Extended Abstracts of the 2002 International Conference on Solid State Devices and Materials, Nagoya, 2002, pp. 482-483

P4-7

Frequency Dependence of Capacitance Measurement for Advanced Gate Dielectrics

Kevin J. Yang, Hideki Takeuchi, Tsu-Jae King, and Chenming Hu

University of California, Department of Electrical Engineering and Computer Sciences
211 Cory Hall, Berkeley, California 94720, USA
Phone: +1-510-643-2558 Fax: +1-510-643-2636 E-mail: kjyang@fermi.eecs.berkeley.edu

1. Introduction

Capacitance-voltage (C-V) measurements are a fundamental characterization technique for MOS devices. However, as the oxide thickness is reduced and gate dielectrics comprised of stacks of novel materials are employed, CV measurement and analysis are made more complex by the frequency-dependence of the measured capacitance. This paper presents an analysis of the sources of the frequency-dependence with guidelines for interpreting frequency-dependent capacitance data.

2. Tunneling Leakage Current

It has been reported that the coexistence of series and shunt parasitic resistances causes the measured capacitance to depend on the measurement frequency [1-3]. The small-signal model for a MOS device biased in accumulation is shown in Fig. 1(a), where C represents the actual (frequency-independent) device capacitance, R_P represents the small-signal resistance due to tunneling current, and R_S represents the small-signal series resistances of the gate and substrate. This lumped model also applies to a MOSFET biased in inversion, as long as the time constant of the distributed RC network (inversion layer) is much shorter than the period of the measurement signal; this can be achieved by using a device with a sufficiently short channel length. Otherwise, a transmission line model [4] must be used in inversion.

From a single measurement of the impedance (magnitude and phase), only two of the three parameters can be determined. In the presence of tunneling leakage current, the parallel model is often used, as shown in Fig. 1(b). When tunneling current is negligible, series resistance is dominant and the series model is used, as shown in Fig. 1(c).

From basic circuit theory, it can be shown that

$$C_P^m(1+D^2) = C + (CR_P^2\omega^2)^{-1} \quad (1)$$

where C_P^m is the capacitance measured using the parallel model and D is the measured dissipation (tan δ), which is independent of the measurement model.

Figs. 2 and 3 show the systematic error in measurements made at a single frequency.

It can be seen from (1) that C can be determined as the slope of $\omega^2 C_P^m(1+D^2)$ vs. ω^2 using data measured at multiple frequencies. This correction method is demonstrated in Fig. 2. Similarly, this method can be applied to capacitance measured using the series model: C can be determined as the slope of $\omega^2 C_S^m$ vs. ω^2.

3. Dielectric Stacks of Different Conductivity Materials

A recent attempt to grow $WSiO_x$ by reactive sputtering of a $WSi_{2.7}$ target in an oxygen plasma, resulted in a material which exhibited a large dispersion in the capacitance measured at frequencies from 1 kHz to 1 MHz, as shown in Fig. 5. Similarly, dispersion was observed for a ZrO_2/SiO_2 film grown by oxidation of a Zr film [3].

It is suggested in [3] that this dispersion is likely caused by unoxidized metal particles distributed in part of the dielectric, resulting in a layer with higher conductivity (due to the particles) together with a layer of lower (intrinsic) conductivity. Such a stack can be analyzed using the small signal model shown in Fig. 1(d), as has been done in [5].

The measured capacitance can be expressed as

$$C_P^m = \frac{R_1\tau_1 + R_2\tau_2 + \omega^2\tau_1\tau_2(R_1\tau_2 + R_2\tau_1)}{(R_1+R_2)^2 + \omega^2(R_1\tau_2 + R_2\tau_1)^2} \quad (2)$$

where $\tau_1=R_1C_1$ and $\tau_2=R_2C_2$. The small signal elements are defined as illustrated in Fig. 1(d). The effective stack permittivity (ε_{stack}) can be extracted as the product of the measured capacitance per unit area and the physical thickness. Fig. 6 illustrates the impact of the ratio of resistivity values of the two layers on the extracted ε_{stack}. The presence of series resistance reduces the measured dispersion.

4. Conclusions

In this work, two sources of frequency-dependence of capacitance measurements have been examined. A new multi-frequency method has been introduced to correct for error introduced by the coexistence of R_P and R_S. The frequency dependence of dielectric stacks of materials with different conductivity has also been investigated.

Acknowledgments

The authors wish to thank P. Ranade for device fabrication. This work was supported by the Semiconductor Research Corporation under contract 98-BC-616.

References

[1] K. J. Yang et al., *IEEE Trans. Electron Dev.* **46**, 1500 (1999).
[2] W. J. Zhu et al., *Proc. Int. Symp. VLSI-TSA* (2001) p. 212.
[3] S. Ramanathan et al., *J. Appl. Phys.* **91**, 4521 (2002).
[4] D. W. Barlage et al., *IEEE Electron Dev. Let.* **21**, 454 (2000).
[5] A. R. von Hippel, *Dielectrics and Waves* (Wiley, NY, 1954).

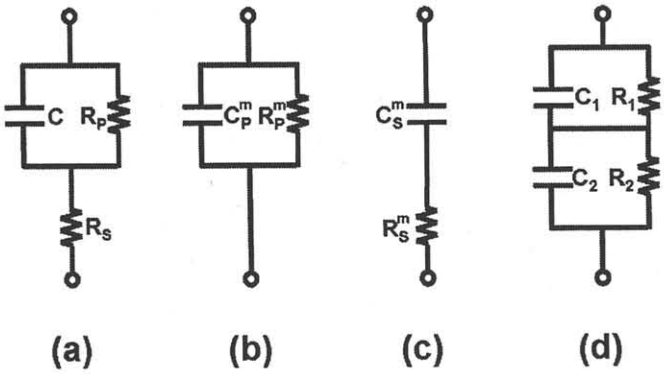

Fig. 1 Small signal circuit representations of MOS capacitors:
(a) Lumped 3-element small-signal model
(b) Parallel mode model
(c) Series mode measurement model
(d) 2-Layer dielectric stack model

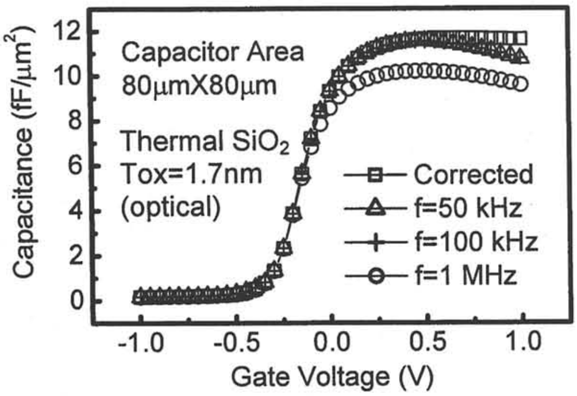

Fig. 2 Measured and corrected high-frequency CV.

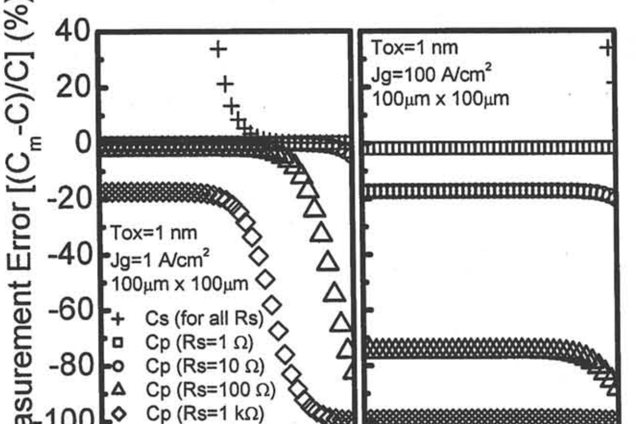

Fig. 3 Systematic error introduced by the coexistence of Rs and Rp. As the measurement frequency increases, the impedance of the capacitor decreases. As a result, the impact of Rp decreases and the impact of Rs increases. Therefore, the error in series mode, which is independent of Rs, decreases with frequency while the error in parallel mode increases with frequency. Higher gate leakage is shown on the right.

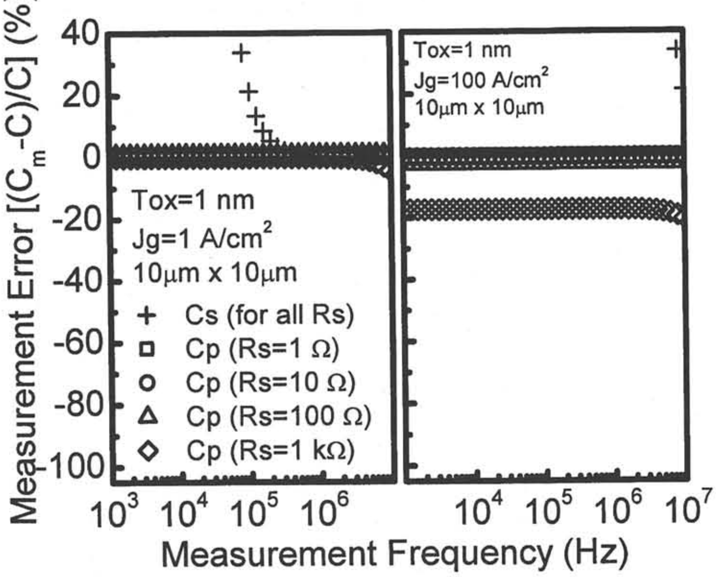

Fig. 4 Systematic error is reduced for smaller device area, consistent with [2]. The series (spreading) resistance does not scale linearly with device area.

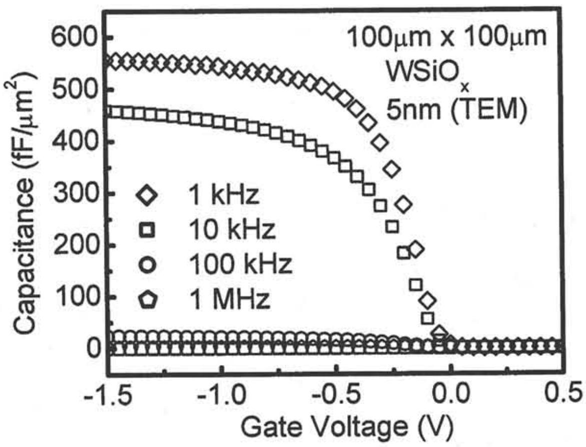

Fig. 5 Three orders of magnitude of dispersion in measured CV.

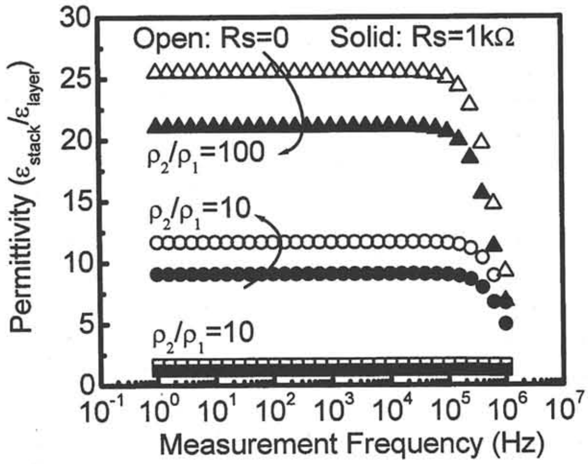

Fig. 6 Dispersion increases as the resistivity ratio ρ_1/ρ_2 increases. Measured dispersion is reduced when Rs is present. This example assumes both layers have the same permittivity ε_{layer}.