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An analysis of Conduction Mechanism and Reliability Characteristics of MIM Capacitor with Single ZrO_2 Layer

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1. Introduction

Metal-Insulator-Metal (MIM) capacitor is one of the key passive devices for integrated circuits for analog, RF and DRAM applications [1]. In order to obtain high density MIM capacitors and to reduce leakage current, MIM capacitors with high-κ (HK) dielectric and high work function metal electrode have been intensively studied [2]. However, energy band-gap (E_g) of HK dielectric and its conduction-band offset ($\triangle E_C$) to metal electrode have the opposite property with increasing the HK dielectric constant [3], which can cause poor electrical performance, reliability and thermal leakage current. Among reported data [4], Zirconium Oxide (ZrO_2) has emerged as one of the most promising HK dielectrics for MIM capacitors due to its outstanding characteristics, including high dielectric constant, low leakage current, high electric performance [4]. However, there was little report on the MIM capacitor with single ZrO_2 layer which is highly necessary for high density capacitors although stacked dielectric with ZrO_2 has been reported. Among various capacitor characteristics, performance variation during operation that is, reliability is particularly important for analog applications where small capacitance variation and lower leakage current is required. Therefore, accurate analysis of the leakage current mechanism of MIM capacitor is highly necessary to assess the reliability of it.

In this paper, current transport mechanism and reliability of MIM capacitor with single zirconium oxide layer are characterized in depth.

2. Experiments

MIM capacitors were fabricated on 8" silicon substrates. A 500nm thick isolation oxide was firstly formed on the Si wafers. Then, the bottom electrode of the MIM capacitor was formed on the isolation oxide using TiN bi-layer metals. Next, ZrO_2 (100Å) dielectrics were formed by atomic layer deposition (ALD). The post-deposition anneal (PDA) at 400°C for 30min was applied to improve the dielectric quality. Finally, TiN was deposited on the HK dielectrics and was pattered to form the top electrode of the MIM capacitors.

3. Results and Discussion

Capacitance density and dissipation factors as a function of frequency at 10 kHz ~ 1MHz are shown in Fig. 1. The high capacitance density of 15.5 fF/um^2 is obtained with small dissipation factor (1/Q factor) of below 0.05 over the entire frequency range [4].

Low voltage coefficient of capacitance (VCC) is one of the important parameters for analog circuit application. The performance of voltage dependence of capacitance is characterized by a second-order polynomial equation [5], $\triangle C/C_0 = [C(V)-C_0]/C_0 = \alpha V^2+\beta V$, where C_0 is the zero biased capacitance, α and β are the quadratic and linear voltage coefficient, respectively. As β can be canceled out by circuit design techniques, α is mainly focused in this work, which is extracted from the $\triangle C/C_0$ versus voltage as shown in Fig 2. The extracted α and β have a strong dependence on frequency as shown Fig 3, which is undesirable but a common property of HK MIM capacitors. The frequency dependency of α can be explained as the change of relaxation time with different carrier mobility in HK dielectrics [5].

Temperature coefficient of capacitance (TCC) is extracted to be 111.01 ppm/°C and 89.497 ppm/°C at 100 kHz and 1 MHz, respectively, at the temperature range from 25°C to 175°C as shown in Fig 4, which is quite reasonable data [6]. To analyze the current transport mechanism, the leakage current of ZrO_2 MIM capacitors is measured at various temperatures as shown in Fig. 5. The leakage current at low field region does not exhibit temperature dependence both at top and bottom injection modes contrary to the high field region, which can be explained that Schottky emission is not dominant at low field region. On the other hand, leakage current has a strong dependence on the temperature at high field region, which is believed that Frenkel-Poole (F-P) emission is dominant due to the field-enhanced thermal excitation of trapped electrons. Although both of top and bottom injections are dominated by F-P emission, the bottom injection at high field region is analyzed here [5]. To confirm our speculation, the relationship between ln(J/E) versus $E^{1/2}$ is plotted in Fig. 6 at different temperature. A linear fitting of the measurement data can suggest the dynamic constant and refractive index [6]. The extracted dynamic constant (~4.013) and refractive index (1.8~2.6) show good agreement with previous study [6]. Furthermore, ln(J) versus 1000/T is plotted at different electric field as shown in Fig 7. The extracted trap energy level calculated by previously obtained dynamic constant at each temperature has 0.973 ~ 0.963eV range as shown in Fig 7. The decreased trap energy level is believed to be due to a increase of the field-induced barrier-lowering effect. The trap energy level at zero bias can be obtained through the extrapolating of the data as shown in Fig. 8. The extracted trap energy level at zero corresponds to the value of the reported data [5].

The Weibull distribution of breakdown voltage is plotted at each stress bias. The average values of the shape parameter (Weibull slope) are, 1.3866 (V_A = 4.2V), 1.4859 (V_A = 4.4V) and 1.3969 (V_A = 4.6V), respectively, which is acceptable compared to the reported data [6].

4. Conclusion

In this paper, conduction behaviors of MIM capacitor with single ZrO_2 have been investigated by analyzing the current transport mechanisms. Although there is little Schottky emission at low field region, F-P emission is observed to be a dominant mechanism at high electric field region. The decrease of trap energy level is due to the field-induced barrier-lowering effect. The average values of the shape parameter (Weibull slope) are, 1.3866 (V_A = 4.2V), 1.4859 (V_A = 4.4V) and 1.3969 (V_A = 4.6V), respectively.

Acknowledgements

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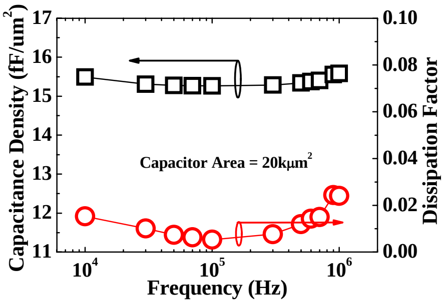

Fig. 1. Capacitance density of ZrO_2 MIM capacitor as a function of frequency. Capacitance density is about 15.3 fF/μm^2 and dissipation factor is below 0.03.

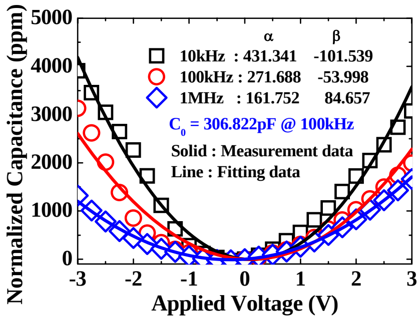

Fig. 2. Normalized capacitance (ΔC/Co) vs. applied voltage of MIM capacitor. Voltage coefficients at 10KHz, 100KHz and 1 MHz are shown in the figure.

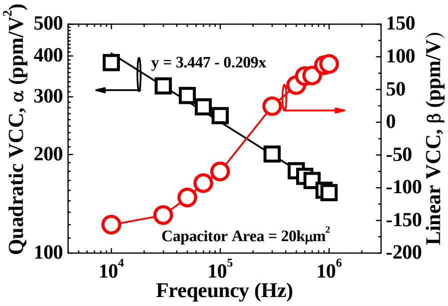

Fig. 3. Frequency dependence of α and β. α is inversely proportional to frequency in log-log scale while β is proportional to frequency in linear-log scale.

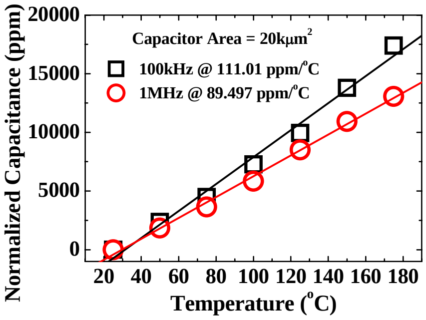

Fig. 4. Temperature dependence of normalized capacitance of ZrO_2 MIM capacitor. It has a linear dependence on the temperature.

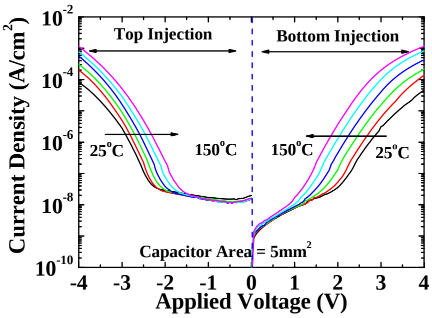

Fig. 5. Temperature dependence of leakage current on the applied bias. There is little Schottky emission at low bias region, i.e., little dependence of leakage current on temperature.

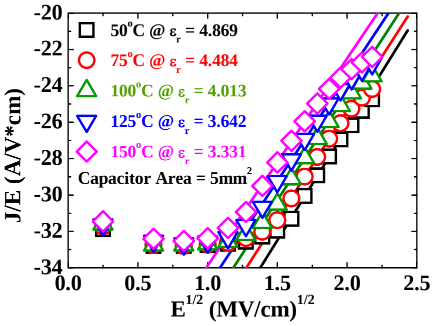

Fig. 6. Ln(J/E) versus E$^{1/2}$ in the high electric field region according to the F-P emission effect at high temperature. Linear fitting is used to extract dynamic constant and refractive index.

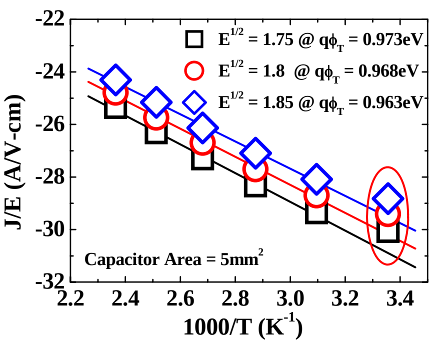

Fig. 7. Ln(J) versus 1000/T for various electric fields. The extracted trap energy level using the slopes for 1.75, 1.8 and 1.85 (MV/cm)$^{1/2}$ is shown in the graph.

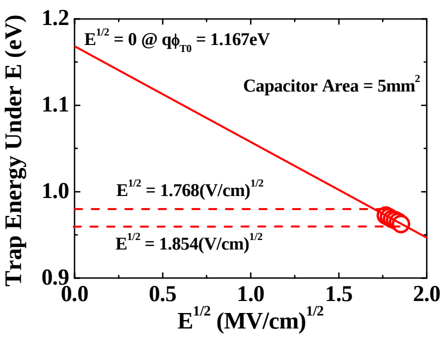

Fig. 8. Trap energy is calculated from the slope at each electric field. Trap energy can be obtained at zero fields by extrapolating of the data.

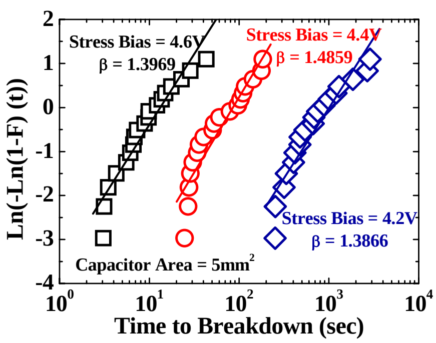

Fig. 9. A Weibull distribution of time to breakdown measured at 125 °C. Weibull slope is 1.3866, 1.4859 and 1.3969 at each stress bias.