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Research paper

Observation of temperature effect on electrical properties of novel Au/$Bi_{0.7}Dy_{0.3}FeO_3$/ZnO/p-Si thin film MIS capacitor for MEMS applications

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ABSTRACT

In this work the dependence of electrical properties on operation temperature (27 °C to 200 °C) of Au-Cr/$Bi_{0.7}Dy_{0.3}FeO_3$ (BDFO)/ZnO/p-Si (MIS device) are discussed. The thin film of BDFO was deposited by pulsed laser deposition (PLD) on p-Si. From the electrical characterization, the devices properties like ideality factor (η), barrier height) (BH) of Au-Cr/BDFO/ZnO/p-Si MIS were determined. The values of η and BH were found to be 1.34 and 0.86 eV at 200 °C and 2.16 and 0.30 eV; respectively, at room temperature (27 °C). The leakage current conduction mechanism of the device was investigated and found to be Schottky emission (SE) in the low electric field (<0.92 MV cm^{-1}) regime and trap assisted Poole–Frenkel (PF) mechanism for high electric field regime. The coexistence of ferroelectric and ferromagnetic coupling and excellent dielectric properties in multiferroic BDFO offers potential in the field of memory devices; sensing and energy harvesting (cantilevers).

1. Introduction

The use of conventional SiO_2 layer is in the scaling of thickness of gate oxide in MIS (or MOSFET) devices. The gate leakage current and reliability issue of a MIS device is the major concern while scaling down of the conventional SiO_2 gate oxide [1–3]. A high-k gate material could be a good alternative to achieve the same gate capacitance and in cost of reduced tunneling current. The tunneling current is strongly dependents (varies exponentially) on the barrier height between the conduction bands of the gate oxide and gate electrode. Hence, to hold the leakage currents within feasible limits, barrier height and band gap of the gate high-k materials should have large values [4–7]. Other high-k materials such as HfO_2, Ta_2O_5, BDFO, ZrO_2, TiO_2 etc. are presently under intense examination as their band gap (E_g ~ 8.8 eV) is similar to that of SiO_2 whereas the permittivity (k = 10–30) are four to five times higher [1]. Generally high-k materials have smaller band gap and offer smaller band offsets with Si as compared to SiO_2 [8]. A new dielectric/semiconductor (BDFO/ZnO) combination as an insulating layer is proposed in this paper with low leakage current, good dielectric and temperature characteristics.

Dy modified $BiFeO_3$ (BDFO) thin films exhibiting outstanding dielectric properties like high dielectric constant (k > 30 at 1 MHz), low leakage current and low interface state density [9,10]. BDFO with a distorted perovskite (ABO_3) structure is an interesting multiferroic material due to its ferroelectric transition temperature and antiferromagnetic temperature (Néel) temperature well above the room temperature (RT). This offers BDFO to be the most auspicious material for the high temperature device application. More interestingly, multiferroic $Bi_{0.7}Dy_{0.3}FeO_3$ (BDFO) having the significant coupling and simultaneously ferroelectric and ferromagnetic ordering at room temperature [9–13]. It exhibits spontaneous polarization with magnetisation in same phase hence polarization states of the MIS Structures can be altered by the applying magnetic fields. This makes them promising material for advance memories by eliminating the need for physical contacts [14,15]. One of the major applications of multiferroics integrated semiconductors devices is in memory applications. It is difficult to obtain a good ferroelectric/semiconductor interface and this is also the main challenge to realize a practical device. To deposit the multiferroic oxide layer, very high deposition temperature and oxidizing atmosphere is required which may resulting in interdiffusion between multiferroic material and semiconducting substrate. This increases the fatigue and imprinting, which may lead to finally device failure. Therefore, an insulating buffer layer is required to prevent the interdiffusion. Moreover, such a possibility may provide low-energy-consuming and higher data storage density devices [16]. Integration of ferroelectric with wide band gap semiconducting materials has a potential importance due to their higher electron mobility, higher breakdown

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field, and higher thermal and chemical stability. Besides of Si and SiO_2, $BiFeO_3$ deposition on wide band gap semiconductors (like GaN) and diluted magnetic semiconducting materials, (like ZnO) have been reported [16]. ZnO is a promising material in the field of semiconductor devices and has unique piezoelectric, optical and electrical properties. Thus is has received an increasing attention for various microelectronic applications (solar cells, photo detectors and MEMS) [17]. ZnO is an II–VI compound, naturally behaves like n-type semiconductor has a wide direct band gap of 3.3 eV (at room temperature) and it also has a large (~60 meV) exciton binding energy [5,18–19]. It is necessary to investigate the structural reactions and other properties such as electrical of ZnO with high-k gate dielectrics films deposited on it, before start producing the electronic devices. Usually, the metal insulator semiconductor (MIS) structures are used for this purpose. To realize the electronic devices, it is also necessary to understand the stability, formation kinetics of the dielectric films and also their reliability when grown on thin ZnO films [5]. Because in the process of device fabrication, ZnO is very sensitive to treatment by temperature, acid bases and even water. Multiferroic materials are fascinating and increased attention due to their potential applications in data-storage media [20] spintronics devices [21] and multiple-stage memories [22]. Multiferroic thin films on the semiconductors are the mostly accepted track for non-volatile memories with two basic aspects as capacitor dielectric and gate dielectric [23].

To the best of our knowledge only Prashanti et al. [9–10] and Deepak et al. [24] have investigated the interface and capacitance-voltage (C–V) characteristics of sputtered BDFO gate dielectric on the p-Si substrate. However, three major issues related to BDFO based Memory devices, viz., the dependence of the device parameters (i) on the temperature, (ii) Dielectric/Semiconductor interface states (iii) conduction mechanisms, have not been explored. Inhomogeneities due to Schottky barrier formation at the Au/BDFO interface and the density of interface states distribution at BDFO/ZnO affects the reliability and performance of the memory devices. Therefore, in the present work, we have discussed and analyzed the barrier formation (BH) at the BDFO/ZnO interfaces along with the temperature dependence of current density at a wide temperature range (27°–200 °C). On the other hand, study of the dielectric properties of BDFO/ZnO have also been carried out at different frequencies of the fabricated MIS devices. The electrical properties of BDFO/ZnO p-MIS were determined by using C_g–V_g and I_g–V_g characterization. The outstanding multifunctional properties of BDFO/ZNO films can be used for a variety of device applications, like sensors, energy harvesting etc. This paper explains the results of our investigations on the temperature dependence of gate leakage current (I_g) in Cr-Au/BDFO/ZnO/p-Si metal–insulator–semiconductor (MIS) structure. The probable conduction mechanism of BDFO/ZnO films has been examined at both room and high temperature. M. Mandal et al. [25] reported superior piezoelectric response of BDFO/ZnO rods as compared to bare ZnO nanorod structure, the investigated conduction mechanism of may be useful for storage purpose of electricity generated by BDFO/ZnO dielectric/semiconductor interface as memory device. In this work, magnetic properties of the parent compound structure of BFO are enhanced by doping with Dy at Bi sites inducing ferromagnetism in this system [26,27]. These (Dielectric, Magnetic and Piezoelectric) superior multifunctional properties of BDFO/ZNO films may be used in fabrication for the range of device applications like NVRAM, FERAM, MERAM, implantable sensors, electricity generators, On chip transformers, RFID tags insulation etc. [28–29].

2. Experimental detail

A p-type (100) Si substrate was used for the MIS device fabrication and standard Radio Corporation of America (RCA) method was carried out to clean the silicon wafer surface. ZnO thin film of 300 nm thickness was deposited by RF dielectric sputter following the parameter as described in the report [17]. BDFO thin films of 300 nm were deposited using PLD (pulsed laser deposition) technique and the deposition conditions are described in the [24].

The top gold (Au) contacts of thicknesses 70 nm and diameter 240 μm were deposited on BDFO by using thermal evaporation technique. Prior to Au a thin layer of 20 nm Cr is also deposited for good adhesion of Au with the BDFO surface. The 3-D schematic of Cr-Au/BDFO/ZnO/p-Si MIS structure is shown in Fig. 1. The X-ray diffraction (XRD) patterns of deposited ZnO and BDFO films were investigated by the Rigaku (Cu-Kα radiation, $\lambda = 1.5405$ Å). XRD technique was used to identify the phases of the thin film. Raith150TWO Scanning Electron Microscope (SEM) was used to inspect the surface morphology, uniformity and grain size of BDFO/ZnO and ZnO films. Nanoscope IV Multimode AFM (in non-contact mode) by Veeco Digital Instrument was used for surface rough analysis. Kaithley 4200 SCS (Please write system name here) was used for the C–V and I–V characterization. A small AC signal of amplitude 30 mV was used to investigate the C–V characteristic.

3. Results and discussions

3.1. Materials characterization

XRD pattern of ZnO and BDFO thin film is shown in the Fig. 2. The diffraction peak of ZnO at 34.19° corresponds to the (002) plan. This indicates the high c-axis preferential growth of the ZnO thin film on the Si substrate [25]. On the other hand, the diffraction peak of BDFO observed at 22.73° and 32.15°, relates to (012) (104) plane, which are similar to the reported literature [11,29].

The average value of grain size of the nanoparticles in the BDFO/ZnO and ZnO films has been determined (~40–44 nm) from XRD peak broadening by using Debye–Scherer relation (Eq. [1]) [23]

$$D = \frac{0.89\lambda_s}{(\beta - \beta_i)\cos\theta} \quad [1]$$

where λ_s is the wavelength of X-ray source (1.5405 Å), β and β_i (arises from the instrument) are the full width at half maximum (FWHM) of the diffraction peaks and the angle of diffraction is θ. The grain size is further calculated by Williamson-Hall methods [29] and found of the order of ~40 nm.

SEM images of BDFO/ZnO and ZnO films at different magnification are shown in Fig. 3(a & b). In Fig. 3(a) it is observed ZnO grains have good orientation and uniform grain morphology with the grain size of the order of 40–50 nm. The thickness of the ZnO film was verified as 300 nm. It can be clearly observed from Fig. 3(b), that the of BDFO films on ZnO films is polycrystalline in nature with granular structure.

In order to investigate the surface topography and structure, the AFM scanning of the ZnO and BDFO/ZnO thin films were performed. The AFM image is shown in the Fig. 4. The root-mean-square (rms) value of the surface roughness BDFO film on ZnO/Si was estimated and found about to be 4.9 nm. The obtained value of surface roughness and grain size validates the observation of SEM and in agreement with earlier reported by Yao Wang and Ce-Wen Nan [30].

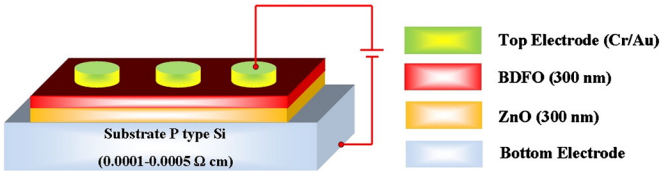

Fig. 1. Schematic of Cr-Au/BDFO/ZnO/p-Si MIS capacitor.