MODELLING AN INSULATED GATE BIPOLAR TRANSISTOR USING BOND GRAPH TECHNIQUES

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SUMMARY

Simulators in power electronics are less developed than in other electronic fields. The main modelling methods are between the numerical simulation of semiconductor device equations that hardly simulate circuits, and equivalent circuit models that show poor accuracy. We propose the application of the bond graph techniques to model modular power semiconductor devices. Furthermore, the IGBT is a new power device which combines a bipolar transistor with a MOSFET transistor. We develop a new IGBT bond graph model. The bond graph techniques give us good primary simulation results. We present in this paper the principle and the results of this modelling method.

NOTATION

\[ T \] Crystal temperature
\[ n \] The charge carrier concentration
\[ A \] The device active area
\[ u_n \] Electron speed
\[ U_n, U_p \] Electron, hole effort
\[ F_n, F_p \] Electron, hole flow
\[ n, p \] Electron, hole carrier concentration
\[ W \] Junction depletion width
\[ Q \] Junction depletion charge
\[ q \] Electronic charge
\[ U_l = kT/q \]
\[ V_{L} \] the limit speed of carrier
\[ n_i \] intrinsic doping concentration

1. CAD TOOLS FOR POWER DEVICES AND CIRCUITS

Power integrated circuits embrace a wide spectrum of different applications ranging from conventional analogue circuits that are operated at non-standard voltage levels, to smart power circuits.

CAD tools in power electronic circuits change with the quality of models used for the semiconductor devices. Models have been developed over the years for the more classical power bipolar and MOS devices, while models for new power devices such as IGBT are still in an early stage of development. One reason for this lack of CAD models for power switches is the complex physical modes of operation.

In order to contribute to the solution of this problem, we propose the application of bond graph techniques to modular modelling of power semiconductor devices.\(^1\)\(^-\)\(^3\) This method is an efficient hierarchical modelling frame. The bond represents the system transient behaviour and the petri net is in charge of the system functional behaviour.
2. PHYSICAL DESCRIPTION OF IGBT

The IGBT is the first device in which is integrated an association of bipolar transistor and MOSFET. It combines the advantages of MOSFET drive with the good power behaviour of bipolar transistor.

The IGBT functions as a bipolar transistor to which a MOSFET supplies the base current. A diagram of the structure of two of several thousands of cells of IGBT is shown in Figure 1.

The collector of the bipolar transistor PNP is shorted to the source of the MOSFET. The source and body diffusions, into the epitaxial layer from MOSFET Cells, with the channels at the surface of the bodies, and with the portion of the epitaxial layer between the body diffusions, serve as the drain. The equivalent IGBT circuit is shown in Figure 2.

3. THE PRINCIPLE OF BOND GRAPH TECHNIQUES

The bond graph techniques are a generalization of the Kirchhoff networks and are principally used for modelling mechanical and hydraulical systems.

Inside any physical system, the parts which exchange information can be isolated. Thus a bond graph shows how power flows between the system parts, while each part state variable model shows how power is stored inside the part. The power flow can be of any nature (electrical, thermal, mechanical), but is always characterized by the value of a power that is the product of a flow variable, such as a current, by an effort variable, such as a tension for electrical power.
Table I. Effort and flow variables for main physical domains

<table>
<thead>
<tr>
<th>Physical domain</th>
<th>Flow variable</th>
<th>Effort variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical</td>
<td>current</td>
<td>voltage</td>
</tr>
<tr>
<td>Thermal</td>
<td>entropy flow</td>
<td>temperature</td>
</tr>
<tr>
<td>Hydraulic</td>
<td>volume flow</td>
<td>pressure</td>
</tr>
<tr>
<td>Mechanical</td>
<td>velocity</td>
<td>force</td>
</tr>
<tr>
<td>Charge carrier</td>
<td>carrier flow</td>
<td>internal energy</td>
</tr>
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</table>

In semiconductor devices we have three kinds of power: the electrical power, represented by $x$, the charge carrier power, represented by $n$ for electrons and by $p$ for holes, and thermal power for accurate models. For charge carrier power, we define the effort $U$ and the flow $F$ as:

$$U = \frac{3}{2} kT n \quad \text{and} \quad F = Au_n$$

On the other hand we can link together the charge carrier effort $U$, the charge carrier flow $F$ and the current $i$ by the following expression:

$$FU = \frac{3}{2} \frac{kT}{q} i$$

An energy flow is represented by a bond and graphically a half-arrow indicates the direction of the flow between two elements (Figure 3).

The bond is characterized by causality too. This property indicates that element A is controlling the flow variable (Figure 4). Obviously an element cannot control both the flow and the effort. Thus if element A controls the flow, then element B will control the effort, and vice versa.

The consistency causality analysis of all the bond causality enables us to study the role of each component within a circuit.

In addition to Kirchhoff network classical components R, L, C, current and voltage sources, and in order to complete the drawing of the bond graph of an electrical circuit, special components must be introduced to ease the connection between the circuit elements:

- a '0' junction represents an electrical parallel combination (Figure 5)
- a '1' junction represents an electrical serial combination

4. THE IGBT MODULAR MODELLING

The IGBT structure is a combination of MOSFET and PNP bipolar structures. To model the MOSFET structure, we can use in this step of work the electrical equivalent circuit model used by Spice simulator (Figure 6).
The output MOSFET nodes control the effort variables $V_{gs}$ and $V_{ds}$, and the global bond graph of the MOSFET structure is illustrated in Figure 7. The model equations of MOSFET describe its internal behaviour and the electrical power transfer.

A semiconductor device is governed by partial differential equations: the Poisson equation and the electron and hole transport equations. Several basic regions within the device, where only one physical mechanism occurs, may be observed separately: space charge region, ohmic region, high and low level injection. This decomposition of the internal device structure is called the regional hypothesis. Each basic region will be analysed and modelled separately. A complete device model will be a combination of these basic region models, which are connected using the bond graph techniques.

The bipolar structure modelling is too complex, so we apply the concept of regional hypothesis to this structure (Figure 8). The main regions in bipolar structure are:

1. the metal junction semiconductor type P
2. the emitter base and the base collector junctions
3. the base
5. THE BOND GRAPH MODEL DESCRIPTION OF BIPOLAR STRUCTURE

5.1. Model of metal-semiconductor junction

This region is characterized by a majority carrier conduction. The analysis of the electron diffusion in the emitter allows the computation of the current of the electrons injected from the base to the emitter $I_{ne}$. So the effort transfer equation is:

$$U_{n2} = \frac{3T}{2kT/q} \ln(e)^{I_{ne}}$$

and hole flow equation is:

$$F_{p2} = \frac{3T}{2kT/q + F_{n2}U_{n2}}U_{p2}$$

The voltage drop in the boundaries is:

$$\Delta V = R_{e}i - U_{i} \ln(p_{i}/n_{i})$$

The final bond graph of the metal semiconductor box is as shown in Figure 9, where

- $x_1, x_2$ electrical power transfer
- $p_2$ hole power transfer in the side 2
- $n_2$ electron power transfer in the side 2

The model parameters are the section area, $A$, the resistance of ohmic contact, $R_{e}$, the minority diffusion length, $L_{e}$, the doping profile geometrical coefficient, $X_{e}$, and the temperature, $T$. 

![Figure 9. Bond graph of the metal-semiconductor junction](image-url)
5.2. Model of space charge regions

In the emitter base junction, the doping profile is approximated by \( D(u) = N_i(1 - \exp(u/x_e)) \). Based on the solution of the Poisson equation in this region we calculate the equations of the state variable, \( W \), and of the base emitter junction voltage, \( U_{be} \) (Figure 10). And the model equations are:

\[
\begin{align*}
U_{n2} &= \frac{3}{2} kT N_i(a_2) \\
U_{p1} &= \frac{3}{2} kT N_e(a_1) \\
F_{p2} &= i U_{p1} \exp(-U_{be}/U_i) \\
F_{n1} &= i U_{n2} \exp(-U_{be}/U_i) \\
i_2 &= i_1 = i \\
U_1 &= u_2 + U_{be}
\end{align*}
\]

The transient state is characterized by the charge \( Q \) equation:

\[ \frac{dQ}{dt} = \frac{dQ}{dw} \frac{dw}{dt} \]

and the static state by:

\[ \frac{dw}{dt} = 0 \]

So

\[ i = (U_{n1}F_{n1} + U_{p1}F_{p1})/(3/2U_i) \]

The emitter base junction bond graph is as shown in Figure 11. The model parameters are: the
junction area, $A$, the base doping profile, $N_b$, the geometrical coefficient diffusion, $X$, and the temperature, $T$. Similar equations are applied to the base collector junction to make its bond graph.

5.3. Model of the base

In the base we consider existence of the space charge zone, which allows hole flow to have its speed limit. The consequence of this is a settlement of the flow value:

$$F_{p2} = A V_l,$$

the current entering in the emitter gives

$$U_{p1} = (3/2kT/q) i_1 + F_n U_{n1}/F_p,$$

The current in the collector side gives

$$F_{n2} = (3/2kT/q) i_2 + F_p U_{p2}/U_{n2},$$

At the end, we write the relation of currents and voltages:

$$i_1 = i_2 + i_3 \quad \text{and} \quad V_2 = V_3$$

So the bond graph representation is as shown in Figure 12. Parameters of the base model are the area, $A$, and the temperature, $T$, of the device, $X_{be}$, $X_{bc}$ the geometrical coefficients of the emitter base junction and the base collector junction.

![Figure 12. Bond graph of the base region](image)

6. THE BOND GRAPH MODEL OF IGBT

Using models of different regions of the PNP bipolar structure and the MOSFET structure, which are described above, enables us to create the bond graph of the N channel IGBT (Figure 13). The model is resolved by the simulator PACTE. The bond graph model of the IGBT is in first validation step. The global waveforms give us a satisfactory device turn-off time. It depends on the lifetime of the minority carrier in the base (Figure 14). The Mos–Miller effect at the threshold voltage, is present in the switching wave forms of the gate voltage (Figure 15).

The width drop of emitter base junction is slower than the base collector one. This is explained by the slow stored charge evacuation in the base emitter junction (see Figure 16).

The model takes into account the main physical phenomena in the IGBT switching. On other hand, the model allows to have access not only to current and voltage transfer but also to the flow and effort parameters of carriers into the device. These data can allow us to better understand the internal region behaviour in the device. The new model can be more accurate by taking into account the temperature effect and the high-level injection in a wide, large base of bipolar structure.
Figure 13. IGBT bond graph model

Figure 14. Output current and voltage of IGBT switching

Figure 15. Gate voltage of IGBT switching
7. CONCLUSIONS

A new model using bond graph techniques is developed for the IGBT. This model can be used to describe the turn-on and turn-off, gate and collector, current and voltage waveforms for general external drive and load circuits.

The stored charge in the base is correctly described and not represented by a capacitance as in equivalent circuit models. The knowledge of carrier movements into the device allows us to study precisely the physical device behaviour.

The modular modelling of the device shows the way in which bond graph modelling is applied to semiconductor devices and especially to power electronic simulation.

The decomposition of the internal device structure simplifies the model writing. Each region will be analysed and modelled separately. Any region model can be used to develop other device models.

Application of bond graph techniques to power electronic circuit modelling requires the study of the role of each component within a circuit and the introduction of an accurate causality analysis. But it appears really efficient during simulation with a good computation time.

In a second step of validation, we will make an accurate IGBT parameters library and we will conduct a comparison with other simulation method results.

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REFERENCES

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