

# Recent advancements in flexible humidity sensors

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Flexible electronics are attracting widespread attention due to their potential applications in wearable health monitoring and care systems<sup>[1]</sup>, holding great promise in the internet of things (IoT), a fundamental concept in which devices and objects can be interconnected to form extensive networks<sup>[2]</sup>. Especially, the rapid developments of various flexible humidity sensors have broadened the scope of flexible electronics for novel applications in the IoT, such as noncontact and real-time sensation, electronic skin (e-skin), telemedicine monitoring, and wearable electronic systems (Fig. 1)<sup>[2-4]</sup>.

Recently, tremendous efforts have been devoted to improve the sensitivity, selectivity, response/recovery speed and stability of humidity sensors<sup>[5]</sup>, and thus various active sensing materials and fabrication methods have been well exploited for high performance humidity sensing materials, including nanostructured ceramics, metal oxides, carbon materials, polymers, nanocellulose, and two-dimensional (2D) materials<sup>[1]</sup>.

**1) Nanostructured ceramics and metal oxides.** Most commercially available humidity sensors are based on ceramics and metal oxides. Despite the low price, great thermal properties, mechanical strength and rapid response of ceramic based humidity sensors, issues regarding aging, rigidity and large hysteresis limit their properties such as long-term operation, flexibility and high accuracy<sup>[6, 7]</sup>. Also, temperature compensation is often required for both ceramics and metal oxides based humidity sensors. This problem can be solved by finding out new sensing materials and fabrication methods. Nanostructured ceramics and metal oxides are interesting candidates to address this problem. Dubourg *et al.* reported a screen-printing process for the deposition of the sensitive material, which was based on TiO<sub>2</sub> nanoparticles, and the humidity sensor showed good overall sensing performance<sup>[8]</sup>. Recently, Shen's group reported a high performance flexible and transparent humidity sensor based on MoO<sub>3</sub> nanosheets with a low-cost and easily manufactured process. The sensor exhibited ultrahigh sensitivity, fast response, and great stability as well as corresponding sensor arrays for practical applications in health-related moisture monitoring and multifunctional noncontact human-computer intelligence terminals. Such high sensing performance derived from the surface adsorption phenomenon of MoO<sub>3</sub> and the formation of H<sub>2</sub>O layers for protons to transfer from one water molecule to another, leading to a significant decrease in resistance<sup>[3]</sup>.

**2) Carbon materials.** Carbon materials have gained widespread attention owing to their combined superiorities such as diversified synthesis approaches, good electrical conductivity, intrinsic and structural flexibility, light weight, high chem-

ical and thermal stability, as well as the ease of chemical functionalization<sup>[9]</sup>. Carbon nanotubes (CNTs) and graphene oxide/reduced graphene oxide (GO/rGO) are the main carbon materials used as sensing materials for flexible humidity sensors<sup>[5]</sup>. However, some of the GO based sensors have been made by complex and costly fabrication techniques, such as etching or layer-by-layer deposition. Worse still, the preparation of GO requires toxic oxidizing chemicals, such as sodium nitrate, potassium permanganate, and sulfuric acid<sup>[10]</sup>. To solve the first problem, Vasiljevixc *et al.* reported an ink-jet printing technology with interdigitated electrodes on a flexible substrate and GO based sensing layer, which achieved very large variation of response and realized cost-effectiveness<sup>[11]</sup>. Furthermore, Zhao *et al.* prepared a flexible temperature and humidity sensor (FTHS) from graphene woven fabrics (GWFs) prepared by chemical vapor deposition (CVD). It was fabricated through an environmentally friendly process which was also easy to operate<sup>[10]</sup>.

Generally, because carbon materials based humidity sensors are working based on the interaction between water molecules and oxygenic functional groups on the carbon materials, they inevitably exhibit relatively low response and recovery speed. However, combining one kind of carbon materials with other sensing materials or exploring new mechanisms can be feasible strategies to improve their sensing performance<sup>[1]</sup>. Wu *et al.* pioneered the fabrication of a carbon nanocoil (CNC) based, highly sensitive, and ultrafast humidity sensor on a flexible substrate, and CNC is a mixture of amorphous, polycrystalline, and helical structure of sp<sup>2</sup> grains and sp<sup>3</sup> amorphous hybridized carbon atoms<sup>[12]</sup>.

**3) Polymers.** Nowadays, polymer-based sensitive films possessing high affinity for water from inherent hydrophilic functional groups are viewed as a feasible potential used in hu-

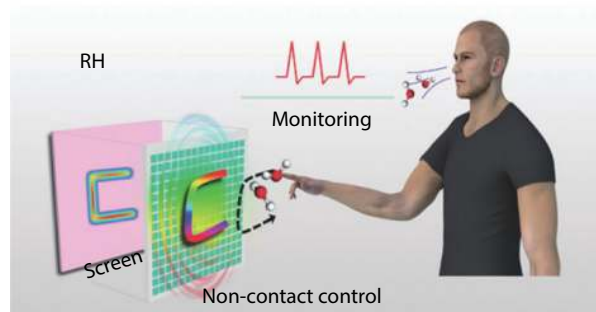


Fig. 1. (Color online) Flexible humidity sensors have broadened the scope of flexible electronics for new applications in the IoT, such as non-contact control and real-time monitoring.

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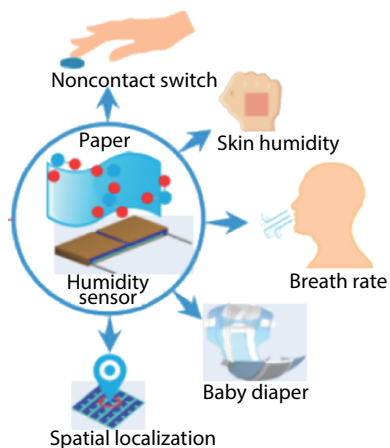


Fig. 2. (Color online) A paper-based humidity sensor with multifunctional applications for breath rate, baby diaper wetting, noncontact switch, skin humidity, and spatial localization monitoring.

humidity sensors, and the low-cost process, high mechanical stability, and flexibility are important for future applications in wearable devices<sup>[7]</sup>. Li *et al.* reported a highly flexible porous ionic membrane (PIM) based humidity sensor fabricated from a polyvinyl alcohol/KOH polymer gel electrolyte, showing a well-defined 3D porous structure<sup>[4]</sup>. Park *et al.* proposed a suitable hydrophilic polytetrafluoroethylene (H-PTFE) based flexible humidity sensor integrated with readout circuitry, wireless communication, and a mobile battery<sup>[6]</sup>.

**4) Nanocellulose.** Nanocellulose, a biodegradable material originating from cellulose fibers, is a promising humidity sensing material due to the massive hydroxyl groups existing in the molecular chains. It interacts with water molecules by hydrogen bonding<sup>[13]</sup>. Nanocellulose has attracted increasing scientific researches and commercial interests recently in flexible devices because of their advantages such as natural abundance, light weight, facile fabrication, specific structural properties, environmental protection, and nontoxicity over their counterparts. Zhu *et al.* developed a flexible cellulose nanofiber/carbon nanotube (NFC/CNT) humidity sensor with high sensitivity performance via fast vacuum filtration<sup>[13]</sup>. However, this sensor still contains carbon materials. One of the noteworthy limitations of complete cellulose based sensors is that the electrodes are prone to cracking if the cellulose paper is folded<sup>[14]</sup>. Thus, choosing a suitable electrode material to enhance the flexibility of the paper-based sensors is challenging and desired. Duan *et al.* developed a multifunctional humidity sensor based on cellulose paper and flexible conductive adhesive tape electrodes, exhibiting good overall humidity sensing performance (Fig. 2)<sup>[14]</sup>.

**5) 2D materials.** Recently, 2D materials have received wide attention due to their various structures, special physical and chemical properties, relatively low cost and prominent electronic properties. With almost all the atoms exposed, the charge carrier is highly sensitive to water molecules. Besides, owing to the Van Der Waals gaps between surface layers, the properties can be regulated by controlling the number of layers. Also, they have great adhesion to many flexible substrates<sup>[15]</sup>. Feng *et al.* found out that peeled off TaS<sub>2</sub> nanosheets have high humidity sensing performance<sup>[2]</sup>. Jenjeti *et al.* demonstrated the ability of few-layer NiPS<sub>3</sub>

nanosheets for humidity sensing and the flexible device exhibited high overall sensing performance<sup>[16]</sup>. However, the high operating gate voltage and complex fabrication process were necessary in recently reported humidity sensors based on 2D-MoS<sub>2</sub> field effect transistors, thus increasing power consumption and preparation cost<sup>[17]</sup>.

In conclusion, flexible humidity sensors have developed rapidly and achieved increasing attention as a promising platform for advanced IoT applications. Despite the great advances in various flexible humidity sensors, several challenges should be further addressed in the future such as novel sensing materials, facile and low-cost fabrication methods, environment friendly preparation process, and system-level integration of multifunctional sensors.

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