

2-D Electrothermal Simulation and Failure Analysis of GTO Turn-off with Complete Chopper Circuit Parasitics

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Abstract

2-D electrothermal simulations of GTO-thyristor turn-off process including a complete chopper circuit and parasitic stray inductances will be presented. Turn-off failure is investigated for a single GTO cell and on a wafer scale using a homogeneous wafer, which has in parallel a one segment GTO representing a local perturbation on the wafer by a slightly different doping or carrier lifetime profile. During the spike voltage extreme power densities may result in the perturbed segment due to current filamentation. In high power GTO turn-off two destruction mechanisms have to be dealt with: 1. current-filamentation during the spike voltage period and 2. dynamic avalanche during the tail-phase.

1. Simulation of Single GTO Cell and Wafer Scale GTO

In this paper* for the first time 2-D electrothermal simulations of GTO-thyristor turn-off process including a complete chopper circuit and parasitic stray inductances will be presented. The device simulator MEDICI [1] solves the complete semiconductor equations (Poisson and continuity equations) together with the heat flow equation for the dynamic development of the lattice temperature within a general external network. Additionally thermal resistors and capacitors can be included in order to allow for the cooling of the device by the packaging.

In Fig.1 the simulated circuit is shown with RCD-protection (snubber) circuit, inductive load, clamp and gate-drive circuit. Fig.2 displays the simulated GTO half cell with anode short-structure and Fig.3 shows a simulation result for a 4.5kV/3000A GTO, that reveals the characteristics of measured results like storage time, spike voltage U_{DSP} , peak off-state voltage U_{DM} and tail-current behaviour.

At the beginning of the turn-off process the GTO has a homogeneous temperature of 300°K. The maximal local temperature of 316°K is attained during the spike voltage at the center junction in the middle under the cathode contact. As was already observed in the isothermal simulations of [2] the power density at that instant is very high, but according to our result not sufficient to cause a dramatic or dangerous temperature increase. In Fig.4 the current density to be turned off is ten times larger. Now temperatures around the silicon melting point of 1700°K arise and would cause thermal destruction. The turn-off failure becomes apparent by the sudden anode-voltage breakdown in the tail-phase. Despite the negative gate-voltage and current

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the device is not able to sustain the blocking voltage, because of the local loss of blocking capability at the center junction (Fig.5 and Fig.6). This is due to the fact that the temperature at the hot spot exceeds the intrinsic temperature of $550^{\circ}K$ considerably.

Turn-off failure in the tail-phase has already been observed in isothermal 1-D simulation ([3] and references cited there) and 2-D simulation [4] and is due to dynamic avalanche generation, i.e. the steepening of the electric field gradient in the n-base by hole transport from the anode. In [4] turn-off failure was solely attributed to this. The measurements of [5] were done without snubber circuit and clamp, so that there was no spike voltage. They revealed that a temperature maximum occurs just after the anode current fall time.

On a wafer scale many individual GTO-Segments (> 2000) in parallel contribute to current transport. Due to inhomogenities between different cells, current redistribution during turn-off takes place [6] (independently of dynamic avalanche) and may destroy those segments, which carry the most heavy load. For a special circuit without stray inductances and snubber circuit (no spike voltage) it was shown in [6], that with a gate current as high as the load current or higher the current filamentation can be damped but for usual gate drives this is not possible. [7] presented an analytical model in order to demonstrate, that during dynamic avalanche current filamentation may take place even for completely homogeneous devices.

The spike voltage, which arises during fall time, may cause destruction due to current filamentation. The current filaments in this case are not caused by dynamic avalanche as in [7] but, as we shall see, by slight inhomogenities in the lateral dopant or carrier lifetime distribution over the device area.

Because of the excessive number of grid-points it is not possible to simulate a whole GTO wafer. Therefore in Fig.7 the result is shown for a homogeneous $2.5kV/2.5kA$ GTO (half cell scaled to full wafer size of $20cm^2$), which has in parallel a one segment GTO ($0.024cm^2$ area) representing a local perturbation on the wafer by a slightly lower p-base doping of 10%. Fig.8 shows that precisely at the time of the spike voltage the one segment GTO takes over a maximum current 100 times larger than its on-state value. Since the maximum current of the small GTO segment exactly matches the time of the spike voltage, extreme power densities occur, which will lead to destruction. Somewhat lower current peaks are observed in the tail-period by dynamic avalanche, when the anode voltage is high. If avalanche generation in the parallel one segment GTO is turned off a smooth behaviour of the tail current emerges, whereas the current peak at spike voltage time is nearly the same. Therefore destruction at spike voltage time occurs independent of dynamic avalanche.

By suitable design the current redistribution can be reduced. In [8] similar isothermal simulations were carried out for 1-D devices in parallel; however without snubber circuit and spike voltage. Even though the p-base doping difference amounted to 28% the current redistribution between the cells was not dramatic.

2. Conclusion

The essential meaning of the spike voltage for GTO turn-off failure is revealed. Two destruction mechanisms have to be dealt with in high power GTO turn-off: 1. current-filamentation during the spike voltage period and 2. dynamic avalanche during the tail-phase. Both failure mechanisms can be investigated in numerical simulation with respect to design variations.

References

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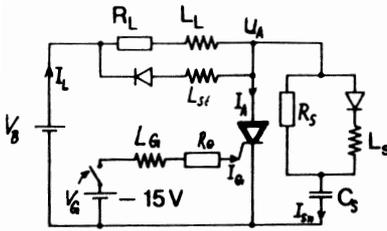


Figure 1: Simulated chopper-circuit for GTO turn-off.

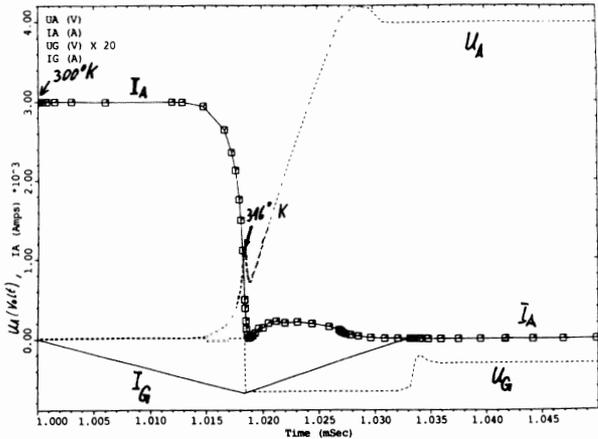


Figure 3: 2-D electrothermal MEDICI simulation of GTO turn-off for circuit of Fig.1. Highest local temperature is marked at the spike voltage.

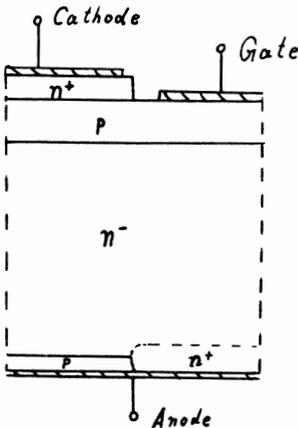


Figure 2: Simulated GTO half cell with anode short structure.

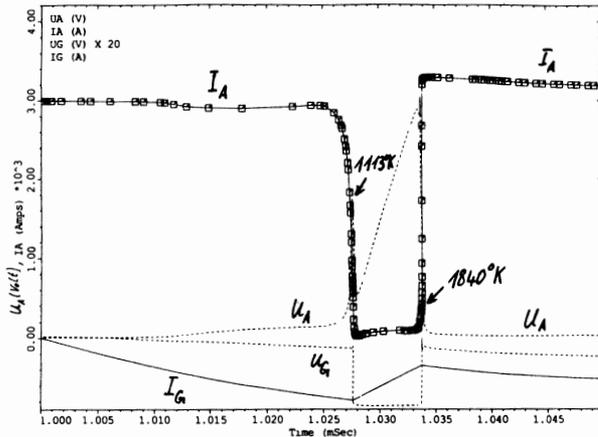


Figure 4: Destructive failure of GTO turn-off in 2-D simulation at ten times the current density of Fig.3.

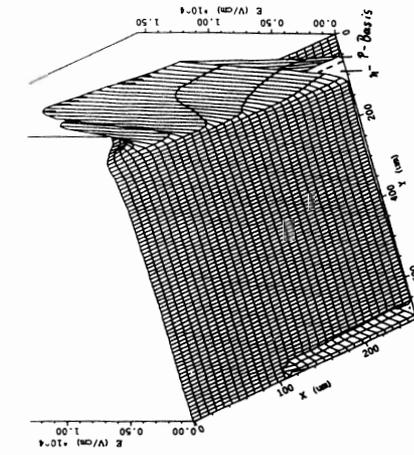


Figure 6: Internal electric field distribution for GTO from Fig.4 at time $t=1.2\text{msec}$. At the hot spot the center pn-junction loses its blocking capability.

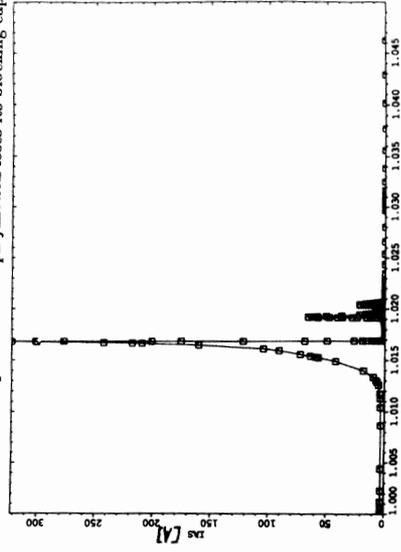


Figure 8: 2-D MEDICI simulation of GTO turn-off for 2.5kV GTO. Anode current of parallel one GTO-segment with 0.024cm^2 displayed (Fig.7). The current maximum at spike voltage time is more than 100 times the on state current of 3A.

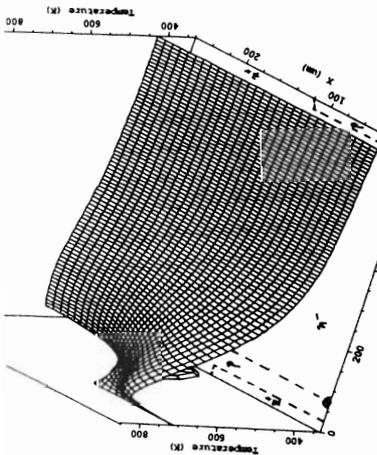


Figure 5: Internal temperature distribution for GTO from Fig. 4 at time $t=1.2\text{msec}$. At the spot the intrinsic temperature of the n-doping of 550K is exceeded.

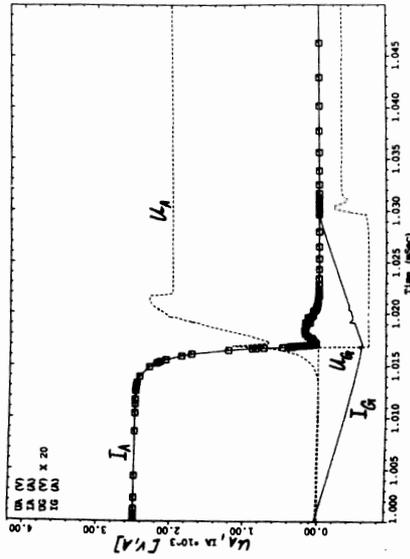


Figure 7: 2-D MEDICI simulation of GTO turn-off for 2.5kV GTO of 20cm^2 area which has in parallel a one segment GTO with 10% lower p-base doping.