Epidermal electronics for health and fitness monitoring

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Abstract

Medical deployment of electronics is frequently hampered by boxy, rigid packaging. Biological tissues are soft and curved, while electronic components are hard and angular. The mechanical mismatch can be alleviated by re-packaging electronics in radical new form factors. MC10 has developed a technology platform using ultra-thin components linked with stretchable interconnects and embedded in low modulus polymers which provide an excellent match to biological tissues.

The MC10 platform is based on packaging today's high-performance active components in new mechanical form factors. The platform has three key elements: thin silicon embedded in film for flexibility, silicon transfer from foundry CMOS wafers to polymer-coated carriers and flexible metallic interconnect on polymer.

On-body and in-body applications are both well suited to the technology platform. Skin-mounted systems resemble electronic tattoos, and can be worn for extended periods without discomfort while providing continuous monitoring. Inside the body, instrumented catheters provide a practitioner with unprecedented electrical information about the interior of the heart.

1. Platform

The technology platform builds on pioneering work by Prof. John Rogers and his team at UIUC[1,2]. Rather than developing novel semiconducting, conducting and insulating materials, the platform exploits the concept that only the top 5-15 µm of a silicon CMOS wafer contributes to functional behavior. Similar considerations apply to other high performance components such as LEDs and photodiodes. That thin layer can be removed and transferred to polymer by a variety of processes. The resulting thin and flexible silicon islands can be interconnected using metallization patterned to permit substantial macro-scale deformation while experiencing minimal micro-scale deformation, just as a coiled spring can stretch several times its own length while keeping the local metal strain within the elastic limit.

1.1 Thin chips at NMP

Figure 1 shows the key principle of using thin chips at the neutral mechanical plane of a film.

Fig 1a. Thin silicon wafer

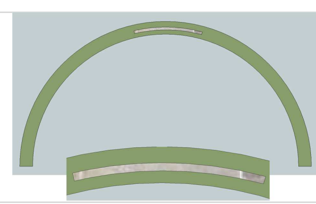


Fig 1b. Thin silicon at neutral mechanical plane

When thinned below ~ 25 µm, a silicon wafer becomes substantially flexible. The principle is the same as that which makes lumber stiff, but paper flexible, in spite of being composed of the same material.

In a polymer film in flexure, one surface is in tension, the other in compression. Towards the center of the film, there is a plane where the strain is zero, known as the neutral mechanical plane (NMP). If a thin chip is embedded in polymer at the neutral mechanical plane, the polymer can undergo substantial deformation with minimal strain in the silicon. Detailed mechanical modeling is generally required to identify the location of the neutral mechanical plane considering the composition of the entire system film stack, which may have a mix of metals and polymers of varying thickness and moduli. Such modeling is a key part of the technology platform.

1.2 Micro-transfer

The active layer of silicon (5-15 µm) can be removed using a variety of methods. One method is to use circuits built on silicon-on-insulator (SOI) substrates and employ a series of micromachining steps to undercut the buried oxide and remove the active layer from its supporting carrier substrate. An alternative approach is to backgrind a conventional wafer, leaving 25 µm or less of silicon remaining. Custom CMOS designs lend themselves to both approaches; off the shelf silicon die or wafers are processed through the second path.

The key to lifting thin silicon layers from their carrier substrate without damaging them is using an elastomeric stamp[4]. By exploiting the viscoelastic surface adhesion of silicones, a stamp can be applied slowly and withdrawn quickly, snapping the chip from the CMOS source. At the polymer destination, the stamp can be placed quickly and withdrawn slowly, leaving the chip on the polymer film. Figure 2 shows chiplets on a CMOS wafer before and after transfer.

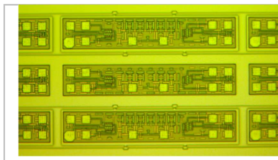


Fig 2a. Optical micrograph of CMOS source wafer showing several nearby chiplets.

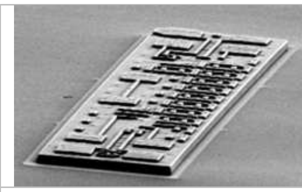


Fig 2b. SEM of CMOS chiplet after removal from CMOS source and placement on polymer target.

2. Stretchable interconnect

In addition to being flexible, circuits should be stretchable for biological applications. When attached to skin, or for instance to a beating heart, a circuit may experience both in-plane as well as out-of-plane deformations. The difference between the two needs is exemplified by a sheet of paper, which is flexible without being stretchable. To achieve stretchability, high modulus materials such as electronic grade polyimides and metals must be patterned in serpentine shapes. The resulting system can then be embedded in a low modulus matrix, such as a silicone, to provide mechanical stability and a conformal coupling to the body. Figure 3 shows how serpentine interconnect allows macro deformations of 20% while keeping local strains under 1%. A key point is that the polymer islands where silicon chips are placed see near-zero strain.

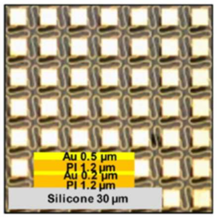


Fig. 3a – micrograph of islands connected by serpentine interconnect

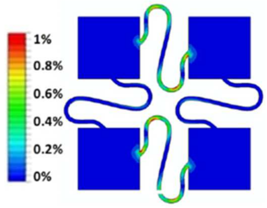


Fig. 3b – local material strain (modeled)[3]

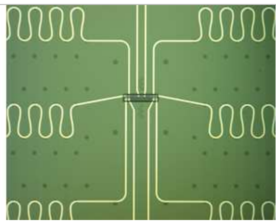


Figure 3c. Silicon chip with serpentine interconnect

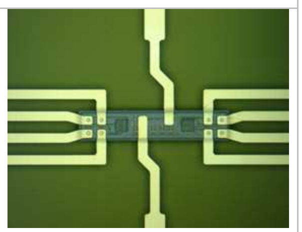


Figure 3d. Close-up of contacts in a different chip. The silicon chip is semi-transparent at this thickness.

1.4 Electrical Performance

A key aspect of the platform is that the components are derived from a high performance silicon processes and retain that performance after transfer.

Figure 4 shows on-current of NMOS and PMOS devices. Excellent device currents are seen, with no systematic changes from on-wafer performance. Some I_{out} droop is seen in the NMOS devices due to operation at high DC power levels with no heat sinking. In general, body electronics are significantly power-constrained, ensuring that devices stay in a safe operating regime.

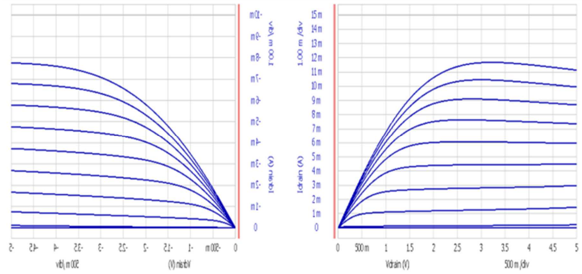


Figure 4. On current of PMOS (left) and NMOS (right) transistors.

Perhaps more significantly, the off-current of the devices is excellent. High levels of strain in the silicon would lead to dislocations and junction leakage. Due to power constraints of body-mounted electronics, it is imperative to maintain low leakage levels. Figure 5 shows sub-threshold data for PMOS and NMOS devices, showing low leakage and million-fold on/off ratios.

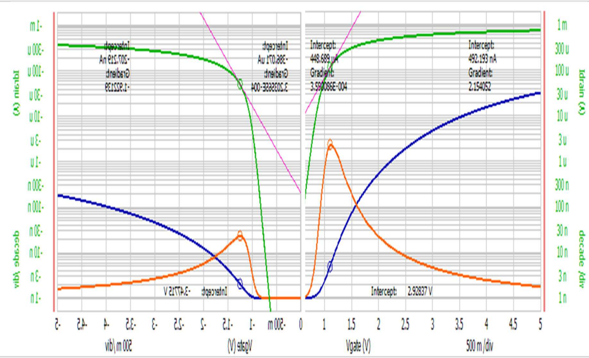


Figure 5. Sub-threshold data of PMOS (left) and NMOS (right) transistors after transfer to polymer.

3. Platform Applications

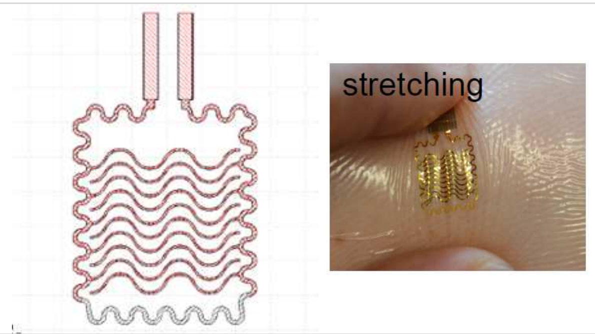
Having described the core technology, two applications are now given. The first is a self-contained skin-based system with power and wireless communication for hydration monitoring. The second is a UV sensor with the same architecture, allowing the continuous recording of UVA and UVB exposure.

2.1 Hydration sensor

The human autonomic nervous system provides relatively slow feedback about fluid loss. A maxim among athletes is "by the time you're thirsty, it's too late". A hydration sensor that can provide real-time updates on fluid loss would allow athletes to extend their performance period while minimizing subsequent ill-effects and speeding recovery. We describe here a hydration sensor that records the hydration level of a soft absorbing material which collects sweat from the skin, and transmits the data to a mobile phone.

2.1.1 Sensor data

The sensor is an inter-digitated capacitor, designed to permit stretch without line breakage (Figure 6).



(a) CAD layout

(b) Photo under stretch

Fig 6. Hydration sensor

The sensor was designed with aid of detailed FEM calculations, to be reported later. The sensor is shown relaxed and in tension in Fig 7.

(a) Relaxed

(b) 50% elongation

Fig. 7 – Hydration sensor under elongation

When mounted on a sweat-absorbing patch, the response to fluid in the patch is unmistakable. The volume of analyte required to saturate the patch was determined in advance, then analyte was titrated onto a dry patch to systematically increase the hydration level. A dramatic drop in impedance is found between 0 and 20% hydration, after which the decline is more gradual, as shown. The causes are still under exploration, but the result is useful in that it provides maximum sensitivity at low concentrations of analyte.

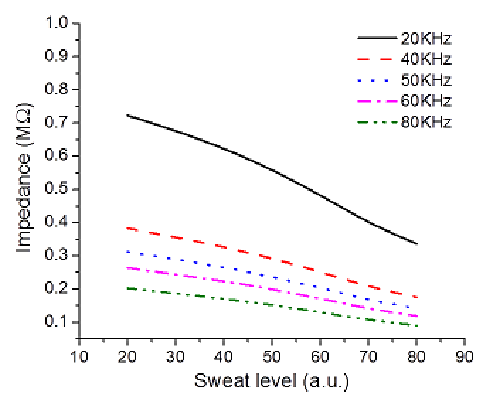


Fig. 8. Impedance of sensor as a function of hydration and measurement frequency.

2.1.2 System architecture

The overall block diagram of both hydration and UV sensing is shown in Fig. 9.

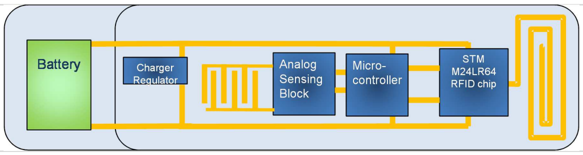


Fig. 9. System block diagram

The battery provides power for sensing only. The microprocessor wakes up periodically, stimulates the analog sensing block, which conditions the signal and delivers it to an A/D port on the microprocessor. The data is stored in non-volatile memory on the RFID chip. When an NFC-enabled phone is brought into proximity with the patch, data is transferred to the phone, where it is interpreted by application software. The data logging and transfer are asynchronous; data logging can occur every minute while transfer may occur episodically.

A prototype sensor with an absorbing layer is shown below. The overall system is dimensions are 3 × 1.5 cm^2. Such sensors have been worn for periods of up to a week without discomfort, and survive daily activities such as exercise and showering. Lifetime is primarily limited by the turnover of cells in the skin.

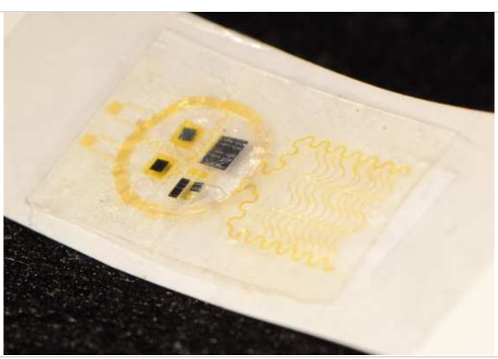


Fig. 10. Prototype hydration sensor.

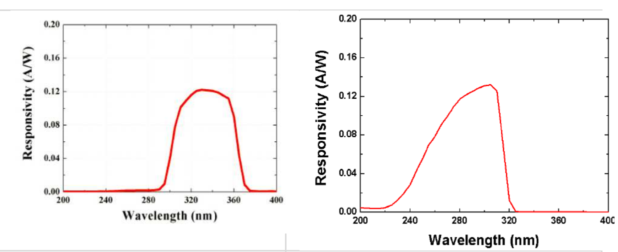
2.2 UV Sensor

The system architecture is similar to that shown in Figure 9, except that the sensor is replaced by a pair of UVA and UVB sensors and a different analog circuit is employed. The power budget for the system is shown as a function of sample interval in Table 1.

					Mean Current			
	Sleep Current	Active Current (µA)			Sense Interval (sec)			
				1	10	60	300	900
microprocessor	0.3	40						
op-amp	0	6						
power conditioni	0.001	0.775						
RF	0	220						
Total	0.301	266.775		1.37	0.41	0.32	0.30	0.30
Active Time (ms)			2					
Lifetime (hours @ 12 µA h battery)				8.77	29.43	37.64	39.40	39.71

The op-amps and RF chip I2C interface are shut down between read operations, taking no standby power. Based on these results, a 12 µAh battery from Cymbet Corporation, with a bare die footprint of 2.8 × 3.5 mm, can support over a day of operation, depending on sampling interval.

The sensor response to wavelength is shown below. The conformal CAD for the system is in design and results will be reported at the conference.



(a) UVA (b) UVB

Fig. 11. Response of UV sensors to sunlight.

4. Summary

There is a wide range of on-body sensors that would benefit from long-term monitoring, some of which are shown below.

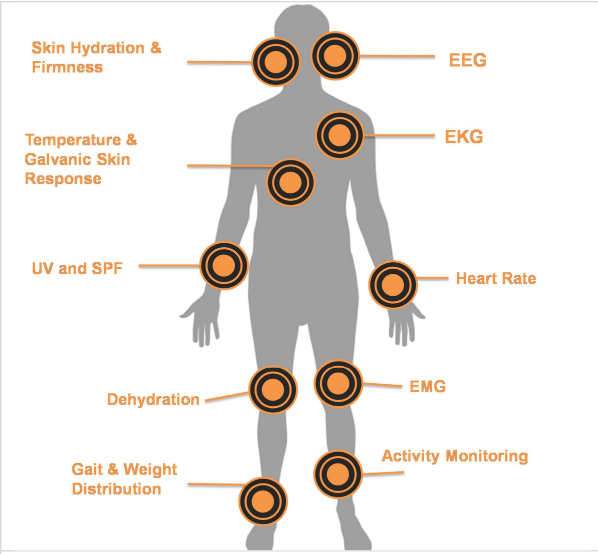


Figure 12. Epidermal electronic targets

A platform technology called Epidermal Electronics is described here. The platform supports conformal on-body electronics that log sensor data at very low power levels over extended periods, while providing wireless communication with handheld devices. We anticipate extending the platform to many of the above applications.

5. Acknowledgements

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6. References

1. Kim D, *et al* (2008) Stretchable and foldable silicon integrated circuits. *Science* 320: 507-511.
2. Kim D, *et al* (2011) Epidermal electronics. *Science* 333: 838-843.
3. Kim D , et al (2010) Stretchable, Curvilinear Electronics Based on Inorganic Materials, *Adv. Mater*. 2010, 22, 2108–2124
4. Meitl M, *et al* (2006) Transfer printing by kinetic control of adhesion to an elastomeric stamp, *Nature Materials* 5: 33-38