Improvement of oxide thickness uniformity by high then low O₂ pressure oxidation in rapid thermal processing*

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This article presents the growth of thin oxides by rapid thermal processing (RTP) under different O₂ pressures, indicating that high pressure oxidation tends to make oxide thickness less uniform as oxidation time increases. However, oxide under low pressure oxidation tends to saturate in thickness and a “self-compensating” phenomenon occurs. Thus in order to grow ultrathin gate oxide in a desired thickness regime with good thickness uniformity, we developed a technology called high then low pressure oxidation. The experimental results show that in thickness and electrical properties the uniformity of oxide obtained by oxidation under high then low pressure would indeed be improved. © 2002 American Vacuum Society. [DOI: 10.1116/1.1453455]

I. INTRODUCTION

Continued downsizing of the gate oxide thickness has contributed to the shrinking of the metal–oxide–semiconductor (MOS) field effect transistor (FET)’s dimension and thus the progress of ultralarge scale integrated (ULSI) circuit technology. According to the 1999 estimation by the Semiconductor Industry Association, the gate oxide thickness of deep subquarter microtechnology will be downsized to less than 30 Å. Moreover, for ultrathin oxide, the leakage current is dominated by the tunneling current, which is very sensitive to nonuniformity of the oxide thickness.^{1–5} Therefore, improving the thickness uniformity of ultrathin oxide is an urgent issue. Rapid thermal processing (RTP) is used in modern ULSI processing because of its small thermal budget. However, temperature nonuniformity is a major problem in RTP, leading to the nonuniformity of gate oxide. Various methods have been reported to improve the uniformity of oxides by RTP, such as system geometry,^{6,7} lamp number and locations,^{8,9} and patterned reflectors.¹⁰ However, changes in the system structure are usually very expensive. In this article, we propose to improve oxide uniformity by changing the oxidation process profile.

Typically, the oxidation operation is carried out under fixed oxygen pressure for a specific duration. However, some special oxidation profiles have also been studied for different purposes. For example, a two-step oxidation profile was used to study the effect of oxide thermal history on its growth properties.¹¹ In this article, a two-step oxidation process is carried out by oxidation under different oxygen pressures and the uniformity of oxides by two-step oxidation is compared with that by typical one-step oxidation.

II. EXPERIMENT

A. Typical oxidation

The experiments were carried out on 3 in. *p*-type (100) wafers with a resistivity of 1–10 Ω cm. After standard RCA

cleaning, the wafers were dipped in H₂O:HF (50:1) and rinsed in de-ionized water before each oxidation operation to avoid the native oxide effects. The oxidation was performed by halogen lamp-heated RTP, and the typical oxidation profile setting is shown in Fig. 1. For stability of the RTP, the ramp-up rate is set to 20 °C/s and at 200 and at 760 °C, and temperatures are kept constant for 20 and 10 s, respectively. The oxidation time t_{O_2} refers to the time period during which the system is set to the final stage temperature, 850 °C. The oxygen is pumped into the chamber at room temperature and the oxygen in the chamber is neither pumped out nor pumped in during the operation. The initial pressure P_{O_2} refers to the oxygen pressure at room temperature. Therefore, the residual oxide thickness at zero oxidation time t_{O_2} is due to the presence of oxidation during the ramp-up period. The operation described above is the typical operation in the experiments. Several typical operations were performed in P_{O_2} of 10, 50, 100, 200, and 500 Torr and for t_{O_2} of 0, 10, 20, 30, and 40 s. The resulting oxide thickness were measured with an ellipsometer by setting the refraction index at 1.46.

FIG. 1. Oxidation profile used for typical samples.

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FIG. 2. Oxidation profile used for sample H+L1 and H+L2.

FIG. 3. Oxidation profile used for sample HL1 and HL2.

B. High then low pressure oxidation

In addition to the above typical oxidation process, we also designed oxidation conditions called high then low pressure oxidation, i.e., H+L and HL. The oxidation profiles for H+L samples are shown in Fig. 2, while those of HL samples are shown in Fig. 3. The reference samples ($T1-T5$) were oxidized using the typical oxidation profile shown in Fig. 1 at 200 Torr O_2 pressure. The oxidation conditions of all samples are summarized in Table I.

After oxidation, Al film was deposited, and MOS capacitors 150 by 150 μm^2 were formed by conventional photolithography. Current-voltage ($I-V$) curves were measured with HP 4154. Time zero dielectric breakdown (TZDB) was measured with gate voltage starting from 0 V and a ramp rate of -0.1 V/s. A gate current exhibiting a sharp increase was identified as breakdown, and the breakdown voltage was defined as the interception at the breakdown current. Breakdown field was calculated from breakdown voltage minus the flatband voltage, i.e., -0.9 V, and then divided by oxide thickness. Time dependent dielectric breakdown (TDDDB) under constant field was measured with a constant negative bias applied to devices and the current was monitored. When the

gate current had a sharp increase, breakdown was identified and time to breakdown was obtained.

III. RESULTS AND DISCUSSION

A. Typical oxidation

To control the growth of thicker oxide (e.g., >50 Å), usually both the oxidation temperature and oxygen pressure are set at high levels (e.g., $>500^\circ C$, >500 Torr) and the oxidation time is the key factor in controlling the oxide thickness. However, in our other experiment, for oxidation time t_{O_2} 4 s and under initial oxygen pressure P_{O_2} of 500 Torr, the average thickness of oxide is already 56 Å at $960^\circ C$ oxidation temperature. Even when the oxidation temperature is as low as $850^\circ C$ with $P_{O_2}=500$ Torr and $t_{O_2}=5$ s in this work, the average oxide thickness is 25.8 Å. Therefore, in order to grow ultrathin gate oxide, we lower not only the temperature but also the oxygen pressure. Figure 4 shows the plot of average oxide thickness as a function of oxidation time under different P_{O_2} at $T_{O_2}=850^\circ C$. In Fig. 4 one can observe a very fast initial growth, followed by the slower

TABLE I. Oxidation conditions for typical (T), H+L, and HL RTO samples ($850^\circ C$).

Smple Typical	Pressure (Torr)		Oxidation time(s)	
	P_{O_2}		t_{O_2}	
T1	200		0	
T2	200		10	
T3	200		20	
T4	200		30	
T5	200		40	
H+L/HL	$P_{O_2}(H)$	$P_{O_2}(L)$	$t_{O_2}(H)$	$t_{O_2}(L)$
H+L1	200	50	10	30
H+L2	200	50	20	30
HL1	200	50	10	30
HL2	200	10	10	40

FIG. 4. Average oxide thickness vs oxidation time under different oxygen pressure at 850 °C.

growth at a later stage. Besides, under low initial pressure, e.g., 50 or 10 Torr, the oxide thickness tends to be saturated for an oxidation time of 40 s.

The average growth rates at different periods during the 40 s oxidation time from Fig. 4 are also calculated. Here, the average growth rate at time t (e.g., $t=10$ s) refers to the difference of the average oxide thickness between time t and the next experimental time, e.g., $t+10$ s, over the time difference, e.g., 10 s. The average growth rate with time under different pressures is shown in Fig. 5. The observation in Fig. 5 is that for relatively lower initial oxygen pressures, e.g., 10 and 50 Torr, after oxidation time of 10 s, the growth rate becomes very slow and the oxide thickness tends to be saturated. However for higher initial oxygen pressures, e.g., 100 and 200 Torr, the oxide tends to grow with relatively high rates even after an oxidation time of 30 s. Therefore, to con-

FIG. 5. Average oxide growth rate vs oxidation time under different oxygen pressure at 850 °C.

FIG. 6. Upper and lower 50% average oxide thickness and oxide thickness standard deviation of oxides grown under 50 Torr oxygen pressure from 20 to 40 s at 850 °C.

trol the growth of the oxide in different thickness regimes under 30 $\text{\AA}$, we can change the oxygen pressure to grow an initial thickness that is in the desired thickness regimes. And then we can precisely control the oxidation time of the slow growth rate region under lower pressure to the desired thickness.

Then, the average oxide thickness of thicker (50%) and thinner (50%) samples on one wafer, and the deviation in oxide thickness, were further analyzed, as shown in Figs. 6 and 7. The average growth rate of the thicker 50% sample at time t , R_U , refers to the difference of average oxide thickness in the upper 50%, between time t and the next experiment time, e.g., $t+10$ s, over the time difference, e.g., 10 s. R_L refers to the growth rate of the thinner 50% sample, respectively. Intuitively, if during a period when the portion of oxide that is thicker grows slower than that which is thinner, the oxide thickness would tend to "self-compensate" and thus be more uniform. Conversely, if during a period when the portion of oxide that is thinner grows slower than that which is thicker, the oxide thickness would tend to be non-uniform. For the case of low pressure, as shown in Fig. 6, between the oxidation time of 20 and 40 s of the oxide with $T_{O_2}=850^\circ\text{C}$ and $P_{O_2}=50$ Torr, the average growth rate of

FIG. 7. Upper and lower 50% average oxide thickness and oxide thickness standard deviation of oxides grown under 200 Torr oxygen pressure from 10 to 20 s at 850 °C.

FIG. 8. Thickness standard deviation vs average oxide thickness for samples listed in Table I.

the thicker 50% sample, i.e., 0.048 Å/s , is smaller than that of the thinner 50% sample, i.e., 0.094 Å/s . Thus the standard deviation becomes smaller after 40 s, compared with that after 20 s. That is to say, if $R_U < R_L$, then $\Delta \text{std} < 0$. But for the case of high pressure, as shown in Fig. 7, between the oxidation times 10 and 20 s of the oxide with $T_{O_2} = 850^\circ\text{C}$ and $P_{O_2} = 200 \text{ Torr}$, the average growth rate of the upper 50%, i.e., 0.235 Å/s , is higher than that of thinner 50%, i.e., 0.180 Å/s . Thus the standard deviation becomes larger after 20 s, compared with that after 10 s. That is to say, if $R_U > R_L$, then $\Delta \text{std} > 0$. Therefore, from the experimental results, one can see that under low initial oxygen pressure (50 and 10 Torr) the oxide thickness tends to saturate and the average growth rates of the thicker 50% is smaller than that of the thinner 50%. We can apply this feature to grow uniform oxide as follows. First, the oxide was grown to a desired region of thickness under higher pressure, and then oxidation under lower pressure was performed to compensate for the thickness deviation.

B. High then low pressure oxidation

Because the uniformity of oxide thickness tends to degrade with oxidation time under high pressure oxidation but exhibits a “self-compensate” behavior in the low pressure oxidation case, the H+L and HL process were explored. Figure 8 shows the thickness standard deviation versus average thickness for samples listed in Table I. For example, for samples HL1 and HL2, whose oxidation profile is shown in Fig. 3, the oxide was initially grown with 200 Torr initial oxygen pressure for 10 s, and then the oxygen in the chamber was reduced to low pressure (50 or 10 Torr). For the case of HL1, the oxygen was reduced to 50 Torr and the oxide was then grown for 30 s to 23 Å . Compared with sample T3, which was grown by a typical oxidation profile and has a comparable oxide thickness of 23 Å , sample HL1 is more uniform with the standard deviation of 1.6 Å , whereas that of

FIG. 9. Weibull plots in oxide breakdown field for HL1 and T3 samples with an oxide thickness of 23 Å .

T16 is 2.0 Å . The “self-compensation” of oxide thickness is evidenced in this case. As for the case of HL2, the standard deviation is still smaller: 1.7 Å . For oxides with comparable average oxide thickness, the results demonstrate that the high then low O_2 pressure oxidation profile advantageously compensated for thickness variation, so that oxide could be prepared more uniformly than that oxidized by the typical oxidation profile. It should be noted that the average thickness of H+L1 and H+L2 is larger than that of HL1 and HL2, which is possibly due to the second ramp-up period in the presence of oxygen.

The TZDB and TDDB comparison in samples HL1 and T3 are shown in Figs. 9 and 10, respectively. It can be seen that for the similar oxide thickness, samples HL1 and T3 exhibited comparable performance in magnitude, but sample HL1 has sharper distributions, which means a better uniformity. This also supports the inference that high then low pressure oxidation provides more uniform oxide thickness than the conventional method.

IV. CONCLUSION

This article examines the growth and the uniformity of ultrathin oxide by RTP under different pressures. The experimental results show that oxide thickness uniformity tends to

FIG. 10. Weibull plots in time to breakdown tested under constant field stress for HL1 and T3 samples with an oxide thickness of 23 Å .

degrade with oxidation time under high pressure oxidation, but exhibits a “self-compensating” behavior in low pressure oxidation. A technology called high then low pressure, which take advantage of the self-compensation of oxidation under low pressure, was investigated. Experimental results including thickness uniformity, and distribution in TZDB and TDDB, indicate that this method improves the uniformity of ultrathin oxide by RTP.

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¹B. Majkusiak and A. Strojwas, J. Appl. Phys. **74**, 5638 (1993).

²C. K. Chow *et al.*, J. Appl. Phys. **34**, 2599 (1963).

³J. Pochobradsky, Solid-State Electron. **10**, 973 (1967).

⁴Z. Hurych, Solid-State Electron. **9**, 967 (1966).

⁵J. Sune, Y. Placencia, F. Campabadal, and X. Aymerich, Surf. Sci. **346** (1987).

⁶B. J. Cho, P. Vandenabeele, and K. Maex, IEEE Trans. Semicond. Manuf. **7**, 345 (1994).

⁷Y. T. Lin, R. Subrahmanyam, A. R. Sitaram, and M. Orlowski, Mater. Res. Soc. Symp. Proc. **303**, 231 (1993).

⁸J. M. Dilhac, N. Nohier, and C. Ganibal, IEEE Trans. Semicond. Manuf. **8**, 432 (1995).

⁹F. Y. Sorrell, M. J. Fordham, M. C. Ozturk, and J. J. Wortman, IEEE Trans. Electron Devices **39**, 75 (1992).

¹⁰J. P. Hebb, K. F. Jensen, and E. W. Egan, Mater. Res. Soc. Symp. Proc. **387**, 21 (1995).

¹¹H. R. Soleimani and A. Philipossian, J. Electrochem. Soc. **140** (1993).