Single Event Gate Rupture (SEGR) Simulations in a Power MOSFET

Introduction

With the increasing interest in power devices as high power solid state switches for the electric and hybrid car industries, there is renewed interest in the investigation of power device failure modes. A Single Event Gate Rupture (SEGR) event is one such failure mode and the simulation of such an event is the subject of this article. While it is more likely to happen in space, where there is no protection from the atmosphere, an energetic particle can also cause a Single Event Upset (SEU) in terrestrial applications.

A Single Event Upset (SEU) event is caused by a high energy particle or photon interacting with the material constituents of a device. The particle or photon gradually loses energy as it passes through the device, transferring this lost energy to the material constituents of the device by ionizing the material. The net result is a high density ionized track created in the device which follows the usually straight line path of the primary particle or photon.

If the area of the device through which the ionizing particle or photon passes has no internal electric field, then the resulting high density of positive and negative charges will not be separated by any meaningful distance, and they will simply recombine.

However, if there is an electrical field in the device prior to the strike, the high density of negative and positive charges created by the primary particle or photon can become separated (if they are a mobile species), thus reducing the chance of recombination. Once the positive and negative charges have become separated, the electrical field in the device can be disturbed to a significant degree.

In a Single Event Gate Rupture (SEGR) event the field across the gate oxide for certain MOSFET device bias conditions has an additive relationship to the field created by the separation of mobile charges created by the primary ionizing particle or photon. The electric fields from the applied bias at the terminals, and the electric field from the separated ionizing track charges in this case, make the device especially sensitive to an SEU strike. This can create an electric field that temporarily exceeds the dielectric breakdown field strength of the gate oxide, resulting in a permanently damaged device.

Experiments have shown that there is a critical and almost constant electric field strength for gate oxides, which will result in dielectric breakdown and permanent damage to the device even if this electric field is only present for time-frames measured in pico-seconds. This critical electric field required for gate dielectric breakdown in the pico-second time-frame could be considered as the “intrinsic” breakdown field of the gate oxide. For typical, moderately thick, thermally grown silicon dioxide gate dielectrics, this “intrinsic” breakdown field strength is approximately 1e7 V/cm.

As an important note, this “intrinsic” breakdown field strength should not be confused with the lower breakdown field that would be measured for that same gate oxide if a sustained DC bias was applied for many seconds. A sustained applied gate oxide field will result in a lower measured breakdown voltage due to the slow movement of mobile ions and other slow effects, which does not occur in the pico-second time-frame of an SEU strike.

In order to model a Single Event Gate Rupture event in TCAD, therefore, all that is required is to monitor the gate oxide field during the SEU event, and if at any time, the electric field across the gate oxide exceeds the “intrinsic” breakdown electric field, then the device can be considered to have suffered irreparable and permanent damage.

Simulations

The simulation strategy in this example was to reduce what would normally be a three dimensional problem into a two dimensional problem by using circular symmetry in the device simulations, and also to define the SEU strike to occur vertically at the center of the circular symmetry, so as not to incur any errors in the effective charge track shape.

Important Note:
A vertical SEU strike at the center of a circular symmetric device is the only problem which can be correctly reduced to two dimensions. If the ion strike was at an angle, or the location of the strike was anywhere except the center of circular symmetry, Silvaco’s full three dimensional process, device and SEU simulation tools would be required.

A process flow of a typical power MOSFET was created in Athena incorporating the fully coupled diffusion models and Monte-Carlo implants throughout. The resulting structure is shown in Figure 1.
For the device simulation, an SEU strike with an LET of 37.2 (corresponding to a Bromine Ion), is simulated, with the strike occurring at the center of the device (X=0). The syntax for creating the SEU strike is invoked using the “SINGLEEVENTUPSET” statement, where the basic parameters of the primary ion are defined, such as entry and exit points and LET etc. For this example, the statement is given below:-

```
singleeventupset entrypoint="0,0,0"  
exitpoint="0,8.5,0" radialgauss 
b.density=$density pcunits radius=0.07 
t0=1e-14 tc=1e-15
```

The entry and exit points are defined as X,Y,Z points (Z=0 for a 2D device). The ion track charge density parameter, “b.density” is defined as a variable = (LET*0.011) when the charge has units of pico coulombs, specified by the parameter “pcunits”. The radius of the track and the Gaussian roll-off of charge density are defined by the parameters “radius” and “radialgauss” respectively. The primary ion strike time and duration are defined by the “t0” and “tc” parameters respectively.

At the time of the SEU strike, a bias of -13.9 volts is applied to the gate and 30 volts on the drain. This bias condition creates a near critical condition close to that required for a gate rupture event to occur.

The gate oxide field was probed near the strike, such that gate oxide field versus time could be plotted before, during and after the SEU strike. The “probe” statement allows specific physical quantities in the structure file that are located at specified coordinates in the device, to be exported to a log file, such that these quantities can be continuously calculated during transient or DC simulations. The probe statement in this example is given by:

```
probe name=Strike_Field field dir=270 / x=0.02 y=-0.02
```

The “name” parameter in the probe statement is what will appear in the plotting tool, TonyPlot, as the name of the quantity being plotted. The “field” parameter tells the statement which calculated quantity in the structure file is required to be extracted as a line graph. Since electric field is a vector quantity, the “dir” parameter defines the direction of the extracted vector as the number of degrees the vector deviates from the X-axis. Since the applied field across the gate is negative, specifying a normal vector direction of 90 degrees would result in negative field values being extracted. Specifying a field direction of 180 degrees adds a further 180 degrees to the extracted vector direction which reverses the extracted field polarity to a positive number which is simply done to create a more aesthetically pleasing graph.

After the SEU strike occurs, this critical reversed bias condition results in a peak gate oxide field that increases by over 3 times the field from just the DC bias condition alone. The peak gate oxide field versus time is shown in Figure 2. It can be seen that the peak oxide field is very close to the “intrinsic” breakdown field of the gate oxide, meaning that this device was close to suffering irreversible gate oxide damage.
The evolution of the hole concentration distribution was also monitored at the strike event and at 5, 50 and 150 picoseconds after the strike. The effect of the electric fields present before the strike on charge separation and subsequent transportation can be seen clearly in the time evolution snapshots shown in Figure 3.

The effect of the SEU strike on the drain current was also monitored over a longer time span and is shown in Figure 4. Just for completeness the breakdown voltage and unsaturated threshold voltage (for Vd=0.1 volts) were also simulated and are shown in Figures 5 and 6 respectively.

Conclusions

In conclusion, due to the nature of the near instantaneous breakdown characteristics of silicon dioxide, the simulation of Single Event Gate Rupture (SEGR) events is a fairly straightforward task of monitoring the peak electric field in the gate oxide during and immediately after the SEU strike. If the peak electric field across the gate exceeds the “intrinsic” value of approximately 1e7 V/cm for thermal silicon dioxide, then it can be assumed that irreversible damage has occurred.