RESEARCH LETTER

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Skin Electronics from Scalable Fabrication of an Intrinsically Stretchable Transistor Array

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Background

- Electronic skin refers to flexible, stretchable and self-healing electronics that are able to mimic functionalities of human or animal skin.
- Skin-like electronics that can adhere seamlessly to human skin or within the body are highly desirable for applications such as health monitoring, medical treatment, medical implants and biological studies, and for technologies that include human–machine interfaces, soft robotics and augmented reality.
- Electronics on human skin generally comprise, but are not limited to, two types of component: input/output devices for human interaction (the input might be, for example, a sensor element; the output might be a display), and electronic circuits for information processing.
- So far, stretchability has been demonstrated for certain input/output devices, but there are still no functional skin-like stretchable circuits, mostly because of the much higher complexity required at both circuit and device levels.
- Hence, realizing skin electronics will rely on the development of intrinsically stretchable circuits composed of densely integrated transistors.

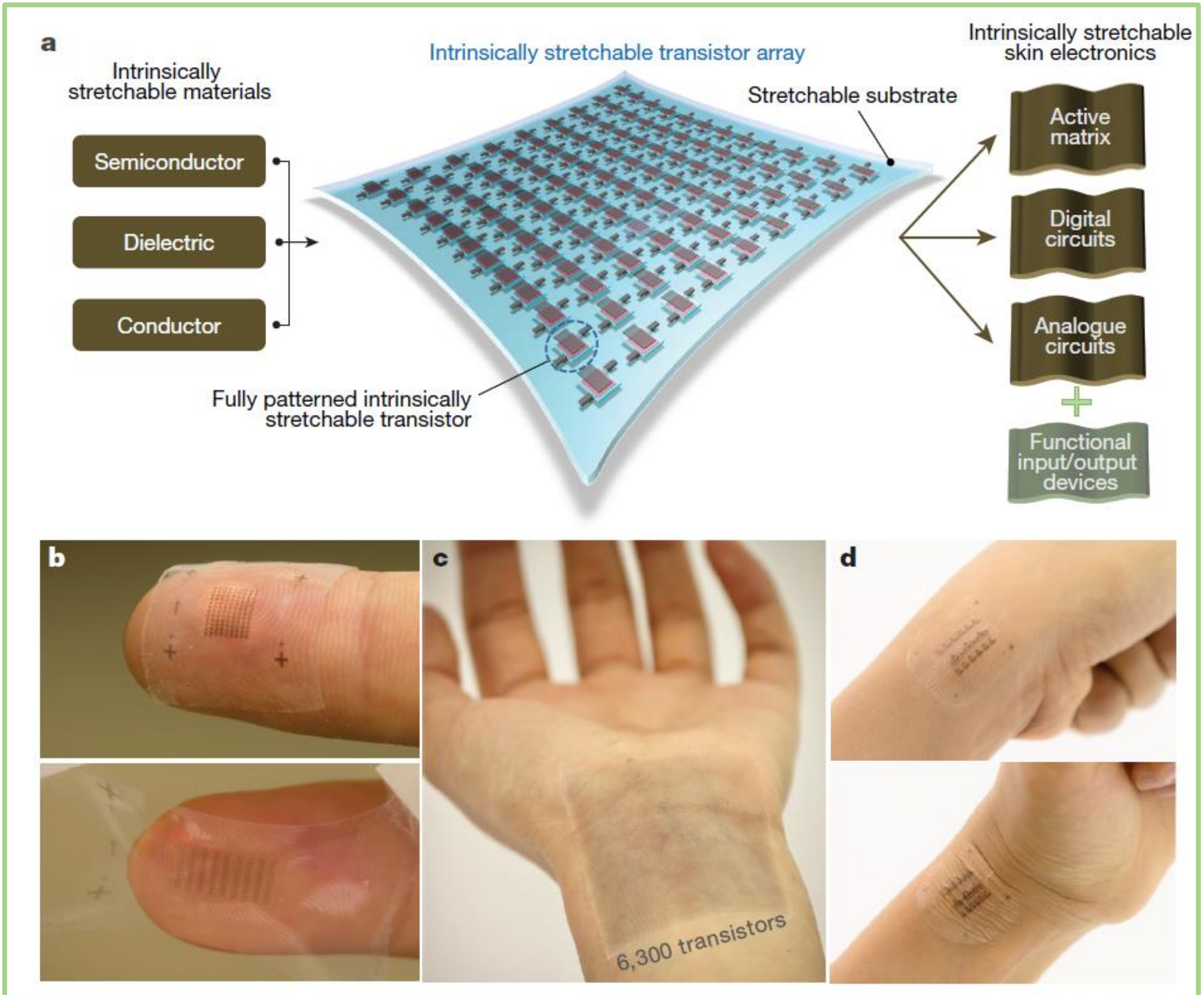
Relevance to Lab

- Ongoing work on nasal filters, microfluidics based sensors and humidity sensors eventually need to be developed into devices that can be attached directly onto surfaces be it human skin or the walls of a room.
- This paper gives an idea of highly stretchable integrated circuit based designs which can be stuck on surfaces.

Introduction

- Fabricating intrinsically stretchable electronics requires intrinsically stretchable materials, especially stretchable semiconductors and conductors that possess uncompromised electrical conduction, even under large strains.
- Recently, polymers have been shown to be the most promising materials family for enabling both high electrical performance and intrinsic stretchability.
- The production of intrinsically stretchable materials and devices is still largely in its infancy. Functional, intrinsically stretchable electronics have yet to be demonstrated owing to the lack of a scalable fabrication technology.
- This work describes a fabrication process that enables high yield and uniformity from a variety of intrinsically stretchable electronic polymers.
- An intrinsically stretchable polymer transistor array with an unprecedented device density of 347 transistors per square centimetre is demonstrated. The transistors have an average charge-carrier mobility comparable to that of amorphous silicon, varying only slightly (within one order of magnitude) when subjected to 100 per cent strain for 1,000 cycles, without current–voltage hysteresis.
- These transistor arrays constitute intrinsically stretchable skin electronics, and include an active matrix for sensory arrays, as well as analogue and digital circuit elements. The process also offers a general platform for incorporating other intrinsically stretchable polymer materials, enabling the fabrication of next generation stretchable skin electronic devices.

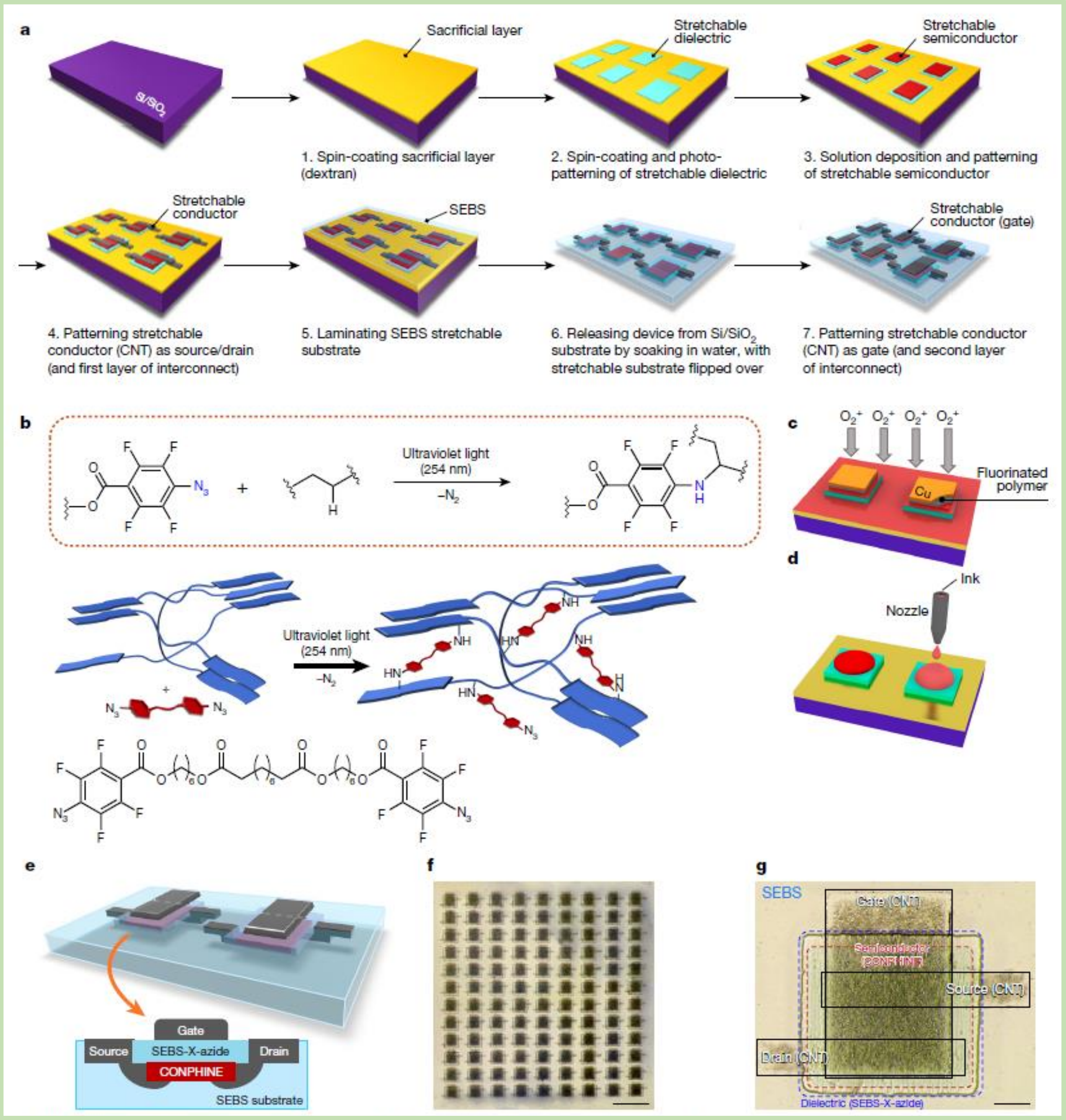
Intrinsically stretchable transistor array as core platform for functional skin electronics



a, Three-dimensional diagram of an intrinsically stretchable transistor array as the core building block of skin electronics.

b, An array of 108 stretchable transistors on a fingertip, showing an unprecedented device density of 347 transistors per cm^2

Platform for fabricating intrinsically stretchable transistor arrays



a, Fabrication process flow.

b, Top, an azide-crosslinking reaction, which is initiated by ultraviolet light and is based on the reaction between azide groups and CH groups. Middle, how the polymer-chain network in an elastomer becomes crosslinked by azides (red) into a three-dimensional network. Bottom, chemical structure of an azide crosslinker.

c, Etching-based process for patterning stretchable semiconductors.

d, Inkjet printing as an additive patterning process for stretchable semiconductor film.

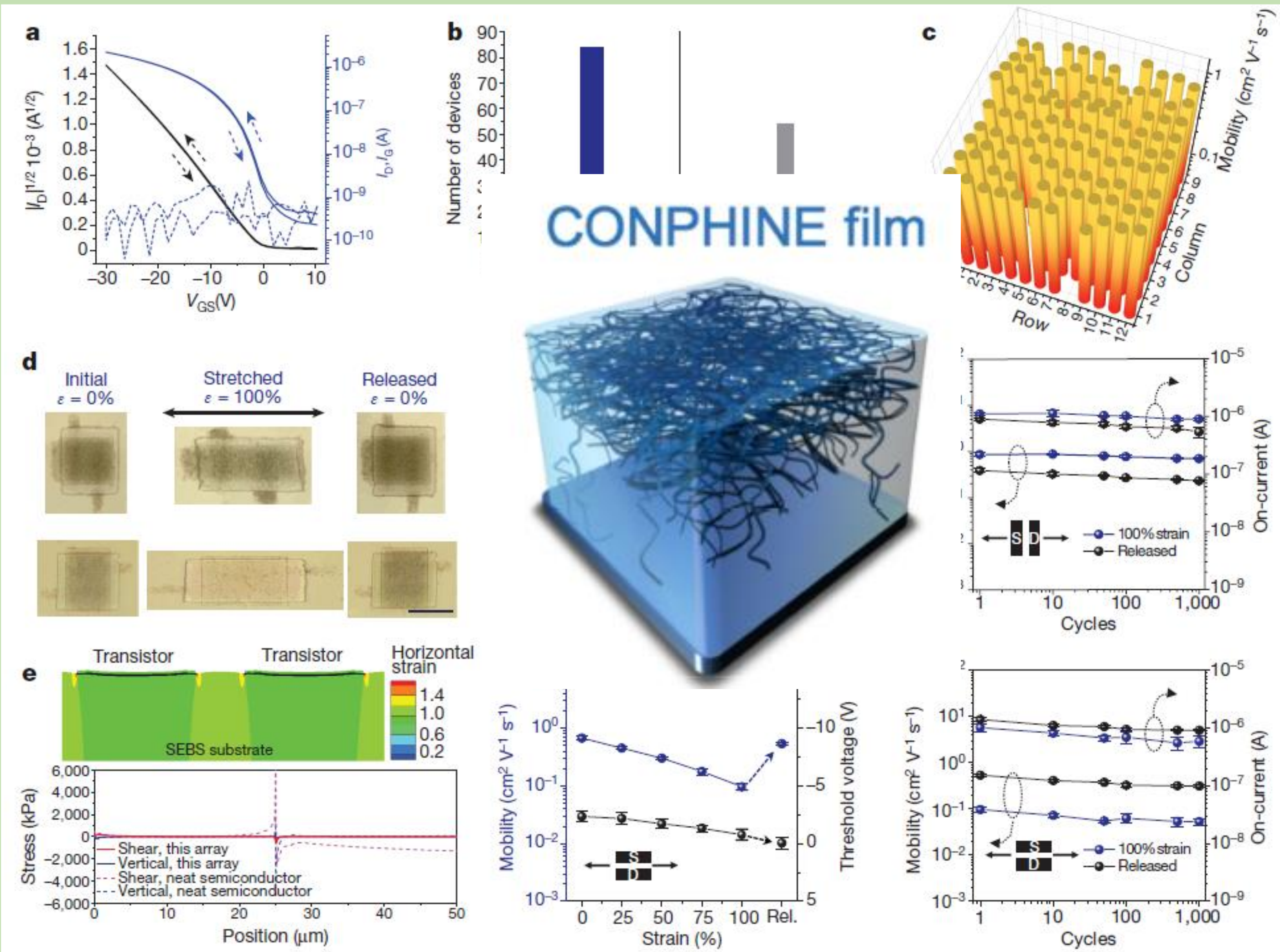
e, Example of an intrinsically stretchable transistor array for performance characterization and demonstration.

f, Optical microscopic image of a transistor array with 108 transistors. Scale bar, 1 mm.

g, Magnified image of one transistor in the array.

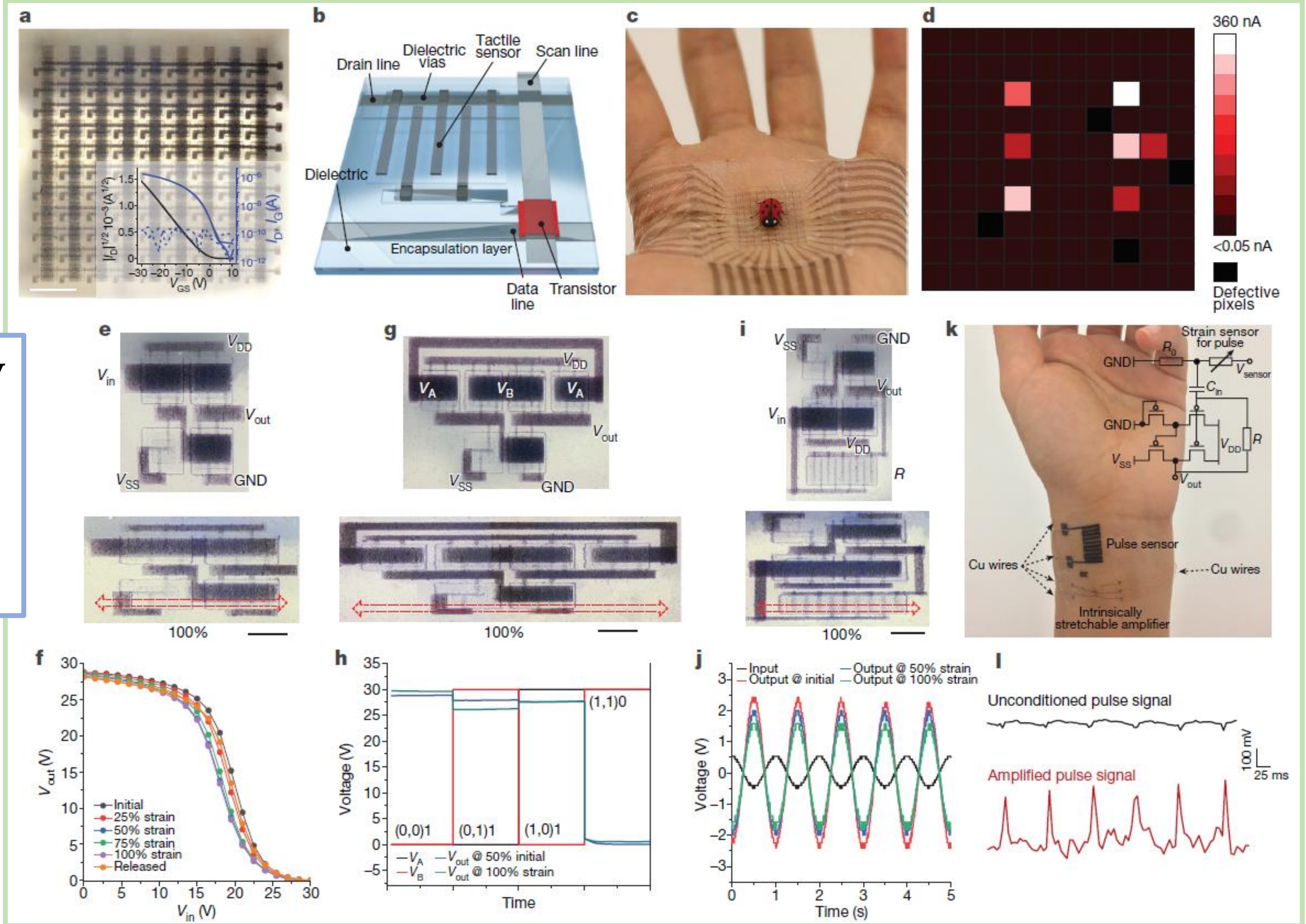
SEBS- polystyrene-*block*-poly(ethylene-*ran*-butylene)-*block*-polystyrene

Electrical performance and stretchability of the intrinsically stretchable transistor array



a, Typical transfer characteristics from the transistor array without strain showing little current hysteresis.
b, Histograms showing on-currents and threshold voltages from the 102 working transistors in the 108-transistor array.
c, Map showing charge-carrier mobility for each transistor location.
d, Optical microscope images showing the arrayed transistors stretched from 0% to 100% strain (ε) and then released, in directions both parallel (top) and perpendicular (bottom) to the channel. Scale bar, 250 μ m.
e, Top, mechanical simulations showing the strain distribution in the array when stretched to 100% strain, Bottom, the shear stress and vertical stress distribution (under 40% global strain) at the dielectric layer's bottom interface ('this array'), and for a control structure in which the CONPHINE semiconductor layer was replaced with a neat conjugated polymer.
f, **g**, Mobilities and threshold voltages during a stretching cycle parallel (**f**) and perpendicular (**g**) to the channel direction. **h**, **i**, Mobilities and on-currents obtained under 100% strain and in a released state during 1,000 stretching cycles, parallel (**h**) and perpendicular (**i**) to the channel direction.

Intrinsically stretchable circuits for skin electronics



a, A stretchable active matrix developed from our intrinsically stretchable transistor array. Scale bar, 1 mm. **b**, Diagram showing a tactile sensor array made from a stretchable active matrix. **c**, The array adheres and conforms to a human palm, enabling accurate sensing of the position of a synthetic ladybug with six conductive legs. **d**, Current mapping in linear scale, showing exact matching with the position of the ladybug. **e**, Optical microscope images of a fabricated intrinsically stretchable inverter with pseudo-CMOS design, in its initial state (top) and after being stretched to 100% strain (bottom). **f**, Transfer curves from the inverter when stretched gradually from 0% to 100% strain. **g**, Optical microscope images of a fabricated intrinsically stretchable NAND gate in its initial state (top) and after being stretched to 100% strain (bottom). **h**, Output–input characteristics of the NAND gate at 0% and 100% strain. **i**, Optical microscope images of a fabricated intrinsically stretchable amplifier in its initial state (top) and after being stretched to 100% strain (bottom). **j**, Input sinusoidal signal, along with output signals after amplification when the amplifier is at 0%, 50% and 100% strain. **k**, Use of the intrinsically stretchable amplifier to amplify arterial pulse signals measured by a stretchable strain sensor.

Conclusion

- Compared with previously reported milestones in developing stretchable transistors and circuits for skin electronics, the reported intrinsically stretchable transistor array has, for the first time (to their knowledge), combined advanced electronic functionality with high skin-like stretchability.
- The reported fabrication process provides a platform on which to readily incorporate future materials advancements into functional electronic circuits and systems with skin like and even 'beyond-skin' softness and deformability.

"When the winds of change blow, some people build walls and others build windmills."

Thank you…