COSMIC RAY INDUCED FAILURES IN HIGH POWER SEMICONDUCTOR DEVICES

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Abstract: We present a general model for cosmic ray induced failures in high voltage devices. The only relevant model assumption is that the local probability depends only on the local electrical field. This model leads to a universal master curve for the failure rates of GTO's, thyristors and diodes. The IGBT is more complex because of the complex field distribution. The predicted and observed failure rates in IGBT's are higher than in GTO devices with comparable axial designs. By comparison with burst charge data on DRAM's we show that for field above 120 kV/cm the failure rate is controlled by neutron induced Si recoils, at smaller field by muon - Si processes.

1. INTRODUCTION

After the surprising announcements [1 - 3] that cosmic rays can induce substantial failure rates in high power devices such as thyristors, GTO's and diodes, the semiconductor industry has reacted. Today the design rules to design GTO's, diodes and thyristors which are robust against this failure mode for a defined operating condition are known and all major manufacturers offer devices which can be safely operated under standard conditions. However, some manufacturers use incorrect extrapolation schemes which could lead to erroneous conclusions for the failure rate under special conditions and for special device designs. Initially it was believed that high voltage IGBT's would behave similar as GTO's and diodes and that n-base resistivities and thicknesses which lead to robust GTO's would also lead to robust IGBT's under the same operating conditions. Reality seems to be more complex.

2. MODELING COSMIC RAY INDUCED FAILURES

Numerous studies [4,5] of failures or soft errors induced by energetic particles in DRAM's give a relatively clear picture:

Energetic particles interact in two basically different ways with silicon. Charged, light particles such as electrons and muons lead to a fairly delocalized ionization wake along the particle trajectory. Heavy particles such as Si lead to localized bursts of charge. Only such bursts can cause catastrophic failures in high voltage devices. The main cause for bursts are Si recoil nuclei resulting from interactions with cosmic neutrons or other particles.

As an introduction we perform a few order of magnitude estimates to check the consistency or nonconsistency of classes of models. We first introduce a characteristic length L_c. L_c characterizes the dimension of the charge cloud induced by an energetic particle. The second and third important parameters are Q_c and E_c, where Ec is the field required to reach an ionization integral = 1 over a distance L and Q_c is the charge required to produce the field E_c.. From DRAM studies we know that cosmic neutrons can release charges of the order 10 - 1000 fClb over characteristic distances of a few μm by creating Si recoil nuclei.

Under operating field conditions the maximum admissible DC field in a high power device is ≤ 100 kV/cm [6]. Under test conditions it may be up to 150 kV/cm. This is far below the avalanche breakdown field. To produce an ionization integral of one in a distance L (assumed to be 1 μm) requires a field E_c = 365 kV/cm. The point charge Q_c to produce this field at a distance L in silicon is 50 fClb or 300'000 e-h pairs. This shows that only Si recoils come close to produce enough e-h pairs over a distance L.

Under the action of the external field the charge in the e-h plasma will separate along the field axis. This generates a dipole field which lowers the axial field inside the dipole but creates field maxima at the poles. If the field enhancement at one of the poles is sufficiently strong, then impact ionization sets in and a transition into a self-supporting filamentary discharge occurs. We abstain from modeling this part of the process and continue with order of magnitude estimates.

The electrical dipole charge in a fully depolarized filament (zero internal field) of length L and radius R in a field E is approximately (for L >> R)

$$\begin{aligned} Q_{fil} &= \pi \cdot \varepsilon \cdot \varepsilon_0 \cdot E \cdot \frac{L^2}{4 \cdot Log} \cdot \left(1 + \frac{1}{Log}\right) \\ Log &= \ln\left(\frac{L}{R}\right) - 1 \end{aligned} \tag{1}$$

For E = 100 kV/cm, L = 0.3mm and R = 1 μm we obtain Q_{fil} = 20 pClb. This is very small compared to the stored capacitive charge in the device which is of order of 100 nClb/cm^2 for devices of 1 cm^2 or more area. If we set the energy required to heat up a filament of radius R and length L = 0.5 mm to the melting temperature equal to the stored capacitive energy of a 1 cm^2 device at 1000 V, then we find R = 3 μm. This is the order of magnitude of the observed damage structures in failed devices. Two conclusions can be drawn from this:

1. The charge in the nascent breakdown filament is too small for destruction. Destruction requires subsequent charge injection from the cathode and/or anode emitters.
2. There is a minimum capacitive energy below which the filamentary discharge is fully reversible. This explains why this failure mode has never been observed in e.g. low voltage Zener diodes.

In diodes, GTO's and thyristors, the electrical field varies slowly on the length scale L. This allows to introduce the concept of a local failure probability $P_{loc}(E_{loc}, n_{flux})$. Eloc is the local electrical field, n_{flux} the flux of cosmic particles. If the particles are neutrons, then the flux will not depend on distance from the surface in the silicon and will only depend on shielding. In the following we will omit the parameter n_{flux} and assume that we have a constant neutron flux characteristic for sea level and moderate latitudes. The resulting total failure probability P_{tot} is obtained by integrating P_{loc} over the volume. The functional form of the local failure probability absorbs all difficulties in modeling the transition from a nuclear collision to a filamentary discharge. At this point we will not specify the functional form of P_{loc}. The total failure probability becomes:

$$P_{tot} = \int_{Vol} P_{loc}(E)dV \qquad (1)$$

In many devices (GTO's, thyristors, diodes) the field distribution in the n-base is to a good approximation trapezoidal. This approximation allows to write eq. (1) as:

$$Ptot = A \cdot \frac{dx}{dE} \cdot \int_0^{E_{\max}} P_{loc}(E) \cdot dE \qquad (2)$$

$$\frac{dE}{dx} = \frac{n \cdot e}{\varepsilon \cdot \varepsilon_0} \qquad (3)$$

where A is the device area, n is the n-base doping and ε the dielectric constant of silicon. By introducing

$$I_{master}(E_{\max}) = \int_0^{E_{\max}} P_{loc}(E) \cdot dE \qquad (4)$$

we obtain for a non-punchtrough (NPT) device

$$P_{tot}(V,n) = A \cdot \frac{\varepsilon \cdot \varepsilon_0}{n \cdot e} \cdot I_{master}(\sqrt{\frac{2 \cdot n \cdot V}{\varepsilon \cdot \varepsilon_0}}) \qquad (5)$$

A similar expression can be derived for a PT device. This means that the total failure probability is proportional to the area, inversely proportional to the n-base doping n and a function of the square root of the product $n*V$. Introducing the n-base resistivity ρ, we write eq. (5) as:

$$P_{tot}(S,\rho) = A \cdot \rho \cdot I(S) \qquad (6)$$

where S [6] is proportional to the maximum electrical field and is given by $S = \sqrt{\frac{V(Volt)}{\rho(\Omega cm)}}$ for a NPT element and $S = 0.2786 \cdot \frac{V(Volt)}{t(\mu m)} + 0.8972 \cdot \frac{t}{\rho(\Omega cm)}$ for PT elements. This means we have succeeded in deriving the scaling parameters for the failure rate without ever specifying the local failure probability. The universal failure integral I(S) [6] can be found experimentally by plotting $\frac{P_{\exp}}{A \cdot \rho}$ vs. the field parameter S.

Fig. 1 shows data for diodes, thyristors and GTO's in the voltage range 2000 - 9000 V, n-base resistivities from 100 Ohm cm to about 600 Ohmcm and four different manufacturers. No correlation between device type or manufacturer has been found. The rms deviation between the master curve and the individual points is about a factor of two. This may be due to statistical errors (time fluctuations of cosmic radiation, poor failure statistics), different radiation levels (different screening of radiation) and over-simplifications of the model (details of the field distribution close to the p-n junction).

The elements of Fig. 1 are all large GTO's, diodes and thyristors, having all qualitatively similar doping gradients in the vicinity of the p - n junction. The error introduced by the triangular field approximation is thus to some extent cancelled because it is commited in the forward direction when extracting the data and in the backward direction when predicting failure rates based on test data. This compensation effect is no longer applicable when applying the expressions to devices having abrupt juntions. Our expression may underestimate the failure rate in abrupt junction devices up to a factor of ten.

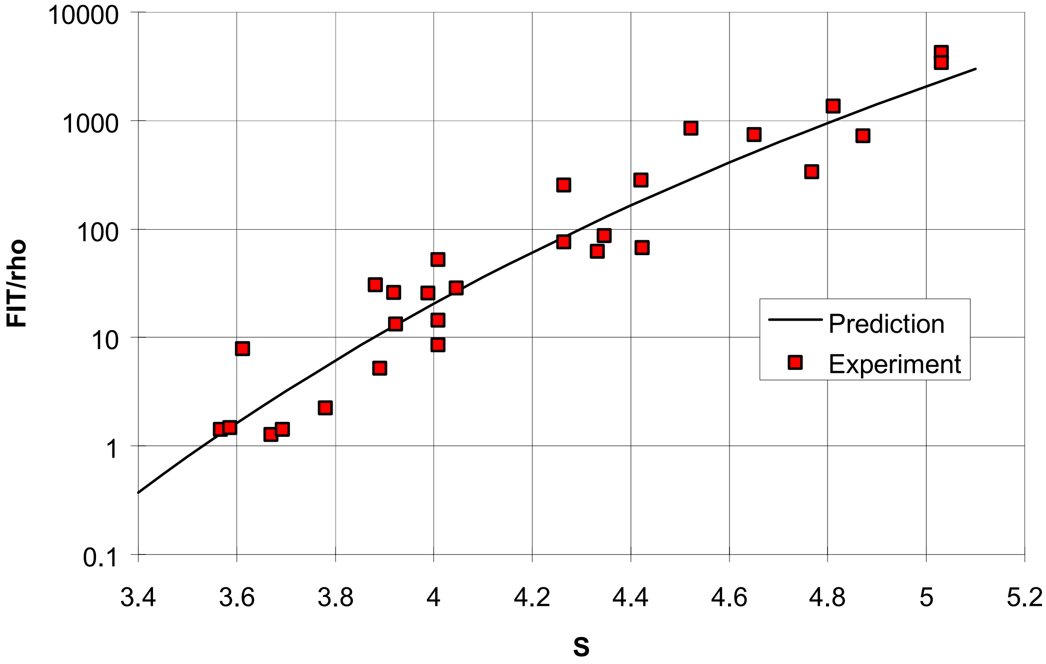

Figure 1 Plot of experimental FIT/cm^2 rates divided by n-base resistivity vs. maximum electrical field S (1 FIT = 1 failure per 10^9 element hours, ρ in Ωcm).

Experiments on cosmic ray induced failures are very time consuming and costly. Therefore there is a strong pressure to minimize the experimental effort to make realistic reliability predictions. Unfortunately the procedure has often been to study one device relatively carefully, to plot the data as log(FIT) vs. voltage and to assume that all other devices have parallel curves. It is then sufficient to measure one point for each additional device. We have shown here, that independent of the functional form of the failure probability, this procedure is incorrect and leads to dangerous conclusions. Our results show, that all data for all devices (with basically one-dimensional field distribution) fall on a master curve. This master curve is the basis for a correct extrapolation to field conditions and for deriving reliable design rules for devices.

Next we are going to discuss the local failure probability P_{loc}. Because the integral P_{tot} is basically exponential, we conclude that also the derivative P_{loc} is basically exponential. We thus write a trial function [3,6] which has to satisfy the following conditions: 1. "Exponential" field dependence, 2. Saturation at high fields (each collision leads to failure). Condition 1 requires an exponent and condition 2 requires that the field is in the denominator. We thus write P_{loc} as

$$P_{loc}(x) = \nu_0 \cdot \exp(-\frac{E_b}{E(x)}) \qquad (7)$$

Note that any coincidence with the functional form of the ionization rate is purely accidental. Fig. 1 shows a fit of $P_{loc}(x)$ to the experimental data resulting in the parameters $\nu_0 = 680\ \mathrm{cm}^{-3}\ \mathrm{sec}^{-1}$ and $E_b = 3.0$ MV/cm. When comparing this to burst events, then the value of ν_0 is too high to represent the total collision collision rate. This can be accounted for by introducing an additional parameter into the functional form of P_{loc}.

$$P1_{loc}(x) = \nu_0 \cdot \frac{1}{\alpha + \exp(\frac{E_b}{E(x)})}) \qquad (8)$$

For exp(-Eb/E) << α both forms are identical, but P1 saturates earlier than P. Saturation occurs at $E > E_b/\ln(\alpha)$. The probability for very small bursts is approx. $10^{-3}\ \mathrm{sec}^{-1}\mathrm{cm}^{-3}$. This translates into $\alpha = 7 \cdot 10^5$ and the field at which saturation is reached becomes 220 kV/cm. This makes sense, at this field even thermally generated carriers can cause breakdown. This agreement gives credibility to this parametrisation.

Parametrisations based on analogy with the ionisation integral [1,7] lead to unphysical slopes of the field dependence of the failure rate and to saturation values inconsistent with the probability of small bursts.

3. COMPARISON OF EXPERIMENTALLY DETERMINED FAILURE RATES AND BURST RATES

The basic idea of this section is as follows: We set the experimentally determined burst rate obtained from DRAM devices by Ziegler et al [4] equal to the failure probability in high voltage devices. The burst probability is a function of released charge and the failure probability a function of local electrical field. If we set the two equal, then we obtain a relation between the amount of released charge required to induce a failure at a given electrical field.

Up to about 600 fClb, the burst probability is dominated by neutron - Si recoils. Above it is dominated by muon - Si processes which have a different slope. The result of this procedure is shown in Fig.2

Below Q = 300 fClb, the dependence is nearly exponential. There seems to be a change in slope at small fields. 0.12 MV/cm is the smallest experimentally accessible field and thus any extrapolations to smaller fields have to be taken with great caution. Nevertheless the curvature of the Q(E) plot in Fig. 2 at small fields indicates that there may be a threshold field below which no breakdown occurs even for a very large released charge. The data, however, are not sufficient to quantify the threshold.

According to [4] the transition from neutron controlled to muon controlled processes occurs around 600 fClb which according to Fig. 2 translates to a field of 120 kV/cm. The burst error function for accelerator neutrons [5] exhibits a cutoff at 360 fClb (corresponding to 130 kV/cm) which is caused by the cutoff in accelerator energy. This means that experiments with accelerator neutrons [7] will not correctly scale with the observed failure rates at fields below 130 kV/cm. In practice this means that such experiments can accelerate tests but cannot provide data at the 100 kV/cm field level which is relevant for device operation.

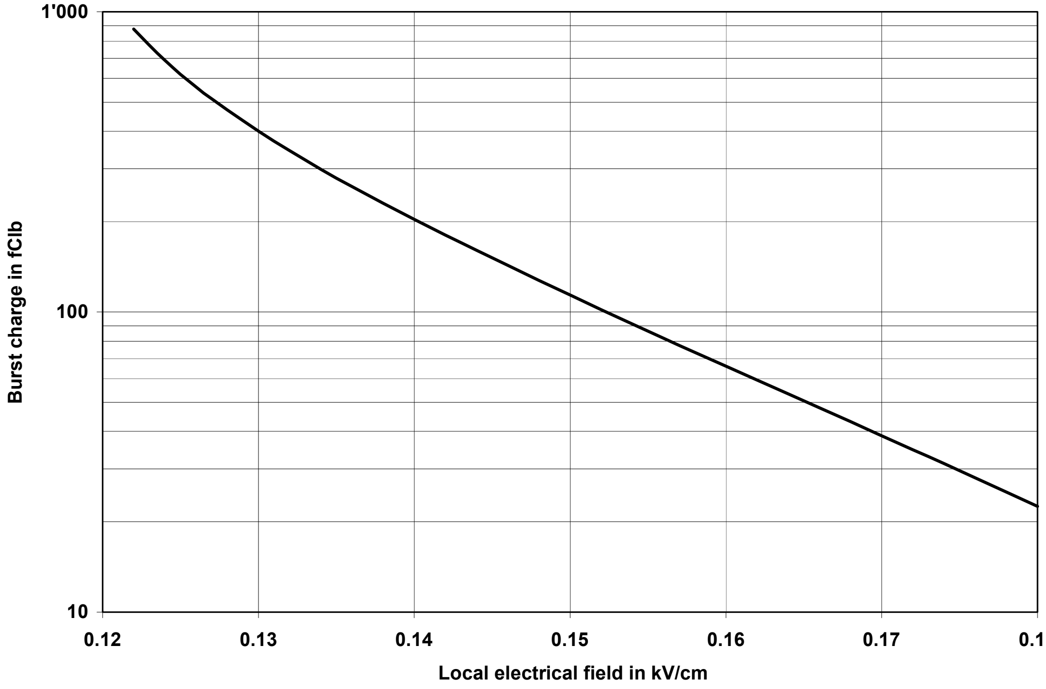

Figure 2 Minimum burst charge required to initiate a filamentary breakdown as a function of the local electrical field.

4. COSMIC RAY INDUCED FAILURES IN IGBT's

Eq.(3) is based on an important and an unimportant assumption. The important assumption is, that the total failure rate can be written as an integral over a local failure probability. The unimportant assumption is that the electrical fields is a linear function of z, where z is perpendicular to the chip surface.

The second assumption is certainly not fulfilled in an IGBT. The space charge region exhibits very strong and very local field peaks close to the cathode. The detailed form of the field peaks depends on details of the cathode design. Thus no analytical ex-

pression for the total failure probability is possible and the failure rate depends in a very complex form on device design. We have performed a numerical integration of the local failure probability based on the numerically computed electrical field distribution in a high voltage IGBT. The result is shown in Figure 3.
However, also the first assumption of a local failure rate is questionable. This assumption is only unproblematic if the electrical fields varies slowly over the characteristic distance of a recoil event. This is no longer true for an IGBT

Fig.3 shows that the field maxima close to the cathode increase the failure rate in an IGBT by about one order of magnitude at test conditions and up to two orders of magnitude at field conditions ($S \cong 3$). The IGBT results are obtained by numerical integration of the local failure rate (eq. (6)) as a function of the computed local field over the IGBT volume. As stated above the validity of this approach is questionable.

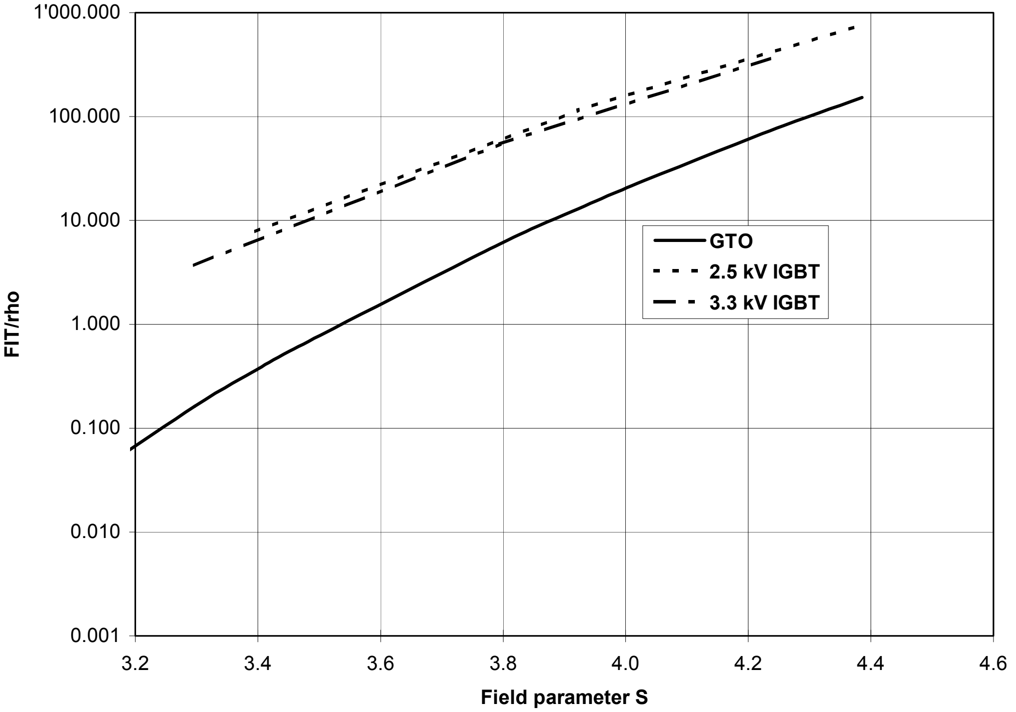

Figure 3 Calculated failure rate per cm^2 divided by n-base resistivity in Ωcm versus field parameter S for IGBT's and GTO's. The IGBT values are obtained by numerical integration, the GTO value is based on Fig. 1.

First experimental data on IGBT's confirm the increased vulnerability of the devices and are thus qualitatively consistent with the above calculations. Local filed enhancements may not be the only reason for this. As opposed to a GTO, the junction is very close to the surface in an IGBT. This makes the junction region accessible to low energy particles, e.g. α-particles originating in the packaging materials.

We thus conclude that cosmic ray induced failures in classical GTO's, thyristors and diodes are well understood, but that more work is needed to arrive at optimized design rules for IGBT's.

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REFERENCES

1. H. Kabza et al., Cosmic Radiation as a Cause for Power Device Failure and Possible Countermeasures, *Proceedings of the 6th International Symposium on Power Semiconductor Devices & IC's*, Davos 1994, Ed. W. Fichtner, A. Jaecklin, D. Aemmer, Hartung-Gorre, Konstanz Germany 1994

2. H. Matsuda et al., Analysis of GTO Failure Mode during DC Voltage Blocking, *Proceedings of the 6th International Symposium on Power Semiconductor Devices & IC's*, Davos 1994, Ed. W. Fichtner, A. Jaecklin, D. Aemmer, Hartung-Gorre, Konstanz Germany 1994

3. H.R. Zeller, Cosmic Ray Induced Breakdown in High Voltage Semiconductor Devices, Microscopic Model and Phenomenological Lifetime Prediction, *Proceedings of the 6th International Symposium on Power Semiconductor Devices & IC's*, Davos 1994, Ed. W. Fichtner, A. Jaecklin, D. Aemmer, Hartung-Gorre, Konstanz Germany 1994

4. J.F. Ziegler and W.A. Lanford, The effect of sea level cosmic rays on electronic devices, *J.Appl. Phys*. **52**, 4305-4312, (1981)

5. W.R. McKee, H.P. McAdams, E.B. Smith, J.W. McPherson, J.W. Janzen, J.C. Ondrusek, A.E. Hyslop, D.E. Russell, R.A. Coy, D.W. Bergman, N.Q. Nguyen, T.J. Aton, L.W. Block, V.C. Huynh, Cosmic Ray Neutron Induced Upsets as a Major Contributor to the Soft Error Rate of Current and Future Generation DRAMs., *1996 IEEE International Reliability Physics Proceedings*, IEEE Catalog No. 95CH35825

6. H.R. Zeller, Cosmic Ray Induced Failures in High Power Devieces, *Solid-State Electronics* **38**, 2041-2046 (1995)

7. P. Voss, K.H. Maier, W. Meczynski, H.W.Becker, E. Normand, J.L. Wert, D.I. Oberg, P.P. Majewski, Irradiation experiments with high voltage power devices as a possible means to predict failure rates due to cosmic rays, *1997 IEEE International Symposium on Power Semiconductor Devices and ICs*, Weimar, Germany 1997, IEEE catalog No. 97CH36086