A fully inkjet-printed transparent humidity sensor based on a Ti$_3$C$_2$/Ag hybrid for touchless sensing of finger motion†

Ning Li, ‡ Yue Jiang, ‡ Yan Xiao, Bo Meng, Chenyang Xing, Han Zhang ‡,* and Zhengchun Peng ‡,*

Inkjet-printing was used to prepare a flexible and transparent humidity sensor with a Ti$_3$C$_2$/Ag hybrid as the humidity-sensitive film and poly(diallyldimethylammonium chloride) (PDDA) as the adhesive layer. The sensor demonstrates an ultrahigh sensitivity (106 800%), a rapid response (80 ms), and excellent bending resistance. We demonstrate that an array of sensors can track moving fingers in a non-contact way and map the distance of the fingers away from the sensor surface. Therefore, our humidity sensors have great potential for novel human–machine interfacing such as touchless control of electronics and collision control between robots and humans in a cobot setting.

1. Introduction

In recent years, flexible electronics have received considerable attention because of their potential applications in displays, intelligent sensors, electronic skin, etc. The detection of external stimuli by recognizing changes in resistance or capacitance is a common method for touch-sensing devices. However, under certain circumstances, sensors need to respond without direct contact. Moisture detection, in particular, is an effective method for achieving noncontact and remote signal induction. For this purpose, sensing materials for high-performance humidity sensors generally need (i) to have high sensitivity, to enable detection of subtle changes in humidity; (ii) to give a rapid response, to enable accurate detection of humidity fluctuations; and (iii) to be transparent so that they do not block the optical function of other electronics such as display panels or phone screens. A large specific surface area, hydrophilicity, rapid interaction with water molecules, and a two-dimensional (2D) sheet structure are therefore important characteristics that must be considered in developing novel moisture-sensitive materials for high-quality flexible humidity sensors.

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ation at room temperature. Various 2D nanomaterials such as graphene, graphene oxide, MoS$_2$, and WS$_2$ have been inkjet-printed.\textsuperscript{21–23} A specific type of MXene ink has been studied for supercapacitors and electromagnetic interference shielding, but it is yet to be used for humidity sensors.\textsuperscript{24–26}

Two key issues need to be considered in the MXene-based inkjet-printing strategy: (i) water-based solvent systems of appropriate viscosity must be used to ensure stability of the jetting process and (ii) good adhesion between the printed film and the substrate is needed. In previous studies, ethylene glycol was mixed with an MXene-based ink to increase its viscosity, and a binder layer corresponding to a MXene film pattern, which was first printed on the substrate, was used to facilitate specific interactions between the interfaces.\textsuperscript{26–28} Compared with other chemical binders, transparent poly(diallyldimethylammonium chloride) (PDDA) is a better match with MXenes because both materials have strong electrostatic self-assembly interactions.\textsuperscript{11} Although many studies of the interactions between PDDA and 2D materials have been performed, the assembly dynamics between PDDA and MXenes during inkjet printing has not been explored.

In this study, we prepared a Ti$_3$C$_2$/Ag hybrid with excellent humidity-sensing properties by a simple physical mixing method. A transparent and flexible humidity sensor with good bending resistance was fabricated by using a full inkjet-printing method. In addition, a proof-of-concept sensor array with a 3D configuration was demonstrated to be capable of accurately tracking finger motion in space. Because of its long-range operation (>15 mm), easy material preparation, and good fabrication scalability, we believe that this novel humidity sensor has many potential applications.

2. Experimental section

2.1. Synthesis of 2D-MXene Ti$_3$C$_2$ nanosheets

All chemical reagents were of analytical grade and used without further purification. Ti$_3$C$_2$ MXene was successfully prepared by etching an Al layer from a Ti$_3$AlC$_2$ phase in HF solution at room temperature. The as-prepared Ti$_3$AlC$_2$ MAX phase (3.0 g) was slowly added to 40 wt% HF etchant solution (60 mL) and the mixture was magnetically stirred at room temperature for 24 h. For safety, the entire reaction was performed under a fume hood. The bulk Ti$_3$C$_2$ product was obtained by centrifugation at 10 000 rpm for 30 min. Similarly to other classic layered materials such as black phosphorus and Bi, 2D Ti$_3$C$_2$ MXene nanosheets were obtained via liquid-phase exfoliation in N-methylpyrrolidone.\textsuperscript{29,30} The 2D Ti$_3$C$_2$ MXene samples were dried at 50 °C in a vacuum oven for 24 h.

2.2. Preparation of a Ti$_3$C$_2$/Ag hybrid ink

Dispersions of the prepared Ti$_3$C$_2$ (0.4 mg mL$^{-1}$) and Ag nanoparticles (0.1 mg mL$^{-1}$, XF-Nano Company, China) were pre-treated by ultrasonication for 1 h. The Ag dispersion was mixed with the Ti$_3$C$_2$ dispersion at various weight percentages (0.5, 1, 1.5, and 2 wt%) and the mixtures were ultrasonicated to obtain uniform dispersions. Ethylene glycol (20 vol%) was added to the Ti$_3$C$_2$/Ag aqueous dispersion to adjust the viscosity to an appropriate level. All the prepared inks are denoted as shown in Table 1.

2.3. Fabrication of a flexible sensor

A transparent interdigital electrode was prepared on a flexible PEN substrate with a PEDOT: PSS suspension diluted with ethylene glycol at a volume ratio of 1:1 by using a commercial printer (Epson 2100, ultra-fine print mode). Thermal treatment was then performed at 120 °C for 10 min. A PDDA linking film was preprinted in the forked finger area of the interdigital electrode. The PDDA dispersion solution itself has a certain viscosity; therefore direct dilution of the PDDA to an appropriate proportion is easy. The prepared Ti$_3$C$_2$/Ag hybrid ink was printed on top of the PDDA linking layers. Multiple printing mode for up to four times was selected to ensure that the sensitive film was continuous. The fabrication process is shown in Fig. 1.

2.4. Characterization

The crystal structures of the prepared materials were determined by X-ray diffraction (XRD; Bruker D8 Advance Phase, Cu Kα radiation, λ = 1.5406 Å). The morphologies of the samples were investigated by field-emission scanning electron microscopy (FESEM; Hitachi-SU8020) and high-resolution transmission electron microscopy (HR-TEM; JEM-2100F, JEOL). X-ray photoelectron spectroscopy (XPS) was performed with a scanning Auger XPS instrument (model 5802, PHI, USA). Fourier-transform infrared (FTIR) spectra of Ti$_3$C$_2$ and the Ti$_3$C$_2$/Ag hybrid were recorded with a PerkinElmer spectrometer. The Brunauer–Emmett–Teller surface areas and pore size distributions of the samples were determined by N$_2$ adsorption–desorption analysis (ASAP 2460, Micromeritics Instrument Corporation, Norcross, GA, USA). The transmission spectra of the films were recorded with an ultraviolet-visible-near infrared spectrometer (U-3900, HITACHI, Japan) in the wavelength range of 200–800 nm.

2.5. Evaluation of humidity-sensing performance

The sensors were placed in a laboratory-built chamber for evaluation of their humidity-sensing performance in their

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normal and curved states. The humidity in the chamber was adjusted by using wet air with different humidity levels. The humidity of the wet air was regulated by mixing high-humidity compressed air and N₂; the humidity level was monitored with a commercial handheld humidity detector (HygroPalm HP22-A, Rotronic). An impedance analyzer (6500, Wayne Kerr, UK) was used to record the sensor’s capacitance responses and for complex impedance spectroscopy (CIS). The flexible sensor could be placed on a sliding table and dynamically bent at any angle to test the humidity response under bending conditions. A schematic diagram and the actual setup of the experimental device are shown in Fig. S1 and Movie S1† respectively, in the ESI.† The fabricated sensor was placed in a small cell to record the dynamic responses of the sensor accurately. The cell was rapidly replenished with N₂ and wet air alternately by using a mechanical toggle switch. An oscilloscope (TDS 2024B, Tektronix, USA) with an 8 ms acquisition time was used to determine the partial voltage change of a resistor (20 MΩ) in series with the humidity sensor, which corresponds to the transient response.

3. Results and discussion

3.1. Characterization

Fig. 2a and b show TEM images of the 2D Ti₃C₂ MXene nanosheets and the prepared Ti₃C₂/Ag hybrid. A comparison of the grayscales in the location of the super-carbon membrane on a copper wire mesh support with or without the materials indicates that the Ti₃C₂ nanosheets were ultrathin and highly transparent (Fig. 2a). The morphological analysis verified that Ti₃C₂ nanosheets with one or a few layers were successfully exfoliated. The HR-TEM images (inset in Fig. 2a) show clear 0.27 nm lattice fringes, which are attributed to the (002) facet of the Ti₃C₂ phase, in accordance with the XRD pattern. Large numbers of Ag nanoparticles were adsorbed and evenly distributed on the Ti₃C₂ nanosheet surfaces because of interfacial adsorption, as shown by the lattice size marked in Fig. 2b and the energy-dispersive X-ray spectroscopy (EDS) mapping results in Fig. 2c and d. We confirmed that the amount of Ag in the Ti₃C₂/Ag hybrid was basically consistent with the estimated value (Fig. S4 and Table S1†). The HR-TEM images (inset in Fig. 2b) show Ag lattice fringes of size 0.236 nm. A comparison of the TEM images of pure Ti₃C₂ and the Ti₃C₂/Ag hybrid shows a large number of wrinkles in the Ti₃C₂ nanosheets in the hybrid. This distinctive structure provides a large specific surface area, which promotes adsorption of water molecules.

Fig. S2† shows SEM images of various samples. Ti₃AlC₂ has a typical compact stacked layer structure. The Al layers in the Ti₃AlC₂ phase were selectively removed by etching with HF. Fig. S2b† shows that the etched product, i.e., layered bulk Ti₃C₂, consisted of loosely packed accordion-like structures. These morphological changes confirm that the majority of the Al phase was successfully removed. This was supported by other characterization results.

Fig. S3a† shows that electrostatic self-assembly interactions caused agglomeration in the Ti₃C₂/Ag-PDDA mixture. Fig. 2e and f show SEM images of the inkjet-printed layers of the Ti₃C₂/Ag hybrid sensing film on a poly(ethylene terephthalate) (PET) substrate with or without PDDA linking layers after 2000 binding cycles. Pure PDDA films and a Ti₃C₂/Ag-PDDA bilayer without bending are shown in Fig. S3b and c† for comparison. The large amount of structural fractures of the Ti₃C₂/Ag film observed in Fig. 2e can be mainly attributed to film self-deformation and peeling from the substrate as a result of multiple bending. However, minimal fractures were present on the Ti₃C₂/Ag-PDDA bilayer. This indicates that the composite film

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Fig. 1 Flow diagram of preparation of the Ti₃C₂/Ag ink-based humidity sensor via the inkjet-printing method.

Fig. 2 TEM images of the as-prepared 2D Ti₃C₂ MXene nanosheets (a) and Ti₃C₂/Ag hybrid (b); insets show corresponding high-resolution TEM (HR-TEM) images. (c) Dark-field image of the Ti₃C₂/Ag hybrid. (d) EDS mapping of Ti and Ag. SEM images of inkjet-printed layers of the Ti₃C₂/Ag hybrid sensing film on the PET substrate with (e) or without (f) PDDA linking layers after 2000 binding cycles.
has good bending stability. This is attributed to the good adhesion between PDDA and substrates and its wide bendability threshold.11

XRD was used to investigate the phase structures of Ti3C2 and Ti3C2/Ag (2 wt%) (Fig. 3a). In the XRD pattern of Ti3C2/Ag, the peaks at 2θ = 38.1°, 44.2°, 64.4°, and 77.5° can be assigned to the (111), (200), (220), and (311) crystalline planes, respectively, of Ag single crystals. These diffraction peaks correspond to those in the standard pattern (JCPDS 04-0783).20 In addition, the position of the (002) peak of Ti3C2/Ag did not change, which indicates that the Ti3C2 nanosheets retained their structure in the assembly environment. No peaks from other phases were detected. These results show that the Ti3C2 nanosheets, and Ti3C2/Ag hybrid. (f) Optical transmittance of the fabricated humidity sensor.

3.2. Humidity-sensing performance

The minimum humidity in the homemade chamber was ~5% relative humidity (RH). This was chosen as the initial state in our experiment, in accordance with the commercially available sensors. Fig. S6† shows the sensitivity of the humidity sensors made from Ti3C2, HF-etched bulk Ti3C2, Ti3C2 nanosheets, pure PDDA and PDDA/ethylene glycol layers, respectively. The sensitivity of the accordion-like Ti3C2 differed little from that of Ti3C2, mainly because of its small specific surface area and the hydrophilic surfaces being hidden in the multilayered accordion-like block structure.

The sensitivity of the sensor made from the Ti3C2/Ag hybrid was significantly better than that of the Ti3C2 nanosheets, and it increased proportionally with the increasing Ag content, as shown in Fig. 4a. The sensitivity (106 800%) of sensor TA2 (Ti3C2/Ag 2 wt%) was 15 times better than that of sensor T (pure Ti3C2). However, the Ag nanoparticle content was limited by the percolation threshold and could not be increased indefinitely.33 When the Ag content of the hybrid exceeded 2 wt%, the resistance of certain Ti3C2/Ag hybrid layers experienced an avalanche drop. This phenomenon became more pronounced with increasing Ag content. The capacitance output of sensor TA2 showed good logarithmic linearity in the RH range 35%–95%.

In order to shield the influence of separate components of the sensing material on the humidity sensing performance, we loaded PEDOT : PSS, PDDA, PDDA/ethylene glycol and pure Ti3C2 on the Au interdigital electrodes on a silicon substrate, respectively, as shown in Fig. S7. Since PEDOT : PSS is a conducting material, the response curve of the resistance vs. RH reflected a very weak performance. Compared with Fig. S6, PEDDA, PDDA/ethylene glycol and Ti3C2 on Au and PEDOT : PSS interdigitated electrodes (IDEs) exhibited similar sensing per-
formance. Meanwhile, Fig. S8† shows that the capacitance output of the sensors was inversely proportional to the channel size and proportional to the sensing area, especially at high RH levels. In a high humidity environment, the enhanced charge conduction of abundant adsorbed water molecules to the sensitive layer is the main factor for enhancing the response of the sensor. Therefore, a smaller channel can facilitate this conduction phenomenon.

Fig. S9a† shows the frequency dependence of sensor TA2. The results indicate that the capacitance was simultaneously dependent on the frequency and RH. Fig. S9b† shows the capacitance response of the sensor to the operation frequency at different humidity levels. It is demonstrated that the operation frequency has a stronger influence on the output of the sensor under low RH conditions. The capacitance increases with increasing RH (especially at RH > 45%) in the low frequency region, and becomes almost independent of RH in the high frequency region, indicating that the capacitance of the humidity sensor is simultaneously dependent on the frequency and the RH. At low RH, only a small amount of water molecules can be adsorbed by the sensing layer, and the capacitance of the humidity sensor is independent of the frequency just like an ideal capacitor. As more and more water is adsorbed, polarization of the adsorbed water molecules occurs and the leak conductance increases.34 The equation $C = (\varepsilon r - i/\omega \varepsilon_0)C_0$ is usually used to represent the relationship between the sensor capacitance output and the physical adsorption process under different moisture conditions.15 In the equation, $\gamma$ indicates the conductance level, $\omega$ is the excitation frequency, and $i$ is the imaginary constant; $\gamma$ is determined by the level of water molecule adsorption in the sensitive layer in different physisorption processes, and increases with increasing RH. The output capacitance $C$ is proportional to $\gamma$ and inversely proportional to $\omega$. In the high frequency region the electrical field changes direction rapidly, the polarization speed of the water molecules cannot catch up with it and hence the capacitance is small and independent of the RH.16,37 A voltage of frequency 100 Hz was therefore used in subsequent experiments.

Fig. 4e shows the response and recovery characteristics of sensor TA2 exposed to different RH conditions. The capacitance proportionally changed toward the RH change and rapidly recovered to its initial state when the sensor was loaded in a dry environment (5% RH). Fig. 4d shows the transient response process for sensor TA2, which was measured indirectly by recording the changes in the partial voltage of a series resistor with an oscilloscope. The response and recovery times for sensor TA2 were about 80 and 120 ms, respectively. The large surface area, increased penetration spaces of the interlayers and massively folded structures, and a very thin sensitive film are factors that accelerate the dynamic equilibrium of the adsorption–desorption of water molecules. Because of its rapid response, the proposed humidity sensor was able to record humidity fluctuations with variations in voice tone when people talk or sing (Fig. 4e). This shows that construction of a new type of biological anticounterfeiting system could be achieved by combining the bio-voiceprint information from moisture variation and the sound spectrum.

As mentioned above, high sensitivity and a rapid response are two important requirements of humidity sensors for achieving near field signal induction and dynamic monitoring.
of humidity change. The fabricated Ti$_3$C$_2$/Ag sensor was used to
to determine RH variations of a fingertip above a surface, from
15 mm to 1 mm. The significant changes in the capacitance
output of the sensor are shown in Fig. S14. The zero shift in
the response signal was caused by the fluctuation in ambient
humidity. Differences in the preparation process were easily
shielded by statistical processing of the overall signal points
(e.g., nondimensionalizing the outputs of all sensors). The
humidity sensors could therefore be used to monitor the dyna-
mically changing position and distance of a human finger
above the sensor.

Fig. 4b and Table S2 show the sensitivity and responding
speed of sensor TA2 and some of the recently reported humidity
sensors.\textsuperscript{20,34,36–59} Due to the adsorption mechanism of the
humidity-sensitive film to water molecules, typical humidity
sensors can only focus on one of the two performance para-
eters: sensitivity or responding speed. In contrast, our sensor
achieved very high sensitivity (106 800%) while meeting the fast
response requirement for non-contact detection and interaction
(response time plus recovery time is less than 200 ms).

Fig. S10 shows the response of sensor TA2 as a function of
RH. In the fitting equation $Y$ is the sensor response and $X$
the RH. The regression coefficient ($R^2$) was 0.99865. Fig. S11
shows the repeatability of sensor TA2 on exposure to 45%,
65%, and 85% RH from the 5% RH level (six cycles for each
RH). A consistent response amplitude with changes in RH was
observed in each cycle. This indicates that the sensor has good
repeatability and low hygroscopicity. Hysteresis was defined as
$H = (C_D - C_H)/S($%RH$)$, where $C_D$ and $C_H$ are the sensing
outputs in the adsorption and desorption processes, respect-
ively, and $S$ is the sensitivity. The maximum hysteresis was
determined to be about 6% RH and occurred at 45% RH (Fig. S12).
These results indicate that sensor TA2 has low hysteresis and good reliability. Fig. S13 shows that sensor TA2
showed stable capacitance values for 40 days, which indicates
excellent long-term stability.

The sensing performance of sensor TA2 was tested under
different bending conditions, as shown in Fig. 4f, to investi-
gate its bending resistance. The results show that the perform-
ance of sensor TA2 was unaffected by mechanical deformation.
Fig. 4g shows that sensor TA2 had excellent endurance against
structural distortion after multiple bending experiments
(bending degree 90°; 2000 cycles). Because of the electrostatic
cross-linking between Ti$_3$C$_2$ and PDDA, there were significantly
more cracks on the pure Ti$_3$C$_2$/Ag-based layer than on the
Ti$_3$C$_2$/Ag-PDDA bilayer after 2000 bending cycles, as shown in
SEM images in Fig. 2e and f. With the antibending character-
istics of the composite film, the developed sensors is very
robust and can be used to establish an sensor array with a
reconfigurable shape in 3D space for novel human–machine
interaction application (to be discussed next).

3.3. Applications
At present, the mainstream interactive screen technology is
pressure-based touch technology. On the other hand, gesture
recognition based on computer vision has limitations due to

![Figure 5](image-url)

**Fig. 5** (a) Transparent sensor matrix built on top of an iPad screen. (b) A reconstructed map of humidity level, registered by the sensor array, while a human finger writes a Chinese character “和” in air above the iPad screen. (c) Design of a sensor array that can be configured into a 3D layout (red lines represent the laser cutting traces). (d) Reconstructed position of each humidity sensor in (c). (e) Response of the sensor array to 3D formation, presence of multiple fingers, and the touchless knob turning motion of the fingers.
finger occlusion or limited camera angle. A humidity-based noncontact interface is an alternative for 3D near-field gesture recognition systems, and it has the advantages of high accuracy, a rapid response, and good scalability. We inkjet-printed a humidity sensor matrix with 15 × 10 sensors on a PET substrate. The capacitance of each sensor was monitored with point-by-point scan through the transparent PEDOT:PSS wire connected to an analyzer (CompactDAQ, NI). The transparent sensor matrix was assembled on top of an iPad screen (Fig. 5a). When a human finger writes a Chinese character “和” in air above the screen, the sensors can register the trajectory of the finger and the variations of the finger height above the screen. Fig. 5b shows a reconstructed map of the humidity level after the finger writing motion is completed. This result shows that the humidity-based noncontact interface can accurately record people’s writing habits and greatly enhance the interactive function of the screen.

The growing trend of foldable phones and tablets has made maintaining an acceptable responsiveness under substantial bending a challenge for physical sensors. On the basis of the previously discussed bending resistance, a deformable sensor matrix was fabricated by inkjet-printing and laser-cutting methods.

Fig. 5c shows a diagram of sensor arrays that can be configured into a 3D layout. The red lines represent the laser-cutting position. Fig. 5d shows the reconstructed positions of each humidity sensor in Fig. 5c. Fig. 5e and Movie S2† show that the hemispherical array of the humidity sensors has excellent endurance under mechanical deformation. And the 3D noncontact interface can accurately detect the presence of multiple fingers and capture the touchless knob turning motion of a human hand. This near-field gesture recognition system, therefore, has great potential in novel human–machine interaction applications such as noncontact control of electronics.

3.4. Humidity-sensing mechanism

3.4.1. Adsorption of water molecules on the Ti$_3$C$_2$/Ag hybrid film. Fig. 6a shows that at low RH values water molecules were primarily adsorbed on the active sites (hydrophilic groups and vacancies) of the Ti$_3$C$_2$ nanosheets via double hydrogen bonds. In the second layer of adsorbed water molecules, adsorption occurred on OH groups via a single hydrogen bond and a penetration process. In subsequent layers, water molecules were mobilized and progressively became identical to those in the bulk liquid. In the bulk liquid, a fraction of the physisorbed water molecules can be ionized by an external electric field and form hydronium ions (H$_3$O$^+$) as charge carriers via a Grothuss chain reaction (H$_2$O + H$_3$O$^+$ → H$_3$O$^+$ + H$_2$O); this can be described as proton hopping. The hydrophilic functional groups on Ti$_3$C$_2$ can be hydrolyzed in the bulk water layers and contribute to the ionic conductivity. The described considerable increase in ionic conductivity ($\gamma$) is partially responsible for the excellent sensitivity of the sensors.

3.4.2. CIS of the Ti$_3$C$_2$/Ag hybrid. Fig. 6b shows a Nyquist plot with the real and imaginary parts of the CIS spectrum of sensor TA2 at various operating frequencies (from 50 Hz to 1 MHz). Two kinds of EC models were obtained by fitting the
impedance spectra data using the software Zview 3.3 and are included in Fig. S15.† At low RH levels (5%, 20%, and 35% RH), the CIS curve shows an incomplete semicircle, which can be attributed to relaxation of the polarization of the intrinsic conductivity of the sensing film. This reflects weak ionic conduction. The corresponding equivalent circuit for sensor TA2 can be represented by a resistor in parallel with a capacitor (inset in Fig. 6b). The radius of the semicircle decreased with increasing humidity.

From 45% RH, the CIS curve showed a line that connected with the semicircle in the low-frequency region, which became clearer with increasing RH, as shown in Fig. 6c. The size of the semicircle in the curve further decreased. This phenomenon is mainly attributed to the Warburg impedance (Zw), which is caused by transfer of charge carriers, mainly diffusion of H2O+ and other ions, across nanostructures.

The CIS spectrum of pure Ti3C2 is shown in Fig. S16† for comparison. The straight line at the tail of the semicircle was observed at 75% RH. This comparison indicates that ionic conductivity was easier in the Ti3C2/Ag hybrid than in pure Ti3C2 at low RH levels. There are two reasons for this. First, the large number of wrinkles in the Ti3C2/Ag hybrid film enhanced the water molecule adsorption capacity.19 Secondly, the Ag nanoparticles can reduce the activation energy required for water molecules to bond with the film. This facilitates bonding of water molecules to the active sites of the sensing film. Furthermore, a liquid water layer is easily formed at this location because of the abundant water molecules around the Ag nanoparticles.25 This enhances ion conduction for humidity sensing. The described humidity sensor based on a Ti3C2/Ag hybrid therefore gives an excellent sensing performance.

3.4.3. Bode diagram of the Ti3C2/Ag hybrid. Fig. S17a† shows bode diagrams of the Ti3C2/Ag hybrid under different RH conditions. At low RH (5%), the impedance module |Z| of the equivalent circuit was denoted as |Z| = 1/√1/R2+(ωC)2.

Due to the absence of adsorbed water molecules, the resistance R was extremely huge, so the term of ωC was the main contributor of Z. Therefore, the curve (impedance vs. frequency) exhibits capacitive behavior at 5% RH. The phase angle is close to −90° in most frequency regions.

From 35% RH, the curve (phase angle vs. frequency) had an inflection point. Moreover, the characteristic frequency corresponding to the inflection point moves to the high frequency region along with the increase of humidity which is consistent with the turning frequency in CIS. So, the low frequency part can be ascribed to be Zw behavior.60 As compared, a clear inflection point can be observed at 5% RH in bode diagrams of Ti3C2 (Fig. S17b†), which reflected the lagging humidity related conduction behavior.

4. Conclusions

In this study, a noncontact interfacing method based on highly sensitive and fast-responding humidity sensors was developed. The sensor employs a Ti3C2/Ag hybrid as the humidity-sensitive film and PDDA as the adhesive layer between the flexible substrate and the sensing layer. From the complex impedance spectra (CIS) analysis, the ionic conductivity is much stronger in the Ti3C2/Ag hybrid than in pure Ti3C2. As a result, the flexible and transparent humidity sensor showed ultrahigh sensitivity (106 800%), a rapid response (80 ms), and excellent bending resistance. Our humidity sensor could record the humidity fluctuations along with the variation in voice tones when people speak or sing. Moreover, with a 3D setting of the sensor array, we demonstrated that the sensors could accurately capture the touchless knob turning motion of a human hand. These demonstrations indicate that our sensor has a range of potential applications in novel human–machine interfacing such as touchless control of electronics and anti-collision of robots to exposed human body parts.

Conflicts of interest

There are no conflicts to declare.

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Notes and references