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On a Schottky diode-type hydrogen sensor with pyramid-like Pd nanostructures

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ABSTRACT

A new Pd/AlGaN/GaN Schottky diode-type hydrogen sensor with pyramid-like Pd nanostructures is fabricated and studied comprehensively. The employed pyramid-like Pd nanostructures cause the substantial increase of surface roughness and surface-to-volume aspect ratio which give the remarkable increase of adsorption sites on the surface for hydrogen molecules. Experimentally, the studied device with pyramid-like Pd nanostructures demonstrates enhanced hydrogen sensing performance, including a large forward-bias current variation of 1.95×10^{-6} A and a high sensing response of 1454 under an introduced 1% H_2/air gas at 300 K. These properties are remarkably superior to those of the conventional planar-surface device. In addition, an improved hydrogen detection limit of 10 ppb H_2/air at 300 K is found for the studied device with pyramid-like Pd nanostructures. The related hydrogen sensing characteristics including transient responses and steady-state analysis are also studied in this work. Therefore, based on the improved sensing properties and advantages of low-cost, easy fabrication, and solid stability of operation, the studied device shows the promise for high-performance hydrogen sensing applications.

Introduction

Recently, hydrogen gas has been considered as a new and clean energy to replace conventional fossil energy sources. In addition, hydrogen has been widely applied in various areas, e.g., industrial fabrication process, medical procedures, laboratories, and energy carrier on vehicles [1,2]. Yet, hydrogen is a flammable gas with physically colorless, odorless, and tasteless features. Thus, the fabrication of a smart sensor to detect hydrogen leakage is an important and necessary issue for the development of hydrogen economy [3,4]. An excellent hydrogen sensor is preferable to exhibit advantages including (i) good detection capability, (ii) wide operation temperature range, (iii) fast response, (iv) reproducibility, (v) high linearity, and (vi) scale-down dimension [5–7]. Although Si-based

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semiconductor gas sensors are favorable due to their mature fabrication technology and low cost, they are not suitable for high-temperature operation caused by those relatively small bandgap of 1.1 eV [8,9]. Materials with wider bandgap, e.g., GaN (3.4 eV) and 4H–SiC (3.2 eV) have been proposed to overcome this drawback [10].

On the other hand, numerous works have been reported to organize nanoparticles, nanorods and nanowires into three-dimensional (3D) ordered complex hierarchical nanostructures [11,12]. These 3D hierarchical nanostructures are effective ways to improve device properties because they could give larger specific surface areas and porous nanostructures [11,12]. Previously, many techniques and device structures have been reported to improve hydrogen sensing responses in II–V nitride based gas sensors [13–16]. In this work, an AlGaN/GaN material system and pyramid-like Pd nanostructures based on polystyrene (PS) nanospheres (NPs) are employed to produce a new hydrogen gas sensor. Experimentally, improved hydrogen gas sensing performance is obtained.

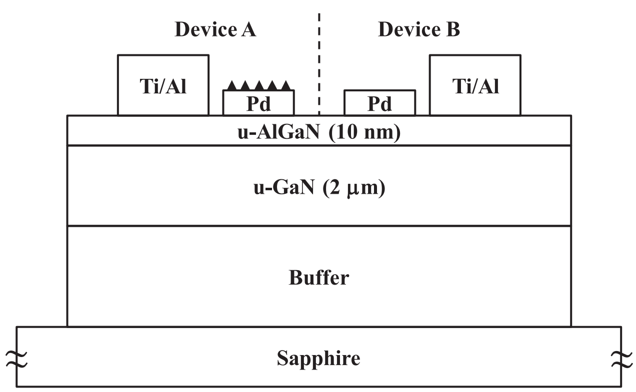

Fig. 1 – Schematic cross section of the studied devices.

Experimental

Fig. 1 depicts the schematic cross-section diagram of the studied Pd/AlGaN/GaN metal-semiconductor (M–S) Schottky diode-type hydrogen sensor with pyramid-like Pd nanostructures (denoted as the device A). Device thin films were grown by a metal organic chemical vapor deposition (MOCVD) system on a 2-in c-plane sapphire substrate. The epitaxial structure included a buffer layer, a 2 μm-thick undoped GaN buffer, and a 10 nm-thick undoped $Al_{0.3}Ga_{0.7}N$ layer. After epitaxial growth, the mesa isolation was achieved by an inductively-coupled-plasma reactive ion etching (ICP-RIE) system. Native oxides and organic contaminants on the device surface were removed by acetone and HCl solutions. Ohmic contacts were made by evaporating 10 nm/150 nm-thick Ti/Al metals sequentially and followed by a rapid thermal annealing (RTA) process at 900 °C for 225 s in an N_2 atmosphere. Schottky contacts were performed by two processes. Fig. 2 depicts schematic diagrams of the fabrication process of pyramid-like Pd nanostructures. First, a 20 nm-thick catalytic Pd (purity ≧ 99.99%) layer was deposited on the specific Schottky contact region with the area of 2.05×10^{-3} cm^2 by vacuum evaporation. Then, PS NSs with a diameter of 250 nm and the second 20 nm-thick Pd layer were coated and evaporated, respectively, on the Schottky contact region by a lift-off technique. After the removal of PS NSs (by butanone and acetone solutions), the pyramid-like Pd nanostructures would be formed on the surface of first Pd layer. Finally, 150 nm-thick Au pads were made to serve as electrical feed-throughs. For comparison, the other device (denoted as the device B, also shown in Fig. 1) was fabricated under the same process only except the absence of pyramid-like Pd nanostructures. In other words, the compared device B has the conventional planar Pd Schottky contact layer. For hydrogen gas sensing, the studied devices were placed in a sealed chamber under a continuous gas flowing ambience.

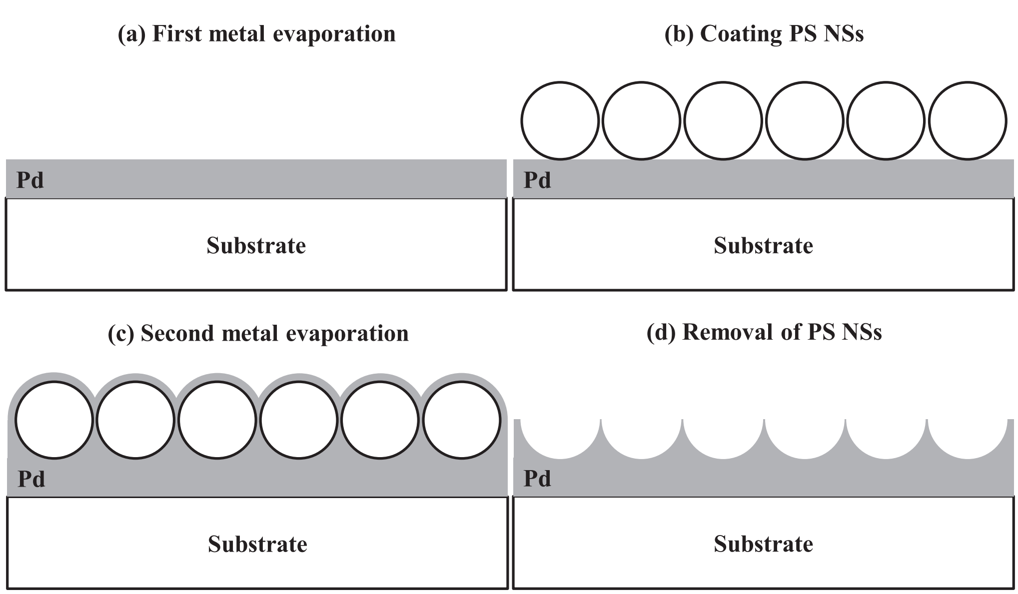

Fig. 2 – Schematic diagrams of the fabrication process of pyramid-like Pd nanostructures.