

Molybdenum Disulfide Biosensor for Cancer Biomarker Detection

Subjects: **Medical Laboratory Technology**

Contributor: Ziyue Qin , Jiawei Zhang , Shuang Li

Molybdenum disulfide (MoS_2) is a promising two-dimensional (2D) nanomaterial, whose unique adjustable bandgap shows excellent electronic and optical properties in the construction of biosensor interfaces. It not only has the advantages of a high catalytic activity and low manufacturing costs, but it can also further expand the application of hybrid structures through different functionalization, and it is widely used in various biosensors fields.

molybdenum disulfide

electrochemical sensor

optical sensor

cancer biomarkers

detection

1. Introduction

Cancer is the world's leading cause of death and the second most common disease ^[1]. At present, more than 200 types of cancers have been found. In general, imaging technologies such as ultrasound, positron emission tomography (PET), magnetic resonance imaging (MRI), and computed tomography (CT) are used for early screening, followed by confirmation through tissue biopsy and histology, so that patients can be treated in a timely manner, which can dramatically reduce cancer mortality ^{[2][3][4]}. However, traditional cancer detection methods are often invasive, expensive, complex, and time consuming. Rapid diagnosis and early prevention are crucial for the clinical treatment and management of cancer ^[5]. Cancer biomarkers, as important components of detection, prognosis, and providing an etiological analysis of cancer, are abnormal quantities of biological molecules generated by the body's response to the disease or directly by the cancer tumor itself, including DNA, RNA, genes, proteins, enzymes, peptides, exosomes, and metabolomics ^[6]. So far, the main cancer biomarkers that have been discovered include carcinoembryonic antigen (CEA), carbohydrate antigen 125 (CA125), carbohydrate antigen 15-3 (CA15-3), human epidermal growth factor receptor 2 (HER2), vascular endothelial growth factor 165 (VEGF_{165}), tissue-specific antigen (TPS), prostate-specific antigen (PSA), alpha-fetoprotein (AFP), squamous cell carcinoma antigen (SCCA), circulating tumour cells (CTCs), microRNAs, and exosomes ^[7]. They typically exist in the blood, urine, tears, oral fluids, and other tissues ^[8]. Cancer biomarker detection has accelerated the process of cancer diagnosis, and can obtain higher sensitivity and faster cancer screening. Enzyme-linked immunosorbent assay (ELISA) ^[9], polymerase chain reaction (PCR) ^[10], clustered regularly interspaced short palindromic repeats Cas9 (CRISPR-Cas9) ^[11], loop-mediated isothermal amplification (LAMP), time-resolved fluorescence spectroscopy (TR-FS), radioimmunoassay (RIA), and electrophoresis ^[12] have been used for the detection of cancer biomarkers ^[13]. In addition, emerging technologies such as artificial intelligence, long read sequencing, microarrays, DNA

methylation, and liquid biopsy are also committed to the development and high throughput profiling of many biomarkers to strengthen cancer management and improve early screening [14][15].

In recent years, compared with traditional technologies, biosensors have potential advantages such as a high sensitivity and selectivity, high accuracy, low cost, fast detection, high stability, availability, and ease of operation. They play an important role in diagnosing and quantitatively analysing biomarker concentrations, and are widely used in various fields such as healthcare, food inspection, and environmental testing [16]. Biosensors use various biomolecules as biometric recognition components, which are fixed on the sensor surface and converted into measurable electronic or optical signals through biological responses with the detection target substance for cancer biomarker detection [17]. Biosensors can be divided into electrochemical, optical, mass-dependent, and radiation sensitive biosensing platforms based on different transduction principles [18][19]. Developing efficient and practical biosensors usually requires consideration of the following aspects: (1) synthesis, manufacture, and assembly of suitable sensing materials; (2) selecting appropriate recognition or capture molecules; and the (3) integration of sensor surfaces with biomolecules [20][21]. With the development of nanotechnology in medicine and biotechnology, more and more researchers are combining different types of nanomaterials with optical, electrical, mechanical, and magnetic sensors to design nanosensors for the detection of cancer biomarkers [22]. Nanobiosensors are generally composed of nanomaterials and a sensor based on biometric recognition elements [23]. They can be combined according to the interaction of the affinity bond, covalent bond, cross-linking, capture, and physical adsorption [24].

Among the various nanomaterials, 2D-layered nanomaterials have attracted widespread research interest due to their quantum confinement, high absorption coefficient, high specific surface area, and tunable bandgap characteristics [25]. Among them, graphene has excellent physical properties, chemical adjustability, and application potential, and its synthesis, properties, and applications are widely known [26]. The impressive performance of graphene in various fields has aroused strong interest in the exploration of a wider range of 2D-layered nanomaterials “beyond graphene” [27]. Transition metal dichalcogenides (TMDs), as a new class of stable inorganic graphene analogues, have been further studied. Among them, MoS₂ is regarded as a representative of TMDs. Its single molecular layer is composed of an atomic layer of transition metal Mo sandwiched between two sulfur elements S [28]. Mo atoms and S atoms are closely connected by forming a strong covalent bond through coordination, and the interlayer is connected by a weak van der Waals force. This weak connection mode between layers provides conditions for MoS₂ stripping to form a single-layer 2D planar structure [29], showing unique electronic, optical, mechanical, and chemical properties [30][31][32]. Most importantly, due to the confinement of electrons/holes in ultra-thin planar structures, MoS₂ is highly sensitive to changes in the microenvironment [33], thus exhibiting advantages in the construction of biosensing interfaces [34][35].

2. Electrochemical Biosensors for Cancer Biomarkers Detection Based on MoS₂

Electrochemical sensors are mainly composed of sensitive components, signal transduction components, and nano modified electrode structures. Electrochemical analysis technology is an important detection method in the

field of biomedicine. Its basic principle is to analyse the changes in current or impedance signals generated by the interaction between the analyte and the electrode surface. It can monitor the charge movement between reaction interfaces and has significant advantages through its fast response [36]. In recent years, sensitive electrochemical biosensors have been developed for the detection of cancer biomarkers [37]. MoS₂ has a hexagonal lattice layered structure, which gives it excellent properties such as a high specific surface area, high electron mobility, thermal stability, catalytic activity, and diamagnetism, which is commonly used in semiconductor materials, catalysts, and lubricating materials, etc. [38][39][40]. The unique adjustable bandgap characteristic of MoS₂ provides excellent photoluminescence properties, which are widely used in optical devices such as photodetectors. Additionally, MoS₂, as a promising emerging nanomaterial, has low manufacturing costs, rich nanostructures, and is easy to functionalize, making it form hybrid structures with other precious metal nanomaterials, which is widely used in the field of electrochemical sensing [41]. This chapter divides electrochemical biosensors into potentiometry, amperometry, impedimetry, and photoelectrochemical (PEC) biosensors according to different signal transductions, and introduces the latest application progress of MoS₂ in cancer biomarker detection.

2.1. Potentiometry

Potentiometric sensors obtain information about analytes by measuring the current when potential changes, mainly including chronoamperometry (CA), cyclic voltammetry (CV), differential pulse voltammetry (DPV), and square wave voltammetry (SWV), which are widely used electrochemical analysis methods. These methods fix the biometric elements (such as antibodies, enzymes and aptamers) on the electrode surface, and monitor the current changes triggered when the analyte combines with the biometric element when the potential between the working electrode and the reference electrode remains constant. Within the linear potential range, the monitored peak current value is directly related to the concentration of the target analyte in the solution, so as to realize the detection of the target.

The electronic properties of MoS₂ are highly dependent on its phase structure. The ultra-thin MoS₂ has a good performance, but it is difficult to maintain stability in an independent state and is easy to aggregate [42]. In order to improve this problem, Ying et al. [43] used liquid-phase exfoliation and surface modification to synthesize 2H-MoS₂, and used platinum nanowire (Pt NWs) arrays as nanopillars, which were added to the ultra-thin 2D MoS₂ interlayer to form Pt NWs arrays@MoS₂ nano hybrid, which improved the specific surface area and porosity, and could be used as “electronic wires” to catalyze electron transfer at the interface, avoiding folding by creating new dimensions. Thus, stability and current signal enhancement were achieved.

Two main reasons that limit the practical application of MoS₂ in electrochemical sensing are that the strong van der Waals force effect between layers, which leads to aggregation and relatively low conductivity in layers [44]. In order to overcome these shortcomings, Su et al. [45] synthesized ionic liquid (IL) functionalized AuNPs/MoS₂/rGO nanocomposites for sensitive detection of cancer-specific target nucleolin. The linear range of the unlabeled electrochemical sensor obtained was 0.5 nM–1.0 μM, and the detection limit was 0.16 nM. Graphene has a large π electronic structure and edge, because of the synergistic effect, and the combination of MoS₂ and graphene can significantly improve the conductivity and large surface area of MoS₂ [46]. In addition, the introduction of AuNPs into

nanocomposites can not only fix the thioaptamer through the Au-S bond, which improves the affinity and specificity, but it can also enhance electron transfer and amplify the electrochemical signal.

2.2. Amperometry

Amperometric sensors achieve quantitative detection of analytes by applying a constant voltage to the sensing platform to detect the current generated by the conversion of corresponding electroactive substances. Because of their convenience and high accuracy, they are widely used in the detection of cancer biomarkers. As a result of the excellent catalytic activity of MoS₂ for the reduction in H₂O₂, Ma et al. [47] used the hydrothermal method to combine MoS₂ nanoflowers (MoS₂ NFs) with p-type metal semiconductor oxide cuprous oxide (MoS₂@Cu₂O), and, at the same time, the introduction of AuNPs generated MoS₂@Cu₂O-Au complexes by Au-S bonds as nanoprobes for signal amplification. The constructed sandwich immunosensor could detect the cancer marker alpha fetoprotein (AFP) of primary liver cancer in the wide linear range of 0.1 pg/mL to 50 ng/mL, demonstrating good application prospects. Ma et al. [48] prepared a sandwich-type electrochemical immunosensor for the sensitive detection of CEA by coupling tri-metallic yolk-shell Au@AgPt nanocubes (Au@AgPt YNCs) loaded on amino-functionalized MoS₂ NFs (MoS₂ NFs/Au@AgPt YNCs) with secondary antibodies. As a result of the biphasic synergistic catalysis, the synthesized MoS₂ NFs/Au@AgPt YNCs as a signal label effectively catalyzed the reduction of H₂O₂ to amplify the current signal, and realized the high-precision detection of CEA in the range of 10 fg/mL–100 ng/mL, with an LOD as low as 3.09 fg/mL (S/N = 3). These works provide ideas for the composite modification of MoS₂ with different nano forms and further applications in biosensing platforms.

2.3. Impedimetry

Impedance sensors are an important type of electrochemical sensing that obtains information about analytes by measuring the conductance through interface reactions on the electrode surface. This type of sensor is very sensitive to the change in electrode, and is in an advantageous position in the detection of biomarkers. Therefore, it is also widely introduced into the construction of the electrochemical sensing platform for the detection of cancer biomarkers. Jia et al. [49] prepared a novel nanohybrid of polyoxometalate-derived MoS₂ nanosheets (pd-MoS₂ NSs) using a hydrothermal method, which exhibited an excellent electrochemical activity and abundant catalytic sites. Furthermore, pd-MoS₂ NSs were vertically grown over β-FeOOH NRs (pd-MoS₂@β-FeOOH), serving as complementary DNA platforms for fixing oncogenes and tumour suppressor miRNA-21, using electrochemical impedance spectroscopy (EIS) to detect miRNA-21, with an LOD as low as 0.11 fM. In addition, microfluidic electrochemical immunochips have been evaluated as a powerful detection platform because of their high sensitivity, low cost, portability, and easy miniaturization. Sri et al. [50] synthesized MoS₂ NFs using the same method, and electrophoretically deposited them on an indium tin oxide (ITO)-coated glass substrate. Because of the morphology of MoS₂ NFs, antibodies can be effectively fixed on the electrode surface through physical adsorption. The biosensor can sensitively detect tumour necrosis factor-α (TNF-α) between 1–200 pg/mL, with an LOD as low as 0.202 pg/mL. Hu et al. [51] first prepared MoS₂ by liquid-phase exfoliation and formed a hybrid film with PDDA, designed a three-electrode system in the microfluidic chip, and introduced a MoS₂/PDDA film modified

with anti-AFP as the working electrode, Ag/AgCl as the reference electrode, and ITO as the counter electrode. The linear range of AFP detected by EIS was 0.1 ng/mL to 10 ng/mL, with an LOD of 0.033 ng/mL.

2.4. Photoelectrochemistry (PEC)

PEC utilizes photosensitive materials at the electrode interface as signal converters to analyse the electrical signals generated by analytes under light irradiation, combining the advantages of spectral analysis and electrochemical technology. MoS₂ exhibits excellent characteristics of a tunable bandgap in its transition from a blocky structure to a layered structure. The quantum confinement effect led to good visible light absorption and photoelectric conversion efficiency of layered MoS₂ as a direct bandgap semiconductor under visible light excitation, resulting in photocurrent generation. Therefore, it has been introduced into the application of photoelectrochemical sensing platforms. Hu et al. [52] utilized this mechanism to design a PEC sensing platform based on MoS₂/Au/GaN for the high sensitivity detection of AFP. MoS₂ can suppress the charge transfer of Au/GaN photoelectrodes, leading to a significant decrease in photocurrent. However, the presence of AFP can reduce the inhibitory effect on the photocurrent, thereby utilizing the difference in photocurrent to detect AFP. AFP detection is achieved in a wide linear range of 1.0–150 ng/mL, with an LOD of 0.3 ng/mL. This method has a good sensitivity and high selectivity for AFP detection. Wei et al. [53] synthesized a light-responsive ZnS/C/MoS₂ nanocomposite to construct a PEC immunosensor for detecting CEA, with a linear range of 2.0 pg/mL–10.0 ng/mL and an LOD of 1.30 pg/mL (S/N = 3), showing good analytical characteristics. In addition to the above sensing methods, other sensing methods based on MoS₂ are listed in **Table 1** to detect various cancer biomarkers.

Table 1. Electrochemical biosensors for cancer biomarkers detection based on MoS₂.

Method	Analytes	Electrode/Label	Linear Range	LOD	Ref.
Chronoamperometry	AMACR	Pt NWs array@2H-MoS ₂ /SPE	0.70–12.50 ng/μL	0.5 pg/μL	[43]
CV	CEA	Ab/rGO/MoS ₂ @PANI/GCE	0.001–80 ng/mL	0.3 pg/mL	[54]
CV	PSA	Ab/ce-MoS ₂ /AgNR/SPE	0.1–1000 ng/mL	0.051 ng/mL	[55]
DPV	CEA	Ab/MoS ₂ -PBNCs/GCE	0.005–10 ng/mL	0.54 pg/mL	[56]
DPV	CEA	Ag/MoS ₂ @Fe ₃ O ₄ -Ab2/CEA/Ab1/Ag/MGCE	0.0001–20 ng/mL	0.03 pg/mL	[57]
DPV	miRNA-182	ssRNA/MoS ₂ /Ti ₃ C ₂ /GCE	1 fM–0.1 nM	0.43 fM	[58]
DPV	CEA	MoS ₂ -AuNPs/HRP-Ab2/CEA/Ab1/MoS ₂ -AuNPs/GCE	10 fg/mL–1 ng/mL	1.2 fg/mL	[59]

Method	Analytes	Electrode/Label	Linear Range	LOD	Ref.
DPV	Nucleolin	TNA/AuNPs/MoS ₂ /rGO/GCE	0.5 nM–1.0 μ M	0.16 nM	[45]
DPV	CEA	Ab/Pd@Pt/MoS ₂ -Gr/GCE	0.00001–100 ng/mL	0.005 pg/mL	[60]
DPV	CA125	Ab/CuBTC@MoS ₂ -AuNPs/SPE	0.5 mU/mL–500 U/mL	0.5 mU/mL	[61]
DPV	anti-retroviral agent indinavir	ZnO NRs/MoS ₂ NSs/SPE	0.01–0.66 μ M & 0.66–7.88 μ M	0.007 μ M	[62]
SWV	CEA	CeO ₂ -MoS ₂ -Pb ²⁺ - Ab2/CEA/Ab1/AuNPs/GCE	0.001–80 ng/mL	0.3 pg/mL	[63]
Amperometry	CEA	Ab/Ag/MoS ₂ /rGO/GCE	0.01 pg/mL–100 ng/mL	1.6 fg/mL	[64]
Amperometry	HBeAg	Au@Pd/MoS ₂ @MWCNTs- Ab2/HBeAg/Ab1/p-GO@Au/GCE	0.1–500 pg/mL	26 fg/mL	[65]
Amperometry	AFP	MoS ₂ @Cu ₂ O-Au- Ab2/AFP/Ab1/AuNPs/GCE	0.1 pg/mL–50 ng/mL	0.037 pg/mL	[47]
Amperometry	AFP	Ab/Pt NDs/PDDA/MoS ₂ @PPy NTs/GCE	50 fg/mL–50 ng/mL	17 fg/mL	[66]
Amperometry	CEA	MoS ₂ NFs/Au@AgPt YNCs -Ab2/CEA/Ab1/AuTNP/GCE	10 fg/mL–100 ng/mL	3.09 fg/mL	[48]
EIS	CML	pDNA/PANI-MoS ₂ /ITO	10 ⁻¹⁷ –10 ⁻⁶ M	3 \times 10 ⁻¹⁸ M	[67]
EIS	AFP	Ab/MoS ₂ /PDDA/Ag/AgCl wire	0.1–10 ng/mL	0.033 ng/mL	[51]
EIS	miRNA-21	cDNA/pd-MoS ₂ @ β -FeOOH/Au	1 fM–5 nM	0.11 fM	[49]
EIS	TNF- α	MoS ₂ NFs	0.01–200 pg/ml	0.202 pg/ml	[50]
PEC	CEA	ALP-Au-Ab2/CEA /Ab1/ZnS/C/MoS ₂ /GCE	2.0 pg/mL–10.0 ng/mL	1.30 pg/mL	[53]
PEC	SCCA	Ab/AuNPs/C/MoS ₂ /GCE	0.005–8 ng/mL	1.8 pg/mL	[68]

Method	Analytes	Electrode/Label	Linear Range	LOD	Ref.	ased
PEC	AFP	DNA/Au/GaN	1.0–150 ng/mL	0.3 ng/mL	[52]	
PEC	MCF-7 cells	PM6:Y6/anti-EpCAM-MNs /Au NPs/Au-aptamer	10–10,000 cell/mL	9 cell/mL	[69]	, disease e working ers tightly

integrated with biological sensing components [70]. Based on different biosensor elements, optical biosensors are divided into colorimetry, electrochemiluminescence (ECL), fluorescence, surface enhanced Raman scattering (SERS), surface plasmon resonance (SPR), and other sensing methods. In combination with MoS₂, the latest application progress in cancer biomarker detection is introduced.

3.1. Colorimetry

MoS₂, with its large surface area and exposed reaction sites, can be used as a nano enzyme to show the catalytic activity and excellent stability of peroxidase, and it simulates natural enzymes to make the substrate colour change. This feature is used to build a colorimetric sensor to detect cancer biomarkers [71][72]. Zhao et al. [73] introduced an aptamer to enhance the catalytic activity of MoS₂ NSs on peroxidase substrates and designed a colorimetric sensor for the intuitive detection of CEA, achieving sensitivity detection of CEA by successfully recording absorbance. The sensor exhibited a linear response in the range of 50 to 1000 ng/mL, with an LOD of 50 ng/mL, demonstrating good specificity and practical application capabilities. Shao et al. [74] utilized the high catalytic activity of MoS₂-AuNPs nanohybrids to reduce NaBH₄ to 4-NP and make the yellow solution colourless, and constructed a colorimetric immunosensor for CEA detection. The absorbance peak intensity of the colorimetric sensor maintained a good linear relationship in the range of 5 pg/mL to 10 ng/mL, with an LOD as low as 0.5 pg/mL. Wang et al. [75] developed a new colorimetric nano biological platform for the efficient and highly sensitive capture of circulating tumour cells (CTC), in which the MoS₂ NSs surface was modified with two kinds of aptamer functionalized PH sensitive heterochromatic dyes used as a visual detection chip, which had a good PH sensitivity and high dyeing ability.

3.2. Electrochemiluminescence (ECL)

ECL is a special form of chemiluminescence caused by the redox between electrogenerated high-energy radicals [76]. It does not rely on external light excitation and avoids the adverse effects of self-luminous and light scattering [77]. Therefore, it has the characteristics of a precise response, easy control, low noise background signal, high sensitivity, good repeatability, and wide linear range, and has become a powerful tool for biomarker detection and clinical diagnosis in recent years [78][79]. MoS₂ can effectively improve the rate of electron transfer, and it is emerging in the construction of ECL sensing platforms for cancer biomarkers [80]. Zhang et al. [81] used ordered mesoporous carbon-MoS₂ (OMC-MoS₂) as a sensing platform and Cu₂O@OMC-Ru (bpy)₃²⁺ as signal tags to develop a sandwich ECL immunosensor for the detection of AFP. As we know, MoS₂ NSs are easy to agglomerate, resulting in a loss of activity, and the synergistic effect of nanocomposites can offset this loss of activity. OMC exhibits an excellent electrocatalytic performance due to its ordered pore structure, high specific surface area, and

high porosity [82]. Therefore, OMC-MoS₂ can synergistically increase the effective surface area and conductivity to improve sensor sensitivity. The ECL detection range of AFP is 0.1 pg/mL–10 ng/mL, with an LOD of 0.011 pg/mL (S/N = 3).

3.3. Fluorescence

Fluorescence analysis is an advanced analytical method with a high sensitivity, selectivity, and practicality, which can qualitatively and quantitatively analyse the changes in fluorescence intensity, emission spectrum, and fluorescence molecular lifetime of substances [83]. Due to the strong adsorption capacity and wide absorption spectrum of MoS₂ NSs to ssDNA, MoS₂ NSs can quench fluorescent groups with different emission wavelengths, showing unique advantages in the construction of fluorescent biosensor platforms [84]. Liang et al. [85] built a fluorescence sensing platform for the hepatocellular carcinoma (HCC) biomarker GP73 based on the Förster resonance energy transfer (FRET). Among them, utilizing the synergistic effect of the MoS₂@rGO composites as a fluorescence receptor further enhanced the quenching effect, and the nitrogen-doped graphene QDs modified by the GP73 aptamer were used as fluorescence donors. The detection range was 5 ng/mL to 100 ng/mL, and the LOD was 4.54 ng/mL (S/N = 3). It also showed a good detection effect in human serum. Wang et al. [86] designed QD molecular beacons (QD-MBs) functionalized with a MoS₂ fluorescent probe (QD-MB@MoS₂) for the dual detection of two kinds of miRNAs related to multiple myeloma (MM), with an LOD as low as the fM level, realizing ultra-high sensitivity detection. In addition, when the MoS₂ crystal becomes very thin, the transition from the indirect bandgap to the direct bandgap will produce a strong fluorescence [87]. MoS₂ QDs have strong quantum confinement and edge effects and other photoelectric properties, and are widely used in fluorescence sensing, catalysis, biological imaging, and other fields [88]. Ge et al., based on the quenching of MoS₂ QDs by the inner filter effect (IFE) and rolling circle amplification (RCA) technology, constructed a label-free and highly sensitive miRNA fluorescence detection platform with a high selectivity and satisfactory recovery [88].

3.4. Surface Enhanced Raman Scattering (SERS)

SERS technology can provide molecular fingerprint information, has a high sensitivity and specificity, and does not cause damage to the sample, and is thus considered as a promising analytical technology in the field of disease analysis [89]. SERS sensor composition mainly include substrates, target detection substances, and SERS capture probes. MoS₂ has been applied in the preparation of SERS capture probes due to its large specific surface area, stability, and excellent catalytic performance. Engine et al. [90] developed a SERS sandwich immunosensor for the ultra-sensitive detection of AFP. Among them, MoS₂ is modified by the monoclonal antibody as the capture probe of AFP, and its high surface area and adsorption capacity for biomolecules make the sensing interface more stable. The SERS immunosensor based on Au@AgNCs/MoS₂ nanocomposites has a good linear response in the range of 1 pg/mL to 10 ng/mL, with an LOD as low as 0.03 pg/mL. Pan et al. [91] developed a sensitive and direct SERS aptasensor for detecting gastric cancer exosomes. AuNSs-decorated MoS₂ NSs (MoS₂-AuNSs) surfaces were assembled with ROX-labelled aptamers (ROX-Apt) used as nano probes to achieve the ultra-sensitive capture of exosomes. This sensor quantitatively detected gastric cancer exosomes over a wide range of SERS signals (55–5.5 × 10⁵ particles/μL), with an LOD as low as 17 particles/μL, which provides a prospective platform for the early

diagnosis of gastric cancer. In addition, Hilal et al. [92] developed a sandwich-type SERS immunosensor for the sensitive detection of CEA, which has a good selectivity and stability and is well applied in clinic.

3.5. Surface Plasmon Resonance (SPR)

SPR provides a non-invasive and label-free method to detect analytes. MoS₂ has a large absorption coefficient and high refractive index at 500 nm, whose structure is conducive to the propagation of the surface plasma. Such photoelectric characteristics enhance SPR signals and improve the sensitivity of the sensor [93]. Therefore, the modification of MoS₂ is also applied in SPR sensors for cancer biomarker detection. Chiu et al. [94] prepared MoS₂ by the liquid-phase exfoliation and covalently functionalized it to form carboxyl-functionalized MoS₂ (carboxyl-MoS₂) acting as a signal amplification sensing modification layer. The carboxylation modification effectively improved the sensitivity of the SPR sensor. The SPR chip based on carboxyl-MoS₂ was used to specifically detect the lung cancer-associated biomarker cytokeratin 19 fragment (CYFRA21-1), which shows a wide linear range (0.05 pg/mL–100 ng/mL) and low LOD (0.05 pg/mL), and has a good specificity, selectivity, sensitivity, and affinity. Compared with traditional SPR bare gold chips, the SPR chip has many characteristics, such as a unique glycan matrix structure, high surface area carboxylic acid groups, and excellent biological affinity. In addition to the above sensing methods, other sensing methods based on MoS₂ are listed in **Table 2** to detect various cancer biomarkers.

Table 2. Optical biosensors for cancer biomarker detection based on MoS₂.

Method	Analytes	Electrode/Label	Linear Range	LOD	Ref.
Colorimetry	CEA	Au NPs-MoS ₂ -Ab2/ CEA/Ab1/MoS ₂ -Au NPs	5 pg/mL–10 ng/mL	0.5 pg/mL	[74]
Colorimetry	CEA	DNA/MoS ₂ NSs	50–1000 ng/mL	50 ng/mL	[73]
Colorimetry	CTC	TP/SYL ₃ C-MoS ₂	5–10 ⁴ cells/mL	2 cells/mL	[75]
ECL	CEA	Ab/MOF-545-Zn@MQDs/GCE	0.18–1000 ng/mL	0.45 pg/mL	[95]
ECL	PSA	GOD-SiO ₂ -Ab2/PSA /Ab1/MoS ₂ -AuNPs/GCE	0.5 pg/mL–10.0 ng/mL	0.20 pg/mL	[96]
ECL	HCV gene	S-BN QDs-hairpin DNA2 (H2)/MoS ₂ Ns	0.5 pmoL/L–1 nmol/L	0.17 pmoL/L.	[83]
ECL	HPV 16 DNA	Zn-doped MoS ₂ QDs & QD- DNA/reductive Cu(I) particles	0.1–200 nmolL	0.03 nmol/L	[97]
ECL	miRNA-210	S dots/Au NP@MoS ₂ NSs	0.1 pM–10 nM	0.03 pM	[98]
ECL	miRNA-21	luminophore/MoS ₂ QDs@Zeolitic Imidazolate 2 Framework-8	Buffer (0.1 mM PBS), co-reactant (2 mM H ₂ O)	14.6 aM	[99]

Method	Analytes	Electrode/Label	Linear Range	LOD	Ref.
Fluorescence	CA15-3	DNA/MoS ₂ NSs	0.01–0.1 U/mL	0.0039 U/mL	[100]
Fluorescence	PD-1	MoS ₂ -NFP	125–8000 pg/mL	85.5 pg/mL	[101]
Fluorescence	miRNA-155 & miRNA-150	QD-MB @MoS ₂	10 fM–1 nM	7.19 fM & 5.84 fM	[86]
SERS	CEA	MoS ₂ NFs@Au NPs/MBA-Ab2/CEA /Ab1/Fe ₃ O ₄ NPs@Au NPs/d-Ti ₃ C ₂ TX Mxene	0.0001–100.0 ng/mL	0.033 pg/mL	[94]
SERS	CA19-9	R6G-tagged MoS ₂ NF	5×10^{-3} –100 IU/mL	3.43×10^{-4} IU/mL	[102]
SERS	exosomes	MoS ₂ -AuNSs/ROX-Apt	55 – 5.5×10^5 particles/ μ L	17 particles/ μ L	[93]
SPR	CYFRA21-1	Ab/COOH-MoS ₂ /Au/Cr/BK7	0.05 pg/mL–100 ng/mL	0.05 pg/mL	[94]

References

- Jayanthi, V.S.; Das, A.B.; Saxena, U. Recent advances in biosensor development for the detection of cancer biomarkers. *Biosens. Bioelectron.* 2017, **91**, 15–23.
- Hasan, M.R.; Ahommed, M.S.; Daizy, M.; Bacchu, M.S.; Ali, M.R.; Al-Mamun, M.R.; Aly Saad Aly, M.; Khan, M.Z.H.; Hossain, S.I. Recent development in electrochemical biosensors for cancer biomarkers detection. *Biosens. Bioelectron.* X 2021, **8**, 100075.
- Rabie, A.M.I.; Ali, A.S.M.; Al-Zeer, M.A.; Barhoum, A.; El-Hallouty, S.; Shousha, W.G.; Berg, J.; Kurreck, J.; Khalil, A.S.G. Spontaneous Formation of 3D Breast Cancer Tissues on Electrospun Chitosan/Poly(ethylene oxide) Nanofibrous Scaffolds. *ACS Omega* 2022, **7**, 2114–2126.
- Gric, T.; Sokolovski, S.G.; Navolokin, N.; Glushkovskaya, O.S.; Rafailov, E.U. Metamaterial formalism approach for advancing the recognition of glioma areas in brain tissue biopsies. *Opt. Mater. Express* 2020, **10**, 1607–1615.
- Ranjan, R.; Esimbekova, E.N.; Kratasyuk, V.A. Rapid biosensing tools for cancer biomarkers. *Biosens. Bioelectron.* 2017, **87**, 918–930.
- Henry, N.L.; Hayes, D.F. Cancer biomarkers. *Mol. Oncol.* 2012, **6**, 140–146.
- Khan, H.; Shah, M.R.; Barek, J.; Malik, M.I. Cancer biomarkers and their biosensors: A comprehensive review. *TrAC Trends Anal. Chem.* 2023, **158**, 116813.
- Sharifi, M.; Avadi, M.R.; Attar, F.; Dashtestani, F.; Ghorchian, H.; Rezayat, S.M.; Saboury, A.A.; Falahati, M. Cancer diagnosis using nanomaterials based electrochemical nanobiosensors. *Biosens. Bioelectron.* 2019, **126**, 773–784.

9. Agnolon, V.; Contato, A.; Meneghello, A.; Tagliabue, E.; Toffoli, G.; Gion, M.; Polo, F.; Fabricio, A.S.C. ELISA assay employing epitope-specific monoclonal antibodies to quantify circulating HER2 with potential application in monitoring cancer patients undergoing therapy with trastuzumab. *Sci. Rep.* 2020, 10, 3016.
10. Dueck, M.E.; Lin, R.; Zayac, A.; Gallagher, S.; Chao, A.K.; Jiang, L.X.; Datwani, S.S.; Hung, P.; Stieglitz, E. Precision cancer monitoring using a novel, fully integrated, microfluidic array partitioning digital PCR platform. *Sci. Rep.* 2019, 9, 19606.
11. Selvakumar, S.C.; Preethi, K.A.; Ross, K.; Tusubira, D.; Khan, M.W.A.; Mani, P.; Rao, T.N.; Sekar, D. CRISPR/Cas9 and next generation sequencing in the personalized treatment of Cancer. *Mol. Cancer* 2022, 24, 83.
12. Udo, R.; Katsumata, K.; Kuwabara, H.; Enomoto, M.; Ishizaki, T.; Sunamura, M.; Nagakawa, Y.; Soya, R.; Sugimoto, M.; Tsuchida, A. Urinary charged metabolite profiling of colorectal cancer using capillary electrophoresis-mass spectrometry. *Sci. Rep.* 2020, 10, 21057.
13. Barhoum, A.; Altintas, Z.; Shalini Devi, K.S.; Forster, R.J. Electrochemiluminescence biosensors for detection of cancer biomarkers in biofluids: Principles, opportunities, and challenges. *Nano Today* 2023, 50, 101874.
14. Ibrahim, J.; Peeters, M.; Camp, G.V.; Beeck, K.O. Methylation biomarkers for early cancer detection and diagnosis: Current and future perspectives. *Eur. J. Cancer* 2023, 178, 91–113.
15. Raghavendra, U.; Gudigar, A.; Paul, A.; Goutham, T.S.; Inamdar, M.A.; Hegde, A.; Devi, A.; Ooi, C.P.; Deo, R.C.; Barua, P.D.; et al. Brain tumor detection and screening using artificial intelligence techniques: Current trends and future perspectives. *Comput. Biol. Med.* 2023, 163, 107063.
16. Yang, G.; Xiao, Z.; Tang, C.; Deng, Y.; Huang, H.; He, Z. Recent advances in biosensor for detection of lung cancer biomarkers. *Biosens. Bioelectron.* 2019, 141, 111416.
17. Thévenot, D.R.; Toth, K.; Durst, R.A.; Wilson, G.S. Electrochemical biosensors: Recommended definitions and classification. *Biosens. Bioelectron.* 2001, 16, 121–131.
18. Choi, S.; Goryll, M.; Sin, L.Y.M.; Wong, P.K.; Chae, J. Microfluidic-based biosensors toward point-of-care detection of nucleic acids and proteins. *Microfluid. Nanofluidics* 2011, 10, 231–247.
19. Kukkar, M.; Tuteja, S.K.; Sharma, A.L.; Kumar, V.; Paul, A.K.; Kim, K.-H.; Sabherwal, P.; Deep, A. A New Electrolytic Synthesis Method for Few-Layered MoS₂ Nanosheets and Their Robust Biointerfacing with Reduced Antibodies. *ACS Appl. Mater. Interfaces* 2016, 8, 16555–16563.
20. Turner, A.P. Biosensors: Sense and sensibility. *Chem. Soc. Rev.* 2013, 42, 3184–3196.
21. Vaddiraju, S.; Legassey, A.; Wang, Y.; Qiang, L.; Burgess, D.J.; Jain, F.; Papadimitrakopoulos, F. Design and fabrication of a high-performance electrochemical glucose sensor. *J. Diabetes Sci. Technol.* 2011, 5, 1044–1051.

22. Bozal-Palabiyik, B.; Uslu, B.; Marrazza, G. Chapter 11—Nanosensors in Biomarker Detection. In *New Developments in Nanosensors for Pharmaceutical Analysis*; Academic Press: Cambridge, MA, USA, 2019; pp. 327–380.
23. Kausar, M. Pesticidal activity of Pakistani *Bacillus thuringiensis* isolates against *Helicoverpa armigera* (Hubner) and *Earias vittella* (Lepidoptera: Noctuidae). *IOSR J. Pharm. Biol. Sci.* 2013, 4, 9–12.
24. Kaya, S.I.; Ozcelikay, G.; Mollarasouli, F.; Bakirhan, N.K.; Ozkan, S.A. Recent achievements and challenges on nanomaterial based electrochemical biosensors for the detection of colon and lung cancer biomarkers. *Sens. Actuators B Chem.* 2022, 351, 130856.
25. Nawz, T.; Safdar, A.; Hussain, M.; Sung Lee, D.; Siyar, M. Graphene to Advanced MoS₂: A Review of Structure, Synthesis, and Optoelectronic Device Application. *Crystals* 2020, 10, 902.
26. Zhu, S.; Liu, Y.; Gu, Z.; Zhao, Y. Research trends in biomedical applications of two-dimensional nanomaterials over the last decade—A bibliometric analysis. *Adv. Drug Deliv. Rev.* 2022, 188, 114420.
27. Gan, X.; Zhao, H.; Quan, X. Two-dimensional MoS₂: A promising building block for biosensors. *Biosens. Bioelectron.* 2017, 89, 56–71.
28. Samadi, M.; Sarikhani, N.; Zirak, M.; Zhang, H.; Zhang, H.; Moshfegh, A.Z. Group 6 transition metal dichalcogenide nanomaterials: Synthesis, applications and future perspectives. *Nanoscale Horiz.* 2018, 3, 90–204.
29. Joswig, J.O.; Lorenz, T.; Wendumu, T.B.; Gemming, S.; Seifert, G. Optics, mechanics, and energetics of two-dimensional MoS₂ nanostructures from a theoretical perspective. *Acc. Chem. Res.* 2015, 48, 48–55.
30. Ataca, C.; Şahin, H.; Ciraci, S. Stable, Single-Layer MX₂ Transition-Metal Oxides and Dichalcogenides in a Honeycomb-Like Structure. *J. Phys. Chem. C* 2012, 116, 8983–8999.
31. Lee, C.; Yan, H.; Brus, L.E.; Heinz, T.F.; Hone, J.; Ryu, S. Anomalous lattice vibrations of single- and few-layer MoS₂. *ACS Nano* 2010, 4, 2695–2700.
32. Huang, Y.; Peng, C.; Chen, R.; Huang, Y.; Ho, C. Transport properties in semiconducting NbS₂ nanoflakes. *Appl. Phys. Lett.* 2014, 105, 093106.
33. Chen, F.; Xia, J.; Ferry, D.K.; Tao, N. Dielectric screening enhanced performance in graphene FET. *Nano Lett.* 2009, 9, 2571–2574.
34. Kalantar-zadeh, K.; Ou, J.Z. Biosensors Based on Two-Dimensional MoS₂. *ACS Sens.* 2016, 1, 5–16.
35. Zhang, W.; Zhang, P.; Su, Z.; Wei, G. Synthesis and sensor applications of MoS₂-based nanocomposites. *Nanoscale* 2015, 7, 18364–18378.

36. Zhang, Z.; Li, Q.; Du, X.; Liu, M. Application of electrochemical biosensors in tumor cell detection. *Thorac. Cancer* 2020, 11, 840–850.
37. Chai, H.; Tang, Y.; Guo, Z.; Miao, P. Ratiometric Electrochemical Switch for Circulating Tumor DNA through Recycling Activation of Blocked DNAzymes. *Anal. Chem.* 2022, 94, 2779–2784.
38. Manzeli, S.; Dumcenco, D.; Migliato Marega, G.; Kis, A. Self-sensing, tunable monolayer MoS₂ nanoelectromechanical resonators. *Nat. Commun.* 2019, 10, 4831.
39. Siao, M.; Shen, W.; Chen, R.; Chang, Z.; Shih, M.; Chiu, Y.; Cheng, C. Two-dimensional electronic transport and surface electron accumulation in MoS₂. *Nat. Commun.* 2018, 9, 1442.
40. Tsai, Y.C.; Li, Y. Impact of Doping Concentration on Electronic Properties of Transition Metal-Doped Monolayer Molybdenum Disulfide. *IEEE Trans. Electron. Devices* 2018, 65, 733–738.
41. Sethulekshmi, A.S.; Saritha, A.; Joseph, K.; Aprem, A.S.; Sisupal, S.B. MoS₂ based nanomaterials: Advanced antibacterial agents for future. *J. Control. Release* 2022, 348, 158–185.
42. Zhang, S.; Wang, J.; Torad, N.L.; Xia, W.; Aslam, M.A.; Kaneti, Y.V.; Hou, Z.; Ding, Z.; Da, B.; Fatehmulla, A.; et al. Rational Design of Nanoporous MoS₂/VS₂ Heteroarchitecture for Ultrahigh Performance Ammonia Sensors. *Small* 2020, 16, e1901718.
43. Ying, Z.; Feng, L.; Ji, D.; Zhang, Y.; Chen, W.; Dai, Y.; Janyasupab, M.; Li, X.; Wen, W.; Liu, C. Phase-Regulated Sensing Mechanism of MoS₂ Based Nanohybrids toward Point-of-Care Prostate Cancer Diagnosis. *Small* 2020, 16, e2000307.
44. Li, F.; Zhang, L.; Li, J.; Lin, X.; Li, X.; Fang, Y.; Huang, J.; Li, W.; Tian, M.; Jin, J.; et al. Synthesis of Cu–MoS₂/rGO hybrid as non-noble metal electrocatalysts for the hydrogen evolution reaction. *J. Power Sources* 2015, 292, 15–22.
45. Su, X.; Han, Y.; Liu, Z.; Fan, L.; Guo, Y. One-pot synthesized AuNPs/MoS₂/rGO nanocomposite as sensitive electrochemical aptasensing platform for nucleolin detection. *J. Electroanal. Chem.* 2020, 859, 113868.
46. Jing, P.; Yi, H.; Xue, S.; Chai, Y.; Yuan, R.; Xu, W. A sensitive electrochemical aptasensor based on palladium nanoparticles decorated graphene-molybdenum disulfide flower-like nanocomposites and enzymatic signal amplification. *Anal. Chim. Acta* 2015, 853, 234–241.
47. Ma, N.; Zhang, T.; Fan, D.; Kuang, X.; Ali, A.; Wu, D.; Wei, Q. Triple amplified ultrasensitive electrochemical immunosensor for alpha fetoprotein detection based on MoS₂@Cu₂O-Au nanoparticles. *Sens. Actuators B Chem.* 2019, 297, 126821.
48. Ma, E.; Wang, P.; Yang, Q.; Yu, H.; Pei, F.; Li, Y.; Liu, Q.; Dong, Y. Electrochemical immunosensor based on MoS₂ NFs/Au@AgPt YNCs as signal amplification label for sensitive detection of CEA. *Biosens. Bioelectron.* 2019, 142, 111580.

49. Jia, Q.; Huang, S.; Hu, M.; Song, Y.; Wang, M.; Zhang, Z.; He, L. Polyoxometalate-derived MoS₂ nanosheets embedded around iron-hydroxide nanorods as the platform for sensitively determining miRNA-21. *Sens. Actuators B Chem.* 2020, 323, 128647.
50. Sri, S.; Chauhan, D.; Lakshmi, G.B.V.S.; Thakar, A.; Solanki, P.R. MoS₂ nanoflower based electrochemical biosensor for TNF alpha detection in cancer patients. *Electrochim. Acta* 2022, 405, 139736.
51. Hu, T.; Zhang, M.; Wang, Z.; Chen, K.; Li, X.; Ni, Z. Layer-by-layer self-assembly of MoS₂/PDDA hybrid film in microfluidic chips for ultrasensitive electrochemical immunosensing of alpha-fetoprotein. *Microchem. J.* 2020, 158, 105209.
52. Hu, D.; Cui, H.; Wang, X.; Luo, F.; Qiu, B.; Cai, W.; Huang, H.; Wang, J.; Lin, Z. Highly Sensitive and Selective Photoelectrochemical Aptasensors for Cancer Biomarkers Based on MoS₂/Au/GaN Photoelectrodes. *Anal. Chem.* 2021, 93, 7341–7347.
53. Wei, Q.; Wang, C.; Li, P.; Wu, T.; Yang, N.; Wang, X.; Wang, Y.; Li, C. MOF Photochemistry: ZnS/C/MoS₂ Nanocomposite Derived from Metal–Organic Framework for High-Performance Photo-Electrochemical Immunosensing of Carcinoembryonic Antigen. *Small* 2019, 15, 1970257.
54. Song, Y.; Cao, K.; Li, W.; Ma, C.; Qiao, X.; Li, H.; Hong, C. Optimal film thickness of rGO/MoS₂@polyaniline nanosheets of 3D arrays for carcinoembryonic antigen high sensitivity detection. *Microchem. J.* 2020, 155, 104694.
55. Gui, J.; Han, L.; Du, C.; Yu, X.; Hu, K.; Li, L. An efficient label-free immunosensor based on ce-MoS₂/AgNR composites and screen-printed electrodes for PSA detection. *J. Solid State Electrochem.* 2021, 25, 973–982.
56. Su, S.; Han, X.; Lu, Z.; Liu, W.; Zhu, D.; Chao, J.; Fan, C.; Wang, L.H.; Song, S.; Weng, L.; et al. Facile Synthesis of a MoS₂-Prussian Blue Nanocube Nanohybrid-Based Electrochemical Sensing Platform for Hydrogen Peroxide and Carcinoembryonic Antigen Detection. *ACS Appl. Mater. Interfaces* 2017, 9, 12773–12781.
57. Wang, Y.; Zhao, G.; Zhang, Y.; Pang, X.; Cao, W.; Du, B.; Wei, Q. Sandwich-type electrochemical immunosensor for CEA detection based on Ag/MoS₂@Fe₃O₄ and an analogous ELISA method with total internal reflection microscopy. *Sens. Actuators B Chem.* 2018, 266, 561–569.
58. Liu, L.; Wei, Y.; Jiao, S.; Zhu, S.; Liu, X. A novel label-free strategy for the ultrasensitive miRNA-182 detection based on MoS₂/Ti₃C₂ nanohybrids. *Biosens. Bioelectron.* 2019, 137, 45–51.
59. Su, S.; Sun, Q.; Wan, L.; Gu, X.; Zhu, D.; Zhou, Y.; Chao, J.; Wang, L. Ultrasensitive analysis of carcinoembryonic antigen based on MoS₂-based electrochemical immunosensor with triple signal amplification. *Biosens. Bioelectron.* 2019, 140, 111353.
60. Lin, Y.; Xiong, C.; Shi, J.; Zhang, J.; Wang, X. Electrochemical immunosensor based on Pd@Pt/MoS₂-Gr for the sensitive detection of CEA. *J. Solid. State Electrochem.* 2021, 25, 2075–

2085.

61. Li, S.; Hu, C.; Chen, C.; Zhang, J.; Bai, Y.; Tan, C.; Ni, G.; He, F.; Li, W.; Ming, D. Molybdenum Disulfide Supported on Metal-Organic Frameworks as an Ultrasensitive Layer for the Electrochemical Detection of the Ovarian Cancer Biomarker CA125. *ACS Appl. Bio Mater.* 2021, 4, 5494–5502.
62. Mehmandoust, M.; Karimi, F.; Erk, N. A zinc oxide nanorods/molybdenum disulfide nanosheets hybrid as a sensitive and reusable electrochemical sensor for determination of anti-retroviral agent indinavir. *Chemosphere* 2022, 300, 134430.
63. Li, W.; Qiao, X.; Hong, C.; Ma, C.; Song, Y. A sandwich-type electrochemical immunosensor for detecting CEA based on CeO₂-MoS₂ absorbed Pb²⁺. *Anal. Biochem.* 2020, 592, 113566.
64. Wang, Y.; Wang, Y.; Wu, D.; Ma, H.; Zhang, Y.; Fan, D.; Pang, X.; Du, B.; Wei, Q. Label-free electrochemical immunosensor based on flower-like Ag/MoS₂/rGO nanocomposites for ultrasensitive detection of carcinoembryonic antigen. *Sens. Actuators B Chem.* 2018, 255, 125–132.
65. Gao, Z.; Li, Y.; Zhang, X.; Feng, J.; Kong, L.; Wang, P.; Chen, Z.; Dong, Y.; Wei, Q. Ultrasensitive electrochemical immunosensor for quantitative detection of HBeAg using Au@Pd/MoS₂@MWCNTs nanocomposite as enzyme-mimetic labels. *Biosens. Bioelectron.* 2018, 102, 189–195.
66. Pei, F.; Wang, P.; Ma, E.; Yang, Q.; Yu, H.; Liu, J.; Yin, H.; Li, Y.; Liu, Q.; Dong, Y. A sensitive label-free immunosensor for alpha fetoprotein detection using platinum nanodendrites loaded on functional MoS₂ hybridized polypyrrole nanotubes as signal amplifier. *J. Electroanal. Chem.* 2019, 835, 197–204.
67. Soni, A.; Pandey, C.M.; Pandey, M.K.; Sumana, G. Highly efficient Polyaniline-MoS₂ hybrid nanostructures based biosensor for cancer biomarker detection. *Anal. Chim. Acta* 2019, 1055, 26–35.
68. Wang, C.; Wu, T.; Wang, X.; Wei, Q.; Wang, Y.; Li, C.; Sun, D. Ultrathin-layered carbon intercalated MoS₂ hollow nanospheres integrated with gold nanoparticles for photoelectrochemical immunosensing of squamous cell carcinoma antigen. *Sens. Actuators B Chem.* 2019, 297, 126716.
69. Luo, J.R.; Zeng, Q.; Liu, S.P.; Wei, Q.Y.; Wang, Z.X.; Yang, M.H.; Zou, Y.P.; Lu, L.M. Highly sensitive photoelectrochemical sensing platform based on PM6:Y6 p-n heterojunction for detection of MCF-7 cells. *Sens. Actuators B Chem.* 2022, 363, 131814.
70. Singh, A.K.; Mittal, S.; Das, M.; Saharia, A.; Tiwari, M. Optical biosensors: A decade in review. *Alex. Eng. J.* 2023, 67, 673–691.

71. Lv, Q.; Chen, L.; Liu, H.; Zou, L. Peony-like 3D-MoS₂/graphene nanostructures with enhanced mimic peroxidase performance for colorimetric determination of dopamine. *Talanta* 2022, 247, 123553.
72. Guo, X.; Wang, Y.; Wu, F.; Ni, Y.; Kokot, S. A colorimetric method of analysis for trace amounts of hydrogen peroxide with the use of the nano-properties of molybdenum disulfide. *Analyst* 2015, 140, 1119–1126.
73. Zhao, L.; Wang, J.; Su, D.; Zhang, Y.; Lu, H.; Yan, X.; Bai, J.; Gao, Y.; Lu, G. The DNA controllable peroxidase mimetic activity of MoS₂ nanosheets for constructing a robust colorimetric biosensor. *Nanoscale* 2020, 12, 19420–19428.
74. Su, S.; Li, J.; Yao, Y.; Sun, Q.; Zhao, Q.; Wang, F.; Li, Q.; Liu, X.; Wang, L. Colorimetric Analysis of Carcinoembryonic Antigen Using Highly Catalytic Gold Nanoparticles. *ACS Appl. Bio Mater.* 2019, 2, 292–298.
75. Wang, X.; Cheng, S.; Wang, X.; Wei, L.; Kong, Q.; Ye, M.; Luo, X.; Xu, J.; Zhang, C.; Xian, Y. pH-Sensitive Dye-Based Nanobioplatfrom for Colorimetric Detection of Heterogeneous Circulating Tumor Cells. *ACS Sens.* 2021, 6, 1925–1932.
76. Ma, C.; Cao, Y.; Gou, X.; Zhu, J. Recent Progress in Electrochemiluminescence Sensing and Imaging. *Anal. Chem.* 2020, 92, 431–454.
77. Zhang, S.; Liu, Y. Recent Progress of Novel Electrochemiluminescence Nanoprobes and Their Analytical Applications. *Front. Chem.* 2021, 8, 626243.
78. Lv, X.; Li, Y.; Cui, B.; Fang, Y.; Wang, L. Electrochemiluminescent sensor based on an aggregation-induced emission probe for bioanalytical detection. *Analyst* 2022, 147, 2338–2354.
79. Du, L.; Zhang, H.; Wang, Z.; Zhuang, T.; Wang, Z. Boosting the electrochemiluminescence of luminol by high-intensity focused ultrasound pretreatment combined with 1T/2H MoS₂ catalysis to construct a sensitive sensing platform. *Ultrason. Sonochem.* 2023, 92, 106264.
80. Ma, C.; Zhang, Z.; Tan, T.; Zhu, J. Recent Progress in Plasmonic based Electrochemiluminescence Biosensors: A Review. *Biosensors* 2023, 13, 200.
81. Zhang, Z.; Yu, H.; Zhang, Y.; Wang, Z.; Gao, H.; Rong, S.; Meng, L.; Dai, J.; Pan, H.; Chang, D. A sandwich-configuration electrochemiluminescence immunoassay based on Cu₂O@OMC-Ru nanocrystals and OMC-MoS₂ nanocomposites for determination of alpha-fetoprotein. *Mikrochim. Acta* 2021, 188, 213.
82. Srinidhi, G.; Sudalaimani, S.; Giribabu, K.; Basha, S.J.S.; Suresh, C. Amperometric determination of hydrazine using a CuS-ordered mesoporous carbon electrode. *Mikrochim. Acta* 2020, 187, 359.
83. Muhammad, M.; Khan, S.; Shehzadi, S.A.; Gul, Z.; Al-Saidi, H.M.; Kamran, A.W.; Alhumaydhi, F.A. Recent advances in colorimetric and fluorescent chemosensors based on thiourea

- derivatives for metallic cations: A review. *Dye. Pigment.* 2022, 205, 110477.
84. Yao, W.; Ling, J.; Zhang, W.; Ding, Y. Highly sensitive fluorescent aptasensor based on MoS₂ nanosheets for one-step determination of methamphetamine. *Anal. Sci.* 2022, 38, 99–104.
 85. Liang, J.; Yan, R.; Chen, C.; Yao, X.; Guo, F.; Wu, R.; Zhou, Z.; Chen, J.; Li, G. A novel fluorescent strategy for Golgi protein 73 determination based on aptamer/nitrogen-doped graphene quantum dots/molybdenum disulfide @ reduced graphene oxide nanosheets. *Spectrochim. Acta A Mol. Biomol. Spectrosc.* 2023, 294, 122538.
 86. Wang, J.; Liu, Y.; Ding, Z.; Zhang, L.; Han, C.; Yan, C.; Amador, E.; Yuan, L.; Wu, Y.; Song, C.; et al. The exploration of quantum dot-molecular beacon based MoS₂ fluorescence probing for myeloma-related Mirnas detection. *Bioact. Mater.* 2022, 17, 360–368.
 87. Chhowalla, M.; Shin, H.S.; Eda, G.; Li, L.J.; Loh, K.P.; Zhang, H. The chemistry of two-dimensional layered transition metal dichalcogenide nanosheets. *Nat. Chem.* 2013, 5, 263–275.
 88. Ge, J.; Hu, Y.; Deng, R.; Li, Z.; Zhang, K.; Shi, M.; Yang, D.; Cai, R.; Tan, W. Highly Sensitive MicroRNA Detection by Coupling Nicking-Enhanced Rolling Circle Amplification with MoS₂ Quantum Dots. *Anal. Chem.* 2020, 92, 13588–13594.
 89. Strobbe, P.; Cupil-Garcia, V.; Crawford, B.M.; Fales, A.M.; Pfeifer, T.J.; Liu, Y.; Maiwald, M.; Sumpf, B.; Vo-Dinh, T. Accurate in vivo tumor detection using plasmonic-enhanced shifted-excitation Raman difference spectroscopy (SERDS). *Theranostics* 2021, 11, 4090–4102.
 90. Er, E.; Sánchez-Iglesias, A.; Silvestri, A.; Arnaiz, B.; Liz-Marzán, L.M.; Prato, M.; Criado, A. Metal Nanoparticles/MoS₂ Surface-Enhanced Raman Scattering-Based Sandwich Immunoassay for α -Fetoprotein Detection. *ACS Appl. Mater. Interfaces* 2021, 13, 8823–8831.
 91. Pan, H.; Dong, Y.; Gong, L.; Zhai, J.; Song, C.; Ge, Z.; Su, Y.; Zhu, D.; Chao, J.; Su, S.; et al. Sensing gastric cancer exosomes with MoS₂-based SERS aptasensor. *Biosens. Bioelectron.* 2022, 215, 114553.
 92. Medetalibeyoglu, H.; Kotan, G.; Atar, N.; Yola, M.L. A novel sandwich-type SERS immunosensor for selective and sensitive carcinoembryonic antigen (CEA) detection. *Anal. Chim. Acta* 2020, 1139, 100–110.
 93. Samy, O.; Zeng, S.; Birowosuto, M.D.; El Moutaouakil, A. A Review on MoS₂ Properties, Synthesis, Sensing Applications and Challenges. *Crystals* 2021, 11, 355.
 94. Chiu, N.F.; Yang, H.T. High-Sensitivity Detection of the Lung Cancer Biomarker CYFRA21-1 in Serum Samples Using a Carboxyl-MoS₂ Functional Film for SPR-Based Immunosensors. *Front. Bioeng. Biotechnol.* 2020, 8, 234.
 95. Xin, W.; Jiang, L.; Zong, L.; Zeng, H.; Shu, G.; Marks, R.; Zhang, X.; Shan, D. MoS₂ quantum dots-combined zirconium-metalloporphyrin frameworks: Synergistic effect on electron transfer and

- application for bioassay. *Sens. Actuators B Chem.* 2018, 273, 566–573.
96. Hou, F.; Hu, X.; Ma, S.; Cao, J.; Liu, Y. Construction of electrochemiluminescence sensing platform with in situ generated coreactant strategy for sensitive detection of prostate specific antigen. *J. Electroanal. Chem.* 2020, 858, 113817.
97. Nie, Y.; Zhang, X.; Zhang, Q.; Liang, Z.; Ma, Q.; Su, X. A novel high efficient electrochemiluminescence sensor based on reductive Cu(I) particles catalyzed Zn-doped MoS₂ QDs for HPV 16 DNA determination. *Biosens. Bioelectron.* 2020, 160, 112217.
98. Hou, S.; Wang, P.; Nie, Y.; Guo, Y.; Ma, Q. A novel work function tuning strategy-based ECL sensor with sulfur dots and Au NP@MoS₂ nanosheet heterostructure for triple-negative breast cancer diagnosis. *Chem. Eng. J.* 2022, 446, 136906.
99. Liu, W.; Su, M.; Chen, A.; Peng, K.; Chai, Y.; Yuan, R. Highly Efficient Electrochemiluminescence Based on Luminol/MoS₂ Quantum Dots@Zeolitic Imidazolate Framework-8 as an Emitter for Ultrasensitive Detection of MicroRNA. *Anal. Chem.* 2022, 94, 9106–9113.
100. Zhao, L.; Kong, D.; Wu, Z.; Liu, G.; Gao, Y.; Yan, X.; Liu, F.; Liu, X.; Wang, C.; Cui, J.; et al. Interface interaction of MoS₂ nanosheets with DNA based aptameric biosensor for carbohydrate antigen 15–3 detection. *Microchem. J.* 2020, 155, 104675.
101. Peng, X.; Wang, Y.; Wen, W.; Chen, M.; Zhang, X.; Wang, S. Simple MoS₂-Nanofiber Paper-Based Fluorescence Immunosensor for Point-of-Care Detection of Programmed Cell Death Protein 1. *Anal. Chem.* 2021, 93, 8791–8798.
102. Jiang, J.; Liu, H.; Li, X.; Chen, Y.; Gu, C.; Wei, G.; Zhou, J.; Jiang, T. Nonmetallic SERS-based immunosensor by integrating MoS₂ nanoflower and nanosheet towards the direct serum detection of carbohydrate antigen 19–9. *Biosens. Bioelectron.* 2021, 193, 113481.

Retrieved from <https://www.encyclopedia.pub/entry/history/show/113243>