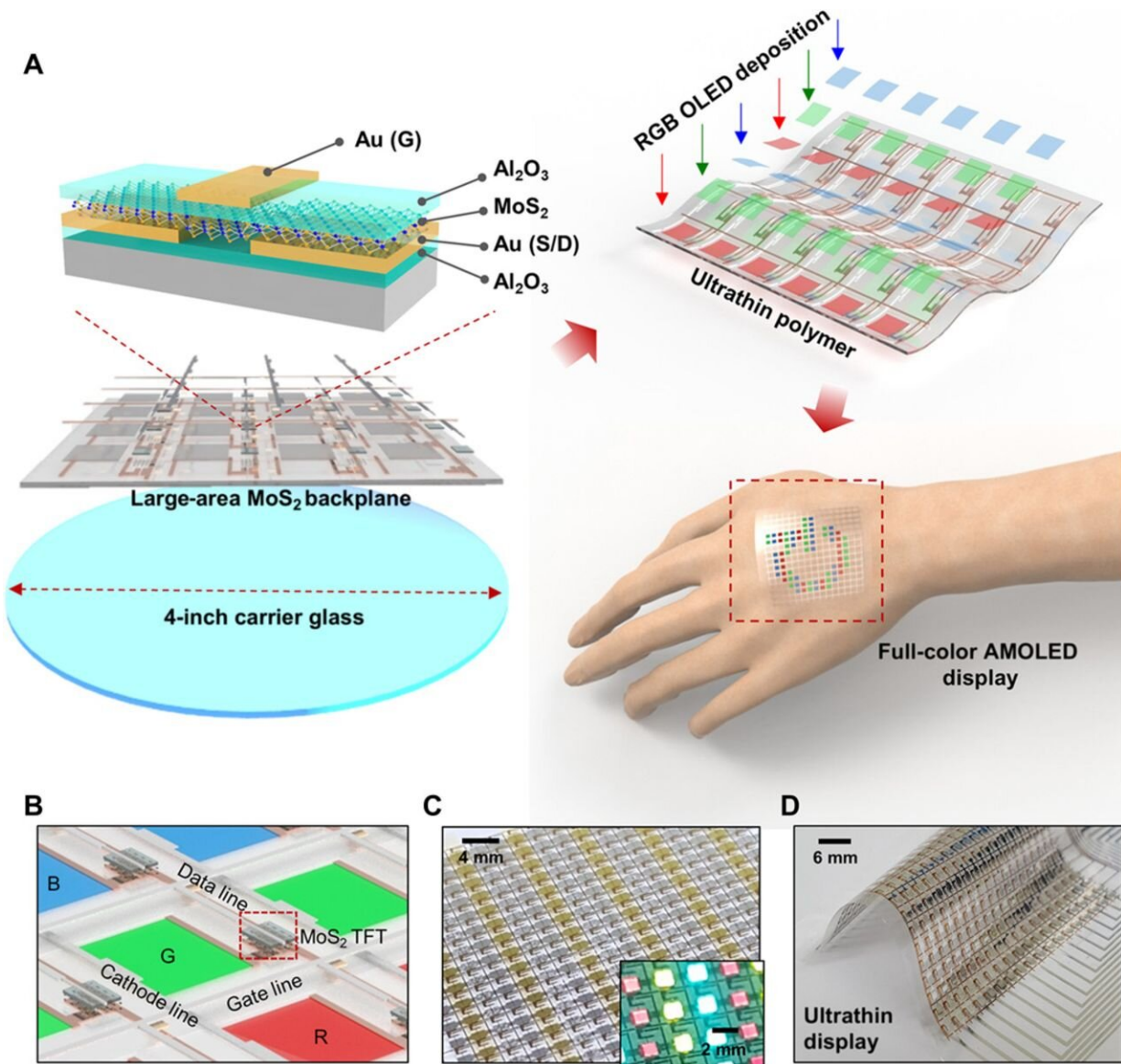


# Active-matrix organic light-emitting diode display on human skin

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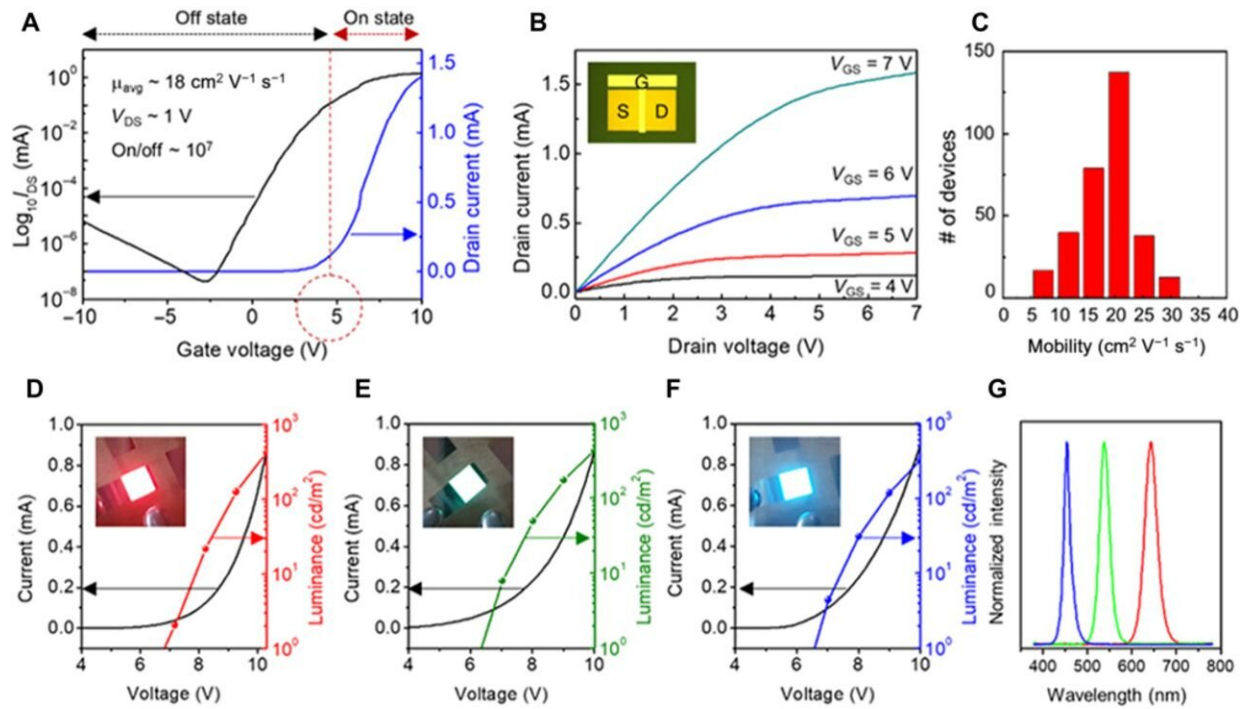


The full-color AMOLED display with large-area MoS<sub>2</sub>-based backplane. (A)

Schematic illustration of the high-performance MoS<sub>2</sub>-based backplane on a 4-inch carrier glass substrate, where an Al<sub>2</sub>O<sub>3</sub> capping layer was applied for n-doping effects on the MoS<sub>2</sub> film (top left), an active-matrix full-color display was applied to the ultrathin polymer substrate (top right), and the large-area full-color display was tested on a human hand (bottom right). (B) Scheme of the active-matrix full-color pixel array integrated with MoS<sub>2</sub> transistors, where each pixel was connected via a gate, data, and cathode interconnector for line-addressing control. (C) Digital photograph of the active-matrix display on the 4-inch carrier glass substrate, where the inset demonstrates the full-color display when switched on. (D) Digital photograph of the large-area full-color display on the ultrathin polymer substrate, demonstrating the flexible mechanical properties due to the low bending stiffness of the ultrathin material. Photo credit: Minwoo Choi, Yonsei University. Credit: *Science Advances*, doi: 10.1126/sciadv.abb5898

The development of electronic applications can take on many new forms to include foldable and [wearable displays](#) to monitor human health and act as medical robots. Such devices rely on [organic-light emitting diodes](#) (OLEDs) for optimization. However, it is still challenging to develop semiconducting materials with high mechanical flexibility due to their restricted use in conventional electronic formats. In a new report on *Science Advances*, Minwoo Choi and a team of scientists in Electronic Engineering and Materials Science in the Republic of Korea, developed a wearable, full-colour OLED display using a two-dimensional (2-D) material-based [backplane transistor](#). They engineered an 18-by-18 thin-film transistor array on a thin [molybdenum disulfide](#) (MoS<sub>2</sub>) film and transferred it to an [aluminium oxide](#) (Al<sub>2</sub>O<sub>3</sub>)/[polyethylene terephthalate](#) (PET) surface. Choi et al. then deposited red, green and blue OLED pixels on the device surface and observed excellent mechanical and electrical properties of the 2-D material. The surface could drive circuits to control the OLED pixels to form an ultrathin, wearable device.

Scientists and engineers must conduct extensive research in the [field of wearable electronics](#) to develop [smart electronic systems](#) focused on flexible devices and ultrathin substrates. Inherent limits of such materials have motivated the use of [alternative semiconductor materials](#) such as MoS<sub>2</sub> for inclusion in [thin-film transistors](#) (TFTs) and logic circuits with [relatively high performance](#). These materials are known as [transition metal dichalcogenides](#) and they provide unique electrical, optical, and mechanical properties for [backplane circuitry](#) of wearable electronics. Researchers had recently developed MoS<sub>2</sub> transistors with sophisticated [red, green and blue \(RGB\) colors](#) as a fundamental and essential requirement for practical displays. In this work, Choi et al. developed a large-area MoS<sub>2</sub> TFT array to operate 324 pixels in a 2-inch RGB OLED, in which the full-color display demonstrated an active-matrix configuration. The RGB OLEDs were made of [different optoelectronic characteristics](#), therefore the team designed the backplane TFTs to control each color pixel. The experimental setup was promising as a wearable display and functioned steadily on human skin without adverse effects. The team used [heterogenous material designs](#) to form optoelectronics in the present work.



Device properties of the MoS<sub>2</sub> transistor and RGB OLEDs. (A) Transfer curve of the MoS<sub>2</sub> transistor on the 4-inch carrier glass substrate, where the average mobility of 18 cm<sup>2</sup> V<sup>-1</sup> s<sup>-1</sup> was sufficient for operating the RGB OLEDs. (B) I-V characteristics of the MoS<sub>2</sub> transistor as the gate bias was increased from +4 to 7 V, where the inset shows the MoS<sub>2</sub> transistor. (C) Statistical analysis of the MoS<sub>2</sub> transistor mobility across 324 samples. (D to F) I-V characteristics (left y axis) and luminance (right y axis) of the RGB OLED as a function of applied bias, where the insets visualize the emission of each OLED color. (G) EL spectra of the RGB OLED pixels. Photo credit: Sa-Rang Bae, Korea University. Credit: Science Advances, doi: 10.1126/sciadv.abb5898

## Large-area active-matrix OLED (AMOLED) display

The team designed a large-area active-matrix OLED (AMOLED) display with an MoS<sub>2</sub> backplane via a sequence of processes. They first formed a thin-film-transistor (TFT) array on a thin MoS<sub>2</sub> film, then deposited an RGB OLED on the drain electrode of the TFTs and peeled

the display from the carrier to transfer it to the human hand (the target). During the process, they synthesized a bilayer MoS<sub>2</sub> film on a 4-inch SiO<sub>2</sub>/Si wafer [via metal organic chemical vapor deposition](#) (MOCVD). Then they coated a polyethylene terephthalate (PET) substrate with [aluminium oxide](#) using atomic layer deposition and transferred the MoS<sub>2</sub> film from the SiO<sub>2</sub>/Si wafer to this PET substrate to produce an MoS<sub>2</sub> transistor array with a driving backplane configuration. The resulting structure was unique and encapsulated with aluminium oxide for [improved metal contacts](#) and carrier mobility. The full-color AMOLED display uniformly controlled the RGB OLED pixels, where each pixel connected to a data and a scanning line and the entire display circuit functioned in an [active-matrix design](#). Choi et al. controlled the pixel current based on the drain and gate signals of the transistor to change the brightness of the OLED. They could then transform the ultrathin display from the carrier glass substrate to a curved surface without device degradation.

## Full color display (Dynamic operation)

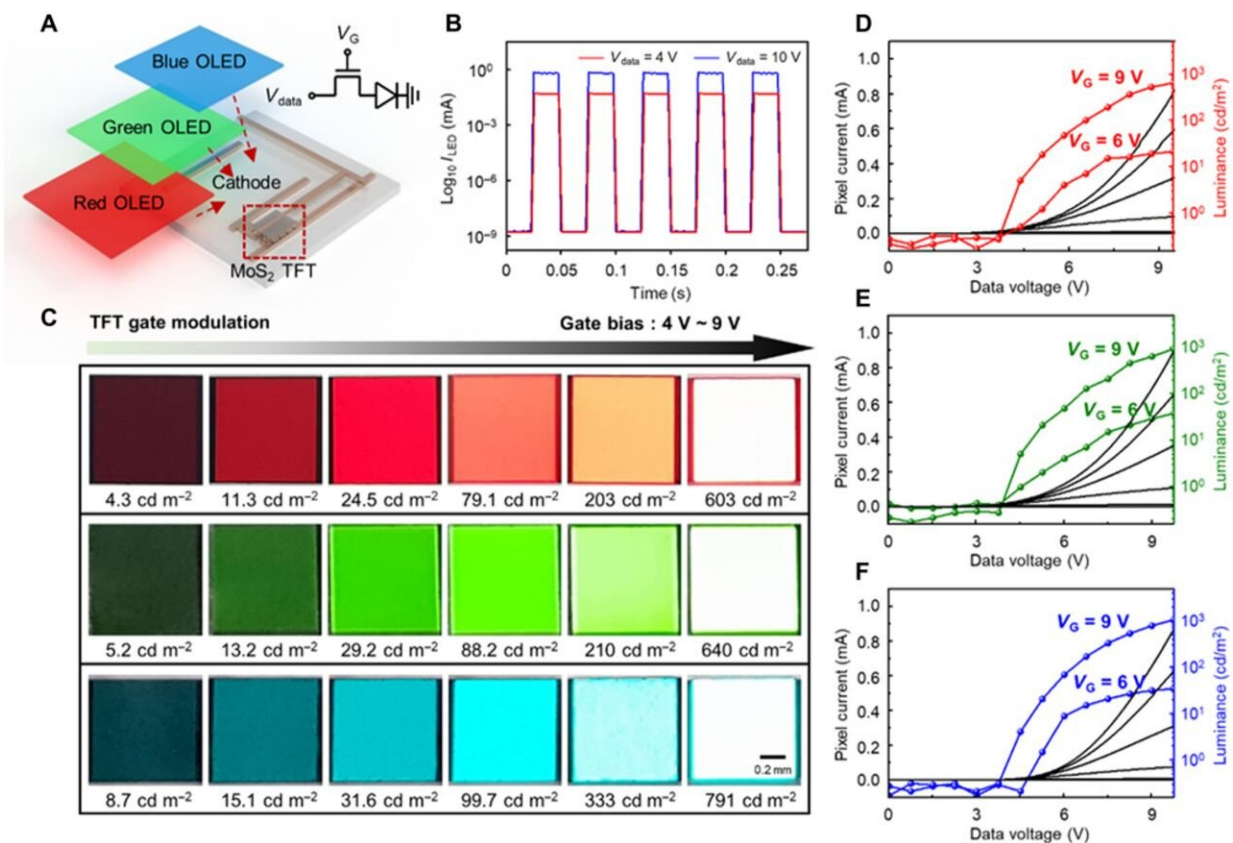
The dynamic operation of the active-matrix display via external circuit control.  
Credit: Science Advances, doi: [10.1126/sciadv.abb5898](https://doi.org/10.1126/sciadv.abb5898)

### **Stable display applications**

The team examined the current-voltage output curves to determine the drain characteristics of the TFTs to illustrate the relationship between the drain current ( $I_{DS}$ ) and the bias voltages ( $V_{DS}$  and  $V_{GS}$ ). The homogeneity of the MOCVD-grown  $\text{MoS}_2$  film allowed high uniformity for stable display applications. The device properties were consistent across all the samples, allowing the single pixel to operate in the full-color AMOLED, while the efficiency did not decrease. The team measured the highest luminescence at 460, 530, and 650 nm for the blue, green and red OLEDs.



At a repeated gate pulse bias of +10 volts, the OLED exhibited a rapid transition between on and off states, although the response time was limited by the measurement system, the delay time was short. Gate modulation did not occur during the off state and the pixel state remained stable, providing efficient leak-proof operation of the TFT. The pixel current also dramatically increased with increasing gate bias ( $V_G$ ) during the on state to reach a threshold voltage of 5 volts across the RGB OLEDs.



The properties of a single pixel integrated with the MoS<sub>2</sub> transistor and RGB OLEDs. (A) Schematic illustration of the RGB unit pixels integrated with the MoS<sub>2</sub> transistor in a series connection for active-matrix configuration. (B) Pixel-switching properties controlled using a gate bias of  $-10$  and  $10$  V at fixed data biases of  $4$  V (red) and  $10$  V (blue). (C) Digital photograph of the luminance change in the RGB OLEDs in a gate bias range of  $4$  to  $9$  V, where the brightness

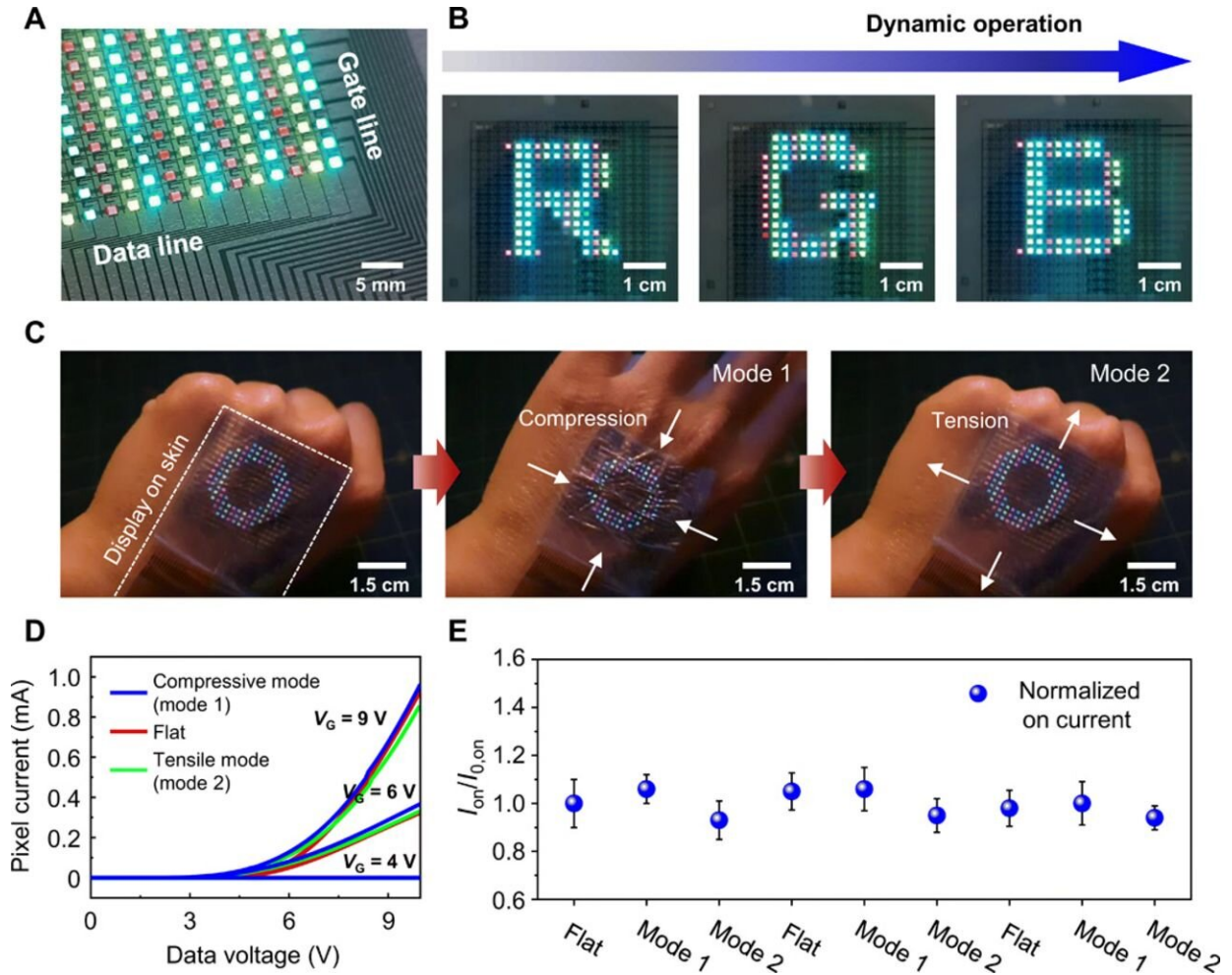
of each OLED was stable and controlled by the gate signal of the MoS<sub>2</sub> transistor. (D to F) The pixel current (left y axis) and luminance (right y axis) as a function of gate signal. Photo credit: Sa-Rang Bae, Korea University. Credit: Science Advances, doi: 10.1126/sciadv.abb5898

## **Proof-of-concept—wearable electronic device**

The team confirmed the performance of the individual RGB pixels using the transistors and integrated an 18 x 18 array (324 pixels) to the data and gate lines of the transistor backplane circuit to form a full-color AMOLED display. They controlled each pixel via the matrix line and maintained consistent light luminescence in each individual pixel in the OLED displays. The RGB OLED pixels showed consistent and uniform brightness due to the stable control of the gate and data signals. Choi et al. drove the RGB pixel arrays sequentially via an external drive circuit configured in a commercial strip pixel structure representing the characters 'R', 'G', and 'B'.

The low stiffness of the ultrathin device prevented the deterioration of optical and electrical properties during substantial mechanical deformation reflexes—after its transfer to a human hand. Based on the current-voltage characteristics ( $I$ - $V$ ), the current level did not change during skin shrinkage or skin stretching exercises and the on-state also did not fluctuate during active-matrix display operation. While the device stability is still in development, the team aim to conduct further engineering to improve the MoS<sub>2</sub> film for practical applications as a wearable, full-color AMOLED display.





Wearable full-color AMOLED display based on MoS<sub>2</sub> backplane circuitry. Digital photographs of the full-color active-matrix display during (A) the “all on” state; (B) the dynamic operation of the active-matrix display, where gate and data signals were individually controlled using the external circuit; and (C) the application of the ultrathin display on a human hand, where the display was deformed by two mechanical modes based on hand motion, namely, compressive mode (center) and tensile mode (right). (D) Plots of the unit pixel current as a function of data voltage at  $V_G$  values of 4 V (off state), 6 V, and 9 V in the compressive (blue), flat (red), and tensile (green) mode. At every applied gate bias ( $V_G$ ), negligible change in pixel current is observed under various modes of deformation, which enables stable operation of AMOLED on human hand. (E) Normalized on-state current variation of the ultrathin display on human hand during mechanical deformation. Photo credit: Minwoo Choi, Yonsei University. Credit: Science Advances, doi: 10.1126/sciadv.abb5898

In this way, Minwoo Choi and colleagues developed a thin (2-inch), wearable and full-color AMOLED [display](#) with 18 x 18 arrays using MoS<sub>2</sub>-based backplane TFTs. They built the transistor array directly on a bilayer MoS<sub>2</sub> film grown using MOCVD and observed a high carrier mobility and on/off ratio. The team controlled the light emission of the RGB OLED pixels by applying a gate-voltage between 4 and 9 volts. They used an ultrathin plastic substrate (PET) combined with 2-D semiconducting materials to directly fabricate OLEDs for excellent electrical, optical, and mechanical performance. This experimental system can be improved for integration in wearable and electronic devices beyond the existing conventional and rigid organic materials.

**More information:** Minwoo Choi et al. Full-color active-matrix organic light-emitting diode display on human skin based on a large-area MoS<sub>2</sub> backplane, *Science Advances* (2020). [DOI: 10.1126/sciadv.abb5898](#)

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