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Platinum/porous GaN nanonetwork metal-semiconductor Schottky diode for room temperature hydrogen sensor

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ABSTRACT

An in-plane electrically conductive honeycomb GaN nanonetwork grown by molecular beam epitaxy was used to fabricate a platinum (Pt)/porous GaN nanonetwork Schottky diode type hydrogen sensor. The Pt Schottky contact is a nanonetwork with typical width of 40 nm. Both the scanning electron microscopy image and current–voltage curve indicates that the Pt/porous GaN nanonetwork Schottky diode with barrier height of 0.497 eV and ideality factor of 38.5 is comprised of parallel nano-Schotttky diodes. The operating temperature of this Schottky diode hydrogen sensor on the porous GaN nanonetwork is successfully decreased to room temperature and it performs well in detecting hydrogen gas with various concentrations from 320 to 10,000 ppm.

1. Introduction

It is of great interest to develop a hydrogen (H_2) sensor that is capable to operate in harsh environmental conditions such as chemically corrosive ambient. Because of its high resistance to acids and alkalis as well as large band gap (3.4 eV) [1], H_2 sensor based on GaN semiconductor could be used for many harsh applications. These include gas sensing operations in a chemical reactor processing, fuel leak detections in space vehicles as well as automobiles, and emissions from industrial process [2,3]. For these sensors, it is important to operate with minimum power consumption near room temperature, especially for a long-term H_2 monitor.

H_2 sensors on the planar GaN film have been investigated. A resistive type H_2 sensor on a GaN film has been demonstrated in 2005 [3]. The primary researches are focused on the platinum (Pt) or palladium (Pd)/planar GaN film Schottky diode type H_2 sensors, of which the catalytic metal Pt or Pd dissociates the H_2 molecules to H atoms [4,5]. Schottky diodes are well formed on the planar GaN film, exhibiting high sensitivity and stability. Additionally, a Pt/SiO_2/GaN (MIS, metal–insulator–semiconductor) Schottky diode type H_2 sensor also has been investigated by Tsai and coworkers, which improves the sensitivity, response time, and thermal stability [6,7]. Both the resistive and Schottky type H_2 sensors on the GaN film, however, are required to be heated, typically to 200 °C [3,5]. The response time [5] is about 7 min in 980 ppm H_2 at 60 °C. On the other hand, nanostructures are promising in improving the performance of H_2 sensor due to its nanosize effect and large surface area to volume ratio [8,9]. To date, there are only a few investigations of H_2 sensors on GaN nanostructures [2,10] partly due to the difficulty of nano-sensor fabrication. Lim and coworkers [2] have reported a resistive type H_2 sensor on the GaN nanowire, which could lower the operating temperature to room temperature. In comparison with a resistive type H_2 sensor, a Schottky diode type H_2 sensor exhibits higher sensitivity [3,5]. Moreover, when the Schottky diode is downscaled to nanoscale regime, the nano-Schottky diode is different from the common large Schottky diode [11,12] and may exhibit promising performance. To our knowledge, there has been no report on a Schottky diode type H_2 sensor made from a GaN nanostructure.

In this work, we demonstrate a Schottky diode type H_2 sensor on a porous GaN nanonetwork. The Ga-polar porous GaN nanonetwork, which is of high quality like a GaN nanowire [13–15], was epitaxially grown on a (1 1 1) Si substrate. Different from a separated nanowire or nanotube, the porous GaN nanonetwork is continuous for electric current in the lateral direction. Because of its in-plane electrical conductivity, fabrication of an electrical device on the porous GaN nanonetwork is expected to be as easy as that on a planar GaN film. The characteristic of a Schottky diode on the porous GaN nanonetwork and its performance in sensing H_2 gas at room temperature was investigated. Using a Si wafer as the substrate, Si-based micromachining as well as integrated circuit (IC) can be applied to fabricate an integrated sensor.

2. Experimental details

A slightly Mg doped porous GaN nanonetwork was epitaxially grown on a 3-in. Si (1 1 1) wafer by a molecular beam epitaxy system under a nitrogen-rich condition. The growth process in detail

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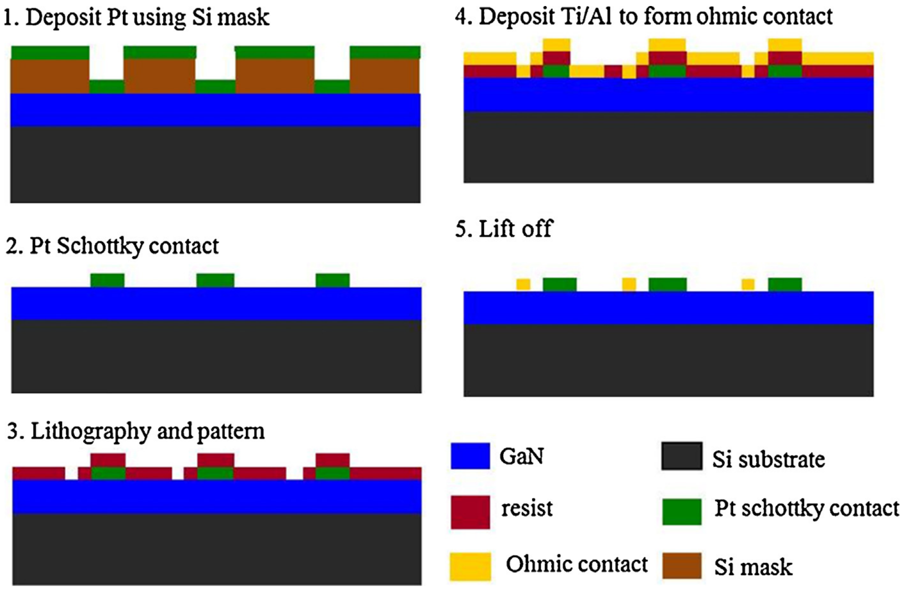

Fig. 1. Two-mask fabrication process of the H_2 sensor on a porous GaN nanonetwork.

was similar to the previous publication [13]. For Mg doping, an Mg cell was heated with pressure in the order of 10^{-9} Torr. The porous GaN nanonetwork was 400 nm thick with electron concentration of about 8×10^{16} cm^{-3} measured by Hall Effect measurement system.

The native oxide on the porous GaN nanonetwork was removed by a solution of $HCl:H_2O = 1:1$. Then a Schottky diode type H_2 sensor was fabricated on this porous GaN nanonetwork by a two-mask process, as shown in Fig. 1. Pt Schottky contact with a thickness of 50 nm and an area of 0.16 mm^2 was deposited on the porous GaN nanonetwork by a sputtering machine using a patterned Si wafer as a mask. Another electrode Ti (20 nm)/Al (80 nm) was deposited by an *e*-beam evaporator and was patterned by photolithography and lift off. After fabrication, the Schottky diode was exposed to various H_2 concentrations diluted in dry air in a steel chamber. The flow rate was kept at 100 sccm.

3. Results and discussions

3.1. Morphology and schematic profile

Under a nitrogen-rich growth condition, GaN grows in the three-dimensional model to a honeycomb GaN nanowall network, namely porous GaN nanonetwork structure as shown in Fig. 2(a), which was measured by a field-emission scanning electron microscopy (FESEM). The GaN nanowalls overlap and interlace with one another, forming an in-plane electrically conductive porous GaN nanonetwork [14,15]. The typical width of the GaN nanowall

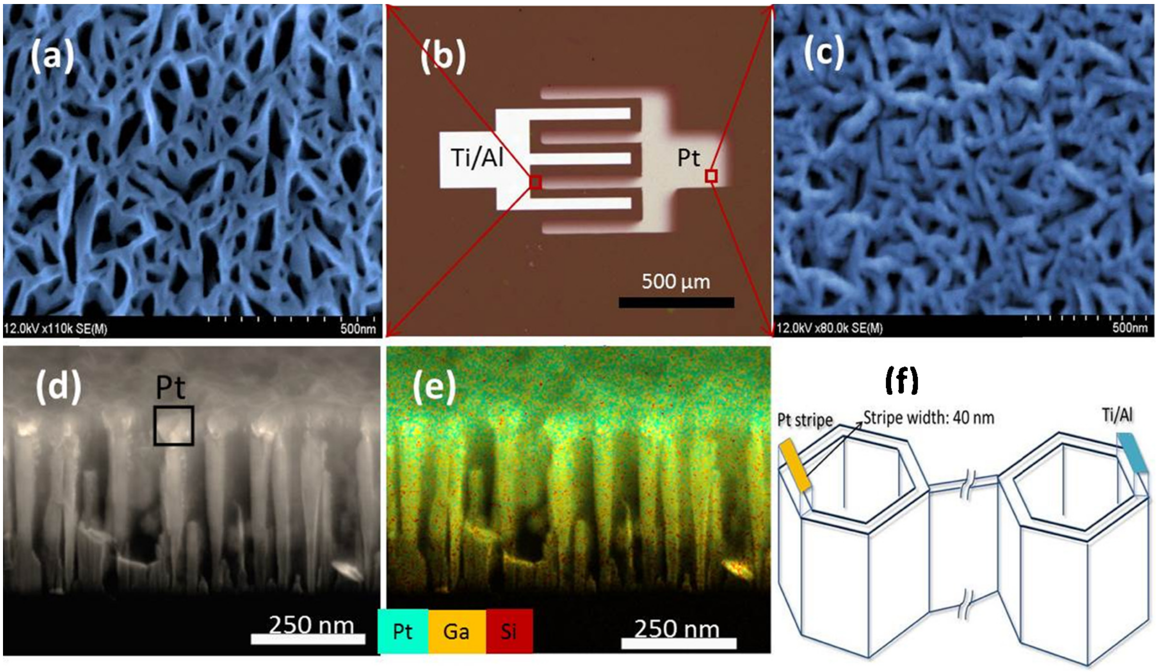

Fig. 2. (a) FESEM image of a porous GaN nanonetwork; (b) optical image of a Pt/porous GaN nanonetwork Schottky diode; (c) FESEM image of the Pt Schottky contact; (d) cross-sectional image of GaN nanonetwork coated with Pt electrode; (e) EDX mapping; and (f) schematic profile of the Schottky diode on the GaN nanowall network.