

Paper-Based Electrical Sensors for Aqueous Heavy Metal Ion Detections

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Abstract

Trace levels of heavy metals such as lead, cadmium, mercury, and arsenic can have harmful effects on human health, causing damage to organs and the nervous system. As a result, it is essential to monitor heavy metal concentrations continuously and in real-time, with detection limits of less than nanomolar to reduce their impact on the environment and human health. The development of paper-based microfluidics in recent years has made it a promising platform for lab-on-a-chip devices capable of detecting heavy metals on a large scale and on-site for environmental purposes. This review article will introduce commonly used paper-based electrical sensing (including electrochemical, FETs, and chemiresistive sensors), existing fabrication and analysis techniques, and various application areas for these heavy metal ion sensors. Additionally, the challenges that must be addressed for paper-based sensors to realize their full potential and future outlooks will be discussed.

Introduction

Significance of heavy metal detection

Heavy metals are a group of naturally occurring elements that can be found in the environment. These metals are produced through natural processes such as volcanic eruptions, rock weathering, metal corrosion, and metal evaporation from soil and water. ¹⁻⁵ However, with the increase in human activities, heavy metal ions (HMIs) have accumulated in our environment due to activities such as mining, industrial production, agriculture, and metallurgical processes. ⁶⁻⁹ These activities have significantly increased the amount of HMIs in the air, drinking water, plants, animals, soil, and the earth's surface. The consumption of polluted plants, animals, and drinking water can lead to the transfer of HMIs to humans. This transfer can result in bioaccumulation and has the potential to cause adverse health effects. It is worth noting that the toxicity of HMIs has a more significant impact on children than on adults. Children are more susceptible to organ damage and neurotoxicity, which may cause behavioral disorders, learning problems, and impaired growth in children's development. ¹⁰⁻¹⁴ Therefore, it is crucial to continuously monitor HMIs in the environment to prevent or reduce the potential harm they may cause. The Environmental Quality Standards Directive List has identified several heavy metals as prime substances of concern in water quality, including arsenic (As), cadmium (Cd), copper (Cu), chromium (Cr), iron (Fe), lead (Pb), mercury (Hg), nickel (Ni), and zinc (Zn). ¹²⁻¹⁶ Although these elements are essential to life in trace quantities, they are hazardous to human health at higher concentrations. Heavy metals are a class of pollutants that pose significant challenges due to their toxicity and non-biodegradable nature. They tend to accumulate in ecological systems, resulting in bioaccumulation and biomagnification.

As heavy metals enter the environment, they can be absorbed by plants and animals, leading to bioaccumulation. Through the food chain, humans can ingest these bioaccumulated plants and animals, leading to the accumulation of heavy metals in the body. ¹⁷⁻²⁰ Unfortunately, there is currently no natural mechanism for the controlled removal of heavy metals from the human body. Therefore, even trace levels of heavy metals like lead, cadmium, mercury, and arsenic can have detrimental effects on human health, including organ damage and nervous system toxicity. ^{18,21-26} Therefore, it is critical to monitor heavy metal concentrations in real-time and continuously to reach low concentrations of less than nanomolar (nM) to mitigate their impact on the environment and human health.

A chemical sensor is a vital device used to convert chemical information, derived from either a chemical reaction or a physical property of the system under investigation, into an analytically useful signal. The International Union of Pure and Applied Chemistry has defined chemical sensors as devices that can transform chemical information into a measurable signal. ²⁷⁻²⁹ Chemical sensors consist of two main functional units - the receptor and the transducer. The receptor, also known as the chemical recognition system, is responsible for providing the sensor with a high degree of selectivity for the analyte being measured. On the other hand, the transducer part is responsible for the sensitivity of the device and transforms the signal from the output domain of the recognition system into an output signal that can be converted into useful data. One popular type of chemical sensor is the electrochemical sensor, which employs physical and chemical changes to generate measurable electrical signals such as potential,

current, or resistance changes. An electrochemical sensor typically consists of a sensing electrode, a counter electrode, and a reference electrode. The sensing electrode is usually modified with various polar materials to improve the sensor's detection limit and sensitivity.^{30–32} Electrochemical sensors are widely used to analyze the content of treated samples, as they can provide accurate measurements of chemical compounds in different environments. Currently, the most widely used electrochemical methods for detecting heavy metals include voltammetry, potentiometry, and conductometry.

On the other hand, chemical sensors and biosensor systems that utilize field-effect transistor (**FET**) technology have shown great promise in detecting heavy metal ions in various environments with advancement in nanomaterials and nanostructures.^{33–35} The FET sensor systems consist of several functional blocks that work together to detect and measure analyte-specific signals. The two critical components of these systems are the recognition element and the transducer. The recognition element is responsible for binding the probes-target, generating a signal that corresponds to the presence of the heavy metal ions and its abundance. Common recognition elements include antibodies, single-stranded DNA, and ion-sensing membranes.³⁶ In bio-/chem-sensors, the recognition element is often immobilized on a solid surface layer on the transducer. The transducer, on the other hand, converts the quantitative or semi-quantitative information about the target into a measurable signal. This signal can be a current, potential, or temperature change. Popular nanosensor transducers used in FET/chemiresistive sensor development include graphene, carbon nanotubes, and silicon. Researchers have explored the potential of several semiconductor materials as transducers in

FET/chemiresistive sensor development.^{37,38} These transducers have been used in various transducer platforms to develop chemical or biosensors for heavy metal ions monitoring. A wide range of recognition elements has been explored to realize the detection of heavy metal ions. The use of FET sensor technology in heavy metal ions detection has numerous advantages, including high sensitivity, low cost, and real-time monitoring capabilities. The use of nanosensors as transducers has also improved the sensitivity and selectivity of these sensor systems. However, the performance of these sensors is affected by several factors, including the stability of the recognition element, the sensitivity of the transducer, and the specificity of the sensing interface. These factors must be carefully considered to ensure the accurate detection and measurement of heavy metal ions in various environments.

Advantages of paper-based sensing platforms

One of the earliest papers on the use of paper-supported electrochemical devices for heavy metal detection was published by the Whitesides group in 2010.³⁹ They demonstrated the sensing of heavy metals through anodic stripping voltammetry, which has since been further investigated by other researchers. However, the interactions between heavy metals and cellulose groups in the paper can introduce challenges to the measurement process, and this work aims to better understand and mitigate their negative impact. By improving our understanding of these interactions, new approaches can be developed to create more effective paper-based sensors for heavy metal detection.

Paper, traditionally known for its use in writing and packaging, has evolved beyond its conventional applications. It has become a versatile material with properties that make it ideal for various applications, thanks to its physical characteristics. Paper is lightweight, flexible, and can be made thin, depending on the pulp processing.^{40–45} It is composed mainly of cellulose fibre, which can be functionalised to alter properties such as hydrophilicity, permeability, and reactivity.^{46–49} The development of paper-based microfluidics in recent years has made it an attractive platform for lab-on-a-chip devices capable of performing complicated laboratory tests on a large scale but on site. Additionally, paper-based sensors have become popular in applications such as clinical, food, and environmental sectors, where practical and simple analytical devices are needed for portable and on-site real-time detection.^{36,50} There is a growing demand for point-of-care (POC) diagnostics that can provide quick test results, a challenge that paper-based sensors could potentially meet.⁵¹ This review will introduce commonly used

paper-based for electrical sensing, existing fabrication and analysis techniques, and various application areas for these heavy metal ion sensors. It will also highlight the challenges that need to be addressed for paper-based sensors to reach their full potential, along with future outlooks.

Detection of heavy metal ions

In a recent study, a research team reported the design and development of a novel chemiresistor (CR) sensor for the detection of cadmium ions (Cd(II)) in water.⁵² The team used ion imprinted polymer (IIP)-functionalized reduced graphene oxide (rGO) to develop the IIP/rGO-CR sensor. The CR transducer of the sensor was made of rGO channel bridging source and drain electrodes. The researchers prepared the electrodes by self-assembly and thermal reduction of graphene oxide (GO) on Au interdigitated electrodes chip fabricated on Si/SiO₂ substrate. After that, they grafted the IIP on rGO using surface-initiated reversible addition-fragmentation chain transfer (RAFT) polymerization. The IIP was developed using polyethylenimine (PEI) and methacrylic acid (MAA) as dual functional monomers, and Cd(II) ions as a template through UV light-initiated copolymerization. This IIP functionalized on rGO acted as an effective recognition element that modulated the resistance of rGO-CR upon binding of Cd(II), enabling Cd(II) detection at ppb level in aqueous solutions. The team demonstrated that the prepared IIP/rGO-CR sensor worked effectively in the linear range of 2 ~ 200 ppb and achieved a limit of detection (LOD) of 0.83 ppb, which is lower than the World Health Organization guidelines of 3 ppb for drinking water quality. The researchers further tested the selectivity of the developed sensor against a variety of trace and heavy metal ions found in water and observed good stability for up to 60 days when stored at room temperature for Cd(II) determination in water. Additionally, the sensor was successfully applied to analyzing Cd(II) spiked in tap, lake, and river waters with a 94.5%–113.5% recovery, demonstrating a high degree of accuracy even in complex water samples. The study provided evidence of the successful imprinting process, binding and washing of the analyte, and the selective

binding interaction of Cd(II) with the IIP of Cd(II)-ion imprinted poly(PEI + MAA) on the surface of rGO, which caused a significant change in the resistance of the rGO-FET device, enabling the detection of Cd(II) at sub-ppb level. The researchers suggested that the CR sensor of IIP functionalized rGO provides a potential platform for sensitive, robust, and low-cost environmental analysis of Cd(II) in water. The simple structure of the chemiresistive sensor combined with IIP functionalization approach makes this sensor an ideal candidate for developing on-site, rapid, and low-cost monitoring tools in real-world applications.

A team of researchers has developed a new microfluidic paper-based analytical device (μ PAD) that combines electrochemical and colorimetric detection to enable high sensitivity and specificity in the simultaneous detection of lead, cadmium, and copper.⁵³ Although a bismuth-modified electrode can increase the sensitivity of lead and cadmium detection, its use in copper detection is limited because the bismuth signal overlaps with the signal for copper. In the new method, the μ PAD is divided into two parts, with the first part utilizing a bismuth-modified boron-doped diamond electrode (Bi-BDDE) for electrochemical detection of lead and cadmium. The limit of detection for both metals was 0.1 ng mL^{-1} . The second part uses colorimetric detection based on the catalytic etching of silver nanoplates (AgNPIs) by thiosulfate ($\text{S}_2\text{O}_3^{2-}$) for the detection of copper. The color of AgNPIs on μ PAD changes from pinkish-violet to colorless upon the addition of copper, which can be monitored by naked eyes, and its detection limit was 5.0 ng mL^{-1} by Image J analysis. The new method was applied to the simultaneous determination of these three metals in real samples, and no significant differences in accuracy and

precision were observed compared to the standard method. The researchers suggest that the new method is cost-effective and simple, and can be used for food and environmental analysis.

Boron-doped diamond (BDD) electrodes have been recognized for their outstanding electrochemical properties in recent years, but their high cost and limited availability have hindered their widespread use. To address this issue, researchers have developed a low-cost electrochemical sensor by combining a BDD paste electrode (BDDPE) with microfluidic paper-based analytical devices (μ PADs).⁵⁴ The BDDPEs are made by mixing BDD powder with mineral oil and can be stencil-printed into various electrode geometries. In this study, the researchers used BDDPEs to detect biological species (norepinephrine and serotonin) and heavy metals (Pb and Cd) using μ PADs, demonstrating the potential of BDDPEs as point-of-care sensors. This study marks the first fabrication and electrochemical characterization of BDDPE for μ PADs. The researchers highlighted its advantageous properties, such as a wide solvent window, low background currents, and resistance to surface fouling. Additionally, the BDDPEs can be easily fabricated and integrated with ePADs, and their cost-effectiveness makes them more amenable to disposable and portable platforms than conventional BDD electrodes. The researchers demonstrated the applicability of BDDPEs by detecting biological species and heavy metals in both ePAD and μ PAD formats. For instance, the ePAD device was capable of simultaneous detection of NE and 5-HT in wide concentration ranges and with low limit of detections. The researchers overcame electrode fouling from 5-HT electrooxidation through anodic electrode treatment, enabling multiple measurements with one electrode.

In heavy metal quantitation, a flow-through μ PAD design with SWASV improved the detection sensitivity compared to a static ePAD system. Therefore, BDDPEs have the potential to become a valuable tool for electrochemical sensing in a variety of applications, particularly when combined with μ PADs. The researchers overcame analytical challenges such as electrode fouling and peak shielding, making ePADs and μ PADs more accessible for wider use in various fields.

A new study presents a new approach to detecting heavy metals in water by using a printed paper-based origami electrochemical sensor.⁵⁵ The results of the study showed that the origami device was able to filter debris from dirty water and detect parts per billion levels of lead and cadmium ions in buffer solution. The proposed device was compared to commercially available screen-printed ceramic electrochemical sensors, and the results showed that the paper-based origami electrochemical sensor device was suitable for detecting heavy metals in water samples. The study demonstrated the potential of the paper-based origami electrochemical sensor device to effectively filter out debris before the sample reaches the sensor for testing. The applications of the device could be extended to the fields of environmental monitoring, medical health, and food safety. Future work will entail testing of heavy metals on the 3D origami devices, and optimizing the detection results for Cd^{+2} ions. Overall, the study presents a promising solution for detecting heavy metals in water using a low-cost and disposable paper-based origami electrochemical sensor.

Researchers developed a portable microfluidic device that combines filter paper strips with screen-printed carbon electrodes (SPCE) for the direct detection of Pb(II) and Cd(II) in aqueous samples.⁵⁶ The device was tested for its analytical performance for the direct quantification of multiple analytes without pretreatment. The square wave anodic stripping voltammetric (SWASV) signal was significantly enhanced and displayed excellent analytical performance for Pb(II) and Cd(II) detection from 0 to 100 ppb with low limits of detection of 2.0 and 2.3 ppb, respectively. The proposed electrochemical devices exhibited good selectivity and stability for analyses of real samples of gas dissolved salty soda water and ground water with physical contamination. This paper-based microfluidic device is simple, low-cost, easy-to-fabricate, and portable, making it an ideal candidate for point-of-care applications in environmental monitoring, public health, and food safety. The microfluidic device consists of filter paper strips and SPCE, which enables direct electrochemical detection of heavy metals. When the sample solution flows along the filter paper and across the surface of SPCE, it provides a thin mechanically stabilized film of water or other fluids on the surface of SPCE and delivers fresh sample for analysis. This feature of the device allows the original samples of gas dissolved and physically contaminated water to be directly applied for electrochemical measurements. Furthermore, the device is cost-effective, with small sample consumption and easy operation, making it ideal for use in under-resourced settings. The successful application of this paper-based microfluidic device for the detection of heavy metals in water holds great promise for further miniaturization and intellectualization in the fields of medical health, food safety, and environmental monitoring.

In a recent study, researchers conducted an investigation on the use of microfluidic paper-based solution sampling coupled with Pb²⁺-ISEs for the analysis of heavy metals in samples with low volumes and/or high solid-to-liquid contents.⁵⁷ They found that acidification of paper substrates prior to use was effective in eliminating the super-Nernstian response of Pb²⁺-ISEs observed otherwise. To determine the optimal pH range of the potentiometric sensors when coupled with acidified paper substrates, 3D approximate analyses of the Pb²⁺-ISEs responses were carried out. The results showed that the acceptable operational pH range for the paper substrate containing the sample solution was found to be between 3 and 4. In order to simplify the analytical protocol for heavy metal sensing using Pb²⁺-ISEs coupled with microfluidic paper-based solution sampling, a colour-coded matching graph was proposed to match the appropriate acidified paper substrate to the pH of the unbuffered sample solution. This approach was then tested in various complex environmental samples with small volumes of solution and/or high solid-to-liquid ratios, such as wet soil, street runoff, chemical spillage, and plant dew. The use of acidified paper substrates was found to be reliable in the determination of lead(II) in complex sample matrices, with results comparable to those obtained using potentiometry and ICP-OES. The study demonstrated that acidification of microfluidic paper-based solution sampling substrates, when coupled with Pb²⁺-ISEs in potentiometric cell design, is useful for samples containing low volumes and/or high solid-to-liquid content. The optimized acidified paper substrates effectively eliminated the super-Nernstian response of Pb²⁺-ISEs, which would otherwise be present when unmodified paper was used. Although the ultimate detection limit of the sensor was not

improved, the developed approach was utilized for the determination of Pb^{2+} in various samples, where Pb^{2+} -ISEs were coupled with acidified microfluidic paper-based solution sampling substrates to analyze lead concentrations in rainwater and ash leachate samples. The researchers suggest that future work could focus on pH optimization with paper substrates to eliminate the super-Nernstian response for other metal ions. Overall, this study provides a new method for paper modification in direct paper-based potentiometric heavy metal detection and has significant potential for use in environmental monitoring and analysis.

In an effort to control the super-Nernstian response commonly observed in heavy metal ion determination using microfluidic paper-based solution sampling, researchers turned to metal modified paper-based substrates. In a study, potentiometric responses of Pb^{2+} -ion selective electrodes (ISEs) coupled with gold, platinum, and palladium coated paper substrates were analyzed.⁵⁸ The researchers found that potentiometric response time was largely dependent on the thickness of the metallic layer deposited on the paper substrate. The team discovered that paper-based substrates coated on both sides with 38 nm gold layers were the most effective at controlling the super-Nernstian response of ISEs in non-equilibrium conditions. Durability studies showed that the lifetime of Pb^{2+} -ISEs could be doubled when used with metal modified paper-based substrates in complex environmental samples with high solid-to-liquid content. In order to validate their method, the researchers determined the concentration of lead in real samples using the metal modified paper substrates coupled with Pb^{2+} -ISEs and confirmed the results using inductively coupled plasma optical emission spectrometry (ICP-OES). The researchers

also performed detailed life cycle assessments for model screen printed potentiometric sensors with and without metal modified paper-based solution sampling substrates, and found that the use of modified paper substrates demonstrated lower environmental impact per potentiometric measurement of Pb^{2+} -ISE in prepared simulated environmental samples as compared to sensors without the use of paper substrates. Overall, this study provides insight into the use of metal modified paper substrates to control the super-Nernstian response in heavy metal ion determination and highlights the advantages of using such substrates in terms of controllable response and environmental impact.

A new paper-based chemiresistive sensor has been developed for the detection of As(III) using a network of single-walled carbon nanotubes (SWCNTs) with electrodeposited gold nanoparticles (AuNPs).⁵⁹ The sensor was fabricated using a water-based SWCNT ink by wax printing and vacuum deposition. The sensitivity of the sensor was improved by optimizing the volume of SWCNTs ink used in the formation of the sensing network and the sweep segment of cyclic voltammetry used for the electrochemical deposition of AuNPs. The proposed sensing strategy involves the electrochemical n-doping of As(0) on the AuNPs-SWCNTs channel. The sensor exhibited a low limit of detection of $1.35 \times 10^{-5} \mu\text{M}$, which is lower than the maximum permissible concentration in drinking water set by the WHO. The sensing mechanism of the proposed chemiresistive sensor was investigated using a liquid-ion gated FET system. The novel sensing strategy combines the n-doping property of As(0), catalysis of AuNPs on the electrochemical reduction of As(III), p-type semiconducting property of SWCNTs and the flexible, cheap and disposable characteristic of the paper substrate. The sensor showed an enhanced

response for different concentrations of As(III) ascribed to the AuNPs-SWCNTs network with a three-dimensional structure formed based on the framework of the paper fibers, which provided an effective electron transfer path and a large specific surface area. The morphological and structural characteristics of the paper-based device confirmed that the AuNPs uniformly covered SWCNTs, and the EDS analysis indicated the successful doping of As(0) on the sensing area, leading to an increase in resistance. The proposed sensing strategy represents an important step towards developing capture probe/receptor-free, ultrasensitive and practical chemiresistive sensors for the detection of As(III) in water. The results of this study offer a simple strategy for developing paper-based chemiresistive sensors with unique properties for practical As(III) determination.

In a recent study, researchers reported the multifarious use of filter paper to detect copper ions in bodily fluids.⁶⁰ The research team exploited this eco-friendly material to synthesize AuNPs without the use of reductants and/or external stimuli, print the electrodes, load the reagents for the assay, filter the gross impurities, and preconcentrate the target analyte. The researchers were able to detect copper ions down to 3 ppb with a linearity up to 400 ppb in standard solutions. They also demonstrated the applicability of the paper-based platform in biological matrices, specifically sweat and serum, through recovery studies and by analyzing these biofluids with the paper-based platform and the reference method (atomic absorption spectroscopy), which demonstrated satisfactory accuracy of the novel eco-designed analytical tool. The study highlights filter paper as a unique platform for merging both the fabrication and detection processes. The porous nature of filter paper allows for the preloading of reagents necessary for the development of the assay and

accumulation of the target analyte prior to the measurements. The electrochemical analysis of copper ions with a porous platform is often limited by the scarce diffusion of metals within the paper structure to reach the electrode area, affecting sensitivity. However, in this study, the in situ fabrication of the AuNP strip allowed for the accumulation of copper ions and detection in a standard solution down to 3 ppb, linearly up to 400 ppb. The platform was also successfully used to detect copper ions in untreated sweat samples with recovery studies indicating high accuracy. The use of filter paper as a comprehensive tool for the realization of a novel analytical device is particularly noteworthy in the context of sustainable development and autonomous monitoring for nonspecialists. Paper, and in particular filter paper, represents a versatile and cost-effective alternative to the more expensive and less sustainable approaches. This approach ensures user-friendly implementation and is a valuable contribution to the development of sustainable analytical tools.

The authors of a recent study have developed a ratiometric fluorescence sensor method for the on-site and rapid determination of Cu^{2+} in drinks.⁶¹ The method is based on the mixture of CdTe QDs and GCNNs, and has been shown to be more precise and accurate, as well as cheaper, simpler, more selective, and sensitive, than other published reports. CdTe QDs and GCNNs were physically mixed together to create the sensor. Under a UV lamp, the fluorescent intensity of traffic yellow CdTe QDs is linearly quenched by Cu^{2+} (used as the detection signal), while blue GCNNs remains unchanged (used as the reference). This results in a distinguishable color change from pink yellow to blue. The limit of detection (LOD) for Cu^{2+} using this sensor is as low as 0.47 ng mL^{-1} with 1.4%

RSD. The researchers successfully applied the established method to detect Cu^{2+} in various drinks with satisfactory results. In addition, the authors developed a paper-based sensor by soaking cellulose acetate membrane in CdTe QDs/GCNs sensor solution. This paper-based sensor has a wide semiquantitative detection range for Cu^{2+} ($0.01\sim 5.0\ \mu\text{g mL}^{-1}$), and has been shown to be effective for the on-site visual detection of Cu^{2+} in red wine without any pretreatment procedure. By comparing the colors of standard and actual samples on the CdTe QDs/GCNs paper-based sensor, the researchers were able to semiquantitatively detect Cu^{2+} . This paper-based sensor has the characteristics of being cheap, fast, on-site, simple, and having a broad intuitive detection range, which makes it highly valuable for the determination of Cu^{2+} in liquid samples.

A team of researchers has developed a sustainable and miniaturized platform for the programmable pre-concentration of analytes and the electrochemical detection of mercury traces in drinking water.⁶² The platform involves the merging of two paper-based substrates, office paper and filter paper, to exploit the unique advantages of each component. Office paper is suitable for printing conductive strips, while filter paper is ideal for storing chemicals. The researchers utilized a wax printing technique to create a 3D configured filter paper that can pre-concentrate real matrices, store reagents, and tune the level of sensitivity, addressing the challenge of achieving effective sensitivity using humble configurations and microliter volumes. The paper-based pre-concentration operation enhances the sensitivity towards mercury ion detection up to 5-fold compared to that of the unique office paper-based screen-printed electrode. Moreover, the design of a 3D-printed holder ensures the use of a compact device. This novel platform

demonstrates the possibility of merging humble materials to maximize their impact on analytical and remediation challenges, highlighting their synergistic significance. The approach is versatile and easily extendable to other in-house systems requiring sensitivity improvement. This represents a significant step forward in the development of sustainable and cost-effective solutions for water monitoring and management.

Another article describes a novel electrochemical three-electrode system integrated on nitrocellulose membrane (NC) using magnetron sputtering technology for the detection of Cu^{2+} and other heavy metal ions.⁶³ The paper-based sensor chip exhibited a uniform arrangement of porous structure without further film modification, which allowed for an increased effective working area of the electrode. The integrated sensor showed good linearity for Cu^{2+} detection within the ranges of $5\text{--}200\ \mu\text{g}\cdot\text{L}^{-1}$ and $200\text{--}1000\ \mu\text{g}\cdot\text{L}^{-1}$ with a limit of detection of $2\ \mu\text{g}\cdot\text{L}^{-1}$. In addition, the paper-based sensor chip was capable of detecting other heavy metal ions such as Zn^{2+} , Cd^{2+} , Pb^{2+} and Bi^{3+} with good linearity. The small size and low cost of the integrated sensor made it an attractive option for on-site rapid detection technology for heavy metal ions. The experimental results demonstrated that the chip had high sensitivity and a wide measurement range, meeting the requirements of the environmental quality standard for surface water in China. Overall, this study highlights the potential of paper-based sensor chips fabricated using magnetron sputtering technology for the detection of heavy metal ions in various environmental settings.

Concluding Remarks and Future Directions for Paper-Based Sensors in Heavy Metal Ion Detection

Paper-based sensors offer a promising platform for a wide range of applications including health diagnostics, environmental monitoring, and food quality control. Compared to plastic and glass substrates, paper is inexpensive, disposable, abundant, and easy to transport. The low cost and ease of use make paper-based sensors attractive for developing world applications where simplicity and affordability are crucial. In the field of environmental monitoring, real-time detection of heavy metals and other pollutants is critical as sample conditions can change throughout the day and during the transportation back to the lab. Thus, there is a need for sensors that can enable on-site detection and accurate monitoring of environmental conditions. Researchers have focused on developing paper-based sensors with simple fabrication techniques and operation, making them suitable for developing world applications where simple and easy-to-use devices are highly desirable. With further research and development, paper-based sensors have the potential to play a significant role in monitoring and improving the quality of our environment, food, and health. Although paper-based sensors have emerged as a promising platform for various applications including health diagnostics, environmental monitoring, and food quality control due to their low cost, disposability, abundance, and easy transport, however, researchers face several challenges in developing paper-based sensors. One significant challenge is the difficulty in multiplex analysis. As the shape and design of the sensors become more complex, there is a potential for cross-talk among the different channels. The future of multiplex analysis may see the development of more

intricate 3-D paper architectures that can detect multiple analytes using a combination of techniques. Another challenge is the need for low power and portable analysis techniques. Despite facing challenges, the significant progress in paper-based sensors over the past few years has resulted in the development of more advanced and intelligent sensors. Experts predict that there will be more breakthroughs in this rapidly evolving research area. To achieve these advancements, future research must concentrate on designing new fabrication techniques and integrating functional materials on the surface. However, it is crucial to keep in mind the benefits of simplicity and low cost associated with paper-based sensors.

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