Thin-film transistors

A flexible chip with embedded intelligence

Standfirst: A flexible processing engine that is hardwired for machine learning can be used to create a smart electronic nose for odour classification.

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While conventional silicon electronics aims to create devices with ever smaller features sizes and higher densities, large-area electronics aims to create devices with novel form factors and features using low-cost fabrication processes. The approach has led to the development of a range of flexible devices, circuits and systems[1-4]. Flexible electronics could also be used to build processing engines – integrated circuits that collect, transmit, and process data – for application in areas such as electronic skins and smart chips. However, though some flexible processing engines have been developed, they are not powerful enough to run algorithms that are of use in meaningful practical tasks. Currently, this problem could be addressed indirectly through cloud computing, but such an approach will be limited by the communication bandwidth and also creates privacy concerns. On-chip (or local) computational capabilities on flexible substrates would thus be preferable. Writing in *Nature Electronics*, Emre Ozer and colleagues now report a powerful flexible processor chip that has hardwired parameters for machine learning and can function as a smart electronic nose[5].

The researchers — who are based at ARM in Cambridge, PragmatIC in Cambridge and the University of Manchester — used a commercial 0.8 μm metal-oxide thin-film transistor technology to develop a domain-specific processing engine that consists of 2,084 field-effect transistors (FETs) and 1,048 resistors over an area of around 5.6 mm^2. They also developed a machine learning algorithm (termed univariate Bayes feature voting classifier) that is based on a Gaussian naïve Bayes algorithm and was directly implemented in the hardware. The flexible processing engine has a gate density of 183 gates /mm^2 — the highest reported for such processors — and could differentiate various types of odours using data collected from several gas sensors.

Building processors on flexible substrates is challenging because conventional electronics rely on bulk silicon, which is not flexible. One strategy is to combine the conventional silicon-based complementary metal–oxide–semiconductor (CMOS) technology with flexible substrates by thinning the silicon chip down to a few micrometres[2]. This though complicates the packaging process and limits the flexibility. Another strategy is to use novel nanomaterials and nanostructures on flexible substrates[6]. This strategy though misses out on the advantages of using CMOS processes and is not compatible with large-scale manufacturing. Ozer and colleagues adopted a metal-oxide thin-film transistor process technology to tackle the scalability problem. The limitation here is that only n-type FETs and resistors can be fabricated because there is currently no viable p-type material — other than silicon — that is mature enough for large-area commercial fabrication. A more complicated layout based on n-type FETs and resistors was thus required to implement the same logic functions. In the long term, materials that can provide CMOS integrated circuits will be needed[1,7,8]. Manufacturing such solutions over large areas and with uniform responses will, however, be a key challenge. Printed electronics based on high-mobility nanostructures could though potentially lead to such large-area electronics[4,6,7], while also decreasing the fabrication costs.

For the implementation of flexible processors, the circuit design also needs careful consideration. In particular, the inference accuracy of a machine learning processor should be as high as possible to meet the requirements of practical applications, but the circuit still needs to be achievable with the technology available. With this in mind, Ozer and colleagues chose a Gaussian naïve Bayes machine learning algorithm from among several state-of-art algorithms, including neural networks, and tailored it for easier hardware implementation. While this arrangement is suitable for odour classification tasks, different algorithms may be preferred for other applications[8-10]. Implementing these machine learning algorithms into hardware — possibly with flexible form factors and over large areas — will though be difficult, and will require innovation in terms of materials, device architecture, and fabrication methods[1].

Flexible processing engines with embedded intelligence can be used to build smart systems for mobile healthcare, food technology, and the Internet of Things. The odour classification approach by Ozer and colleagues could, for example, be used in smart food packaging that monitors food quality and predicts the expiry date of perishable food (Fig. 1). Flexible processing engines could also be of use in the development of electronic skins, where for, instance, multiple sensors (measuring pressure, temperature, and strain) are combined with distributed computing to create prosthetic limbs capable of sensing touch[1,9,11].

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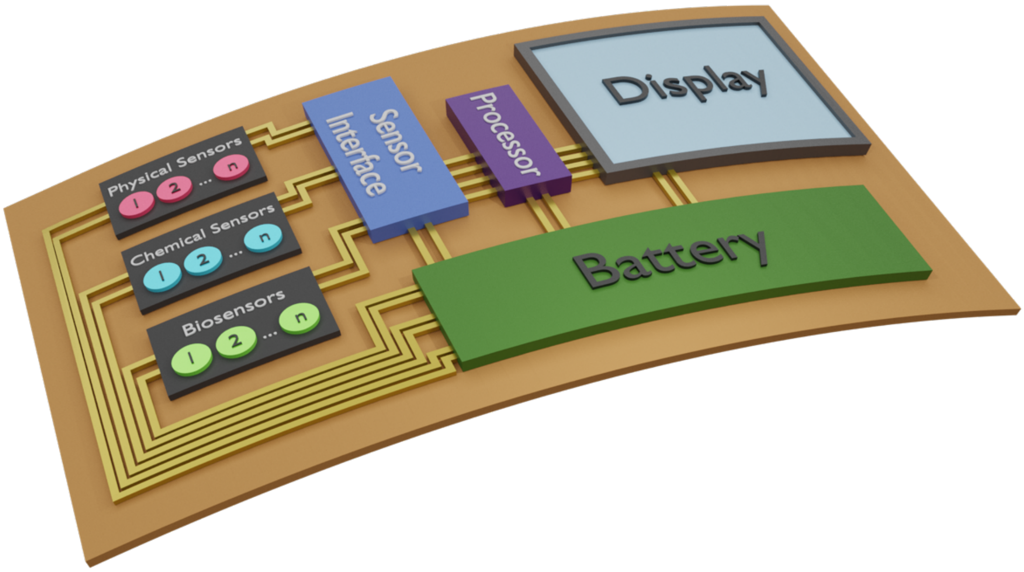

Figure 1: **A flexible smart food package with embedded intelligence and multi-sensory inputs**. The chip uses odour classification to monitor the quality of food and predict its expiry date. Such information could help store managers to plan their purchases, while helping to improve customer satisfaction.