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# Modelling of IGBTs and LIGBTs for Power Circuit Simulation

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**Abstract**

A network model for the insulated gate bipolar transistor (IGBT) is presented for circuit analysis programs, such as PSPICE and SABER. The model contains a fast and rather accurate description of internal plasma dynamics, and accounts for shorted-anode lateral IGBT structures on Dielectric Isolated substrates. Good agreement has been obtained between measured data and simulation results.

## 1. Introduction

The insulated gate bipolar transistor is a MOS-gate controlled power switching device, which presently replaces the power bipolar junction transistor in many applications. Similarly to thyristors, the on-state characteristics are determined by ambipolar current transport and conductivity modulation.
Basically there are vertical IGBT structures (VIGBT), which are mainly used as discrete devices in high-power applications, and lateral IGBT structures (LIGBT), which serve as output devices integrated with MOS logic in power IC's. Lateral devices with dielectric isolation on SOI-substrates have been manufactured, with and without anode shorts. The cross sections of the considered device structures are shown in Fig.1.

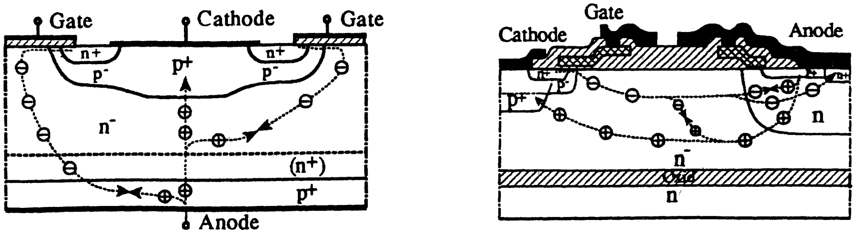
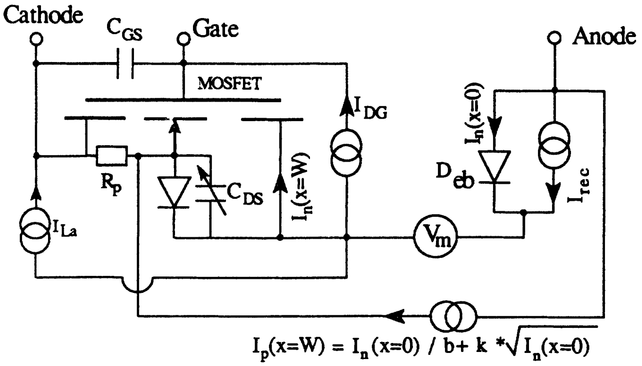


Figure 1: Cross section of VIGBT structure and the shorted-anode LIGBT structure

## 2. Static Analysis

Structurally, the IGBT works as a bipolar transistor that is supplied base current by a MOSFET. But standard models of bipolar transistors like Gummel-Poon are not suitable or applicable for the modelling of IGBT, as they do not consider appropriately the high injection-effects and the recombination in the base region. Our network model for the LIGBT is based on a "vertical" model, which has been presented in detail in [1]. The modified network model for the LIGBT structure is shown in Fig .2. The parameter b is the ambipolar mobility ratio. The material-parameters k, C1, C2, C3 depend on the base high-level lifetime, the base doping concentration, carrier mobilities, emitter parameter and the base width.



$$I_n(x=0) = I_{s1} \cdot (e^{Veb / Vt} - 1)$$

$$I_{rec} = I_{s2} \cdot (e^{Veb / (2 \cdot Vt)} - 1)$$

$$I_{La} = I_{sla} \cdot (e^{V_{Rp} / Vt} - 1)$$

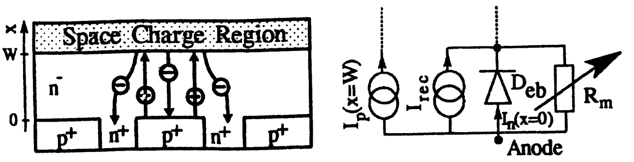
$$V_m = (C1 + C2 \cdot \sqrt{I_n(x=0)}) \cdot \ln(1 + C3 \cdot I_n(x=0))$$

Figure 2: The electrical network model of the LIGBT

Since the IGBT operates under high-injection (conductivity modulated) conditions in the n⁻-base region ($p \approx n >> n^-$), the current transport in the base can be described by the one-dimensional ambipolar transport equation. Using the quasi-equilibrium simplification (p•n-product at emitter-base junction), assuming high level injection in the base, the solution of the ambipolar diffusion, the continuity and the current density lead to the proposed network model for IGBT.

### 2.1. Modelling of the shorted anode emitter

The anode short structure, combined with an $n^+$-buffer, has been proposed to reduce turn-off switching power loss. The critical difference between this structure and a conventional LIGBT is the incorporation of an $n^+$-drain diffusion together with the $p^+$-anode that is shorted by a metal contact.



$$R_m = \frac{R_0}{1 + k_1 \cdot \sqrt{I_n(x=0)}}$$

Figure 3: representation of the physical mechanism in the anode short structure

The $p^+$-emitter layer provides conductivity modulation of the drift region, whereas the $n^+$-layer provides an electron extraction path during device turn-off. Fig. 3 illustrates the physical mechanism of the anode short structure.

The "anode short" effect is in the network model represented by the emitter-base-diode shunted by the shorting resistance. The shorting resistance is modulated by the injected excess carrier concentration in the base.

## 2.2. Modelling of DMOS-Transistor in the IGBT-structure

The device operation of the inherent DMOS in the IGBT-structure is very different from the standard MOSFETs, due to the laterally varying doping concentration in the channel region [2]. The electrons reach the saturation velocity first on the source side with increasing source drain voltage and drift with that velocity across the channel. Therefore this device shows no pinch-off behavior in the classical sense. On the basis of Kim-Fossums-DMOS-model, a simplified version is introduced that easily can be implemented in the circuit simulator. The current flowing throughout the channel in the triode region ($V_G > V_{th}$ and $0 < V_{ch} < V_{sat}$) can be derived as

$$I_{ch} = \frac{\mu_{n0} \cdot c_{ox} \cdot (w/L)}{1 + \theta(V_G - V_{th})} \cdot \frac{\left(V_G - V_{th} - \frac{a}{2} V_{ch}\right) \cdot V_{ch}}{1 + V_{ch}/V_C} \; ; \qquad V_C = L \cdot E_C \tag{1}$$

Where L is the the gate length, $E_C$ the critical field, $\mu_{n0}$ the low field inversion layer mobility, $V_{ch}$ the drain-source-voltage on the channel and $\theta$ the normal field dependence parameter. The depletion charge and the nonuniform doping effect can be considered by the parameters a and $V_{th}$. A realistic assumption for the saturation of the DMOS ($V_G > V_{th}$ and $V_{ch} \geq V_{sat}$) is, that near the source the channel current is limited by velocity saturation, when the drain voltage goes to saturation. We assume the following model for the saturation current in the channel.

$$I_{ch} = \frac{1}{2a} \cdot \frac{\mu_{n0} \cdot c_{ox} \cdot (w/L)}{1 + \theta(V_G - V_{th})} \cdot \frac{V_C \cdot (V_G - V_{th})^2}{V_C + (V_G - V_{th})} \; ; \quad V_{sat} = \frac{V_G - V_{th}}{a} \cdot \frac{1 + 0.5\lambda}{1 + \lambda} \cdot \left(1 - \sqrt{1 - \frac{1 + \lambda}{(1 + 0.5\lambda)^2}}\right) \; , \quad \lambda = \frac{V_G - V_{th}}{V_C} \tag{2}$$

## 3. Transient Analysis

For quantitative simulations of IGBT turn-off behaviour, the time dependent plasma distributions and the moving space charge layer boundary have to be considered.

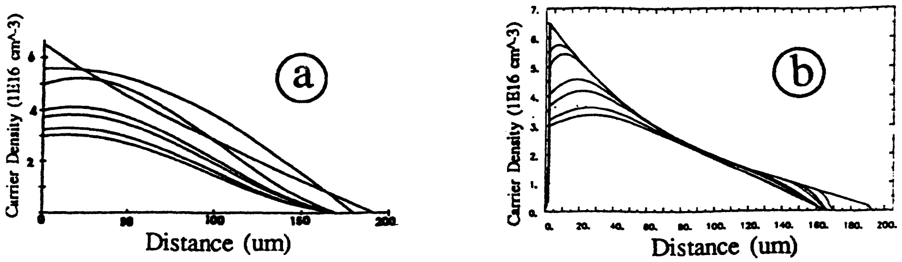


Figure 4: Calculated carrier distribution in the base region by
a) the Galerkin method b) a device simulator

The time-dependent carrier transport in the base of the IGBT is described by the ambipolar diffusion equation

$$\frac{\partial p(x,t)}{\partial t}=D_a\cdot\frac{\partial^2 p(x,t)}{\partial x^2}+\frac{p(x,t)}{\tau_H} \qquad (3)$$

Boundary conditions for the ambipolar diffusion equation are a function of the time and are represented in the form

$$\left.\frac{\partial p}{\partial x}\right|_{x=0}-\left.\frac{\partial p}{\partial x}\right|_{x=W(t)}=\frac{h_p\cdot p^2(x=0,t)+p(x=W(t))\cdot\partial W/\partial t}{D_a}\ ; \qquad \frac{\partial p(x=W(t))}{\partial t}=\frac{\partial W(t)}{\partial t}\cdot\left.\frac{\partial p}{\partial x}\right|_{x=W(t)} \qquad (4)$$

Where $h_p$ is the emitter parameter, $D_a$ the ambipolar diffusivity, $\tau_H$ the base high-level lifetime. Conventional charge control models cannot cover a wide range of switching conditions with reasonable accuracy. Finite difference methods which have been used in diodes and GTO modelling [3] are very exact but require much computation time. We have found that a reasonable way for fast and rather accurate modelling is based on the use of linear superpositions of suitable basis functions, which is optimized using the methods of weighted residuals. This has recently been proposed for BJT modelling [4]. Divergent from that paper we have used the Galerkin method to optimise superpositions of linear and sine-wave-type functions. The method is especially useful if very different p-emitter properties are considered, as is required to simulate advanced IGBT devices. Implementation of the corresponding device model is performed in SPICE and SABER. In order to illustrate the model accuracy in a transient analysis, in figure 5 the comparision between the experimental and simulated output characteristics for a manufactured LIGBT with shorted-anode is shown.

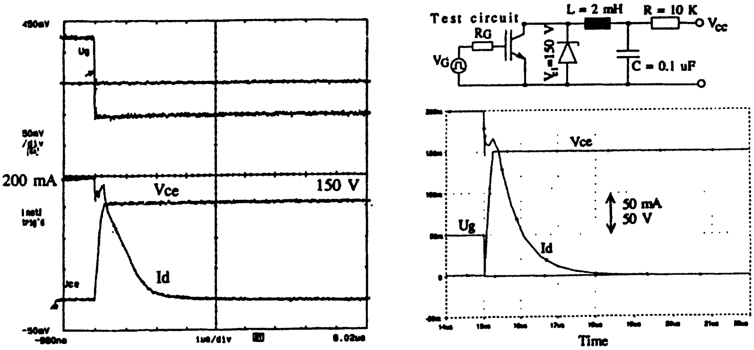


Figure 5: The turn- off process of LIGBT measured (a) and modelled with SPICE (b)

## References

[1] B. Fatemizadeh, D. Silber, "*A Versatile Electrical Model for IGBT Including Thermal Effects*", PESC'93, Seattle, June 1993

[2] Y. Kim and J. G. Fossum , "*Physical DMOST Modeling for High-Voltage IC CAD*", IEEE Trans. Electron Devices, vol. ED-37, pp. 797-803, March 1990

[3] T. Vogler and D. Schröder, "*A New and Accurate Circuit-Modeling Approach for the Power-Diode*", PESC'92, Toledo, June 1992, pp. 870-876

[4] B. Allard, H. Morel and J. P. Chante, "*State-Variable Modeling of High-Level Injection Regions in Power Devices*", PESC'92, Toledo, June 1992, pp. 885-892