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Effect of Mg doping in ZnO buffer layer on ZnO thin film devices for electronic applications

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ABSTRACT

Zinc Oxide (ZnO) thin films have been grown on p-silicon (Si) substrate using magnesium doped ZnO (Mg: ZnO) buffer layer by radio-frequency (RF) sputtering method. In this paper, we have optimized the concentration of Mg (0–5 atomic percent (at. %)) ZnO buffer layer to examine its effect on ZnO thin film based devices for electronic and optoelectronic applications. The crystalline nature, morphology and topography of the surface of the thin film have been characterized. The optical as well as electrical properties of the active ZnO film can be tailored by varying the concentration of Mg in the buffer layer. The crystallite size in the active ZnO thin film was found to increase with the Mg concentration in the buffer layer in the range of 0–3 at. % and subsequently decrease with increasing Mg atom concentration in the ZnO. The same was verified by the surface morphology and topography studies carried out with scanning electron microscope (SEM) and atomic electron microscopy (AFM) respectively. The reflectance in the visible region was measured to be less than 80% and found to decrease with increase in Mg concentration from 0 to 3 at. % in the buffer region. The optical bandgap was initially found to increase from 3.02 eV to 3.74 eV by increasing the Mg content from 0 to 3 at. % but subsequently decreases and drops down to 3.43 eV for a concentration of 5 at. %. The study of an Au:Pd/ZnO Schottky diode reveals that for optimum doping of the buffer layer the device exhibits superior rectifying behavior. The barrier height, ideality factor, rectification ratio, reverse saturation current and series resistance of the Schottky diode were extracted from the measured current voltage (*I–V*) characteristics.

1. Introduction

Zinc oxide (ZnO) is an emerging and promising metal oxide semiconductor for electronic and optoelectronic device applications such as light emitting diodes, solar cells, laser diodes, spintronics and sensors [1]. It belongs to II–VI group compound semiconductor having a wide bandgap of 3.4eV and a large exciton binding energy (60 meV) which makes it a better ultraviolet (UV) emitting phosphor than GaN and leads to higher UV emitting efficiency at room temperature [2]. In addition, the material is inexpensive, non-toxic and can be deposited at low temperature on a variety of substrates. It is also a strong competitor to the most widely used transparent conductive oxide (TCO), Indium tin oxide (ITO), which is used as

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transparent electrodes in devices like flat panel displays, LEDs, solar cells, etc. [3–6]. In addition, ZnO has a high optical transparency, high conductivity and stability under hydrogen environment [7]. It also exhibits a self-organized growth property that enables easy formation of ZnO nanostructures on a variety of substrates ranging from GaN, SiC, Si, glass, plastic/fibre and paper to textile fabric [8]. From the device fabrication point of view, it is always desirable to grow a good quality of thin films at low temperatures. So as far as the growth of ZnO thin film on Si substrate is concerned, the major challenge is posed by the large lattice mismatch between Si and ZnO. Direct deposition of ZnO on Si substrate is also constrained by easy oxidation of Si substrate in the oxygen environment, high strain and structural defects. These constraints can be overcome by using either an appropriate substrate or alternatively by introducing a suitable buffer layer on the substrate prior to deposition of thin films. Extensive studies by various researchers revealed that aluminium doped ZnO (AZO) can be used as a buffer layer in order to reduce surface wettability [9,10]. In addition, uniform grain size, smooth surface, preferably c-axis orientation, less strain and very strong Raman Scattering can be achieved by using ZnO buffer layer prior to deposition of the active thin film of ZnO [11]. Previous works demonstrated that the optical properties also get improved with the inclusion of a buffer layer [12]. Reported results also affirm that the crystalline nature and quality of ZnO thin film can also be controlled by varying the thickness of the buffer layer [13]. Moreover, the residual strain has also been found to decrease with the formation of uniform grains throughout the deposited ZnO thin films by using titanium dioxide (TiO_2) buffer layer [14]. Some other materials have also been tried in the past as a buffer including magnesium oxide (MgO), gallium nitride (GaN) [15] and silicon dioxide (SiO_2) [16] in order to achieve good quality thin film.

The primary role of the buffer layer is to facilitate the growth of an active oxide semiconductor that is functionally more dynamic. This has in fact influenced the researchers to explore different types of doped ZnO as possible buffer materials. The motivation behind considering the Mg as a potential dopant in a buffer layer has been the fact that the bandgap of MgO (7.8 eV) is higher than that of ZnO (3.37 eV). This allows tailoring the energy bandgap of the film linearly [17] beyond 3.37 eV. In addition, the atoms of Mg are easily soluble in the zinc blend structure as the tetrahedral ionic radius of Mg^{2+} (~0.57 Å) is very close to that of Zn^{2+} (~0.60 Å) [18]. Therefore introduction of Mg impurity in ZnO improves the crystallinity without tailoring the wurtzite structure of the ZnO film [19]. Some researcher also found that the intensity of the near-band edge emission can be improved and the deep-level emission suppressed by inserting the MgZnO layer in between the substrate and the film due to the carrier confinement and recombination of charge carriers [20]. The above factors prompted us to study the potential II–VI metal oxide semiconductor alloy (MgZnO), which has an outstanding optical properties and very close lattice constants to those of ZnO. This work also explores the role of Mg doped ZnO as a buffer layer in modulating the electrical and optical properties of the active ZnO thin film. In order to investigate the same Schottky barrier diode based on buffer layer mediated ZnO thin films have been fabricated and characterized by changing the composition of the buffer layer. The basic device is useful in many applications; including thin-film based metal semiconductor field-effect transistors (MESFETs), high-electron-mobility transistors (HEMTs) and photodetectors [21–23]. Over the past few years, ZnO thin films with and without a buffer layer have been grown by various methods e.g., RF/DC magnetron sputtering [24–26], pulsed laser deposition (PLD) [27], molecular beam epitaxy (MBE) [15], hydrothermal methods [28], sol-gel solution method [29] and low-pressure metal-organic chemical vapor deposition (MOCVD) [30].

This paper demonstrates a simple but a very effective technique for fabrication of Schottky diode based on ZnO thin film. The film has been grown successfully by radio frequency (RF) sputtering technique on a p-type Si substrate with pre-deposited Mg (0–5 at. %): ZnO buffer layer by thermal evaporation. The objective of this work is to find out the optimum content of Mg in ZnO buffer layer that assists the growth of very high quality thin films for development of reliable electronic and optoelectronic devices. The crystalline nature, surface morphology, surface topography and optical properties of buffer layer mediated ZnO thin films have been studied. Usually a single metal contact is used to form a Schottky contact on ZnO thin films [22]. In the present study Au:Pd alloy contact has been used in order to improve the electrical property of the contact. The electrical properties of the Schottky barrier diode were characterized by using semiconductor parameter analyzer.

2. Experimental details

2.1. Wafer cleaning

The ZnO thin films were deposited on a p-type (100) silicon substrate with a pre-deposited buffer layer of Mg:ZnO by RF sputtering technique. The growth procedure and ambient conditions play an important role in shaping the characteristics of the device. Prior to deposition, the Si wafers were cleaned by following procedures of RCA (the Radio Corporation of America) cleaning. The RCA cleaning involves two steps e.g., RCA-1 and RCA-2 which remove organic impurities and ionic impurities respectively. The RCA-1 solution contains a mixture of de-ionized (DI) water, ammonium hydroxide (NH_4OH) and hydrogen peroxide (H_2O_2) in the ratio of 5:1:1 while the RCA-2 cleaning solution consists of DI water, hydrochloric acid (HCL) and H_2O_2 in the ratio of 5:1:1. The DI water was obtained from Milli-Q water plant (Millipore, USA). The RCA-1 and RCA-2 mixture were heated up to 343 K and then Si wafers were soaked for 15 min. The Si wafers were then soaked into a buffered hydrofluoric acid (HF) solution (HF: DI: 1: 10) for 10 s to remove the oxide layer. Finally, the samples were rinsed with DI water.