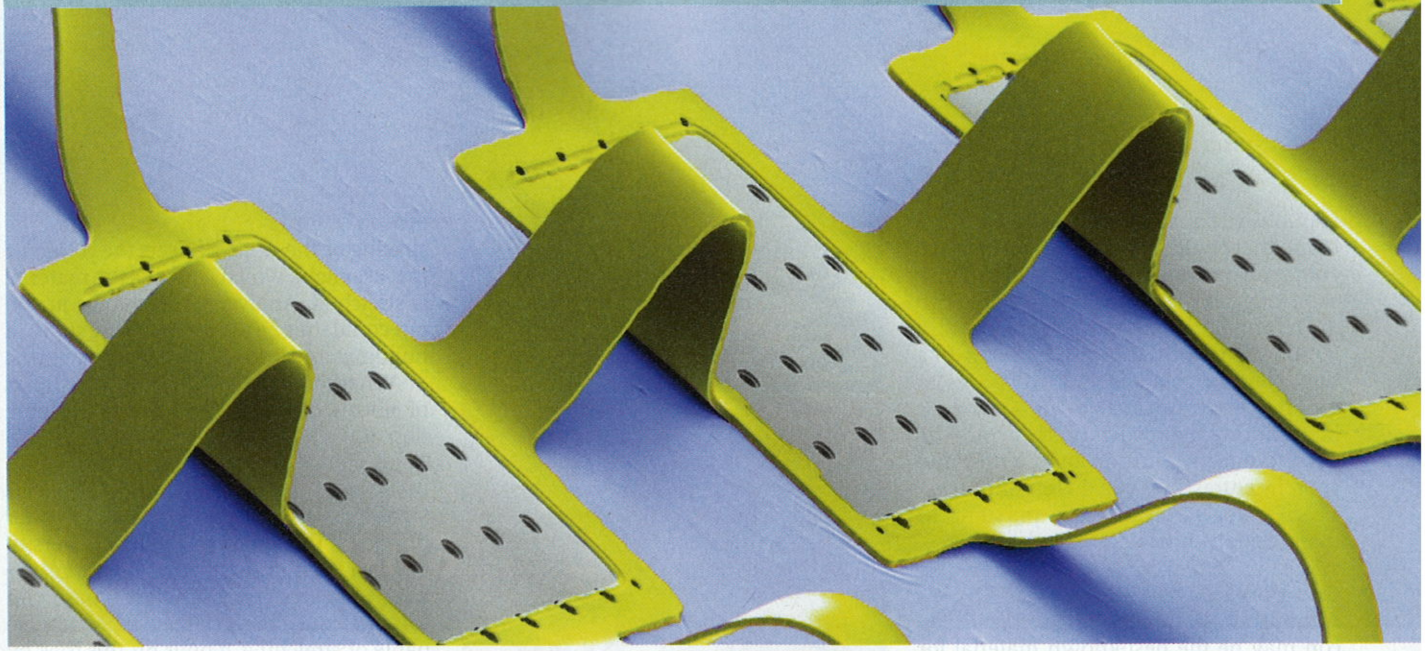

A shapely future for circuits

Electronics: Flexible circuits that can bend and stretch with their surroundings could have a wide range of uses

FOR years engineers have dreamed of building electronic circuits that would bend and stretch, rather than being confined to rigid chips and boards. Flexible circuitry would be able to do many things that rigid circuits cannot. Stretchable electronic skin could connect an artificial hand to the nervous system. Combat uniforms and helmets containing flexible, lightweight impact sensors could help medics prescribe better treatment if a soldier is wounded in an explosion. A neuroscientist who wants to understand the electrical storm that occurs in the brain of an epileptic patient could watch seizures unfold in real time with a circuit that conforms to the gyri of the brain. Flexible circuits would also make portable devices more resilient; they could be worn like clothing or jewellery rather than carried.

Researchers are pursuing a number of different approaches to making circuitry more pliable. Rigid chips and circuit boards will not be going away any time soon, because they are so inexpensive to manufacture on a massive scale. The trick is to find the appropriate ways to combine rigid and flexible circuit elements—and to identify the most promising applications for the bendy sort.

The fundamental difficulty in building flexible circuitry is that single-crystal silicon—the sort which is used to make high-performance components such as microprocessors and radio chips—is rigid. But in 2006 John Rogers, a materials scientist at the University of Illinois Urbana-Champaign, came up with a way to stretch single-crystal silicon without breaking it. Silicon itself doesn't naturally stretch, but the trick is in its preparation: it must be ultra-thin, only about 100 nanometres thick. (A nanometre is a thousand-millionth of a metre.) Any material is flexible if it is thin enough, says Dr Rogers. You can crumple a piece of paper, but not a plank of wood.

Flexible strategies

He and his colleagues have developed two basic approaches to stretching circuits built on ultra-thin, bendable silicon. The first involves transferring ultra-thin sheets of silicon onto a sticky, rubber-like material that has already been stretched. When the rubber is released, the silicon buckles but does not break, forming a sort of herringbone pattern. Dr Rogers has designed entire circuits based on this principle, with working transistors, logic gates and oscillators.

The second way to stretch a circuit is to make tiny islands of rigid silicon and connect them with wires that provide the flexibility. This approach works because the islands are small enough to withstand small amounts of strain and the connectors are designed in such a way to accommodate any stretching. For instance, the wires can arc out of plane or spiral like springs.

Using the silicon-island approach, Dr Rogers and his colleagues recently demonstrated an eyeball-shaped camera in which the curve of the lens and an array of silicon sensors change shape to zoom in and out. Matching the curved lens with a curved sensor array reduces distortions that can occur when using the flat sensor-arrays found in most cameras, says Dr Rogers.

Another use for stretchable silicon is to make new types of medical devices that can reduce the invasiveness of certain procedures. One of Dr Rogers's projects, outlined in a recent paper in *Nature Materials* equips a standard balloon catheter, used in angioplasty, with an array of sensors and radio circuitry. Instead of being an inert balloon that is used to break up a blockage, the sensor-laden catheter can monitor blood flow, temperature, pressure and electrical activity within the body. Wirelessly powered electrodes can also burn away tissue or cauterise as needed.

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to publish a paper on a thin artificial membrane that could allow flexible sensor circuitry to be transferred onto a patient's skin, for example to produce an electrocardiograph. He likens the membrane to a temporary tattoo. He is also working on a thin, conformable sheet of electrodes to monitor electrical activity in a patient's brain during neurosurgery. This could be used to track seizures or map motor and speech centres. "We can do lots of things," says Dr Rogers, "and we're pursuing as many opportunities as we can handle."

Going organic

Although high-quality single-crystal silicon may be the best-known material for making electronic components, it isn't the only one—and it's not the only one being teased into different shapes. Stéphanie Lacour, a researcher at the École Polytechnique Fédérale de Lausanne, is using organic transistors as pressure sensors on flexible materials, including silicone rubber, that can function as stretchable electronic skin. Organic transistors, as their name suggests, are made of carefully layered organic materials rather than being etched into a rigid crystal of silicon. Although they are flexible, they are not as small or fast as silicon transistors. But for sensing there is no need for extremely fast switching, says Dr Lacour.

The idea is that this flexible material could be wrapped around a prosthetic limb, with electrical signals from the sensors connected to an amputee's nerves to convey sensations. Dr Lacour has already made a prototype sensor with Nokia, a mobile-phone giant, consisting of a thin, stretchable, touch-sensitive film. This could be applied to the outside of a curved phone in place of a keyboard, or used to control a device in the form of a flexible wrist-band. Dr Lacour's stretchable electronic skin can be made using the same processes used to produce organic light-emitting diode (OLED) displays, which are found in many mobile phones.

Takao Someya of the University of Tokyo, who is one of the pioneers of electronic skin, has also built stretchable circuits using organic transistors on a rubber backing. He hopes to equip robots with sensitive skin to make them more aware of their environment. In addition, he has demonstrated a working OLED display on a stretchable surface. In a paper recently published in *Nature Materials*, he and his colleague Tsuyoshi Sekitani described some tricks to ensure that organic circuits continue to work even when drastically deformed. The backing material must be as smooth as possible, and the circuitry sealed beneath a layer composed of a polymer-metal-polymer sandwich. This acts as a barrier to oxygen and moisture to keep the device working. These tricks, they report, allow a flexible circuit to be bent with a radius of curvature of less than 0.1 millimetres—in other words, folded like paper—without breaking.

Ultra-thin circuits on pre-stretched rubber (top and bottom); silicon "islands" with flexible links (centre, and previous page)

At Princeton University, meanwhile, Sigurd Wagner has also developed organic optical devices, including an organic laser on a stretchable rubber surface. Organic lasers are not as powerful as traditional lasers made with gallium or indium compounds, but they can be easily printed or deposited directly on any type of surface. In Dr Wagner's laser, the organic layer that produces laser light is deposited onto prestrained rubber. When the strain is removed, it forms a ripply surface, and the spacing of the ripples affects the colour of the laser light, which varies as the material is stretched. Analysing the change in colour could thus be used to measure strain in buildings and bridges, Dr Wagner suggests.

Whether they are based on tiny slivers of silicon, organic circuitry or a combination of the two, stretchable devices will require power to operate. Stretchable electronics will need stretchable batteries, says Siegfried Bauer, professor of soft-matter physics at the Johannes Kepler University in Linz, Austria. Last year his group announced a new type of battery, based on standard zinc-carbon chemistry, that is capable of stretching. It pulls off this trick by using stretchy polymers, called elastomers, in conjunction with conductive gels, to transport charged particles between the battery's terminals.

Dr Bauer is also working on a stretchable battery that is rechargeable. And his team is looking for ways to exploit stretchable materials so that energy used to deform the material can be captured and converted to electrical energy—an idea known as "energy harvesting". This might allow devices to be powered by shoes or clothing that harvest energy from the wearer's movement, for example.

It may also be possible to make solar cells in a flexible, stretchable form. Dr Rogers and his colleagues are exploring a type of semiconductor material called gallium arsenide, which is usually inflexible, for just this purpose. He proposes dividing a rubber substrate into squares separated by trenches, and transferring tiny islands of rigid gallium arsenide onto those squares when the rubber is stretched. These tiny solar collectors would be connected with wires that form bridges over the trenches between the squares, and which buckle when the rubber is relaxed. This protects the rigid gallium arsenide components from strain, but the system as a whole is flexible and stretchable.

It is, in short, possible to see how logic circuits, input sensors, output displays and power supplies can all be made in flexible form. Traditional electronics are cheap and widespread today because they are made in huge quantities in extremely efficient factories. Stretchable electronics are not there yet. It is likely to be some time before you are offered a mobile phone in the form of a flexible rubber bracelet, a smart tattoo attached to your skin, or even an implant that flexes along with your body. But researchers have already taken the first steps towards such exotic devices. ■

Stretchable electronics

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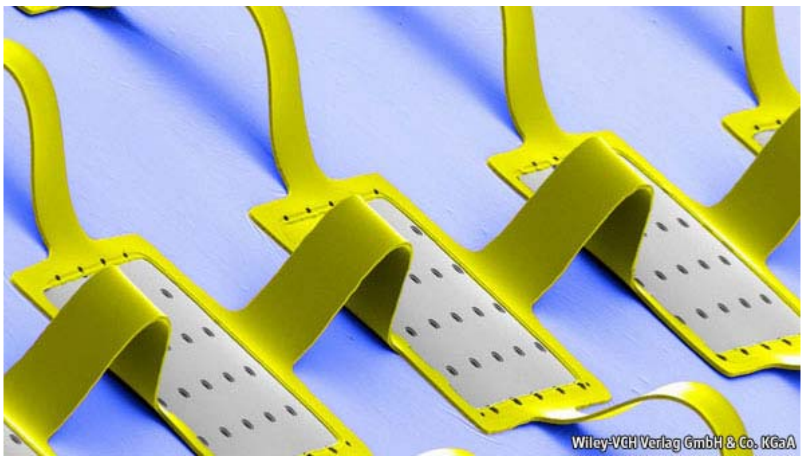

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Silicon “islands” with flexible links (top and above)

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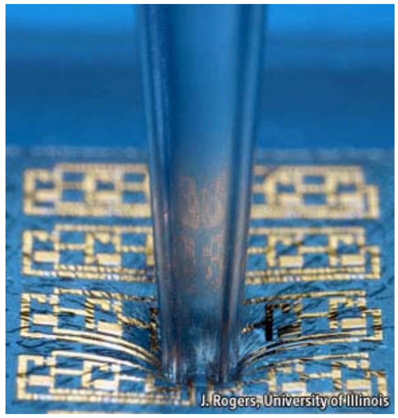

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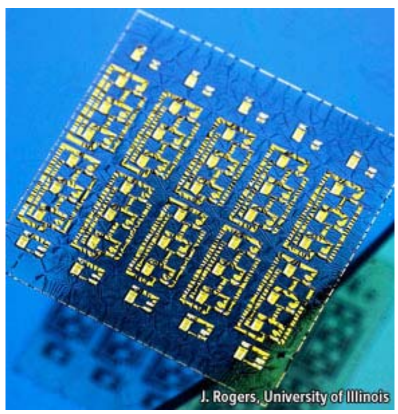

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