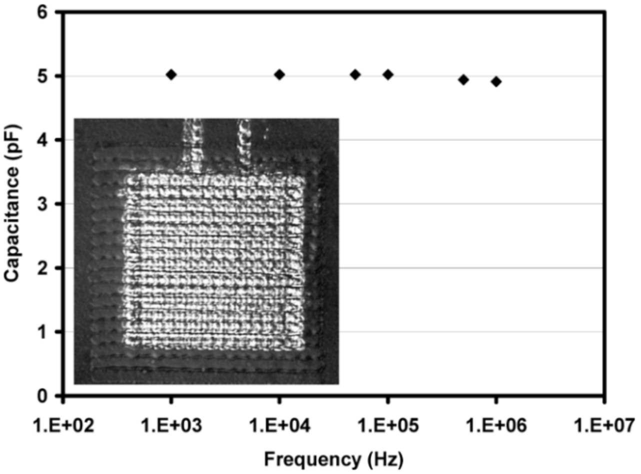

Fig. 3. Parallel capacitor fabricated using alternating layers of nanoparticles and polyimide dielectric. There is insignificant k-degradation in the frequency ranges of interest for printed RFID.

At 13.56 MHz, this is used for providing power to the tag via inductive coupling, besides serving its primary role in RF communication (Note that item-level tracking tags will almost certainly have to support bidirectional communication, since this will probably be required to realize the anti-collision algorithms used to enable a reader to talk to a large number of tags in its read-field). At the low operating frequencies that will likely be used for item-level RFID, the antenna inductor and capacitor are generally fairly large. In particular, given the large size of the inductor, Q of the tag is usually limited by series resistance. Since high Q is necessary to ensure adequate operating range, the realization of a reel-to-reel compatible low-resistance printed metallization technology is crucial.

We previously demonstrated such a technology, based on metallic nanoparticles [10]. Small-diameter nanoparticles (typically 5 nm or less) have reduced melting points relative to their bulk material counterparts. For example, the melting point of bulk gold is $> 1000\ ^\circ$C, while nanoparticles will melting temperatures of $< 150^\circ$C have been demonstrated. By printing and subsequently sintering metallic nanoparticles and plastic-compatible temperatures, it is therefore possible to produce low-resistance metal lines, thus providing a pathway to realization of high-Q passive components and also to multilevel interconnects [11]. We have reported on appropriate processes for gold, silver, and copper [12].

Our printing technology is currently based on ink-jet, chosen based on its use of low-viscosity inks and digital input. For manufacturing applications, it is not clear that ink-jet has the requisite throughput or process stability, and therefore, alternative printing technologies such as gravure, etc., must be investigated. Using ink-jet, we have demonstrated low resistance metal lines and have used these to demonstrate inductors with Qs in the range of one to two (Fig. 1) [11]. Optimization of the linewidth/linespace has allowed us to boost the Q as high as ~ 5. These Q levels, unfortunately, are insufficient for RFID. To achieve higher Q, two possible solutions exist. First, the Q may be increased substantially by reducing the spacing between adjacent lines (which is often limited by process stability in ink-jet systems) or by increasing the thickness of the lines (which is often limited by throughput in these same systems). It is likely that gravure printing may be able to solve both these problems directly; however, as an alternative solution, we have recently realized a printing plus electroless plating process, in which printed nanoparticle patterns form the seed layer for growth of thick metal films (Fig. 2). Since electroless plating requires no electrical contact to the seed layer, it is promising as a reel-to-reel compatible technology for the growth of high-Q passive components. We have realized sheet-resistance reductions of almost two orders of magnitude over the aforementioned all-printed process, which will enable a corresponding increase in Q to 30–100,

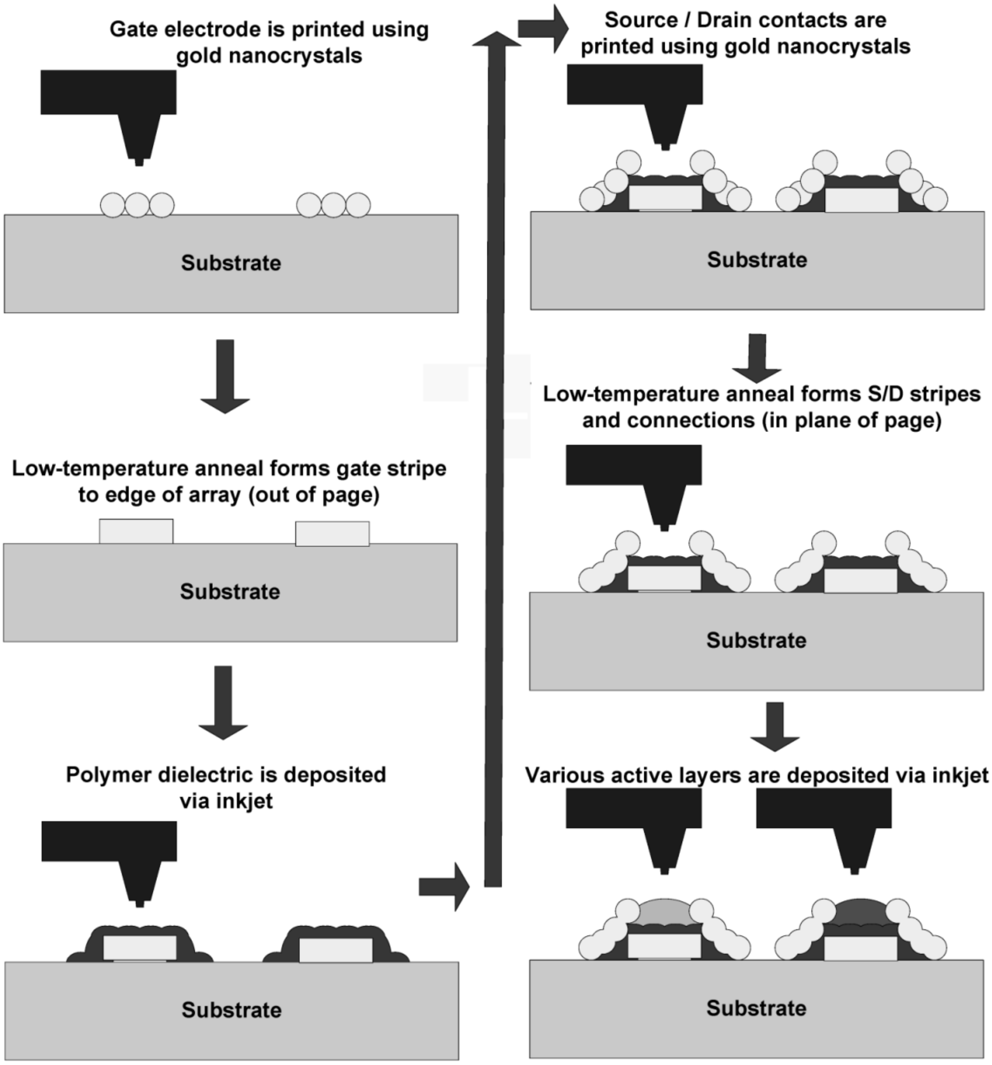

Fig. 4. Process flow used to fabricate printed transistors. Various p-type and n-type printable semiconductors have been developed.

depending on the plated film thickness. Even with films as thin as 5 μm, Q of ~ 30 has been achieved while maintaining excellent mechanical flexibility. This is likely adequate for RFID applications [13].

To fabricate capacitors and dielectrics for multilevel interconnects, we use printed polymer dielectrics [11]. These show little dispersion up to 13.56 MHz (Fig. 3) and are able to produce multilevel interconnects with high yield [11]. Thus, using printing, we are able to meet the likely passive component requirements for item-level RFID.

B. Active Component Technology

To realize item-level RFID, high-performance all-printed transistors are required. Printed diodes are also required in certain implementations, but will not be reviewed here. To realize printed transistors, we use the general process flow shown in Fig. 4 [14]. A metallic gate line is printed, followed by a polymer dielectric. Next, source and drain contacts are printed, followed by a printed semiconductor. The net result is the realization of a printed bottom-gate inverted staggered transistor structure. Using this structure, we typically obtain carrier mobilities of approximately 0.2 $\text{cm}^2/\text{V-s}$ (Fig. 5), without any optimization of contacts or interfaces. AC performance of these devices is, unfortunately, inadequate for 13.56-MHz RFID applications, though it is likely adequate for 135-kHz RFID. Based on limitations of our ink-jetting technology, it is difficult to produce transistors with channel lengths less than 10 μm without substantial gate/source and gate/drain overlap capacitance. However, by accounting for this capacitance, achievable ac performance of these devices fabricated with a more precise printing technology with reduced overlap ($\sim 5\ \mu$m) has been estimated to be $\sim$ 500 kHz, which is reasonable for 135 kHz RFID, but is inadequate for 13.56 MHz RFID. Note that it is not necessary for the tag circuitry to run at the carrier frequency; communication may be performed using a subcarrier. However, to ensure the proper stability requisite for most communication strategies, this subcarrier will either have to be frequency divided from the carrier or will have to be extremely stable.

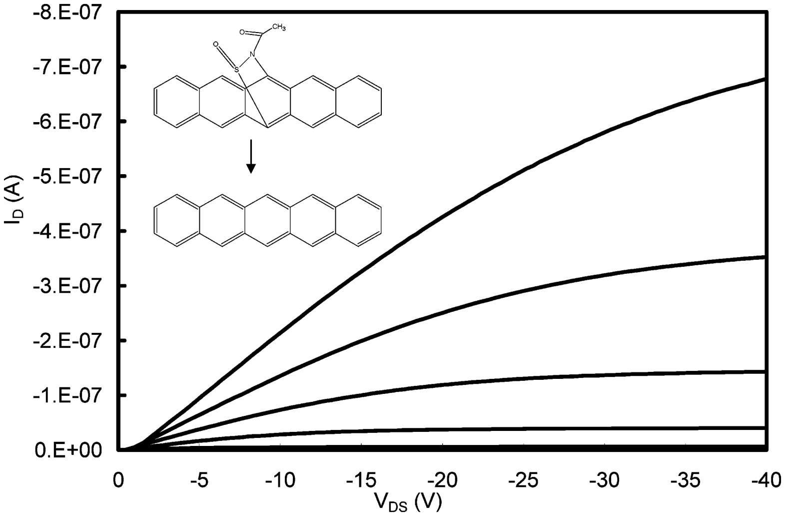

Fig. 5. Output characteristics of printed pentacene transistor using a pentacene precursor that converts to insoluble pentacene upon heating (inset).

Both solutions will likely require transistors with f_T significantly higher than we are currently able to achieve or, for that matter, have been achieved by other groups working on printed electronics. However, given that evaporated organics have achieved performance in the range required for 13.56-MHz operation, there is hope that printed electronic materials will reach this performance realm as progress is made toward producing higher performance printed films.

Essentially all high-performance organic transistors demonstrated to date are pMOS. We have demonstrated printed transistors with an active layer consisting of an annealed soluble pentacene precursor [15]. This material has been found to provide mobilities, as has as 0.3 $\text{cm}^2/\text{V-s}$ in a printed, unoptimized structure. Other researchers have demonstrated mobilities approaching 1 $\text{cm}^2/\text{V-s}$ using this material in spin-cast films [16], so further improvement is almost certainly possible. The key to obtaining high performance in organic materials lies in depositing channel films with excellent ordering; this ensures good pi-orbital overlap between adjacent molecules, allowing efficient hopping of carriers between molecules. To this end, we have initiated a program aimed at developing highly crystalline organic semiconductors formed by printing.

Most small-molecule organic semiconductors, including both pentacene and oligothiophene, are insoluble and therefore not printable; they must be functionalized with solubilizing groups to ensure printability. In the approach used by various groups, including ours, the solubilizing groups are subsequently removed by heating to ensure the formation of highly crystalline films. For this work, we have focused on oligothiophene derivatives [17].

Most recently, we have demonstrated a novel oligothiophene derivative functionalized with thermally labile solubilizing groups (Fig. 6). After printing, the films are heated, removing these groups. During this transition, the molecules show high surface mobility and spontaneously reorganize to form highly crystalline structures. Due to the crystallinity, mobilites of $> 10^{-1}$ $\text{cm}^2/\text{V-s}$ have been obtained in unoptimized structures, suggesting that substantial performance improvement is possible using this approach [18].

Aside from improving mobility, off-state behavior and stability are also equally important concerns for RFID. Since RF tags are typically power constrained, good off-state behavior is crucial. Stability is important for good analog circuit operation. We have exploited the high surface mobility of our oligothiophene derivatives to demonstrate devices with excellent off-state behavior and stability without sacrificing on-state behavior. In TFTs, on-state conduction typically happens within the first few nanometers of channel material next to the gate dielectric interface. The remaining material contributes purely to off-state leakage. In silicon microelectronics, this has resulted in great interest in ultrathin-body devices, which eliminate these extra leakage paths. We have achieved a similar structure via printing of our oligothiophene materials. By using appropriate surface chemistries and ink dilutions, we can exploit the high surface mobility of our oligothiophene derivative to ensure that the printed channel droplet reorganizes upon heating to form a device with a channel consisting entirely of a single monolayer of material [19]. Since this molecule is only 3 nm tall, this results in the formation of an ultrathin-body device, offering excellent electrostatics. Also, serendipitously, it appears that by eliminating the thick film structure, we are able to greatly reduce the trap density in the active layer, resulting in devices with substantially reduced hysteresis and improved subthreshold slope (Fig. 7).

The final two issues that remain to be addressed are the high operating voltages of these devices and the absence of nMOS materials. Low operating voltage is required to provide adequate operating range; indeed, the 20–30-V operation in most of the devices above is entirely unacceptable for RFID—sub-5-V operation is clearly required. Fortunately, a solution in this regard is apparent based on the research of several groups. All the devices above make use of relatively thick dielectrics (100-nm equivalent oxide thickness (EOT) or more). To reduce operating voltage, the EOT of these devices

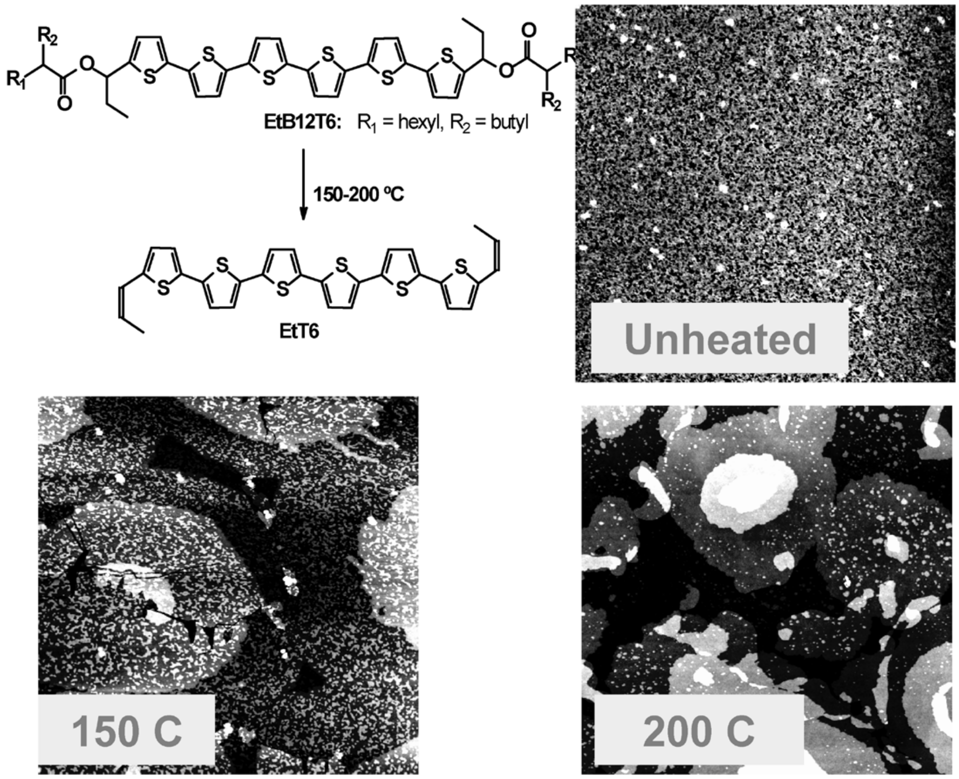

Fig. 6. The soluble oligothiophene EtB12T6 converts to the rigid molecule EtT6 with strong packing characteristics upon thermolysis, as evidenced via atomic force microscopy. The precursor is soluble due to the bulky end chains.

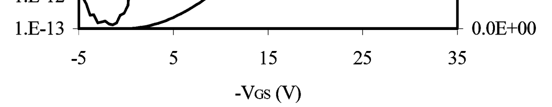

Fig. 7. ID-VG characteristic for printed monolayer device ($W/L = 250/3$ mm, VD $= -35$ V), showing excellent off-state characteristics due to near-ideal electrostatic configuration. Swing is $\sim$ 200 mV/dec for a 100-nm EOT oxide, compared to typical printed device S of $\sim$ 1 V/dec.

may be reduced. Unfortunately, the reliable printing of thinner layers is difficult; however, alternative strategies that look promising have been demonstrated. In a first strategy, a self-assembled monolayer has been used to demonstrate 2-V operation and 100-mV/decade swing [20]. This technique may potentially be printing compatible (along the lines of the monolayer devices above). In a second strategy, high-κ dielectrics may be used [21]. We have recently demonstrated the use of soluble high-κ dielectric precursors to demonstrate devices with sub-4-V operation (Fig. 8) [9]. While substantial work remains to be done to reduce low field leakage, etc., the promise of this technique is clear.

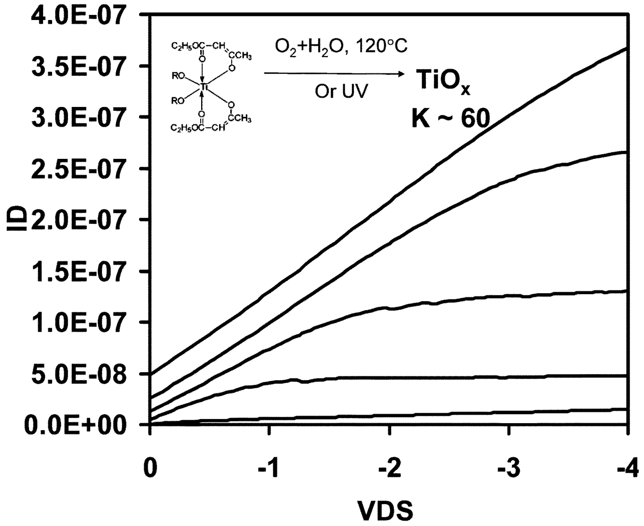

Fig. 8. Output characteristics of an organic TFT with a high-κ dielectric. The large low leakage is evident and is caused by the formation of a porous, leaky TiO_x dielectric from the Ti precursor (inset).

The dielectric is clearly an important concern in all field-effect devices, and relatively little effort has been dedicated to this in printed electronics. Aside from the performance implications above, recent results indicate that the dielectric interface also contributes to degraded device stability; continuous electrical stressing of printed devices results in degradation of drive current without a degradation of mobility (Fig. 9). This indicates that the primary degradation

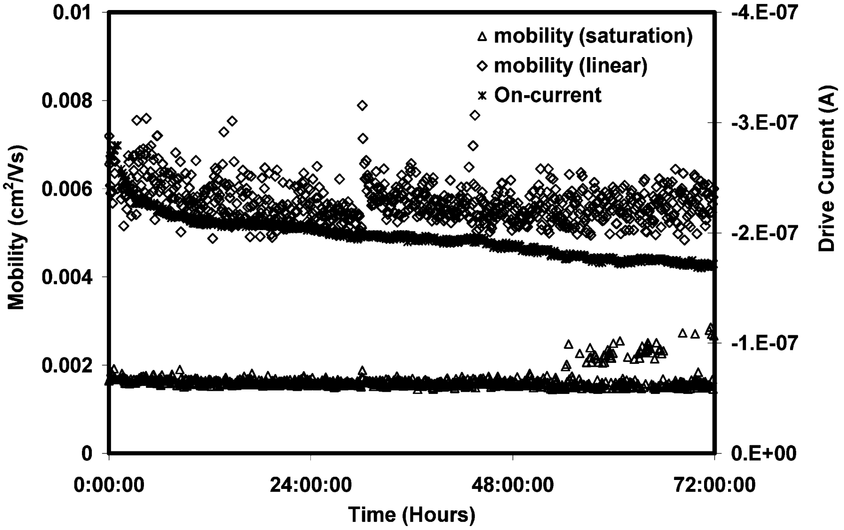

Fig. 9. Degradation characteristics of printed FETs showing mobility stability versus drive current degradation. This degradation is due to V_T instability.

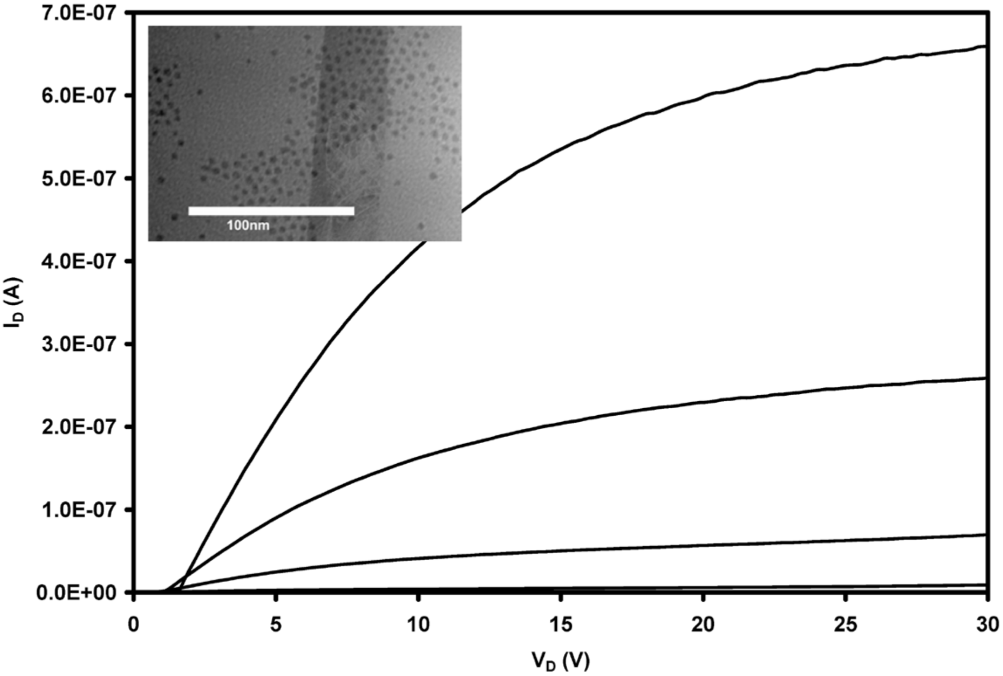

Fig. 10. Output characteristics of a ZnO nanoparticle (inset)-based FET with mobility > 0.1 cm^2/V-s. The device suffers from poor carrier injection due to a large source-side barrier, yet results in the highest mobility reported for a solution-processed nMOS device.

mechanism is a threshold voltage shift, likely taking place at/near the dielectric interface.

All the results above focus on pMOS. Clearly, the absence of an adequate nMOS material is a significant barrier to realization of CMOS, with its associate design simplicity and low-power benefits. Unfortunately, all organic nMOS materials known to date have substantially poorer performance ($< 10^{-2}$ cm^2/V-s mobility) and poor stability [22]. Recently, we have demonstrated an alternate solution to this problem. Using zinc oxide nanoparticles and sintering them in a process similar to the metallization scheme discussed above, we have demonstrated stable nMOS devices with mobilities of >0.1 cm^2/V-s (Fig. 10) [23]. While the results are early, they attest to the potential of a hybrid nanoparticle/organic-based approach to realizing printed electronics.

III. CONCLUSION

Printed electronics provides a promising potential pathway toward the realization of ultralow-cost RFID tags for item-level tracking of consumer goods. Using printing, we have realized high-Q passive components with performance suitable for RFID applications. We have also realized printed pMOS and nMOS transistors formed entirely using printed films including various novel organic semiconductors, dielectrics, and nanoparticle-based conductors. While the performance of these devices is currently inadequate for operation at the frequency of choice, i.e., 13.56 MHz, improvement has been steady, and further improvements in knowledge along with the associated technology optimization may ultimately enable the realization of all-printed RFID tags, ushering in an era of enhanced inventory efficiency and consumer convenience.

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