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Dielectric Characteristics of Barium Strontium Titanate Based Metal Insulator Metal Capacitor for Dynamic Random Access Memory Cell

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In this research work, the Metal-Insulator-Metal (MIM) capacitor structure is designed and fabricated with barium strontium titanate (BST) oxide material as the capacitor dielectric material and silver as both top and bottom electrodes for dynamic random access memory (DRAM) cell. This designed capacitor consists of about 2 mm BST pellet and about 1 mm silver top and bottom electrodes. The composition of the BST is chosen as $Ba_{0.5}Sr_{0.5}TiO_3$ due to its better dielectric characteristics. The dielectric characteristics of both the fabricated MIM and the simulated MIM are compared and it is found that the experimental values and practical values are found to be comparable. The simulated dielectric constant, dielectric constant, charge storage density, leakage current density are found to be 1250, 0.025, 5 μC/cm^2 and 5 pA/cm^2, respectively against the corresponding experimental values of 1164, 0.063, 3.5 μC/cm^2 and 49.4 pA/cm^2.

Keywords: Barium strontium titanate, Capacitor, Electrodes, Dielectric constant, Dielectric characteristics

1. INTRODUCTION

MIM offers higher level of miniaturization, flexibility and performance characteristics than conventional discrete capacitors. MIM has been prepared and characterized with different kind of stacks and dielectric materials in recent years. The parameters such as high dielectric constant, low dielectric loss, high charge storage capacity, and low leakage current density are important factors in selecting dielectric material. BST thin film is one of the more promising candidates as the requirements above are fulfilled. BST is a metal oxide material with high dielectric constant, high breakdown strength, small dielectric loss, and good thermal stability. In particular, BST thin film is considered one of the most promising dielectric materials for high density capacitors in DRAMs [1, 2] with high charge storage density. BST thin films are expected to replace the conventional dielectric material (SiO_2) which cannot provide the required charge storage density and as the tunneling limit of 2.5 nm was high leakage current density was observed [3].

Of the challenges faced, the BST material preparation with high dielectric constant, low dielectric loss and low leakage current density, and the type of electrodes used for the capacitor in DRAM cell. Among the many methods used to prepare the BST powders, sol-gel processes [4-7] are commonly applied in the preparation of BST powders and thin films due to the precise control of composition, ease of homogenous distribution of elements, cost effectiveness and simple process requirements. Most reported works in BST powder preparation by sol gel process focused on injection of mixed precursor solutions by using pipette, syringe or programmable peristaltic pump. In the experimental work, a simple dripping system with 21G (0.723 mm) diameter syringe was used in order to provide slow injection of the barium/strontium precursor solutions into the mixed solutions of titanium iso-propoxide and ethylene glycol ethyl during the powder synthesis. The detailed experimental procedure can be found here [8]. $Ba_{0.5}Sr_{0.5}TiO_3$ has been chosen due to its superior electrical properties in the paraelectric phase as well as minimum aging and fatigue effects at room temperature [2]. In addition, reasonably high dielectric constant, low dielectric loss and low leakage current density [9] are possible. The uniform nanoparticles of $Ba_{0.5}Sr_{0.5}TiO_3$ were successfully synthesized using a simple slow precursor injection procedure in standard sol-gel process. Single phase cubic perovskite structure of $Ba_{0.5}Sr_{0.5}TiO_3$ was achieved at a calcination temperature of 800°C. The $Ba_{0.5}Sr_{0.5}TiO_3$ nano powder synthesized was highly homogenous with a narrow size distribution of 4% with a particle size of about 40 nm. At room temperature, optimum dielectric constant of 1164, dielectric loss of 0.063 and the lowest leakage current density of 49.4 pA/cm^2 at 5 V for a $Ba_{0.5}Sr_{0.5}TiO_3$ pellet capacitor [8].

In this work, the BST metal oxide as a dielectric material with silver as both top and bottom electrodes are considered and the various parameters of dielectric characteristics such as dielectric constant, charge storage density and temperature dependent leakage current density are simulated using MATLAB software and the results are compared with the practical BST pellet based capacitor.

2. EXPERIMENTAL DETAILS

In the experimental work, barium acetate (99 %, Aldrich - 24367), strontium acetate (99.995 %, Aldrich - 437883) and titanium (IV) iso-propoxide (97 %, Aldrich 205273) were used as precursor materials for the BST synthesis. Acetic acid was used as solvent, whilst the particles size and stability of the titanium iso-propoxide solution was controlled by adding ethylene glycol ethyl (99 %, Aldrich 128082). All the acids and chemicals were of Analytical Reagent (A.R.) grade. The slow-rate injection procedure enabled better control of the reaction to form the transparent gel. The sol-gel process was accomplished in less than 30 minutes. The as-prepared BST gels were dried at room temperature for 24 hours in air. The BST dried gels were subsequently calcined at different temperatures for 3 hours in a Carbolite muffle furnace and eventually ground into powder form by agate mortar and pestle.

Pellets of $Ba_{0.5}Sr_{0.5}TiO_3$ calcined at different temperatures were prepared by a stainless steel die measuring 12 mm in diameter. Sufficient amount of powders were added, cold pressed uniaxially, and then sintered in order to increase the mechanical strength and to reduce the inter-granular resistance in the pellets. The $Ba_{0.5}Sr_{0.5}TiO_3$ pellets, with an average thickness of 1.90 mm and a disc diameter of 12 mm, were then sintered in a heat-cool cycle at 1250 ^{o}C, 1300 °C and 1350 °C, respectively at a rate of 5 °C /min and a soaking time of 3 hours.

For capacitance measurements, both surfaces of the sintered $Ba_{0.5}Sr_{0.5}TiO_3$ pellets were polished by roll grinder (Buehler Handimet 2) and grinder polisher (Imptech 10 V). Electrodes were attached using silver pastes that were dried at 250 °C for 10 minutes. LCR meter (HP 4284A with test fixture 16451B) was employed to measure the capacitance (C_p) and dielectric loss (D) of the samples at ambient temperature. The LCR meter was calibrated for 1 V (rms) for C_p-D measurements. The measurement frequency was varied from 100 Hz to 1 MHz and the corresponding C_p-D data were recorded. The dielectric constants (corrected for geometric factor) were calculated by using the standard equation (1) as given by

$$\varepsilon' = C_p / C_o \tag{1}$$

where ε' = dielectric constant and C_o = the free space capacitance.

The BST pellets attached with silver electrodes of 1 mm thickness were tested for the leakage current using precision semiconductor parameter analyzer (Agilent 4156 C). The leakage current measurements were conducted by varying the voltage from -10 to 10 V at temperature 27 °C.

3. SIMULATION

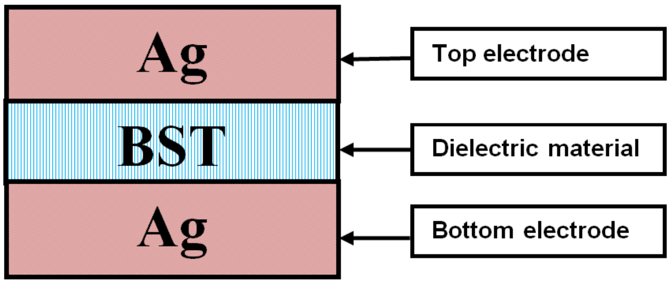

Figure 1. Structure of MIM capacitor for DRAM cell

MATLAB is used to simulate the capacitor's parameters such as dielectric constant, charge storage density and leakage current density. These parameters are important properties of BST thin film capacitor for storage application in DRAM. High storage charge density reduced the capacitor area necessary to meet charge storage requirements. The effects of polarization and leakage characteristics have been widely studied for different thin films and electrodes [9-11].

Hence, the prototype BST capacitor has been fabricated in which MIM consists of silver (Ag) as both top and bottom electrodes with BST, in nanometer range, as the dielectric material. The structure of the designed MIM capacitor is as shown in Fig. 1.

4. RESULTS AND DISCUSSION

4.1. Dielectric constant

The dielectric constant could be varied by changing the ratio of barium to strontium in the barium strontium titanate material. In this work, a capacitor with an operating frequency of 1 kHz (usually it is for the capacitor frequency for the DRAM application), has been designed under the stoichiometric condition of $Ba_{0.5}Sr_{0.5}TiO_3$.

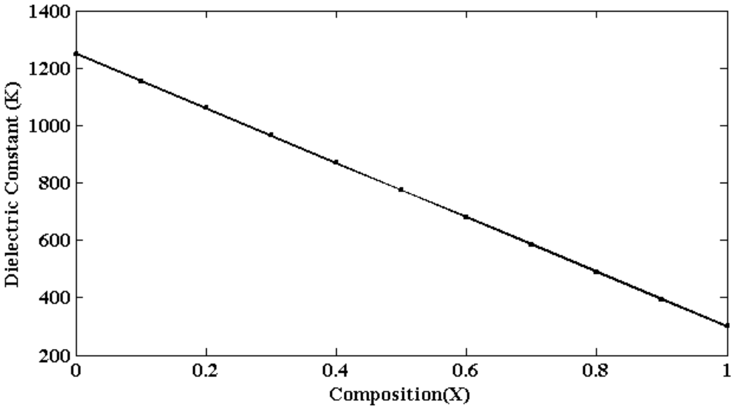

Figure 2. Composition of BST with dielectric constant

As the maximum value of the dielectric constant could be varied up to 1250 using BST, the ‘k’ has been chosen for this work to be less than 1000 as high ‘k’ value increases temperature coefficients of the material [12]. Fig. 2 shows the relationship between the dielectric constant and the compositions of barium / strontium materials. From the practical MIM capacitor, the value of the dielectric constant was 1164 which is very close and comparable to the simulated results.

4.2. Charge density

The requirement for a memory cell is to store larger amount of charge within a smaller area of memory device. The minimum charge storage requirement for the memory cells within the DRAM is 30 fF [13]. In this work, for the optimized composition of $Ba_{0.5}Sr_{0.5}TiO_3$ with dielectric constant, the maximum charge storage capacity of 35 $\mu C/cm^2$ at and for the operating voltage of 1 V, 5 $\mu C/cm^2$ is obtained in the simulation work [Fig. 3]. However, for the practical MIM capacitor, 3.5 $\mu C/cm^2$ was obtained which is very close to the theoretical value. The fabricated capacitor has produced about 0.35

nF, which is very well above the minimum requirement for a capacitor in DRAM application, with dielectric thickness of 1.9 mm.

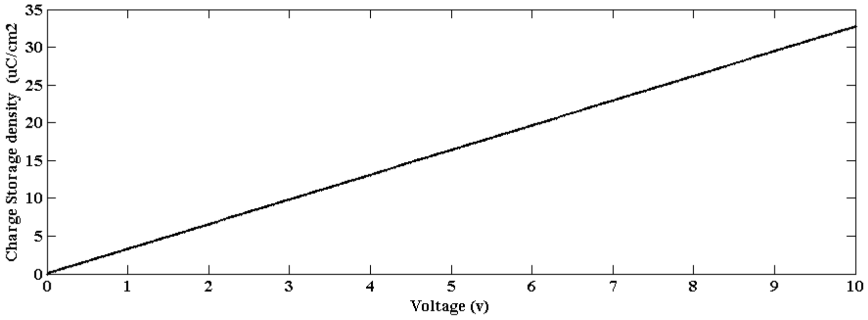

Figure 3. Charge storage density

The enhancement of the above storage capacity has been achieved with a smaller area using the proposed stack design. This charge density would be enough to keep the charge intact.

4.3. Dielectric loss

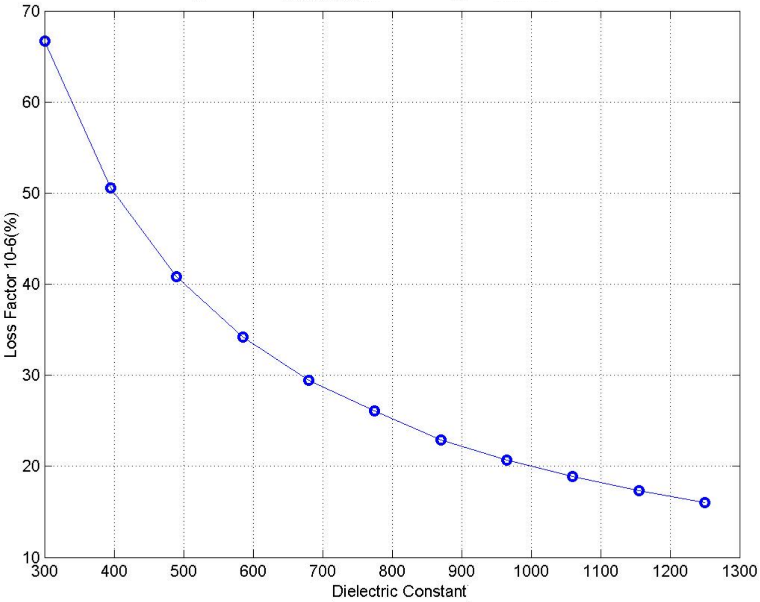

Figure 4. Relationship between dielectric constant and dielectric loss at 1 kHz

Fig. 4 shows the simulated result of dielectric constant against dielectric loss at 1 kHz for the capacitor proposed. It is understood that the dielectric loss is about 0.02 at the chosen BST composition ($Ba_{0.5}Sr_{0.5}TiO_3$). However, for the practical MIM capacitor fabricated, the dielectric loss was 0.063. It could be due to finer particles of 40 nm produced during the experimental work.

4.4. Leakage current density

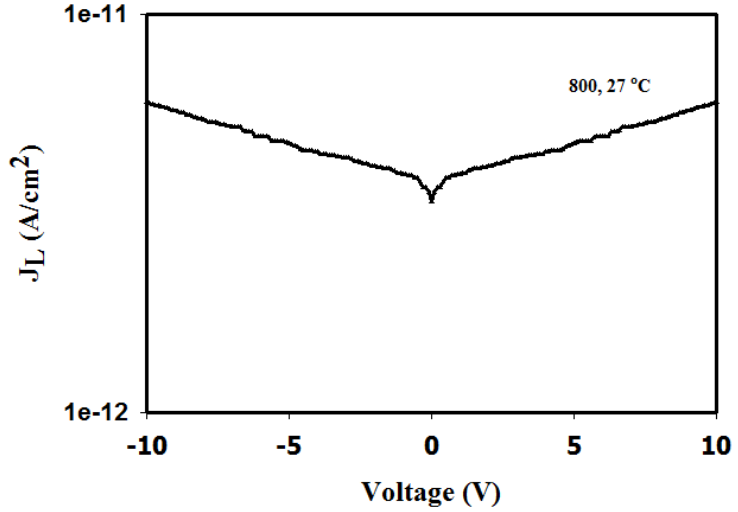

Figure 5. Simulated leakage current density at room temperature at 1 kHz

Fig. 5 shows the simulated leakage current density against the applied voltage at room temperature for the MIM capacitor and Fig. 6 [8] which is experimental leakage current density at room temperature is reproduced here for the comparison with the simulated results. The theoretical equation for the leakage current density [14] as function of applied voltage is summarized as shown below.

$$J_L = A^*T^*\exp(-W_B/kT)^*\exp(q/kT(1/4\pi\varepsilon)^{1/2}\ E) \qquad (1)$$

Where

J_L = Leakage current density, A/cm^2
A = Richardson constant
T = Temperature, Kelvin
W_B = Barrier potential, eV
k = Boltzmann's constant = 1.38×10^{-23} J/K
q = Charge of an electron = 1.609×10^{-19} C
$\varepsilon = \varepsilon_0\varepsilon_r$ = dielectric constant / permittivity
$\varepsilon_0 = 8.852 \times 10^{-12}$ F/m
E = Electric field intensity = V/d, V/m

In the simulation, the voltage was varied from -10 V to + 10 V, the value of the barrier potential is taken from the slope of the experimental leakage currents results. It was found that the simulated leakage current density is about tenfold lower than the experimental results. However, the nature of the characteristics is found to the same. In the experimental work, the measurement was made at the temperatures of 27 °C (300 K) in order to identify the dominant leakage mechanism in the BST samples. The symmetry of the curves indicate the same barrier height for both silver top and bottom electrodes due to the similar work function [15].

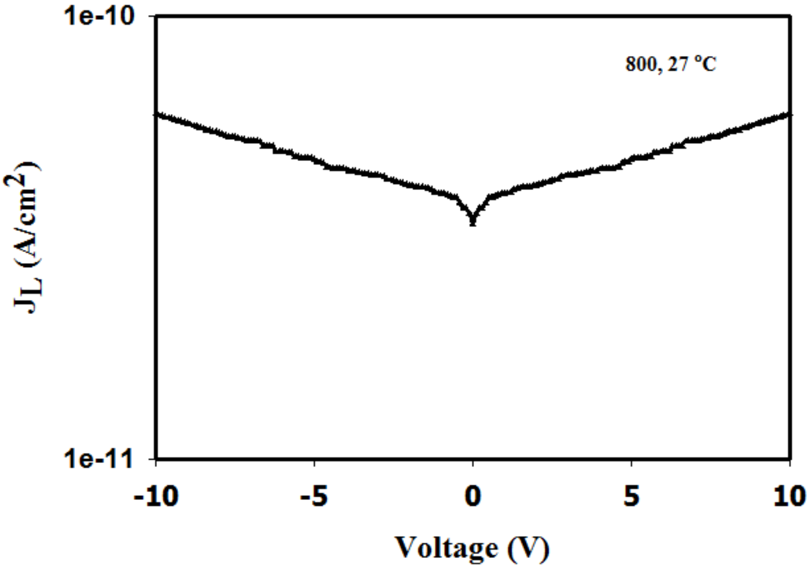

Figure 6. Experimental leakage current density at room temperature at 1 kHz [8]

In Fig. 5 and Fig.6, two distinctive slopes in the (0-5V) and (5-10V) regions respectively are observed. The leakage mechanism of BST is usually described by Ohmic conduction in the low voltage region, and by Poole-Frankel emission or Schottky emission in the high voltage region [16]. It was also noted that BST with small average grain size of about 45 nm, exhibits a much lower leakage current density of 49.4 pA/cm^2 at room temperature which are below the typically required leakage threshold. In general, the leakage properties of BST samples depend on a variety of factors such as microstructure, stoichiometry, electrode materials, sintering treatments, charge density and distribution [17]. The variation in leakage currents may include slight changes in microstructure or composition caused by slight variations of the processing parameters, as leakage will be very sensitive to the defect microstructure [18]. The results shown here are likely attributed to the grain boundary effect, *i.e.*, large grains developed in the BST at higher calcination temperature. It could be understood that smaller grain size might have a large number of grain boundaries. These grain boundaries are highly resistive in nature, which inhibits charge-transfer across the material [19, 20]. At a constant applied voltage (5 V), larger number of grain boundaries leads to decrease in the voltage per grain boundary and hence decrease of the leakage current. On the other hand, this is also likely due to a wider energy band-gap in which samples with smaller grain size exhibit larger band-gap energies and longer leakage pathway if compared to samples with larger grains [21]. Hence, it has been concluded that the leakage currents are found to be about 5 pA/cm2 in the simulation result.

4. CONCLUSION

The prototype BST capacitor has been fabricated in which MIM consists of silver (Ag) as both top and bottom electrodes with BST, in nanometer range, as the dielectric material. The dielectric characteristic parameters such as dielectric constant, dielectric loss and charge storage density have been simulated for 1 kHz for DRAM application and subsequently leakage current density for a variation of voltage from 0 to 10 V for room temperature and compared with the experimental results. The as-prepared MIM capacitor structure has delivered dielectric constant of 1164, dielectric loss of 0.063, and leakage current density of 49.4 pA/cm^2 and charge storage density of 3.5 μC/cm^2 which are well above the requirements for a DRAM cell. When compared with the previous reported reports, the designed MIM structure showed a promising potential as a capacitor in terms of dielectric characteristics for the dynamic random access memory cell.

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