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Reliability Investigations up to 350°C of Gate Oxide Capacitors Realized in a Silicon-on-Insulator CMOS Technology

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Abstract—**It is difficult to use standard bulk-CMOS-technology at temperatures higher than 175°C due to high pn-leakage currents. Silicon-on-insulator-technologies (SOI), on the other hand, are usable up to 250°C and even higher, because leakage currents can be reduced by two to three orders of magnitude. Nevertheless, performance and reliability of SOI devices are strongly affected at these high temperatures. One of the main critical factors is the gate oxide quality and its reliability. In this paper, we present a study of gate oxide capacitor time-dependent dielectric breakdown (TDDB) measurements at temperatures up to 350°C. The experiments were carried out on gate oxide capacitor structures realized in the Fraunhofer 1.0 μm SOI-CMOS process. The gate oxide thickness is 40 nm. Using the data of the TDDB measurements, the behavior of field and temperature acceleration parameters at temperatures up to 350°C was evaluated. For a more detailed investigation, the evolution of the current in time was also studied. An analysis of the oxide breakdown conditions, in particular the field and temperature dependence of the charge to breakdown and the current just before breakdown, completes the study. The presented data provide important information about accelerated oxide reliability testing beyond 250°C, and make it possible to quickly evaluate the reliability of high temperature CMOS technologies at operation temperature.**

Keywords—**Oxide reliability, silicon-on-insulator (SOI), time-dependent dielectric breakdown (TDDB).**

Introduction

Most high temperature electronic components are only able to satisfy demands for temperatures of not more than 175°C. However, there are several applications that require even higher temperatures [1]. This is why a 1 μm complementary metal-oxide-semiconductor (CMOS) process was developed at the Fraunhofer Institute for Microelectronic Circuits and Systems (Fraunhofer IMS). This process can withstand temperatures up to 250°C, and with reduced performance even operate above this level [2]. This process is based on 200 mm silicon-on-insulator (SOI) wafers. Since common bulk technology comes to its limit at temperatures above 175°C due to increasing pn-leakage currents, the SOI technology is a good concept if temperatures of 250°C or more should be targeted [3, 4]. As is necessary for each process, a process which is designed to be used at these high temperatures must be characterized and qualified for the maximum operation temperature. For the Fraunhofer IMS 1 μm SOI-CMOS-technology, this means that the reliability for operation at 250°C has to be proven.

Among the reliability aspects which have to be considered from the technological point of view, the main important issues are electromigration phenomena in the metallization, the gate oxide integrity, as well as the transistor reliability in terms of wear-out mechanisms, such as negative bias temperature instability (NBTI) and hot carrier integrity (HCI). Concerning the metallization, electromigration does not pose a threat since the Fraunhofer IMS 1 μm SOI-CMOS-process uses tungsten as metal layers. As is well known, tungsten does not exhibit electromigration effects at temperatures below 1800°C [5]. The impact of hot carriers is low since this phenomenon becomes worse with decreasing temperature. The most important aspect seems therefore to be the gate oxide integrity.

The gate oxide thickness of the investigated process is 40 nm. For modern small technology nodes, the decreasing oxide thickness is what affects the gate oxide reliability. For the presented SOI-CMOS-technology, the high temperature is the critical factor. The standard test-procedure for lifetime evaluation in the context of gate oxide degradation is the time-dependent dielectric breakdown (TDDB) method [6, 7]. For accelerated testing, test temperatures are recommended to not exceed 200°C. As the maximum operation temperature of the Fraunhofer IMS 1 μm SOI-CMOS technology is already 250°C, accelerated reliability testing must be performed at even higher temperatures.

In the literature, TDDB measurements are described for a wide range of electric fields and temperatures, even for temperatures above 250°C [8, 9]. However, no data for TDDB measurements up to 350°C of a 40 nm thick oxide is presently available. It should also be noted that in the literature, it remains an open issue which physical model is the best to describe oxide breakdown. There are several competing models (see the Theoretical Aspects of Time-Dependent Dielectric Breakdown Measurements section). One aspect of the presented study was therefore to verify that the known test method is applicable for our gate oxide at temperatures above 200°C. In particular, the

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temperature and electric field acceleration parameters were studied for temperatures above 200°C. Additionally, we have analyzed the breakdown conditions, such as the charge to breakdown and the current just before breakdown using the TDDB data. The aim of the presented work is to provide information about gate oxide reliability testing at temperatures above 200°C.

Theoretical Aspects of Time-Dependent Dielectric Breakdown Measurements

The TDDB method consists of the application of a constant electric field (realized by a constant voltage) at a constant temperature to a capacitor structure and the determination of the time to oxide breakdown t_{BD}. Oxide breakdown is defined as a sudden increase in current. With various stress fields, the calculation of a field acceleration parameter is possible. Several stress temperatures give a temperature acceleration factor (i.e., the activation energy). For this purpose, a certain number of samples is stressed for each temperature–field stress combination, and the times to breakdown are plotted in a Weibull diagram.

The extrapolation from test temperature to operating temperature is possible using Arrhenius' law [10]

$$t_{BD} = t_0 \cdot \exp\left(\frac{E_A}{k \cdot T}\right) \tag{1}$$

where t_{BD} is the time to breakdown, t_0 is a time constant, E_A is the activation energy, k is the Boltzmann constant, and T is the temperature. For the calculation of the field acceleration, there exist several different models. The two main models are the E model, shown in eq. (2) [11] and the $1/E$ model, shown in eq. (3) [12]

$$\ln(t_{BD}) \propto \frac{E_A}{k \cdot T} - \gamma \cdot E_{ox} \tag{2}$$

$$\ln(t_{BD}) \propto \frac{E_A}{k \cdot T} - G \cdot \frac{1}{E_{ox}} \tag{3}$$

where γ is the field acceleration factor for the E model, G is the field acceleration factor for the $1/E$ model, and E_{ox} is the electric field.

The E model, also known as thermochemical model, was developed by McPherson and Baglee [11], and is based on observations of Crook and Berman [13, 14]. This model emanates from the assumption that the applied electric field interacts with weak Si-O bonds in the silicon oxide, which causes the bonds to break. The broken bonds are interpreted as oxide traps, and a large number of traps leads to oxide breakdown. In contrast to this molecular-physical approach, the $1/E$ model interprets oxide degradation as a consequence of hot holes that flow through the oxide. The $1/E$ model is also called anode hole injection model and was developed at the same time as the E model [12, 15, 16]. It is based on the idea that hot holes, which were caused by energetic electrons that drifted from the cathode to the anode, tunnel into the oxide where they create defects. The oxide breakdown occurs when a critical number of defects is reached.

The E model is more often used for field acceleration determination than the $1/E$ model and is recommended by the standard TDDB test procedure [6, 7]. In this study, both models are applied in order to evaluate the field acceleration for high test temperatures. Note that lifetime calculation with the E model often results in lower lifetimes than with the $1/E$ model and is more frequently used for this reason.

Experimental Details

The Fraunhofer IMS 1 µm SOI-CMOS process is based on 200 mm thin-film SOI wafers. It uses a LOCOS isolation and features, among others, three layers of tungsten metallization with excellent reliability properties, voltage independent capacitors, high resistance resistors, and single-poly-EEPROM cells. The passivation consists of a phosphosilicate glass (PSG) and a silicon nitride layer.

The investigated gate oxide capacitor structures fabricated in this process were planar (active area and poly layer not structured), and not covered by metal. The test structures consisted of capacitors with a 40 nm thick silicon dioxide layer between an n-doped silicon film and an n-doped polysilicon layer. The area of each test structure was 0.2 mm^2. The gate oxide is an oven oxide, grown at a temperature of 960°C. The polysilicon is n-doped with $POCl_3$ and structured by plasma etching.

As for the TDDB measurements, a variety of different temperature-field combinations was applied to the test structures in order to be able to calculate temperature and field acceleration factors. For every temperature–field stress combination, 10 samples were stressed in accumulation, which means that a positive voltage was applied to the polysilicon gate. The tests were performed at wafer level up to 300°C, and on packaged devices in an oven with a nitrogen environment for temperatures between 250°C and 350°C.

Results and Discussion

The section begins with the discussion of the results of the TDDB measurements concerning field and temperature acceleration, which is followed by the analysis of the breakdown conditions, that is, the current and charge at or just before breakdown.

A. Gate Oxide Lifetime: Electric Field and Temperature Acceleration

In Fig. 1, the current development with time up to oxide breakdown is presented for four different electric fields

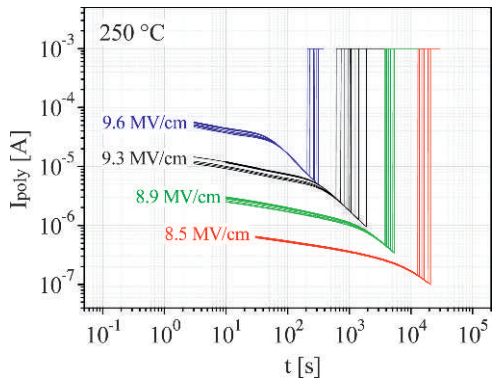

Fig. 1. Current-time curves up to oxide breakdown for TDDB-measurements at 250°C and four different electric fields.

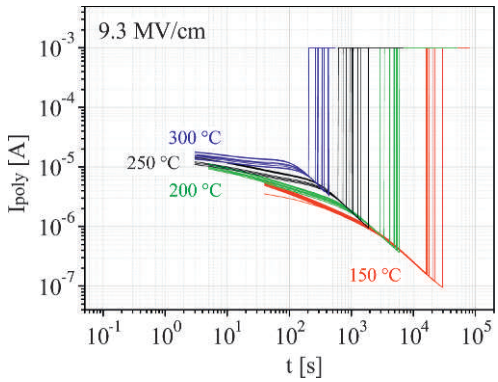

Fig. 2. Current-time curves up to oxide breakdown for TDDB-measurements at 9.3 MV/cm and four different temperatures.

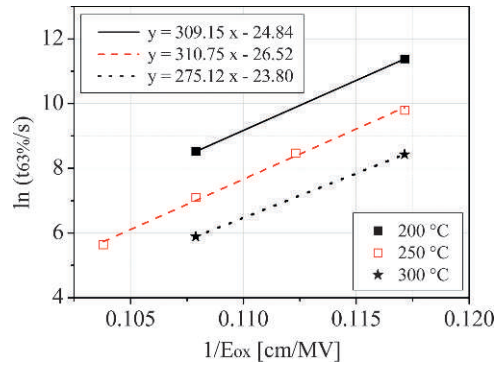

Fig. 4. Logarithm of the times to breakdown at a Weibull value of $W = 0$ (i.e., the characteristic Weibull times $t_{63\%}$ where 63% of the samples failed) as a function of the inverse electric field.

between 8.5 and 9.6 MV/cm at a temperature of 250°C. Fig. 2 depicts the current-time behavior for a constant field of 9.3 MV/cm and temperatures between 150°C and 300°C. Before breakdown, the current decreases due to the accumulation of negatively charged traps, which act as Coulombic repulsive centers [17, 18]. The larger the electric field and the temperature are, the larger is the current in the beginning, and the faster the breakdown. Only hard breakdowns (a current change at breakdown of more than one decade) were observed.

For further analysis, the time at which 63% of the samples for a specific temperature-field combination failed, that is, the characteristic Weibull time at a Weibull value of 0, was extracted using Weibull plots. Fig. 3 shows this time as a function of the electric field [cf. eq. (2)] for temperatures of 200°C, 250°C, and 300°C. Fig. 4 depicts the dependence on the inverse electric field [cf. eq. (3)]. The figures show that in the presented temperature and field range, the E and the $1/E$ model can both be applied. This behavior is often found in the literature when a limited electric field range is used [19, 20].

The field acceleration factors (i.e., the slopes of the fitted curves) seem to be slightly dependent on temperature, as the slopes decrease slowly with increasing temperature. This corresponds to the observations made in the literature [11, 21, 22], and also the obtained values are well consistent with the values found in the literature. For the factor γ (E model), we obtain a value between 3.5 and 3.9 cm/MV, and for the factor G ($1/E$ model) a value between 275 and 311 MV/cm.

The temperature acceleration, that is, the dependence of the times to breakdown on temperature, is illustrated for two different electric fields in Fig. 5. The slopes of the curves correspond to the activation energies. The slope for the weaker electric field of 8.5 MV/cm is slightly larger than that for the stronger field. This increase of activation energy with decreasing electric field can also be found in the literature [8, 9, 11, 23, 24].

The dependence of the field acceleration parameters on temperature and the field dependence of the activation energy make it difficult to accurately extrapolate from stress to use conditions in order to obtain information about the gate oxide lifetime. Since the field acceleration factors were already calculated at the maximum operation temperature of 250°C in our case, lifetime calculation is possible. A typical circuit in the presented SOI-CMOS technology has a gate oxide area of approximately 85 mm^2 and is supplied with an electric field of 3 MV/cm. For such a circuit, 1 ppm (part per million) of the gate oxide area should not fail within 2000 years, using the acceleration parameters obtained in our analysis. This is consistent with other data from the literature.

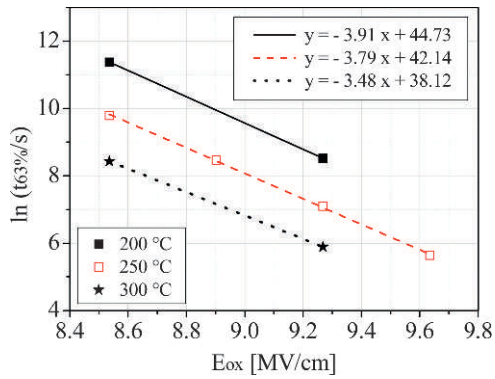

Fig. 3. Logarithm of the times to breakdown at a Weibull value of $W = 0$ (i.e., the characteristic Weibull times $t63\%$ where 63% of the samples failed) as a function of the electric field.

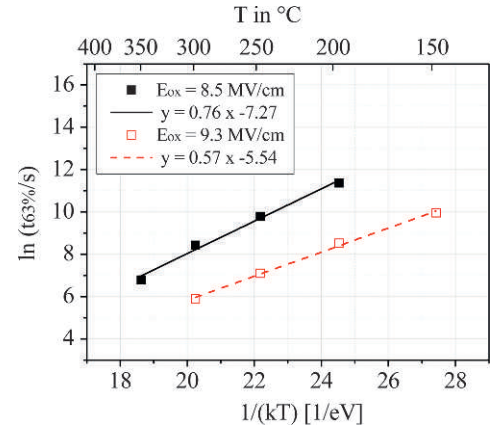

Fig. 5. Logarithm of the times to breakdown at a Weibull value of $W = 0$ (i.e., the characteristic Weibull times $t_{63\%}$ where 63% of the samples failed) as a function of $1/kT$.

B. Gate Oxide Characteristics: Analysis of the Breakdown Conditions

The aim of TDDB measurements is an analysis of the temperature and electric field acceleration parameters in order to determine the oxide lifetime. However, there is more information included in the current-time curves (see Figs. 1 and 2). The intention of this section is to show some characteristics of the breakdown current, or more precisely of the current which can be detected just before breakdown, and the charge to this breakdown.

As shown in Figs. 1 and 2, the breakdown current varies with the electric field and the temperature. The larger the field or the higher the temperature, the larger is the current at oxide breakdown. A closer view of this behavior is depicted in Figs. 6 and 7. In Fig. 6, the breakdown current increases with the electric field for all three temperatures. For 250°C, a fit shows an exponential behavior. Concerning the temperature dependence, there is an exponential decrease with $1/kT$ in Fig. 7. These observations are of interest since the breakdown current for a certain temperature–field stress combination could be predicted using the presented curves.

However, there is an even more important relation between the current just before breakdown, the electric field, the temperature, and the time to breakdown. Having a look at the current,

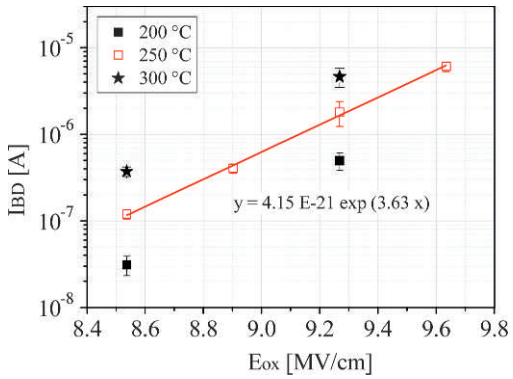

Fig. 6. Current at oxide breakdown as a function of the electric field for temperatures of 200, 250, and 300°C.

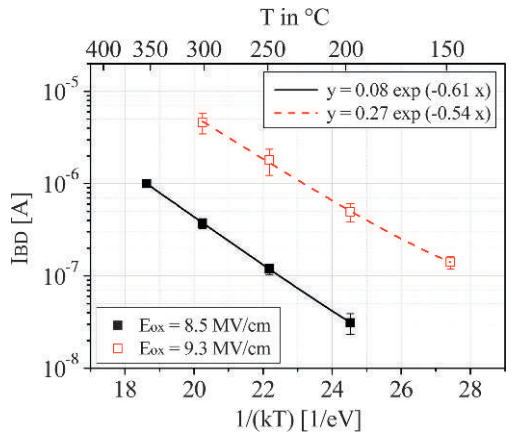

Fig. 7. Current at oxide breakdown as a function of $1/kT$ at electric fields of 8.5 and 9.3 MV/cm.

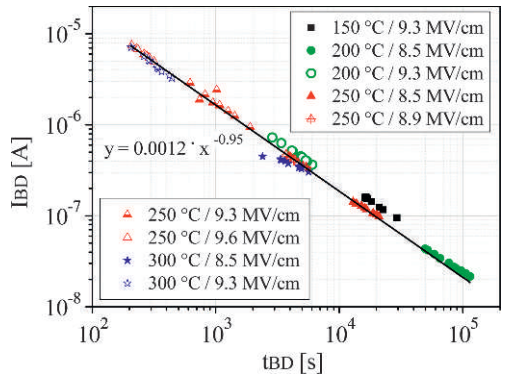

Fig. 8. Current at oxide breakdown as a function of the time to breakdown for different temperatures and electric fields.

which decreases with time in Figs. 1 and 2, it can be seen that all curves approach the same straight line. Corresponding to this observation, the breakdown current is drawn in Fig. 8 as a function of the time to breakdown for all the different temperatures and electric fields together in one plot. It is remarkable that all points, coming from different temperature and field stress condition combinations, lead to one straight line in a double-logarithmic plot. This line has the form

$$I_{BD} = A \cdot (t_{BD})^{-B} \tag{4}$$

where I_{BD} is the current just before breakdown, t_{BD} is the time to breakdown, A and B are constants, and B = 0.95. Note that eq. (4) is valid for all used temperature–field combinations.

In addition to the investigation of the current at oxide breakdown, the charge to breakdown, or more precisely the integrated current from $t = 0$ to $t = t_{BD}$ of the curves in Figs. 1 and 2, was analyzed. Fig. 9 shows the integrated current $q_{integrated}$ up to oxide breakdown as a function of the electric field. The values for $q_{integrated}$ increase with the field. The increase is small but visible for all three temperatures.

From the results presented in Fig. 10 it follows that with increasing temperature, the integrated current decreases. Once again, this behavior can be described by an exponential fit. The observed behavior corresponds to what can be found in the literature [24, 25] and indicates that for a higher temperature, less charge is required for oxide breakdown.

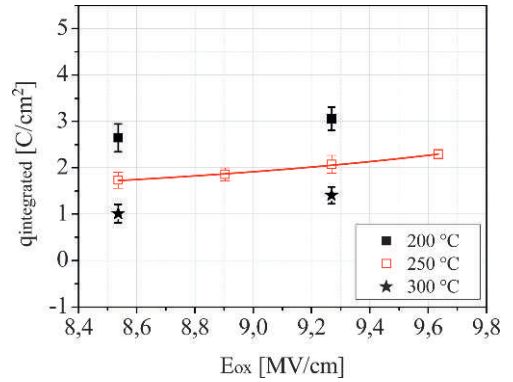

Fig. 9. Integrated current $q_{integrated}$ up to oxide breakdown as a function of the electric field for temperatures of 200, 250, and 300°C.

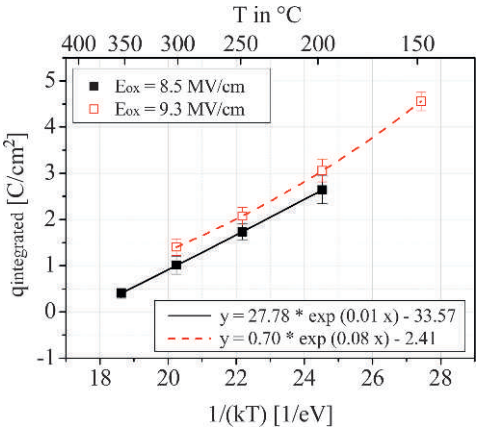

Fig. 10. Integrated current $q_{\text{integrated}}$ up to oxide breakdown as a function of $1/kT$ at electric fields of 8.5 and 9.3 MV/cm.

The findings from Figs. 9 and 10 show that the absolute value of $q_{\text{integrated}}$ is not the only determining factor for the dielectric breakdown, as this integrated current depends on the electric field and the temperature. However, there is a general relation [eq. (4)] for the breakdown, which is followed by all used temperature–field stress combinations.

Conclusion

The presented paper deals with TDDB testing on 40 nm thick gate oxide capacitors at temperatures above 200°C. The aim of this work is to provide a basis for gate oxide reliability evaluation at high temperatures.

First, the temperature and the electric field acceleration parameters were analyzed. It was shown that both the E model and the $1/E$ model are applicable in the stress condition range that was used. For the activation energy, a slight dependence on the applied field was detected. The field acceleration parameters that were found for the E and the $1/E$ model also lie in a range known from the literature. The obtained lifetime for 1 ppm of a gate oxide area of 85 mm^2 in the presented technology is at least 2000 years for a field of 3 MV/cm and a temperature of 250°C.

In addition to the typical TDDB analysis, the breakdown conditions, such as the charge to breakdown and the current just before breakdown were studied using the TDDB data. It was shown that there exists a relation which describes the breakdown current as a function of the time to breakdown and which is independent of the temperature–field stress combination that is used.

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