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An Efficient Process-Evaluation Method for Ultra-Thin Gate Oxides

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Abstract

A novel conversion scheme is proposed to correlate Q_{BD} measured from exponential current ramp stress (ECRS) and constant current stress (CCS), providing a fast evaluation method to monitor oxide performance toward continuous process improvement for ultra-thin as well as thin oxides.

Introduction

Thin dielectrics such as SiO_2 have been a major concern throughout the history of MOS integrated circuits [1-3]. Namely, the quality of gate oxide is of great importance, which is particularly true when oxide thickness is continually reduced or more stringent customer requirement is demanded. It is, therefore, essential to monitor oxide performance in production to provide early warning of reliability excursions and measures toward continuous process improvement.

It's widely accepted that highly accelerated measurement of Q_{BD} can be used as a process monitor/control parameter [2, 4]. Traditionally, Q_{BD} is determined through CCS because it simply equals to the product of current density (J) and time-to-breakdown (t_{BD}). However, the measurement associated with CCS is time consuming and thus limits quick monitoring and improvement of gate oxide quality.

On the other hand, ECRS provides a rather quick way in measuring Q_{BD}. Thus, for production monitoring, ECRS has a significant speed advantage over CCS. Accordingly, ECRS should replace CCS in industry for fast oxide evaluation provided that it can well correlate with CCS [4]. Different methods have been proposed for the correlation of Q_{BD} [5-6]. This paper further reveals a novel (but rather simple) conversion method to correlate Q_{BD} of ECRS and CCS.

Physical Model

A. Oxide Breakdown Process

The correlation of Q_{BD} between ECRS and CCS is based on the impact ionization process. Electron injection from cathode results in some injected electrons gaining sufficient energy to cause impact ionization and create e-h pairs. Some of the holes can be trapped in the oxide, and the oxide breaks down when hole trapping reaches a critical value Qp.

B. Q_{BD} Obtained through ECRS

The Q_{BD} under ECRS is obtained by adding all the charge fluence of each individual step of the ramp and can be approximately expressed as: $Q_{BD}=[10^{1/s}/(10^{1/s}-1)]\, J_{BD}\, t_d \equiv r_o J_{BD}\, t_d$, where s is the step numbers per decade of J, J_{BD} is the current density of last step, and t_d is the holding time of each step.

Qp can be expressed as: $Qp=\alpha r_o J_{BD}\, t_d\, \eta$, where η is the trapping coefficient, while the impact ionization coefficient depends on electric field E and is written as: $\alpha = \alpha_o \exp(-H/E)$. Moreover, J_{BD} also depends on E and can be written as: $J_{BD} = A_t \exp(-B/E)$, where A_t is a general form for FN and direct tunneling. The field dependence of α_o and A_t is relatively weak compared to the exponential term, thus neglected.

After equation manipulation, a concise form for Q_{BD} is:

$$Q_{BD} = A_{ECR}\,(t_d)^n, \qquad (1)$$

where $A_{ECR} = (Qp/\eta\alpha_o)^{1/(1+m)}(r_o\, A_t)^n$ with m = H/B and n ≡ m/(1+m). Eq. (1) indicates that Q_{BD} at a specific CDF has a power-law dependence of t_d with power index n.

Fig. 1 shows the experimental results of Q_{BD} (median point) versus t_d under ECRS for oxide thickness varying from 35 Å to 135 Å, in which the power-law dependence between Q_{BD} and t_d is explained by Eq. (1).

C. Q_{BD} Obtained through CCS

The Q_{BD} under CCS is: $Q_{BD} = J\, t_{BD}$, where J, similar to the case of ECRS, also depends on electric field and thus has the same form. By the same algebra as used for ECRS, a concise form for Q_{BD} can be easily obtained as:

$$Q_{BD}=A_{CCS}(J)^{-m}, \qquad (2)$$

where $A_{CCS}=(Qp/\eta\alpha_o)(A_t)^m$. Similar to ECRS, Eq. (2) implies a power-law dependence between Q_{BD} and J.

The power-law relationship between Q_{BD} (at a specific CDF) and J derived in Eq. (2) is confirmed by Fig. 2.

D. Correlation of Q_{BD} between ECRS and CCS

From Eqs. (1) and (2), A_{CCS} can be related to A_{ECR} as:

$$A_{CCS}=(r_o)^{-m}\,(A_{ECR})^{m+1}. \qquad (3)$$

Eqs. (1) ~ (3) form a simple conversion method of Q_{BD} between ECRS and CCS.

E. Model Verification

A comprehensive experiment for tox from 35 to 135 Å was conducted. The results are summarized in Table I where the units are based on A/cm^2 (J), sec (t_d), and C/cm^2 (Q_{BD}).

Data in columns 3~6 of Table I (i.e. n, A_{ECR}, m, & A_{CCS}) were directly obtained from ECRS and CCS measurements, while data in column 7 were the values of A_{CCS} converted from ECRS using the proposed method. Moreover, the CCS Q_{BD} (@J_{SPEC} = 0.1A/cm^2) both obtained directly from CCS and converted from ECRS are listed in columns 8 and 9, respectively. Comparing columns 6 & 7 or 8 & 9, we can conclude that an excellent agreement is reached between the proposed method and data from measurements made within a large range of oxide thickness from 35 Å to 135 Å.

Methodology

The methodology for efficiently evaluating oxide performance is schematically illustrated by Fig. 3. The ECRS is first performed using a small value of t_d since it takes a much shorter time than the CCS. Next, convert the ECRS Q_{BD} data into CCS Q_{BD} at specified stress condition (say, J_{SPEC}). The converted CCS Q_{BD} can then be compared to industrial specifications that are usually specified by CCS test.

References

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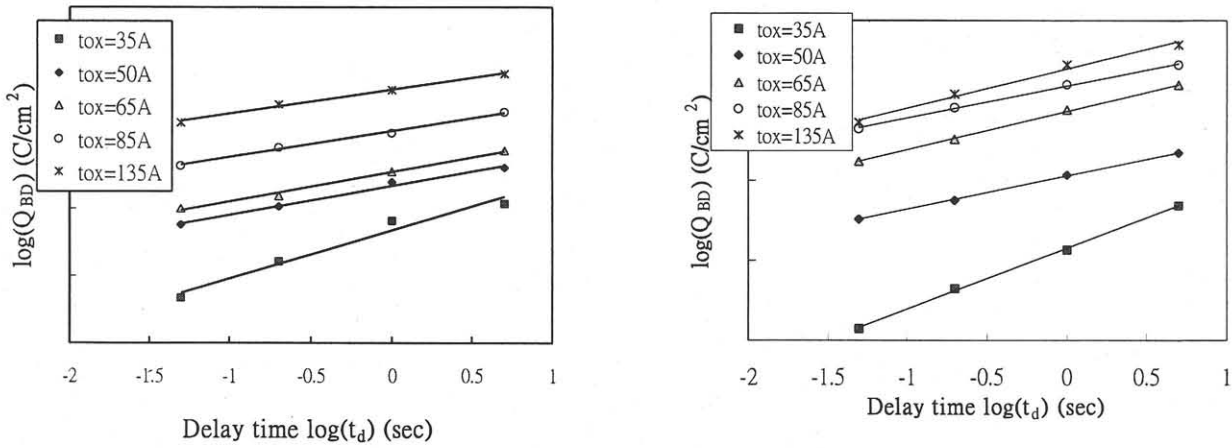

Fig. 1. Q_{BD} (median point) vs. t_d under ECRS for five different oxide thickness with (a) positive and (b) negative gate injections.

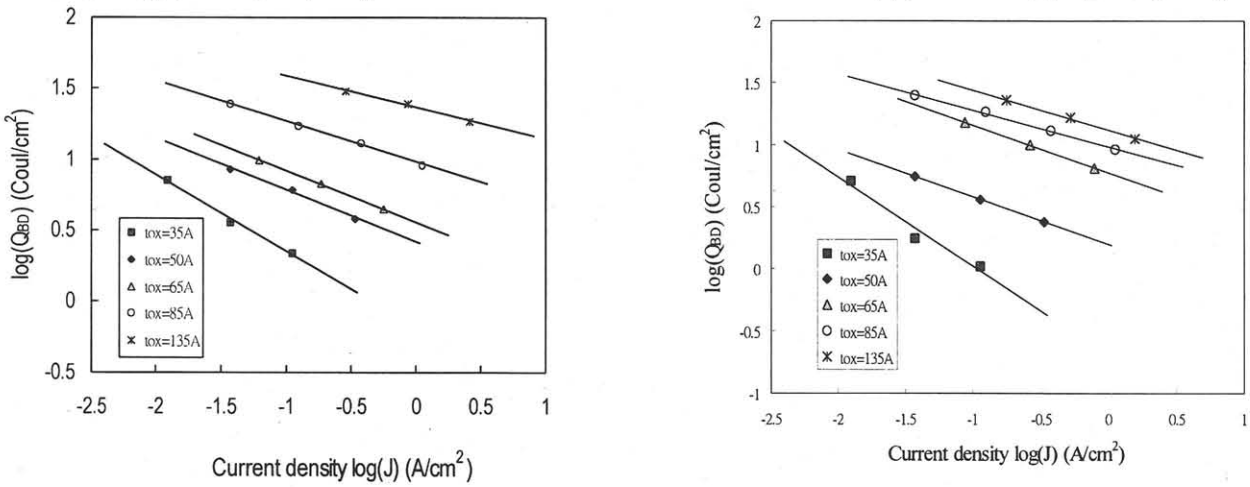

Fig. 2. Q_{BD} (median point) vs. J under CCS for five different oxide thickness with (a) positive and (b) negative gate injections.

TABLE I: SUMMARY OF PARAMETERS FOR ECRS AND CCS

	tox (nm)	n	A_{ECR}	m	A_{CCS}	A_{CCS} converted from ECRS	Q_{BD} obtained from CCS	Q_{BD} obtained from ECRS
Positive gate injection	**3.5**	0.36	1.80	0.54	*0.65*	*0.66*	**2.25**	**2.29**
	5.0	0.22	3.86	0.37	*2.60*	*2.59*	**6.09**	**6.07**
	6.5	0.22	4.90	0.36	*3.60*	*3.62*	**8.25**	**8.29**
	8.5	0.20	9.95	0.28	*9.60*	*9.59*	**18.29**	**18.27**
	13.5	0.18	20.19	0.22	*23.17*	*22.91*	**38.45**	**38.02**
Negative gate injection	**3.5**	0.38	0.98	0.72	*0.19*	*0.17*	**0.99**	**0.89**
	5.0	0.21	2.75	0.38	*1.59*	*1.60*	**3.81**	**3.84**
	6.5	0.24	6.93	0.37	*5.95*	*5.77*	**13.95**	**13.53**
	8.5	0.21	10.10	0.29	*9.67*	*9.76*	**18.85**	**19.03**
	13.5	0.24	12.88	0.32	*13.14*	*13.41*	**27.45**	**28.02**

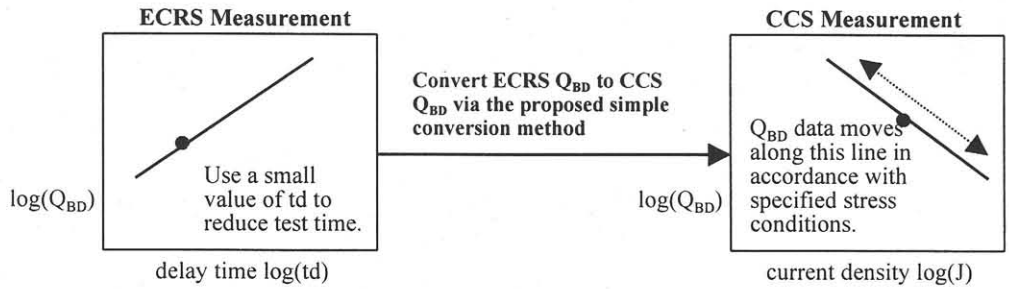

Fig. 3. Diagram illustrating the methodology for an efficient process evaluation of gate oxide.