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A New Method to Correct Capacitance of High-leakage Ultra-thin Gate Dielectric

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1. Introduction

With the progress of VLSI technologies, the gate oxide thickness scales down quickly to ensure device performance. Precise determination of gate dielectric thickness becomes more and more important. The effective oxide thickness (EOT) is typically calculated from the capacitance-voltage characteristics measured by an impedance meter. Parallel or serial model is employed to derive the capacitance. However, as tunneling current becomes higher, the simple two-element equivalent circuit can not obtain valid result. To solve this problem, several equivalent circuit models have been proposed [1-4].

K. J. Yang and C. Hu took the series resistance arising from Si substrate, metal contact, and cables into consideration [1]. A two-frequency method was proposed to extract valid capacitance from the three-element equivalent circuit. The applicability limits of the two-frequency method were examined by A. Nara et al. [2]. How to select the two frequencies to minimize the effect of measurement errors was proposed in their work. However, some researchers observed that the three element/two-frequency method does not work well on their samples [3, 4]. H. T. Liu proposed an improved two-frequency method according to a four-element equivalent circuit [3]. A series inductance was added and the parallel resistance in [1] was replaced by dielectric loss (tanδ). For high leakage current samples, DC loss due to shunt resistance can not be ignored. Therefore, the proposed method is not valid for high leakage current samples. Recently, Z. Luo and T. P. Ma proposed a different four-element equivalent circuit (parallel RC method) [4]. A parasitic capacitance in parallel with the series resistance was suggested. Unfortunately, this method is not so effective due to the neglect of parasitic inductance.

In this work, we propose a new methodology based on a new four-element equivalent circuit model. A simple extraction procedure combining capacitance-voltage (C-V) and current-voltage (I-V) measurements is developed to extract the valid values of the four elements. It is demonstrated that the new method is more efficiency than previously published methods and can be applied over a wide frequency range.

2. New Four-element Model

Fig.1(a) shows the proposed four-element equivalent circuit model. C represents the ideal MOS capacitor. R_p represents the effective resistance of the actual MOS capacitor due to tunneling current. It is assumed to be frequency independent. R_s represents the parasitic resistance from Si substrate, gate electrode, and the measurement system. L represents the parasitic inductance from cables and measurement systems. The two-element model used by the impedance meter is shown in Fig.1(b).

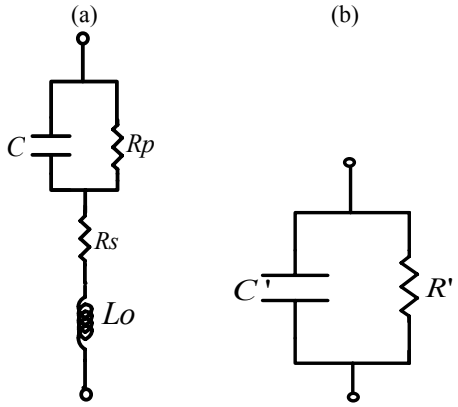

Fig. 1 (a) Proposed four-element equivalent circuit model. (b) Equivalent circuit of the parallel mode of an impedance meter.

The impedances of the circuits in Fig.1(a) and 1(b) can be expressed as eq.(1) and eq.(2), respectively :

$$Z_{4-element} = \left(R_s + \frac{R_p}{\omega^2 C^2 R_p^2 + 1} \right) + j\left(\omega L - \frac{\omega C R_p}{\omega^2 C^2 R_p^2 + 1} \right) \quad (1)$$

$$Z_{2-element} = \frac{1}{j\omega C' + \frac{1}{R'}} = \frac{D' - j}{\omega C'(1 + D'^2)} \quad (2)$$

, where $D' = \frac{1}{\omega C' R'}$. The imaginary part of eq.(1) should be equal to that of the eq.(2). Under the assumption of $\omega^2 C^2 R_p^2 \rangle\rangle 1$, we obtain $-\frac{1}{\omega C} + \omega L = \frac{-1}{\omega C'(1 + D'^2)}$. The C and L can be easily solved by measuring C' and D' at two different frequencies.

$$C = \frac{-\frac{\omega_2}{\omega_1} + \frac{\omega_1}{\omega_2}}{\frac{-\omega_2}{\omega_1 C_1'(1 + D_1'^2)} + \frac{\omega_1}{\omega_2 C_2'(1 + D_2'^2)}} \quad (3)$$

$$L = \frac{\frac{-1}{C_1'(1 + D_1'^2)} + \frac{1}{C_2'(1 + D_2'^2)}}{\omega_1^2 - \omega_1^2} \quad (4)$$

The R_s and R_p can be extracted from the real part of impedance. Although two-frequency method can be applied,

here we suggest a simpler method. Under the same assumption of $\omega^2 C^2 R_p^2 \rangle\rangle 1$, it is easy to obtain

$$R_s = \frac{D'}{\omega C'(1+D'^2)} \quad (5)$$

Finally, R_p can be extracted from the DC resistance (R_{DC}) by

$$R_p = R_{DC} - R_s \quad (6)$$

, where R_{DC} can be obtained by I-V measurement.

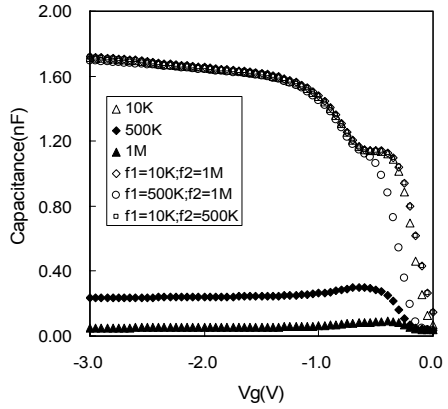

Fig.2. Measured and corrected Capacitance-voltage (C-V) charateristics of the TaPt/ HfO_2(3nm)/SiO_2(1.5nm)/Si sample.

3. Results and Discussion

To verify the validity of the proposed model, the circuit shown in Fig.1(a) was built with four discrete elements. The values of the four elements are C=1nF, R_p=17.3MΩ, R_s=1KΩ, and L=4.7μH. The extracted values according to eqs.(3)-(6) are C=1.02nF, R_p=17.7MΩ, R_s=1.48Kohm, and L=7.83μH. The slightly higher extracted R_s and L is attributed to the additional parasitic resistance and inductance.

Fig.2 show the C-V characteristics measured at different frequencies and the corrected C-V characteristics. The sample structure is TaPt/HfO_2(3nm)/SiO_2(1.5nm)/Si. The apparent C-V distortion and severe frequency dispersion indicate that this is a non-ideal capacitor. However, the corrected C-V characteristics from any two frequencies are almost identical to the C-V measured at 10KHz.

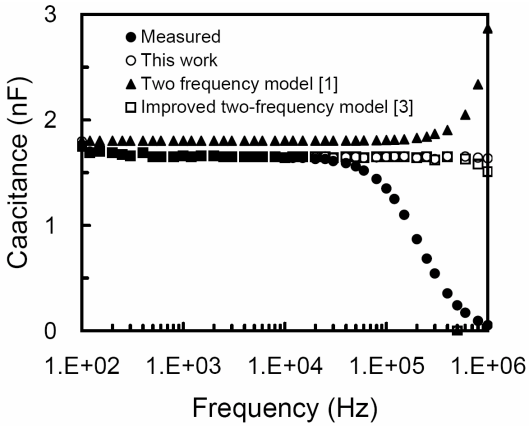

Fig.3. Frequency dependence of the corrected capacitance using different methods. One of the two frequencies is fixed at 500KHz.

Fig.3 compares the corrected capacitance of the same sample in Fig.2 using different methods. One of the two frequencies is fixed at 500KHz. The Yang's simple two-frequency method proposed shows large error because parasitic inductance was not considered. The Lue's improved two-frequency method is powerful than the Yang's method but error still occurs at high frequency due to ignoring DC loss. The proposed method exhibits the best result. Although severe frequency dispersion occurs at frequency higher than 70KHz, the corrected capacitance is constant up to 1MHz.

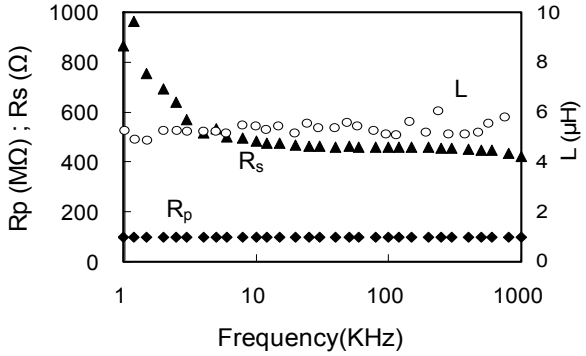

Fig.4. Frequency dependence of the measured capacitance and the extracted R_p, R_s, and L.

Fig.4 shows the frequency dependence of the extracted R_p, R_s, and L. The values of the extracted L, R_s and R_p are around 5μH, 450Ω, and 65MΩ, respectively. All of these values are reasonable.

4. Conclusions

We proposed a new four-element equivalent circuit to model the MOS structure with leaky gate dielectric. A simplified procedure combining C-V and I-V measurements is developed to extract the values of the four elements. Experiments show that the proposed method can obtain valid results over a wide frequency range even if the MOS device is distorted seriously. The proposed method is more efficient than those published methods and can be applied to leaky dielectric if the assumption of $\omega^2 C^2 R_p^2 \rangle\rangle 1$ is valid.

Acknowledgment

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