# Extraction of the Physical Oxide Thickness Using the Electrical Characteristics of MOS Capacitors

K. Eikyu, H. Takashino, M. Kidera, A. Teramoto, H. Umeda, K. Ishikawa, N. Kotani and M. Inuishi
ULSI Development Center, Mitsubishi Electric Corporation, Itami, Hyogo 664-8641, Japan
Phone : +81-727-84-7325, Fax : +81-727-80-2693, E-Mail : eikyu@lsi.melco.co.jp

*Abstract*-**The physical oxide thickness of ultrathin oxides is extracted using tunneling current characteristics of MOS capacitors. An extraction tool has been developed for the semiautomatic extraction. The tool has implemented nonlinear least square solver and GUIs. A tunneling current model is incorporated into the device simulator MIDSIP-T and it is used as a core simulator of the extraction system. It is found that the transition layer should be considered in the extraction of very thin oxide thickness below 4nm. A unified parameter set, $\phi_b$=3.3eV and $m_e^*/m_0$=0.41, is obtained after the extraction of various samples.**

## I. INTRODUCTION

Recently semiconductor device scaling has been accelerating and it has been reported that the gate oxide thickness of MOSFETs will probably be scaled down below 2nm [1]. Generally oxide thickness $t_{ox}$ is measured by ellipsometric method because of its simplicity of measurement. But the accuracy of the ordinary ellipsometer cannot be guaranteed for these very thin oxides. This makes it difficult to control process variation in fabrication lines as well as to obtain accurate oxide thickness.

There exists an alternative method of cross-sectional TEM. It is a more accurate method of determining physical oxide thickness, but it is not practical because of its high cost and low throughput. Recently $t_{ox}$ extraction has been attempted from electrical data of MOS capacitors or transistors [2], [3]. However, the methods used include model parameters, such as oxide barrier height and electron effective mass in the oxide, the values of which show some difference in the literature. Therefore it is the general approach to determine parameter value so as to fit extracted $t_{ox}$ to ellipsometric value or TEM value. In this work, we have attempted to determine these model parameter values without assuming the $t_{ox}$ of thin oxide thickness.

## II. EXTRACTION TOOL

We have developed the general purpose parameter extraction tool "PROMPT2". The $t_{ox}$ extraction system can be easily constructed by modifying the scripts of PROMPT2. The block diagram of the $t_{ox}$ extraction system based on PROMPT2 is shown in Fig.1. It is mainly composed of core simulators, the nonlinear least square (NLSQ) solver and GUI. Simulators and NLSQ solver are controlled by *perl* scripts. Since simulators and NLSQ solver are independent software, the system is easily adjusted for general purpose parameter extraction by modifying the *perl* scripts. Users can do such operations as param-

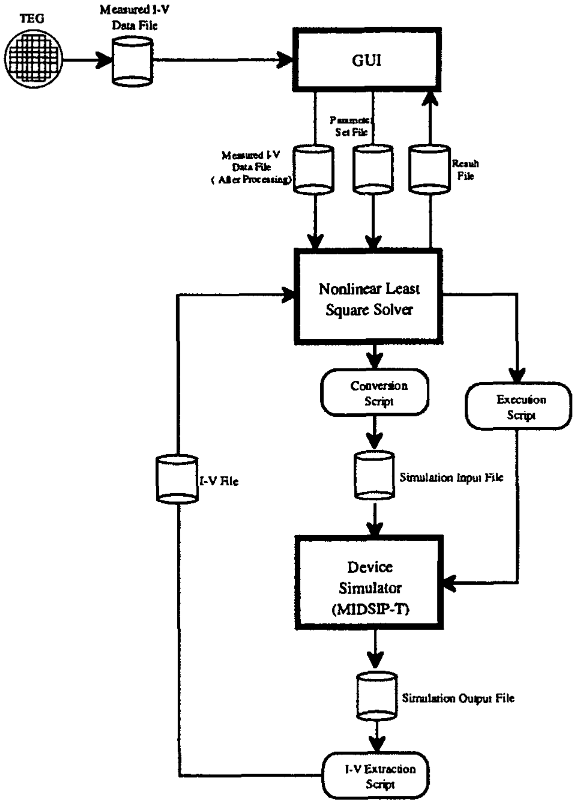

Fig.1 Block diagram of $t_{ox}$ extraction system based on PROMPT2.

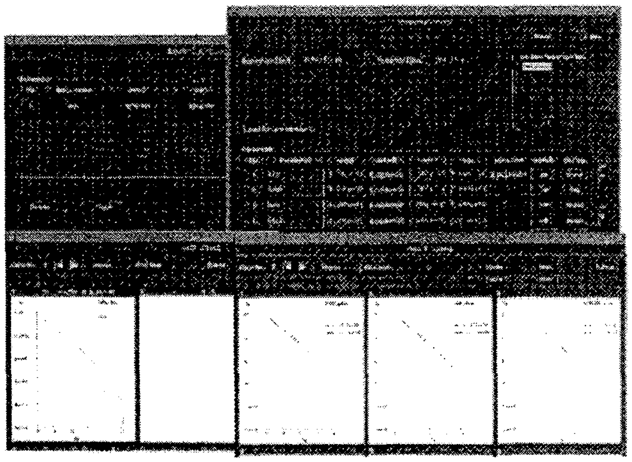

Fig.2 GUIs of PROMPT2

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eter setting, execution of extraction and result display efficiently through GUIs (Fig.2).

Our in-house device simulator MIDSIP-T, which includes the gate tunneling current model [4], is used as core simulator in this work. In this system, $t_{ox}$ extraction and model parameter calibration are possible from C-V as well as from I-V characteristics.

## III. EXPERIMENT AND SIMULATION MODEL

C-V and I-V characteristics in the accumulation regime of $n^+$ poly gate $p$-substrate MOS capacitors were used because the poly gate depletion effect could be ignored and the gate poly could be treated as metal. MOS capacitors were fabricated on $p$-type (100) silicon wafers (resistivity 10 Ω cm). The gate oxides were thermally grown by furnace oxidation in dry or wet atmosphere at 750°C. Then highly phosphorus-doped polysilicon was deposited and patterned. Process condition and average $t_{ox}$ measured by ellipsometer of samples used in this work are listed in Table 1.

Firstly, parameters of van Dort's Quantum Mechanical correction (QM) model [5] were calibrated using C-V characteristics in the range of $t_{ox}$ =3 - 10 nm (Fig.3). QM model parameters obtained here are consistent with [6]. C-V characteristics cannot be measured accurately in very thin oxide samples. Therefore I-V characteristics are preferable in extracting the $t_{ox}$ of such samples.

TABLE 1

Sample condition used in $t_{ox}$ extraction.

| sample No. | oxidation | $t_{ox}$ by ellipsometer [nm] |
|---|---|---|
| #2 | dry | 2.33 |
| #3 | dry | 2.76 |
| #4 | dry | 3.40 |
| #5 | dry | 4.07 |
| #6 | wet | 2.98 |
| #7 | wet | 3.41 |
| #8 | wet | 3.81 |
| #9 | wet | 4.98 |
| #11 | wet | 10.07 |

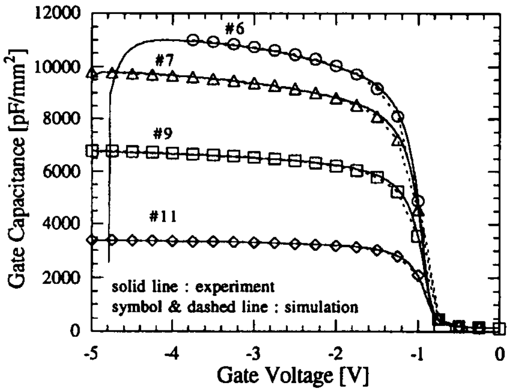

Fig.3 C-V characteristics after QM model calibration.

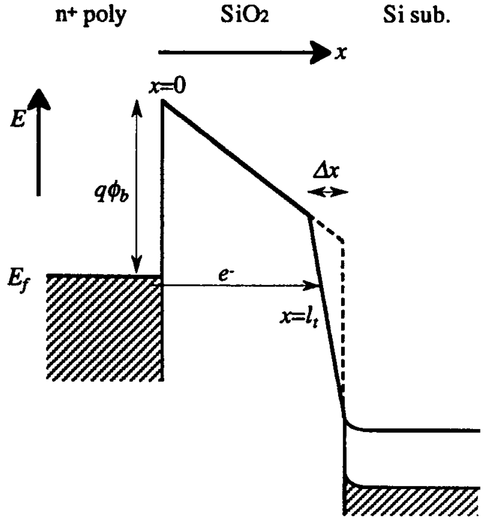

Fig.4. Schematic illustration of tunneling current model including transition layer. $m_v^*/m_0$=5 and $E_g$=9.0eV is used. These two parameters are not so sensitive to the tunneling current.

Tunneling current is expressed as follows:

$$J_T = q \int_{-\infty}^{q\phi_b + E_f} N_{in}(E)\, T(E)\, dE \tag{1}$$

$$N_{in}(E) = \frac{4\pi mkT}{h^3} \ln\left(1 + \exp\left(-\frac{E - E_f}{kT}\right)\right) \tag{2}$$

where $h$ is Planck's constant, $k$ is Boltzman's constant and $\phi_b$ is barrier height at the gate/SiO$_2$ interface. Tunneling probability $T(E)$ is calculated by WKB approximation :

$$T(E) = \exp\left(-2 \int_0^{l_t} \kappa(x)\, dx\right) \tag{3}$$

using two-mass Franz-type $\kappa$-$E$ dispersion relation :

$$\kappa = \frac{1}{\hbar} \frac{\sqrt{2m_c^* E'\left(1 - \frac{E'}{E_g}\right)}}{\sqrt{1 - \left(1 - \frac{m_c^*}{m_v^*}\right)\frac{E'}{E_g}}} \tag{4}$$

$$E' = V(x) - E + E_f$$

[7]. $V(x)$ is the tunnel barrier function and $E_g$ is band gap of SiO$_2$ and $m_c^*$ and $m_v^*$ are effective mass of electron in conduction band and valence band of SiO$_2$ respectively. By numerically integrating $T$ with careful consideration of the limit of tunneling length $l_t$, eq.(1) can be used for both FN tunneling and direct tunneling. Barrier lowering effect by image force

has a large influence on the tunnel probability [8], so it was also included in $V(x)$ according to [9].

It is reported that there exists a "transition layer" of one atomic layer level at the interface of Si/SiO$_2$ [10]. This means that the barrier height does not change abruptly at the interface but is continuous in the transition layer (Fig.4). This layer does not have a large influence in relatively thick oxide, but the thinner the oxide, the greater the influence. This transition layer model was also incorporated into MIDSIP-T as a modification of $V(x)$ in the calculation of $T$.

## IV. RESULTS AND DISCUSSION

Parameters to be fixed are barrier height $\phi_b$ and effective mass $m_c^*$. In Fig.5, extracted $m_c^*$ and fitting error of 10nm wet oxide sample (#11) are shown assuming $t_{ox}$ is ellipsometric value and $\Delta x$=0. The fitting error is very small over a wide range of $\phi_b$. Therefore we cannot determine a unique set of parameters from this relatively thick sample.

Then we performed $t_{ox}$ extraction with other samples (#9, #7, #6) using each value of the ($\phi_b$, $m_c^*$) set of Fig.5. In Fig.6, fitting error is plotted. In thinner samples, the fitting error has a minimum in each sample. If all the minimums are obtained with the same parameter set, then that set is the unique parameter set. In Fig.6, $\phi_b$=3.5eV and $m_c^*/m_0$=0.34 gives totally good fits for these three samples. The $\phi_b$ value is a little bit larger than that of the literature.

In Fig.7, the same plot is shown assuming $\Delta x$=0.26nm. By taking the transition layer into consideration, $\phi_b$=3.3eV and $m_c^*/m_0$=0.41 is obtained as the unique parameter set. Furthermore, the fitting errors of #7 and #6 are smaller than those of $\Delta x$=0. The $t_{ox}$ extracted in the case of Fig.7 is plotted in Fig.8. A higher value of thickness is obtained with higher $\phi_b$ and extracted $t_{ox}$ is

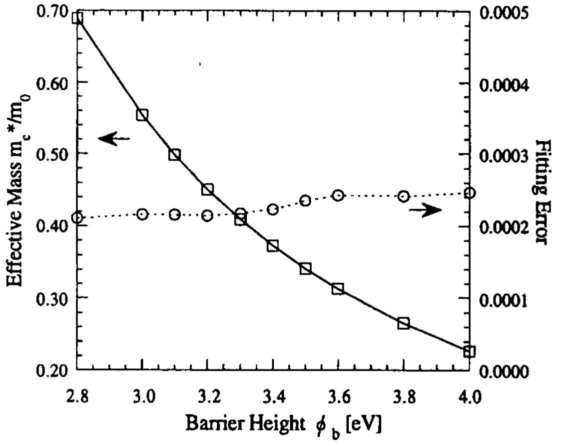

Fig.5. Result of parameter extraction using sample #11 assuming $t_{ox}$=10.07nm (ellipsometric value). Simulations agree with experimental data very well over a wide range of $\phi_b$.

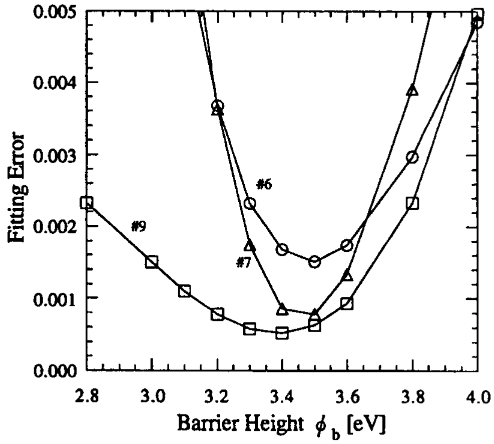

Fig.6. Fitting error of $t_{ox}$ extraction of samples #9, #7, #6 assuming $\Delta x$=0.

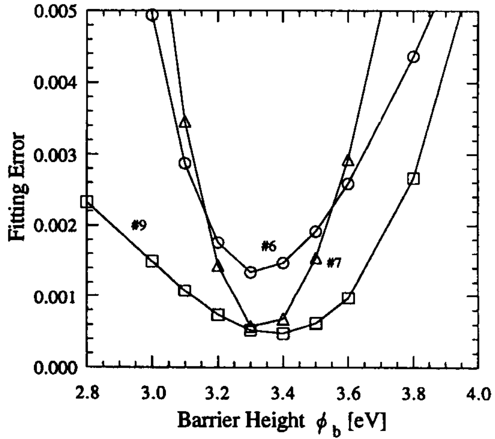

Fig.7. Fitting error of $t_{ox}$ extraction of samples #9, #7, #6 assuming $\Delta x$=0.26nm.

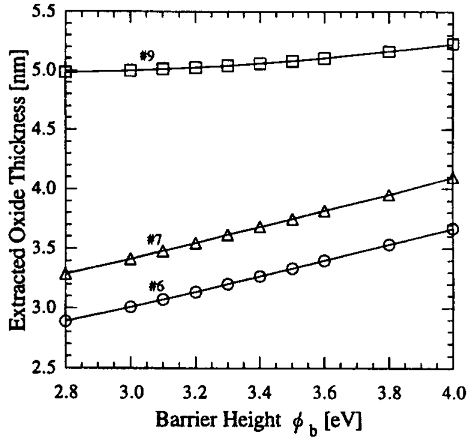

Fig.8. Extracted $t_{ox}$ of samples #9, #7, #6 assuming $\Delta x$=0.26nm. $t_{ox}$ of #7 and #6 are very sensitive to $\phi_b$.

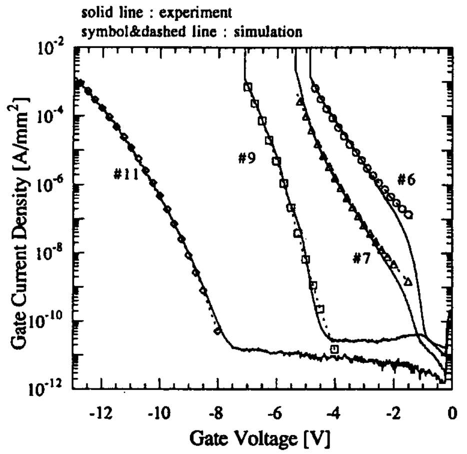

Fig.9. I-V characteristics when extracting $t_{ox}$ assuming $\Delta x$=0.26nm.

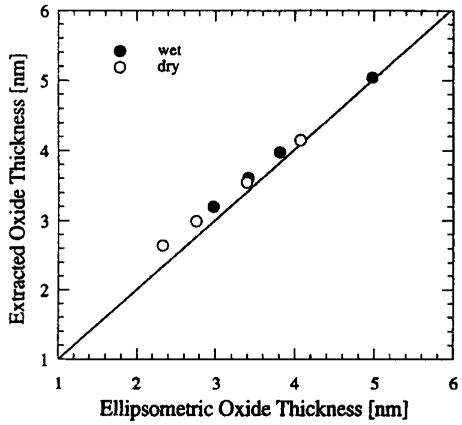

Fig.10. Comparison of extracted $t_{ox}$ with ellipsometric $t_{ox}$. Results of wet and dry oxidation samples are plotted.

more sensitive to $\phi_b$ in thinner samples in which direct tunneling current is observed. In Fig.9, I-V characteristics of $\phi_b$=3.3eV and $m_c^*/m_0$=0.41 are shown. A very good match is seen.

The validity of assuming $\Delta x$=0.26nm is verified by Maserjian's FN current oscillation method [10] using sample #9. Extracted $t_{ox}$ is plotted in Fig.10 against ellipsometric $t_{ox}$. It is clear from this figure that the physical $t_{ox}$ is thicker than the ellipsometric value for thinner samples. It is deduced that this difference originates in the fact that the transition layer occupies a larger portion of the whole gate oxide with decreasing oxide thickness, while the ellipsometer gives $t_{ox}$ assuming the vertical uniformity of gate oxide.

## V. CONCLUSION

We have developed a semiautomatic $t_{ox}$ extraction system based on the nonlinear least square method. The physical oxide thickness was extracted using I-V characteristics of MOS capacitors. When QM model, image force effect and transition layer are taken into consideration, a unified parameter set for tunneling current model, $\phi_b$=3.3eV and $m_c^*/m_0$=0.41, is obtained. We clarified that the physical oxide thickness is thicker than the ellipsometric value when taking the transition layer into consideration. This $t_{ox}$ extraction system is also useful as a process variation monitor.

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