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Exploiting nanostructure-thin film interfaces in advanced sensor device configurations

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ABSTRACT

In this report, we present a study on the exploitation of nanostructure-thin film interfaces. Here, the objective is to utilize such interfaces for developing nanostructures for advanced sensing devices, while using state-of-the-art microelectronic technology that enables batch production. In this context, growth of ZnO nanostructures on the GaN/AlGaN heterostructure layers was studied. A fabrication process, based on a hydrothermal growth method, was used for preparing the interfaces of nanostructured thin film. Samples were characterized by X-ray diffraction (XRD) and scanning electron microscopy (SEM) and obtained results suggested near epitaxial quality of the hetero-interface. Field-effect transistors (FETs) based on ZnO nanorods/GaN heterostructures were fabricated and tested in a controlled gas environment. Thus, it was demonstrated that nanostructures could be exploited in unconventional ways by employing them in scalable and batch-producible conventional semiconductor devices.

1. Introduction

Semiconductor nanostructures have been studied extensively in many device schemes over the last decade [1,2]. There have been interesting works on the gas sensing properties of oxide nanostructures [3,4] and, among the oxides, ZnO stands out as one of the most investigated nanomaterial. The high sensitivity of ZnO, towards the exposure to NH_3, H_2, O_3, CO, NO_2, and ethanol, makes it viable for gas sensing applications [5,6]. In this context different device configurations have been proposed to exploit the novel properties of nanostructures. However, the potential of using nanostructures in the new device architectures and for practical applications have rarely been reported. The major limitation, constraining practical applications of nanostructures comes from the fact that it is very difficult to produce nanostructures with similar dimensions and orientations in a single batch process at well-defined positions. In addition, it is difficult to reproduce devices integrated with nanostructures. The present study encompasses these issues and reports on the exploration of controlling nanostructured material interfaces for gas sensing applications. Most of the earlier studies exploit the conductance modulation in ZnO nanostructures as a sensing mechanism. However, this work relies on exploiting the surface and interface effects induced on exposure of sensors to gas species, which results in conductance modulation in the underlying material (GaN) and not in the ZnO nanomaterial itself. Thus, no direct electrical connection to the nanostructure is required. The electrical conduction in the sensor device takes place through drain and source terminals in the GaN material, via the field-effect transistor (FET) operation mechanism, while ZnO serves as a gas sensitive, and electrodeless, gate nanomaterial. In this way, the requirement to produce oriented and alignedand position-controlled nanostructures may be eased. As a result, batch processing becomes feasible.

2. Experiments

The solution-based hydrothermal growth technique [7] is a recently-used method to prepare ZnO nanorods with aligned nanorod growth directions and with optimal density. This method was used to prepare ZnO nanorods on the GaN surface. Similarities in the material and electrical properties of ZnO and GaN materials suggest a favourable electrical interface for device applications. Scanning electron microscopy (SEM) was used to study the growth morphology and growth statistics. The X-ray diffration (XRD)

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method was used to investigate the growth quality of ZnO on GaN surfaces. The hydrothermal growth process was tuned to control the nanorod growth and produce nanorods of certain length and density. This method was used in conjunction with a photolithographic process to achieve selective area growth. The GaN/AlGaN/GaN heterostructures were prepared by an metal-oxide chemical vapour deposition (MOCVD) technique, on sapphire substrates. A selectively doped AlGaN layer (20–40 nm) was grown on a 2.5 μm thick GaN buffer layer prepared on a sapphire substrate. A GaN cap layer (5 nm) was used to passivate and protect the underlying AlGaN layer. Using these heterostructures, HFET structures were fabricated with a bare gate area. Ohmic contacts at drain and source terminals were prepared by electron beam evaporation of Ti/Al metals, and subsequent rapid thermal annealing in a nitrogen environment at 650 °C for 40 s. ZnO nanorods with desired target dimensions were then grown by the hydrothermal growth method. The ZnO nanorods grown in the bare gate area act as arrays of floating electrodes. FET-like sensor structures were then packaged in commercially available dual in-line (DIL) ceramic packages and wire-bonded. The electrical response test devices produced by this technique, in vacuum or in a controlled gas environment, was recorded by collecting current–voltage (*I*–*V*) measurement data under different conditions. Test devices were kept in a chamber that facilitates controlled gas flow and sample heating. A sensor structure without any nanorod in the gate area served as a control device.

3. Results and discussion

In general, dense and uniformly distributed ZnO nanorods were grown on the GaN surfaces. The SEM image in Fig. 1 shows surface morphology of a representative sample. A statistical distribution in the length (and width) of the nanorods is seen. Practically all nanorods, in the figure, have hexagonal apperance with faceted surfaces that possibly indicate the single-crystalline nature of the ZnO nanorods. The fields of ZnO nanorods with dimensions of the FTE gate electrodes were chosen to be suitable for the fabrication process. The designed length of the nanorods was ~1 μm, while their width was ~30 nm. This length is compatible with the lithography requirements, and the width allows a high density of statistically similar nanorods to be formed. The high density of nanorods is favourable for higher gas adsorption, while a reasonable separation between the nanorods is necessary for the ambient gas to access the large surface area of the nanorods. Statistical variation in the growth dimensions of nanorods is shown in Fig. 2.

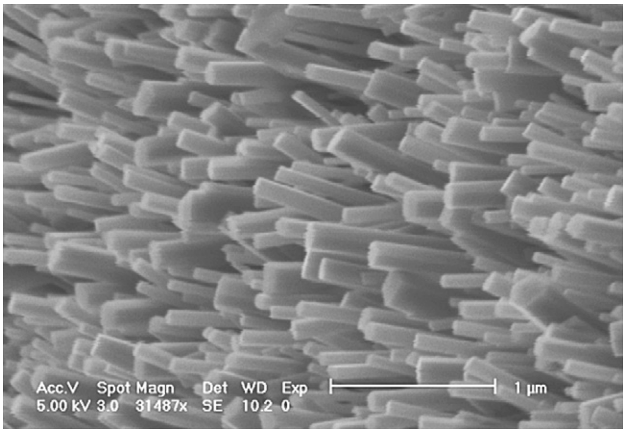

Fig. 1. SEM image of ZnO nanorods as grown over a GaN substrate.

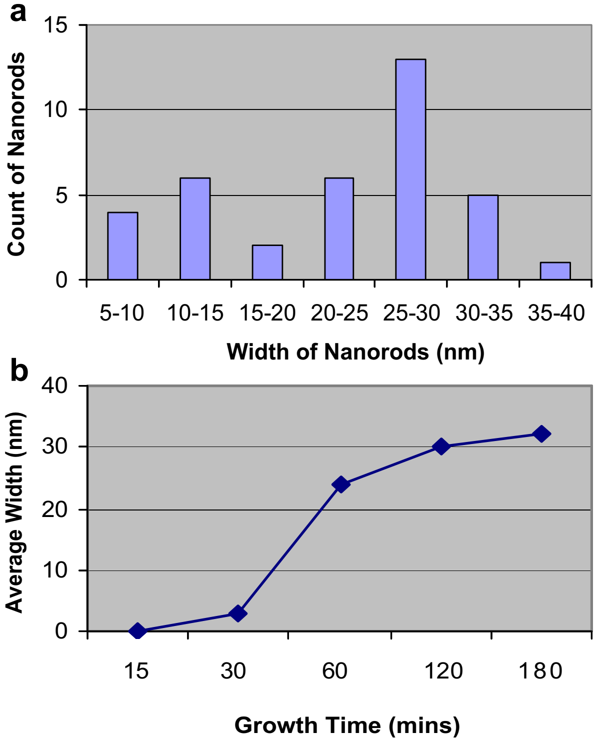

Fig. 2. (a) Bar chart showing width distribution of nanorods; (b) Growth time dependence of nanorod dimension (width).

As clear from the Fig. 2(a), most of the nanorods grown for 2 h have widths ranging from 25 to30 nm. The average width of nanorods increases with the growth time, as shown in Fig. 2(b). A very rapid change in the width is evident between the growth time from 30 min to 60 min. However the nanorod width tends to maintain a constant value at growth greater than 120 min. Consequently, the growth time of 2 h is inferred to be the optimum. Fig. 3 shows an X-ray diffraction (XRD) pattern of a control structure (GaN/AlGaN heterostructure) and ZnO nanorods (grown on the control structure). The larger (and dark) peak corresponds to the control structure, while the smaller (and lighter shade) peak signifies ZnO

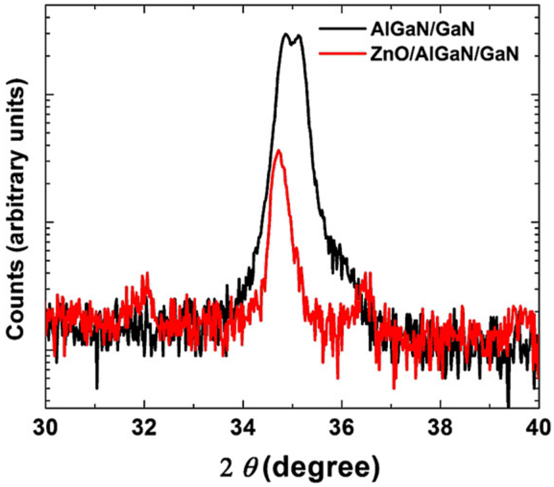

Fig. 3. XRD pattern ((0002) reflections) as obtained for a control substrate and ZnO nanorods grown over the same control substrate.