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The Static and Dynamic Behaviour of NPT-IGBTs with Different p^+-Anode Designs

W. Feiler, W. Gerlach, and U. Wiese

Institut für Werkstoffe der Elektrotechnik, TU Berlin
Jebensstraße 1, D-10623 Berlin, GERMANY

Abstract

Two analytical models for the NPT-IGBT are presented. The first model explains the static carrier distribution in the on-state and gives approximate values for the emitter efficiency. The second model describes the turn-off behaviour under inductive load conditions. The results of the analytical models are compared with 2D-simulations obtained with the device simulator TMA-MEDICI. Moreover the influence of a shorted anode on the behaviour of the IGBT is investigated by numerical simulations.

1. The static model for the NPT-IGBT

In this model it is shown, that the carrier distribution in the NPT-IGBT and the emitter efficiency can be calculated based on the two-dimensional current flow equations within the device. For this purpose the IGBT is devided into two one-dimensional sections (Fig.1), which are coupled via the lateral electron current below the p^+-cathode-well. In both regions of the model the current flows one-dimensionally in positive x-direction between $-w_0 \leq x \leq -d_1$, where d_1 is chosen as half the cell width. Due to the electric field in the space charge region (SCR) the electron current cannot enter the p^+-cathode in the pnp-transistor part (section II). Therefore the electron current has to flow laterally into the pn-diode part (section I). It is assumed, that this lateral electron current is constant between $-d_1 < x < 0$. Furthermore a lateral hole current is neglected. The electron current grows therefore linearly in this area of section I, whereas for $x \geq 0$ it flows undisturbed into the accumulation layer below the gate. Because the hole current is zero in the accumulation layer, it must change its direction between $0 \leq x < d$ and has to flow laterally into the p^+-cathode. For simplicity it is assumed, that here the lateral hole current density is constant. Neglecting recombination, the carrier distri-

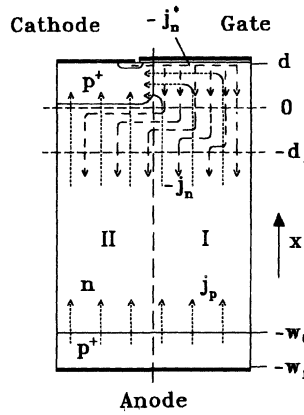

Fig. 1: The two sections of an IGBT
Part I: pn-diode Part II: pnp-transistor

bution within the two sections of the IGBT can be calculated for high injection conditions in the base region by simply solving the current equations in the ambipolar form

$$j_n = \frac{\mu_n}{\mu_n + \mu_p} \cdot j + q \cdot D \cdot \frac{dp}{dx} \qquad j_p = \frac{\mu_p}{\mu_n + \mu_p} \cdot j - q \cdot D \cdot \frac{dp}{dx} \tag{1}$$

The solution of this calculation is shown in Fig.2 together with 2D-simulation results, which are extracted along the cuts AA´ and BB´. Both curves show rather good agreement. Due to the neglected recombination the carrier distribution falls off linearly between $-w_0 \leq x \leq -d_1$, whereas the constant lateral current density is responsible for a parabolic decrease below the p^+-cathode and a parabolic increase under the gate. As the slope of the carrier density can be deduced from the model, it is possible to derive an analytical expression for the emitter efficiency γ_p:

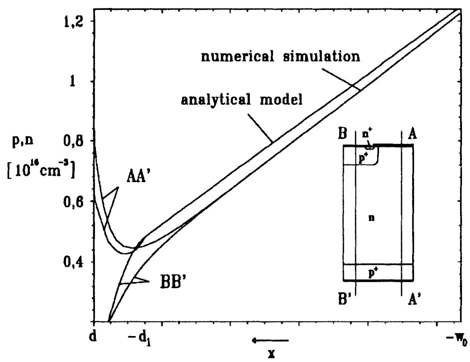

Fig. 2 : Carrier concentration in the IGBT

$$\frac{\gamma_p}{\gamma_p + 1} = \frac{\mu_p}{\mu_n} \cdot \left(1 - \frac{d_1}{2 w_0} + \frac{2 \cdot q}{w_0} \cdot \sqrt{\frac{(w_1 - w_0) \cdot D_n \cdot N_A}{q \cdot j_n}} \right) \tag{2}$$

In Fig.3 the emitter efficiency according to (2) is compared with the values extracted from the MEDICI-simulation. The dependence of the analytical emitter efficiency on the current density (solid lines) is in a good agreement with the results derived by MEDICI (dashed lines). Generally the emitter efficiency decreases with increasing current density. For normal operating conditions ($j \approx 40$ A/cm^2) emitter efficiencies between 0,3 and 0,65 can be achieved. For low current densities γ_p tends to 1. This effect results in a extended tail during turn-off.

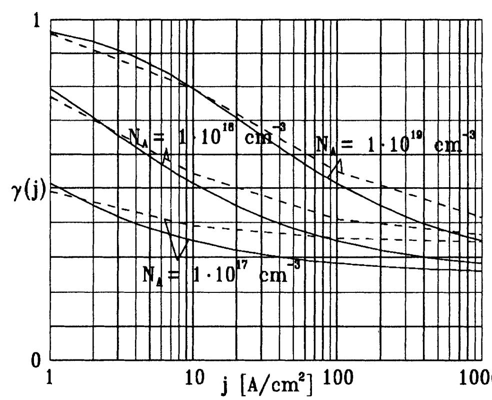

Fig. 3 : Emitter efficiency of uniform p^+-emitters

2. The dynamic model for the NPT-IGBT

An IGBT is considered, which is driven in a chopper-circuit with a clamped inductive load, carrying a current of j_0 = 20 A/cm^2. When the IGBT is switched off, the electron current from the MOS-channel is interrupted. Due to the inductive load the anode current remains constant. Consequently carriers are extracted from the base, the SCR is growing. The anode voltage increases up to the external supply voltage. Then the extraction of electrons from the SCR periphery stops and the anode current begins to fall. As it is known from the numerical simulation the first phase of this decrease is characterized by an increase of the ratio j_n/j_p. For this case the behaviour of the total current and the extraction of the carriers from the base is described by the developed dynamic model. For this purpose the ambipolar diffusion equation

$$D \cdot \frac{\partial p^2}{\partial x^2} = \frac{\partial p}{\partial t} - \frac{p}{\tau} \tag{3}$$

is solved taking advantage of the Laplace-transform method. For that purpose the initial carrier distribution is approximated by two linear functions as it is shown in Fig. 4 :

$$p_I(x,0) = \frac{j_0}{2\,q\,D_p} \cdot x = c_1 \cdot x \tag{4}$$

$$p_{II}(x,0) = c_1 x_1 + \Delta p \left(\frac{x - x_1}{w - x_1} \right) \tag{5}$$

The boundary conditions are given by

$$p(0,t) = 0 \tag{6}$$

$$\left.\frac{\partial p}{\partial x}\right|_{x=0} = k \cdot \left.\frac{\partial p}{\partial x}\right|_{x=w} \tag{7}$$

The parameter k in (7) is a measure for the ratio j_n/j_p at the anode x = w. For simplicity a vanishing hole current density at the anode is assumed. For this case k = -3. This yields the following expression for the hole density :

$$p(x,t) = 2 \cdot w \cdot e^{-\frac{t}{\tau}} \cdot \sum_{n=-\infty}^{\infty} \frac{\sin\left((\varphi + 2 \cdot \pi \cdot n) \cdot \frac{x}{w} \right)}{(\varphi + 2 \cdot \pi \cdot n)^2 \cdot \sin(\varphi + 2 \cdot \pi \cdot n)} \cdot \left\{ \frac{c_1}{k} - c_2 + (c_2 - c_1) \cdot \cos\left((\varphi + 2 \cdot \pi \cdot n) \cdot \left[1 - \frac{x_1}{w} \right] \right) \right\} \cdot e^{-\left(\frac{\varphi + 2 \cdot \pi \cdot n}{w/L} \right)^2 \cdot \frac{t}{\tau}} \tag{8}$$

where the value φ is determinated from $\varphi = \arctan\left(\sqrt{k^2 - 1}\right)$. At x = 0 the total current density j is given by the hole current only. The current can therefore be derived from the hole density (8) according to

$$j(t) = -2 \cdot q \cdot D_p \cdot \left.\frac{\partial p}{\partial x}\right|_{x=0} \tag{9}$$

Fig. 5 shows the carrier profiles according to (8) and Fig. 4 visiualizes the total current density (9) in comparison with the results of MEDICI. It can be seen, that the accordance of the results from the analytical model and the numerical simulations are in a remarkably good agreement. Only for the very first time interval the profiles are different, due to the simplified initial condition (4), (5). Nevertheless the model describes the time-dependence

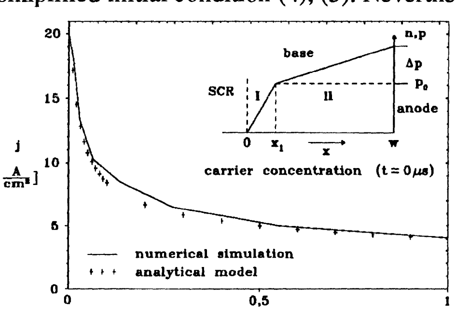

Fig. 4 : Total current density j during turn-off

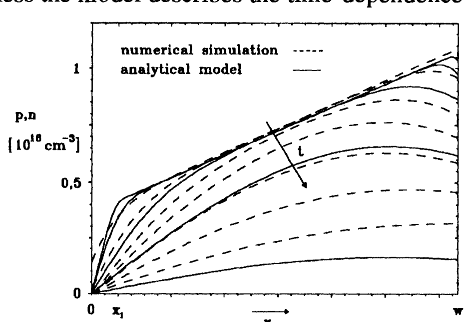

Fig. 5 : Carrier profiles in the neutral base

of the total current very well, until the current-ratio j_n/j_p decreases and the assumption (7) is violated. This is the case in the exponential phase of the tail, where the current-ratio tends to zero

3. The NPT-IGBT with a shorted anode

In order to improve the dynamic behaviour of the IGBT in the exponential phase of the tail, it is recommended to introduce an anode, which has a low emitter efficiency for low current levels. It is shown in the first section of this paper, that this cannot be achieved by lowering the doping concentration in the anode. However by introducing a shorted anode this aim can be accomplished (Fig. 6). The doping concentration in the p^+-section of the anode is chosen quite high ($N_A = 10^{20} cm^{-3}$) to ensure a high conductivity modulation in the base during the on-state; the narrow n^+-shorts have a doping concentration of $N_D = 10^{17}$ cm^{-3}. Fig. 6 shows the resulting static IV-characteristic for the IGBT with a shorted anode (KS-IGBT) and two devices with uniform anodes, which have doping concentrations of $N_A = 10^{17}$ cm^{-3} (IGBT17) and $N_A = 10^{20}$ cm^{-3} (IGBT20). For high current levels the KS-IGBT is superior to the IGBT17, but it doesn't achieve the low forward voltage of the IGBT20. The advantage of the shorted anode becomes evident in Fig. 7, where the simulation data for the total current density in the IGBTs during turn-off is plotted. The KS-IGBT has only a short tail, resulting in a small turn-off loss of 2,5 mWs/cm^{-2}. In contrast the IGBT17 has a turn-off loss of 3,9 mWs/cm^{-2} and the IGBT20 of 12,5 mWs/cm^{-2}.

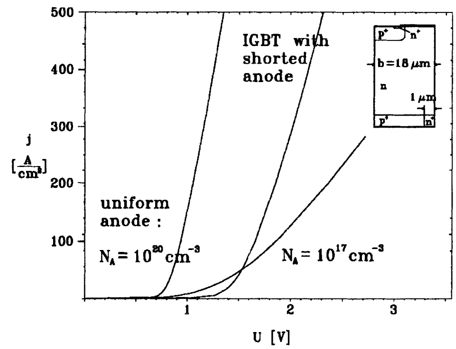

Fig. 6 : IV-charactristic of IGBTs with different anode designs

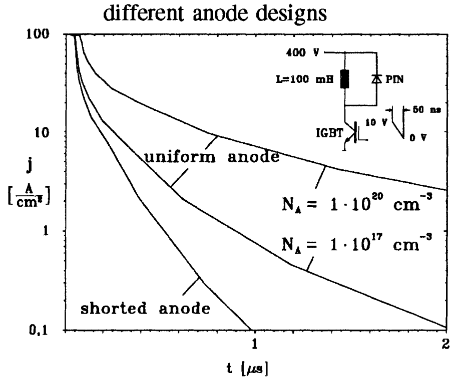

Fig. 7 : Current density during turn-off

4. Conclusions

Two analytical models have been presented, one describing the NPT-IGBT in the on-state, the other one representing the turn-off behaviour under inductive load conditions. The first model explains the static carrier distribution in the IGBT on the basis of the two-dimensional current flow and gives an analytical expression for the emitter efficiency γ_p. It has been shown, that for an uniform anode, γ_p increases with decreasing current density, causing a long tail during turn-off. The second model describes the total current and the carrier profiles in the first phase of the turn-off neglecting the hole current in the anode. Good agreement with the results of numerical simulations has been obtained. Furthermore it has been shown, that an extended tail during turn-off can be avoided using a shorted anode.