Correlation between BTI-Induced Degradations and Process Variations by Measuring Frequency of ROs

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***Abstract*—We analyze the correlation between BTI (Bias Temperature Instability)-induced degradations and process variations. BTI shows a strong effect on highly scaled LSIs in the same way as the process variations. It is necessary to predict the combinational effects. We should analyze both aging-degradations and process variations of MOSFETs to explain the correlation. We measure initial frequencies and the aging-degradations of ROs (ring oscillators) of 65-nm process test circuits. The initial frequencies of ROs follow gaussian distributions. The degradations can be approximated by logarithmic function of stress time. The degradation at the "fast" condition of the variations has a higher impact on the frequency than the "slow" one. The correlation coefficient is 0.338. In this case, we can reduce the design margin for BTI-induced degradations because the degradation at the "slow" conditon on the variations is smaller than the average.**

***Keywords*—BTI, process variation, reliability**

I. Introduction

BTI is one of the most significant aging-degradations on LSIs. It is called NBTI (Negative BTI) that appears in PMOS transistors. Because threshold voltages of PMOS transistors increase with time when their gates are stressed by negative bias. It is also called PBTI (Positive BTI) that appears in NMOS transistors. NBTI is known as one of dominant factors that determine life time of circuits after 65-nm process technology [1].

BTI is a result of random discrete-charge-induced variations [2]. It is time-dependent phenomenon. Behavior of a single charge in the channel is becoming a significant problem on heavily scaled LSIs. Characteristics of the MOSFETs are fluctuated by the charge behavior. It is called the RTN (Random Telegraph Noise). The origin of BTI is the defects trapping and detrapping carriers in gate oxide. BTI is basically the same degradation as the RTN. But it has the effect for the longer-term than RTN. BTI and process variations are becoming dominant reliability problems on highly scaled LSIs. Traditionally, the main source of the variation is the RDF (Random Dopant Fluctuation). It is location-dependent phenomenon. Now the main sources of the variation are random discrete-charge and RDF. The accurate prediction of the combinational effects is necessary.

In this paper, we analyze BTI-induced degradations and process variations. We expect the frequencies are varied by the process variations according to locations on the test chips. They should follow the gaussian distribution. We focus on the groups of the highest, average and lowest frequencies. We measure the aging-degradations of the three groups by the accelerated test. We assume that the degradation at the highest frequency group is larger than one at the slowest frequency group, because there are more carriers in the highest group transistors than the slowest one. BTI is assumed to have a large impact on the highest frequency group transistors. We examine the correlation among BTI-induced degradations and process variations.

II. Measurement Setups

We measure ring oscillators (ROs) to analyze BTI-induced degradations and process variations. The measurement set-up is as follows. A 65-nm bulk process test chip contains 1764 11-stage ROs. The micrograph of our test chip is shown in Fig. 1. Those ROs are divided into 18 types. They have different structures such as stages and wiring capacitance/resistance. Power supply voltages are 1.8V and 2.0V. Temperature conditions are 25°C and 80°C. Numbers of oscillation are detected by on-chip counters. It is important to minimize the control signal delays when we measure BTI. Because the degradation amount is changing in very short time. To achieve accurate measurement results, we use an engineering LSI tester.

III. Measurement Results

A. Results of Process Variations

Figs. 2 and 3 show the distributions of frequencies of 98 11-stage ROs. Frequencies of all RO types follow the gaussian distributions. We describe the 10% of the highest frequency group as the "fast" conditon, the 10% of the average group as the "typical" conditon and the 10% of the lowest group as the "slow" conditon.

NBTI should be affected by process variations. The origin of NBTI is carrier-capturing and emitting activities of the defects in the gate oxide [3]. The amount of carriers is fluctuated by the process variations. There are more carriers in the fast conditon transistor than the slow one, NBTI should has a large impact on the fast condition transistors.

B. Results of BTI-Induced Degradation

NBTI-induced degradations can be detected by measuring the frequencies of ROs through the degradation time. When the oscillations stop, the ROs degrade over time. We measure the frequencies of the ROs of the fast, typical and slow conditions, periodically. The ROs repeat the degradation intervals and oscillations/measurements. The total degradation time is 3600 s.

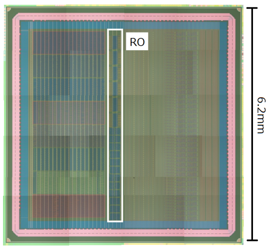

Fig. 1. 65-nm bulk process test chip micrograph.

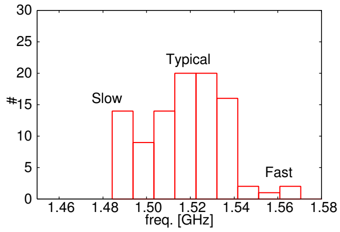

Fig. 2. Frequency distribution of 98 ROs, chip A, RO#15, $V_{dd} = 2.0$V, $T = 80°$C.

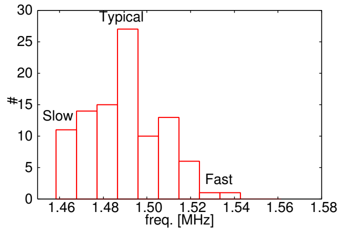

Fig. 3. Frequency distribution of 98 ROs, chip B, RO#15, $V_{dd} = 1.8$V, $T = 25°$C.

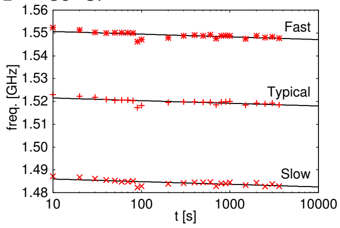

Fig. 4. Frequency degradations of fast, typical and slow conditions, chip A, RO#15, $V_{dd} = 2.0$V, $T = 80°$C.

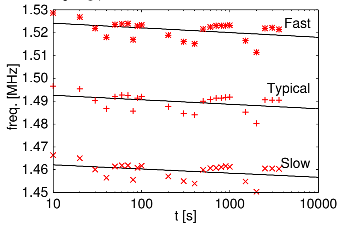

Fig. 5. Frequency degradations of fast, typical and slow conditions, chip B, RO#15, $V_{dd} = 1.8$V, $T = 25°$C.

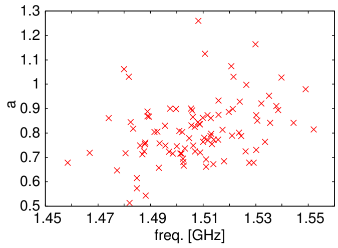

Fig. 6. Variable a of same type ROs on the ASIC.

The frequency-degradations of three variation conditions are shown in Fig. 4 and Fig. 5. Note that the x axis is a log-scale. The degradations follow (1).

$$f(t) = -a \times \log(t) + b \tag{1}$$

The variable a is the degradation factor. The degradation trend is increased with a.

We examine correlations between NBTI-induced degradations and process variations. To compare the trends of the degradations, we focus on the variable a of (1). If a is larger, the degradation is larger. The variables a of the three conditions are compared in Table I and Table II. The results show the average of a at the fast condition is the largest among three conditions in Table I and is larger than the slow condition in Table II.

Fig. 6 shows a of the 98 ROs of the same type. The x axis is initial frequencies of the ROs. We calculate the correlation coefficient c of the frequencies f and a.

$$c = \frac{\sum_{i=0}^{n}(f_i - f_{avg})(a_i - a_{avg})}{\sqrt{\sum_{i=0}^{n}(f_i - f_{avg})^2}\sqrt{\sum_{i=0}^{n}(a_i - a_{avg})^2}} = 0.338 \tag{2}$$

Variables f_{avg} and a_{avg} are averages of f and a, respectively. It shows a weak increasing trend with the frequency.

IV. Conclusion

In this paper, we analyze the correlation between BTI-induced degradations and process variations. We analyze those reliability issues to measure the frequencies of the ROs. The initial frequencies follow the gaussian destribution. The frequencies decrease with time because of BTI. The degradations follow logarithmic functions. The correlation coefficient of the degradation factors and the initial frequencies is 0.338. In this case, we can reduce the design margin for BTI-induced degradations because the degradation at the "slow" conditon is smaller than the average.

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References

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TABLE I
VARIABLES a OF FAST, TYPICAL AND SLOW CONDITIONS, CHIP A, $V_{dd} = 2.0$V, $T = 80°$C.

#	Fast	Typ.	Slow
0	0.795	0.849	0.682
1	0.976	1.009	0.992
2	1.033	1.039	1.016
3	0.935	0.839	0.792
4	0.812	0.734	0.814
5	0.820	0.731	0.824
6	0.953	0.826	0.904
7	1.117	0.898	0.834
8	0.896	0.841	0.843
9	0.820	0.787	0.806
10	0.810	0.781	0.808
11	0.829	0.780	0.728
12	0.598	0.525	0.499
13	0.606	0.561	0.570
14	0.577	0.596	0.532
15	0.513	0.508	0.502
16	0.436	0.487	0.393
17	0.454	0.444	0.435
av.	0.777	0.735	0.721

TABLE II
VARIABLES a OF FAST, TYPICAL AND SLOW CONDITIONS, CHIP B, $V_{dd} = 1.8$V, $T = 25°$C.

#	Fast	Typ.	Slow
0	1.580	1.536	1.520
1	1.505	1.453	1.497
2	1.658	1.582	1.446
3	1.261	1.408	1.348
4	1.340	1.294	1.313
5	1.378	1.231	1.275
6	1.428	1.434	1.481
7	1.474	1.549	1.425
8	1.473	1.448	1.557
9	1.261	1.349	1.299
10	1.344	1.362	1.272
11	1.282	1.408	1.343
12	0.837	0.995	0.948
13	0.886	0.865	0.896
14	0.900	0.932	0.816
15	0.895	0.852	0.789
16	0.934	0.738	0.879
17	0.734	0.781	0.778
av.	1.232	1.234	1.216