Journal of Progress in Electronics and Communication Engineering, ISSN: 3048-7625 Vol. 2, No. 2, 2025 (pp. 10-20)
RESEARCH ARTICLE WWW.PECEJOURNAL.COM

Graphene Innovations in Flexible and Wearable Nanoelectronics

[1]Chuong Van[1], MH Trinh[2], T Shimada[3]
[1-3]*School of Electrical Engineering, Hanoi University of Science and Technology, 1 Dai Co Viet, Hanoi 11615, Vietnam*

KEYWORDS:
Graphene-based Sensors;
Flexible Electronics;
Wearable Technology;
Transparent Conductive Films;
Energy Storage Devices

ARTICLE HISTORY:
Received : 24.11.2024
Revised : 08.12.2024
Accepted : 23.06.2025

https://doi.org/10.31838/ECE/02.02.02

Abstract

Graphene, a two-dimensional form of carbon known for its exceptional electrical, mechanical, and thermal properties, has emerged as a revolutionary material in the field of flexible and wearable nanoelectronics. Its remarkable flexibility, high conductivity, and transparency make it ideal for applications requiring lightweight, stretchable, and durable electronic components. Innovations in graphene-based flexible electronics encompass a wide range of devices, including flexible transistors, sensors, supercapacitors, and transparent conductive electrodes. These advancements enable the development of next-generation wearable technologies for health monitoring, smart textiles, and portable energy storage.Graphene's unique attributes facilitate the creation of highly sensitive and accurate biosensors capable of real-time health tracking and diagnostics. Additionally, graphene-based flexible supercapacitors offer superior energy storage capabilities, essential for powering wearable devices. Transparent and flexible graphene electrodes enhance the functionality and aesthetics of smart textiles and electronic skin applications. Research is ongoing to optimize the synthesis, integration, and scalability of graphene in flexible electronics to overcome current challenges such as material defects and large-scale production.Overall, graphene's innovations are poised to transform the landscape of wearable nanoelectronics, driving advancements in health monitoring, personal electronics, and beyond, underscoring the material's potential to revolutionize future technologies.

Author e-mail: choung.van@hust.edu.vn, trinhmh@hust.edu.vn, shimada.t@hust.edu.vn

How to cite this article: Van C, Trinh MH, Shimada T. Graphene Innovations in Flexible and Wearable Nanoelectronics, Journal of Progress in Electronics and Communication Engineering, Vol. 2, No. 2, 2025 (pp. 10-20).

Introduction

Graphene, the revolutionary nanomaterial hailed as a "wonder material," has captured the attention of scientists and engineers worldwide due to its exceptional properties.[1] Isolated for the first time in 2004, this single-layer carbon allotrope exhibits remarkable strength, electrical conductivity, and thermal properties, making it an ideal candidate for flexible and wearable nanoelectronics.[2]

With a honeycomb-like structure just one atom thick, graphene not only outperforms steel in terms of strength but also demonstrates superior thermal and electrical conductivity compared to most conventional materials used in electronics.[3-6] These unique characteristics have paved the way for innovative applications in flexible sensors, bendable displays, implantable biosensors, and smart wearable devices that can conform to the human body while monitoring various health parameters through accurate chemical detection[7-10] as shown in Fig. 1.

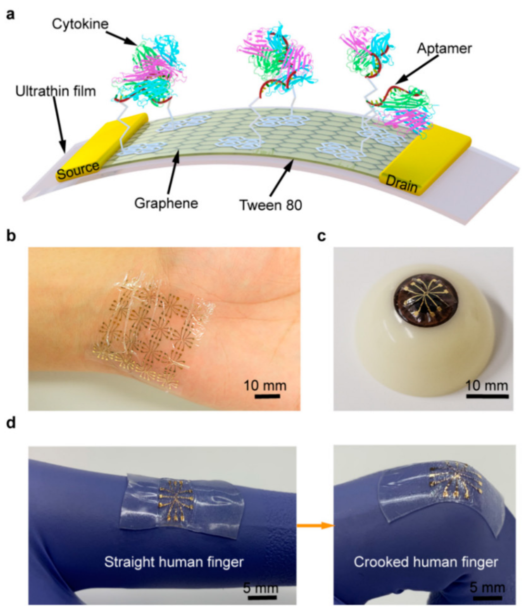

Fig. 1: Deformable Graphene-Based Affinity Nanosensor

Wearable Nanoelectronics: An Overview

A. Importance of real-time health monitoring

Wearable devices are real-time and noninvasive biosensors allowing for the continuous monitoring of individuals, providing sufficient information for determining health status and even preliminary medical diagnosis. Over the past few decades, the tremendous development of electronics, biocompatible materials, and nanomaterials has resulted in the development of implantable devices that enable diagnosis and prognosis through small sensors and biomedical devices, greatly improving the quality and efficacy of medical services.

Wearable biosensors have received tremendous attention over the past decade, mainly concentrated in the healthcare industry, which attempts to apply physical signals such as heart rate, blood pressure, skin temperature, respiratory rate, and body motion to extract clinically relevant information. These wearable sensors have opened a new area of personalized health monitoring by accurately measuring physical states and biochemical signals.[11]

B. Emergence of flexible and wearable devices

Flexible and wearable electronics challenge the very notion of what a device can be. With the advent of bendable displays and smart clothing, the boundaries of design, functionality, and integration are being pushed to new limits. Wearable biosensors refer to biological sensors, including watches, clothing, bandages, glasses, contact lenses, and rings, that are conveniently attached to a person's body and provide a function that distinguishes them from existing devices in terms of portability, ease of use, and environmental adaptability.

Wearable devices have gradually been developed in the form of accessories, integrated clothing, body attachments, and body insertions. Current advances in wearable technology have made flexible materials increasingly important, as they are used to create the batteries, sensors, and other electronic components that make up wearable devices, making it easier for many users to keep their devices on them 24/7.[12]

C. Advantages of wearable nanoelectronics

Wearable health technology based on flexible electronics has gained tremendous attention in recent years for monitoring patient health owing to attractive features, such as lower medical costs, quick access to patient health data, ability to operate and transmit data in harsh environments, storage at room temperature, non-invasive implementation, mass scaling, etc. This technology provides an opportunity for disease pre-diagnosis and immediate therapy.

Flexible materials are more suitable for use in the healthcare industry, as they often offer comparatively inexpensive mass production, portability, and ease of use, as well as increased comfort for the user, taking up less space on the body and requiring less discomfort than many traditional devices. An increasing number of these materials are also waterproof, which means that fitness devices don't have to be removed for activities like showering, swimming, or running in the rain.

Despite the progress to date in the development of wearable sensors, there are still several limitations in the accuracy of the data collected, precise disease diagnosis, and early treatment. This necessitates advances in applied materials and structures and using artificial intelligence (AI)-enabled wearable sensors to extract target signals for accurate clinical decision-making and efficient medical care.

D. Flexible and Wearable Sensors for Chemical Monitoring

Wearable chemical sensors offer a real-time, non-invasive alternative to traditional laboratory blood analysis, serving as an effective tool for exploring novel biomarkers in alternative body fluids such as sweat, saliva, tears, and interstitial fluid (ISF). These sensors convert the levels of various analytes in body fluids into measurable electrical, optical, or piezoelectric signals, enabling continuous measurement of chemical biomarkers like electrolytes, metabolites, nutrients, drugs, hormones, and proteins in blood surrogate biofluids[13] as shown in Fig. 2.

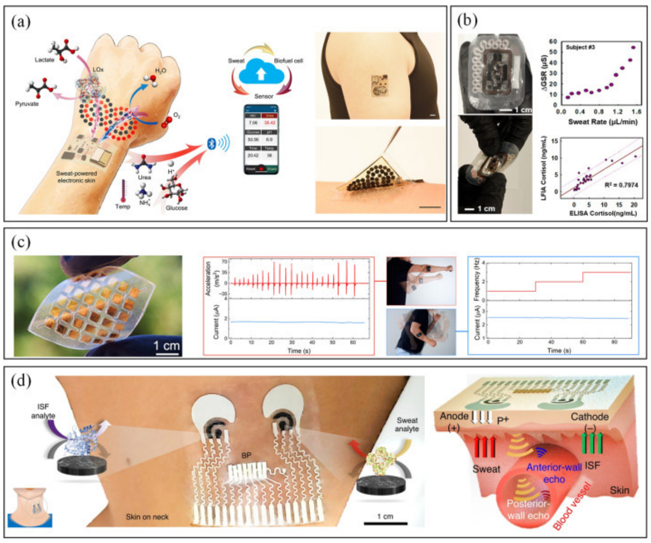

Fig. 2: Flexible, wearable biosensors for digital health

E. Types of chemical molecules monitored

Wearable sensors can analyze various bodily fluids such as sweat and ISF, providing information about individuals' biochemical statuses. This information can be used to improve personal health through early disease detection and pave the way for early intervention in patients. Many types of transducers, including thermoelectric, capacitive, piezoelectric, optical, and electrochemical transducers, are employed in wearable sensors.[14]

- Thermoelectric converters measure thermal changes.
- Capacitive converters measure physical signals like force, pressure, and displacement.
- Optical converters measure photosensitive reactions.
- Electrochemical converters measure redox changes in chemical reactions.

Recent years have seen a rise in sensor designs based on electrochemical and optical converters for wearable sensor studies.[15].

F. Importance of monitoring chemical factors

Biomarkers are crucial biological indicators in medical diagnostics and therapy. Wearable chemical sensors offer an attractive approach to address the challenges of biomarker discovery and validation by simultaneously monitoring a broad spectrum of molecular signatures, enabling multi-omics analysis. Their unique ability to perform continuous monitoring and identify temporal patterns can be a great asset in discovering biomarkers that vary rapidly within a short period.

To be suitable for wearable-based biomarker discovery, the molecule or molecular fragment candidates should be present in alternative biofluids like sweat, saliva, and ISF. These candidates should ideally be stable, charged species with small molecular weight for easy partition from blood and have potential links with their blood counterpart or targeted health condition.[16]

Materials and Design Considerations

A. Stretchability and Softness

Mechanical properties are the most fundamental characteristics of skin device electrodes. Due to the freely flexible nature of the skin, the skin device electrode must fit well with the skin and be securely attached. The electrodes must effectively interact with the skin despite disturbing factors such as body movement and sweat.

The most crucial aspect to consider is stretchability. As the shape of the skin continuously changes with the wearer's movements, a skin device must possess stretchable characteristics to accommodate these maneuvers. Stretchable materials like elastomers, hydrogels, and liquid metals are often employed to ensure conformity with the skin's dynamic nature.

In addition to stretchability, softness is another essential property for skin-interfaced devices. Soft materials minimize discomfort and irritation, enabling prolonged wear and accurate physiological monitoring. Polymers, gels, and flexible substrates are commonly used to achieve the desired softness and flexibility.[17] as shown in Fig. 3.

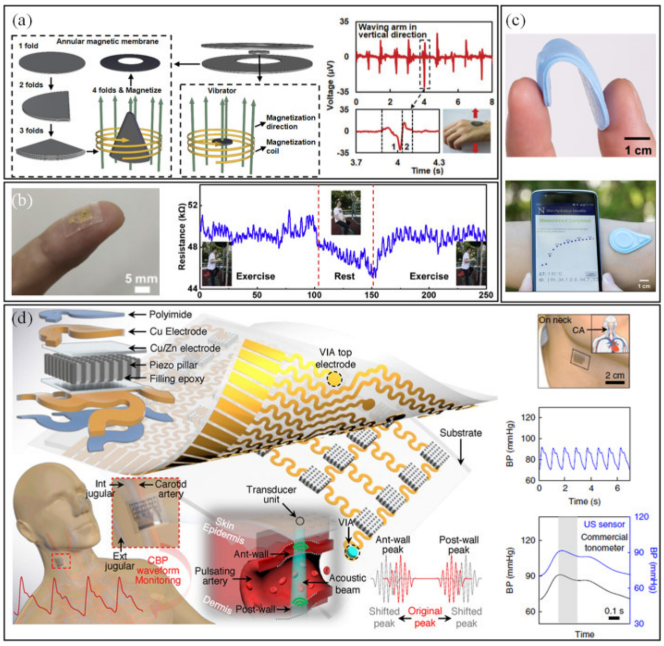

Fig. 3: Skin Adhesion and Breathability analysis

B. Skin Adhesion and Breathability

The second consideration is adhesion, which is crucial for patient comfort and stable physiological monitoring. To effectively monitor physiological signals by attaching to the skin, the device must adhere to the skin for extensive periods without causing issues. Adhesive materials like hydrogels, silicones, and adhesive tapes are often employed to ensure secure skin attachment.

In addition, conformability to the skin is also critical. Conformability is not only important for stable attachment but also for providing comfort and enabling effective physiological monitoring. Flexible and stretchable materials, combined with appropriate adhesives, can achieve high conformability to the skin's contours.

Breathability refers to the ability of the electrode to allow air to pass through. Mainly, breathability is a characteristic required for clothing that comes in contact with human skin, such as clothes and shoes. This breathability is a characteristic applied to help the wearer feel comfortable and healthy, and it also can be applied to skin electrodes attached to the skin. Porous materials, mesh structures, and breathable fabrics are often used to ensure adequate breathability in skin-interfaced devices.[18]

C. Biocompatibility

Biocompatibility is regarded as the most significant criterion for skin electronic devices to ensure safe application to the human epidermis. Conventionally, biologically inert metals have been selected as electrode material. However, the recent research trend focuses on the combination of conductive materials with elastic material to overcome many on-skin scenarios such as dynamic stretching caused by body movement.

Biocompatible materials like hydrogels, silicones, and certain polymers are widely used in skin-interfaced devices to minimize adverse reactions and ensure safe long-term wear. Additionally, surface coatings, encapsulation techniques, and material purification processes are employed to enhance biocompatibility further [19].

3. pH Sensors

A. Operating principles

Wearable pH sensors reflect real-time physiological information and health status by continuously monitoring biochemical markers like pH levels in biological fluids such as sweat, tears, and saliva [20]. These flexible electrochemical sensors play a crucial role in health monitoring since pH affects most biochemical reactions in the human body. pH indicators can aid in disease diagnosis, treatment, and monitoring biological processes.[21]

The performance and applications of wearable pH sensors significantly depend on the properties of the pH-sensitive materials used. Currently, existing pH-sensitive materials are mainly based on:

1. 1. Polyaniline (PANI)
2. 2. Hydrogen ionophores (HIs)
3. 3. Metal oxides (MOx)

The pH response of PANI is considered a reversible protonation and deprotonation process. PANI has three basic oxidation states: fully reduced leucoemeraldine base (LEB), half-oxidized emeraldine base (EB), and fully oxidized pernigraniline base (PNB). Among these, EB can be protonated to form the conductive emeraldine salt (ES) due to the presence of amine and imine groups. The reversible protonation and deprotonation of EB and ES confer pH-sensitivity to PANI.[21]

The response mechanism of HIs to H+ can be described by classic ion-selective membrane (ISM)-based solid-contact ion-selective electrodes (SC-ISEs). Common HIs used for H+ recognition include tridodecylamine (hydrogen ionophore I), 4-nonadecylpyridine, octadecyl isonicotinate, dipropylaminoazobenzene, and Nile blue,[21] as shown in Fig. 4.

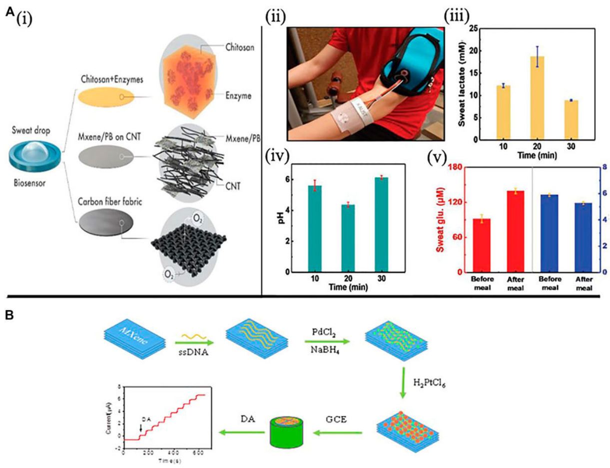

Fig. 4: Wearable and Flexible Electrochemical Biosensors

The pH-sensitive mechanism for MOx materials is quite complex and strongly correlates with their surface properties. In the 1980s, Fog and Buck demonstrated near-Nernstian pH responses for a series of MOx (PtO2, IrO2, RuO2, etc.) in a wide pH range of 2-12. They proposed possible mechanisms like ion exchange through surface -OH groups, H+-involved redox reactions with MOx, H+-intercalated redox reactions, H+-involved oxygen deficit redox reactions, and electrode corrosion.[21]

B. Recent advancements

Among various metal oxides, IrOx has become the most widely used wearable pH sensor due to its high sensitivity, good biocompatibility, and fast response.[21] In addition to IrOx, other metal oxide-based extended gate field-effect transistors (EGFETs) and ion-sensitive field-effect transistors (ISFETs) have also been used to fabricate wearable sensors.[21]

Apart from PANI, HIs, and MOx, other materials like single-walled carbon nanotubes (SWCNTs) and tanningraphene (TA-RGO) supramolecular aggregates have also been used to fabricate wearable pH sensors.[21]

Liao et al. coupled PDMS and PU to produce non-invasive, high-tensile sweat senso0 rs. PDMS provides a flexible substrate, and PU optimizes the adhesion between the electrode and the substrate, increasing the hydrophobicity of the electrode surface by introducing graphene-carbon nanotube materials. The sensor demonstrated a wide detection range of NH4+ from 10^-6 M to 10^-1 M with high stability and sensitivity, showing a sensitivity of 59.6 ± 1.5 mV/log [NH4+] and a limit of detection lower than 10^-6 M. Under 40% strain, the sensor still showed a sensitivity of 42.7 ± 3.1 mV/log [NH4+].[22]

Moon et al. developed bare amino acid-mediated cationic amphiphilic surfaces based on polyimide (PI) for wound healing and monitoring pH. They modified the PI surface via a simple waterborne dipping process, which did not affect its physical properties. The modified PI surface can inhibit bacterial contamination through repulsion and simultaneously kill bacteria due to its cationic amphiphilic properties. The pH sensor was made with an Ag/AgCl reference electrode and polyaniline with Nafion resin deposited by screen printing. The entire device is covered with a modified PI film except for the sensor electrodes.[22]

C. Challenges in 2wearability

While significant progress has been made in developing wearable pH sensors, several challenges remain in terms of wearability:

1. **Cost**: Among metal oxides, IrOx is the most widely used due to its high sensitivity and fast response; however, its cost is high, limiting widespread adoption.[2a]
2. **Response time**: MOx-based EGFET and ISFET have not demonstrated a rapid response time, despite their high sensitivity.[21]
3. **Sensitivity and stability**: WO3-based potentiometric pH sensors have great potential due to their low cost, high stability, and good biocompatibility. However, intrinsic WO3 usually exhibits a sub-Nernstian response and a slower pH response. Proton intercalation methodology offers a strategy for improving the sensitivity.[21]
4. **Wearability and comfort**: Achieving optimal wearability and comfort for prolonged use remains a challenge. Factors like stretchability, softness, skin adhesion, breathability, and biocompatibility need to be carefully considered in the design and material selection of wearable pH sensors.[15]

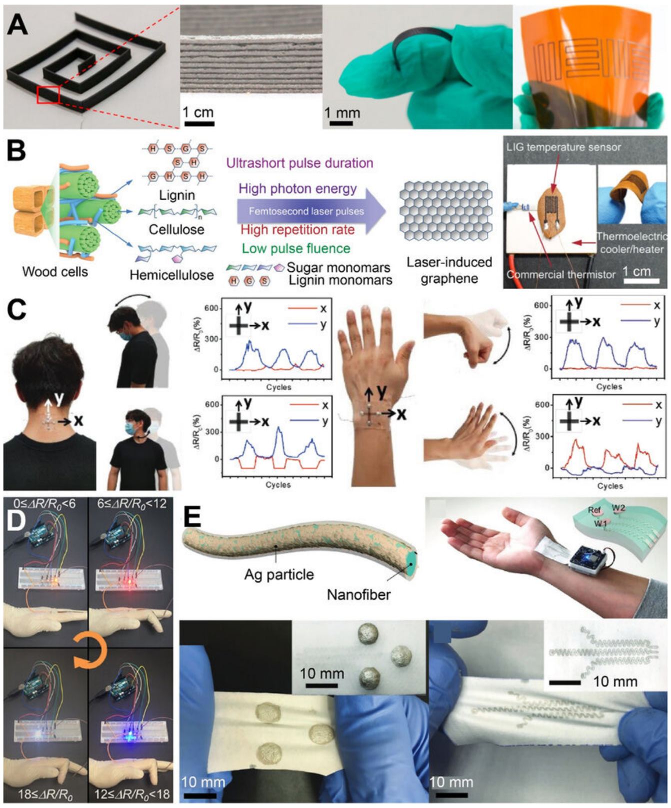

Fig. 5: Nanomaterials can be used to 3D print

Addressing these challenges through continued research and development in materials, fabrication techniques, and sensor design is crucial for realizing the full potential of wearable pH sensors in various healthcare and biomedical applications, as shown in Fig. 5.

Sensors for Glucose, Lactate, and Uric Acid

A. Importance of monitoring these molecules

Monitoring the concentration of glucose, lactate, and uric acid in the body is crucial for managing various health conditions and maintaining overall well-being. These molecules play a vital role in physiological processes, and their levels can have significant implications for an individual's health.

B. Glucose

Glucose is the primary source of energy for the body, and its concentration is closely linked to overall health. When glucose levels are too high, a condition known as hyperglycemia can occur, leading to potential complications like:

- Increased thirst and frequent urination (a sign of high glucose levels)

- Fatigue and sluggishness due to the body's inability to use glucose properly
- Potential long-term damage to organs like the kidneys and eyes

On the other hand, if glucose levels are too low, a condition known as hypoglycemia can occur, which can be dangerous if not addressed promptly. Hypoglycemia can cause shakiness, dizziness, and even unconsciousness if the glucose levels are extremely low, as shown in Fig. 6.

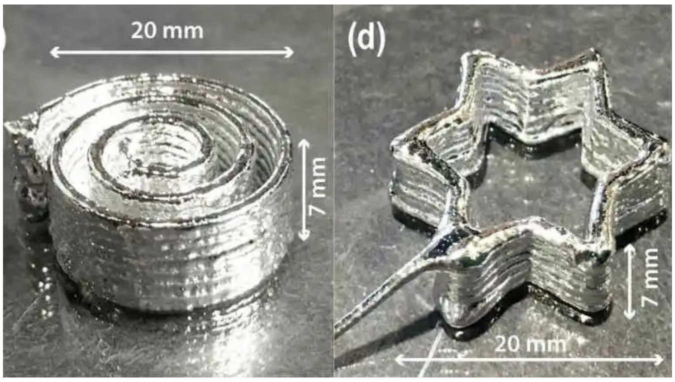

Fig. 6: Novel 3D-printable alloy for flexible devices

C. Lactate

The presence of lactate in the body is a natural byproduct of intense physical activity. During exercise, the body's demand for oxygen exceeds its supply, resulting in the production of lactate. While lactate is not inherently harmful, its accumulation can lead to a condition known as "Burn," which is characterized by a feeling of heaviness and fatigue in the muscles. This condition is often referred to as a "Burn" and is a positive indicator of an effective workout, as it signals that the body is being challenged and is adapting to the increased demand for oxygen.

Ion Sensors

A. Importance of monitoring ions

Monitoring ion levels in the body is crucial for maintaining overall health and well-being. Ions play vital roles in various physiological processes, and their imbalances can lead to severe health complications. Wearable ion sensors offer a non-invasive and continuous approach to tracking ion concentrations, enabling early detection and timely intervention.

Ions like sodium (Na+), potassium (K+), calcium (Ca2+), and chloride (Cl-) are essential for regulating various bodily functions. For instance, sodium and potassium are responsible for maintaining proper fluid balance, nerve impulse transmission, and muscle contraction.[1] Calcium ions are crucial for bone health, blood clotting, and muscle function, while chloride ions regulate pH balance and fluid distribution.[1]

Monitoring these ions can provide valuable insights into various health conditions. Elevated sodium levels may indicate dehydration, kidney dysfunction, or hypertension, while potassium imbalances can lead to muscle weakness, irregular heartbeats, and even cardiac arrest.[1] Calcium deficiencies can contribute to osteoporosis, and chloride imbalances can disrupt the acid-base balance, leading to respiratory or metabolic disorders.[1]

By continuously tracking ion levels through wearable sensors, individuals and healthcare professionals can identify potential imbalances early and take appropriate preventive or corrective measures. This proactive approach can help mitigate the risk of severe complications and improve overall health outcomes.

B. Wearable sensor platforms

Graphene, owing to its extraordinary properties, such as high carrier mobility,[1] excellent electrical conductivity, superior thermal conductivity.[2] large theoretical specific surface area [2], high optical transmittance,[2] high Young's modulus,[12] and outstanding mechanical flexibility.[2] is a promising 2D material for developing wearable ion sensors and implantable devices for health monitoring.

The advantages of graphene for ion sensors include its high specific surface area and atomic thickness, which allow entire carbon atoms to be in direct contact with analytes, resulting in superior sensitivity compared to traditional materials like silicon.[2] Additionally, graphene's mechanical flexibility and ultrathin nature enable conformal, intimate contact with organs of interest, such as the skin,[2] brain,[2] and eyes,[2] facilitating the acquisition of high-quality signals without irritation, motion artifacts, or contamination.[2]

Researchers have explored various graphene-based platforms for wearable ion sensors, including field-effect transistors (FETs), electrochemical sensors, and optical sensors. Graphene FETs leverage the material's exceptional electrical properties to detect changes in ion concentrations, while electrochemical sensors utilize graphene's high surface area and conductivity for electrochemical reactions. Optical sensors, on the other hand, exploit graphene's unique optical properties to detect ion-induced changes in light absorption or emission.

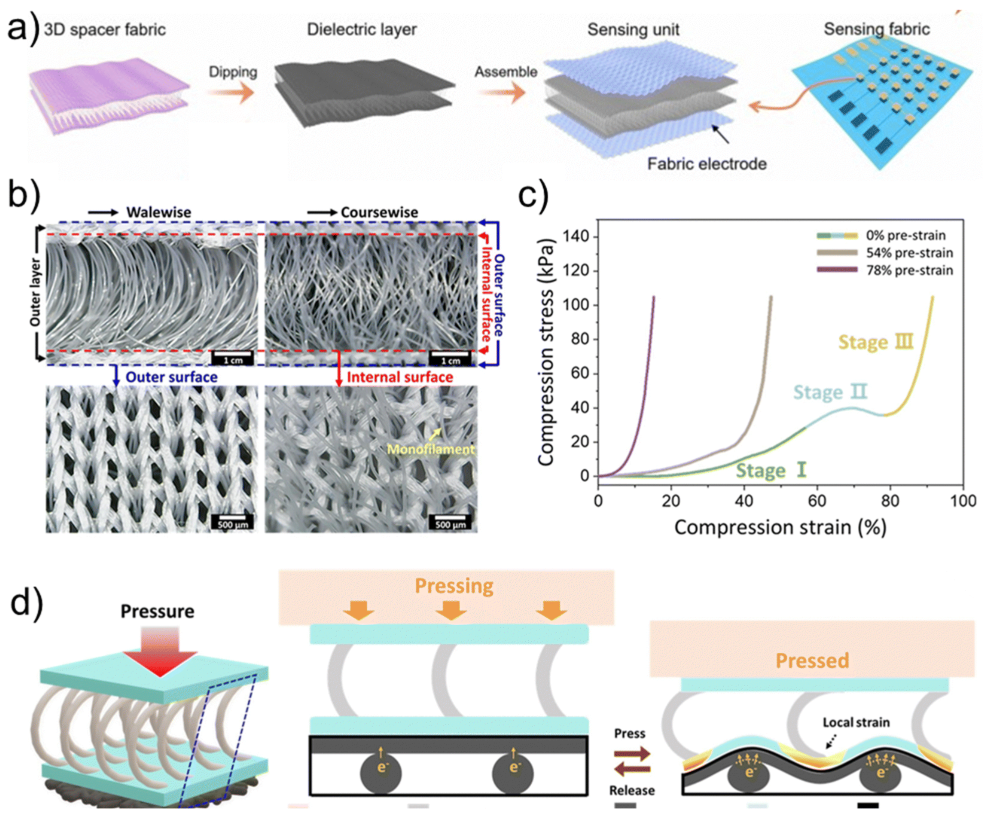

Fig. 7: Recent advances in the material design for intelligent wearable devices

C. Challenges in material selection and wearability

Despite the promising potential of graphene and other 2D materials for wearable ion sensors, several challenges remain in terms of material selection, device fabrication, and wearability.

As shown in Fig. 7, One of the primary challenges is the device-to-device variability caused by intrinsic defects, gate oxide nonuniformities, and parasitic effects.[3] These variations can significantly impact sensor performance and reproducibility, raising concerns about reliability in real-world applications involving complex physiological samples.[3]

Additionally, the fabrication process itself can introduce batch-to-batch variability in sensor response, further compounding the issue of reproducibility.[3] Most sensor studies have focused on optimizing and evaluating the performance of individual sensors for specific analytes, but the real-world application of these devices in complex biological environments remains a challenge.[3]

Another critical aspect is ensuring wearability and user comfort. Factors such as stretchability, softness, skin adhesion, breathability, and biocompatibility must be carefully considered in the design and material selection of wearable ion sensors.[4] Achieving optimal wearability while maintaining high sensor performance and reliability is an ongoing challenge that requires interdisciplinary collaboration between material scientists, engineers, and healthcare professionals.

To address these challenges, researchers are exploring new material synthesis techniques, device architectures, and fabrication methods to improve the uniformity and reproducibility of graphene-based ion sensors. Additionally, strategies for enhancing wearability, such as incorporating stretchable and biocompatible materials, are being investigated to ensure user comfort and long-term monitoring capabilities.

Cytokine Sensors

A. Role of cytokines in health monitoring

Human biofluids like saliva, tears, and sweat contain numerous cytokines (with a molecular weight lower than 70 kDa)[17] These biofluids can be easily collected without piercing the skin[17] Abnormally elevated levels of cytokines in human biofluids are closely related to the attack of severe diseases, such as COVID-19 and chronic diseases.[17-19] Hence, the continuous detection of cytokine levels in human biofluids for high-risk populations is significant for offering information on health conditions and gaining valuable time to take preventative measures before disease attacks.[17-19]

Wearable sensors that can be attached to the non-planar human body surface and perform on-site signal transduction seem capable of monitoring cytokine levels.[17-19] Graphene, an attractive two-dimensional nanomaterial, is extremely sensitive to its surface charge distribution and widely used as a transducer for sensors due to its outstanding electrical properties.[17-19] With the aid of aptamers, graphene field-effect transistors (GFETs) can enable sensitive, rapid, and label-free detection of cytokines.

B. Wearable sensor designs

Efforts have been made to use GFET biosensors in wearable applications due to graphene's high mechanical flexibility. These sensors are fabricated on polymer sheets like polydimethylsiloxane (PDMS), polyester (PET), and polyethylene naphthalate (PEN). However, these polymer sheets, with thicknesses of 100 μm or more, can hardly sustain large deformations and curvatures (with radii ranging from 4 to 40 mm). Therefore, GFET biosensors with an extremely thin substrate that can withstand large deformations involved in physiologically and biochemically relevant measurements on non-planar human body surfaces are highly desirable, as shown in Fig. 8.[13-19]

Researchers have presented a wearable and deformable aptameric GFET biosensor designed to enable sensitive, consistent, and time-resolved monitoring of cytokines in human biofluids[19] The biosensor is fabricated on a biocompatible and ultrathin polymer-supporting substrate (2.5 μm thickness). Due to this substrate's thinness, the biosensor can conform to non-planar surfaces like human skin or eyeballs and withstand large deformations, including bending and stretching, while maintaining consistent and sensitive responses. Tween 80 is used to modify the graphene surface to effectively suppress nonspecific adsorption, enabling the biosensor to detect cytokines like TNF-α and IFN-γ (significant inflammatory cytokines) in artificial tears.

C. Challenges in specificity and stability

Interleukins are preferred targets for single or multiple detections with electrochemical approaches. IL-6 has been the most employed cytokine biomarker for detection with electrochemical methods like impedance, cyclic voltammetry (CV), differential pulse voltammetry (DPV), electrochemical impedance spectroscopy (EIS), FET, and square wave voltammetry (SWV). Several sensing platforms have been designed by integrating

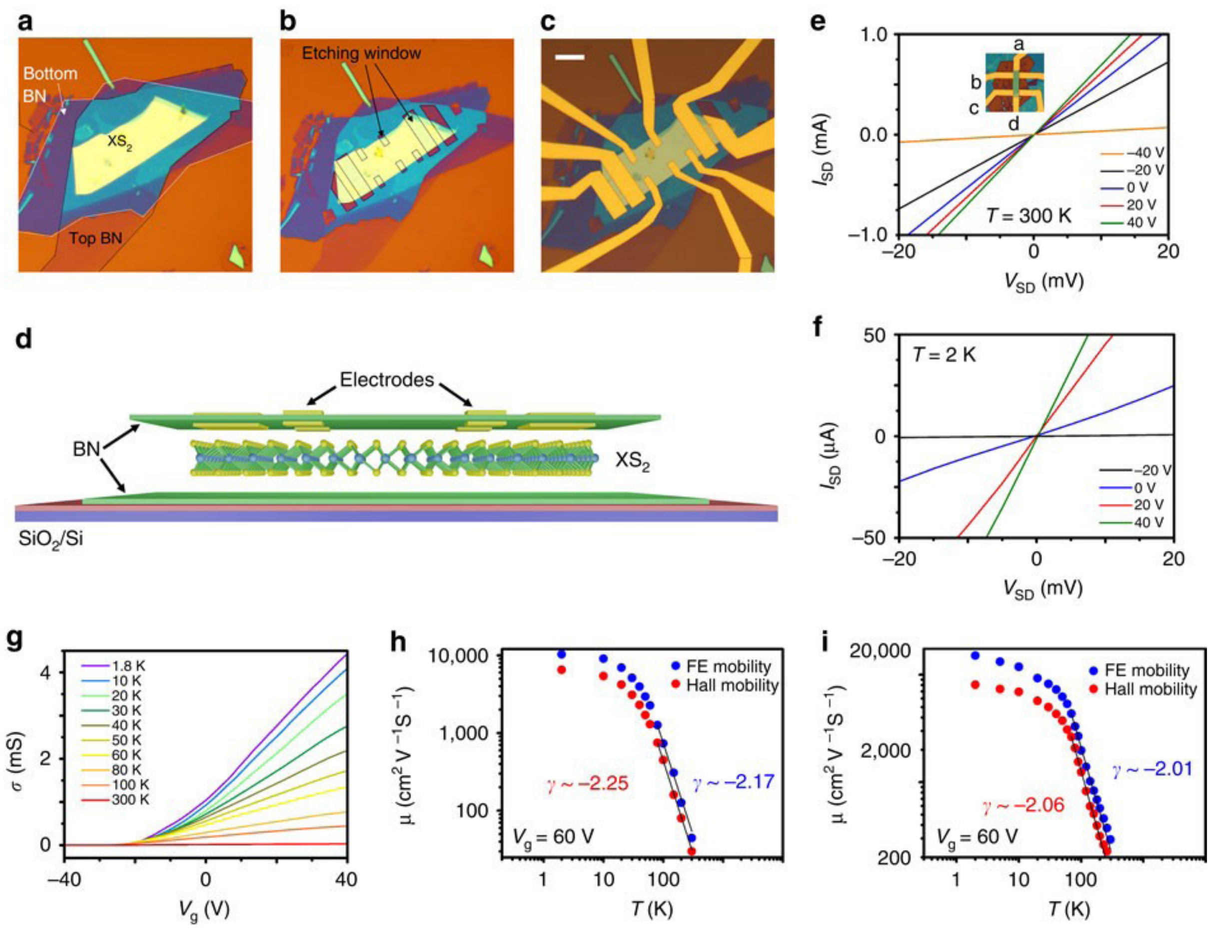

Fig. 8: Even-odd Layer-dependent Magnetotransport

graphene-based materials (GDMs) within the sensor recognition part, such as electrodes, typically decorated with aptamers or antibodies against IL-6, aiming to provide recognition specificity.

Furthermore, the simultaneous detection of relevant inflammatory cytokines with novel graphene materials has been applied to detect IL-6 alongside IL-17, TNF-α, and IFN-γ. Related methodologies based on GDMs and electrochemical biosensors were developed to detect additional critical inflammatory interleukins, such as IL-4, IL-8, IL-10, IL-13, IL-15, and IL-22. In these works, GDMs and their nanocomposites played a key role in improving the detection of cytokines in human biological fluids like saliva, serum, cell lysates, and tissue extracts.[20]

However, ensuring specificity and stability in complex biological environments remains a challenge.Device-to-device variability caused by intrinsic defects, gate oxide nonuniformities, and parasitic effects can significantly impact sensor performance and reproducibility, raising concerns about reliability in real-world applications involving complex physiological samples. Additionally, the fabrication process itself can introduce batch-to-batch variability in sensor response, further compounding the issue of reproducibility.[3]

Nutrient Sensors

A. Importance of nutritional monitoring

Circulating nutrients are essential indicators for overall health and body function [1] Amino acids (AAs), sourced from dietary intake and gut microbiota synthesis, and influenced by personal lifestyles, are important biomarkers for a number of health conditions[2] Metabolic profiling and monitoring are a key approach to enabling precision nutrition and precision medicine.[13] Current gold standards in medical evaluation and metabolic testing heavily rely on blood analyses that are invasive and episodic, often requiring physical visits to medical facilities, labour-intensive sample processing and storage, and delicate instrumentation (for example, gas chromatography–mass spectrometry (GC–MS)).[14]

Sweat is an important body fluid containing a wealth of chemicals reflective of nutritional and metabolic conditions. The progression from blood analyses to wearable sweat analyses could provide great potential for non-invasive, continuous monitoring of physiological biomarkers critical to human health.

B. Wearable vitamin sensors

Currently reported wearable electrochemical sensors focus primarily on a limited number of analytes including electrolytes, glucose and lactate, owing to the lack of a suitable continuous monitoring strategy beyond ion-selective and enzymatic electrodes or direct oxidation of electroactive molecules. Thus, most clinically relevant nutrients and metabolites in sweat are rarely explored and undetectable by existing wearable sensing technologies.

By integrating mass-producible laser-engraved graphene (LEG), electrochemically synthesized rationally assembled redox-active receptors (RARs) and ‘artificial antibodies’, researchers have demonstrated a powerful universal wearable biosensing strategy that can achieve selective detection of a broad range of biomarkers (including all essential AAs, vitamins, metabolites, lipids, hormones and drugs) and reliable in situ regeneration.[21-26]

Challenges and future prospects

1. Current wearable sensor technologies primarily focus on a limited set of analytes, such as electrolytes, glucose, and lactate, due to the lack of suitable continuous monitoring strategies beyond ion-selective and enzymatic electrodes or direct oxidation of electroactive molecules.
2. Developing wearable sensors capable of measuring more specific physiological events, such as confirming fetal health, differentiating seizures from physical exertion, monitoring dehydration, tracking blood glucose levels, and mapping viral infections, remains a challenge.
3. In some cases, advanced techniques like fluid handling, preconcentration, incubation, and others may be required to satisfy the most challenging applications in detection through wearable sensors.
4. Achieving effective contact between sensors and skin is crucial for acquiring high-quality physiological signals, as incompact contact can lead to lower signal quality.
5. Identifying physiological signs in real-time during daily living is critical to maximize the quantity of data for accurate monitoring and interventions.

Despite these challenges, wearable graphene sensors have the potential to raise the quality of physiological information and have a promising future in healthcare and telemedicine due to their flexibility, biocompatibility, and electrical properties.

The researchers envision that this wearable technology could play a crucial role in the realization of precision nutrition through continuous monitoring of circulating biomarkers and enabling personalized nutritional intervention. Additionally, this technology could be reconfigured to continuously monitor a variety of other biomarkers towards a wide range of personalized preventive, diagnostic, and therapeutic applications.

Conclusion

The field of flexible and wearable nanoelectronics has witnessed remarkable advancements, driven by the exceptional properties of graphene. This revolutionary nanomaterial has paved the way for innovative sensors capable of continuous, non-invasive monitoring of various biomarkers and physiological parameters. From tracking pH levels and monitoring essential nutrients to detecting cytokines and measuring ion concentrations, graphene-based wearable sensors offer a promising approach to personalized healthcare.While significant progress has been made, challenges remain in terms of device reproducibility, specificity in complex biological environments, and achieving optimal wearability and user comfort. However, ongoing research efforts in material synthesis, device architectures, and fabrication techniques hold the potential to overcome these obstacles. As the field continues to evolve, wearable nanoelectronics powered by graphene's remarkable capabilities are poised to play a pivotal role in revolutionizing healthcare, enabling real-time monitoring, early disease detection, and personalized interventions for improved patient outcomes.

References:

1. Bae, S., Kim, H., Lee, Y., Xu, X., Park, J. S., Zheng, Y.,... & Kim, K. S. (2010). Roll-to-roll production of 30-inch graphene films for transparent electrodes.Nature Nanotechnology, 5(8), 574-578. https://doi.org/10.1038/nnano.2010.132
2. Bonaccorso, F., Sun, Z., Hasan, T., & Ferrari, A. C. (2010). Graphene photonics and optoelectronics.Nature Photonics, 4(9), 611-622. https://doi.org/10.1038/nphoton.2010.186
3. Chen, J., Yao, B., Li, C., & Shi, G. (2013). An improved Hummers method for eco-friendly synthesis of graphene oxide.Carbon, 64, 225-229. https://doi.org/10.1016/j.carbon.2013.07.055
4. Geim, A. K., &Novoselov, K. S. (2007). The rise of graphene. Nature Materials, 6(3), 183-191. https://doi.org/10.1038/nmat1849
5. Pittala, C.S., et al., "1-Bit FinFET carry cells for low voltage high-speed digital signal processing applications," Silicon, 15(2), 2023, pp.713-724.
6. Nizam, Taaha, et al. "Novel all-pass section for high-performance signal processing using CMOS DCCII." TENCON 2021-2021 IEEE Region 10 Conference (TENCON). IEEE, 2021.
7. Geim, A. K. (2009). Graphene: Status and prospects.Science, 324(5934), 1530-1534. https://doi.org/10.1126/science.1158877
8. Goler, S., Vollebregt, S., Zhang, G. J., & De Smet, L. C. P. M. (2016). Graphene oxide as an enabling material for flexible and wearable nanoelectronics.Advanced Materials, 28(11), 2292-2315. https://doi.org/10.1002/adma.201502694
9. Lee, C., Wei, X., Kysar, J. W., & Hone, J. (2008). Measurement of the elastic properties and intrinsic strength of monolayer graphene.Science, 321(5887), 385-388. https://doi.org/10.1126/science.1157996
10. Liu, Z., Li, J., Sun, Z., & Xu, Y. (2013). Graphene-based sensors for wearable electronics.Small, 9(16), 2815-2831. https://doi.org/10.1002/smll.201202385
11. Luo, Z., Ma, L., Wang, Z., Tang, D., Shi, H., & Liu, F. (2016). Graphene-based flexible electronics and photonics.Journal of Materials Chemistry C, 4(34), 7614-7621. https://doi.org/10.1039/C6TC01649K
12. Babu, D. Vijendra, et al. "Digital code modulation-based MIMO system for underwater localization and navigation using MAP algorithm." Soft Computing (2023): 1-9.
13. Selvam, L., et al. "Collaborative autonomous system based wireless security in signal processing using deep learning techniques." Optik 272 (2023): 170313.
14. Novoselov, K. S., Fal'ko, V. I., Colombo, L., Gellert, P. R., Schwab, M. G., & Kim, K. (2012). A roadmap for graphene. Nature, 490(7419), 192-200. https://doi.org/10.1038/nature11458
15. Pang, H., Zhang, C., Chen, Z., & Ma, J. (2018). Wearable electronics: Advanced materials and devices.Advanced Functional Materials, 28(43), 1801208. https://doi.org/10.1002/adfm.201801208
16. Rani, B. M. S., et al. "Disease prediction based retinal segmentation using bi-directional ConvLSTMU-Net." Journal of Ambient Intelligence and Humanized Computing (2021): 1-10.
17. Sahoo, S., Polaki, S. R., Jaiswal, A., & Rout, C. S. (2019). Recent progress in the development of graphene-based flexible devices for healthcare applications.Biosensors and Bioelectronics, 126, 504-518. https://doi.org/10.1016/j.bios.2018.11.050
18. Rani, B.M.S., et al., "Road Identification Through Efficient Edge Segmentation Based on Morphological Operations," Traitement du Signal, 38(5), 2021.
19. Vijay, V. and Srinivasulu, A., "A novel square wave generator using second-generation differential current conveyor," Arabian Journal for Science and Engineering, 42(12), 2017, pp.4983-4990.
20. Stoller, M. D., Park, S., Zhu, Y., An, J., & Ruoff, R. S. (2008). Graphene-based ultracapacitors.Nano Letters, 8(10), 3498-3502. https://doi.org/10.1021/nl802558y

21. Sun, Z., Yan, Z., Yao, J., Beitler, E., Zhu, Y., & Tour, J. M. (2010). Growth of graphene from solid carbon sources. Nature, 468(7323), 549-552. https://doi.org/10.1038/nature09579
22. Tang, L., Wang, Y., Li, Y., Feng, H., Lu, J., & Li, J. (2009). Preparation, structure, and electrochemical properties of reduced graphene sheet films.Advanced Functional Materials, 19(17), 2782-2789. https://doi.org/10.1002/adfm.200900377
23. Tian, H., Shu, Y., Wang, X. F., Mohammad, M. A., Bie, Z., Xie, Q. Y., & Yang, Y. (2014). A graphene-based resistive pressure sensor with record-high sensitivity in a wide pressure range.Scientific Reports, 5(1), 8603. https://doi.org/10.1038/srep08603
24. Wu, W., & Pan, T. (2017). High-performance flexible and stretchable electronics with intrinsically designed and optimized structures.Advanced Materials, 29(21), 1605210. https://doi.org/10.1002/adma.201605210
25. Yang, X., Zhang, X., Ma, Y., Huang, Y., Wang, Y., & Chen, Y. (2008). Superparamagnetic graphene oxide–Fe3O4 nanoparticles hybrid for controlled targeted drug carriers.Journal of Materials Chemistry, 19(18), 2710-2714. https://doi.org/10.1039/b818547c
26. Zhang, Y., Tang, T., Girit, C., Hao, Z., Martin, M. C., Zettl, A.,... &Crommie, M. F. (2009). Direct observation of a widely tunable bandgap in bilayer graphene.Nature, 459(7248), 820-823. https://doi.org/10.1038/nature08105