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Review

Advances of SiC-based MOS capacitor hydrogen sensors for harsh environment applications

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ABSTRACT

SiC-based hydrogen sensors have attracted much attention due to applications in harsh environments. In this paper, harsh environment is defined. Characteristics of SiC-based hydrogen sensors for harsh environment applications are reviewed. Various types of SiC-based field effect hydrogen sensor in terms of their respective history, structure, advantages and disadvantages have been discussed. SiC-based MOS capacitor hydrogen sensor will be conferred in detail. The reasons for selecting SiC in fabricating MOS capacitor hydrogen sensor for harsh environment applications are elucidated. Different hydrogen sensing mechanisms depend on the temperatures and the conditions of catalytic metal layer are highlighted. MOS capacitor SiC-based sensors fabricated by previous research groups are listed. Each catalytic electrodes and oxide layers selected have their significant properties. Examples of nanostructured materials that have been used in forming oxide layer are illustrated. The future challenges in terms of material (metal electrodes and oxide layers) properties and surface properties of materials are described. It is concluded that MOS capacitor SiC-based hydrogen sensors promote green technology.

Contents

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1. Introduction

The awareness in environmental conservation in many countries has increased. Scientists and engineers alike are making efforts in producing green products, which are environmentally friendly. One of these products is the hydrogen sensor. This electronic device is important in various applications for safety reasons [1–4]. It is of great attention mainly for detection of hydrogen leakage [1,2,5,6], which is below the lower explosive limit (LEL) of 4% by volume ratio of hydrogen to air [7–9]. By nature, hydrogen is explosive [3]. If hydrogen flows into the air from a tank or valve, it will pose hazardous. On top of this, hydrogen is a major cause of corrosion. This happens when tiny hydrogen atoms penetrate into steel and other metals and deteriorates the metals internally, which results in hydrogen blistering or hydrogen embrittlement where properties of metals, for instance ductility, strength and fracture toughness, are affected [10]. Hydrogen that is absorbed as low as 1 ppm can cause cracking [11]. This is especially important for elevated temperature applications [12].

Consequently, development of hydrogen sensor has been stimulated. Hydrogen sensors are required to have high sensitivity [5,6,13], selectivity [3,5], reliability [6], long-term stability [3], low hydrogen concentrations workable, fast response [13,14], and cost effectiveness [5,11]. In addition, a wide detection range is also desirable [2], where development of gas sensors for 10–1000 ppm of hydrogen is of high interest [1]. For the applications in aerospace and automotive industries, hydrogen sensors that can operate at high temperatures and under potentially corrosive conditions are required [5]. The existence of hydrogen gas is particularly destructive in aircraft and gas pipeline applications [12].

Likewise, hydrogen sensor is needed for the safe take-off of rocket and in-flight safety systems [15]. Hydrogen is consumed in rocket fuel [5], which is the main gas evolving under pyrolysis at the initial stage of combustion [1]. The other main application of the hydrogen sensor is in fuel cells [4,5,16]. Fuel cell is a charming alternative to fossil fuel combustion engine, which is consumed in vehicles for their efficiency, versatility and environmental friendliness [10]. Besides this, it is used as battery replacements for personal electronics and as portable or stationary emergency power [3,10,11]. Fuel cells use hydrogen to generate electricity. No emissions are involved in the generation of electricity form. It is a new, clean and renewable energy source [2,3,6,12,17] that converts hydrogen and oxygen to electricity, heat and water [18,19]. On the other hand, hydrogen sensor is important in some industries such as glass, chemical and petroleum industries (occurs in storage tanks and in refining process) [10,12], where the release of hydrogen is unavoidable.

Harsh environment, in some papers, is termed as extreme environment [13,20], hostile environment [21], rough environment [22] or "unfriendly" environment [20]. This environment is always referred to the situation involving high temperature [5,17,18,20,23], high frequency, high power [24], high electromagnetic interference (EMI) [25], intense vibrations, erosive flows [15], high radiations and high aggressive media exposure [20]. In addition, harsh environment is related to the condition which is likely to cause significant corrosion-related degradation [5,26]. Typically harsh environment applications are related to automotive, aerospace, avionics, micropropulsion, turbomachinery, industrial process control, nuclear power, communication and well-logging industries [20,25,27,28,15]. In these industries, not only the operational temperatures are high but also the inability to provide cooling system. Thus, this would cause conventional pure Si-based electronic systems to fail [20,28].

Consequently, there is a need for semiconductors with good thermal stability and wide bandgap for stable electronic properties at elevated temperatures [15]. Semiconductors such as silicon carbide (SiC), group-III nitrides (AlN, GaN and AlGaN) and diamond have these properties and have been used as a substrate to develop hydrogen sensors for harsh environment applications [14,20,29]. These wide bandgap semiconductors offer great potential to fabricate active high-temperature electronics and micro-systems for applications in very-high-temperature regimes (more than 300 °C) [17,20,26,30]. Furthermore, wide bandgap semiconductors may offer additional advantages in terms of high power and high frequency applications [24]. However, the most mature, in terms of film growth and process technology, among all of the wide bandgap semiconductors is SiC [14]. Therefore, development of SiC-based hydrogen sensor is of strong concern [20,30].

SiC has additional attractive features compared with other wide bandgap semiconductors. SiC substrates are commercially available, it has known device processing techniques and it has an excellent ability to grow a good quality of thermal oxides [20,26]. As a result, SiC is now in the forefront of wide bandgap semiconductor research [31]. There are almost 250 polytypes of SiC that have been discovered [20,21,32]. For different polytypes, the bandgap ranges from 2.2 eV for the cubic configuration to 3.3 eV for the hexagonal configuration [33–35]. This range of wide bandgap allows high temperature operation up to 1000 °C [20,26,30,31]. This property of SiC allows hydrogen sensors based on this material to be integrated with high-temperature electronic devices on the same chip. Moreover, it has excellent thermal conductivity (3–4.9 W/cm K), chemical inertness and radiation hardness [31].

Most of the SiC-based hydrogen sensors are grouped into field effect devices, which properties are determined largely by the effect of an electric field on a region within the devices. The unique working principle of SiC field effect devices makes it a gas sensor with high sensitivity and good selectivity towards a variety range of gases, such as hydrogen or hydrocarbons [30,36]. Furthermore, these SiC-based devices able to perform as rapid sensors over a broad range of temperatures [30], where the response is in the order of milliseconds [26]. Gas sensor of this structure has a great stability and reliability for harsh environment applications. Among these field effect devices, metal-oxide-semiconductor (MOS) SiC-based hydrogen sensor is preferred. MOS capacitor hydrogen sensors are very simple to fabricate. Thus, it is preferred in research works.

There are several published papers which review SiC gas sensors (Table 1). This review paper does not intend to emulate the aforementioned works; instead it aims to annotate the materials that have been used for both catalytic metal electrode and dielectric layer in fabricating MOS capacitor SiC-based hydrogen sensor for harsh environment applications. An executive summary table is presented which incorporates various MOS capacitor SiC-based hydrogen sensors that have been demonstrated throughout the years.

2. SiC-based hydrogen sensor for harsh environment applications

Sensors are devices that measure physical quantities (real-world conditions), such as heat, pressure or acceleration, and converts it into an analog or digital representation. For accuracy, all sensors need to be calibrated against known standards. Therefore a gas sensor is a device that detects the presence of assorted gases within an area. Increasing amounts of gasses and chemicals released into the environment draws the attention on research and development of advanced gas sensors to control pollutant emissions [18,30,48]. It can be used to detect oxygen [49]; explosive and combustible gases such as hydrogen [1–3,5,6,50], hydrogen sulphide [50] and hydrocarbon gases [14,26,35,44,50]; toxic gases for instance, NO_x [40,51], CO_x [26,40,51], nitrogen [40,52], ammonia [14,50] and sulphur dioxide [40]. In this paper, the scope is further narrowed down by focusing on hydrogen sensors.