Ion-Gated Transistor: An Enabler for Sensing and Computing Integration

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With the rapid development of the Internet of Things, the amount of data we involved in our daily life is growing exponentially, which poses significant challenges for data processing and transmission to the conventional terminal sensors that passively acquire external data. Inspired by biological sensory nervous systems, building artificial intelligent sensory systems with both sensing and computing capability is regarded as a promising way to address these challenges, by which the acquired data can be preprocessed locally and timely before transmitting them to the remote server for further processing. Ion-gated transistors (IGTs), which have been widely used in sensors and have been recently investigated for neuromorphic computing, exhibit great potential in this domain. Herein, the essential operation principles, device structures, and electrical characteristics of IGT are introduced, and the recent developments in biosensors, neuromorphic computing, and intelligent sensors with near-sensor computing and in-sensor computing modes are summarized. To conclude, the current challenges and future development of IGT for intelligent sensory systems are presented.

1. Introduction

Driven by the rapid development of the Internet of Things, the demands for intelligent life, including remote medical treatment, automatic drive, digital manufacture, robotics, and so on, are generated increasingly, resulting in explosive growth of data. Sensors, as terminals of the Internet of Things, play an indispensable role in the acquisition of external data, by which some intelligent tasks such as inference, learning, and decision-making can be fulfilled. With the advances of science and technology, although the sensitivity, device size, and detection mode of sensors have been improved greatly, the way to respond to external changes is mainly in a passive mode, that is, gathering a large amount of redundant data and then transmitting them to the remote computing platforms such as cloud server for further processing.

With the complexity of intelligent tasks increasing, however, the passive mode incurs excess time delay and energy consumption for data transmission and processing, and ultimately drags down the time and energy efficiency of the sensory system. One of the effective ways to address these issues is to develop intelligent sensory systems with edge computing capability by which the analysis and processing of the gathered data can be accomplished locally at the terminals.

The biological sensory nervous system can be regarded as the most intelligent system in nature, which has high-efficient information perception, processing, and decision-making capabilities. Neuroscientific research has shown that neurons are the basic units of the biological neural network. It mainly consists of three parts: dendrite, soma, and axon (Figure 1). In general, the receptors locating at the dendrites are responsible for acquisition of external information, and the acquired information gathers in soma and then transmitted through axon to the synapse where the neuron connects with the other neurons. Next, this information is stored and processed by changing the connection strength of the synapses, i.e., synaptic weight, and then the processed information is transmitted to the brain for further decision-making. The changes of synaptic weight, called synaptic plasticity, underlie the memory and learning of neural networks. Using the plasticity of synapses, the neural networks of biosensory system can be trained adaptively in response to environmental changes to improve the speed and accuracy of sensory information processing. Therefore, biosensory systems can be regarded as an integration of sensing, storage, and processing in one system with real time, adaptability, and low energy consumption (1–100 fJ per synaptic event). Given the excellent characteristics of the biosensory system, traditional electronic devices, such as static random-access memory (SRAM), FLASH, and digital/analog circuits, have been...
used to simulate the function of synapses and neurons, and then constructed artificial neural networks (ANNs). By combining ANN with sensors, intelligent sensory systems can be formed. Nowadays, there is still a huge gap between the current intelligent sensory system and the biological neural network in terms of energy consumption, real-time response, and adaptability. For example, SRAM is volatile memory and cannot remember the trained data in power-off condition. Moreover, multiple devices are required to achieve a simple synaptic function, which unavoidably increases the device area, circuit complexity, and energy consumption of the system. FLASH is nonvolatile but suffers from the high operating voltage and limited endurance. Recently, a wide variety of memristive devices such as phase change memory (PCM), resistive random-access memory (RRAM), and ion-gated transistors (IGTs) have been widely investigated as neurons and synapses. These emerging devices show excellent properties due to their analog switching performance and biodynamic similarity. Compared with two-terminal memristive devices such as RRAM and PCM, three-terminal IGTs provide decoupled write/read operations, where the gate terminal is used for channel conductance modulation and source/drain terminals for readout. Such a decoupling improves not only the precision of synaptic weights and programming energy but also the symmetry and linearity of weight update, both of which are critical to computing accuracy of neural network. More intriguingly, IGTs have been widely used in the field of sensors due to their high signal amplification capability and simple device structure. Therefore, it provides a platform to achieve intelligent sensors, where sensing and computing are performed simultaneously in the same device.

In this review, we start from the basic mechanism of IGTs to their applications in sensors and neuromorphic computing, and then to the development of intelligent sensors that combine neuromorphic computing functionality with sensors. Section 2 gives the basic knowledge about IGTs, including the basic operating mechanism, typical device structures, and electrical characteristics. Section 3 gives the application of IGTs as sensors for the detection of biophysical and biochemical signals. Section 4 gives the application of IGTs in neuromorphic computing. Section 5 gives the current research status of intelligent sensors with near-sensor and in-sensor computing modes. Section 6 outlooks the future development and application of IGTs in intelligent sensor systems.

2. Ion-Gated Transistors

2.1. Operation Mechanisms

IGTs have similar structure and voltage bias mode as the traditional metal–oxide–semiconductor field-effect transistors (MOSFETs), as shown in Figure 2a. Unlike traditional MOSFETs in which an insulating gate dielectric is used, IGTs use an electrolyte, which is electron insulating and ion conductive, as the gate dielectric. The difference in the type of gate dielectric materials makes IGTs have different working mechanisms from MOSFETs. MOSFETs work based on gate electric field, which is coupled to semiconductor channel, resulting in electrostatic doping of carriers in the semiconductor channels. This is a pure capacitive charging process and involves only the movement of electrons. In fact, IGTs are developed on the basis of traditional MOSFETs. Similar to the functions of traditional MOSFETs, the channel current of IGTs is also controlled by the gate voltage with the difference that the movement of ions in the electrolyte would take place at a certain gate voltage.

According to the type of channel materials, including impermeable and permeable channel materials, IGTs have two working mechanisms: electrostatic and electrochemical carrier doping mechanisms. Figure 2b shows the schematic of the structure of an IGT where an impermeable channel is used. It can be seen that, when a positive voltage is applied to the gate, the positive and negative ions in the electrolyte move toward the channel and the gate, respectively. As the channel material is impermeable, the positive electrolyte ions accumulate at the electrolyte side around the electrolyte/channel interface. And then, the accumulated ions induce charges with opposite
When the system reaches equilibrium state, the gate voltage drops mainly on the two EDLs.[25] Because of the existence of EDLs, IGTs based on impermeable channels are generally referred to as electric double-layer transistors (EDLTs).[30] As there are usually two EDLs in one EDLT and they are connected in series, to obtain stronger gate control capability, one of effective ways is to enlarge the electrolyte/gate interface capacitance (i.e., by optimizing the gate area) to ensure more gate voltage drop on the channel.[25]

Figure 2c shows another working mechanism of IGTs, in which permeable channels are used. When a positive voltage is applied to the gate, positive ions in the electrolyte migrate toward the channel. As the channel material is permeable, the injection of electrolyte ions occurs when the applied gate voltage is large enough.[32–35] To compensate for the charges caused by the ion injection, equal amount of carrier charges with opposite polarity are injected into the channel through external circuit. As the ion injection usually involves the redox reaction in the channel material, it is referred to as electrochemical doping mechanism. On the contrary, the negative ions in the electrolyte migrate toward the gate. According to the permeability of gate material, they can either accumulate at the electrolyte/gate interface to form EDL, or undergo electrochemical redox reactions with the gate. The former corresponds to a polarizable gate and the latter a nonpolarizable gate.[25,36–41] Usually, under the condition of the same electrolyte/gate area, a nonpolarizable gate has a much larger capacitance than a polarizable gate.

Therefore, in IGTs with permeable channel, the use of a nonpolarizable gate tends to cause more gate voltage drop on the channel, resulting in better gate controllability.[17] Of course, even in the case of polarizable gates, a better gate controllability can be obtained by increasing the area of the electrolyte/gate interface. IGTs based on electrochemical doping are also called electrochemical transistors (ECTs).[41] As organic materials are good candidate materials as permeable channels due to their easy ion injection properties, organic electrochemical transistors (OECTs) as main branch of IGTs have been widely studied.[20,42–44]

With regard to the location where the channel conductance modulation takes place, electrochemical doping is a volume doping mechanism, and electrostatic carrier doping caused by the formation of EDL is a surface doping mechanism. As shown in Figure 2d, Rivnay et al. found that in the IGTs they prepared, the channel capacitance increased proportionally to the increase in the channel volume (i.e., channel thickness when the channel length and width are kept constant).[20] The plausible explanation for this phenomenon is that the electrolyte ions have penetrated into the channel, inducing a volume-effect characteristic of the channel capacitance. Due to the limited penetration depth in the channel, the penetration works only within a certain thickness range of the channels. In contrast, the capacitance of the impermeable channel shows no dependence on the channel thickness.

Another way to distinguish between volume capacitance and surface capacitance is to measure the relationship between capacitance and the applied voltage. Shang et al. have studied the capacitance–voltage curves under different frequency conditions,[81] as shown in Figure 2e. Under 2 kHz frequency, the capacitance of IGTs increased with the voltage bias. As the capacitance of EDL is independent of the voltage, they attribute the increasing part of the capacitance with the applied voltage to the pseudocapacitance caused by Li-ion electrochemical doping. With the increase in voltage, the pseudocapacitance increases with the amount of injected Li-ions, indicating that the electrostatic and electrochemical doping mechanism are dominant in

Figure 2. The operation mechanisms of IGTs. a) Schematic of the structure of IGTs. b) Electrostatic doping mechanism in which channel materials do not allow electrolyte ions to penetrate. The red line represents the potential profile. c) Electrochemical doping mechanism in which channel materials allow electrolyte ions to penetrate. Here, a polarizable gate is adopted. Nonpolarizable gates have larger capacitance than polarizable gates and thereby have a stronger adjustability. d) In electrochemical doping mechanism, channel capacitance is proportional to the thickness of channel, which can be used to distinguish from electrostatic doping mechanism where the channel capacitance is volume (i.e., thickness) independent. Reproduced with permission.[20] Copyright 2015, American Association for the Advancement of Science. e) Capacitance–gate voltage curve under different frequencies. The electrostatic and electrochemical doping mechanisms can exist in the same device, with the former and latter being dominant in the low and high voltage domain, respectively. Reproduced with permission.[31] Copyright 2018, John Wiley and Sons.
the low and high voltage range, respectively.\cite{21,38} In general, there is an energy barrier at channel/electrolyte interface to block the electrolyte ions inserting into the channel. Thus, a relatively large gate voltage is required. For some organic channel materials and electrolytes (such as PEDOT:PSS and aqueous KCl electrolyte), it has been demonstrated that the ions that have been inserted into the channel can be almost completely extracted from the channel without a reverse voltage.\cite{49}

As for the electrochemical doping, the specific intercalation and deintercalation process of electrolyte ions inside the channel material are related to both the electrolytes and the channel materials. For the interfaces between the liquid electrolytes and the solid channels, if the difference in the radius between the movable anions and cations in electrolyte is little, in general, they can both be injected into the channels even under one polarity of the gate voltage.\cite{46,47} bringing difficulties to the analysis of the working mechanism. In addition, in various aqueous solutions, as the electrolyte ions usually exist in the form of solvated ions, the solvent molecules could be inserted into the channel material together with the electrolyte ions.\cite{32} For solid electrolytes, they usually could only conduct one kind of ions that have a relatively small ion radius such as Li\(^{+}\), Na\(^{+}\), H\(^{+}\), O\(^{2-}\), and so on.\cite{41,48} In fact, there is no ideal electron-blocking and ion-conducting solid electrolyte.\cite{48} Although IGTs work based on the ion movement, the movement of electrons in the solid electrolyte cannot be avoided when a gate voltage is applied.

Although the electrostatic and electrochemical doping have been widely studied, a comprehensive understanding about the charge transfer at the electrolyte/channel interface and the diffusion inside the channel materials is still required. Note that the expansion and contraction of channel materials might occur with the injection and extraction of electrolyte ions, leading to structural changes and in turn deterioration of the device performance.\cite{32,45} Moreover, the channel materials are usually electron–ion mixed conductors. The ion–electron coupling process and the movement of ions in the direction parallel to the electrolyte/channel interface in the channel have not been well understood so far.\cite{35,41}

### 2.2. Device Structures

IGTs have a variety of structures in practical application. They can be roughly divided into two categories, planar and vertical structure. Planar structure can be further subdivided into co-plane and lateral thin-film transistor (TFT) structure. Figure 3a is a schematic diagram of a co-plane structure, which is characterized by the source, drain, and gate electrodes being in the same plane.\cite{52} The co-plane structure is appropriate to liquid or gel-like electrolytes, which are hard to be prepared by traditionally physical thin film deposition and to prepare gate electrode on them.\cite{24,52} To fabricate co-plane structure, the source, drain, and gate electrodes are usually deposited on the substrate simultaneously, and then the electrolyte is deposited on them by spin-coating or drop-casting techniques. Such structure is often used to explore some novel physical properties of materials,\cite{52–55} based on electrostatic or electrochemical doping mechanism.\cite{52–57} This structure is also popular for sensors that do not have special requirements on device miniaturization. It is required to expose the active area of the device, i.e., the channel part of IGTs, to environment instead.\cite{18} In addition, due to the simplicity of this structure and ease fabrication, some prototype devices for emerging applications, such as neuromorphic computing, are often investigated based on this structure.\cite{49,58–61}

Another type of planar structure of IGTs is similar to the structure of lateral TFTs, as shown in Figure 3b.\cite{50} According to the relative positions of the source, drain, and gate electrodes, the lateral TFT structure of IGTs can also be subdivided into four structures, namely, top-gate top contact, top-gate bottom contact, bottom-gate top contact, and bottom-gate bottom contact.\cite{62,63} Compared with the co-plane structure, due to the higher process maturity, the lateral TFT structure can be integrated into arrays. However, there have been few reports on the large-scale IGT

![Figure 3. Three typical structures of IGTs.](image)

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**Figure 3.** Three typical structures of IGTs. a) Co-plane structure and d) a typical device example where α-MoO\(_3\), ionic liquid, and Au are adopted as channel, electrolyte, and electrodes, respectively. Reproduced with permission.\cite{49} Copyright 2017, John Wiley & Sons. b) Lateral TFT structure and e) a typical device example where Nb\(_2\)O\(_5\), Li\(_2\)SiO\(_3\), and Cr/Au are used as channel, electrolyte, and gate electrode, respectively.\cite{50} c) Vertical structure and f) a typical device example where organic semiconductor solution (OSC, diketopyrrolopyrrole–tertiophene donor–acceptor polymer), ionic liquid and Au are adopted as channel, electrolyte, and source/drain electrode, respectively. Reproduced with permission.\cite{51} Copyright 2019, Springer Nature.
array so far. Moreover, the power consumption and operating speed of IGTs are still required to be improved further. One possible way is to scale down the device dimensions, especially reduce the channel length. Compared with the planar structures of the IGT, vertical structure shows great advantage to address these issues.

Vertical field-effect transistors (vFETs) have been developed to improve saturation current and switching frequency.\[^{64–66}\] A larger saturation current means that a smaller operating voltage can be obtained under the same current, which is highly useful in reducing power consumption. It is reasonable to believe that vertical structure would be in favor of the power consumption and switching speed of IGTs as well.\[^{65,66}\] Figure 3c shows a schematic of IGT with vertical structures. By skillfully converting the channel thickness into the channel length, IGTs with ultrashort channels can be achieved because the thickness of the channel film can be easily and accurately controlled at the nanoscale. It should be pointed out that vertical structures might bring some adverse problems such as short channel effects and the reduction of switching frequency due to the source/drain overlap.\[^{66}\] Similar problems should also be possible in IGTs with vertical structure.

2.3. Electrical Characteristics

IGTs are developed on the basis of the traditional MOSFET, with its original purpose being used as a switch in analog and digital circuits.\[^{22}\] Here, based on their specific electrical characteristics, we mainly focus on its two important applications, namely, sensors and neuromorphic computing.\[^{15,18}\] Due to the ion movement mechanism, IGTs have huge channel capacitance and thereby large transconductance compared with conventional transistors, making them very suitable for the amplification of small signals (Figure 4a).\[^{18,20}\] The channel current of IGTs will change dramatically even under a small change of gate voltage. This feature enables IGTs to be used as sensors with high sensitivity. Usually, to obtain strong selectivity, the surface of the channel or gate is often coated with a specific material that is only sensitive to the target materials.\[^{18}\] When adding the target material to the electrolyte, the target material changes the value of the voltage applied to the channel by reacting with the sensitive material, and then changes the current through the channel. As the concentration of the target material changes, the channel current of the device will also change in a step-like manner, as shown in Figure 4b. Due to the slower dynamics of ions, IGTs generally have hysteretic characteristics in their transfer curves compared with conventional transistors based on electrons, as shown in Figure 4c. The hysteresis phenomenon is more obvious in ECTs owing to the fact that the injected electrolyte ions can stably stay in the channel until a relatively high reverse voltage is applied to extract them out of the channel.\[^{21}\] When the gate voltage is applied in the form of electric pulses, each pulse injects a certain amount of ions into the channel, inducing extra carriers in the channel and then a gradual increase in the channel conductance with the number of pulses (Figure 4d).\[^{67,68}\] Based on these unique properties, various applications of IGTs have been explored, including neuromorphic computing,\[^{11,69}\] chemical and physical sensors,\[^{70–72}\] neural interfaces,\[^{72}\] artificial sensing,\[^{73–79}\] printed circuits,\[^{25}\] electronic skins,\[^{80}\] and human–machine interactions.\[^{77}\]

3. Biosensor Application

Biosensor is an analytical device for physicochemical detection. Through material selection and structure optimization, IGTs can quantitatively convert physicochemical signals into the easily detectable electrical signals, achieving direct sensing to the change in external environment or life entity.\[^{78,79,79–82}\] According to the difference of signals, the IGT-based biosensors can be divided into two categories. One category is used for the detection of biophysical signals, such as light, cardiac rhythm, and brain activity, and the other category is used for the detection of biochemical species, such as glucose, cell receptors, enzymes, antibodies, nucleic acids, and so on. Both biosensors are closely related to our daily life and play an important role in biomedical domain, as they offer advantages over standard analytical methods in sample preparation, handling, and real-time detection.

3.1. Biophysical Detection

Human body is a complex and well-designed information highway composed by cells, tissues, and fluids. Measuring the electrical activity of organs, tissues or even single cell is favorable for checking its integrity and understanding its function.\[^{91}\] IGTs as powerful sensors allow researchers to detect these signals in a simpler way.\[^{78}\] Khodagholy et al. developed an enhancement-mode biosensor based on IGTs.\[^{94}\] Figure 5a shows the structure and application scenario of this IGT. The IGT is used to acquire a wide range of electrophysiological signals, such as electrocardiography (ECG), electromyography (EMG), local field potential (LFP), and action potential (AP). A soft, biocompatible, long-term implantable neural processing unit for the real-time detection of
epileptic discharges is created. Interestingly, the IGT device works well on the entire electrophysiological frequency spectrum (0.1–10⁴ Hz) and provides appropriate signal-to-noise ratio (SNR) for each signal’s amplitude (Figure 5b). The IGT can serve as a reliable component for bioelectronics to promote the development of health and fitness monitoring.

To evaluate in vivo physiological functions, ultraflexible, multielectrode arrays (MEAs) were recently fabricated to establish conformal contact on the surfaces of organs to measure electrophysiological signal propagation with high spatial–temporal resolution. However, MEAs are often prepared by opaque materials, limiting their use in applications related to optical observation and optical stimuli localization. Lee et al. prepared an ultraflexible and active MEAs, which consist of transparent IGTs and Au grid wirings. The MEA could address the limit of optical observation and light stimulation in the process of use. The device is placed on the cortical surface of an optogenetic rat (Figure 5c). Through mapping of activation potentials, it can locate the light stimulation point (Figure 5d). Later, Lee et al. also developed another MEAs, which allowed long-term ECG monitoring in the beating hearts of rats, even with capillary bleeding. Due to high conformability of the grid structure, artifact noise caused by dynamic moving was removed in the recorded data. IGT-based MEAs sensors can not only locate the stimulation sites but also map the distribution of the physical signals triggered by the stimuli in the adhesion regions of the array structures, which is of great significance in elucidating the physiological functions of biological tissues.

The development of a technique that enables estimation of the electrical status of the heart in a noninvasive way may decrease the pain of patient and reduce the burden on patients. Hyunjae et al. developed an ultrathin IGT sensor that uses the nonvolatile and thin glycerol gel as an electrolyte (Figure 5e). It can measure biological signals even under dry skin conditions. Figure 5f shows the ECG data continuously monitored by the sensor for 8 days. The stable and low SNR indicates that the IGT-based sensors have strong practicability.

Measuring in situ real-time biophysical signals is very important to observe and understand time-dependent transient events during cell culture process. The cardiac action potential exhibits
a brief change in voltage (i.e., membrane potential) across the cell membrane because of the movement of charged ions between inside and outside of the cell through ion channels. By using 16-channel IGT-based biosensor, Gu et al. successfully detected the action potentials of neonatal Sprague–Dawley rat cardiomyocytes and mapped their propagation in real time. The device structure is shown in Figure 5g. Cardiomyocytes were cultured directly on fibrin-coated IGT arrays. After 24 h of incubation, cardiomyocytes began to adhere to the array surface. Action potentials were triggered by pacemaker cells. Subsequently, the adjacent cells were triggered by current, resulting in the action potential propagation along the cell adjacent to the stimulus site. The propagation of action potentials was recorded in real time and mapped simultaneously, as shown in Figure 5h.

3.2. Biochemical Detection

IGTs, especially OECTs in most of the case, detect the target biochemical substances mainly through two mechanisms. One is based on the transfer of ions in liquid or gaseous atmosphere into the channel films, changing doping states and accordingly the conductivity of channel. The gate material is also crucial to the sensitivity of IGTs. The main challenge, however, is to create a selective biosensor that is only sensitive to a specific substance, such as glucose, because channel conductance of IGTs may also be altered by other biochemical substances. The other is based on the assistance of enzyme. Enzymes are protein molecules that act as biological catalysts. They can bind/ react with specific substances and are regarded as excellent bioreceptors. By changing the kinds of enzyme, the biosensors can be used to monitor various specific substances. The combination of IGT and enzyme increases both the selectivity and sensitivity.

Prevention and monitoring of human health are the main applications of biochemical sensors. IGTs provide an effective platform for ultrafast and ultrasensitive detection of metabolites. One of the urgent requirements is to develop effective diagnostic tests to detect high-risk drinking behavior and alcohol-induced tissue damage. Figure 6a,b shows the first alcohol sensor made by an OECT integrated with the enzyme alcohol dehydrogenase (ADH) and its cofactor. It was fabricated on an inexpensive, disposable, and biodegradable paper support by using printing techniques. The OECT is made by the conductive polymer poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS). ADH and its cofactor nicotinamide adenine dinucleotide (NAD\(^+\)) are immobilized on IGT using an electrolyte gel. The detection of alcohol is achieved by monitoring source–drain current. When the sensor is exposed to exhaled vapor containing ethanol, the enzymatic reaction between ADH and ethanol converts NAD\(^+\) to nicotinamide adenine dinucleotide (NADH), resulting in marked decrease in source–drain current, as shown in Figure 6c. This work can facilitate the development of eco-friendly, breathalyzer for real-time human alcohol content monitoring.

Another urgent requirement is monitoring glucose in blood for diabetic patients. The conventional method by taking blood samples is uncomfortable. Zhang et al. developed a highly sensitive, flexible, and affordable biological sensor based on IGTs. It can detect glucose levels in a noninvasive way (Figure 6d). Both the channel and gate of the IGT are made by graphene grown by chemical vapor deposition. The sensing mechanism is attributed to the H\(_2\)O\(_2\) produced by glucose oxidation near the gate. As shown in Figure 6e, the graphene gate electrodes are modified with the enzyme glucose oxidase (GOx). Pt nanoparticles (PtNPs), and biocompatible polymers (including chitosan [CHIT], Nafion). It can catalyze the oxidation of glucose in a solution. The enzymatically produced H\(_2\)O\(_2\) will be oxidized, which will change the potential drop on the gate electrode, and thus change the channel current. For different glucose concentration levels, the corresponding gate voltage and channel current can be read out from the transfer curve. Therefore, they use effective gate voltage changes (\(\Delta V_{GSET}\)) as a function of glucose concentration (Figure 6f). The glucose sensor shows a detection limit of as low as 0.5 \(\mu\)M, showing great potential for noninvasive glucose detection in human body fluids. Human sweat is the rich and easily accessible source for sensing biochemical information of patient.

By monitoring the ion concentrations in sweat, a wealth of health information such as dehydration and fatigue can be acquired. Recently, wearable sweat sensing device has attracted considerable attention because it provides a convenient and fast way to be accessed on virtually any region of the body. Keene et al. developed a wearable sweat sensor based on ion-selective OECT for multiplexed detecting of NH\(_4\)\(^+\) and Ca\(^{2+}\) in sweat. (Figure 6g).\(^{[102]}\) The OECTs are fabricated on highly stretchable and flexible styrene–ethylene–butylene–styrene (SEBS) where PEDOT:PSS is used as channel layers. And then it is covered with a laser-patterned microcapillary sweat acquisition layer to collect sample and protect the IGT surface. An ion-selective membrane between the OECT and the sweat acquisition layer is used to filter nondetected ions. After ions passing through the membrane, they can penetrate into the channel, resulting in channel conductance change. Thus, the evolution of NH\(_4\)\(^+\) and Ca\(^{2+}\) concentrations during physical exercise can be measured by monitoring the channel conductance. The measured results show good consistency with those determined by analytical standard ion-selective electrodes (Figure 6h,i).

In general, the attractive advantages of IGT-based biosensors are easy fabrication, good flexibility, and high biocompatibility. However, they still have deficiencies which are needed to be improved further. The comparison of the performance between IGT-based biosensors and commercial biosensors is shown in Table 1.

4. Neuromorphic Computing

Inspired by the high energy efficiency, high parallelism, and in-memory computing of the brain in processing information, building a computing system with brain-like computing paradigm, called neuromorphic computing, has received broad attention from both science and engineering fields. In biological brains, neuron is the basic unit, each connecting to other ones through synapses to form a huge neural network. The information is stored and processed simultaneously through tuning synaptic weight, which is defined as the strength of connection between two neighboring neurons. The tunable
The feature of synapse, called synaptic plasticity, provides an optimal way to emulate the brain functions on the level of hardware through developing artificial synaptic devices. Given the feature of flexible operation for tuning the channel conductance, IGTs are favorable for artificial synaptic devices and thereby being used for neuromorphic computing.
IGTs based on electrostatic doping mechanism, that is, EDLTs, have been first used to emulate artificial synapses.[154–158] Based on a proton-conductor solid electrolyte and an indium zinc oxide channel, Zhu et al. constructed a laterally coupled IGT with co-plane structure.[158] The volatility of EDLTs in the transistors is used to comprehensively emulate the short-term plasticity of synapses, including pair pulse facilitation, dynamic filtering, and spatiotemporal information processing. Using the characteristics of the co-plane structure which can be easily used to build multi-gate and multichannel devices, a small IGT array has been fabricated, demonstrating the potential in building neural networks. Recently, in addition to electrostatic doping mechanism, the electrochemical doping mechanism has attracted intensive attention due to its nonvolatile characteristics which can be used to emulate long-term plasticity of synapses. Burg et al. reported an electrochemical neuromorphic organic transistor with inexpensive and commercially available plastic materials that behaves as an artificial synapse.[69] A large number of nonvolatile and reproducible states (>500) were achieved with ultralow operating voltage. However, the devices suffer from the high channel conductance values (500–2000 μS), leading to a higher demand for current capacity and excessive power dissipation on wires as array dimensions increase.[21,137] Note that by diluting the conductive polymer with an insulator to decrease the channel conductance, synaptic weight readout with <10 nA has been achieved later.[137]

Compared with organic materials, inorganic materials show advantage in the operating current and energy consumption. Shang et al. developed an IGT based on layered transition metal oxide α-phase molybdenum oxide (α-MoO₃), which is highly insulating due to the wide bandgap.[22,49] Proton-based electrochemical doping mechanism was determined through investigating systematically the influence of moisture on device operation.[49] Since the use of ionic liquids as gate isolation layers, and the influence of the environmental humidity, it is not conducive to the space-efficient fabrication such as array integration. Subsequently, the ionic liquid was replaced with a solid-state Li⁺ electrolyte and all-solid-state synaptic transistors were achieved (Figure 7a).[21] Under the action of the gate voltage, the intercalation (extraction) of Li⁺ into (out of) the layered α-MoO₃ channel takes place, resulting in reversible analog switching of the α-MoO₃ channel conductance (Figure 7b,c). Due to the introduction of Li⁺ as dopants, the channel conductance switching can be achieved under vacuum conditions (<10⁻⁵ Torr), showing independence on the external environment. The neuromorphic computing simulation showed that three-layer neural network (784 × 300 × 10) constructed with the synaptic transistor array could realize the training and recognition of the handwritten digit from Modified National Institute of Standards and Technology (MNIST) dataset with the recognition accuracy reaching to 87.3%. Moreover, the α-MoO₃-based synaptic transistors show ultralow conductance (<75 nS) during switching, which is highly favorable for the energy efficiency and large-scale crossbar array fabrication.

Although the feasibility of IGTs as synaptic devices has been demonstrated, the improvement of device performance including linearity and symmetry of analog switching, power consumption, and operation speed is still required to be studied further.[10,11,14] Compared with the planar configuration of the IGTs, vertical structure might be more convenient for meeting these requirements.[64–66] Lenz et al. adopted a clever method to fabricate IGTs with vertical structure.[51] Figure 8a,b shows the structure diagram of the vertical IGT. They first made an Au/Ti/SiO₂/Ti/Au sandwich stack with cross structure, and then used HF to selectively etch Ti and SiO₂ to construct empty spaces along the direction perpendicular to the stacking orientation. The void height, equivalent to the channel length, and depth in indentation direction are dictated by the thickness of SiO₂ layer and etching time, respectively. Finally, the fabrication of vertical IGTs is accomplished by spin-coating organic semiconductors to fulfill the already-constructed voids (removing those outside the channel) and then drop-coating ionic liquid. The vertical IGTs show high on-state current densities above 3 MA cm⁻² and 10⁶ on/off current modulation ratios (Figure 8c). In addition, the vertical IGT was utilized as low-power synaptic device to emulate the short- and long-term plasticity of biological synapses (Figure 8d). A sub-100 fJ energy consumption per event was achieved, which is much lower than those of most of other devices with the same type but in a planar structure, although it is still higher than that of biological synapses. This work demonstrates the bright prospect of adopting vertical structure in IGTs in performance optimization. Apart from the aforementioned structure, there are also diverse vertical forms for IGTs.[65,66] By using a comb-like source electrode and constructing the channel at its edge, Wan et al. achieved sub-10 nm length channels.[154] Regardless of their forms, the purpose is to achieve larger on-state current and high switching frequency by shorting the channel length of IGTs.[66] When adopting vertical structures, the change in working mechanism may occur due to the significant reduction in device size, and some side effects such as short-channel effect found in vFETs may also appear in IGTs. Therefore, many spaces involving fabrication, operation mechanism, and electrical performance of vertical IGTs are still required to be studied in the future.

A comparison of IGT with other devices for neuromorphic computing implementation is shown in Table 2. As can be seen, IGTs are inherently suited for neuromorphic computing due to the combination of the unique device structure and operating mechanism, possessing the merits such as a large number of separable states, ultralow power consumption, and near-ideal linearity and symmetry. However, the retention time of IGTs is usually from seconds to days, which is mainly due to the non-ideal properties of materials (i.e., the electrolyte is not completely electrically insulated) and the occurrence of side reactions (i.e., the electrolyte reacts chemically with the electrode and the channel). The retention can be improved by optimizing the electrolyte material, the electrode/electrolyte and electrolyte/channel interfaces, and the device encapsulation. Moreover, the instability of the materials used in IGTs and their incompatibility with existing complementary metal–oxide semiconductor (CMOS) technology are the main issues in terms of the reliability. For example, the instability and incompatibility of Li-based solid electrolytes make many large fabs reluctant to embrace them, even though Li-based IGTs have demonstrated impressive device performance. To address these issues, one feasible way is to develop stable and compatible materials, such as oxygen ion conductors, and the other is to develop new manufacturing processes and equipment for Li-containing
materials, as is possible to be tried in factories that have lost competitiveness in advanced manufacturing.

5. Intelligent Sensors

In conventional information processing architecture of sensing systems, sensors and computing units are physically separated. The information flows as follows: the sensors acquire external information and convert it into electrical analog signals which include a lot of redundant information; after conversion by analog-digital converter (ADC) and amplification by amplifier, the digital signals are transmitted to the remote computing unit for further processing. When meeting with complex intelligent tasks, this kind of architecture leads to two important problems, that is, latency and energy consumption, which are rooted in the lack of processing capability of sensory units. The biosensory systems are remarkably complex, yet high energy efficient.

The integration of IGTs with high-performance sensors provides a promising way to build intelligent systems to simulate human senses such as tactile, visual, auditory, and olfactory. Based on the spatial location of sensor and computing units, the intelligent sensor systems can be achieved through two modes: near-sensor computing and in-sensor computing.

5.1. Near-Sensor Computing

Near-sensor computing is a concept that aims at avoiding the transmission of raw data to remote computing units. It is usually achieved by deploying dedicated hardware blocks with computing capability closely connected to the sensor terminals in order that the acquired signals can be processed directly. It is particularly promising for applications involving classification because a mass of data can be processed before transmitting them out for conversion. Figure 9a shows the architecture of

Figure 7. The application of IGTs in neuromorphic computing. a) The atomic force microscope (AFM) photograph of the α-MoO$_3$-based IGT structure. b) Transfer curve of the α-MoO$_3$-based IGT with obvious hysteresis. c) The reversible channel conductance modulation with good linearity and symmetry. d) Schematics of a three layer (one hidden layer) neural network. e) Schematics of the synaptic weight layer composed of IGT crossbar array and access devices. f) The recognition accuracy for handwritten digital image from MNIST. Reproduced with permission. Copyright 2018, John Wiley & Sons.
near-sensor computing systems where the computing units can be performed by neuromorphic computing devices. The application of IGTs in the field of neuromorphic computing provides the possibility for their integration with sensors to perform near-sensor computing.

The architecture of near-sensor computing mode is very similar to that of human sensory organs such as skin, eyes, and muscle, showing advantages in simulating human sensory functions. The skin is at the heart of human tactile perception. The simulation of tactile perception can be achieved by near-sensor computing mode where pressure sensors are used to emulate stimulus perception and IGTs are used for information processing. Based on the conception, Zhang et al. developed a tactile-sensing device by coupling a nanogenerator (TENG) with IGTs for information processing.

**Figure 8.** a) Structure diagram of the fabricated vertical IGT after cross bar multilayer stacking, laterally wet etching, OSC spin-coating and directional oxygen reactive ion etching. b) Cross section of the IGT with ionic liquid. c) The comparison between this work and others in on-state current densities and on/off ratios. The vertical structure can obtain large on/off ratio and saturation current simultaneously, which is highly useful for the achievement of low power consumption. d) EPSCs versus time. The short- and long-term plasticity of synapses both has been simulated and a low sub-100 fJ power consumption per event was also obtained. Reproduced with permission.[51] Copyright 2019, Springer Nature.

**Table 2.** Comparison between IGT and other devices for neuromorphic computing implementation. RRAM, resistive random-access memory; PCM, phase change memory; FTJ/FeFET, ferroelectric tunnel junctions/ferroelectric field-effect transistor; MTJ/STT-MRAM, magnetic tunneling junction/spin-transfer torque magnetoresistive random-access memory; MOSFET, metal–oxide–semiconductor field-effect transistor.

| Device            | Maximum no. of states | Maximum operation speed | Minimum operation energy | Nonlinearity | Asymmetry | Maximum endurance | Maximum retention |
|-------------------|-----------------------|-------------------------|--------------------------|--------------|-----------|-------------------|------------------|
| IGT               | 10,000[149]           | 5 ns[165]               | 1.23 fJ[159]             | Low          | Low       | 10¹[137,160]      | > 25 h[161]      |
| RRAM              | 64[162]               | 85 ps[163]              | 115 fJ[164]              | High         | High      | 10¹[162,164]      | > 1000 years @ RT[167] |
| PCM               | 16[168,169]           | 700 ps[170]             | 1 pJ[171]                | High         | High      | 10¹[117,172]      | > 1000 years @ RT[173] |
| FTJ/FeFET         | ∼ 10¹[123,174,176]    | 70 ps[172]              | 100 fJ[174]              | High         | High      | 4 × 10⁶[177]      | ≈ 3 days[176]    |
| MTJ/STT-MRAM      | 2[177,178]            | 200 ps[179]             | 10 fJ[180]               | High         | High      | 10¹[121,181]      | 10 years @ RT[183] |
| MOSFET            | 2[181]                | < 10⁹ ns (SRAM) < 10¹⁰ ns (DRAM) [183] | 1–10 fJ[183]            | High         | High      | > 10¹⁵[181]       | ≈ 1–10 ns[183]   |
The pressure sensor TENG is made by assembling a silk fibroin/indium tin oxide (ITO)/polyethylene terephthalate (PET) film with another untreated ITO/PET film through adhesive tape. IGTs are prepared on ITO/glass substrates with indium gallium zinc oxide (IGZO) as the channel and ITO as the electrode material. Dynamic pulse pressures can be converted into gate voltage pulses to modulate the channel conduction of the IGT and emulate the behaviors of biological synapse. Typical tactile sensing of skin to perceive dynamic pressures with different intensities, amounts, and frequencies is studied. Indeed, a successful imitation of human skin using electronic components would comprise physical pressure, strain, and temperature sensors to mimic the full touch sensation that humans can feel. Similar tactile perception systems based on IGTs have been widely reported.

The eyes are the main sensory organ of the visual system, through which more than 80% of the information from the outside world reaches the brain. Visual reception occurs at the retina, which takes in the physical stimuli of light rays and transduces them into electrical and chemical signals that can be interpreted by the brain to construct physical images. Mimicking the function of vision can be achieved using optical sensors integrated with IGTs. Sung et al. provide an artificial visual device to emulate the light-adaptable functions of visual systems (Figure 9c). This artificial visual system consists of a photovoltaic divider and an IGT, which play the roles of artificial retina and optic synapse, respectively. Particularly, the photovoltaic divider consisting of CdSe photosensor and an IGZO load transistor is designed to transform the visible light information into electrical output signals. The IGT, which is constructed by sodium (Na)-incorporated aluminum oxide (SAO)
solid-state electrolyte as the gate dielectric layer and IGZO as the channel layer, is the key component performing the ionic-tronic conversion and neuromorphic operations to emulate the biological synaptic functions. The artificial visual devices with near-sensor computing successfully emulate the neuromorphic behaviors such as short-term plasticity and long-term plasticity, and exhibit strongly environmental adaptability in pattern recognition, which is a human-like light information processing.

Apart from preprocessing signals, the other advantage of near-sensor computing is to realize the local control of the appliances because the computing results can be directly reflected back to instruct next operation. This characteristic has been used to emulate human-like motor function, which has been one of the main motivations for bioinspired engineering, especially for the development of electronic prostheses and biorobots. Lee et al. engineered a light-activated sensorimotor artificial synapse based on a stretchable organic nanowire synaptic transistor (s-ONWST). The s-ONWST was prepared based on polymeric organic nanowires and ionic gel electrolytes. It can convert light to electrical signals which enable an artificial muscle to flex and stretch (Figure 9d). Next, they added a photodetector to the s-ONWST. In the light the photodetector generates voltage spikes that drive s-ONWST to emit excitatory postsynaptic currents (EPSCs). To construct the neuromuscular electronic system, a polymer actuator was connected to the s-ONWST through a transimpedance circuit, which was used to convert the generated EPSCs to voltage signals to operate the fabricated polymer actuator. Figure 9e shows the state of polymer actuator after receiving different amount of spikes from the organic optoelectronic synaptic transistor. This human-like driving principle based on near-sensor computing system provides a promising strategy for the development of next-generation biomimetic soft electronics, soft robotics, neurorobots, and electronic prostheses.

At present, the achievements of in-sensor computing system are few, especially IGT-based in-sensor computing. There is still no unified computational standard for in-sensor computing systems with respect to power consumption, computing speed, reliability, and other related important indexes. The near-sensor computing systems based on CMOS-based devices have been appeared in recent years. The implementation is mainly attributed to the powerful neural network to process the data collected by sensor nodes. The main challenges of the CMOS-based near-sensor computing system are operating power consumption (≈μW μm⁻²) and communication bandwidth capacity. Because the IGT itself can be regarded as a synaptic device to process the collected data directly, it can greatly reduce the power consumption (≈μW μm⁻²) of the whole system. However, the computing speed, integration, and endurance of IGT-based near-sensor computing systems are still far from the level of CMOS-based near-sensor computing systems and need to be further improved.

5.2. In-Sensor Computing

Near-sensor computing could shorten the distance between the sensor unit and computing unit, and thereby alleviate the burden of data transmission. In principle, however, it still holds the feature of two separate parts. The information processing still suffers from the data transporting. Recently, in-sensor computing, that is, the sensor itself can realize computing tasks, has gradually attracted an intensive attention. It provides a more time- and energy-effective way to process detected signals. Learning from the biological sensory nervous systems, empowering sensor array itself with neuromorphic computing functions of neural network is known as a feasible way to realize in-sensor computing. Zhou et al. developed an optoelectronic resistive random access memory (ORRAM), which shows a unique light-tunable synaptic function. By using the ORRAM array, the image detection and pretreatment have been realized. It has been demonstrated that the contrast enhancement caused by the in-sensor pretreatment effectively increased the subsequent image recognition efficiency.

Based on a photodiode array of 2D material, Mennel et al. built an image sensor with a neural network structure and realized a more powerful in-sensor computing. Figure 10a shows the structure design of the sensor array, where multiple sensors are arranged into a planar array and group them according to certain rules. Each photodiode represents a subpixel. In the entire array, similar subpixels in different pixels are connected in parallel to generate the same type of photocurrent. The equivalent circuit diagram of any each pixel is shown in Figure 10b. The photodiodes are modulated by two split gates (Figure 10c), resulting in a tunable photosensitivity. The structure of the actual sensor array with different scaling magnification is shown in Figure 10d–f. The experimental results of the sensor arrays playing as a classifier are shown in Figure 10g. By adopting one-hot encoding, each letter corresponds to each output neuron, that is, each determined current channel. When an image representing a certain letter is input, the corresponding neuron is fired, and the corresponding current channel also outputs the largest current. The sensor array can also work as an autoencoder (Figure 10h). Different input images representing different letters are encoded as different combinations of code-layer neurons. By decoding, the encoded images are accurately reconstructed. The fault tolerance characteristics of the autoencoding of this sensor array are shown in Figure 10i. Note that the in-sensor computing introduced here is not a complete calculation but a pretreatment of the signals. The pretreated signals are still needed to be transported to an external processing unit for further processing.

In addition to optical detection, it is possible to extend the in-sensor computing mode to other sensory signals such as tactile, auditory, olfactory, biophysical, and biochemical signals. As has been stated earlier, IGTs have been widely used as core component of sensors to detect various physical and chemical signals. Furthermore, by utilizing the ion movement and electrochemical doping processes, IGTs can realize the reversible analog modulation of the channel conductance to simulate the synaptic plasticity, which have been used for neuromorphic computing. These two characteristics endow IGTs with the great potential to realize in-sensor computing, although the specific implementations are still required to be investigated.
6. Conclusion

Herein, we have introduced the basic operating principles, device structures, and electrical characteristics of IGTs. Then the applications around IGTs for biosensors, neuromorphic computing, and intelligent sensors with near-sensor and in-sensor computing modes are reviewed. IGTs as biosensors for detecting biochemical and biophysical signals are mainly due to the following two reasons. First, the operating principles of IGTs, which is relying on the transport of ions, are highly similar to that in organisms where the signal transmission is based on the release of ions (i.e., Ca$^{2+}$, Na$^+$, K$^+$). Second, IGTs have a relatively high gain even at a low operating voltage, resulting in a relatively large output sensitivity to the input changes. Both of the aforementioned characteristics make them competent candidates as biosensors. However, some restrictions to the practical application are needed to be overcome. For example, biosensors should have excellent ductility and flexibility in regard to wearability, and the materials used to contact directly to the human body ought to be biocompatible because this is a
prerequisite not only for ensuring nonirritating contacting interfaces but also for eliminating potential allergic or toxic reactions.

Neuromorphic computing inspired by working mode of human brain has the characteristics of non-von Neumann architecture and high parallelism. It is capable of processing signals through learning and memorizing functions, and shows significant advantages in time and energy efficiency over the conventional computing paradigm. To achieve neuromorphic computing, it is crucial to emulate the plasticity of synapses using electronic devices. IGTs show superior performance in analog switching of channel conductance due to the decoupling between writing and reading of the channel conductance, making them highly suitable for serving as synaptic devices. However, further improvement is still needed in terms of device size, operation speed, and large-scale array integration.

The investigation and application of IGTs in sensors and neuromorphic computing provide an insight into developing intelligent sensory system on the basis of IGTs, as shown in Figure 11. The current intelligent sensory systems could be roughly divided into two categories, that is, near-sensor computing and in-sensor computing. Near-sensor computing can be realized by integrating IGTs with neuromorphic computing function with sensors. The sensors are responsible for detecting signals and then transmit them to the IGTs for processing. When applying them in the Internet of Things, near-sensor computing could significantly reduce the amount of data for transmission between the cloud and edge devices, thereby the latency and energy consumption for signal processing. To realize fully compact integration, such as on-chip integration of sensors and IGTs, near-sensor computing systems bring more restriction to the materials and preparation technologies of IGTs, that is, the materials and preparation technologies of IGTs should have good compatibility with those of specific sensors. Compared with near-sensor computing, in-sensor computing, which enables the sensing and processing of signals to be completed in the same one device, is supposed to be a promising way for information processing because it shows the potential to further reduce device size and alleviate data transmission, and then improve energy efficiency. However, in-sensor computing might pose a challenge to the contradictory demand for the electric characteristics of IGT. For example, large transconductance is preferred for sensors with high sensitivity, whereas a gradual change in channel current with gate voltage is required for neuromorphic computing. Moreover, in-sensor computing would be only applicable for some specific signals, even though some IGT-based multisensory devices have been developed. Compared with in-sensor computing, near-sensor computing shows good generalization because the IGT-based computing units are independent of the detected signals. Whether near-sensor computing or in-sensor computing, IGT arrays would be crucial to the realization of intelligent sensor systems. However, the preparation of large-scale IGT arrays is still in infancy, limiting the complexity of the sensory tasks. Clear theoretical guidance on the fabrication technology and performance optimization such as response speed and energy consumption for both near-sensor computing and in-sensor computing are still required to be further investigated. Nevertheless, the attention to IGT-based sensors and neuromorphic computing devices is growing rapidly. We believe IGTs are a promising building block for both sensors and neuromorphic computing which are recognized as the trendsetting approach toward intelligent sensors, and it would promote the advances of the Internet of Things and then the innovation development of intelligent society.

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Conflict of Interest
The authors declare no conflict of interest.

Keywords
biosensors, intelligent sensors, ion-gated transistors, neuromorphic computing
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