# Evolving into an Era of Natively Flexible Smart Systems †

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## Abstract

***Natively flexible electronics allow for ultra-thin functionality to be added to wearable, conformal large-area sensing applications, reducing or eliminating the need for bulky rigid components and dramatically improving both form factor and cost of the final system. Flexible Hybrid Electronics (FHE), which combine flexible and rigid components, are increasingly used for sensing applications like health patches, industrial sensing, robotics, augmented and virtual reality, etc. Thin-Film Transistor (TFT) display manufacturing technologies are well established and have been leading the drive for cost and form-factor optimization. In this article, we review an intersection of these technologies for sensing applications, predicting the emergence of smart systems made up of only low cost natively flexible electronic components including printed sensors, flexible ICs, printed batteries, printed antennas, and flexible displays.***

## Author Keywords

Natively Flexible Smart Systems, Thin-Film Transistors, Flexible Integrated Circuits

## 1. Natively Flexible Smart Systems

Global challenges such as healthcare require innovative approaches to enable better monitoring, detection and treatment. Natively Flexible Electronics can be a key role in enabling a paradigm shift in the healthcare ecosystem. There is a strong trend in healthcare moving from reactive to proactive, for example diagnostics shifting from in-hospital to patients' homes. McKinsey predicts up to $265 billion's worth of care services in the US could shift to the home by 2025. This represents up to 25% of the cost of care and a 4x increase over today's level. Simultaneously, the wearable technology market is expected to exceed $180 billion by 2030 with a CAGR of 14.9% over the forecast period (1). The idea of having control over one's health parameters 'on the go' is becoming increasingly appealing, with commercial systems – such as monitors for sleep quality, heart rate and step count – on a trajectory to becoming as ubiquitous as smartphones. To date, this has mostly been driven by traditional, rigid, silicon electronics. However, there are applications where conformability is expected to be of paramount importance. Here, we introduce Natively Flexible Smart Systems (NFSS) and discuss how these could support, or even replace, flexible hybrid electronics (FHE) (2) to enable new and disruptive smart health systems that purely rigid systems cannot support, such as brain machine interfaces capable of conforming to the irregularities of the brain's surface for Brain Computer Interfaces (BCIs) (3), smart bandages offering wound tracking and treatment (4,5) or smart skin patches (6). These are systems that are typically required to cover relatively large areas; sense physical or chemical events; convert these stimuli to electrical signals; and condition them as close to the source as possible to avoid noise and minimize dependance on external electronics. All of this could be developed through well-established TFT technology (7).

A good example of an NFSS has been recently demonstrated by Pragmatic Semiconductor, Arm, University of Manchester and Unilever (8). This NFSS consisted of an electronic nose (e-nose) sensor array based on organic FETs fabricated on a PET substrate, and a flexible integrated circuit (FlexIC) combining a sensor readout interface with a digital processing engine fabricated with TFTs on a polyimide substrate. The specific application in the study was to score human malodor for deodorant industry. The malodor exposed to the e-nose sensor array is converted to digital data by the sensor readout interface in the FlexIC. Then, the digital data is processed by a machine learning engine (MLE) in the FlexIC. The MLE classifies the malodor in a pre-determined score scale. The work developed a proof-of-concept prototype of the NFSS for a benchtop experiment that also included conventional electronics to drive a pump. However, the authors envisage that the prototype could evolve into a compact smart swatch, integrating all the components in a form factor of a matchbox, as shown in Figure 1.

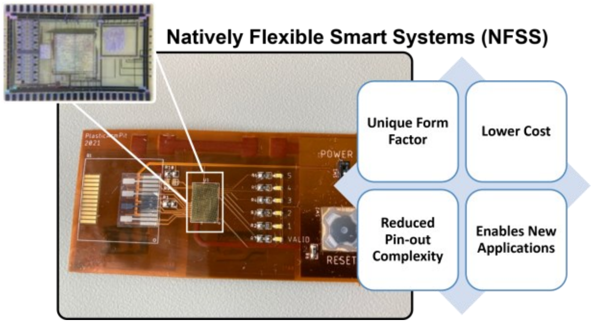


**Figure 1 –** The NFSS envisaged as a smart swatch to score human armpit malodor. An e-nose sensor array of four organic FETs on the left is connected to the FlexIC in the middle combining the sensor readout interface and machine learning engine.

From a practical point of view, NFSS also provides the opportunity to reduce pin-count and assembly complexity. Here, NFSS excels over FHE since it offers a unique, fully flexible form factor, and low integration cost – achieved through NFSS interposers. NFSS interposers consist of a single flexible substrate with thin-film resistors, capacitors and transistors replacing multiple discrete components. Crucially, this results in a significant reduction in manufacturing cost and complexity. NFSS interposers would also better match the mechanical properties of the large-area flexible carriers and enable fewer bond joints when replacing multiple individual rigid components. This would result in large area flexible systems that are expected to be more stable when bent.

In this review, we outline the progress of NFSS and how all-native, large-area platforms can address current and emerging sensing applications with a focus on healthcare applications. We outline significant technology achievements and developments that can enable fundamental improvements to healthcare through intelligent and targeted design. As such, we first review how NFSS are already capable of supporting incumbent health systems by optimizing their logistic chains, and how they can evolve to the more complex, complete systems necessary to enable truly innovative devices.

**Figure 2 –** Flexible RFID chips offer low-cost alternative to RFID tracking. A) FlexIC by Pragmatic Semiconductor on antenna. B) Representative applications enabled by low-cost flexible RFID chips.

## 2. Enabling a New Healthcare Ecosystem

While patient care is changing, most health data (e.g. sample analysis and medical test results) is still acquired and processed in hospitals and laboratories. As an example, the UK is moving to super pathology laboratories – state-of-the-art facilities serving doctors and practices across the country. These facilities process around 10,000 samples per day, so a robust logistic chain is fundamental. Challenges observed due to the sheer volume of samples include phantom samples, which are logged by the doctor but do not make it to the lab, or mis-matched paperwork, which makes the sample invalid. In addition, the environmental conditions the samples are exposed to in transit can affect their validity; having information about variations in these conditions is crucial.

### *2.1. Item-Level Tracking*

There are various ways to track and identify items, with perhaps the most common being barcodes. However, barcodes require line of sight to the tag on each item, which can be impractical. A viable and equally common method is based on Radio Frequency Identification (RFID) tags. In applications where cost is a factor, e.g., identifying every sample vial on medical applications, passive tags with short read-ranges generally offer a better trade-off than their active, battery-powered counterparts. Furthermore, for such applications, the pin-out complexity is not generally a concern, since silicon NFC/RFID ICs are already simple and can already be utilized to create comfortable FHE systems (9). However, NFSS such as the RFID FlexIC shown in Figure 2A offer a cheaper alternative without sacrificing functionality. As an example, SamplePod Ltd. (10) designed a universal, multi-use unit to securely pack and transport medical samples. However, the high cost of standard RFID silicon chips made the return on investment uninteresting and the payback period too long. In comparison, flexible integrated circuits (ICs) offer a cheaper way to enable this application and could save the UK National Health Service up to £400M annually (11). Other examples of the potential of this technology include supply chain logistics, recycling, and food waste reduction (Figure 2B). Another crucial element to consider, and one of the main challenges that NFSS faces in this context, is related to power. While FHE and rigid systems can make use of standard rigid batteries to create long-range active devices, using them in NFSS can be counter-productive, as they typically increase the overall cost of the device and add rigidity to the system. Furthermore, the disposal of large volumes of small tags with individual batteries has potential to create significant amounts of hazardous waste – a factor that cannot be overlooked. To tackle this, options such as the bioenzymatic fuel cells on paper developed by BeFC (12) or Zinergy's printed cells (13) provide an affordable, environmentally conscious and fully flexible power source for NFSS.

### *2.1 Continuous Monitoring*

In the previous section we outlined how item-level tracking can support the healthcare ecosystem by effectively adding traceability to sensitive items. Looking forward, we envision smart tags capable of continuous monitoring of critical parameters, such as temperature or light exposure, by adding sensors to each tag. Equally, this principle could be expanded to many sensors in an array format to produce more complex systems capable of sensing critical health parameters. Currently, FHE offers the fastest route towards compact systems incorporating multiple sensor options. A recently demonstrated smart patch for application in neonatal intensive care units (NICU) integrated an NFC system-on chip (SoC), Cu tracks, both Red and IR LEDs, and a photodetector on a single flexible substrate, to create two systems capable of acquiring both Electroencephalogram (EEG) and Photoplethysmography (PPG) data in a wireless and battery-free format (Figure 3A) (14). This enabled the extraction of heart rate variability, blood oxygen level (SpO2) and respiratory rate and could potentially replace traditional sensor systems which often need cables, requiring newborns to remain in the crib. Similarly, a fully integrated high-resolution EEG monitor within a miniaturized skin-conformal system was fabricated on a flexible PCB and incorporated both standard silicon ICs and soft dry electrodes (15). The novelty of these systems is generally considered to be the integration of standard silicon components in cleverly designed flexible substrates. Here, the integration between the sensing components and the rigid conditioning electronics is generally seen as one of the barriers to obtaining better, more stable devices. We envision that the outlined systems can greatly benefit from replacing the current rigid and discrete components – with their accompanying large amounts of assembly joints – with flexible systems built on a single substrate and optimized input/output (I/O) pins. As sensor systems become more complex, cost becomes less of an issue, as the integration and system costs begin to exceed the cost of the IC and electronics. Because of this, the pin-out and form factor benefits provided by NFSS become more attractive. Here, there

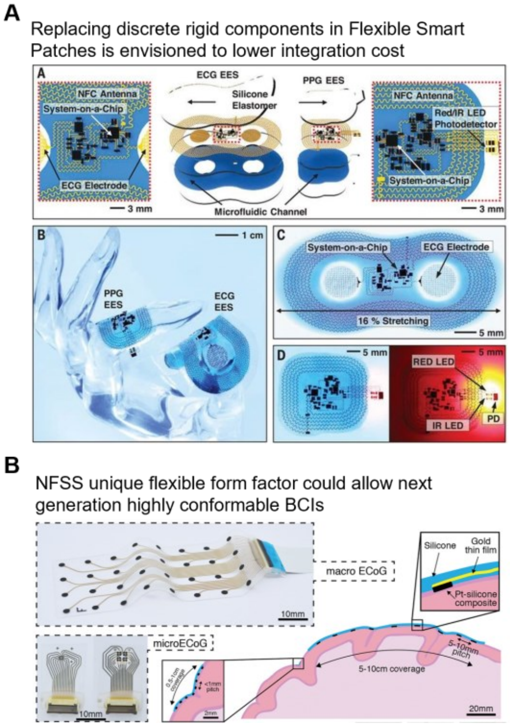


**Figure 3 –** A) Smart patch including EEG and PPG sensors adapted from (14). B) Highly conformable MRI compatible µECoG arrays adapted from (3).

are two main opportunities for all-native, large-area smart platforms: interposers and high-density conformable sensing arrays (Figure 3B). With regards to interposers, it is already possible to replace resistors, capacitors and some active components and circuits on FHE systems with a single, fully flexible IC which would only have the bare minimum and essential I/O pins. On the other hand, and perhaps more interesting, is the opportunity to develop next-generation Brain Computer Interfaces (BCIs) through developments in NFSS. A recent article (16) outlined the advantages of flexible sensors for this application, highlighting their superior mechanical and topological match to the natural features of the human brain. In addition, if made stretchable, it is envisioned that these sensors could be part of implants that would expand and adapt as the BCI users themselves grow, so covering their entire lifespan. Furthermore, the authors noted that one of the requirements for the rise of flexible electronic technology would be effective industry pipelines, i.e., an ecosystem for design, manufacturing and packaging. This is an opportunity for large-area TFT and flexible IC manufacturers to collaborate on the development of high-density flexible arrays. These next-generation devices are envisioned to deliver in vivo electrophysiology implantable arrays, allowing monitoring of activity in the cerebral cortex (7). In addition to contributing to a better understanding of the human brain, these devices could play an important role in monitoring brain-related diseases or even the control of next-generation prosthetics and robots.

## 3. Smart Healthcare

So far, we have outlined how NFSS can disrupt item-level tracking and continuous monitoring, with potential applications in healthcare logistics, BCIs and smart patches. However, these systems would still pale in comparison to traditional healthcare systems, e.g., electrocardiogram (ECG) and EEG monitors, which are generally supported by computers to process medical data and so can detect and "understand" abnormalities. Modern monitoring systems, such as the Freestyle Libre 2 (17) replace this with a simple phone app connected to a sensor on the skin of people with diabetes. The information between the sensor and the phone is then shared via a Bluetooth link, allowing the smartphone app to alert the user when their blood-sugar levels reach a defined value. A potential step forward would see a sensor system that could log data continuously, but only transmit it when a given event occurred, or when prompted by the user. This would minimize power consumption due to the wireless communication channel, increasing the lifetime of each sensor unit and increasing user comfort while minimizing waste. This would also reduce the communication requirements between each sensor node and the main smartphone/computer, enabling more efficient networks of connected devices. Smart health monitors are evolving to become more complete systems capable of sensing and data transmission, but also selecting and/or logging information. The system proposed by Quad Industries (18) uses a rechargeable rigid system, attached to a flexible patch that can be worn for periods of up to 24 hours. While in use, this smart patch records ECG data, which can then be recovered from the system while it re-charges. Using a different approach, Gao et. al. (19) presented a multimodal FHE sensing system capable of measuring temperature and distinguishing different sweat biomarkers. This system incorporated various signal conditioning circuits and a Bluetooth transceiver, as well as – interestingly – a microcontroller unit that calibrated, compensated and relayed the data obtained by the individual sensor elements.

While smart health monitors extract information from their environment to inform the user or medical professional, actuator systems can deliver treatment on-the-go, ideally without input from the patient. This last step would see sensing, detection and treatment on a single footprint to provide closer and smart healthcare. Song et. al. demonstrated a bioresorbable, wireless and battery-free electrotherapy system that operates on power harvested from a magnetically coupled coil at resonant frequency of 13.56MHz (5). This system applied an electric stimulus to improve wound recovery in diabetic mice, as well as tracking progress by measuring impedance variations (Figure 4). This is an example of an FHE system, where rigid, off-the-shelf electronic circuits were used. However, NFSS could already replace many of these devices to create a more comfortable device footprint while reducing cost and assembly complexity.

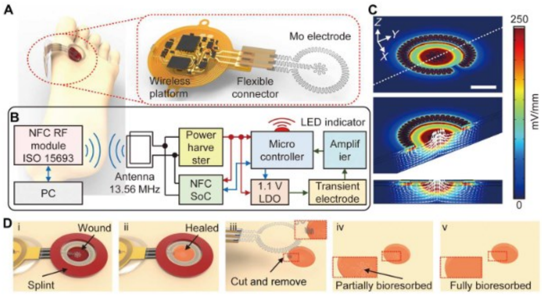
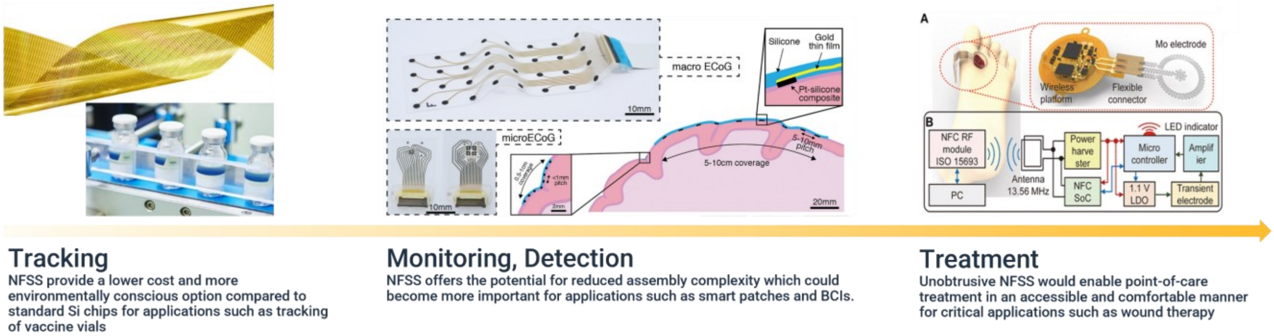


**Figure 4 –** Bioresorbable, wireless and battery-free electrotherapy system adapted from (5)



**Tracking**
NFSS provide a lower cost and more environmentally conscious option compared to standard Si chips for applications such as tracking of vaccine vials

**Monitoring, Detection**
NFSS offers the potential for reduced assembly complexity which could become more important for applications such as smart patches and BCIs.

**Treatment**
Unobtrusive NFSS would enable point-of-care treatment in an accessible and comfortable manner for critical applications such as wound therapy

**Figure 5 – Roadmap for applications improved and enabled by the development of NFSS. μECoG arrays and electrotherapy patch adapted from (3) and (5), respectively.**

## 4. Roadmap for Smart Healthcare and Flexible Smart Systems

NFSS are envisioned to disrupt healthcare by enabling new solutions for the current Healthcare ecosystem e.g., through effective, low-cost item tracking, and by offering a unique, flexible form factor that paves the way to unobtrusive smart patches, BCIs and point-of-care treatment (Figure 5). However, this will require additional interaction between high-performance FlexIC designers and manufacturers, such as Pragmatic Semiconductor, sensor array manufacturers supported by the TFT industry and main stakeholders for smart healthcare deliverables i.e., governments, hospitals and academia. We expect that the opportunities provided by NFSS will result in a closer collaboration in this field and usher in a new era where healthcare can be delivered in a sustainable and accessible way worldwide.

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