Recent Advances in Flexible Field-Effect Transistors toward Wearable Sensors

Ming-Zheng Li, Su-Ting Han,* and Ye Zhou*

The introduction of the “Internet of Things” (IoTs) concept has spawned a series of research and development of wearable sensors. Flexible field-effect transistors (FETs) are considered to be potential sensing devices due to the variety of material utilization and the self-amplifying function on electrical signals. FETs have demonstrated the ability of detecting different kinds of external stimuli and continuous monitoring functionalities. Herein, the recent progress achieved by the academia in wearable sensors based on flexible FETs, including pressure, temperature, chemical, and biological analytes, which are vital for the manufacturing of smart wearable devices, is summarized. The sensing mechanism for different sensors is introduced and an in-depth discussion is presented, including material engineering, problems at the current stage, and future challenges.

1. Introduction

Recent decades have seen the prosperous development of technologies, especially in information technologies, intelligent sensing, and control, where devices are of great significance for detecting the statuses of products, humans, and relative surrounding environment.[1–3] Research surrounding sensing devices aims at preparations for the imminent fourth industrial revolution and development of services for the “Internet of Things” (IoTs) era.[4] In this respect, light-weight, portable, flexible, and easily adaptable sensors for detecting and collecting data from human life or environment are essential for promoting the development of ubiquitous electrical devices.[5–7] Applications of these devices included bendable/rollable displays,[8] wearable sensors,[9–12] electronic skins,[13–16] implantable medical devices,[17] and so forth.[18] Currently, various materials have been fabricated into different kinds of wearable sensors.[19–24] In addition to the material applications, reports were also found to use different kinds of electronic devices as the sensing units,[25,26] among which FET-based sensors have drawn the interest of researchers. In addition to the conventional applications of field effect transistors (FETs) in logic circuits as signal amplifiers, etc., FETs play a significant role in sensing devices by fabricating organic/inorganic semiconductor (OSC) materials into sensor devices with a simple layer-by-layer structure,[27,28] to improve the sensitivity and stability. An FET, used as the signal amplification cells or manufactured using sensitive materials as subcomponents, is capable of detecting specific type of stimuli from the external environment.[29] It is an ideal type of electronic device for sensors due to its small magnitude and diverse functional material usage for different sensing functions. Various kinds of stimuli–response devices based on FETs have been reported, including chemical,[30–32] biological,[33–35] physical,[36,37] or photo sensors,[38–40] etc.[39–42] Flexibility is one of the most significant characteristics of the wearable sensor as these devices are used in various scenario where the working conditions usually confront unexpected external interferences.[43] In recent years, researchers have attempted to develop mechanically durable, flexible, and anti-interference sensing devices based on FETs and satisfying progress has been achieved.[41,44–49] Semiconductors play a significant role in the working of FET sensors, which is responsible for current transmission, consequently infecting the sensitivity of the detecting devices.[50] Organic semiconducting materials have demonstrated application potentials in FETs because of the low cost, lightweight, molecule diversity, excellent optoelectronic characteristics, and large-scale synthesizable properties. Moreover, organic semiconducting materials have better environmental compatibility and are easier for preparation.[51] These materials therefore meet the current requirement of the development for flexible devices, e.g., wearable intelligent devices and medical monitoring equipment. The organic semiconducting materials can be tuned in charge transportation characteristics by reasonable designing the molecular structure or surface functionalization and generating specific electrical, chemical, or optical properties.[52] Among various kinds of sensors, amperometric sensors play significant roles in the sensing mechanism of OSCs, which enables devices’ continuous monitoring of external...
stimuli in the working environment and excellent mechanical flexibility. However, the working mechanism of organic electronic materials required further investigation. Studying electronic structures, electron migration, energy transfer, and photoelectric conversion remains at the exploration stages and a widely accepted theoretical model has not been introduced, which can rationally explain the electrical phenomena. In this context, flexible electronics has become an important research area that is rapidly developing and emerging in academia. As a frontier area, the manufacturing and application of flexible FET (F-FETs) have attracted the interest of researchers. The number of papers related to F-FETs and flexible electronic devices have rapidly increased recent years.

A typical FET comprises three parts of components, three terminals (i.e., gate, source, and drain electrodes), a dielectric as the insulating layer, and an active layer which uses semiconductors to induce charge transport. Comparing with conventional sensors with only two electrodes, FET sensors can tune and amplify the electrical signals from sensors by simply applying tuned voltages to the gate electrode. Being exposed to the external environment, electrical characteristics of semiconductors in the FET are changed by trapping or doping through target analytes. In addition to the modification of semiconductor layers, properties of three electrode components in an organic FET (OFET) device can be altered as well to achieve specific detection of target analytes or sensing functions. Due to the diversity of organic materials, F-FETs have been studied in fields of chemical and biochemical analytes detection, pressure sensing, temperature measuring, and especially optoelectronic property investigation and applications. Numerous studies surrounding organic materials in FETs to achieve specific detection functionality have been reported and remained increasing rapidly.

In this Review, the development of F-FET based sensors is reviewed and state-of-the-art approaches in increasing detecting sensitivity of sensors are summarized. We focus on demonstrating applications of F-FET-based sensors in detecting external stimuli, such as pressure, strain, analytes of chemical and biological species, temperature and light, etc. Furthermore, we have discussed the methods in improving device performance, e.g. increasing sensitivity, reducing response and recovery time, and improving robustness against unexpected environment changes.

2. Structure and Working Mechanism of Organic FETs

A basic FET comprises three components, i.e., a semiconductor layer, a dielectric insulating layer, and three electrodes (drain, source, and gate). Figure 1 shows a typical bottom-gate top-contact F-FET. Generally, F-FETs control the current between drain and source electrodes via applying tunable voltage between the gate and source electrodes. As $V_{GS}$ is applied to the gate, and electric field redistribution inside the dielectric layer generates a dual-electrical layer; consequently, charge carriers can transport in the channel region of the semiconductor layer near the interface adjacent to the dielectric. Based on the energy-level relationship between the semiconductor and drain/source electrodes, holes ($h^+$) and electrons ($e^-$) worked as the charge carriers in the semiconductor layer, which exhibits different conducting behaviors. According to the polarity of the carriers in the semiconductor, typical F-FETs are categorized into p-channel, n-channel, and ambipolar type. The F-FETs work in either linear regime or the saturation regime, primarily depending on the voltage applied on the electrodes. The drain current
$I_D S$ in the linear or saturation regime is theoretically calculated as per Equation (1) or (2), respectively.

$$I_{DS}^{\text{lin}} = \frac{W}{L} C_{ox} \mu (V_{GS} - V_T) V_{DS}, \quad V_{DS} \ll V_{GS} - V_T$$  \hspace{1cm} (1)

$$I_{DS}^{\text{sat}} = \frac{W}{2L} C_{ox} \mu (V_{GS} - V_T)^2$$  \hspace{1cm} (2)

Here, $I_{DS}$ denotes the drain current and superscript lin and sat represent linear regime and saturation regime, respectively. $W$ and $L$ are the channel width and length in the semiconductor in an FET. $C_{ox}$ is the capacitance of the dielectric and $\mu$ represents the carrier mobility. $V_{DS}$ and $V_{GS}$ denote the applied voltages between drain and gate with the source electrode, respectively.

For an F-FET, basic electrical characteristics are the carrier mobility $\mu$, threshold voltage $V_T$, and the ON/OFF ratio of the current.

Reports have demonstrated numerous types of F-FET sensors that were fabricated through different methods, such as vacuum evaporation,[69–71] solution process,[72–74] and crystal growth.[75,76] Due to the amplification function of F-FETs, F-FET sensors exhibit higher sensitivity in detecting external stimuli than two-terminal sensors by modulating voltages applied to the gate electrode.[77] In addition, sensors based on F-FET possess advantages of high off-state resistance, low power and noise, a high dynamic range, low operating voltages, and a wide safe operating range.[78] Structures of F-FETs can be customized by adjusting device structures and material utilizations to meet the requirement of detecting specific external stimuli. The electrical properties of F-FETs are modulated by various factors, including electrode materials, capacitance of dielectric layers, charge mobility of semiconductors, and the adoption of the floating gate layer in devices, as illustrated in Figure 2. Influenced by external stimuli, characteristics of components in an F-FET are altered, which eventually change the current–voltage properties of the devices. Consequently, the F-FETs could achieve detecting target stimuli by fabricating specialized materials, according to the types of external stimuli (chemical analytes, biomaterials, mechanical stress and strain, temperature, pressure or light, etc.). Demands for detecting various stimuli have significantly broadened the applications of F-FET sensors. Using the charge carrier changes of semiconductors when confronted with different external analytes, F-FETs can be applied to detect chemical materials or biological materials. By integrating optoelectronic materials into the F-FET devices as floating gate, the photogenerated charges can alter the properties of the conductive channel. Therefore, F-FETs of this type become photosensitive devices when exposed to electromagnetic waves of specific wavelength. The changes in the dielectric layer by mechanical deformation of F-FETs are used for F-FET-based pressure sensors. The conductivity changes by temperature can be used for temperature sensors. Enlightened by the mechanism of conductivity changes, the F-FET with a delicate structure design can be utilized to detect mechanical deformations and pressure changes.[79] Using piezoelectric materials in the F-FET devices, generated voltage can be used for detecting the pressure changes of the external environment as well.

3. Pressure Sensors Based on F-FET

The increasing demand of the accurate sensing of tactile information is one of the fundamental essentials for the development of “IoTs.”[80–82] Therefore, the requirement for the accurate and

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Figure 2. Mechanism of typical FET, I–V curves, and F-FET-based Sensors.
fast response sensing technology with a wide sensing range has become a hotspot among the academia and industry. Researchers have proposed various kinds of sensors to detect the mechanical deformation of humans and products, aiming to integrate sensing information with applications in intelligent portable devices and biomedical engineering.

In this section, we introduce the state-of-the-art research on F-FET sensors that are used for detecting pressure and strains and future human–machine interactions. Sensors detect the external pressure changes primarily based on three mechanisms: piezoelectricity changes, capacitance changes, and piezoresistivity changes, as shown in Figure 3. In situ health monitoring and medical diagnoses have become attractive applications for F-FET pressure sensors.

3.1. Piezoresistivity-Based F-FET Pressure Sensors

Sensors based on the resistance variations are one common type of pressure-sensing devices. Resistance changes by the external stimuli (pressure variations) are transduced into current signals via piezoresistivity F-FET sensors. Current changes in these devices can be easily read out when force or pressure is exerted and these changes vary with the stimuli magnitude accordingly. Due to the simple structure of the device, the high pixel density of sensor arrays is achievable. In addition, piezoresistivity-type sensors are promising in detecting pressures over a large range.

Graphene, as a promising 2D material with various extraordinary properties, has been widely investigated in fabricating different kinds of devices as the functional additives. Lee et al. proposed a pressure sensor based on composites of carbon nanotubes (CNTs) and graphene. Figure 4a shows the schematic illustration of the F-FET sensor, which measures the normal pressure exerted onto the sensing region, even under extreme bending conditions. Semiconductor dinaphtho[2,3-b: 2′,3′-f]thieno[3,2-b]thiophene (DNTT) acted as the conducting materials in the F-FET that used parylene as the dielectric layer. When pressure was exerted on the sensor fiber pad, the resistance of the nanofiber varied (Figure 4d) and resistance changes were transduced into electric signals that were connected to the source electrode of the FET. Pressure changes could therefore be transformed into readable current changes for subsequent analysis. The integrated sensing device demonstrated a high sensitivity of measuring pressure of ≈800 Pa (Figure 4e) and a stable sensing performance under different bending conditions (from 15 mm to 80 μm). This research has solved the problem in separately detecting the individual normal pressure from mechanical press when two soft objects were pressed together. CNTs have demonstrated excellent resistivity variations under different external pressures. Chortos et al. introduced F-FET sensors with mechanical durability and high stretchability via CNTs. As shown in Figure 4f, in the F-FET sensor, the semiconductor layer and electrodes in the device use polymers incorporated with semiconducting CNTs and unsorted CNTs, respectively. Both substrate material and dielectric layer consist of thermoplastic polyurethane (TPU) to offset the tear propagation. The as-produced FET was with a 50 μm channel length and 400 μm width under 0% strain. Flexible sensor arrays were stretched in two directions, parallel and perpendicular to the charge transport direction. Normalized drain current under different a strain status was investigated (Figure 4h) and property recovery after stretching is shown in Figure 4i. The results have proved that the change in electrical properties after stretching was irreversible and the devices showed pressure-independent characteristics and stable current/leakage current readouts when under pressure stimuli.

By use of CNTs, Tee et al. also proposed a piezoresistive type of pressure sensor based on F-FETs. Polyurethane elastomer (PU) was molded into pyramidal microstructures, where CNT composites were dispersed in the PU, demonstrating a wide-impedance piezoresistor, as shown in Figure 4h. The effective modulus was reduced with the incorporation of pyramidal structures and the electrical field was also concentrated, which improved piezoresistive properties compared with an unstructured film. By controlling the CNT content in PU, the sensor demonstrated different resistance responses under various pressure stimuli (Figure 4i).

Figure 3. Diagrams of different pressure-sensing mechanisms for F-FET pressure sensors; a) piezoresistive, b) capacitance, c) piezoelectricity. Reproduced with permission. Copyright 2015, The Royal Society of Chemistry.
Based on this result, the sensitivity of the resistive-type sensor can be controlled at the fabrication stage where CNT was dispersed into PU pyramids. A real sensing set was then introduced as a Digital Tactile (DiTact) sensing system with a wearable glove to demonstrate the frequency changes of the voltage signal after applying pressure onto the wearable system (Figure 5a). Inspired by this pyramidal microstructured design for resistive sensing, Wang et al.\[112\] developed a piezoresistive-type F-FET sensor that used the same structural design in the device. However, a novel operating mechanism was proposed, based on the contacts between the semiconductor and conductive electrodes. A similar pyramidal structure was fabricated based on polydimethylsiloxane (PDMS) and patterned Au nanolayers deposited onto PDMS pyramids as drain/source electrodes, as shown in Figure 5d. The contact resistance between the semiconductor and source/drain is determined by material characteristics and contact area between electrodes and the semiconducting layer. The injection efficiency of carriers was increased with the increased contact area between semiconductor and electrodes, thus reducing the contact resistance, which was characterized via an electric signal readout (Figure 5e). The sensitivity of the pressure was tuned by the piezoresistive effect and modulated gate voltages. As a result, the sensor showed a high sensitivity of 514 kPa$^{-1}$ and loading and unloading response time of 1.8 ms and 6.7 ms, respectively. Moreover, the sensor of this design also showed tunable sensitivity to decrease the risk of detecting unexpected disturbing stimuli, primarily by regulating the voltage applied on the gate electrode (Figure 5f). In practical applications, the sensor achieved the detection of wrist motion and in situ monitoring of weak signals of wrist pulses.

### 3.2. Capacitance-Based F-FET Pressure Sensors

A capacitor is a passive electronic component that stores energy in an electric field by an electrical charge form. A typical capacitor
consists of two conductive plates which are separated by a dielectric medium. In a capacitor, the capacitance value varies with the external pressure exerted on the plates. Therefore, the capacitance changes induced by the stimuli can transduce into electrical signals, i.e., the $I_{DS}$ fluctuations in the sensing circuit. With the application of flexible dielectric materials, F-FETs have become promising devices for pressure detectors. In a parallel-structured capacitor, the capacitance is calculated according to the equation $C = \varepsilon_0 \varepsilon_r A/d$,\textsuperscript{(46)} where the $\varepsilon_0$ and $\varepsilon_r$ denote the permittivities of the vacuum and dielectric layer between the electrode plates, $A$ represents the overlapped area of the two parallel plates, and $d$ is the distance between them. Intuitively, dimension changes occur when external pressure is applied to the capacitor, leading to changes in $A$ by shear forces and/or $d$ changes by normal pressures with mechanical deformation of the device by pressure stimuli. Sensing pressure stimuli becomes operable using flexible capacitors in the sensor system. F-FET sensors based on measuring the capacitance changes have been extensively reported.\textsuperscript{(112)}

Figure 5. Piezoresistive-type F-FET sensors for tactile sensing. a) Integration of piezoresistive sensor based on CNTs dispersed in the pyramidal-structured PU and an organic ring oscillator. b) Pressure response of sensors as a function of CNT concentration. c) Image and circuit schematic of a model hand with DiTact sensors on the fingertips connected with stretchable interconnects. Reproduced with permission.\textsuperscript{(63)} Copyright 2015, American Association for the Advancement of Science. d) Schematic illustration of a pyramidal electrode-based F-FET pressure sensor. e) Drain current variations under different pressure stimuli. f) Tunable sensitivity of the sensor under different gate voltages from $-60$ to $-10$ V. Reproduced with permission.\textsuperscript{(112)} Copyright 2015, Wiley-VCH.
fabricated a top-gate FET pressure sensor using PDMS as the dielectric layer in the device. PDMS was modulated into classical pyramidal-shaped microstructures and laminated onto an indium tin oxide (ITO)-coated flexible poly(ethylene terephthalate) (PET) sheet. A single-crystal rubrene was grown using physical vapor transport onto the bottom-contact gold electrodes. The use of thin single-crystal rubrene exhibited a field-effect hole mobility in the order of 1 cm²V⁻¹s⁻¹, leading to a very low threshold for transistor operation. The schematic illustration of the sensor integration is shown in Figure 6a. Under different loadings, the F-FET sensor showed different output curves in Figure 6b,c and the use of single-crystal rubrene signiﬁcantly increased the sensitivity to ≈0.15 kPa⁻¹. The study also showed a tunable pressure-sensing range and sensitivity by modifying the shape of PDMS pyramids. A similar mechanism was also used by Yin et al.[114] to fabricate a capacitance-based FET pressure sensor, as shown in Figure 6d. Microstructured elastic ionic polycrylamide hydrogel (EIJH) was patterned onto ITO/PET using a 365 nm UV radiation process. Two different OSCs, poly[4,8-bis(5-(2-ethylhexyl)thiophen-2-yl)benzo[1,2-b:4,5-b’][dithiophene-2,6-diyl-alt-(4-(2-ethylhexyl)-3-fluorothieno[3,4-b]thiophene]-2-carboxylate-2,6-diyl)] (PTB7-Th) and poly(indacenodithiophene-co-benzothiadiazole): tetracyanoquinodimethane (PIDT-BT:TCNQ), were separately fabricated onto the PET substrate which was deposited with patterned gold source and drain electrodes through thermal evaporation. Two individual substrates with dielectric and OSC layers were laminated together under ambient conditions by mechanical pressure. Sensitivities of the pressure sensors based on the two OSCs were calculated as 12.64 and 17.95 kPa⁻¹, respectively. In addition to modifying the morphology of dielectric layers, Liu et al.[115] used a suspended semiconductor/dielectric/gate structure in an F-FET. The basic structure of the organic FET is shown in Figure 6g. Polymers including poly(indacenodithiophene-co-benzothiadiazole) (PIDT-BT) and poly(3-hexylthiophene) (P3HT) were used as the semiconductor materials in the FET, with controllable polyelectrolyte composites of poly(ethylene glycol) (PEG) and polyacrylic acid (PAA) as the high-capacitance dielectrics. A total of 30 wt% PEG of the PAA:PEG material was used as the dielectric layer and a novel suspended OSC/dielectric/gate structure FET pressure sensor was successfully fabricated according to the schematic illustration in Figure 6h. The low operating voltage (−0.7 V) of the FET led to signiﬁcant increment of the sensor sensitivity, up to 452.7 kPa⁻¹, and short response time of less than 58 ms (Figure 6i,j). These characteristics made it a promising candidate for low-power pressure sensor in wearable electronics. To further increase the sensitivity, Zang et al.[116] designed the structure of the gate electrode to achieve the sensitive measuring of external pressure stimuli. A ﬂexible suspended gate FET was introduced based on the schematic illustration which is shown in Figure 6k. The suspended gate electrode that consisted of polyimide/aluminum foil (PI/Al) was incorporated with the support layer and fabricated onto the protective dielectric layer of 400 nm-thick poly(perﬂuorobutenylvinylether) (CYTOP) under ambient conditions. The design enabled the integration of different semiconductors into the sensing device units and the electrical performance of the sensors was optimized by fine modulating the properties of the suspended gate, reaching the response pressure limit of 3 Pa with this sensor setup (Figure 6l). With the optimization process, the F-FET sensor was able to achieve a high sensitivity of 192 kPa⁻¹ and ultralow working power of ≈100 nW. Successful real-time sensing of acoustic waves and wrist pulse demonstrated the promising application in artificial intelligence and healthcare systems using pressure sensors.

For capacitance-based F-FET pressure sensors, sensing performances are primarily characterized by the capacitance variations of the dielectric layer besides inherent properties such as OSC materials, transistor structure designs, and so on. It is therefore vital to rationally design the dielectric layer to increase the sensor’s sensitivity. Researchers have proposed different methods to increase the capacitance changes toward different external pressure stimuli, including the design of suspended gate in FET structures,[115,116] fabricating microstructured dielectric layers such as porous,[117] pyramidal,[118,119] and other types of structures,[113,114] and the introduction of microstructured electrodes and air gaps between electrodes and dielectric layers.[120] Due to these rational designs, capacitance-based pressure sensors have demonstrated high sensitivity and can be used in different sensing scenarios.

3.3. Piezoelectric F-FET Pressure Sensors

In addition to the piezoresistive and capacitance types of FET pressure sensors, piezoelectric materials are also commonly used for fabricating pressure sensors, primarily due to the high sensitivity in the piezoelectric materials. When mechanical stress is applied on speciﬁc types of materials, electrical dipole moments are generated inside the substances.[121] The neutral characteristic of material was primarily due to the parasitic effects which tend to recombine the piezoelectric charges. Because of the high sensitivity and fast response time, piezoelectric sensors are widely used in the detection of dynamic pressures such as vibrations by sound waves. In addition, the self-generated electrical dipole made piezoelectric materials promising for developing sensing devices that are low power consuming or self-powered. However, the transducers are not able to effectively detect static pressure stimuli or forces with little variation. To solve this problem, piezoelectric sensors are usually combined with other kinds of pressure sensors or electronic devices; a common method is to combine piezoelectric sensors with an ampliﬁer, e.g., transistors. The integration of F-FET and piezoelectric sensors has become a regularly used approach to fabricate flexible pressure sensors to improve sensor sensitivity.[122]

Chen et al.[123] presented a piezoelectric-induced ﬂexible pressure sensor based on the structure illustration shown in Figure 7a. 2.3 μm-thick poly(pyromellitic dianhydride-co-4,4’-oxydianiline) (PI) was used as a ﬂexible substrate and a graphene film was grown on the substrate via the chemical vapor deposition (CVD) process, followed by the evaporation of patterned gold electrodes. Subsequent to this process, PbTiO₃ nanowires were applied on the surface of graphene and protective PDMS was applied to encapsulate the device. When external stimuli were exerted on the device, the electric performance of the device was dominated by the synergistic mechanisms between the carrier change of the graphene layer and strain-induced polarization.
Figure 6. Capacitance-type F-FET sensors. a) Schematic illustration of pyramidal-structured dielectric layer FET pressure sensor consisting of thin rubrene single crystals and structured PDMS dielectric film. b) Output curves ($I_{DS}$-$V_{DS}$) of a transistor-based sensor with different external pressures applied. The legend lists the applied loads in the order of the original loading cycle. c) The change in $I_{DS}$, $\Delta I_{DS}$ (diamond symbols), is proportional to the measured relative change in capacitance, $\Delta C/C_0$ (scaled data from Figure 2a overlaid as the red curve), as expected in the OFET saturation regime. The gate current remained more than two orders of magnitude below $I_{DS}$. The inset shows time-resolved measurements with excellent response and relaxation times. Reproduced with permission.[113] Copyright 2010, Springer Nature Limited. d) Schematic illustration of micropatterned dielectric capacitance FET pressure sensor; e,f) saturated current responses of the two OTFT pressure sensors with the OSC layers of PTB7-Th and PIDT-BT:TCNQ; Reproduced with permission.[114] Copyright 2019, Elsevier Ltd. g) Structure of the flexible FET. h) Schematic illustration of the F-FET based pressure sensor (gap $\approx$310 $\mu$m) in the initial state (left) and pressed state (right). i) Transfer characteristics of the OTFT sensor under different pressures. j) Relative change of $I_D$ in response to external pressure for the F-FET sensor at both constant $V_D$ and $V_G$ of -0.7 V. Reproduced with permission.[115] Copyright 2019 WILEY-VCH. k) Schematic illustration of the gate suspended. l) Current response at the pressure limit of 3 Pa. m) Pressure response of the source–drain current at constant voltage, $V_{GS} = -60$ V and $V_{DS} = -60$ V. Reproduced with permission.[116] Copyright 2015, Springer Nature Limited.
charges in nanowires. Cyclic static measurements were carried out on the device, and results demonstrated successful detections of static pressure stimuli (Figure 7b). Due to the introduction of PTNWs/graphene heterostructure, the sensor demonstrated an excellent linear response to the pressure from 0 to 1.4 kPa with a high sensitivity of up to 9.4 $\mu$C$/C^2$ and a high sensitivity of up to 10 $\mu$C$/C^2$. Moreover, a low hysteresis was observed through the test, demonstrating a short response time, as shown in Figure 7c, which was 5–7 ms. Further applications of the PTNWs/graphene F-FET sensors were introduced to monitor the radial artery of humans, and the design of sensors provided a new concept for fabricating wearable and implantable health monitors. Wang et al.[124] proposed a pressure-sensing device using flexible ZnO nanorod (NR) arrays as the pressure sensor and piezoelectricity voltage induced by ZnO NR was amplified by a 2D indium selenide (InSe) F-FET, which possessed high mobility and electrical stability. The reported pressure sensor was able to detect a minimum loading of 0.1 g with 0.2 mV voltage change. A new strategy was proposed here to fabricate a piezoelectric pressure sensor that integrated pressure-sensitive arrays using ZnO NRs on flexible ITO substrate, with potential-sensitive FET based on InSe 2D materials. The integration of flexible piezoelectric materials and FETs (Figure 7d) is a prospective application of wearable devices with stable signal output. Figure 7e shows the transfer curve of the InSe-based FET devices. Measured with the sweeping range from −10 to 10 V at the $V_{DS}$ of 1 V, the transistor demonstrated a steep subthreshold slope of 800 mV dec$^{-1}$, indicating a fast ON/OFF switch, i.e., potentially fast response speed. Figure 7f shows the drain current response against different loadings on ZnO NR sensors, and the measuring of objects with different weight is demonstrated in Figure 7g. The proposed device presented a linear response to loads over a range of 0.1–500 g with the sensitivity from 19.6 Pa to 0.1 g loading.

Apart from inorganic materials, piezoelectric phenomena were also found in some specific types of organic materials. Kim et al.[125] presented their study that used an organic piezoelectric material to fabricate the F-FET sensor for achieving bimodal sensing of external stimuli from pressure and temperature. The structure of the F-FET sensor is shown in Figure 8a. Due to the flexoelectricity-enhanced piezoelectric effects by the pyramidal-shaped microstructures of the ferroelectric material poly(vinylidenefluoride-trifluoroethylene) (P(VDF-TrFE)),...
the pressure responsivity of F-FET sensor was significantly increased. In the slow adapting (SA) mode, the sensitivity of the F-FET sensor was measured to be 1.02 kPa $^{-1}$ under static pressure stimuli (Figure 8b) and the lowest detectable pressure was estimated as 20 Pa. Comparison of sensitivity between OFETs with microstructured and thin-film P(VDF-TrFE) as the gate dielectric (RA mode). As shown in Figure 8c, the sensitivity in the RA mode increased to 0.028 kPa $^{-1}$ compared with the thin-film structured FET sensors (0.003 kPa $^{-1}$). Similarly, Thuau et al. [126] designed an electro–mechanical transducer with cutting-edge structures based on an active organic FET. The structural schematic illustration of the FET design can be referred to in Figure 8d; P(VDF-TrFE) was used as the gate active dielectric layer in the sensor and mounted on a polymeric microcantilever (Figure 8e). Highly efficient transduction from mechanical deformation to electronical signals was achieved by the novel structural design and the poling process, as shown in Figure 8f,g. The benefit from the piezoelectric effect was apparently demonstrated via the large enhancement of the strain sensitivity close to $V_{th}$ by factor 18 after poling. At a low strain level (3%), the poled P(VDF-TrFE)/pentacene FET sensor exhibited linear strain sensitivity ($\Delta I_{DS}/I_{DS}$) of 600, which was much higher than other types of FET sensors, e.g., unpoled P(VDF-TrFE)/pentacene, poled P(VDF-TrFE)/DNTT, etc. The bimodal sensing functionality of the sensor was also reported as a humidity sensor, with the sensitivity of the humidity being estimated to 7500 ppm/%. Based on above literatures, the representative F-FET pressure sensors are shown in Table 1.

4. Temperature Sensor Based on F-FET

Detections of the conditions of products, humans, and relative environment are vital for the development of IoTs in the big-data
era. For instance, body temperature is a vital indicator for human health. By use of in situ wearable sensing devices, abnormal rise in body temperature can be instantly reported to medical services for prompt quarantine or further diagnosis, especially in the severe current situation of the COVID-19 epidemic. A series sensitive temperature sensors had been proposed by researchers, among which F-FET-based temperature sensors have been developed and reported widely recent years using various approaches.

To obtain uniform detecting performance and reduce sensing error from other stimuli, Zhu et al. reported their circuit design using static and dynamic differential readout methods, which suppressed the drain-dependent errors and achieved a measured error within only ±1 °C being operated under the strain of 0–60%. In this research, stretchable thin-film transistors were fabricated with a bottom-gate/top-contact structure, as shown in Figure 9a. Unsorted single-walled carbon nanotubes (SWCNTs) were patterned on the flexible styrene–ethylene–butadiene–styrene (SEBS) substrates by photolithography and a nonpolar SEBS thin film was used as the gate dielectric layer. Subsequently, supramolecular-polymer-sorted SWCNTs were grown on the dielectric layer, and another layer of unsorted SWCNT layer was patterned on it as the source and drain electrodes. Due to the use of nonpolar SEBS as the dielectric layer, negligible hysteresis was observed in the dual sweep, as the transfer curve shown in Figure 9b. Under different strains, the performance of sensors was further evaluated (Figure 9c, up to 60% strain). The output voltage ($V_O$) varied substantially with the strain at a constant temperature. Integrating the device into the static differential sensing circuit, identical sensing curves between different samples were observed, indicating that the circuit was able to eliminate the sample-to-sample variation of $V_O$ by a one-point calibration (Figure 9d). Tien et al. proposed a flexible FET sensor array that could achieve bimodal sensing of both pressure and temperature. As shown in the structural photograph in Figure 9e, the bottom-gate/top-contact F-FET was fabricated with P(VDF-TrFE) and BaTiO$_3$ nanoparticles (BT NPs) as the dielectric layer and piezo-thermoresistive OSC and pentacene as the conductive channel. The extraction of temperature or pressure signals from the bimodal FET sensors was achieved by applying AC bias to the gate electrode, as shown in Figure 9f. To further investigate the bimodal sensing performance of the F-FETs, a 4 × 4 device array was fabricated to detect pressure and sensor simultaneously. The sensor reported in this research showed sufficient response time for practical applications in mimicking human finger activities such as holding objects with different hardness and temperature.

Ren et al. reported their direct conformal temperature measurement using flexible FET arrays (16 × 16). They embedded discontinuous Ag NPs onto the pentacene film as the semiconductor and fabricated the structure onto a 12 μm PEN substrate film, as shown in Figure 10a. Drain and source electrodes of the flexible FET sensor units in the array were connected to the thermistors in series. The Ag NPs doped in the pentacene layer allowed the sensitive hopping-dependent electrical conductivity varying with temperature. The large sensing range of the temperature sensor, from 20 to 80 °C (Figure 10b), was demonstrated by a large change in the drain current. The semilog plot of the conductivity in Figure 10c exhibits its good linearity with temperature under different Ag NPs doping conditions. Furthermore, after being bended 104 times at 3.2 mm bending radius, the temperature sensor still demonstrated mechanical stability due to the 6 μm parylene C encapsulation layer, which guaranteed the active layer close to the neutral bending position. By use of the 16 × 16 sensing array, an explicit temperature output can be obtained (Figure 10d).

Another approach is to apply intrinsic thermoelectric material into FET structures. Zhao et al. reported a P3HT-based electrolyte-gated transistor, coupled with ionic thermoelectric supercapacitor (ITESC), whose electrodes were connected to the gate and drain electrodes of the transistor, as shown in the schematic diagram in Figure 10e. In the bottom-contact/top-gate transistor, regioregular P3HT acted as the active semiconducting layer and poly(vinylphosphonic acid-co-acrylic acid) (P(VPA-AA)) was used as the polyanionic electrolyte insulator. The electrolyte dielectric layer enabled the FET to operate at...
voltage of less than 1 V. Subsequently, ITESC was fabricated using PEO–NaOH electrolyte, with a Seebeck coefficient of 7 mV K⁻¹. When a temperature difference ΔT was applied between the two electrodes of ITESC, Na⁺ cations diffused fast toward the cold side, and uncompensated alkoxylate and carboxylate anions with less mobility remained at the hot side. By combining the FET and ITESC, the electrical signals generated by the ITESC, due to the temperature gradient, were amplified by the FET. As the operating voltage of the FET was in the same order of magnitude as the voltage variation of ITESC, the

Figure 9. Temperature sensors based on F-FETs. a) Schematic illustration of the structure of an intrinsically stretchable SWCNT F-FET device. b) Transfer curve (I(DS–VGS, line) and gate leakage curve (I(OGs–VGS, scatter) of an F-FET with forward and backward sweep at V(DS) = −50 V with W/L = 10 (inset: transfer curve [I(OGs–VGS] with forward and backward sweep at V(DS) = −20 V). c) Temperature-sensing performance based on a single F-FET (the absolute electrical output V(O changes substantially with strain at a constant temperature). d) Single-point calibration of the stretchable temperature sensors based on static differential sensing circuit architecture under different strains and cycle numbers. Reproduced with permission.© 2018, Springer Nature Limited. e) The structure of physically responsive FETs with the bottom-gated and top-contact structures, where the gate dielectric comprises P(VDF-TrFE) or nanocomposite of P(VDF-TrFE) and BaTiO₃ NPs and the channel is OSC of pentacene. f) Changes in I(DS signals of F-FET with P(VDF-TrFE) upon applying pressure and temperature. g) Read-out pressure and temperature measurements of a sensor array with half of the devices are being depressed by a human thumb. Pressed devices are observed to show higher-pressure and temperature responses, when compared with unaffected devices. Reproduced with permission.© 2014, Wiley-VCH.
output current was tunable in more than two orders of magnitudes. Here, the ITESC demonstrated a response time of 25–50 s (with 70–90% saturated voltage). The relative slow thermal conducting and slow response of temperature sensor may limit the simultaneous monitoring. Moreover, this work demonstrated that heat signals can be transduced for logic circuits for the first time. Based on above literatures, Table 2 summarized the crucial characteristics of F-FET temperature sensors.

5. Chemical and Biological Sensors Based on F-FETs

Personalized medical service has received tremendous interest under the background of rapid development of big data and increasing awareness of telecommuting. Research of wearable devices that can continuously and closely monitor conditions of individual health status or conditions of the surrounding environment has become a hot topic. Biological substances per se are also chemical materials. The detecting of chemical and biological analytes shares the similar mechanism. F-FET could serve as an ideal platform for designing detectors of specific types of mechanical and biological analytes due to its flexibility and stretchable characteristics. Similar to the pressure FET sensors, the chemical and biological sensors also used the fundamental working mechanism introduced in Section 2. In these sensors, electrical characteristics of FETs, e.g., output currents, threshold voltages, and mobility of the semiconductors, are adjusted due to the doping or trapping effects of the analyte molecules. When the target analytes come in contact with the functionalized sensing layer of the FET devices, the active layers, which are usually the semiconducting or dielectric layers, demonstrate an altered electrical characteristic due to the interactions between analyte molecules and

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**Figure 10.** F-FET-based temperature sensing arrays and electrolyte gate structures. a) Schematic illustrations of flexible FET arrays and the enlarged diagram of one temperature sensing unit. b) Transfer $I-V$ of organic transistors at different temperatures, where the solid line represents $I_{DS}$ and dashed line represents the corresponding $I_{GS}$. c) Arrhenius plot of conductivity against temperature of pentacene/Ag NPs thermistor with different Ag NPs thicknesses. d) Schematic diagram of temperature measurement setup and temperature distribution measured from the sensor array. Reproduced with permission. Copyright 2014, Wiley-VCH. e) Schematic diagram of an electrolyte-gated transistor and the ionic thermoelectric-gated inverters. f) Output current tracking with the variation of $\Delta T$. Reproduced with permission. Copyright 2017, Springer Nature Limited.
molecules in the active layer. Therefore, the charge carrier density distribution in these layers is accordingly altered, leading to changes of output current of the FET. The varied output current can be measured as electrical signals to demonstrate the existence and variation of target analytes.

FETs with specific active layers can be used for in situ monitoring of the conditions of daily life and work environment. Single- and multifunctional sensors based on FETs have been reported to detect various types of chemical analytes, including the detection of volatile organic compounds (VOCs), detrimental gases, aqueous-phase analytes, and specific organic molecules. Basically, these sensors were fabricated primarily based on the induced carrier mobility changes or capacitance changes in the FETs by the interactions and reactions between chemical analytes and functionalized active materials.

5.1. F-FET Sensors for Detecting Environmental Conditions

Pollutions caused by the rapid development of industry have become an urgent problem because the substances not only pollute the environment, but also are detrimental to the health of humans. It is therefore essential to monitor these polluting substances effectively and accurately. The sensing behavior of chemical sensors generally is based on the interactions between target substances and sensors, including charge transfer, hydrophobic/hydrophilic interactions, dipole-dipole interactions, capacity variation, and hydrogen bonding. In the FET chemical sensors, using semiconductor materials with small molecular weights, the analyte molecules penetrate into the semiconductor layer through the grain boundary, rather than through the cluster due to the dense molecular packing. Analyte molecules in the semiconductor layer act as the trapping site; therefore, the charge carrier density and molecular properties of the semiconductors are therefore influenced, leading to the change of the charge-transfer characteristic, i.e., reducing the semiconductor conductivity.

Kang et al. fabricated an organic FET-based chemical sensor with improved crystallinity using an organic heterointerface and successfully controlled the morphology of an organic thin film. For the dielectric layer, m-bis(triphenylisilyl) benzene (TSB3) was thermally vaporized on the substrate with a low glass transition temperature. Subsequently, the highly crystalline pentacene film was grown on the TSB3 layer under identical vacuum ambient, and nanoporous structures with distinct grain boundaries were developed on the nanoporous dielectric layer. As shown in the schematic diagram in the text, because of the reduced grain boundary, the highly crystalline pentacene with nanoporous structures improved charge carrier transport and sensing performance, which enabled the diffusion of analyte molecules into the semiconductor layer to change the carrier charge mobility. A significant current increase was observed with the use of TSB3 into the FET sensor. The detecting performance of sensors was improved because of the vertical macropores in the pentacene/TSB3 layer by enhancing the penetration of chemical molecules into the channel region. Results shown in Figure 11c indicate that the introduction of the TSB3 porous structure significantly increased the sensitivity and reduced the response time of FETs toward methanol vapors, compared with conventional pentacene FETs.

In addition to the diffusion of analyte molecules to the boundaries, analytes are also able to permeate into the grain due to the lamellar clustering structures of some OSCs with higher molecular weights. Inside these OSCs, the molecular clustering was looser than small molecular weight substances, which allows permeated analytes to modify the structure of OSC clusters and furthermore the electrical performances of OSC layers in the sensors. For the detection of VOCs, Li et al. investigated the performance of a series of polythiophene-based copolymer semiconductors for sensing different types of VOCs. A two-terminal sensing system was initially fabricated to explore the intrinsic responses of sensors toward VOCs, primarily depending on the morphology of semiconductors and interactions between analyte molecules and different types of polythiophene-based copolymers by the addition of a second polymer at the end of the polythiophene chain. Different sensing responses were obtained with respect to different analytes and copolymer-based sensors, due to the variations of the interactions between analyte molecules and semiconducting layers. Ten kinds of VOCs, including both polar and nonpolar types, were injected into the sensing system and copolymer-based sensors demonstrated different responses and the conductivity changes of sensors are shown in Figure 11d. Results indicated multiple mechanisms dominated the sensing responses. However, chemical reactions between analytes and copolymers were first excluded due to the fully recoverable conductivity, after being exposed to a VOC of any kind. One main factor in the sensing process was the influence of the second polymer block that was added to the end of the polythiophene chain. Moreover, the polarity of analytes was also a vital factor that determined the conductivity changes of the sensing layer. Conductivity could be influenced by the degree of crystalline order and the nanostructure boundaries, as well. For a homopolymer, the conductivity of sensors was increased by the induced dipole moments which reduced the average polymer molecule distance, whereas decreased by the enlarged molecule spacing of the polymer.
materials as per the swelling effect from nonpolar analytes. Following the results, the author conducted further research on the sensing response based on P3HT FET sensors and obtained the current responses toward different VOCs (Figure 11e).\[182\]

Previous reports describe the sensing responses that were independent with voltages applied between gate and source electrodes \(V_{GS}\). However, the changes in \(V_{GS}\) of the FET-based chemical sensors could lead to competitions of multiplex mechanisms in analyte detections. In an FET, the majority of charge carrier transport behaviors occurred at the interface between the semiconducting and dielectric layers, rather than in the bulk of layers.\[183\] Application of different \(V_{GS}\) caused the changes in carrier transport behaviors, which was manifested in forms of sensing responses. In sensory responses toward different analytes, sensing performances were influenced by the competitive result of charge-carrier transport of intragrain and grain boundary effects. When \(V_{GS}\) was small, the charge transfer inside the films (intragrain effects) dominated the output current value; in contrast, at a large \(V_{GS}\), the grain boundary effect demonstrated greater influences on the sensing response. In addition to the changes of drain current induced from \(V_{GS}\),\[182\] interactions between analytes and dielectric layers also affected the drain current of FET chemical sensors in the similar way as the intragrain and grain boundary effects of semiconducting layers.\[92,184\]

To increase the sensitivity of FET-based (bio)chemical sensors, a series of approaches have been demonstrated to modify the characteristics of gate dielectric layers, including the modification of gate dielectric layers by introducing carbon quantum dots,\[185\] use of metal-organic framework (MOF) membranes,\[186–188\] or using porous structured functional layers\[92,189\] (Figure 11f) and additional functionalized methods at the semiconductor or dielectric layers.\[190,191\]

5.2. F-FET Sensors toward Health Monitoring

Chemical sensors can be used to monitor the health conditions by monitoring the interactions between specific biological molecules and functionalized materials.\[192–195\] Flexible FET sensors, due to high flexibility and conformability, is an ideal platform for personalized clinical treatment as they are able to provide continuous and close monitoring of the health status.\[196\] With respect to FET-based biochemical sensors, biochemical substances are absorbed on the active layer, which is usually a biochemical recognition semiconductor, and can modify the carrier density and the doping level of the receptor.\[197,198\] By capturing data

Figure 11. Chemical sensors toward environment monitors based on F-FET. a) Structure illustration of the FET chemical sensor with a pentacene/TSB3 heterointerface. b) Current–voltage curves for pentacene FETs with and without TSB3, measured inside a nitrogen-filled glovebox. c) Sensing performance of FETs with and without TSB3 layers toward methanol vapor. Reproduced with permission.\[71\] Copyright 2014, Springer Nature Limited. d) Conductance response of P3HT-based chemical sensors toward acetone and toluene detection, carrier gas 1 L min\(^{-1}\) N\(_2\). Reproduced with permission.\[181\] Copyright 2006, American Chemical Society. e) The sensing response in the form of normalized \(I_{DS}\) current at different gate voltages. Reproduced with permission.\[182\] Copyright 2008, American Chemical Society. f) Demonstration of significant increment in detecting limit based on monolayer molecular crystal FET sensors with other OSCs. Reproduced with permission.\[90\] Copyright 2020, Wiley-VCH.
of specific molecules from the human body, F-FET biochemical sensors are able to retrieve more insightful health information. In conventional clinical or laboratory scales, health examinations primarily depend on blood analysis. The invasive monitoring method is not able to provide dynamic and continuous information. In recent years scientists have proposed numerous flexible biosensors that are able to monitor substances from body fluids, e.g., representative ions or DNA molecules to retrieve the health status.

Stoliar et al.[199–201] fabricated an ultrathin FET based on pentacene as the semiconducting layer to achieve the label-free sensing of DNA molecules. As shown in Figure 12a, the DNA molecules were absorbed onto the two-monolayer-thick pentacene film from a solution because of electrostatic adsorption. Transfer

Figure 12. F-FET sensors toward health monitoring. a) Schematic diagram of a label-free DNA sensor based on pentacene-based FETs. b) Transfer characteristics for the transistors at different DNA concentrations. Reproduced with permission.[34] Copyright 2009, Elsevier B.V. c) Schematic diagram of DNA oxidation on the solution-processed IZO flexible FET-based biochemical sensor. d) Transfer characteristics of the low-temperature solution-processed IZO FET-based biochemical sensor before and after DX DNA immobilization with the detection limit of 50 nM. Reproduced with permission.[202] Copyright 2016, Elsevier B.V. e) Photograph of the fabricated WO3-based pH sensor; Reproduced with permission.[212] Copyright 2014, American Chemical Society. f) Schematic illustration of the basic structure of the selective ion-sensing FET. g) Electrostatic gating effect for an unfunctionalized CNT–FET upon changes in the electrolyte concentration. The threshold voltage $V_{th}$ of the unfunctionalized CNT–FET is plotted as a function of the salt concentration, either KCl (black) or CaCl$_2$ (gray). Reproduced with permission.[219] Copyright 2015, IEEE. h) Schematic illustration of RuO$_x$ FET sensor, with the functionalized 4-CPBA glucose sensing layer. i) Transfer characteristics of RuO$_x$ on PET-based FET sensor in different pH buffer solutions (pH = 2–12). j) Transfer characteristics of the RuO$_x$ on PET-based EG-FET biosensor for detection of glucose in PBS (10 mM, pH = 7.4). k) $V_{BEFF}$ shift of the RuO$_x$-based EG-FET biosensor plotted as functions of various saccharide concentrations in PBS (10 mM, pH = 7.4). Reproduced with permission.[228] Copyright 2019, Elsevier B.V.
curves of the FET sensors in regard to different DNA concentrations are shown in Figure 12b. The pinch-off voltage variation across a wide range of DNA concentrations was observed with a sensitivity of 74 ng cm$^{-2}$ corresponding to a concentration of 650 ng mL$^{-1}$. The trends of the I–V curve indicated that the negative charge in DNA induced capacitive coupling and increased positive charge carriers in the pentacene layer. To increase the sensitivity of DNA sensors based on electrostatic forces, Jung et al.\textsuperscript{1202} reported their low-temperature solution-processed In–Zn–O (IZO) FET capable of detecting DNA molecules in a low molecular concentration. Three types of double crossover (DX) DNA solvents, i.e., nonpolar, polar, and aqueous based, were presented to the IZO semiconductor channel, as shown in Figure 12c. Transfer characteristics of the IZO TFT were measured under prior to and subsequent to the immobilization of varying DNA concentrations and the representative I–V curve toward a detection limit (0.5 µl of 50 mM), as shown in Figure 12d. Superb sensitivity was observed in a DNA-immobilized FET, attending a significant negative shift of the turn-on voltage and decrease in ON/OFF ratio without recovery, which suggested that the existence of DNA enhanced the conductivity of IZO FETs. The authors implied that this phenomenon was the result of DNA oxidation process with reactive oxygen species on the carrier supplier IZO semiconductors. Researchers have also reported DNA sensors by use of single-stranded (SS) DNA samples onto gold electrodes\textsuperscript{[204,205]} and solution-gated graphene.\textsuperscript{[204,205]}

Sweat is a vital and easily accessible body fluid comprising a series of chemicals reflecting the clinical information of individuals.\textsuperscript{[206,207]} Abnormal health conditions could significantly influence the compositions and specific types of analytes in sweat.\textsuperscript{[31,160,208–210]} F-FET-based biochemical sensors could provide in situ monitoring of the sweat compositions in a noninvasive way.\textsuperscript{[211]} Considering the complexity of sweat compositions, numerous sensors have been reported toward different ingredients, including pH sensors,\textsuperscript{[67,147,210,212–217]} ion sensors,\textsuperscript{[67,147,218–223]} glucose sensors,\textsuperscript{[71,45,48,159,224–226]} lactate sensors,\textsuperscript{[227]} etc. Based on WO$_3$ NP, Santos et al.\textsuperscript{[221]} reported a representative F-FET-based pH sensor for in vivo applications (Figure 12e). WO$_3$ NPs were first synthesized using hydrothermal synthesis and then deposited on to a flexible PI substrate, with a reduced sensing area of 1 mm$^2$. The sensor could stably detect the pH value ranging between 9 and 5 because of the thin WO$_3$ layer with improved surface area. As an alternative for conventional material, the insulator layer in the pH sensor was fabricated using wax printing method since the wax is compatible with the solution and low-cost process. The electrodes were well conformed to curved surfaces of PI substrates and the use of flexible PI made the sensor suitable for wearable biochemical devices. To achieve multifunctional sensing, Melzer et al.\textsuperscript{[219]} reported their research on the selective sensing of Ca$^{2+}$ and K$^+$ based on flexible electrolyte-gated CNT FETs. As the basic structure of FET shown in Figure 12f, the CNT network was randomly distributed onto the PI substrate, on which predefined source and drain electrodes were placed. By integrating different compositions of poly(vinyl chloride)-based ion-selective membranes into the CNT network (sodium tetraakis NaTFPB and valinomycin for K$^+$; sodium tetraakis NaTFPB and N, N-dicyclohexyl-N’, N’-diodacetadecyl-3-oxapentanediamide for Ca$^{2+}$), an ion-selective response toward K$^+$ and Ca$^{2+}$ was achieved. The membrane potential changes at the membrane/electrolyte interface was the primary sensing mechanism that transduced ionic signals into electrical ones, leading to the variation of effective gate potentials and therefore changing the charge-carrier transport in semiconductors. By characterizing the transistor performances and extracting the threshold voltages ($V_{th}$), different concentrations of cations were successfully distinguished even with interfering ions (Figure 12g). The selective and sensitive detection of ion type and concentration was successfully achieved, even in the solutions with the highly concentrated background of interfering ions.

In respect to glucose sensing, Singh et al.\textsuperscript{[228]} successfully fabricated a flexible PET-based extended-gate FET sensor for pH monitoring which could detect the concentration of glucose simultaneously. A 40 nm sol–gel RuO$_x$ sensing membrane was deposited onto the ITO-coated PET substrates using the spin-coating process, as shown in Figure 12h. In the sensing region, a radius of 2 mm of the RuO$_x$ film was defined as the segregating layer by an epoxy resin and transferred onto a printed circuit board (PCB) for further sensing tests, with the nonsensing region of the FET being encapsulated by an epoxy resin to decrease the leakage current. The increment of the hydroxyl ion concentration decreased the accumulation of negative charge on the sensing surface, which simultaneously attracted the positively charged holes and repulsed negatively charged electrons toward the interface. Therefore, the pH-dependent $V_{th}$ behavior of the FET sensor was observed and based on this redox reactions, a super-Nernstian pH response of 65.11 mV pH$^{-1}$ in a wide pH range of 2–12 was achieved with an excellent linearity of 99.8%, as shown in Figure 12i. Based on this mechanism, the authors further used 4-carboxyphenyl boronic acid (4-CPBA) as the transducer surface to form preferential bindings toward glucose. Negative charges by the glucose–boronate ester complex induced a shift of the $V_{th}$. As shown in Figure 12j, consistent and stable signals demonstrated sensitive monitoring of the functionalized FET toward glucose of different concentrations, with a sensitivity of 6.89 mV mM$^{-1}$. The flexible pH and glucose sensor could be used as a reliable supplementary for clinical diagnosis and wearable device fabrication. Representative F-FET sensors for (bio)chemical analytes have been summarized in Table 3.

5.3. Performance Optimization of (Bio)chemical F-FET Sensors

The selectivity and sensitivity toward specific types of (bio)chemical analytes are vital for the performance of chemical sensors or biosensors. Various kinds of methods have been proposed to guarantee the selectivity of (bio)chemical sensors, which can be generally categorized into nonenzymatic mechanism-based and specific receptor-based sensors. Researchers had reported their attempts in increasing the selectivity of sensors, for instance, using the surface doping characteristics between specific cations and semiconductors (Hg$^{2+}$ and p-type OSCs blending with polyostereone).\textsuperscript{[229]} using high-active-facet NPs combined with 1D nanofiber/wires,\textsuperscript{[230,231]} functionalized nanostructured metal oxides as molecular sieving for selective sensing,\textsuperscript{[232]} modifying receptors on the semiconducting layers,\textsuperscript{[233]} designing and developing aptamer-based sensing layers for specific species of
By modifying the receptors on the active semiconductor layers using specific chemical methods, the performance of FET-based biochemical sensors could also be optimized in sensitivity and selectivity. For instance, glucose oxidase (GOx) could be used as the functionalized receptor onto the poly(3,4-ethylenedioxythiophene–poly(styrene-sulfonate) (PEDOT:PSS) layer to enzymatically detect glucose concentration [235] or using conducting hydrogels in the form of self-assembled guanosine (G) and KB(OH)₄ to achieve glucose detection. [236] An increase in $I_{DS}$ was observed when the concentration of glucose increased, due to the redox characteristics of PEDOT:PSS. By tailoring functional interlayers in the FET, the sensor can achieve desired functionalities, especially for the application of label-free, ultra-selective, and sensitive biochemical sensors. By integrating streptavidin (SA) into an FET sensing device between the dielectric layer and P3HT semiconductors, Angoine et al. successfully fabricated a biotin sensor based on the strong binding effect between SA and biotin molecules. The SA-based FET sensor exhibited label-free biotin sensing with high sensitivity and selectivity in detecting biotin of 10 parts per trillion concentration. [237] Although the immobilized receptor modification could significantly increase the selectivity and sensitivity of biochemical sensors, the slow response, low stability, and complicated fabrication process are still the remaining problems to be solved. To address these issues, biological recognition elements were used instead of enzymatic substances. An F-FET sensor based on cucurbit[6]uril (CB[6]) as the receptor was reported to detect acetylcholine (ACh⁻). [218] which provided excellent sensitivity toward the low concentration of 1 pM ACh⁻.

In addition to surface functionalization on the active layers of FETs, sensors’ performance, including sensitivity, selectivity, stability, response time, reusability, etc., can also be modified by integrating suitable materials into the FET structure. Among these features, the reusability is a vital characteristic because sensors are typically used in real-time sensing scenarios. In most cases, the analyte molecules usually permeated into the boundaries of semiconductor grains, into the active layers, or at the interface between the semiconductor and gate dielectric layer. To decrease the response time, researchers have attempted to fabricate thin-film active layers, porous structured semiconducting layers, and so forth to increase the performance of sensors. Moreover, the stability of FET-based sensors toward applications in chemical analyte detection is also an obstacle when being confronted with an aqueous operating environment. Research on the fabrication of highly stable chemical sensors was reported, e.g., by use of passivation layers [242,243] and introducing cross-linking agents [32,244] 1D and 2D materials were also widely used in increasing the sensitivity of (bio)chemical sensors [245,246] such as introducing nanowires and nanotubes into the active layers to form the direct path for charge transport. [247–249]

**Table 3. Flexible FET sensors for chemical and biochemical analyte detection.**

| Semiconductor | Mobility [cm² V⁻¹ s⁻¹] | Target compound | Sensitivity | Detectable range/limit | Flexibility | Additional strategy |
|---------------|-------------------------|-----------------|-------------|------------------------|------------|---------------------|
| Pentacene/TSB3[71] | 6.3 | Methanol vapor | NA | NA | NA | Nanoporous-structured semiconductor |
| ND13HU-DTYM2[72] | NA | NH₃ | NA | 0.1 ppb | NA | Porous monolayer |
| P3HT-azole[73] | 0.32 | Liquid analytes | NA | 1% methanol or ethanol | NA (PEN) | Container molecules |
| Pentacene[74] | 0.014 | DNA | 74 ng cm⁻² | 650 ng ml⁻¹ | NA | NA |
| Graphene[75] | NA | DNA | NA | 1 FM | NA | ssDNA on Au electrodes |
| Graphene-PDM5[76] | NA | DNA | NA | 1 nM | NA | Solution gated |
| InZnO[77] | NA | DX DNA | NA | 50 nM | PI | NA |
| WO₃ NPs[78] | NA | Proton | –56.7 mV/pH | pH 9–5 | PI | NA |
| CNTs[79], [80] | NA | K⁺, Ca²⁺ | NA | 10 nM | 1.35 cm (PI) | Selective compositions |
| RuO₂[81] | NA | Proton | 65.11 mV/pH | pH 2–12 | PI | NA (PET) |
| RuO₂[82] | NA | Glucose | 6.89 mV/mM | 1–8 mM | NA (PET) | 4-CPBA functionalization |

(bio)chemical molecules, and integrating bioenzymes into sensing layers to detect biochemical substances. Reports surrounding the enhancement of FET sensors have been massively put out using surface-functionalized semiconducting materials to increase the device sensitivity and selectivity. A water-stable FET chemical sensor was reported using a polyisodioindio-based polymer functionalized with siloxane-containing solubilizing side chains (PII2T-Si) as the semiconducting layer to selectively sense the Hg²⁺ cations in aqueous solutions. The PII2T-Si based FET sensor exhibited stable operation performances in both ambient conditions and aqueous solutions. With the introduction of DNA-functionalized Au NPs onto the PII2T thin film, the sensor demonstrated precise detection of Hg²⁺ cations even in the environment with contaminants of Zn²⁺ and Pb²⁺. In contrast with FETs that Au NPs were not functionalized with DNA, the reported sensor could achieve a sensing limit of 10 μM, whereas no response was observed in the nonfunctionalized FETs, which indicated that the direct binding between Hg²⁺ cations and DNA molecules was the main mechanism. In detecting liquid-phase chemical analytes, utilization of calix[8]arene (C[8]A) was reported as the functional material onto the semiconducting layer. Due to the functional groups and the cavity structure within the molecules, chemical analytes were able to interact with the C[8]A molecules, leading to enhancement in sensitivity of the FET sensors. The sensitivity of sensors reported here was enhanced, approximately one order of magnitude, compared with the sensor without functionalized C[8]A molecules. Different responses toward polar and nonpolar solvents were observed, with the detecting limit of 1 vol% of methanol, ethanol, etc. in toluene solvent,
6. Strategies toward the Optimization of F-FET Sensors

Currently, explorations in flexible FET sensors have been widely reported, including using different mechanisms for the measurement of external pressure stimuli, modifying surface functionalities of active layers of FETs, and developing new fabrication processes to introduce new structures, e.g., thin films and porous films.[250,251] In this section, strategies toward increasing flexibility and sensing performances are concluded and discussed in respect of material considerations and fabrication procedures.

6.1. Material Development for F-FET Sensors

F-FET sensors are primarily based on functional materials which are mainly organic materials. With respect to FET (bio)chemical sensors, the poor resistance toward organic solvents limits its performance. Challenges still exist in sensing chemical analytes in the liquid-phase operating environment. By introducing specific types of organic functional materials, the environmental and operational stabilities of FET sensors can be significantly enhanced, which has accordingly expanded the application range of these sensors.[252]

Polymer semiconductors, with intrinsic soft nature, are promising materials for fabricating F-FETs and these FET devices have demonstrated much lower modulus than that fabricated using inorganic substrates.[253,254] In addition to the soft features, polymer semiconductors also demonstrated acceptable carrier mobility and solution processable characteristics,[255] which made them promising candidates in FET devices. However, the polymer semiconductors usually demonstrated unsatisfied electrical performance because of the semicrystalline characteristics.[256]

In addition to the semicrystalline structures, monomers in the polymers determine the bulk mechanical characteristics of one material. To increase deformability, a high-flexible-linear side chain material oligo (ethylene oxide) was investigated. The low-bandgap conjugated polymer's side chain materials demonstrated excellent mechanical properties and acceptable electronic performances.[257,258]

In addition to the utilization of polymers with side chains in molecular structures, copolymers, which enable the combination of different functional monomers, drew the attention of researchers for performance optimizations. By integrating biodegradable materials into the block of stretchable semiconducting materials, researchers have fabricated FET sensors with optimized detecting performances.[259] Rigid semiconductor conjugated segments based on diketopyrrolopyrrole (DPP) flanked by the furan ring were fabricated into stretchable poly (a-caprolactone) insulators. At over 100% strain loading, the FETs based on this copolymer could still demonstrate excellent field-effect mobility when flexible compounds accounted up to 90 wt% in the copolymers. Utilization of copolymer materials was an operable approach to regulate the electrical performances. Ji et al.[260] reported their preparation of poly (amic acid)-based random copolymers using a low-temperature treatment method to control the imidization process. The dielectric layer using this random copolymer demonstrated soft and robust characteristics. With the high-density packed phenyl rings and alicyclic rings, insulating properties of the dielectric layer significantly increased. Moreover, the polar functional groups, such as carboxyl (−COOH) and amide groups (−CO−NH−), benefitted the molecular packing of semiconductors and carrier transportation at the interface between dielectric and semiconducting layers. The stable mechanical properties of FET devices using this random copolymer were also reported, with only 10% performance degradation under 5 mm bending radius for 1000 times bending test.

Small molecules are another type of flexible substance used in fabricating flexible sensors.[261] By molecular modifications, small-molecule materials can present an acceptor–donor–acceptor characteristic, which has demonstrated promising application potentials on fabricating flexible electronic devices. Kim et al.[262] reported their fabrication of flexible ambipolar FETs using different electron-accepting functional groups (dicyanovinyl, cyanorhodanine, and cyanoidanone, INCN) to modify oligothiophene–phenylene molecules. The extended π-conjugation via the INCN moiety enhanced the intermolecular cofacial π-π stacking and generated a sufficient carrier pathway in the transistor channel. Using this material, mechanical durable FETs were successfully fabricated based on PET. Furthermore, semiconducting layers with dense molecular packings were fabricated using small molecules, such as 5,5-bis-(7-dodecyl-9H-fluoren-2-yl)-2,2’-bithiophene (DDFTTF) with hydrophobic long dodecyl alkyl chains onto the conjugated backbones. FET sensors based on this material had demonstrated aqueous stable electronic devices.[238,263]

6.2. Structure Modification and Material Fabrication

Apart from using chemical approaches to modify molecular structures of the active materials, introducing additional substances into FET structures and altering the structure design are also operable approaches to enhance sensing performances of the FET-based sensors.

Cross-linking of semiconductor molecules through physical or chemical process is a viable approach for enhancement of sensor performance. As a photo-initiated cross-linking agent, azide functional groups were used to fabricate robust semiconductor layers. Using cross-linked semiconductors, the chemical FET sensors demonstrated excellent chemical-resistive characteristics,[264] hence becoming applicable to liquid-phase sensing.[12]

To enhance the performance of FET sensors, researchers integrated nanowires into the active layers of FETs. Due to the high surface-to-volume ratio and robust nature of 1D nanowires, sensors with 1D materials demonstrated modified electric performances and excellent sensing behaviors.[265] Serpentine-like structured nanowires were fabricated and used as semiconducting materials in the F-FET. Polymer semiconductors were prepared in the nanowire form based on fused thiophene diketopyrrolopyrrole, which were bound by high-molecular-weight polyethylene oxide as the deformability enhancer.[266] With this novel structure design, the FETs exhibited excellent stretchability when attached to a volume-varied balloon and negligible electronic performance degradations.
The application of thin films in a flexible FET was another representative method to increase the flexibility of FET-based sensors. However, decreasing the film thickness usually leads to the decrease in electric performances such as the insulating properties of the dielectric layers. In applying thin-film structures in the flexible FETs, the commonly used methods were based on CVD or using self-assembled monolayer (SAM). By the CVD method, the thickness of poly(1,3,5-trimethyl-1,3,5-trivinyl cyclotrisiloxane) (pV3D3) film was achieved to 6–7 nm, which generated a reasonable capacitance for the low operating voltages. \[267\] The integration of organic and inorganic materials using CVD could further enhance the dielectric constant of thin-film layers. Using 2-hydroxyethyl methacrylate and trimethylaluminum as the monomer, stable AlO\(_x\)-grafted ploy(2hydroxyethyl methacrylate) dielectric layers were fabricated using one-step-initiated CVD. The FET based on the reported thin-film dielectric layers demonstrated better electrical performance while showed similar flexibility in comparison with the single pV3D3 film FETs. \[268\] In addition to fabricating thin-film layers for FETs, the SAM method is also a good strategy to add various functional groups to the molecules of the thin-film layers, which endows additional functionalities. By introducing a SAM-modified dielectric layer, Yokota et al. \[269\] fabricated a thermal stable FET on PI substrates, which was able to operate even at 250 °C. The n-tetradecylphosphonic acid was assembled onto a 4 nm Al\(_2\)O\(_3\) dielectric layer and the operation voltage was decreased to 2 V with this method.

In contrast with (bio)chemical FET sensors, temperature and pressure sensors based on FETs do not directly detect the stimuli from semiconductors. Detecting capacitance changes, resistance changes, piezo effects, or thermoelectric phenomena are the primary mechanisms for these sensors. Therefore, the development of structural design \[42,46,106,113\] and introducing functional materials into the FET structures \[60,114,270\] are viable approaches to fabricate FET sensors with simple structures and better sensing performance. The continuing development in functional materials will be able to provide fundamental knowledge and exciting ideas for fabricating flexible sensors with high qualities.

7. Conclusions and Outlooks

Here, we have reviewed recent progresses that have been made on F-FETs in the field of flexible sensing devices and they have shown great potential in various applications. Flexible electronics have been widely studied due to the variety of possible materials, novel structural designs, and different sensing mechanisms. The flourishing stage that flexible FETs stand at shows us a bright future of the possibility of the IoT era and brings us to a simplified and intelligent life in the future.

In the FET-based sensors, the OSC layer which directly comes in contact with external stimuli can both generate and amplify the sensing signals without further assistance from other devices. Due to the amplification inherent in the transistor, sensitivity of the FET-based sensors could be significantly increased in comparison with other types of sensors. To increase the flexibility and conformability, proper flexible materials should be carefully selected and engineered along with the material and device development. Using flexible materials, which are usually organic types, FET-based sensors are becoming potential candidates for fabricating flexible sensors for detecting external stimuli and specific types of (bio)chemical analytes. Diverse strategies have been used to increase the flexibility and conformability, such as adopting copolymers structures, integrating elastomers or nanowires, and introducing cross-linking methods. The rational design of material engineering and molecular structure in fabricating FET sensors guarantee the flexibility and durability of FETs under different kinds of mechanical deformations. Moreover, chemical and material approaches used in FET fabrication could introduce the desired sensing performance and guarantee electrical performances at the same time.

Due to its layer-by-layer structure, various functional materials can be integrated into the FET to achieve different sensing functionalities, such as (bio)chemical, pressure, temperature-sensing, etc. The performances of F-FET-based sensors have been greatly improved by introducing feasible materials and additional functional substances into the active layers, using different sensing mechanisms and using different structural designs. Although exciting progress has been achieved, most of the results remain in the laboratory stage. Noninvasive sensors require to be investigated for multifunctional applications. To exploit applicable wearable sensing devices for actual utilization, sensors with multifunctions require further study, such as achieving the detection of different chemical analytes in the one-step operation. Moreover, mechanical deformation also remains a problem for the stability of sensing devices as these devices have to be wearable. Researchers have decoupled the signals from sensors under different deformation conditions using rational logic circuits and algorithms to decrease the sensing errors induced by unexpected external stimuli. By integrating different sensing units, it is achievable to fabricate a multifunctional sensing system, which is another promising approach to reduce background noises or transform interferences into useful signals. Furthermore, the development of material science is vital for the flourishing of sensing devices. The utilization of new and feasible materials in the wearable sensors is one of the most used methods to solve the remaining problems and this requires the development of chemistry and material science. The mechanical durability of flexible devices is another problem remaining to be solved. A conformal interface is vital for generating the chemical interface, which could guarantee the mechanical stability of layer-by-layer structured FET sensors, for instance, using (3-aminopropyl)triethoxysilane (APTES) surface treatment to form strong siloxane bonds (Si–O–Si). As the molecular structure plays a role in determining the mechanical properties of a film, the selection of substrate materials and processing conditions of different layers significantly influences the mechanical properties of flexible electronic devices, for example, affecting ordering and degree of crystallinity of a thin film. The bulk mechanical durability of F-FET sensors also requires the development of material science and delicate fabrication technology. Finally, the development of low-power voltage sensors and self-powered systems will significantly promote the practical application of F-FET sensors.
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Conflict of Interest
The authors declare no conflict of interest.

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Ming-Zheng Li is a postdoctoral researcher at Shenzhen University. He received his Ph.D. in mechanical engineering from University of Liverpool and Dalian University of Technology. His research interests include organic/inorganic material nanodevices, sustainable manufacturing, and environmental cleaning.
Su-Ting Han is an associate professor at Shenzhen University and a visiting associate professor at The University of Michigan. She received her M.Sc. in analytical chemistry from Hong Kong Baptist University and her Ph.D. in physics and materials science from City University of Hong Kong. Her research interests include functional electronic devices and flexible, stretchable, and wearable electronics.

Ye Zhou is an IAS Fellow and group leader in the Institute for Advanced Study, Shenzhen University. His research interests include flexible and printed electronics, organic/inorganic semiconductors, surface and interface physics, nanostructured materials, and nanoscale devices for technological applications, such as logic circuits, data storage, energy harvesting, photonics, and sensors.