Integrated arrays of air-dielectric graphene transistors as transparent active-matrix pressure sensors for wide pressure ranges

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Integrated electronic circuitries with pressure sensors have been extensively researched as a key component for emerging electronics applications such as electronic skins and health-monitoring devices. Although existing pressure sensors display high sensitivities, they can only be used for specific purposes due to the narrow range of detectable pressure (under tens of kPa) and the difficulty of forming highly integrated arrays. However, it is essential to develop tactile pressure sensors with a wide pressure range in order to use them for diverse application areas including medical diagnosis, robotics or automotive electronics. Here we report an unconventional approach for fabricating fully integrated active-matrix arrays of pressure-sensitive graphene transistors with air-dielectric layers simply formed by folding two opposing panels. Furthermore, this realizes a wide tactile pressure sensing range from 250 Pa to ~3 MPa. Additionally, fabrication of pressure sensor arrays and transparent pressure sensors are demonstrated, suggesting their substantial promise as next-generation electronics.

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Integrated electronic circuitry with pressure sensors have been extensively researched as a key component for emerging electronics applications such as electronic skins (e-skins)\textsuperscript{1-12} and health-monitoring devices\textsuperscript{11-12}. Various types of pressure-sensing devices have been developed based on the sensing mechanisms of piezoresistivity\textsuperscript{1-2}, capacitance\textsuperscript{3,8}, piezoelectricity\textsuperscript{10,12} and field-effect transistor (FET)\textsuperscript{4,5,11}. A piezoresistive type of device has a simple structure, high sensitivity and fast response time, but the pixel density can be low when the sensors are integrated as array forms. A capacitive type has a simple device structure and operating principles, but they are susceptible to neighbouring interference\textsuperscript{9}. A piezoelectric type has high sensitivity and fast response time, but sensing properties can be unreliable because common piezoelectric materials also present a pyroelectric property\textsuperscript{8}. Sensor arrays using these three types of transduction mechanism are electrically controlled by passive matrix addressing, which cannot prevent low contrast ratio and crosstalk effect. In contrast, an FET-type pressure sensor can exploit the advantages of active-matrix sensor arrays that allow high-array uniformity, high spatial contrast and facile integration with electrical circuitry. However, these FET-type pressure sensors have complicated device layouts, where additional pressure sensing components such as pressure-sensitive and conductive elastomers need to be interconnected to individual FETs and hence require relatively expensive fabrication processing costs\textsuperscript{4}.

Here we introduce the concept of fabricating an active-matrix, pressure-sensitive graphene FET array with air-dielectric layers which are formed by folding an origami substrate, which is composed of two plastic panels and a foldable elastic joint. All electrodes of the integrated FET array can be formed together by patterning source (S)/drain (D)/interconnects on one plastic panel, and gate (G)/interconnects on the other panel simultaneously, which can simplify the overall processing steps. The elastic joint which connects these two plastic parts allows the substrate to be completely folded without any damage. The integrated arrays of top-gated transistors with local air gaps as dielectrics can be simply formed by folding this substrate to stack these two panels (one with source/drain and the other with gate). These air-dielectric graphene FETs show outstanding electrical properties and high reliability under ambient conditions, due to the clean interface between graphene channel and air. The height of air gaps is determined by the thickness of elastomeric partition spacers between the graphene and top-gate, and decreased by applying pressure with increasing capacitance of the metal-air-graphene structure. This pressure-sensitive capacitance change enables the individual FET to act as a single tactile pressure sensor solely, for a wide detection range from 250 Pa to \( \sim \) 3 MPa. Therefore, the simple integration of these FETs, with no additional component or layer, forms active-matrix pressure sensor arrays directly, which can lead to low fabrication costs and densifications of these sensor arrays. Furthermore, the fabrication of a transparent pressure sensor by utilizing silver nanowire (AgNW)-graphene hybrid transparent electrodes is presented for further applications such as transparent e-skin, or an analogue touch screen panel.

**Results**

**Fabrication of graphene FETs with air-dielectric layers.**

Figure 1a,b present the schematic illustrations of the device layout before and after folding the origami substrate, respectively. The detailed fabrication process is illustrated in Supplementary Fig. 1 and also explained in the Methods section. After forming the origami substrate composed of two plastic panels and a foldable elastic joint, graphene channels, electrodes of S/D/interconnects and elastomeric partition spacers of photo-patternable polydimethylsiloxane (p-PDMS) to define local areas of air gaps are patterned on one panel side. Also, electrodes of G/interconnects are located on the other panel. Here all electrodes of Cr (5 nm)/Au (60 nm) are simultaneously formed on both panels of the substrate using single photolithography step and metal evaporation to reduce the processing steps. The top-gate electrodes are brought into conformal contact with the p-PDMS layer and cover the top of the air-dielectric layer by folding the origami substrate in half, which completes formation of the integrated graphene FET array with local air gaps as dielectric.

Pressure-sensing performances of the graphene FETs.

When the FET array is pressed by normal mechanical force, the thicknesses of the air gaps and elastomeric partition spacers (p-PDMS) decrease, with increasing the capacitance of the
metal-air-graphene structure. Due to the elastic property of p-PDMS, the individual FET can act as a single pressure sensor solely with no integration of additional components or layers. Figure 2a illustrates the pressure sensing mechanism using a custom-designed tripod pressure applying machine from 5 kPa to \( \sim 10 \) MPa. Transfer and output characteristics of this graphene FET, under different magnitudes of pressure, are presented in Fig. 2b,c, respectively. In both curves, \( I_D \) proportionally increases with the applied pressure at \( V_G = 25 \) V and \( V_D = 0.1 \) V. The FET shows a typical ambipolar behaviour and positive charge neutrality point of \( \sim 19 \) V under no compression (black line in Fig. 2b). As the applied pressure increases; however, transconductance in p-type significantly reduces (close to zero) while the transconductance in n-type changes negligibly. This phenomenon can be attributed to the occurrence of corona discharge, as described in Supplementary Note 1. Another intriguing feature of the transfer characteristics is the left shift in the charge neutrality voltage with increasing the pressure. As the air-dielectric layer becomes thinner with resulting in a higher capacitance of the metal-air-graphene structure by increasing pressure, smaller \( V_G \) can induce the amount of charge relevant to the charge neutrality condition\(^{23}\). The plot of the normalized change in drain current (\( \Delta I_D/I_o \)) versus applied pressure, extracted from the transfer characteristics at \( V_D = 0.1 \) V and \( V_G = 25 \) V, is shown in Fig. 2d. The detectable maximum pressure value is \( \sim 3 \) MPa and \( \Delta I_D \) saturates beyond this pressure range, in which the sensitivity is calculated as \( \sim 2.05 \times 10^{-4} \text{ kPa}^{-1} \) at a lower pressure regime (below 500 kPa) and \( \sim 9.43 \times 10^{-6} \text{ kPa}^{-1} \) at a higher pressure regime (above 500 kPa). The pressure sensor array capable of detecting the wide range of pressure has its significant importance, especially for the prospect of diverse applications. For example, the pressure sensor array in this work can be potentially used not only for the prosthetic electronic skins of robotics (from \( \sim 10 \) to \( \sim 100 \) kPa, which is in the range of a gentle touch to object manipulations)\(^{10,24}\) but also for the human weight distribution measurement during walking or clinical purposes (from 200 kPa to \( \sim 1.3 \) MPa, which is in the range of non-uniform foot pressure)\(^{25}\). The sensitivity of the pressure sensor is defined as the normalized change of electrical signal per a certain amount of the pressure and it is represented in the unit of \( \text{ kPa}^{-1} \) in this work. For calculation of the changes in height of air gap by the pressure, the initial thickness of the p-PDMS film...
was measured (Supplementary Fig. 5) and a compression test of the p-PDMS film was carried out to obtain the strain on this film for a specific pressure (Supplementary Fig. 6). True stress-strain curve was measured for this compression test, rather than that of the p-PDMS film was carried out to obtain the strain on this film for a specific pressure (Supplementary Fig. 5) and a compression test of the fabricated pressure sensor and true stress-strain curve from p-PDMS film compression test. (f,g) Real-time measurements of normalized drain current changes for applied pressures at $V_D = 0.1\, \text{V}$ and $V_G = 25\, \text{V}$. The different amounts of pressure are stacked one by one sequentially representing step-like features (f). Pressure (267 kPa) is loaded and unloaded repeatedly to evaluate stable and reliable operation (g).

Figure 2 | Electrical responses of graphene FETs to the applied pressures. (a) Schematic illustrations for the pressure sensing mechanism using an air-dielectric graphene FET. (b,c) Electrical responses of FET under different amount of applied pressures. Transfer characteristics ($V_G = 25\, \text{V}$) (b), Output characteristics ($V_G = 0.1\, \text{V}$) (c), respectively. (d) Plot of normalized drain current changes versus applied pressure. The inset illustrates relative change in the field effect mobility under applied pressure until $\sim 3\, \text{MPa}$ showing almost constant values (error bars indicate the standard deviations calculated from the 1,000 times cyclic pressure loading test). (e) Comparison between electrical responses of the fabricated pressure sensor and true stress-strain curve from p-PDMS film compression test. (f,g) Real-time measurements of normalized drain current changes for applied pressures at $V_D = 0.1\, \text{V}$ and $V_G = 25\, \text{V}$. The different amounts of pressure are stacked one by one sequentially representing step-like features (f). Pressure (267 kPa) is loaded and unloaded repeatedly to evaluate stable and reliable operation (g).
3,000 kPa was statistically investigated (Supplementary Fig. 7). This average thickness of air was compared with the air thickness obtained from the compression test of p-PDMS, and these values were very similar. Thus, it is reasonable to use the air thickness value from the compression test for calculating the device’s field effect mobility using a standard metal-oxide-semiconductor FET model. To ensure the reliability and durability of the pressure sensor, a mechanical compression test of p-PDMS with a cycle of loading-unloading up to 10 MPa was carried out (Supplementary Fig. 8). Also, the repetitive compression test presents that this sensor can endure the applied compressive pressures without failures (Supplementary Fig. 9). As shown in Fig. 2e, changes in the thickness of the p-PDMS layer and air gap can modulate capacitances and therefore signals of the pressure sensor ($\Delta I_D/ I_0$) dominantly. As plotted in Fig. 2g, the recovering behaviour in pressure sensing with negligible hysteresis is exhibited during the repeated loading–unloading tests with a pressure of 267 kPa. From the four-time loading-unloading tests, the signal-to-noise ratio was calculated as $B_1 = 1,068$ and the minimum pressure sensing range was estimated to be $B_2 = 250$ Pa, accordingly (Supplementary Note 3).

Active-matrix pressure-sensitive FET array. To exploit pressure sensors in various applications such as artificial electronic skins, touch screen panels or weight-distribution measurement devices for robotics, automotive electronics and medical diagnosis, it is necessary to fabricate integrated pressure sensor matrices with high densities of sensors. Fig. 3 demonstrates active-matrix pressure sensors using these graphene FETs with air-dielectrics. As an example, Fig. 3a shows a $12 \times 12$ active-matrix sensor array which allows selective readout of electrical response. After covering gate electrodes onto the top side of the air-dielectric layer, an integrated form of the active-matrix pressure sensor can be fabricated. In this sample, the size of individual FETs is $600 \times 600 \mu m$, providing a total distance (that is, pixel resolution) between adjacent transistors of 1 mm, which is smaller than a human’s spatial resolution for tactile sensing (1–2 mm) (ref. 26). Figure 3b illustrates the electrical circuit of this active-matrix, in which a targeted pixel can operate selectively according to the combination of row and column selection. For pressure distribution measurements, $I_D$ was measured with biasing $V_G = 25\,V$ and $V_D = 0.1\,V$ under the pressure of approximately 240 kPa. The statistical distribution of electrical responses of 2500 FET array under applied pressure of 240 kPa is shown in Supplementary Fig. 11.
setup, the 50 × 50 pressure sensor array with a pixel resolution of 400 µm (Supplementary Fig. 12) was pressed down using a tripod-shaped pressing machine (column diameter: 0.8 mm), as illustrated in Fig. 3c,d presents a colour gradation contour plot of the resultant signals (ΔI/I₀), and three white circles correspond to the locations of tripod legs. Each FET of this integrated array operates as individual sensor solely with no additional component or layer, and therefore pixel resolutions of their active matrix forms can be improved further by reducing the FET size. Contrast to the previous studies using suspended gate12, the use of foldable substrates presented in this work can localize the array of air gaps selectively with the designed structures, and provide highly integrated active-matrix sensors with fine resolutions. The multi-touch sensing on the 20 × 20 pressure sensor array is shown in Supplementary Movie 2, and this setup is illustrated in the ‘Methods’ section. Furthermore, the high pixel resolution implies the potential of integrating these pressure-sensitive FETs with other electronic components such as displaying panels or energy-storage devices for next-generation electronics.

**Fabrication of transparent pressure sensor.** Transparent forms of pressure sensor arrays can be advantageous for applications in touch screens for displays, invisible e-skins, intraocular pressure sensors, or for smart living. The fabrication of transparent, active-matrix pressure sensors by utilizing transparent electrodes using AgNW-graphene hybrid structures which allow high electrical conductance with transparency and oxidation stability27 is demonstrated (Fig. 4). In this approach, AgNWs were spun and photolithographically patterned. Then a chemical vapour deposition (CVD)-synthesized graphene layer was transferred and patterned to cover the entire top surfaces of the integrated FETs where graphene connects the channel and S/D area monolithically. In this device layout, therefore, graphene and the AgNW-graphene hybrid parts serve as the channel and all electrodes of S/D/G/interconnect, respectively, as shown in Fig. 4a. The morphology characteristics of AgNW-graphene hybrid surfaces was examined through the atomic force microscopy analysis (Supplementary Fig. 13). From atomic force microscopy analysis, this hybrid structure does not present a significantly rough surface (r.m.s. roughness: ~14 nm), which enables the integration of the hybrid parts to other electronic components. After forming the p-PDMS partition layer with air holes (Fig. 4a), the substrate was folded to stack the two panels (one with channel/source/drain and the other with gate), which completes the fabrication of transparent, integrated pressure-
sensor arrays. Figures 4b,c show optical micrographs of the S/D electrodes using the hybrid with local air gaps under a bright and dark field conditions, respectively. Photos of this transparent sensor sample before and after folding the substrate are displayed in Fig. 4d,e, respectively. This transparent pressure sensor has a transmittance of ~82% at a wavelength of 550 nm including the substrate (Supplementary Fig. 14). Transfer and output characteristics of this transparent device under different pressure levels are plotted in Fig. 4f,g, respectively. This transparent FET can also detect pressure up to ~3 MPa, which is similar to the results of Fig. 2e. Real-time measurement of $\Delta I_D/I_D$ under various pressures is presented in Fig. 4h, which exhibits the response time of 31 ms and almost complete recovery behaviour in 49 ms (Supplementary Fig. 15).

**Discussion**

The integrated electronic devices with tactile pressure sensors have been widely researched for the emerging technologies such as electronic skins or health-monitoring devices. Although pressure sensors based on various transducing mechanisms were researched, it was challenging to develop integrated pressure sensor arrays with wide pressure detection ranges. This work presented the formation of active-matrix pressure-sensitive graphene FET arrays with air-dielectrics for sensing wide tactile pressure ranges. Local air spaces formed by folding the substrate induced the clean interface between the graphene channel and air, which demonstrated the integrated arrays of top-gate graphene FETs with the pressure sensitivity under ambient conditions. Also, high pixel densities and relatively fast response time are other advantages. Furthermore, the wide detection range of these pressure sensors broadens their application areas such as human touch, medical diagnosing and weight measurement for robotics, or automotive electronics. In this work, however, the large off-state current of graphene FETs is a drawback of active-matrix pressure sensors. The normalized difference of electrical current between before and after applying drain and gate voltage. The spatial pressure distribution was plotted by calculating out inside of the probe station by reading out the drain current while supplying the pressure is defined as the applied force per force-exerted area, we can apply the pressures from 5 to 10 MPa. The real-time pressure sensing experiment was carried out inside of the probe station by reading out the drain current while supplying drain and gate voltage. The spatial pressure distribution was plotted by calculating the normalized difference of electrical current between before and after applying the pressure. For multi-touch sensing on a 20 × 20 pressure sensor array, two sources (Keithley 2400), system switch (Keithley 3706), relay card (Keithley 3723), and peripheral devices were used to interconnect the pressure sensor array with processing modules. The output signal was exhibited using the Labview-based programmed software. The optical transmittance of transparent pressure sensor was measured using ultraviolet–vis spectroscopy (Aglent Cary 5000).

**Device characterization.** The electrical performances such as transfer and output characteristics of the fabricated device were characterized by probe station (Keithley 4200-SCS). To test the pressure sensing performances, pressure was applied in situ in a probe station using a custom-made pressure-applying machine composed of two building blocks. First one are the weights (50 g × 1 and 500 g × 4), and the applied weights can be from 50 g to 2.05 kg. The second one are the cylinder-shaped columns delivering pressures from the weights to the sample, which have seven different diameters of 11, 9.6, 8, 6.4, 4.8, 3.2 and 1.6 mm. Since the pressure is defined as the applied force per force-exerted area, we can apply the pressures from 5 to 10 MPa. The real-time pressure sensing experiment was carried out inside of the probe station by reading out the drain current while supplying drain and gate voltage. The spatial pressure distribution was plotted by calculating the normalized difference of electrical current between before and after applying the pressure. For multi-touch sensing on a 20 × 20 pressure sensor array, two sources (Keithley 2400), system switch (Keithley 3706), relay card (Keithley 3723), and peripheral devices were used to interconnect the pressure sensor array with processing modules. The output signal was exhibited using the Labview-based programmed software. The optical transmittance of transparent pressure sensor was measured using ultraviolet–vis spectroscopy (Aglent Cary 5000).

**Data availability.** The data that support the findings of this study are available from the corresponding author upon request.

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Author contributions

S.-H.S. and S.I. designed and performed the experiments, fabricated the devices and analysed the data. S.C. supported the preparation and synthesis of materials, K.-H.P. and B.W.A. conducted experiments for fabricating the devices. J.P. synthesized and transferred the graphene, J.K. contributed to the transparent sensor fabrication. J.-Y.K contributed to the analysis of mechanical durability of the sensor. K.-S.L., S.-Y.K., J.H. and B.-G.P. analysed the electrical performance of the air-dielectric graphene FETs. J.-U.P. oversaw all research phases and revised the manuscript. All authors discussed and commented on the manuscript.

Additional information

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