

A review of field-effect transistor transducing system in quantum transport measurements

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ABSTRACT

Field-effect transistor (FET)-based sensors have entered the market as they have high sensitivity and are portable electronic devices. Their performance has been enhanced by coating smart nanomaterials in the channel of the FET device as sensing elements. They find applications in medicine, environmental monitoring and food industries. Quantum materials exhibit quantum mechanical properties that are useful for high precision measurements. Quantum sensing technologies will become more efficient when integrated with the fields of artificial intelligence and internet of things. They can measure various physical parameters such as magnetic field and gravity as they benefit from quantum phenomena such as entanglement and quantum interference. They are superior to conventional sensing devices as the sensing quantum materials exhibit wavelike nature and the property of entanglement in which two or more particles are intertwined regardless of the distance between them. Quantum sensors can provide the solution for a big demand of accurate and reliable measures existing globally. The market of quantum sensing grows faster when compared to other kinds of quantum technologies such as quantum computing and quantum communication. Measurements of many physical parameters with quantum sensing have been demonstrated practically and have been made as commercial. Even at its infant stage, this technology is capable for doing business and highly applicable for various industries. Field-effect transistor-based sensors possess high charge sensitivity, low power consumption, scalability and compatibility with advanced semiconductor devices. Detection of electrical, magnetic, optical, and biochemical signals with high precision can be achieved using low-dimensional materials and quantum transport engineering. This work explores various FET transistors including graphene FETs, carbon nanotube FETs, and two-dimensional material-based transistors with quantum confinement and carrier transport properties. Quantum phenomenon such as quantum tunneling, Coulomb blockade, ballistic transport, and surface charge modulation are also discussed. The applications of FET-based quantum sensors in spin detection, magnetic field sensing, biosensing, environmental monitoring, and quantum information technologies are introduced. The opportunities in quantum sensing to develop highly sensitive, miniaturized, and energy-efficient sensing devices are also explained in detail. To inline the potentials of FET into the current cutting-edge scenario, this overview explored the fundamentals of FET in quantum sensing and updated.

Keywords: Quantum sensing; Field effect transistor; Food security; Water quality analysis

1. INTRODUCTION

The quantum phenomena exhibited by novel materials provide high precision for sensing applications. Materials with such superior properties include diamonds with nitrogen-vacancy centers, graphene quantum dots, cold atoms, topological insulators, two-dimensional materials such as graphene, MXenes, borophene and molybdenum disulfide [1]. A high sensitivity is achieved when the materials that possess extraordinary quantum properties are synthesized. The two-dimensional materials are generally synthesized by chemical vapor deposition, mechanical methods and chemical methods [2]. The sensing ability of the materials is greatly improved by the quantum phenomena of entanglement and coherence. Innovative synthesis methods should be adopted to control the quantum states of materials that will maintain coherence and entanglement. Sensor devices with high sensing capacity will then be developed with these kinds of materials. Besides, two-dimensional materials are characterized by atomic force microscopy, Raman spectroscopy, and quantum

transport measurements to analyze their quantum characteristics. The transport of charge carriers within these materials are investigated using quantum transport measurements. Nanoscale materials possess quantum qualities and find applications in quantum computing, electronics and quantum sensing. A revolution has been created for quantum sensing that exceeds the existing semiconductor technology. Thus, sustainable technologies will be developed with portable sensor devices and reduced energy consumption [3].

2. QUANTUM TRANSPORT MATERIALS AND MEASUREMENTS

Quantum sensors find applications in many fields. Quantum-based atomic clocks have been developed to analyze the atomic transitions. Measuring magnetic fields is highly useful for geological surveying and medical imaging using highly sensitive magnetometers. Geological measurements related to volcanic activity and subsurface mapping are made with quantum

gravimeters. Quantum sensors are also applied in rotational dynamics with highly sensitive gyroscopes for navigation. Quantum related chemical and gas sensors detect even trace amounts of molecules in environmental monitoring and medicine. Rapid diagnosis of several diseases is made using high-precision quantum sensors. Quantum sensors help in navigation like aerospace in high altitudes. They detect electromagnetic radiation for defense applications. Power management systems use quantum sensors to measure consumption of energy in smart grids [4]. There are two types of quantum sensing, one is photonic quantum sensing and the other is non-photonic quantum sensing. In photonic quantum sensing, quantum dots are used as sensing materials where the quantum confinement effect brings more accuracy. Non photonic quantum sensing is used to measure physical quantities such as temperature and magnetic field. Here the quantum parameters such as spin qubits and trapped ions are clearly defined [5].

Scanning Tunneling Microscopy has been used to analyze the surfaces of quantum materials using the concept of quantum tunneling. The properties of quantum materials such as surface topography, electronic properties and manipulation of individual atoms are provided by this high-end equipment. The instrument has a sharp and tungsten/platinum-iridium tip that probes the sample to extract the properties of the sample. The electrons tunnel the potential barrier when an external voltage is applied. The tunneling current provides information regarding the surface topography. The electronic structure and energy levels of quantum materials are obtained by measuring their density of states values. Scanning Tunneling Microscopy is used to analyze the quasiparticle excitations of superconducting materials.

The electronic properties of two-dimensional materials, domain structures of ferromagnetic materials and strongly correlated electron systems are also analyzed by this instrument. Topological materials are investigated using scanning tunnelling microscopy for their energy band structures, Landau-level spectroscopy, quasi-particle interference and electron correlations in low-dimensional structures. Charge density-tuned scanning tunnelling microscopy is used to study the correlated electrons in two-dimensional quantum material. The instrument allows advanced surface-imaging subatomic spatial resolution and energy-resolved density of states [6]. Scanning tunneling microscopy is especially used to characterize graphene at the atomic level. It shows the presence of ripples, wrinkles, grain boundaries, and defects of graphene. The density of states and the transport of charge carriers in graphene can be investigated in detail with this equipment [7].

Conductive atomic force microscopy (CAFM) with its single-atom resolution is used to identify the defects in two-dimensional materials such as molybdenum disulfide and graphene. CAFM analyzes the quantum mechanical properties of materials through measurement of topography, electrical, magnetic, and mechanical properties. The electrical properties of materials as revealed from CAFM correlate the structure of materials with their electrical conductivity using a phenomenon termed Fermi-level pinning at interfaces. The conductive AFM tip made of platinum, diamond, or highly doped silicon provides the information about both topographical imaging and electrical conductivity. The height variations of the sample's surface are related to the topography. The conductive AFM tip scans the sample and the current between the tip and the sample is measured. The measurements of voltage-current (V-I) characteristics give the value of resistance of the sample [8]. Figure 1 shows how CAFM is used to analyze various two-dimensional materials such as graphene, hexagonal boron nitride and some other heterostructures of 2D materials [9].

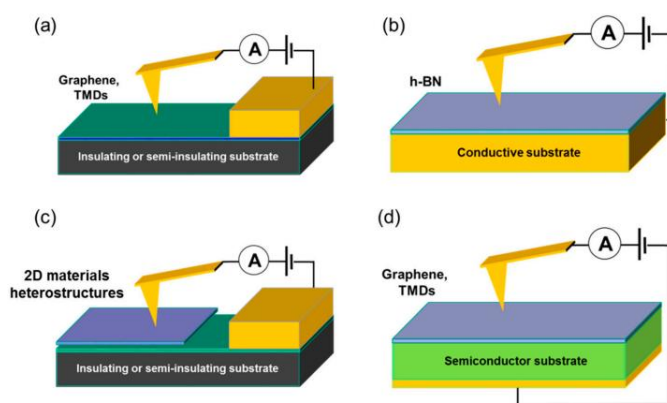


Fig. 1. Conductive atomic force microscopy to measure the electrical conductivity of quantum materials [9].

FET devices are used to fabricate biosensors and gas sensors. The sensing mechanism of a FET device is measuring the change in the current between the electrodes when an electric field is applied to the gate. The gate dielectric is often made of silicon with a silica layer which is used as a substrate. Sensing materials such as metal oxides, 2D materials like graphene or MoS₂ and carbon nanotubes are coated on the dielectric gate that are immobilized with probes like enzymes, antibodies and aptamers [10]. The surface of the device is passivated using SU-8 photoresist to protect the device from short circuits. The performance of the FET sensor is evaluated through the analysis of the transfer and output characteristics of the device.

2.1. Quantum materials and their potentials

Quantum dots are small semiconductor nanocrystals with quantum confinement that find applications in displays and solar cells. Single molecules possess unique electronic structure and exhibit quantum properties and are useful in semiconductor devices. One-dimensional carbon nanotubes show ballistic transport for long distance because of their high electrical conductivity and more strength. Two-dimensional materials like graphene with their exceptional electronic properties can replace silicon in electronic industries (Table 1). The quantization of resistance at low temperature and high magnetic field from quantum Hall measurements of graphene provide the values of charge of the electron and Planck's constant thus making graphene as a material for quantum resistance standards.

Semiconductor materials with low-dimensional structures such as quantum dots, quantum wells and nanowires exhibit quantum behavior as their charge carriers obey spin-orbit coupling. Doping nitrogen atoms in the graphene lattice gives nitrogen-doped graphene quantum dots which is a promising quantum material. The material has excellent quantum size effects, electronic and optical properties suitable for quantum sensing. The doping of nitrogen is performed by the methods such as hydrothermal or ultrasonic treatments. The quantum transport measurements have been carried out in many quantum materials such as Graphene, transition metal dichalcogenides, and topological insulators as these materials are well-known for their electronic properties. Superconducting materials are regarded as quantum materials since their quantum phenomena arise from the formation of Cooper pairs i.e. pair of electrons couple together due to the interaction of the crystal lattice. Van der Waals heterostructures are emerging quantum materials where two-dimensional materials are stacked one over the other

and their interaction is due to weak van der Waals forces. They possess unique properties such as superconductivity or topological states. Topological Insulators are the quantum materials that conduct electricity over the surfaces and exhibit insulating behavior as a whole. Three-dimensional topological insulators are useful for quantum sensing because of their surface states, robust against perturbations and spin-momentum locking. The materials are used to measure magnetic fields and electric fields and to develop various bio sensors. Bismuth selenide, bismuth telluride and mercury telluride are identified for this application. Quantum anomalous Hall insulators exhibit quantum Hall effect at zero magnetic field that find applications

in quantum sensing. Bismuth selenide possesses metallic surface states protected by time-reversal symmetry. It shows a high performance towards gas sensing for the detection of nitrogen dioxide of with very low limit of detection of 0.06 ppb [11]. Table 1 presents a comparative analysis of the physical and electrical properties of various two-dimensional (2D) materials. Key parameters, including carrier mobility, quantum transport behavior, electrostatic gate control, band gap, carrier scattering, and current saturation, are compared to highlight their distinctive features and suitability for quantum sensing applications.

Table 1. Comparative analysis of physical/electrical properties related to 2D materials

Property	Graphene	MoS ₂	WS ₂	Black Phosphorus
Crystal Structure	Hexagonal honeycomb lattice	Layered hexagonal TMD	Layered hexagonal TMD	Orthorhombic puckered structure
Band Gap	0 eV (semi-metal)	~1.8 eV (monolayer)	~2.0 eV	0.3–2.0 eV (thickness dependent)
Carrier Mobility	Very High (>10,000 cm ² V ⁻¹ s ⁻¹)	Moderate (10–200 cm ² V ⁻¹ s ⁻¹)	Moderate–High	High (~1000 cm ² V ⁻¹ s ⁻¹)
ON/OFF Current Ratio	Low (~10)	Very High (~10 ⁸)	High (~10 ⁶)	High (~10 ⁵)
Quantum Transport Behavior	Ballistic transport, Dirac fermions	Strong charge confinement	High carrier velocity	Anisotropic transport
Electrostatic Gate Control	Weak	Strong	Strong	Strong
Spin–Orbit Coupling	Weak	Moderate	Strong	Moderate
Thermal Conductivity	Extremely High	Moderate	Moderate	Moderate
Carrier Scattering	Low	Moderate due to phonons	Reduced scattering	Direction-dependent scattering
Current Saturation	Poor	Good	Good	Excellent
Environmental Stability	Excellent	Good	Good	Poor (oxidation sensitive)
Major Advantages	Ultra-high mobility and conductivity	Excellent switching and gate modulation	Strong spin-valley coupling	High mobility with finite band gap
Major Limitations	Absence of band gap	Contact resistance	Complex fabrication	Air instability
Best Quantum Applications	Quantum Hall effect, ballistic transport	Coulomb blockade, low-power FETs	Spintronics, valley trionics	Infrared sensing, anisotropic transport
Suitability for Quantum Transport Measurements	Excellent	Very Good	Excellent	Very Good

Nitrogen-vacancy centers are created in diamond by locating a nitrogen atom in the place of a carbon atom. These quantum materials are promising for quantum computing, quantum sensing, and nanoscale imaging. They exhibit optical sensing properties to detect various physical parameters such as magnetic fields, electric fields, temperature, and pressure. The manipulation of these materials at the sub-atomic level is highly useful in high-resolution imaging of materials and biological samples. They can be easily grown by chemical vapor deposition process. Vacancies in diamond can also be created by the processes of irradiation and annealing [12]. Cold atoms are cooled down very close to absolute zero by laser cooling and magnetic traps and are regarded as quantum materials. They are used as qubits in quantum computing and can be controlled with lasers. They are applied in quantum sensing for the detection of gravity, rotation, and magnetic fields. The sensors with cold atoms exhibit improved sensitivity and a high reliability. The quantum mechanical properties of cold atoms emerge only when they are cooled to very low temperatures using lasers. The



measurement of acceleration, rotation and gravitational fields are achieved through interference patterns obtained from the technique of atom interferometry. Electric fields can be measured by Rydberg atoms that have a single electron with more energy because of a high polarizability. Gravity and inertial forces are more accurately measured using sensors of cold atoms that find applications in underwater navigation. Information related to general relativity and dark matter can be explored using atom interferometers. A high sensitivity of cold atom sensors allows for measuring gravitational fields over vast scale in space. They are able to detect the natural resources such as water, oil, and minerals present in the underground. Climate change is monitored through the analysis of mass distribution of the earth, ice sheets and sea levels. Borophene is a two-dimensional material made from boron atoms which is recognized as a quantum material due to its remarkable electronic and mechanical properties. It can be used for the fabrication of batteries, supercapacitors, optoelectronic, and sensor devices with high performance [13].

2.1.1 Properties of quantum materials

The first and foremost measurement in quantum transport measurements is to measure the property of electrical resistance which provides the information regarding the flow of electrons inside a material. Measurements using Hall effect apparatus provide the details about the mobility of charge carriers, carrier concentration and the polarity of charge carriers. The quantization of resistance when the electrons are allowed to move in two-dimensions is analyzed from the data acquired from quantum hall measurements. The energy levels and electronic structure of quantum materials can be derived from tunneling spectroscopy. The analysis of the flow of heat in quantum materials supplies the information regarding quantum coherence. Quantum transport measurements not only clarify the fundamental laws of physics and the behavior of materials at the nano scale but also, they allow to design new electronic devices with unique properties for various applications. They also help to tune the electronic properties of materials so that new technologies can be explored. The understanding of properties of quantum materials is more important to build quantum bits essential for quantum computing applications. The quantum properties of the materials are analyzed by studying the transport of charge carriers in the materials through various quantum transport phenomena. When the size of the materials is in the nanoscale, quantum mechanical properties come into effect. Quantum confinement come as the mainstay when the size of the materials is the same as the de Broglie wavelength of the electrons and holes or the time of collision. The field of quantum technology describe the properties such as ballistic transport, quantum tunneling and quantum Hall effect as the main characteristics for a quantum material. Ballistic transport allows the propagation of electrons inside a material without scattering thus paving the way for quantum coherence. Electrons rarely scatter thus resulting in a diffusive transport. Electrons with less energy tunnel through the potential barriers in many low-dimensional materials. A change in the resistivity due to the application of magnetic field and a very low temperature results in quantum Hall Effect. Single electron transistor transfer electrons between the electrodes of the field effect transistor one by one which is able to control the tunneling of electrons [35, 36, 37].

2.1.2. Properties of quantum materials

The quantum mechanical properties of materials are analyzed using the measurements of transport of electrons or holes when electric or magnetic fields are applied. The results will then explore various phenomena like superconductivity, topological effects and quantum Hall effects that are essential for the

development of new quantum technologies. High-speed transistors, quantum computers, and spintronic devices can be developed using quantum technology. The performance of solar cells and batteries can be made more efficient through understanding of quantum transport phenomena. The existence of qubits in both the states allows for executing complex calculations in quantum computing. The properties of superposition and entanglement are the most important quantum phenomena for the applications of quantum materials in computing. Superposition means for a qubit with a combination of states at the same time whereas entanglement means linking two or more qubit regardless of the distance between them. Quantum materials with magnetic properties are analyzed using Magnetic Force Microscopy which is similar to of atomic force microscopy. This technique possesses a magnetized tip to probe the material and provides the magnetic interactions and the surface magnetic structure of the sample with more resolution. The scanning is performed in a non-contact mode, and the images of magnetic domains are displayed. The analysis of quantum effects is greatly improved with the results of the experiments such as Quantum Hall Effect and single-electron transistors. The information regarding exotic quantum state, the relation between topology and the movement of electrons and resistance quantization are inferred from quantum Hall effect measurements through the application of magnetic field over the quantum materials. Experiments with single electron transistors lead to the development of nano electronics. All these quantum mechanical effects have been demonstrated in nanostructures with one dimension at the nanoscale [38, 39, 40]. The phenomenon of quantum confinement has been explained in low-dimensional quantum materials where electrons make transition between specific energy levels. Some other quantum transport properties include single electron tunneling, negative differential resistance and the Kondo effect i.e. the electrical resistance at low temperature is decreased by the addition of magnetic impurities with the metals. In quantum materials, the spin-dependent transport of charge carriers exhibits the behavior that can be used to develop spintronic devices. The electron transport is often limited by inelastic scattering and energy dissipation within the materials [14].

3. FABRICATION OF FET TRANSISTORS FOR DOWNSTREAM APPLICATIONS

FET systems are used for biosensing, by measuring the changes in electrical properties when exposed to biomolecules. These devices make use of a semiconductor channel called as gate which is immobilized with a recognition element that will bind to the target molecules. The device is fabricated with two electrodes such as source and drain that are separated by a gate. The current flow between the two electrodes is controlled by the gate with an insulating layer. FET is normally fabricated on a silica substrate. The silicon wafer is oxidized for a thickness of 100 nm to silicon dioxide to form the gate dielectric. Lithography techniques are applied to pattern electrodes such as source, drain, and gate. Lithography involves coating the silicon wafer with a photoresist which is illuminated with light or electron beam through a mask. The electrodes are deposited with the required materials and etched to obtain the desired structure and finally FET is passivated and checked for its performance. The concentration of the biomolecule is quantified by measuring the current flow between the two electrodes. As the device is portable, it can be used for making wearable sensors. Fabrication of non-enzymatic sensors is another added advantage with FET transistor- based sensing devices. FET transistors are used to fabricate sensors with high sensitivity, high selectivity, fast response times and real-time monitoring. They are integrated with electronic devices due to their compatibility with high end CMOS fabrication methods. Nowadays, healthcare monitoring is being modernized through the development of wearable sensors, enabling non-invasive, continuous detection. FET transistors are

emerging as suitable candidates for the fabrication of biosensors in this field.

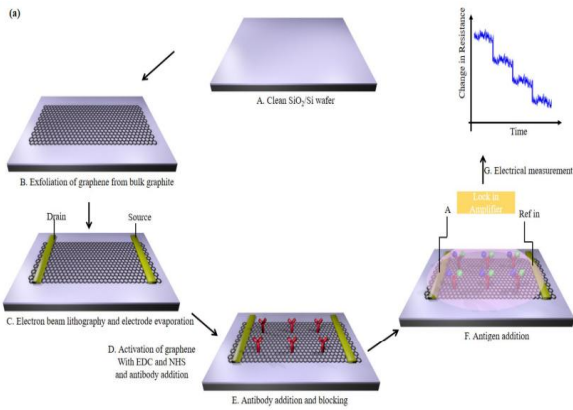


Figure 2: Fabrication of the biosensor using graphene [15].

The electrode-patterning of FET transistors can be fabricated by electrohydrodynamic printing method where electric field is applied to coat materials over a substrate. The fabrication of the device is optimized for the number of printing cycles and concentration of the ink. The optimized device is tested for its sensing ability by performing output characteristics and transfer characteristics of the device. FET sensors are fabricated using $\text{Ti}_3\text{C}_2\text{T}_x\text{-MXene}$ as the sensing material by electrohydrodynamic process. A high sensitivity is attributed to the high electrical conductivity of $\text{Ti}_3\text{C}_2\text{T}_x\text{-MXene}$ materials. These FETs greatly adhere to the substrate and provide a wide range of resistance. The biosensor is used to detect aflatoxin B1 by using aflatoxin antibody as the biomarker. The fabricated FET sensor is able to detect up to 0.01 ppb with a limit of detection of 5.69 ppb of aflatoxin B1. This method is superior to conventional chromatographic techniques as it does not involve any complex sample preparation methods [16].

FET sensors are developed by drawing the sensing materials on paper for the detection of glucose, pH and temperature. The electrodes of the device are fabricated using the conducting polymers like PEDOT: PSS(Poly(2,3-dihydrothieno-1,4-dioxin)-poly (styrene sulfonate)) in the substrate of PDMS(Polydimethylsiloxane). The semiconductor gate channel is formed with the composite of copper oxide/multiwall carbon nanotubes / Ti_3C_2 MXene. The fabrication steps with the sensor is shown in Figure 2 for generating high sensitivity and stability. Figures 3 and 4 show the sensor for temperature, glucose and pH sensing integrated within a single device. Figure 4 provides the sensing response of the gate materials in terms of output characteristic curves of FET sensor device for glucose, temperature and pH sensing [17].

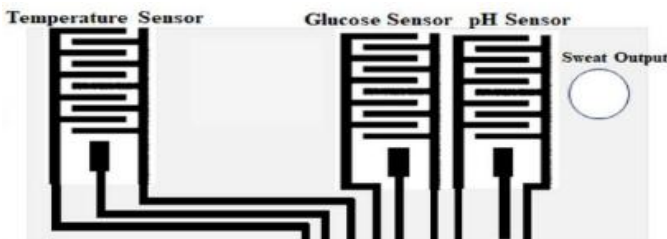


Figure 3: electronic skin drawn on paper [17]

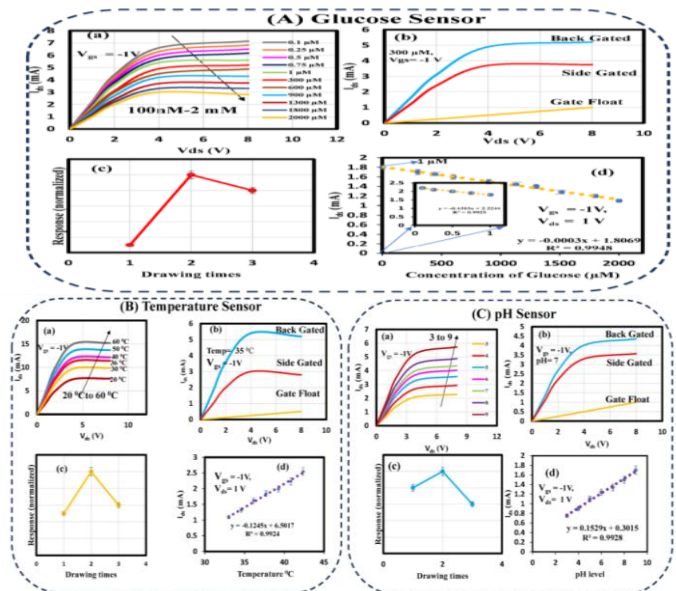


Fig. 4. Sensing response of the gate materials in terms of output characteristic curves of FET sensor device for a. glucose b. temperature and c. pH sensing [17].

FET sensors are fabricated by spin coating method through deposition of semiconductors and dielectrics. The solution of the materials is dispensed over a substrate and is spun at high speed to distribute the solution as a uniform thin film. All the components of FET such as the semiconductor channel, the gate and the source/drain electrodes are coated using this process. The parameters such as concentration of the solution, the spin speed, and the spin time are adjusted to vary the thickness of the layers. The coated layer is then sintered using laser to prepare the electrodes for FET device. Spin coating is a simple, low-cost method that provides precise control over the thickness of films. The electrodes of the device are fabricated using conducting materials such as silver nanoparticle ink and conducting polymers. FET transistors are fabricated using self-patterning with high resolution where the expected patterns are created using the interactions of materials [18].

As FET sensors are portable, they can be integrated with wearable devices. Extended-gate Field-Effect Transistor is a special kind of FET in which the gate is separated from the transistor's channel. This allows a high sensitivity, stability of the device and immersion of the device in a solution becomes possible thus reducing hysteresis and drift. In extended-gate FET sensors, the geometry and materials of the sensing element can be optimized and can be made cost effective. They find applications in various fields including early diagnosis of diseases, detection of pollutants, detection of pathogens in food, detection of gases and chemicals in industries. EG-FET sensors have great scope in entering the market as powerful sensing platforms due to their highly sensitive and selective detection capabilities [19].

4. FET TRANSISTORS FOR QUANTUM SENSING

The electrons are trapped inside circular loops in graphene quantum dots. They travel with high velocity and are highly sensitive to applied magnetic fields. These graphene quantum dots can be used to develop sensors with high sensitivity to measure magnetic fields. Also, electrons in graphene behave like massless particles like photons and move with greater velocity. They are termed as Dirac fermions and ultra-relativistic. Graphene quantum dots with such electrons are like atoms and molecules thus exhibiting quantum phenomenon [20].

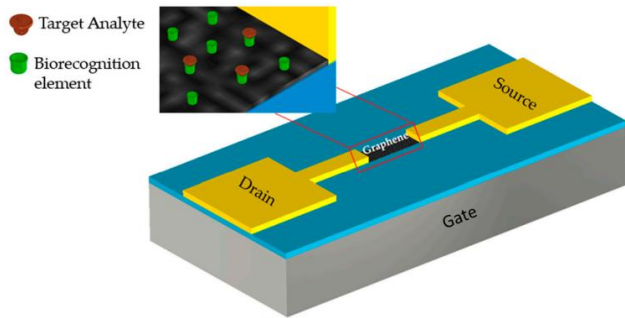


Fig. 5. Graphene FETS for biosensing [21].

Quantum sensors are superior to conventional sensors in that they are able to measure very small changes in the quantity of target molecules. They allow for stable superposition of states and is described as quantum coherence. The superposition results in interference patterns that are used to detect the changes in physical quantities. Quantum materials possess entangled particles that are connected together in a manner and separated by a finite distance. This kind of entanglement is the reason for increased precision in quantum sensors. Biomedical sensors with high spatial resolution and sensitivity for brain imaging to single-cell spectroscopy are enabled due to quantum coherence properties (Table 2) [22]. Table 2 summarizes the best-performing two-dimensional (2D) materials with respect to key physical, electrical, and optoelectronic properties.

Table 2. Comparative analysis of the performance of quantum materials.

Property	Best Performing Material
Highest Mobility	Graphene
Best ON/OFF Ratio	MoS ₂ / WSe ₂
Best Infrared Detection	Black Phosphorus
Best Optical Quantum Response	WS ₂ / WSe ₂
Best Substrate/Dielectric	h-BN
Best Electrochemical Sensitivity	MXenes
Best Scalability	MoS ₂
Best Environmental Stability	h-BN and WS ₂

4.1. Carbon material incorporated into field-effect transistors

4.1.1. Graphene field-effect transistors

Graphene field-effect transistors with graphene's high electrical conductivity, high electron mobility and remarkable physical properties can recognize biomolecules, chemicals and gases with more sensitivity. Graphene possesses large surface area which is used to detect even very low concentration of the target molecule. Graphene can be functionalized for specific molecules particularly for the diagnosis of some specific diseases [23]-[24]. The carbon atoms in graphene do not react with the target molecules. So, enzymes, antibodies and aptamers are adsorbed over the sensing surface to achieve biomolecular recognition. Then, covalent bonding, electrostatic forces or Van der Waals forces allow for change in the charge transport of graphene. Graphene FETs have been demonstrated for the identification of Chorionic Gonadotropin antigen, a hormone used to check pregnancy and cancer at 1 pg per ml. Graphene FETs fabricated with graphene/hexagonal boron nitride attain a mobility of 100,000 cm²V⁻¹s⁻¹ and charge carrier density of 5 × 10¹¹ cm⁻². Field-effect transistors are fabricated by coating carboxyl groups functionalized graphene on Si/SiO₂ substrate to detect Japanese encephalitis and Avian influenza virus.

4.1.2. Carbon nanotube field-effect transistors

Carbon nanotubes are used to fabricate the gate as sensing platform using photolithography and lift-off techniques in FET transistors. An increase in the sensing ability of FET transistors has been shown by measuring drain source voltage and gate-source voltage of the device from the transfer curves obtained between drain and source. The sensing ability is also inferred from Ion/Ioff ratio and source-drain current versus gate voltage curve [25]. GFET sensors are reported to detect DNA, proteins, glucose, microorganisms, biomarkers of diseases like cardiovascular and cancer. The electrical sensing is analyzed using a Keithley source meter in 0.001× PBS solution. The gate voltage varies from 0 to 1.2 V at a scan rate of 0.03 V s⁻¹ and the source-drain voltage is maintained as 0.1 V [26]. The sensing ability of the FET can be increased by using hybrid materials as the sensing platform. MXene/graphene hybrid materials are developed to detect viruses such as influenza virus and SARS-CoV-2. The sensor exhibits a high sensitivity due to the high chemical sensitivity from MXene and a large surface area of single layer graphene [27].

4.1.3. MXene nanotube field-effect transistors

Biological fluids are enriched with nonspecific proteins and microorganisms. The interaction between these fluids and sensing materials results in more noise while analyzing with FET sensors. The semiconductor gate channel, which acts as a sensing platform is fabricated by encapsulating sensing materials inside hydrogels. SARS-CoV-2 and *E. coli* permeate inside the hydrogel embedded with MXene/graphene in a controlled manner. Detection is achieved with high sensitivity, high specificity and a very low concentration of 1 fg/mL is detected [28]. MXene/graphene is deposited over a polydimethylsiloxane microfluidic channel to develop an FET sensor. The PDMS substrate is laser-cut on which the source/drain electrodes are created using Galinstan, a liquid metal. Graphene grown by chemical vapor deposition and MXene are deposited one by one over the microfluidic channel. The obtained FET sensor is applied for the detection of viruses such as the influenza virus and SARS-CoV-2 [27].

4.1.4. Molybdenum disulfide nanotube field-effect transistors

Molybdenum disulfide (MoS_2) is used in FET sensors for sensitive and non-enzymatic detection. The material has two-dimensional structure and suitable bandgap that allows for easy fabrication and responds more effectively to the applied electric field. Point of care diagnosis and continuous monitoring are the strengths of this technology. These FET sensors possess a high reproducibility and biocompatibility [29]. FET sensors fabricated with two-dimensional materials can be easily transformed into commercial health monitoring devices as they are more economical, portable and rapid detection. Films of MoS_2 grown by chemical vapor deposition method are reported for DNA sensing. The fabricated FET sensors are used in prenatal testing for the identification of trisomy 21 syndrome. The detection ability of up to one femtomolar is achieved with the device when MoS_2 is decorated with small sized gold nanoparticles [30]. FET sensors using MoS_2 have been demonstrated for the detection of proteins such as immunoglobulin, β -actin and prostate-specific antigen. The presence of protein is detected from the channel doping and gate voltage offset. A concentration of $10^{-7} \mu\text{g } \mu\text{L}^{-1}$ of immunoglobulin causes a change in the channel doping of $\sim 37.9\%$ enhancement and gate voltage offset of 1.3 V. The FET sensor shows a different sensing mechanism for the proteins such as β -actin and prostate-specific antigen [31].

4.1.5. Field-effect transistors in potential sensing

Even though FET sensors offer rapid detection for biosensing, highly sensitive and reliable devices are required for the detection of low concentration of biomarkers. FET sensors are fabricated using MoS_2 as the sensing material for the detection of cytokine, signaling molecules in the immune system. The semiconductor gate channel is equipped with more reactive sites by ion etching process. The fabricated FET sensor with aptamer as the recognizing element provides a detection limit of up to 10^{-5} nM [32]. FET sensors are fabricated by the deposition of MoS_2 on Si/SiO_2 substrate as pH sensors. The source and drain electrodes are constructed using lithographic techniques whereas Ti/Au is coated by e-beam evaporation. Dielectric materials with high dielectric constant such as Hafnium (IV) oxide and Alumina/Hafnium (IV) oxide are deposited by atomic layer deposition as the insulating gate material that acts as the active material for pH sensing [33]. The charge transport properties of zinc oxide nanowire field effect transistor make them to find applications in nanoelectronics. Figures 6 & 7 shows the ZnO nanowire FET, its SEM image, output and transfer characteristics and measurements [34].

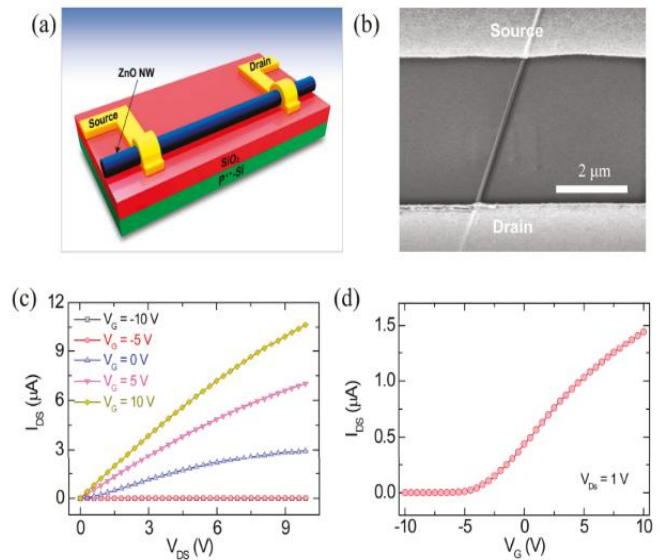


Fig. 6. Zinc oxide nanowire FET (a), SEM image (b), output (c), and transfer characteristics (d) [34].

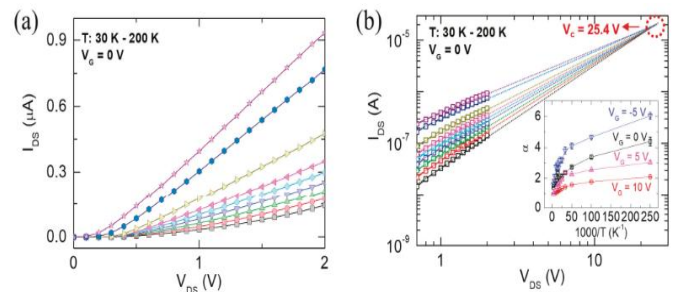


Fig. 7. (a&b) Temperature-dependent V-I measurements of the ZnO nanowire FET [34].

5. Conclusions

Materials such as diamond with nitrogen-vacancy centers, quantum dots, cold atoms, topological insulators and two-dimensional materials exhibit quantum properties. The high-end equipment like scanning tunnelling microscope and atomic force microscope are used to analyse the quantum materials. FET transistors are the best transduction devices to measure physical quantities with its excellent electrical characteristics. Smart nanomaterials are used as sensing elements in these devices in both label and label free detection. These devices show a high sensitivity and selectivity towards the target with the quantum confinement effect of the active materials. The device provides a high limit of detection even for a very low concentration of the analyte. Quantum sensing technology will provide solutions to the problems existing in the society particularly in the field of early diagnosis of dangerous diseases. Field-effect transistors are promising platforms for quantum transport measurements because they have high charge sensitivity, tunable carrier modulation and low-power operation. FET transducers enable most of the quantum phenomena such as Coulomb blockade, quantum Hall effects, ballistic transport, tunneling mechanisms, spin-dependent transport, and single-electron dynamics. The advantages include high carrier mobility, gate controllability, signal amplification, and environmental stability that make FET transducers suitable for quantum sensing. The contact resistance, device reproducibility, interface defects, thermal instability, fabrication complexity, and scalability should be improved for practical implementation of the device to find applications in quantum computing, quantum sensing, nanoelectronics, and optoelectronic systems.



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Competing interests: None

Data availability statement

No data has been generated to declare.

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