V-Ramp test and gate oxide screening under the "lucky" defect model

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Abstract: The persistent (after exhaustive wafer cleaning) extrinsic breakdown distribution of thick gate oxides requires an early breakdown mechanism that goes beyond the popular local thinning model to explain. The success of the 'Lucky" defect model in fulfilling this role deserves a further exploration of its implications. This work examines the implications of using the V-Ramp and the high-voltage screening methods to identify early failures. In this study, it is shown that the V-Ramp method fails to produce useful information about the oxide quality at operation voltages and that the high-field screening method fails to screen out early failures.

To ensure the reliability of power MOSFETs and to minimize early failures, the quality of the gate oxide is closely monitored during development. Time-dependent-dielectric-breakdown (TDDB) is a standard method for monitoring gate oxide quality. Fig.1 shows a typical SiO_2/SiC TDDB distribution. Similar distributions containing a long tail of extrinsic failures are often found in the literature for thick gate oxides [1-3].

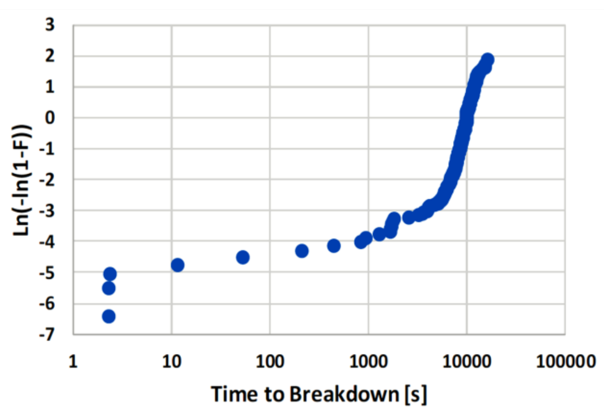

Fig. 1 Weibull distribution of Time-Dependent-Dielectric-Breakdown (TDDB) test for 50 nm thick SiO_2 on SiC substrate. Extensive extrinsic failures are present even after exhaustive wafer cleaning improvements before oxide growth. (F is the failed fraction)

TDDB measurements involve a variety of accelerated stress fields and temperatures. To properly capture the extrinsic part of the breakdown distributions, each stress condition must have at least several hundred devices. Such tests are very time consuming and expensive. As a result, rapid tests such as voltage ramp (V-ramp) are often used instead [4-9].

The persistent extrinsic breakdown means significant early failures may occur for products in the field. To minimize these early failures, high-voltage screening is commonly employed to screen out the weak parts [10-12].

The key assumption for both the V-Ramp method and high-voltage screening method is that the degradation mechanism remains the same regardless of the stress field [4-8, 10, 11] and that the degradation is accumulative and additive. For intrinsic breakdowns, little contradictory evidence exists to refute these assumptions. For extrinsic breakdowns, these assumptions may or may not be satisfied. While extrinsic breakdowns are universally attributed to defects, what these defects are and how they lead to extrinsic breakdown is not well established.

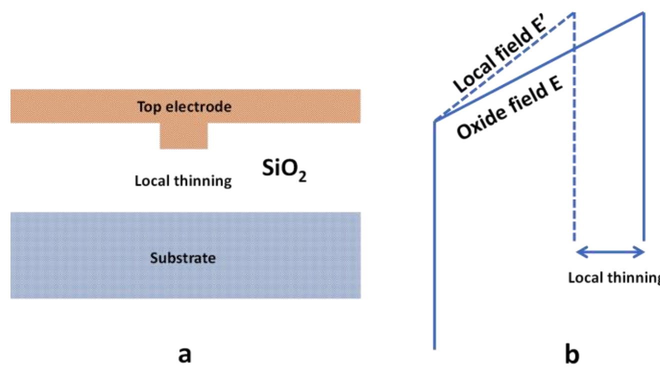

Fig. 2 a. Illustration of the local thinning model. The gate oxide growth is suppressed at the spots where particulate or contamination exist, leading to a physically thinner region, b. The band diagram of the gate oxide under electrical stress field *E* showing the field at the local thinning spot, *E'* is higher than the rest of the device.

The local thinning model [13, 14] posits that defects are caused by particulates and/or contaminants, leading to a local reduction of oxide thickness. Fig. 2a illustrates the local thinning model and fig. 2b shows the associated change in electric field (E) at the local thinning spot. The higher field at the thin spot accelerates breakdown locally. For thicker oxides with weak area scaling (area-dependent breakdown lifetime), the result is early breakdown (extrinsic failure) for a given stress voltage.

Fig 2b suggests that while the local thin spot has higher field, the degradation mechanism remains the same (E or $1/E$ dependent) as the rest of the device. Thus, if the early failures are all due to local thinning, the V-Ramp method and high-field screening are justified. However, in production technologies, extensive effort has been made to minimize extrinsic failures through cleaning improvements. Considering the considerable cleaning effort, it is difficult to link the remaining persistent extrinsic failures to local thinning due to particulates or contaminants. Using breakdown data with impressive statistics, Degraeve et al. showed that the local thinning model cannot explain the extrinsic failures [15]. The cleanliness independent persistent extrinsic failures [16] suggests the presence of a different failure mechanism [17]. In addition, the expected breakdown distribution from the local thinning model is bimodal because the effect of thinning on lifetime is dramatic, not the continuous distribution observed [1-3, 15, 16].

A "lucky" defect model was introduced more recently [18] and further refined [17] to explain the persistent extrinsic failures. In essence, point defects in the oxide film with the appropriate energy level and spatial location can lead to drastically shorter breakdown lifetime, or extrinsic failures. Unlike the local thinning model, the defect increases local current without a locally enhanced electric field.

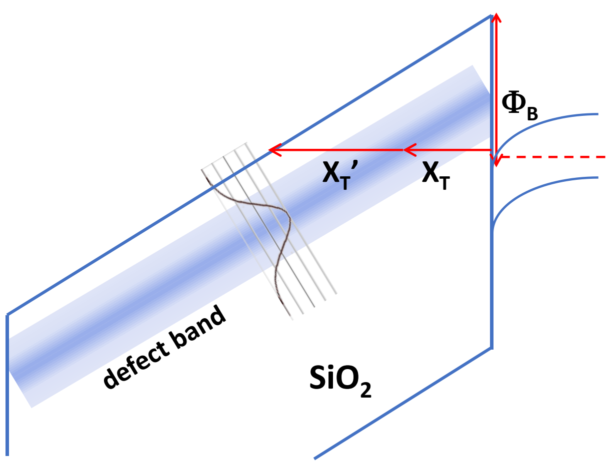

Fig. 3 The band diagram of the "lucky" defect model for extrinsic breakdown. The defect band is assumed to be uniform throughout the thickness of the SiO_2 layer. X_T is the location of the "lucky" defect that produce the highest trap-assisted-tunneling (TAT). X_T' is the distance of tunneling for the second step of the TAT. Φ_B is the conduction band offset between substrate and SiO_2. Broken line is the substrate Fermi level.

Fig. 3 shows the band diagram of the "lucky" defect model. Defects at energy 1.5 ± 0.3 eV above the electron injection energy level are found to drastically enhance Trap-Assisted-Tunneling (TAT) if they are at the right distance from the SiO_2 substrate interface [17]. With the higher current, the time to reach the critical-charge-to-breakdown (Q_{BD}) is drastically shorten for the local area, leading to extrinsic failure. This model successfully produced the observed breakdown distributions [1-3, 15, 16]. An example is shown in fig. 4 using the defect distribution of fig. 3 with a notably modest defect density of 1 x 10^8/cm^3. Note the similarity between fig. 4 and fig. 1.

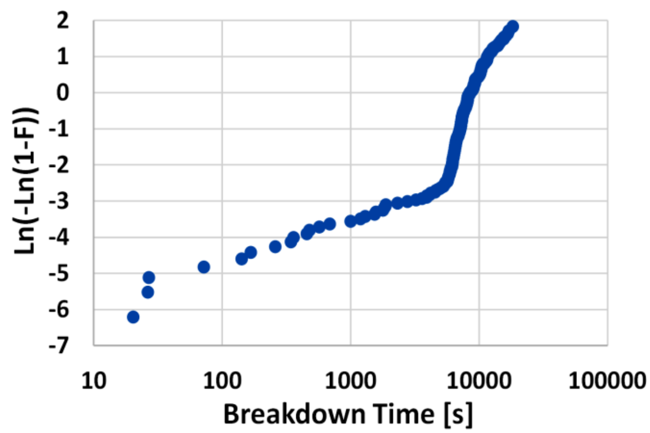

Fig. 4 Simulated breakdown distribution using the band diagram of fig. 3. The defect density was 1 x 10^8/cm^3. The oxide was 50 nm thick. The substrate was silicon. The starting (defect-free) distribution has a characteristic breakdown down time of 1 x 10^5 seconds and a Weibull slope of 40.

As the defect must have both the appropriate energy level and the appropriate spatial location to be 'Lucky", different set of defects are responsible for the life-shortening effect under different stress field. Thus, the assumption of an invariant degradation mechanism is no longer true. As will be shown, the assumption that degradations are accumulative, and additive also fails.

To get a microscopic understanding of why V-Ramp and high-voltage screening won't work when extrinsic failures are due to "lucky" defects, we examine these processes more closely.

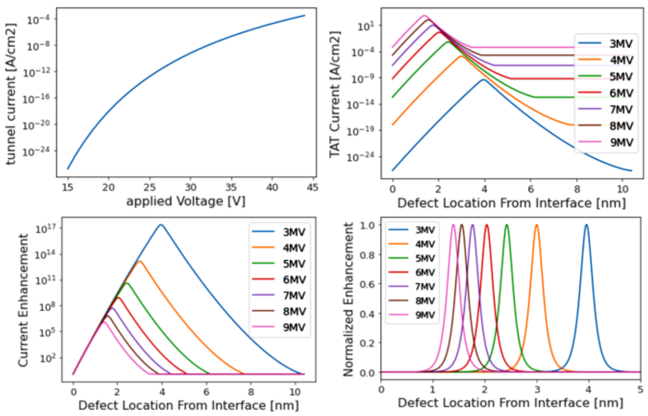

Fig. 5 a. Fowler-Nordheim (FN) tunneling current density as a function of applied voltage for a 50 nm thick oxide film, b. the calculated trap-assisted-tunneling (TAT) current density as a function of defect location for defects that matches the injection energy level for various stress fields, c. the current enhancement factor which is the TAT current normalized to the FN current, d. the peaky behavior of the enhancement factor as a function of defect location.

Fig. 5b shows the TAT current for a 50 nm thick gate oxide in a SiO_2/Si system under substrate injection conditions as a function of defect location (X_T) for different electric fields. As is well-known, the TAT current for any given stress field is strongly defect location dependent. The peak TAT current is higher for higher stress field. This may seem counter to the familiar knowledge that TAT is much more noticeable at lower stress field. This observation is because TAT is normally observed as a current increase from the pure Fowler-Nordheim (FN) level (fig. 5a). To make it clearer, the TAT current is normalized to the FN current to produce the current enhancement (fig. 5c). The enhancement at low field is indeed dramatically greater than at higher fields. To highlight the defect location sensitivity of TAT, the results in fig. 5c are replotted on a linear scale after normalizing the peak of each trace to the value of 1 (fig. 5d).

Let us first examine high-field screening. Fig. 6 shows the TAT band diagram for screening and operating conditions. Screening chooses the highest stress field (fig 6, left) to weed out the weak devices without harming the good devices. In the local thinning model, the defect associated with the weak devices is the same at both high and low field and screening should work. In the "lucky" defect model, defects associated with weak devices at low field are not the same defects associated with weak devices at high field. Screening removes devices with defects at spatial locations that have no/limited roles at low field and therefore have no effect on the extrinsic population at low field (fig. 6, right).

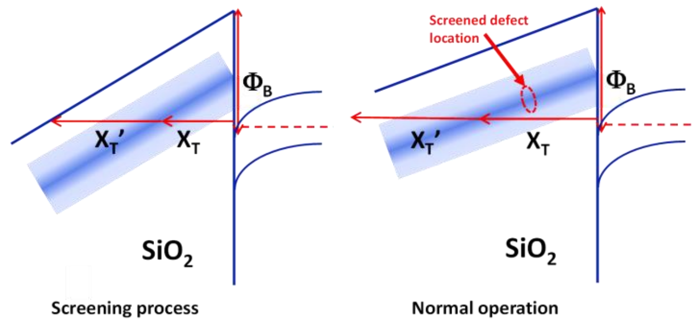

Fig. 6 Left panel: High-field screening applies a stress field that is high but not high enough to cause degradation. Under this condition, weak devices are those having 'lucky' defects at a location associated with that particular field. Right panel: under normal operation, the field is much lower and the defects that can cause early failures are at a location deeper into the oxide. The removal of weak devices at the screening field has no effect on the weak devices at the operating field. Thus, screening fails.

For a V-Ramp test, the voltage is ramped up from a low value to as high as it takes to break the device. The ramp rate is kept constant and relatively fast, so time spent at each stress field is short. However, in the 'lucky" defect model, each stress field has its own associated defects and therefore its own breakdown distribution (fig. 7). Here the lifetime has been assumed to be inversely proportional to tunneling current (an oversimplification). A short stress at low field would have almost no effect in changing the low field distribution. As the stress field increases, a different distribution is impacted because different defect locations will enable the TAT. Eventually, at very high stress fields, the short dwell time can break all devices. The "degradation" at each stress field has almost no relationship with the distributions at adjacent fields except at very high fields where overlapping defect locations occur (fig. 5d). So, at very high fields, some degree of accumulative and additive degradation can be claimed. At lower fields, this assumption is invalid. From the goal of monitoring extrinsic failures at the operation fields, V-Ramp fails.

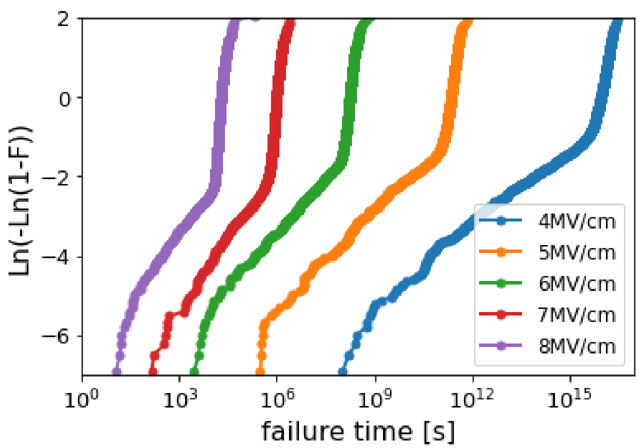

Fig. 7 Simulated breakdown distributions for different stress field. The parameters are the same as in fig. 4. The lifetime is assumed to be inversely proportional to current. Lower field has lower current and therefore longer characteristic lifetime.

In summary, extrinsic failures due to local thinning can be effectively monitored by V-Ramp tests and screened by high-voltages. However, both methods will be ineffective for extrinsic failures due to "lucky" defects.

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