Superior Damage-Immunity of Thin Oxides Thermally Grown on Reactive-Ion-Etched Silicon Surface in N_2O Ambient

S. Y. Ueng, T. S. Chao, P. J. Wang,
W. H. Chen, D. C. Chang, and H. C. Cheng

***Abstract*—Thin oxides thermally grown on reactive-ion-etched silicon surfaces in N_2O ambient have been studied. As compared with pure oxides grown on the etched silicon in dry oxygen, N_2O-grown oxides exhibit significantly stronger immunity to the RIE-induced damages. A great improvement in both time-zero-dielectric-breakdown (TZDB) and time-dependent-breakdown (TDDB) characteristics is observed for the N_2O-grown oxides on RIE-treated silicon surfaces. Accelerated tests have shown that the N_2O oxide grown on the RIE silicon surface can achieve a lifetime longer than the pure oxide grown on the correspondingly etched silicon surface with a factor over 10^8.**

I. INTRODUCTION

As device dimensions get smaller, a high definition etching technique, such as reactive ion etching (RIE), is required. Hence, the effects of RIE processes have been widely studied for the ultra-large-scale-integrated (ULSI) technology. For advanced semiconductor devices, such as tunnel oxides for electrically erasable read-only memory (EEPROM) devices and dielectrics for trench capacitors, thin thermal oxides are frequently grown on a RIE-treated silicon surfaces. Due to the ion bombardment, the induced damages in the silicon can not be avoided during the dry etching. The quality of thin thermal oxides grown on the RIE-treated silicon will be therefore degraded by these residual defects. Many authors [1], [2] have studied on the issues of damages induced by the RIE. On the other hand, the benefits of N_2O-grown oxides have also been extensively studied in the past few years. Strong interface stability, low electron traps, and large charge-to-breakdown have been observed by many authors [3], [4] for the N_2O oxides. In this letter, the damage-immunity of the thin oxide grown on the reactive-ion-etched silicon surface in N_2O ambient will thus be proposed.

II. EXPERIMENTAL PROCEDURES

(100) oriented, 2.5–3.5 Ω-cm, boron-doped silicon wafers were used. At first, 350 Å-thick oxides were grown in O_2 ambient at 900°C. To introduce the damages on the silicon surface, the oxide stripping was performed by a RIE system. A two-step oxide-etching recipe using $CHF_3/CF_4/Ar$ and CF_4/O_2 was employed. After the oxide etching, thermal oxides ($\sim$80 Å) were grown at 900°C in N_2-diluted O_2 and wholly N_2O ambient, respectively. Some samples without RIE treatments were accompanied for each run to evaluate the impacts of the defects induced by the RIE. Subsequently, an *in situ* post-oxidation annealing was performed in N_2 ambient at 900°C for 10 min. After a 4000 Å-thick polysilicon deposition and subsequent $POCl_3$ diffusion, MOS capacitors were fabricated to analyze the characteristics of the dielectrics.

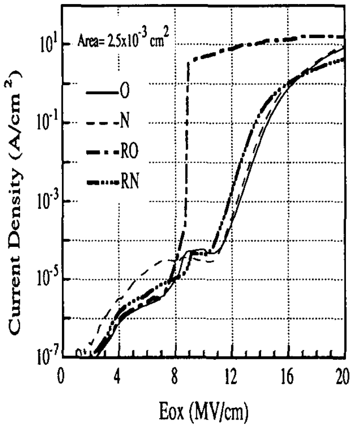

Fig. 1. Curves of current density (J) versus electrical field (E_{ox}) obtained by the voltage ramping technique with a ramping rate of 1 V/s.

III. RESULTS AND DISCUSSION

In order to avoid the effects of high-temperature annealing, pure oxides were grown in N_2-diluted O_2 ambient to keep the oxidation time comparable to that for the N_2O-oxidation process. The time for dry oxidation and N_2O-oxidation are 85 min and 78 min, accordingly. The dependence of current density (J) on electrical field (E_{ox}) for different dielectrics are shown in Fig. 1. It is clearly noted in this figure that the sample RO, with pure oxide grown on the RIE-treated silicon, exhibits a remarkable degradation. Due to the ion bombardment from RIE, contaminations and damages will be induced on the silicon surface [5], [6]. As is well known, surface stacking faults via the contaminations can occur after high-temperature oxidation for RIE samples, which degrade the oxide breakdown voltages [5]. Therefore, the damages induced by RIE is conjectured as the main cause for the early breakdown events of the sample RO. On the contrary, the sample RN, i.e., N_2O-oxide grown on the RIE-treated silicon, displays a great improvement over the sample RO in the leakage currents and breakdown fields. It indicates that thermal oxides grown on the RIE-treated silicon surface in N_2O atmosphere can remedy the RIE-induced defects. The cumulative distributions of TZDB characteristics for various dielectrics are shown in Fig. 2. Oxide breakdown field (E_{bd}), is defined as the electrical field at which the gate current reaches to 1 mA/cm^2. For the samples without RIE, pure oxide, O, and N_2O oxide, N, show no difference in TZDB characteristics. These results were consistent with what have been reported [3], [4] that N_2O-grown oxides and pure oxides have similar TZDB characteristics. However, for the RIE-treated specimens, the sample RN possess higher breakdown fields and tighter distribution than the sample RO. Furthermore, the breakdown field and its distribution of the sample RN are similar to those of the sample N and O. Lots of AES and SIMS [7] data have shown that nitrogen pileup near the interface exists for the N_2O-grown oxides. It is believed that these nitrogen atoms must play an important role to passivate the RIE-induced damages.

Fig. 3 shows the time-to-breakdown (t_{BD}) characteristics of the MOS capacitors (area = 1.6×10^{-3} cm^2) for various dielectrics under a constant voltage stressing of 13 MV/cm. The sample O and N also show a narrow-range distribution and little difference in t_{BD}, as was reported by other authors [3]. It indicates that the oxidation

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S. Y. Ueng and H. C. Cheng are with the Department of Electronics Engineering and Institute of Electronics, National Nano Device Laboratory, National Chiao Tung University, Hsinchu, Taiwan, R.O.C.

T. S. Chao, P. J. Wang, W. H. Chen, and D. C. Chang are with the National Nano Device Laboratory, National Chiao Tung University, Hsinchu, Taiwan, R.O.C.

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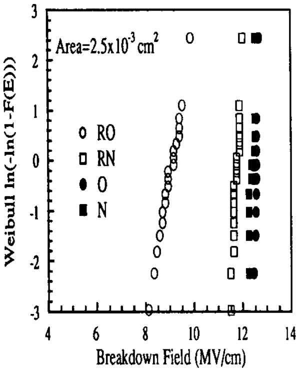

Fig. 2. Cumulative probabilities of the time-zero dielectric-breakdown characteristics using voltage ramping technique for the MOS capacitors with an area of 2.5×10^{-3} cm^2. Breakdown field is defined as the field at which the gate current density reaches to 1 $\mathrm{mA/cm}^2$.

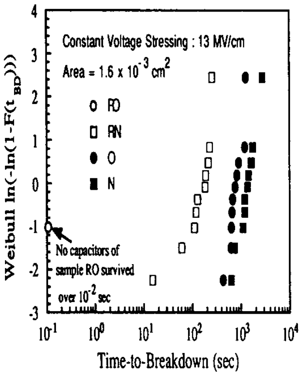

Fig. 3. Weibull plots of the time dependent dielectric breakdown (TDDB) characteristics at a constant stressing electrical field of 13 MV/cm for the capacitors with various dielectrics.

environment, including initial cleaning and device fabrication, is normal in this experiment. On the other hand, the RIE-treated samples show a significant difference between pure oxides and N_2O-grown oxides in TDDB characteristics. From the data, no capacitor of the sample RO survives over 10^{-2} s with a constant field stressing at 13 MV/cm. In contrast, the sample RN exhibits a tolerable range of t_{BD} and a distribution for practical applications. According to the TDDB model [8], the early breakdown is caused by the weak spots from the high density of hole traps at the cathode, thinner oxide thickness, lower barrier height due to the contamination, or crystalline defects. The improved TDDB characteristics of N_2O-grown oxides are attributed to the nitrogen pileup at interface with reducing dangling bond densities of Si and strained Si-O [3]. Therefore, the weak spots at the SiO_2/Si interface caused by RIE treatment are strengthened.

In order to compare the lifetime of N_2O oxides and pure oxides grown on the RIE-treated Si surface, accelerated TDDB tests [9] were demonstrated. The log (t_{BD}) versus 1/E plots of the sample RO and RN are shown in Fig. 4. The slopes, G, of the projection lines for the sample RO and RN are 360 MV/cm and 352 MV/cm, respectively. They are close to the data reported by Chen *et al.* (320 MV/cm) [10]. The dielectric lifetimes of the sample RO and RN were then projected by extrapolating the TDDB projection curve at the $E_{OX} = 8$ MV/cm. The t_{BD} of the sample RN is estimated to have about nine orders as large as that of the sample RO.

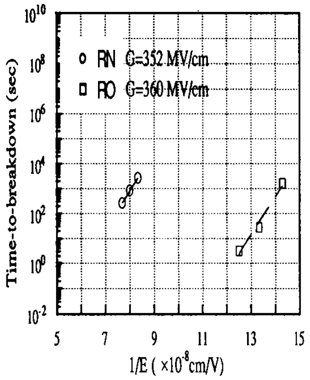

Fig. 4. TDDB data and projection lines of the capacitors for the samples RN and RO.

IV. SUMMARY AND CONCLUSIONS

Thin N_2O-oxides grown in N_2O ambient have been shown to exhibit superior immunity to the RIE-induced damages than pure oxides. This process could provide higher breakdown fields, lower leakage current, and significantly improved TDDB characteristics for the thermal oxides on the RIE-treated silicon substrates. The N_2O-oxides grown on the etched Si surface could achieve a quality comparable to the thermal oxides grown on nonetched wafers. Therefore, N_2O-grown oxides will be a promising candidate for the future ULSI application, especially the subsequent oxidation after the RIE process.

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