Progress on polymer-based materials and composites for humidity sensors applications: Materials aspects to sensor performances

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Table S1. Categorization of humidity sensor based on working mechanism, advantages and disadvantages.

Types of sensor	Working Mechanism	Advantage	Disadvantage
Resistance based	It operates on the principle of the Grotthus chain reaction and provides feedback in terms of resistance [1] [2]	i) It has a wide resistance variation ii) High sensitivity and significant conductance which enhances humidity detection accuracy iii) Fast response and recovery time iv) At high humidity charge carrier mobility is enhanced v) It can be customized and scalable [2]	i) Senor performance depends on the hydrophilic properties of a material ii) There could be low sensitivity at lower relative humidity and mechanical instability at higher relative humidity based on material iii) At a specific humidity range, the sensor can show a nonlinear response, which could affect sensing accuracy [2]
Capacitance based	Its process is identical to that of a resistance-based humidity sensor; however, it responds in terms of capacitance [3]	i) High sensitivity ii) Adaptable structural design iii) The extensive surface area improves sensing performance. iv) Has rapid response and recovery time v) Exhibits a clear correlation with humidity [2]	i) This sensor depends on frequency specifically. The capacitance value diminishes as frequency increases, complicating readings. ii) Exhibits complexity in the design of the sensor layer. iii) Alterations in ambient conditions may impact sensor performance. iv) Performance of sensor depends on material v) Required high cost for advanced design of sensor [2]

Impedance based	This also pertains to the proton leaping process, wherein variations in relative humidity and frequency result in alterations in impedance [4] [5]	i) Sensitivity is contingent upon frequency. So, enhanced sensitivity occurs with lower humidity levels. ii) Stable and reliable output iii) It typically demands minimal power consumption. iv) It can function throughout a wide frequency spectrum [2]	i) Demand meticulous frequency optimization for precise outcomes. ii) At elevated frequencies, sensitivity diminishes due to the inability of water molecule polarization to synchronize with variations in the electric field. iii) Performance depends on sensing material iv) Impedance may be affected by environmental conditions, which can result in measurement mistakes [2]
Voltage based	It operates on the Grotthus reaction; nevertheless, it does not need a continuous power supply. When humidity interacts with active material, it generates an electric current [2]	i) It is self powered sensor ii) It is environmentally sustainable and features a design conducive to prolonged usage. iii) Enhancements in sensor performance can be achieved by alterations in surface structure. iv) The energy produced by the sensor is adequate to power low-energy gadgets. v) It has a compact design [2]	i) Low power output ii) Environmental dependence iii) Only small-scale applications are better suited for this technology [2]

Optical intensity based	It detects humidity by detecting changes in the refractive index or transmitted light intensity resulting from water absorption by a sensor material [6] [7]	i) Extremely sensitive to humidity ii) Fast response time iii) The sensor is perfect for environments with a lot of electrical noise since it is impervious to electromagnetic interference. iv) These sensors are lightweight and compact. [6]	i) Has a sophisticated design ii) Has a temperature sensitivity, which may impact the ability to sense humidity. iii) Is more expensive to fabricate than other sensors. iv) Mechanical stress and extreme environmental conditions may harm a sensor [6]
Frequency (Gravimetric) based	It detects humidity by measuring frequency shifts resulting from mass changes in a moisture-absorbing sensor material, utilizing Quartz Crystal Microbalance (QCM) or Surface Acoustic Waves (SAW) technology [7]	i) High sensitivity towards humidity ii) Quick reaction and time to recovery iii) Have a comparatively simple experimental setup to test humidity. [7]	i) Temperature changes may impact humidity sensing since the sensor is temperature sensitive. ii) The adsorption sensing layer influences the sensors performance iii) More substantial than other sensors [7]
Resonant (Magnetoelastic) frequency based	It detects humidity by measuring the resonant frequency changes resulting from mass alterations as the sensor material absorbs moisture	i) Applications for wireless (remote) sensing may make advantage of it. ii) Extremely sensitive to moisture iii) The sensor is based on non-contact. For example, it uses a magnetic field to measure humidity, so it doesn't need physical touch	i) Has complex design. ii) An external electromagnetic field may have an impact on the sensor. iii) The cost of this sensor technology is high. iv) Over time, the moisture-sensitive layer may

	[7]	[7]	deteriorate, affecting the sensors long-term accuracy and stability. v) Responds more slowly [7]

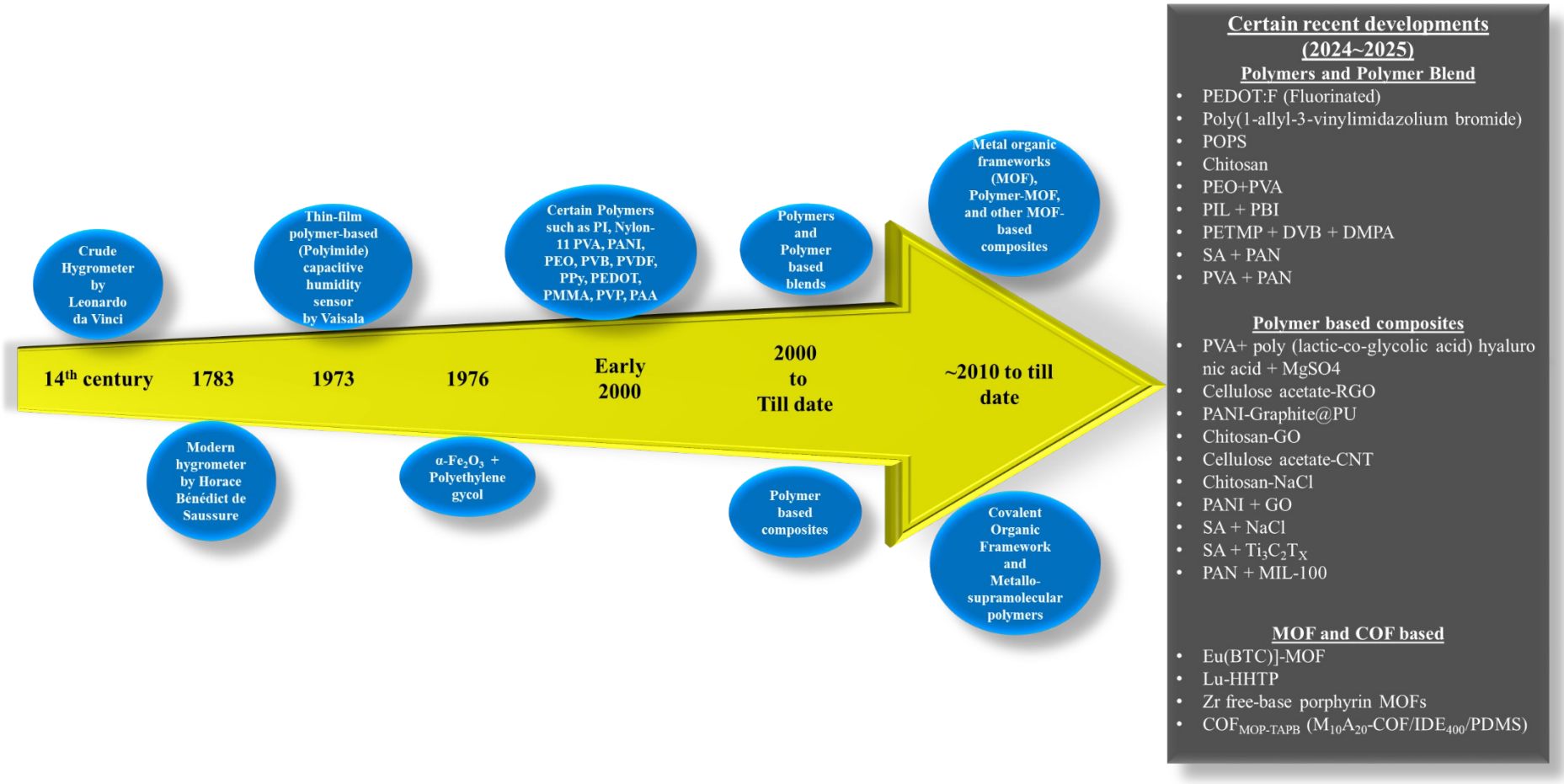

Figure S1. Historical development of polymer based humidity sensor

References

[1] D. Zhang, Z. Xu, Z. Yang, X. Song, High-performance flexible self-powered tin disulfide nanoflowers/reduced graphene oxide nanohybrid-based humidity sensor driven by triboelectric nanogenerator, Nano Energy, 67 (2020) 104251.

[2] Y. Lu, G. Yang, Y. Shen, H. Yang, K. Xu, Multifunctional flexible humidity sensor systems towards noncontact wearable electronics, Nano-Micro Letters, 14 (2022) 150.

[3] H. Yu, J.-G. Liang, C. Wang, C.-C. Liu, B. Bai, F.-Y. Meng, D.-Q. Zou, L. Ali, C.-Q. Jing, M. Zhao, Target properties optimization on capacitive-type humidity sensor: Ingredients hybrid and integrated passive devices fabrication, Sensors and Actuators B: Chemical, 340 (2021) 129883.

[4] Y. Zhang, Z. Duan, H. Zou, M. Ma, Drawn a facile sensor: A fast response humidity sensor based on pencil-trace, Sensors and Actuators B: Chemical, 261 (2018) 345-353.

[5] D. Zhang, X. Zong, Z. Wu, Y. Zhang, Ultrahigh-performance impedance humidity sensor based on layer-by-layer self-assembled tin disulfide/titanium dioxide nanohybrid film, Sensors and Actuators B: Chemical, 266 (2018) 52-62.

[6] A. Kapic, A. Tsirou, P.G. Verdini, S. Carrara, Humidity sensors for high energy physics applications: A review, IEEE Sensors Journal, 20 (2020) 10335-10344.

[7] C.-Y. Lee, G.-B. Lee, Humidity sensors: a review, Sensor Letters, 3 (2005) 1-15.