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Innovative Approaches to Gas Sensing: Bridging Theory and Human Applications

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Abstract:
In this study, a comprehensive analysis of gas sensor technology was conducted, focusing on various types and their applications in industrial instrumentation. The technical characteristics of different gas sensors, both static and dynamic, are explored, along with an examination of working principles. Connection methods with other devices were demonstrated using simulation software for wiring diagrams and microcontroller programming. An analysis of circuit characteristics was presented, with a focus on input-output relations such as amplitude and sensitivity. Additionally, a conceptual design for a new type of gas sensor was proposed, utilizing existing components. This study not only contributes to the understanding of current gas sensor technologies but also outlines key directions for future innovations, specifically focusing on optimizing sensor efficiency for human-based technology applications.

Keywords: Gas sensor; Instrumentation; Characteristics of gas sensor; Human application

1. INTRODUCTION

Gas sensor technology, a cornerstone in industrial instrumentation, has evolved significantly, paralleling advancements in materials science and electronics (1). The origins of gas sensors can be traced back to early chemical detection methods, which have since transformed into sophisticated systems based on cutting-edge principles of gas detection. These developments have been bolstered by breakthroughs in semiconductor physics, nanotechnology, and microfabrication techniques, leading to enhanced sensitivity, selectivity, and miniaturization.

In the industrial realm, gas sensors play a critical role in hazard prevention, particularly in environments where exposure to toxic or explosive gases is a concern. Their applications extend to environmental monitoring, where they are vital in tracking air pollutants and greenhouse gases, contributing to efforts in air quality management and climate change mitigation. In healthcare, gas sensors are being integrated into breath analysis systems, offering non-invasive diagnostic capabilities that align with the increasing trend of personalized medicine and digital health technologies.

This study aims to provide a comprehensive exploration of gas sensor technologies, focusing on their structural differences and functional characteristics. It delves into the operational principles of both traditional and emerging sensor types, alongside integration strategies that utilize simulation tools and microcontroller platforms for practical demonstrations. A key innovation of this study is the conceptual design of a new type of gas sensor, which leverages existing components to improve performance, flexibility, and adaptability for future applications. This investigation not only enhances the understanding of current gas sensor technologies but also charts a forward-thinking trajectory for their integration into human-centered technologies, particularly in industrial, environmental, and healthcare contexts.

2. GAS SENSOR TECHNOLOGY

The evolution of gas sensor technology dates to the early 20th century, initially focusing on detecting harmful gases in mining environments. As scientific understanding deepened, the 1950s and 1960s saw significant advancements, particularly with the introduction of semiconductor-based sensors (2). These were pivotal in detecting a wide range of gases with greater sensitivity and specificity. The scientific basis of gas sensors is rooted in the interaction between gas molecules and sensor materials. This interaction leads to measurable physical or chemical changes, forming the core principle of gas detection. The progress in nanotechnology and microfabrication in recent decades has been instrumental in enhancing performance and reducing the size of these sensors.

In industrial settings, gas sensors have become indispensable for ensuring workplace safety, especially in chemical and petrochemical industries. Environmentally, they play a crucial role in monitoring air quality and detecting greenhouse gases, aligning with global efforts in environmental conservation. In the medical field, the application of gas sensors for breath analysis has opened new avenues in non-invasive diagnostics, aligning with trends towards patient-friendly

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technologies (3). The future of gas sensor technology appears promising, with potential advancements including the integration of Internet of Things (IoT) for real-time monitoring and the application of artificial intelligence for enhanced data analysis and predictive capabilities.

3. THEORY OF GAS SENSORS

The fundamental principles of gas detection in sensors involve the response to the presence of different gases, based on chemical or physical changes. When a target gas interacts with the sensor, it triggers a change, which can be a variation in electrical resistance, light absorption, or a chemical reaction. For example, semiconductor-based sensors detect gases through changes in electrical resistance when gases interact with the sensor's surface. Electrochemical sensors, on the other hand, rely on chemical reactions that produce electrical current. The nature of the interaction is determined by the type of gas and the sensor's material, making specificity and sensitivity crucial aspects. This interaction is then translated into a measurable signal, which is processed to determine the presence and concentration of the gas.

Gas sensors are diverse in their design and function, catering to specific detection needs (4). Electrochemical sensors excel in environments requiring high sensitivity and specificity, ideal for gases like carbon monoxide, hydrogen sulfide, and oxygen. Semiconductor sensors, using metal oxides, are versatile for a wide range of combustible gases. Infrared sensors leverage the unique infrared absorption characteristics of gases, particularly effective for carbon dioxide and hydrocarbon detection. Photoionization Detectors (PIDs) are valuable for detecting low concentrations of volatile organic compounds (VOCs), while catalytic bead sensors are commonly used for detecting combustible gases through a catalytic oxidation process. Each sensor type presents a unique set of advantages and limitations, shaped by its operating principle, sensitivity, and environmental adaptability.

Gas sensors are designed to detect specific gases and can vary based on the type of gas they are meant to detect. Key types include sensors for oxygen, carbon monoxide, carbon dioxide, ammonia, chlorine, hydrogen sulfide, nitrogen oxide, volatile organic compounds, methane, hydrocarbons, and hydrogen. Different technologies underpin the function of gas sensors.

3.1 Electrochemical Sensors

Electrochemical sensors use an electrochemical reaction to generate an electrical current when a target gas interacts with a working electrode. The reaction produces a current proportional to gas concentration. These sensors offer linear responses, simplifying calibration, but may show cross-sensitivity to other gases. Temperature compensation is necessary for reliable performance across different environments. These sensors are commonly used in medical, environmental, and industrial applications due to their high sensitivity and affordability.

3.2 Photoionization Detectors (PID)

Photoionization detectors detect gases, particularly VOCs, by ionizing gas molecules with ultraviolet light. The resulting ions generate a current proportional to the gas concentration. Photoionization detectors are fast and effective for detecting low concentrations of VOCs but are less specific and sensitive to environmental factors such as humidity and temperature.

3.3 Solid-State/Metal Oxide Semiconductor (MOS) Sensors

Solid-State/Metal Oxide Semiconductor (MOS) sensors detect gases by measuring changes in the conductivity of a metal oxide material when exposed to target gases. They offer high sensitivity, especially at low concentrations, but require high operating temperatures and can be sensitive to humidity and cross-sensitivity to other gases. They are commonly used in air quality monitoring and industrial leak detection.

3.4 Catalytic Sensors

Catalytic sensors detect combustible gases through a catalytic oxidation process (Figure 1). The sensor consists of two beads, one exposed to the target gas and one acting as a reference. The difference in resistance between the two beads, measured by a Wheatstone bridge (Figure 2), indicates the gas concentration. These sensors are reliable but can be affected by certain substances and require oxygen to operate.

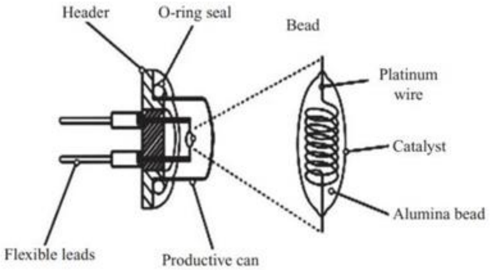

Figure 1. Schematic of catalytic sensor.

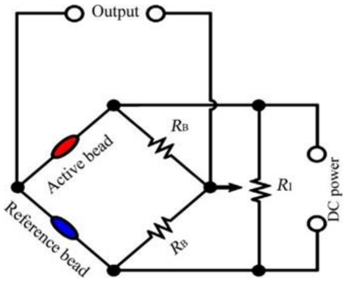

Figure 2. Catalytic sensor used in Wheatstone bridge.

3.5 Infrared (IR) Sensors

Infrared (IR) sensors detect gases based on their absorption of infrared light at specific wavelengths (Figure 3). The absorption is proportional to the gas concentration. These sensors are non-contact, low-maintenance, and highly selective for gases like carbon dioxide and methane. However, they cannot detect gases without significant infrared absorption (Figure 4) characteristics and can suffer from interference.

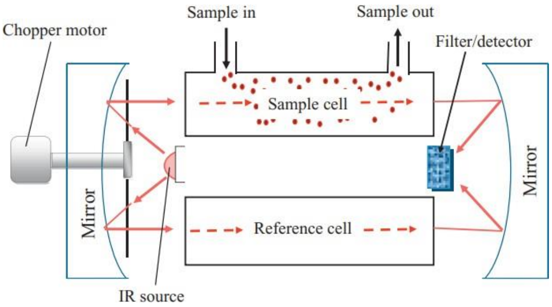

Figure 3. Schematic of IR sensor.

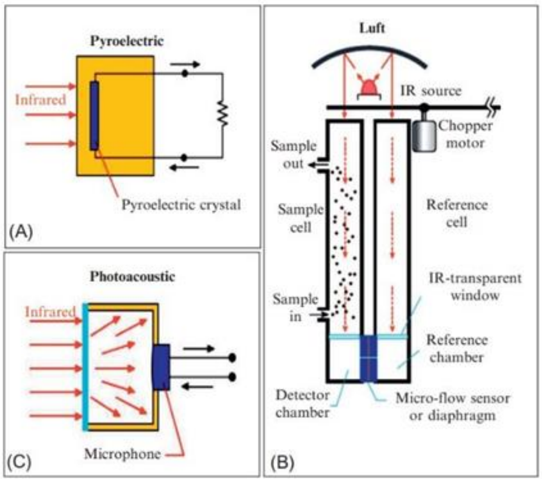

Figure 4. Different types of detectors: (A) pyroelectric, (B) luft, and (C) photoacoustic, are used to convert electromagnetic radiation energy into electrical impulses.

3.6 Laser, Zirconia, and Holographic Sensors

Laser sensors use tunable diode laser absorption spectroscopy to detect gases with high accuracy and sensitivity. Zirconia sensors detect oxygen by measuring ion conductivity in zirconium dioxide. Holographic sensors, still in development, utilize holographic techniques to detect chemical changes, offering high sensitivity and specificity for real-time measurements.

4. TECHNICAL CHARACTERISTICS

Understanding the technical characteristics of gas sensors, including both static and dynamic aspects, is essential for selecting the right sensor for specific applications and accurately interpreting sensor data (Table 1). Static characteristics refer to key parameters such as sensitivity, which is the sensor's ability to detect small changes in gas concentration, and selectivity, which allows the sensor to identify a specific gas among others. The sensor's range defines the minimum and maximum gas concentrations it can detect, while accuracy indicates how closely its readings match the actual gas levels, accounting for factors like sensor drift and calibration over time. Additionally, resolution refers to the smallest detectable change in gas concentration, and response time is the time it takes for the sensor to stabilize after exposure.

On the dynamic side, the sensor's performance is evaluated based on its ability to respond to changes in gas concentration and environmental conditions. This includes response time (the time taken to react to the presence of gas) and recovery time (how quickly the sensor returns to baseline after the gas is removed). Repeatability ensures that the sensor delivers consistent results under the same conditions across multiple tests. Long-term stability assesses the sensor's ability to maintain accuracy and sensitivity over prolonged use. Furthermore, over-range performance evaluates how the sensor behaves when exposed to gas concentrations exceeding its maximum range, with some sensors capable of withstanding such conditions without damage. Cross-sensitivity considers how other gases might influence the sensor's readings. Finally, environmental factors like temperature, humidity, and pressure can impact performance, with dynamic characteristics reflecting how resilient the sensor is under varying conditions.

To illustrate these characteristics in practical applications, consider the use of gas sensors in industrial safety. For example, a sensor used to detect carbon monoxide (CO) in an industrial setting must have high sensitivity and selectivity to ensure it can differentiate CO from other gases, like nitrogen or hydrogen, in the air. Similarly, in environmental monitoring, sensors deployed to track methane emissions must exhibit long-term stability and low cross-sensitivity to other gases, such as carbon dioxide (CO_2), which could interfere with accurate measurements. These real-world examples demonstrate how both static and dynamic characteristics are critical in ensuring the reliability and precision of gas sensors across different applications.

Table 1. A comprehensive overview of the key static and dynamic characteristics of different gas sensors (3).

Characteristic	Electrochemical	PID	MOS	Catalytic	Infrared (IR)	Laser	Zirconia
Sensitivity	High	High for VOCs	High	High for combustible gases	High	Very High	High for oxygen
Selectivity	Varies	High for specific VOCs	Moderate	Low	High	Very High	High for oxygen
Range	Depends on specific sensor	Varies	Wide	Limited to combustible gases	Varies	Varies	Limited to oxygen
Accuracy	High	High	Moderate	High	Very High	Very High	Very High
Resolution	High	High	High	Moderate	High	Very High	High
Response time	Fast	Very Fast	Moderate	Fast	Fast	Very Fast	Fast
Repeatability	Good	Good	Moderate	Good	Excellent	Excellent	Good
Long-term stability	Good	Moderate	Good	Good	Excellent	Excellent	Excellent
Over-range performance	Moderate	Moderate	Poor	Good	Good	Good	Good
Cross-sensitivity	Low to moderate	Moderate	High	High	Low	Low	Low
Environmental factors	Sensitive to temperature and humidity	Sensitive to temperature and humidity	Very sensitive to temperature and humidity	Sensitive to temperature and humidity	Less sensitive to environmental factors	Moderate sensitive to environmental factors	Sensitive to environmental factors

5. PREVIOUS FINDINGS

The papers by Rezende *et al*. (1) and Sun *et al*. (2) both made significant contributions to the field of photoionization detectors (PIDs) but with different focal points and outcomes. Rezende *et al*. (1) concentrated on miniaturizing PIDs for gas chromatography, achieving smaller detectors without sacrificing performance, which results in faster analysis and lower detection limits. In contrast, Sun *et al*. (2) aimed to enhance PID performance through structural innovations, specifically by integrating a novel "nozzle" structure and an annular accelerating electrode in the ionization chamber, leading to ultra-low background noise and improved sensitivity for low-concentration gas detection. While Barsan *et al*. (7) emphasized compact design, Poloju *et al*. (4) focused on enhancing sensitivity and rapid response, showcasing different but complementary advancements in PID technology.

Nazemi *et al.* (6) offered a critical review of experimental techniques applicable in the study of conductometric gas sensors based on semiconducting metal oxides. The authors focus on evaluating and modeling sensor performance in realistic conditions using a combination of phenomenological and spectroscopic techniques. They provide a detailed

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analysis of the achievements and limitations of various experimental methods, using selected examples to demonstrate the proposed approach. The paper aimed to set objectives for future research in this domain, emphasizing the need for more comprehensive and realistic testing methods to advance the understanding and development of metal oxide-based gas sensors. This work is a significant contribution to the field, particularly in guiding future research and development efforts in gas sensor technology.

Pham *et al*. (8) discussed various methods for gas detection. For chemi-resistive methods, they explore how changes in electrical resistance of MOFs are used to detect gases. In capacitive methods, the focus is on the change in capacitance induced by gas adsorption on MOFs. Optical methods are detailed as well, where the interaction of gases with MOFs leads to changes in optical properties, such as luminescence or colorimetric changes. Each of these methods leverages the unique properties of MOFs for effective gas sensing. As discussed by Liu *et al*. (9), an innovative approach to nitric oxide (NO_2) gas sensing using MoS2-based optoelectronic sensors. The method involves utilizing red light illumination to match the direct band gap of single-layer MoS2, which enhances the sensitivity and detection limit of the sensor. The study reported significant advancements in NO_2 gas detection, achieving a sensitivity of 4.9 %/ppb and a detection limit as low as 0.1 ppb. This approach far exceeds the U.S. Environmental Protection Agency's requirements for NO_2 gas detection at ppb levels. The research contributes notably to the field of gas sensor technology, especially in the context of optoelectronic enhancements for improved sensor performance.

Yuan *et al*. (10) introduced a unique approach to CO_2 gas detection using graphene-based electroluminescent (EL) sensors. The authors developed this sensor by integrating graphene as a sensing material in the EL structure. They fabricated the sensor using screen-printing and drop-coating methods, focusing on its sensitivity to CO_2 at various concentrations and its selectivity against other gases like ammonia, ethanol, and toluene. The study demonstrates the sensor's effectiveness in detecting CO_2, providing insights into its potential for practical applications in gas sensing. Korotcenkov (11) introduced an innovative carbon dioxide (CO_2) sensor based on alternating-current electroluminescent (AC-EL) devices, incorporating a graphene gas-sensing layer. This sensor operates at room temperature and is fabricated using screen-printing and chemical vapor deposition (CVD). It demonstrates high responsiveness to CO_2 in concentrations ranging from 100– 1000 ppm, distinguishing itself with notable selectivity against other gases such as NH_3, C_2H_5OH, and C_7H_8. Its sensing mechanism relies on the resistance change in the graphene layer due to charge transfer processes between CO_2 and the graphene surface. The research highlights the sensor's repeatability, reproducibility, and accuracy, suggesting a promising new direction in gas sensor technology based on EL principles.

Seekaew and Wongchoosuk (12) focused on developing gas sensors using ZnO nanoparticles, ZnO/CuO, and Al-ZnO/CuO nanocomposites, prepared through co-precipitation and sol-gel methods. The study explored the structural and morphological characteristics using XRD, Raman spectroscopy, HRTEM, and SEM. Notably, the Al-ZnO/CuO nanocomposite sensor exhibits excellent gas sensing performance, especially for ammonia detection at room temperature, marked by high response, good stability, and rapid response and recovery times. XRD and Raman analyses confirm the composite formation without any alloy phase, indicating the successful integration of materials while maintaining their distinct properties. This work underscores the potential of Al-ZnO/CuO nanocomposites in enhancing gas sensing applications.

6. CONCEPTUAL DESIGN

In this section, a systematic approach is detailed, employed the integration and evaluation of MQ2 gas sensor with the Arduino V4.0 board. The procedures and techniques used are outlined, encompassing the setup, and wiring of the sensor to the Arduino board, followed by programming of the microcontroller for data collection and analysis. This section aims to provide a comprehensive and replicable conceptual design, ensuring a clear process understanding for gas detection and monitoring in various environments.

6.1 MQ2 Gas Sensor

The MQ2 sensor, a semiconductor device for detecting flammable gases, changed its resistance in the presence of target gases as shown in Figure 5. This changed in resistance altered the voltage across the sensor, which was then processed by the operational amplifier. The amplifier's output triggered a response, such as lighting a light-emitting diode (LED) to indicate the detection of gas. Additionally, the output signal was made available through a connector, which interfaced with a microcontroller or other devices for further processing or trigger alarms.

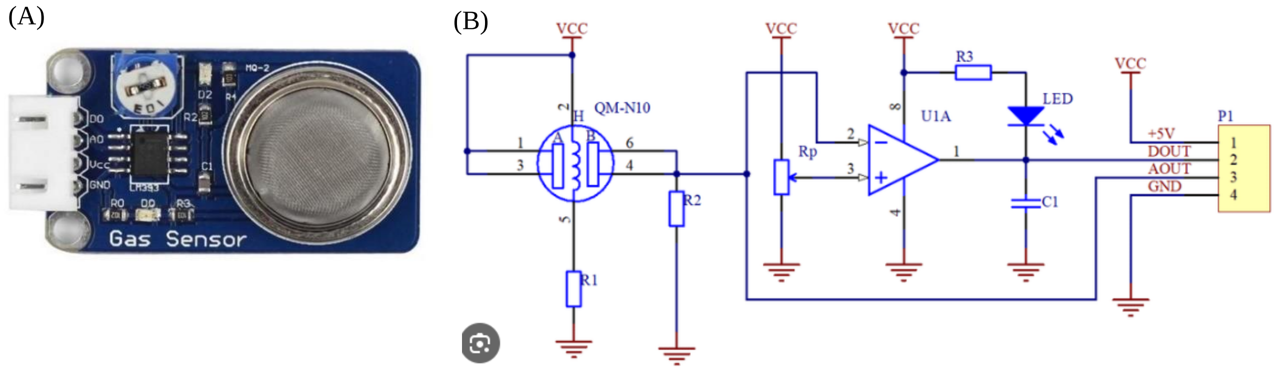

Figure 5. (A) MQ2 sensor and (B) circuit schematic of MQ2.

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The module typically has four pins as shown in Figure 6 such as VCC for power, GND for ground, a digital output that went low when gas was detected, and an analog output that provided a variable voltage depending on the gas concentration. The onboard potentiometer allowed the adjustment of the sensor's sensitivity. The RL resistor, positioned near the digital out LED, was part of the circuit that helped to indicate when the digital threshold has been reached.

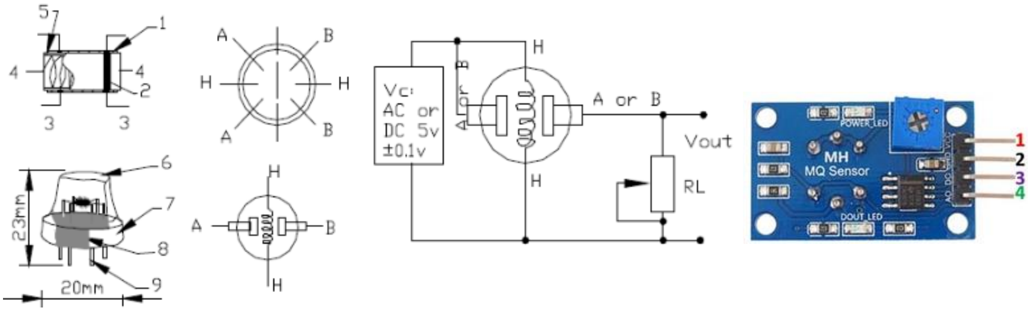

Figure 6. MQ2 sensor pin diagram

As shown in Figure 7, the graph represents the sensitivity characteristics of the MQ2 sensor, detailing its response to various gases. The sensor's resistance ratio (RS/R0), which is a measure of resistance in a gas compared to clean air, varies for different gases. A higher RS/R0 ratio indicated greater sensitivity. The graph shows that the sensor was most sensitive to LPG, hydrogen, and methane, with a notably higher response at lower concentrations. In contrast, the response to CO and alcohol was less pronounced. These data are crucial for calibrating the sensor in applications where these gases need to be detected, as it informs about the sensor's response pattern to different concentrations of gases.

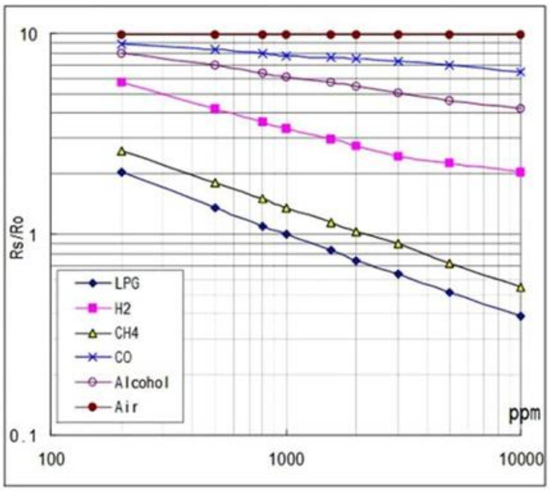

Figure 7. Sensitivity characteristics of MQ2.

6.2 Integration and Programming of Gas Sensors with Microcontroller Systems

Integrating the MQ2 gas sensor with an Arduino V4.0 board involved establishing a physical connection and programming the board for data acquisition (Figure 8). The MQ2 sensor, designed for smoke and flammable gas detection, conneced to the Arduino with its VCC pin to the 5V supply, GND pin to a ground, and analog output to an analog input like A0. Programming in the Arduino IDE included initializing the sensor's pin, reading its output, and optionally converted this to concentration values. Data were displayed on the Arduino's serial monitor or an external display, facilitating real-time monitoring of gas concentrations.

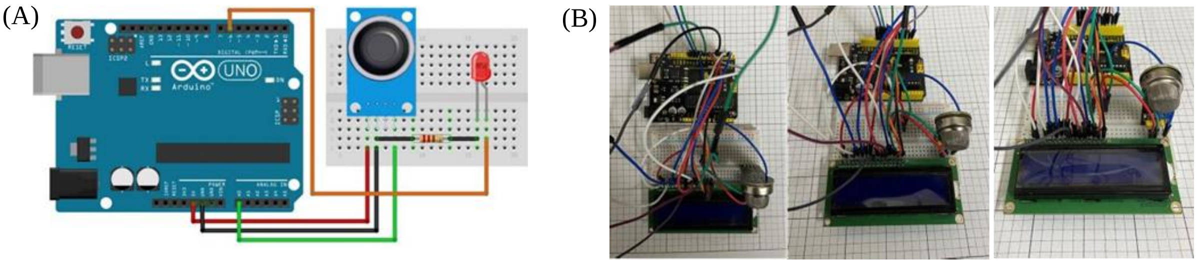

Figure 8. (A) Circuit connection for MQ2 and (B) circuit connection for testing.

6.3 System Interpretation

The system interpretation demonstrated the MQ2 sensor's swift detection capabilities. When exposed to gases such as carbon monoxide (CO) and methane (CH_4), the sensor's resistance changed rapidly, indicating a quick reaction to the presence of these gases. This rapid response is crucial for applications that require immediate alerts, such as human safety and environmental monitoring. The data suggests that the sensor is not only sensitive to gas presence but also recovers quickly to baseline levels after the gas dissipates, showcasing its potential for reliable and responsive gas detection in various settings.

7. CONCLUSION

This report effectively synthesizes a comprehensive understanding of gas sensor technologies, with a special focus on the MQ2 gas sensor integrated with an Arduino V4.0 board. It encompasses a detailed examination of various sensor types, their distinctive properties, applications, and the intricacies of connecting these sensors to microcontrollers for practical use. Additionally, the report highlights the sensitivity and selectivity of the MQ2 sensor in detecting different gases, the programming approaches for data acquisition, and the sensor's vital role in safety and environmental monitoring. Conclusively, it acknowledges the scope for future advancements in sensor technology, integration methodologies, and digital innovations, underscoring the dynamic nature of this field and its significance in various applications.

AUTHORSHIP CONTRIBUTION STATEMENT

Osama Gamal Mahmoud: writing – original draft, formal analysis; Nur Athirah Syafiqah Noramli: writing – review and editing; Herlina Abdul Rahim: conceptualization, supervision, writing – review and editing.

DATA AVAILABILITY

Data are available within the article.

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