Restoration of Post-Breakdown Gate Oxide by White-Light Illumination

T. Kawashima, K. S. Yew, Y. Zhou, D. S. Ang, M. K. Bera, and H. Z. Zhang

***Abstract*—From conductive-atomic-force-microscope probe measurement, we show that electrical conduction through a nanoscale percolation path in the MOSFET gate oxide can be disrupted, either completely or partially, by white-light illumination. This phenomenon is consistently observed in the SiO_2 and HfO_2 gate oxide materials, and thus is believed to have originated from a common mechanism – light-stimulated oxygen migration and recombination with vacancy sites that constitute the percolation path. The finding points to the prospect of reliability rejuvenation by light-assisted restoration of post-electrical-breakdown gate oxides, as well as light-enabled memory operation based on logic MOSFET devices.**

***Index Terms*—CMOS memory, gate oxide breakdown, high-kappa gate oxide, time dependent dielectric breakdown.**

I. INTRODUCTION

ELECTRICAL-STRESS-INDUCED breakdown of the SiO_2 gate oxide is a serious reliability issue that has received widespread attention for many years [1]. Studies have shown that gate-oxide breakdown can be broadly classified as soft or hard [2]. Ultra-thin gate oxides (< 5 nm) typically exhibit the former. As soft breakdown (SBD) typically does not lead to a total loss of transistor functionality, there has been much interest on the breakdown mechanism and its evolution towards eventual hard breakdown. With HfO_2 replacing SiO_2 as the gate oxide, recent attention was mostly centered on the reliability of the metal/HfO_2 gate stack [3]. It has been found that SBD of HfO_2 can be electrically reversed with a greater ease as compared to SiO_2 [4], [5], prompting considerable interest on the recovery mechanism as well as the role of the metal electrode [6]. In the paper, we report, *for the first time*, that a nanoscale percolation path in SiO_2 and HfO_2 can be disrupted upon exposure to white light. The disruption is either complete or partial, depending on the resistance of the percolation path determined at the point of breakdown, i.e. the breakdown hardness. Possible mechanisms and implications of the finding are discussed.

II. EXPERIMENTAL DETAILS

Localized breakdown of SiO_2 or HfO_2 film formed on a p-Si substrate was achieved using a diamond-coated Si probe in an RHK 3500 ultra-high vacuum ($\sim 5 \times 10^{-10}$ Torr) conductive atomic force microscope (C-AFM). The contact area between the C-AFM probe and oxide is estimated to be 25.5 nm^2, based on an applied force of 28 nN and the properties of the diamond-coated Si probe [7]. The SiO_2 film is 5-nm thick, formed by a standard plasma-enhanced chemical vapor deposition process with SiH_4 and N_2O. The HfO_2 film was achieved by atomic layer deposition involving Tetrakis (dimethlyamino) hafnium and water vapor and has a 4-nm thickness. The C-AFM probe was connected to a Keithley SCS4200 parameter analyzer and the substrate was grounded. Breakdown stressing, with a constant voltage at the probe, was applied and interrupted when the current exceeded a preset compliance limit. A LED lamp, positioned at a quartz window of the C-AFM system, functioned as a white-light source. The light intensity at the sample surface was 1 mW/cm^2, estimated based on the separation between the sample and light source, using a Daystar DS-05A solar meter. The entire experiment was carried out at 297 K. Negligible light-induced heating was confirmed by periodic measurement of the sample temperature using an infrared thermometer. As SBD exhibits initial relaxation after stress interruption, light exposure was carried out only after a 45-minute wait period. Probe stability was verified by monitoring the breakdown current for extended period (> 8 hours).

III. RESULTS AND DISCUSSION

Fig. 1 depicts a typical set of results for the SiO_2 film. The experimental sequence is shown in Fig. 1(a) and the time-dependent evolution of the current under constant-voltage stressing in Fig. 1(b). The current compliance limit in this case was set at 0.5 nA. After an initial stress period where the current remained unchanged, a gradual increase of the current towards the compliance limit could be observed, signaling the onset of progressive SBD [8]. Clearly, the post-SBD *I-V* curve is significantly shifted towards the low-voltage regime. Interestingly, a shift towards the pre-stress curve is evident after a 10-minute light exposure. Upon a further 15-minute exposure, the *I-V* curve now almost coincides with the pre-stress curve (Fig. 1(c)), indicating that the insulating property

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T. Kawashima, K. S. Yew, Y. Zhou, D. S. Ang$^+$, M. K. Bera and H. Z. Zhang are with the Nanyang Technological University, School of Electrical and Electronic Engineering, Block S2, Nanyang Avenue, Singapore 639798 (E-mail$^+$: edsang@ntu.edu.sg).

T. Kawashima is also with Toshiba Corporation, 33, Shin-Isogo-Cho, Isogo-ku, Yokohama 235-0017, Japan.

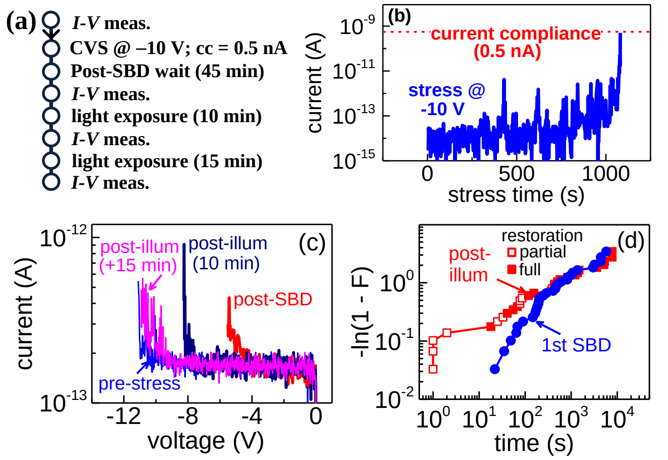

Fig. 1. (a) Sequence of experimental steps; (b) Evolution of current during constant negative-voltage stress, where the onset of progressive soft breakdown (SBD) is evident after ~800 s. Stressing was arrested when the current compliance (cc) limit of 0.5 nA was reached. (c) Current-voltage (*I-V*) characteristics, showing a near-complete restoration of post-SBD *I-V* curve to the pre-stress state after white-light illumination (d) Weibull distributions for the time of first SBD and of subsequent SBD during re-stressing of the same location after white-light-induced restoration.

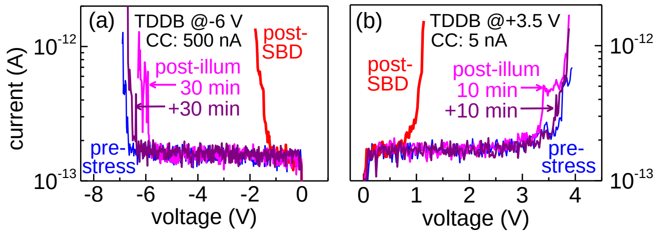

Fig. 2. White-light illumination can also restore the insulating property of the HfO_2 gate dielectric after it has suffered soft breakdown under (a) positive and (b) negative constant-voltage stressing.

of the breakdown spot has been restored. To probe the quality of the restored oxide, re-stressing was performed at the same voltage. The distribution of breakdown time is compared to that of the first SBD for 30 different locations (Fig. 1(d)). Due to material and breakdown variations, not all locations exhibit full restoration under a fixed illumination. While partially restored sites exhibit early failures when re-stressed at the same voltage, the distribution of fully restored sites clearly merges with that of the first SBD, showing that white-light had restored these sites almost to their original states. A similar restoration of SBD is obtained for positive-voltage-stress-induced SBD (not shown), as well as on the HfO_2 sample for negative- (Fig. 2(a)) and positive-stress-induced SBD (Fig. 2(b)). The similar response of post-SBD HfO_2 to white-light exposure implies a common restoration mechanism.

As reported in some studies (e.g. [9]), a decrease of stress-induced leakage current (SILC) can occur under an opposite-voltage sweep due to emission of charges from oxide traps. To determine if the recovery observed in Fig. 1 was due to trapped-charge emission, constant-voltage stressing was reapplied to the location studied in Fig. 1. Post-breakdown *I-V* measurement using an opposite positive-voltage sweep, however, did not yield any apparent recovery of the *I-V* curve (Fig. 3(a)). Extending the positive-voltage sweep range resulted in a harder breakdown, as can be seen from a further shift of the *I-V* curve towards lower voltages. But following a 30-minute light exposure, the *I-V* curve is restored to almost the pre-stress state. This result shows that the possible role of trapped-charge emission behind the observed white-light-induced breakdown recovery may be ruled out.

The impact of breakdown hardness on white-light-induced restoration was also studied. Harder breakdown was induced by increasing the current compliance limit during stressing. As can be seen from Fig. 3(b), for breakdown induced at a higher current compliance limit, white-light illumination remains effective in restoring breakdown, but only partial restoration can be achieved for the same exposure period.

Physical analysis of the breakdown location in SiO_2 by high-resolution electron-energy-loss spectroscopy [10] has revealed an increasing proportion of Si oxidation states having values lesser than +4 when the current compliance limit is raised. In addition, a lateral growth of the oxide region having lower Si oxidation state values is correspondingly observed. These observations imply that more O is depleted from the stressing location when the stress is interrupted at a higher compliance limit, due to greater O migration by increased Joule heating. Based on this oxide breakdown framework, we propose a possible explanation (Fig. 4) for the light-induced breakdown-restoration observed in Figs. 1-3. Although a directed motion of O, released from oxide-field-induced bond dissociation, towards the anode occurs during breakdown transient, the stochastic nature of ion transport, exacerbated by Joule heating (estimated to produce a substantial local temperature increase [11]), results in lateral propagation and some O populating interstitial sites in the vicinity of the percolation path when the breakdown is arrested [12]. Migration of the interstitial O back to the vacancy-rich percolation path entails the overcoming of an energy barrier (~0.3-0.6 eV) [13] and thus does not readily occur in the absence of an external excitation. Under illumination by white light (with energies ranging from 1.8-3 eV), photon absorption electronically excites the interstitial O, thus decreasing their migration barriers [14]. Aided by the vacancy-interstitial dipole field [15], the excited interstitial O may then be able to migrate towards the vacancy sites in the percolation path. Subsequent recombination with the vacancies there eliminates the percolation path and restores the insulating property of the oxide. Compared to the larger bandgap energy of SiO_2 or HfO_2, the relatively low photon energies of white light are insufficient to “dislodge” lattice O and thus would not cause harder breakdown. At a higher current compliance limit, increased Joule heating enhances the lateral propagation of O ions, thus decreasing the portion of ions populating interstitial sites in the proximity of the percolation path when stress is terminated. As a consequence, only a limited number of the photon-excited interstitial O can migrate back to the percolation path, resulting in only a partial restoration (Fig. 3(b)). Stochastic transport would restrict interstitial O located further away from returning to the percolation path.

The lack of breakdown-oxide restoration under restricted positive-voltage sweep (Fig. 3(a); “after pos-sweep 1” curve) should be further addressed. Electrically induced breakdown

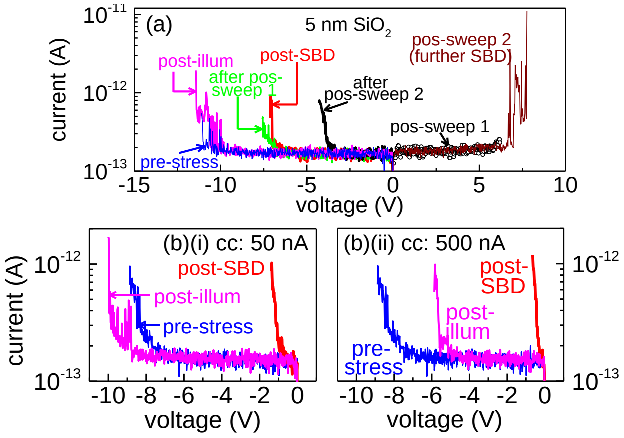

Fig. 3. (a) Positive-voltage sweep (after soft breakdown (SBD) by negative constant-voltage stressing) yielded no substantial recovery (after pos-sweep 1) but a further SBD when the voltage-sweep range was extended (pos-sweep 2; after pos-sweep 2). Nearly full restoration was achieved by a 30-minute white-light exposure after the second positive-sweep-induced SBD (post-illum). (b)(i) Complete restoration of SBD at a low breakdown-current compliance (cc); (ii) partial restoration for higher cc.

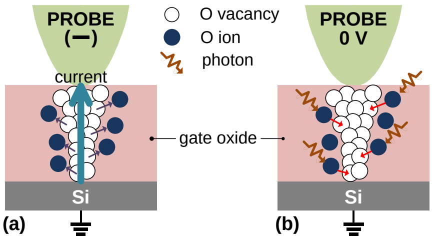

Fig. 4. (a) Joule-heating-induced migration of oxygen (O) ions away from the percolation path at the instant of soft breakdown. When the electrical stress is arrested quickly, a portion of the released O may populate interstitial sites in the proximity of the percolation path. (b) Photon-induced excitation of interstitial O and their migration back to vacancies sites in the percolation path, aided by vacancy-interstitial dipole field.

recovery has been found to exhibit electrode dependence [6]. It is believed that the metal(anode)/oxide interface region, adjacent to the percolation path, acts as a "storage" place for O released during breakdown. These O could then drift back to the percolation path under an opposite-polarity voltage sweep. The possibility of the Si anode "immobilizing" the O, through Si-O bond formation, during negative probe-voltage induced breakdown may explain the lack of recovery during the post-breakdown positive probe-voltage-sweep. A similar absence of recovery during a negative probe-voltage-sweep is also observed for breakdown induced by a positive probe-voltage (not shown), and may be ascribed to the escape of O from the uncapped oxide. On the other hand, it is intriguing that near-complete restoration can be achieved by white-light illumination, regardless of the breakdown-voltage polarity. This may imply the concurrent role of other mechanisms and/or defect-passivating agents (e.g. hydrogen [16]), which require further investigation.

IV. SUMMARY

It is shown for the first time that the insulating property of post-electrical-breakdown SiO_2 and HfO_2 may be restored via exposure to white light. A possible explanation, involving the migration of photon-excited interstitial O from the percolation-path vicinity and subsequent recombination with the vacancy sites, is proposed. The finding provides an opportunity, via integration of III-V light-emitting devices, for rejuvenating SBD gate oxides for reliability extension, and realizing memory operation of a MOSFET device (with oxide SBD to achieve a high-current state and light-induced reset to a low-current state) for compact logic-memory integration.

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