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A highly sensitive evaluation method for the determination of different current conduction mechanisms through dielectric layers

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Current conduction mechanisms through a metal-oxide semiconductor capacitor with a 9.6 nm thick SiO₂ dielectric layer are characterized via Fowler-Nordheim (FN) and Poole-Frenkel (PF) plots, as well as through the analysis of the power exponent parameter $\alpha = d(\log I)/d(\log V)$. It is shown that the evaluation by means of α is much more sensitive in the accurate identification of different current conduction mechanisms. If FN tunneling and PF conduction occur simultaneously, evaluation using the α -voltage (α -V) plot actually allows one to determine the fraction of each conduction mechanism quantitatively. Even a slight current saturation due to minority carrier depletion, which cannot be detected through the evaluation of the current-voltage characteristics using FN or PF plots, can be detected by the α -V plot. © 2011 American Institute of Physics. [doi:10.1063/1.3631088]

INTRODUCTION

The electrical properties of gate dielectrics are usually characterized via conventional macroscopic current-voltage (I - V) and capacitance-voltage (C - V) measurements of metal-oxide-semiconductor (MOS) capacitors with electrode areas of at least several μm^2 . In contrast to SiO₂, however, high- k dielectric materials—the gate dielectrics for the next technology generation¹—can have various morphologies (e.g., amorphous, nanocrystalline, polycrystalline) and show more complex and diverse leakage current conduction mechanisms² than does optimized SiO₂ film. The actual morphological and electrical parameters thereby strongly depend on the fabrication process and the quality of the materials.

Therefore, in high- k dielectric films, as well as in damaged or non-optimized SiO₂ films or, e.g., Si₃N₄ films,³ several current conduction mechanisms might occur simultaneously, such as Fowler-Nordheim (FN) tunneling⁴ [see Eq. (1)], trap-assisted tunneling,⁵ Poole-Frenkel (PF) emission⁶ [see Eq. (4)], and Schottky emission.⁷ Typically, the current conduction mechanisms of dielectric films are evaluated by converting data from I - V measurements and plotting them in a specific manner for each conduction mechanism (e.g., a FN plot in which $\ln(I/V^2)$ is plotted as a function of V^{-1} , a PF plot in which $\ln(I/V)$ is plotted as a function of $V^{0.5}$, or a Schottky plot⁷). Once a plot shows linear behavior, potentially the corresponding current conduction mechanism exists. In such cases, the relevant parameters are extracted directly from the slope of the linear regression (see below for a FN plot and a PF plot), and one can check to see whether they are physically meaningful. The FN tunneling current [Eq. (1)] and FN plot [Eq. (2)] can be expressed as⁸

$$I_{FN} = A_{FN} V^2 \exp(B_{FN}/V), \quad (1)$$

$$\ln(I_{FN}/V^2) = \ln A_{FN} + B_{FN}/V, \quad (2)$$

$$B_{FN} = -\frac{8\pi d \sqrt{2m_* (q\phi_b)^3}}{3qh}, \quad (3)$$

where $\ln(A_{FN})$ and B_{FN} are the intercept and the slope of the FN plot, respectively; q is the elementary charge; ϕ_b is the barrier height; h is Planck's constant; m_* is the effective mass of electrons in the dielectric; and d is the thickness of the dielectric film. The PF emission current [Eq. (4)] and PF plot [Eq. (5)] can be expressed as⁹

$$I_{PF} = A_{PF} V \exp(B_{PF} \sqrt{V}), \quad (4)$$

$$\ln(I_{PF}/V) = \ln A_{PF} + B_{PF} \sqrt{V}, \quad (5)$$

$$B_{PF} = \frac{q}{k_B T} \sqrt{\frac{q}{\pi \epsilon_0 K d}}, \quad (6)$$

where $\ln(A_{PF})$ and B_{PF} are the intercept and the slope of the PF plot, k_B is Boltzmann's constant, T is the temperature, ϵ_0 is the vacuum permittivity, and K is the high frequency dielectric constant of the dielectric (i.e., the square of the refractive index n of the dielectric for ordinary light).⁶

It is, however, difficult to determine the current conduction mechanisms unambiguously by using only these evaluations, because different plots often show the relevant linear dependence for the same measurement data simultaneously. Therefore, usually additional measurements, such as time consuming and elaborate temperature dependent I - V measurements, are performed in order to enable more assured verification of the current conduction mechanisms. It is therefore advantageous to develop novel and more sensitive

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evaluation methods that ideally do not need additional measurements for the analysis of the current conduction mechanisms of dielectric films.

One research group has reported an analytical procedure for the discrimination of current conduction mechanisms through dielectric layers in metal insulator metal (MIS) capacitors by using the power exponent parameter $\alpha = d(\log I) / d(\log V)$.¹⁰ In contrast to conventional FN and PF evaluation, the evaluation by means of α , in principle, is a numerical method that potentially has the capability of being equally sensitive to all possible current conduction mechanisms in a sample. This group has also applied their method to extract physical parameters such as the saturation current, the barrier height, and parasitic resistances (e.g., linear and nonlinear series as well as parallel leakage resistance) of non-ideal Schottky, p-n, and p-i-n diodes using physical models appropriate for such devices.¹¹ They used the same physical models in combination with their method to fit the current flow mechanisms through high-k dielectric films in MOS capacitors. However, as current conduction through dielectric films is based on different physical effects compared to Schottky or p-n diodes, they could not interpret α in dependence on the applied voltage in a physical meaningful way.¹² Furthermore, they adapted their method by using current conduction models suitable for insulators for the evaluation of current conduction mechanisms for TiO₂ MIS capacitors. However, they could not evaluate and model their measurement data for the whole voltage range consistently.¹³

In this paper, the current conduction mechanisms for conventional MOS capacitors with SiO₂ layers, for which the possible conduction mechanisms are well known, are investigated by means of α -voltage (α -V) plots using, for the first time, successfully physical meaningful PF and FN modeling to demonstrate the potential of the method. The presented results suggest that the α -V plot is a very sensitive evaluation method for the current conduction mechanisms of dielectric films. It is further shown that even multiple conduction mechanisms and their fractions can be identified and evaluated nearly unambiguously and quantitatively via this method, without the need for additional measurements (e.g., I - V characteristics at different temperatures).

EXPERIMENTAL PROCEDURES

Conventional MOS capacitors with SiO₂ as the dielectric were fabricated. First, SiO₂ films with a thickness of 9.6 nm were grown via dry oxidation on p-type Si substrates (1 to 6 Ω cm). The gate contacts (electrode area of 10⁴ μ m²) consisting of 20 nm TiN and 300 nm Al stacks were deposited via plasma sputtering and patterned via photo lithography and dry etching, respectively. Finally, a forming gas annealing (FGA) at 430 °C for 30 min was performed. For the deposition of TiN, plasma sputtering was chosen intentionally. The thereby created physical damage leads to traps near the gate electrode that cannot be recovered by FGA.¹⁴ This will result in a defect rich silicon dioxide in which, next to FN, further current conduction mechanisms will occur that make the evaluation of the current conduction mechanisms more challenging.

Conventional I - V measurements were conducted on the MOS structures using a semiconductor parameter analyzer (HP 4156 A). A positive (i.e., inversion) and negative (i.e., accumulation) bias voltage were applied to the gate electrode. In the case of inversion, first an I - V measurement without light illumination and, second, an I - V measurement with light illumination were performed on the same gate structure. In the case of accumulation, I - V measurements with and without light illumination were performed on different gate structures, respectively, as for each measurement in accumulation the voltage was increased until electrical breakdown of the structure occurred. A large number of I - V measurements in inversion and accumulation were obtained with and without light illumination at room temperature. In the following, representative I - V curves for the different measurement conditions are presented and discussed.

The voltage V_s across the SiO₂ layer, which is the voltage of interest for the evaluation of FN or PF current conduction (i.e., voltage V in Eqs. (1) and (4), respectively), is calculated from basic physical considerations¹⁵:

$$V_s = V_g - (\phi_{MS} / q + \phi_s), \quad (7)$$

where V_g , ϕ_{MS} , and ϕ_s are the gate voltage, work function difference between the gate electrode and the Si substrate, and surface potential of the Si substrate, respectively. In this study, a value of -0.6 eV is used for the work function difference between the work function of the TiN gate electrode ϕ_{gate} (4.35 eV) and that of the p-Si substrate ϕ_{p-Si} (in our case, approximately 4.95 eV). The surface potential ϕ_s in general depends on the applied voltage. However, for the studied samples, in a good approximation, ϕ_s is constant for the voltage regimes in inversion and accumulation, respectively, where the current is governed by FN or PF current (i.e., ± 6 to 11 V; see Fig. 1 and Fig. 2). For these regimes, the surface potential is approximately 1.0 V for inversion and -0.4 V for accumulation, respectively. Therefore,

$$\begin{aligned} V_s &= V_g - 0.4 \text{ V (inversion),} \\ V_s &= V_g + 1.0 \text{ V (accumulation),} \end{aligned} \quad (8)$$

are used as the relevant voltages throughout this study instead of the applied gate voltage.

RESULTS AND DISCUSSIONS

Figures 1(a), 1(b), 1(c), and 1(d) show the I - V curves, the FN and PF plots, and the α - V plots for the investigated SiO₂ MOS capacitor in inversion with and without light illumination, respectively. The I - V curve in the dark shows saturation at 8.35 V at a current of 1.9 nA, whereas with light illumination much higher currents can be measured. The saturation of the I - V curve in the dark is due to minority carrier depletion in inversion. The FN plot and the PF plot each show a linear dependence. The extracted parameters from both FN and PF plots are summarized in Table I. Using an effective mass of $0.4m_e$ (m_e is the electron rest mass) for electrons in SiO₂,⁸ the values for the tunneling barrier height between SiO₂ and the Si substrate extracted from the slopes of the FN plots were 3.21 eV for the measurement in the

FIG. 1. (Color online) (a) Measured (symbols) I - V curves in inversion with and without illumination, and the corresponding (b) FN and PF plots and (c), (d) α - V plots [(d) shows a zoomed view of (c)] for a MOS capacitor with an Al/TiN gate electrode, a SiO₂ dielectric 9.6 nm in thickness, and p-type silicon. The gate area is $10^4 \mu\text{m}^2$. The calculated (lines) I - V and α - V curves using the parameters from Table I are shown for comparison and evaluation. For all calculated curves, the leakage current is considered.

dark and 3.26 eV for the measurement with light illumination. These values are within the range of the reported values of 3.15 to 3.25 eV for the barrier height between SiO₂ and the Si substrate.^{8,16} The high frequency dielectric constant ϵ_{SiO_2} of SiO₂ extracted from the slope of the PF plot is 1.51 for the measurement in the dark and 1.65 for the measurement with light illumination. These values are rather low compared to the ideal high frequency dielectric constant of 2.13 for SiO₂ (assuming that the refractive index for SiO₂ is 1.46 [Ref. 17]). Therefore, for this sample the dominant tunneling current conduction mechanism in inversion for high voltages (i.e., above approximately 6.5 V) is identified as FN tunneling current from the conventional FN and PF plot evaluation.

The leakage current at low voltages (below approximately 5.85 V), which might be due to the experimental setup, was also extracted from the experimental I - V curve via the least squares fitting of a nonlinear leakage component [see the corresponding fit in Fig. 1(a)]. Considering only FN tunneling together with leakage current allows one to model consistently both of the experimental I - V curves obtained in inversion, except for the highest voltages without illumina-

tion [i.e., voltages above 8.35 V; see Fig. 1(a)]. In contrast, the corresponding calculated α - V curves deviate significantly from the experimental data for voltages above 7.2 V in the dark and above approximately 9.1 V with light illumination. The α - V plot for the illuminated measurement shows ideal FN tunneling for voltages in the range from 7.5 V to 9.1 V. Most probable, the difference between the experimental and calculated α - V plots is due to the minority carrier depletion in the inversion condition. Especially using α - V plotting, the minority carrier depletion is found to already occur at 7.2 V for the measurement in the dark, which cannot be detected by conventional evaluation methods (i.e., I - V curves, FN plot, or PF plot). For the illuminated case, conventional evaluation methods fail completely in the detection of minority carrier depletion. In addition to the capability of the α - V plot to properly evaluate the current conduction mechanisms, these results indicate that the α - V plot is also much more sensitive in the detection and quantification of parasitic effects such as minority carrier depletion.

Figures 2(a), 2(b), 2(c), and 2(d) show the I - V curve, FN and PF plots, and α - V plot for the SiO₂ MOS capacitor in accumulation without light illumination. The experimental

FIG. 2. (Color online) (a) Measured (symbols) I - V curves in accumulation without illumination, and the corresponding (b) FN plot and PF plot and (c),(d) α - V plots [(d) shows a zoomed view of (c)] for the same MOS capacitor as in Fig. 1. The calculated (lines) I - V and α - V curves using the parameters from Table I are shown for comparison and evaluation. Curves that take into account both FN and PF currents are indicated by their fraction in %. For all calculated curves, the leakage current is considered.

data of the illuminated sample are not shown here because the characteristic is almost the same as that without light illumination. The I - V curve indicates breakdown of the SiO_2 at -11.6 V. Both FN and PF plots show excellent linear dependence. Using an effective mass of $0.4m_e$ for electrons in SiO_2 , the tunneling barrier height between the TiN electrode and the SiO_2 layer extracted from the slope of the FN plot is 3.0 eV, which is lower than the ideal value of 3.45 eV (assuming that the work function of TiN is 4.35 eV and the conduction band energy of SiO_2 with respect to the vacuum level is 0.9 eV [Ref. 18]). The high frequency dielectric constant of SiO_2 extracted from the slope of the PF plot is 4.06, which is rather high compared to the ideal value of 2.13.

Therefore, the dominant leakage current conduction mechanism in accumulation for the sample of this work cannot be clearly identified when using conventional FN and PF plot evaluation.

For a more detailed evaluation, several I - V curves were calculated using the parameters extracted from FN and PF plots (see Table I). In the cases in which both FN and PF currents were considered, the fractions of FN and PF current are defined as the ratio of the current calculated by the parameters extracted from solely the FN plot or the PF plot, respectively (e.g., in the case of 30% FN current and 70% PF current, $0.3 \cdot A_{FN} = 0.0164 \text{ A/V}^2$ is used for the FN current calculation, and $0.7 \cdot A_{PF} = 6.13 \times 10^{-31} \text{ A/V}$ is used for the

TABLE I. Parameters extracted from FN plots and PF plots [see Eqs. (2) and (5)] for the different measurement conditions (i.e., in inversion or accumulation, with or without light illumination).

	$A_{FN} (\text{AV}^{-2})$	$B_{FN} (\text{V})$	$\phi_b (\text{eV})$	$A_{PF} (\text{AV}^{-1})$	$B_{PF} (\text{V}^{1/2})$	ϵ_{SiO_2}
Inversion without light	107.1	-238.2	3.21	1.21×10^{-40}	24.4	1.51
Inversion with light	251.3	-244.1	3.26	2.14×10^{-39}	23.4	1.65
Accumulation without light	0.0545	-214.8	3.00	8.76×10^{-31}	14.9	4.06

PF current calculation; see Table I). In a first approximation, this numerical treatment does not affect the tunneling barrier height or dielectric constant, because the values of the slopes of both plots are not changed by this treatment. The leakage current at low voltages (below approximately -6.4 V) was also extracted and considered for all calculated I - V curves. As can be seen from Fig. 2(a), independent of the current mechanisms, all calculated curves describe very well the experimental I - V curve up to the breakdown of the SiO_2 layer. In contrast, the α - V plot clearly shows differences between the calculated curves as shown in Fig. 2(d). All calculated curves correlate very well with the experimental data for voltages smaller than -8.0 V. However, pure FN and PF currents cannot describe the experimental data for voltages above -8.0 V. For the calculated curves in which both FN and PF conduction are considered, the best fitting can be obtained when the fractions of the FN current and the PF current are 30% and 70%, respectively. In a first approximation, the percentage of the FN current and of the PF current can be interpreted as the effective area where each current conduction mechanism is dominant. Most of all, α - V plot evaluation evidences its advantage by clearly showing that multiple current conduction mechanisms exist in the given SiO_2 film in accumulation. Furthermore, even the fraction of each current conduction mechanism can be systematically and accurately determined for all voltages via an α - V plot without any additional temperature dependent measurements.

For ideal SiO_2 films, the dominant current conduction mechanism is pure FN tunneling for both polarities of the applied voltage (i.e., in inversion and accumulation).⁸ The α - V evaluation for the sample of this work, however, clearly indicates both FN tunneling and PF emission current in accumulation. As already mentioned, the difference between the leakage current conduction mechanisms for the studied sample in accumulation and in inversion can be explained, respectively, by the plasma process induced damage of the SiO_2 surface and the surface near the bulk region during gate metal formation.¹³ Most probable, Ti is reacting during FGA with oxygen, resulting in oxygen deficiencies in the SiO_2 near the gate electrode that represent traps for charge carriers. In accumulation, the created traps act as traps for PF emission, resulting in multiple current conduction mechanisms (i.e., FN tunneling and PF emission). In contrast, in the case of inversion, no significant trap density for PF emission exists near the interface between the Si substrate and SiO_2 . Therefore, the dominant current conduction in inversion is ideal FN tunneling. In order to confirm the evaluation results for the current conduction mechanisms with conventional or commonly accepted methods, temperature dependent I - V measurements were also performed in the range from 30°C to 150°C . Figure 3(a) shows the temperature dependent I - V measurements for both inversion and accumulation, and Fig. 3(b) shows the corresponding Arrhenius plots for various electrical fields for I - V measurements in accumulation. The leakage current in accumulation noticeably increases with temperature, as expected for PF conduction. In contrast, the I - V curves in inversion practically do not show any temperature dependence, as shown in Fig. 3(a). The Arrhenius plots for various electrical fields in accumula-

FIG. 3. (Color online) (a) Temperature dependent I - V curves in both inversion (with illumination) and accumulation (in the dark) and (b) corresponding Arrhenius plots with various electrical fields for I - V curves in accumulation.

tion show a linear dependence, as shown in Fig. 3(b). The average trap energy level for PF emission extracted from the slope of the Arrhenius plots for various electrical fields in accumulation is 1.77 eV. These results support the evaluation results from the α - V plot.

CONCLUSIONS

The great potential of the α - V plot to evaluate and differentiate current conduction mechanisms through dielectric films is demonstrated by a comparison with conventional evaluation methods (e.g., FN or PF plots). For this comparison, a non-ideal SiO_2 sample was used intentionally with nearly ideal characteristics in inversion but with trap-related non-ideal effects in accumulation. Therefore, the current conduction mechanisms for the analyzed SiO_2 films were found to be different depending on the polarity of the gate bias. In the case of inversion, pure FN tunneling was identified as the dominant leakage current conduction mechanism by both α - V plots and conventional FN and PF evaluation. However, parasitic effects such as a slight minority carrier depletion could clearly be detected by α - V plots when conventional evaluation failed. In the case of accumulation, even multiple conduction mechanisms such as FN and PF conduction and their fractions could be identified and evaluated nearly unambiguously and quantitatively via the α - V method without the need for additional measurements (e.g., at different temperatures). These results indicate that the α - V

plot is a highly sensitive and effective evaluation method for the determination of current conduction mechanisms through dielectric films. The method works very well for the ideal part of the I - V curves (i.e., in inversion) and has even more advantages when non-ideal effects occur.

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