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for germ cell development, and the sex of the germ cells must match that of the soma for proper gametogenesis to occur (*2*). A key question facing researchers is how the germ line coordinates signals from the soma with its own sex chromosome constitution to achieve proper sexual identity.

Hashiyama *et al*. demonstrate that in *Drosophila*, a gene named *Sex lethal* (*Sxl*) acts as a key switch in regulating germline sex determination. Expression of *Sxl* is sufficient to allow germ cells with an XY genotype, which would normally be male, to produce eggs when they are transplanted into a female soma (ovary)—something that a male germ cell would normally never do. There are several reasons why this work is exciting. First, *Sxl* expression is able to overcome the incompatibility between a male germ line and a female soma. This offers insight into how the two distinct inputs from the germ line and soma contribute to germline sex determination. Second, the fact that *Sxl* is sufficient to activate female germline identity is interesting given that it is also the key switch gene in determining the sex of the soma (*3*), yet it acts differently in the germ line. Lastly, Hashiyama *et al*. show that sex determination in the germ line occurs earlier than was thought. Previous studies showed that germ cells exhibit sex-specific behaviors and gene expression at the time they first associate with the somatic gonad (*2*). However, female-specific expression of *Sxl* begins much earlier (*1*)—as soon as the germ cells are believed to generally activate zygotic transcription (*4*). Thus, germ cells have a sexual identity even before they are influenced by sex-specific signals from the somatic gonad.

This exciting work raises as many questions as it answers. How is *Sxl* activated in female germ cells? Although *Sxl* expression in both the soma and the germ line is regulated by the number of X chromosomes present, it appears that the way the cell's biochemical machinery "counts" X chromosomes in the germ line differs from the way it counts them in the soma (*5*, *6*). Further, what are *Sxl*'s targets in the germ line? *Sxl* encodes an RNA binding protein; in the soma, it acts as a regulator of alternative RNA splicing and translation, and controls both sexual identity [by regulating *transformer* (*tra*)] and X chromosome dosage compensation (by regulating *male specific lethal 2*). However, neither of these key *Sxl* targets in the soma are important in the germ line (*7*, *8*), indicating that *Sxl* must regulate other, unknown factors there. Hashiyama *et al*. also found that activation of *Sxl* in

male germ cells did not interfere with normal spermatogenesis; when *Sxl*-expressing male germ cells were left in a male environment (testis), they produced sperm, as observed previously (*9*). Thus, *Sxl* cannot feminize a germ cell in all respects, because a female germ cell is unable to make sperm in a male environment.

Compatibility between the germ line and the soma is also an issue for mammalian germ cells. In humans who are XXY (Klinefelter's syndrome), the soma is male because of the masculinizing influence of the Y chromosome. However, the presence of two X chromosomes is incompatible with male germline development and these individuals are sterile; their testes have severely reduced germline characteristics, including loss of premeiotic spermatogonia and spermatogonial stem cells (*10*). This defect is due to the number of X chromosomes in germ cells; any foci of spermatogenesis observed in these patients are from germ cells that have lost one X chromosome (*11*, *12*). Germ cell defects are also seen in females with Turner's syndrome, which is characterized by the presence of only a single X chromosome (XO) (*13*). Although recent studies have identified signals by which the somatic gonad influences germline sex determination in mammals, how the sex chromosome constitution affects this process remains unknown.

The appearance and function of sperm and egg are similar throughout the animal kingdom, which suggests that the process of germline sexual development may be highly conserved. Thus, a better understanding of how germline sexual identity is regulated by the soma, and by the germ line's own sex chromosome constitution, will have far-reaching implications for our knowledge of animal development and human fertility. Hashiyama *et al*. have now brought us one step closer to this goal.

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MATERIALS SCIENCE

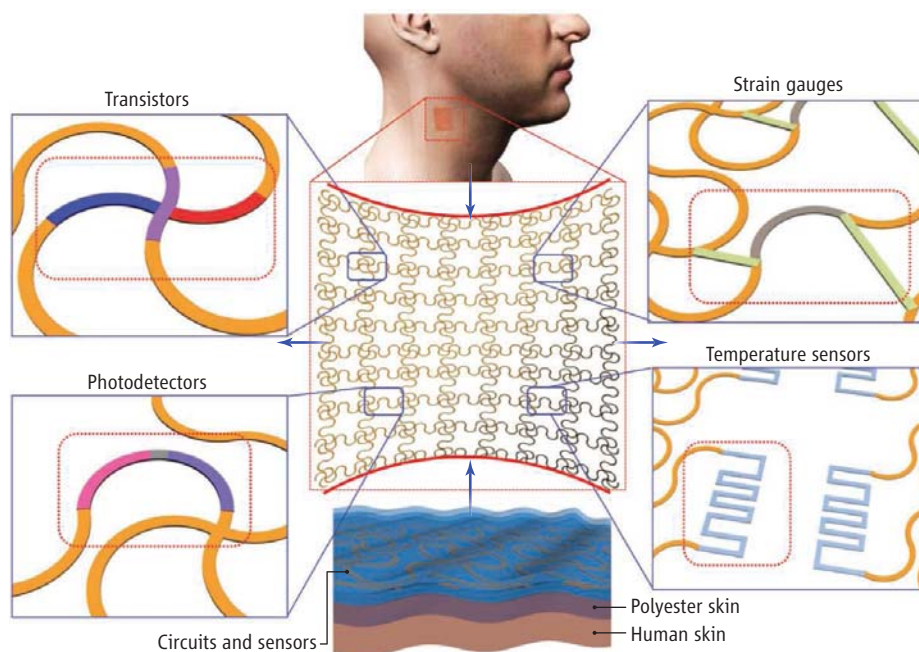# An Electronic Second Skin

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Small, flexible devices that attach to the skin without adhesives or gels monitor physiological signals.

In clinical health monitoring, the diagnostic machines that perform physiological measurement and stimulation through skin are connected to patients with wires and cables. Such complicated wiring can be inconvenient and distressing for both patients and physicians. For example, a patient who may have heart disease is usually required to wear a bulky monitor for a prolonged period (typically a month) in order to capture the abnormal yet rare cardiac events. The current best electrodes are gel-coated adhesive pads. Many people, particularly those who have sensitive skins, will develop a rash, and

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the electrode locations have to be constantly moved around, interrupting monitoring. Clinical physicians strongly desire more compact and even wireless health monitoring devices. An electronic skin recently developed by Kim *et al*. (*1*), reported on page 838 in this issue, will help solve these problems and allow monitoring to be simpler, more reliable, and uninterrupted. These devices were made through "transfer printing" fabrication processes that create flexible versions of high-performance semiconductors that are brittle as bulk materials.

The electronic skin concept was initially developed for applications in robotics (*2*–*4*). Robots could be provided with pressure sensing ("touch") that would allow them to grip objects securely without damaging them (the

Information caught by film. A flexible electronic device attaches to the skin like a bandage tape and can be used to acquire physiological information without bulky electrodes. Kim *et al.* developed an electronic skin in the form of a highly stretchable net, consisting of various sensors and electronics of serpentine shapes, that is sandwiched between two protection layers of equal thickness. The device layer sits on a polyester layer that was engineered with mechanical properties to match those of natural skin.

"picking up an egg" problem). These electronic skins, which mainly consist of pressure-sensing materials and associated electronic devices for pressure reading, might also provide touch sense to prosthetic devices such as artificial legs or arms.

One challenge for making these devices is that the transistors (and the semiconductors in them) that amplify weak signals must be flexible in order to act like skin. The ability of transistors to amplify signals—their gain—depends on the mobility of the charge carriers in their semiconductor under the gate layer (or in their gated semiconductor layer). Doped single-crystalline silicon wafers are used in most computer chips because of their high carrier mobility, which allows operation with low applied voltage and low power. However, the wafers are brittle, so alternative materials have been pursued. Some of the candidate flexible semiconductors, such as conducting polymers (*2*, *3*), have much lower carrier mobilities. The higher voltages needed to use these materials as transistors may not be suitable for electronic skin that makes direct contact with a patient's skin, and may quickly exhaust small power supplies.

Another approach is to convert brittle semiconductors into more flexible forms. For example, silicon and germanium are highly flexible as nanowires (*4*, *5*). However, their carrier mobility, although much higher than that of conducting polymers (*2*, *3*), is still much lower than that of doped silicon. With these types of materials, it is difficult or impossible to achieve the performance needed to amplify very weak signals acquired from natural skin.

The electronic skin demonstrated by Kim *et al.* uses thin single-crystal silicon that has superior flexibility and a mobility equivalent to that of the silicon used in personal portable devices. The approach, a printing method developed previously by Rogers's group (*6*), could be called "inking and printing." A thin silicon layer is bonded to a silicon dioxide release layer. The silicon layer is cut into a lattice of micrometer-scale "chiplets," and a transfer stamp layer is then attached to the top of the divided silicon. The transfer layer and chiplets are then lifted and transferred to a flexible substrate.

Attaching electronic skin to natural skin is more difficult than attaching it to robots or prosthetics. Natural skin is soft and delicate and already has touch-sensing functions. The electronic skin that can be used for physiological monitoring must have a supporting layer with mechanical properties that match those of natural skin to avoid any discomfort resulting from long wearing. The electronic skin must not be too thick, too rigid, too hard, or too heavy, but must have conformal contact, intimate integration, and adequate adhesion with the natural skin.

Special materials that are properly designed through accurate modeling were needed to achieve these properties. The support layer of the electronic skin is an elastomeric (rubbery) polyester engineered to have mechanical properties well matched to those of natural skin. The circuitry part of the electronic skin consists of two protection layers that sandwich a multifunctional middle layer (see the figure). With their equal thicknesses, the protection layers develop opposite strains that cancel, so the middle circuit layer experiences little stress no matter which direction the device is bent. The middle layer consists of the metal, semiconductor, and insulator components needed for sensors, electronics, power supplies, and light-emitting components, all of which are in the serpentine shape that forms a stretchable net. The serpentine shapes allow the net to deform drastically with little effect on its functionality. This innovative design contains all of the necessary components in an ultrathin layer about the thickness of a human hair.

The electronic skin designed by Kim *et al.* can be simply mounted onto or peeled off natural skin in the same way as bandage tape. Physiological information has been collected from heart, brain, and skeletal muscles with a quality equivalent to that collected with bulky electrodes and hardware. Other forms of physiological information collection based on the electronic skin are readily feasible because they could use components that have more sophisticated functions.

The transfer-printing fabrication approach (*6*) has proved to be viable and low-cost in this demonstration, which will greatly facilitate the practical clinical use of the electronic skin. Because of the higher quality of the transferable thin silicon, wireless communication directly from the electronic skin should be feasible, given recent demonstrations of this capability in other devices (*7*). Other types of electronic skins with applications beyond physiology, such as body heat harvesting and wearable radios, may also point to interesting directions for future work.

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