

The Reverse Behavior of the NPT-IGBT in its On-State

1 Reverse States of the IGBT in Inverter Circuits

Causes for Reverse States

The use of the IGBT in inverter circuits does not come without its problems. During the switching cycle the signs of current and voltage applied to the switching device change temporarily caused by the inversion of the flux of energy between supply and load. The IGBT has no provision for carrying negative voltages, therefore it must be terminated with an antiparallel or a series diode. However, it is not possible to completely suppress transient reverse states of the IGBT, which are caused by the transient behavior of the diode (which shows forward and reverse recovery) and are also due to parasitic inductance within the circuit. Character and effect of these stresses are dependent on the trigger point and the electrical behavior of the switching scheme. But they are also influenced by the carrier densities inside the IGBT at the start of the commutation process. A further improvement of switching performance may be achieved by optimizing triggerpoints and substituting the supplementary diode in different NPT-IGBT applications. There is an immense risk in these schemes to expose the non protected IGBT to a high reverse stress caused by changing driving and load conditions.

Classification of Reverse States

The reverse states can be distinguished by different parameters of the switching configuration. First of all the switching state allows to qualify the carrier density inside the IGBT at current zero crossing. The state is predicted by the drive only. Secondly the commutation is characterized by the derivatives of current and voltage at the device with respect to the time. The commutation rates determine the behavior of the circuit. A third parameter is based on the energy impressed into the IGBT.

Switching State

It is possible to relate the state of the switch during commutation to the inverter scheme. A characteristic of the current-fed inverter is, that the supply current cannot change quickly. An overlap of the switches on-states maintains the continuous current flow in the DC-rails at any time of the inverter cycle. The IGBT encounters the reverse stress with an turn-on gate, and in the case of fast commutation with the carrier distribution of the forward state. In duality an overlap of the switches off-states has to prevent a voltage-fed inverter from a short. That is why, the gate is turned off during commutation and the carrier distribution is that of the steady off-state.

Commutation Rates

The behavior of the whole commutation branch has to be considered optimizing commutation rates. In general they increase qualitatively with the inverter frequency and cause the recovery effects of terminated diodes. Because they do not reflect the reverse stresses directly, a quantitative marking does not make sense.

Energy

A parameter summarizing the properties of the circuit is the energy E_{REV} , which the inverter impresses into the IGBT during the reverse state:

$$E_{REV} = \int |i_{rev} \times v_{rev}| \partial t_{rev} \quad \text{equation 1}$$

i_{rev} and v_{rev} are the current through the collector and the voltage from collector to emitter during the whole time of reverse stress t_{rev} .

A parameter characterizing the IGBT is the energy $E_{REV}(Q)$ which can be stored by displacement of charge until reverse breakdown at V_{brrev} :

$$E_{REV}(Q) = \int^{V_{brrev}} Q_{rev}(i, v) \partial v_{rev} \quad \text{equation 2}$$

Q_{REV} is the charge displaced by the reverse stress until reverse breakdown.

The ratio of the energies $E_{REV}/E_{REV}(Q)$ can be taken as an extent for the reverse stress of the IGBT. Whereas E_{REV} can be obtained recording v_{rev} , and i_{rev} the calculation for $E_{REV}(Q)$ is more difficult. In the steady off-state only Q_{REV} reduces to the value of the fixed charges in the depleted region and is a function of v_{rev} alone. In the on-state Q_{REV} depends on the forward current and is expected to follow a square root law. The influence of the reverse bias appears more complicated and shall be explained in **section 2**. But mostly the commutation rates do not affect Q_{REV} due to the order of minority lifetime in common IGBTs.

Table 1 shows the classification of reverse stresses in common inverters. Stresses in switches rise beside the optimal trigger point. So the effects of parameter drift have to be considered for an estimation of the extents at actual inverter schemes.

Table 1

Classification of the Reverse Stress of IGBT in Common Inverters by the Conducting State, the Commutation Rate and the Ratio of Impressed and Storable Energy

Inverter Scheme	IGBT	$d(v, i)/dt$	$E_{REV} / E_{REV}(Q)$
Current-fed inductive load	On	Low	Low
Voltage-fed inductive load	Off	Low	Middle
Parallel resonant load	On	Middle	Middle
Serial resonant load	Off	Middle	High
Quasi resonant (zero current) switch	(On)	High	High

2 The NPT-IGBT in its Reverse State

Assumption

The reverse behavior of the IGBT shall be explained describing the junctions with the assumption that a drift of carriers through the junction does not effect the imrefs of electrons and holes along it:

$$\text{grad } \phi_{n(j)} = \text{grad } \phi_{p(j)} = 0 \quad \text{equation 3}$$

$\phi_{n(j)}$ and $\phi_{p(j)}$ are the imrefs of electrons and holes along the junction. Then the following expression can be used to simplify semiconductor equations:

$$\phi_{p(j)} - \phi_{n(j)} = V_j - V_{bi} \quad \text{equation 4}$$

V_j is the voltage applied to the junction and V_{bi} is the built-in voltage. It must be noted for transient behavior that the validity of this expression disappears with increasing frequency. A growing part of the current through the junction flows by drift and the imrefs across the junction incline.

Function

The structure of the IGBT is similar to that of a MOSFET with an additional junction, which injects the minority carriers into the drift region to decrease the on-state voltage drop (**Figure 1a**). This junction also functions as a series diode, which makes the internal antiparallel diode in the source junction of the MOSFET unoperable. The whole IGBT structure has to be considered for describing the blocking capability of this series diode.

Static Characteristic

The blocking capability of the drain junction is dependent on the injection of electrons from the source junction. In the case of reverse state, the p⁺-well (which in the following discussion is named emitter), n⁻-substrate (base) and p⁺-emitter (collector) compound of the IGBT constitute a bipolar transistor, the emitter of which is modified by the MOS channel.

Figure 1b shows the equivalent circuit of the NPT-IGBT working in its reverse state. For the steady state collector current of this pnp-transistor the following equation is valid:

$$I_C \cong \alpha_T \gamma I_{E0} e^{\frac{qV_{EB}}{kT}} + I_{C0} (1 - e^{\frac{qV_{CB}}{kT}}) \quad \text{equation 5}$$

And also the steady state base current can be expressed:

$$I_B \cong (1 - \alpha_T \gamma) I_{E0} e^{\frac{qV_{EB}}{kT}} - I_{C0} (1 - e^{\frac{qV_{CB}}{kT}}) \quad \text{equation 6}$$

α_T and γ are the standard symbols for the transport factor and the injection efficiency, q is the elementary charge, k the Boltzmann constant and T the temperature. I_{E0} and I_{C0} are expressions for the emitter and collector saturation current respectively and V_{EB} and V_{CB} for the voltage across the emitter-base and the collector-base junction respectively.

Transient Behavior

To describe the transient behavior of the IGBT, equations 5 and 6 must be completed with further terms to calculate the stored charges in the transistor. These charges are caused similarly by emitter and collector functions. Therefore the following equations are written in a common way.

The diffusion capacitances can be described as a function of the injected carriers. It can be derived that the diffusion capacitance of the n-region $C_{\text{diff}(n)}$ caused by injected holes is given with:

$$C_{\text{diff}(n)} = \frac{q}{kT} \times \frac{qL_p p_{(n)0}}{2} \exp\left(\frac{q(V_j - V_{bi})}{kT}\right) \quad \text{equation 7}$$

An equivalent expression follows for the diffusion capacitance of the p-region $C_{\text{diff}(p)}$ caused by injected electrons:

$$C_{\text{diff}(p)} = \frac{q}{kT} \times \frac{qL_n n_{(p)0}}{2} \exp\left(\frac{q(V_j - V_{bi})}{kT}\right) \quad \text{equation 8}$$

L_p is the diffusion length and $P_{(n)0}$ is the equilibrium carrier concentration of holes in the n-region. L_n is the diffusion length and $n_{(p)0}$ is the equilibrium carrier concentration of electrons in the p-region. Similar equations can be obtained for the conductances modulated by diffusion $G_{\text{diff}(n)}$ and $G_{\text{diff}(p)}$:

$$C_{\text{diff}(n)} = \frac{q}{kT} \times \frac{qD_p p_{(n)0}}{L_p} \exp\left(\frac{q(V_j - V_{bi})}{kT}\right) \quad \text{equation 9}$$

$$C_{\text{diff}(p)} = \frac{q}{kT} \times \frac{qD_n n_{(p)0}}{L_n} \exp\left(\frac{q(V_j - V_{bi})}{kT}\right) \quad \text{equation 10}$$

D_p and D_n are the diffusion constants of holes and electrons respectively.

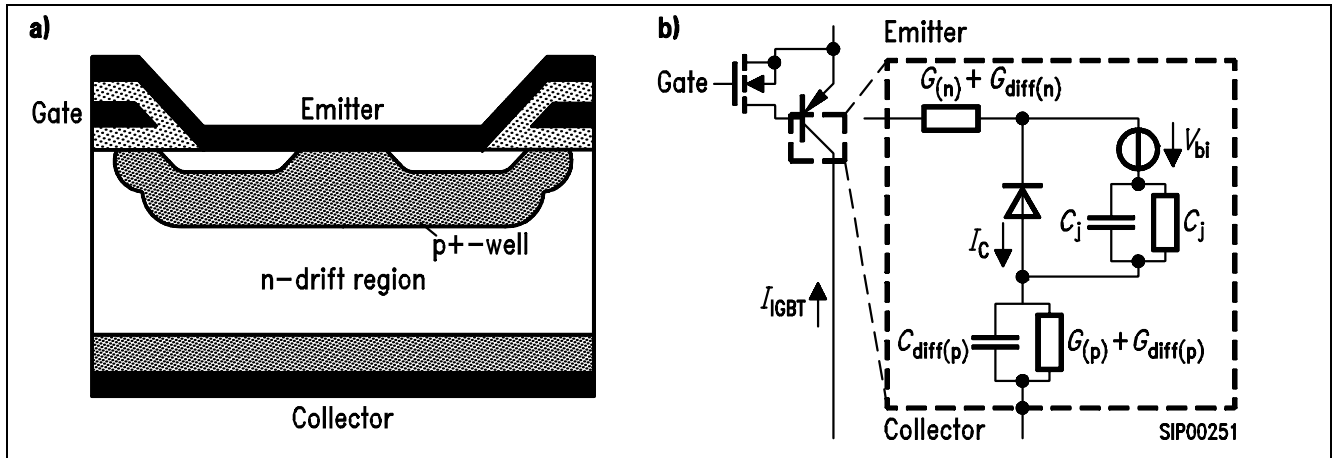


Figure 1

a) Cross Section of a NPT-IGBT

b) Equivalent Circuit for the Reverse State (It should be noted that the equivalent bipolar transistor does not reflect the properties of the forward biased device).

Further it can be written for the junction capacitance C_j using the simplification from van Halen:

$$C_j = \frac{C_0}{\sqrt{1 - \frac{V_j}{V_{bi}} + \frac{kT}{2qV_{bi}} \exp\left(\frac{q(V_j - V_{bi})}{kT}\right)}} \quad \text{equation 11}$$

with:

$$C_0 = \sqrt{\frac{q\epsilon_{si}N_B}{2V_{bi}}} \quad \text{equation 12}$$

ϵ_{si} is the permittivity of silicon and N_B is the background doping. The junction conductance is determined by the carrier density, the mobility of the carrier in the junction and its width:

$$G_j = \frac{q\mu}{L_j} \times n_i^2 \exp\left(\frac{q(V_j - V_{bi})}{kT}\right) \quad \text{equation 13}$$

μ is the ambipolar mobility, n_i the intrinsic density and L_j is the junction length. L_j can be extracted by a comparison of equation 11 with the well-known function $C = \epsilon/L$. To obtain the voltage across the junction the voltage drops across the regions adjacent to the junctions have to be calculated. The conductances caused by the impurity concentrations are to be considered in addition to the conductances caused by injected carriers.

The conductances of the n-region $G_{(n)}$ and of the p-region $G_{(p)}$ can be written as follows:

$$G_{(n)} = \frac{N_D q \mu_n}{w_{(n)}}; \quad G_{(p)} = \frac{N_A q \mu_p}{w_{(p)}} \quad \text{equation 14}$$

N_D is the donor impurity density, μ_n is the mobility of electrons and $w_{(n)}$ is the width of the n-region. N_A is written for the acceptor impurity density, μ_p for the mobility of holes and $w_{(p)}$ is the width of the p-region. In the case of small drift currents the conductances due to impurity concentrations are in parallel to the conductances due to injected carriers of the same region (condition for equation 4).

3 Simplifications for the Reverse On-State

The set of equations developed above are reduced in the special case that the IGBT is switched on during the applied reverse stress.

Then the emitter is shorted by the MOS-channel and does not affect the carrier density across the base. Therefore all terms for the emitter vanish and equation 5 becomes the Shockley equation:

$$I_C = I_{C0} \left(1 - e^{\frac{qV_{CB}}{kT}} \right) \quad \text{equation 15}$$

The voltage across the collector junction must be positive ($V_{CB} \geq 0$) to meet the condition for equation 4. That is why further simplifications are possible. A look at equations 7 - 10 shows that the time constant given by equations 7 and 9 is much larger than the same given by equations 8 and 10 for an actual device. This means that a small change of the stored charge occurs in the base until the stored charge in the collector is completely removed or until the end of injection from the junction which is the same. The stored charge in the base has not to be considered.

Figure 1b shows the equivalent circuit of the switched-on NPT-IGBT under reverse stress with small currents. It implies the equations 4 and 8 - 15.

4 Test Equipment

Test Circuit

For the measurement of reverse behavior of the IGBT a chopper circuit is supplemented with an auxiliary switch and completed with an additional inductive load in parallel to the device under test (**Figure 2a**). The inductance of the additional load L_R , is much higher than the inductance L_F . This circuit is distinguished by a minimal dependence of measured properties from auxiliary and parasitic elements and it allows the prediction of the parameters – forward current, reverse current, commutation rate, and the operating point of the MOS channel – during the commutation process.

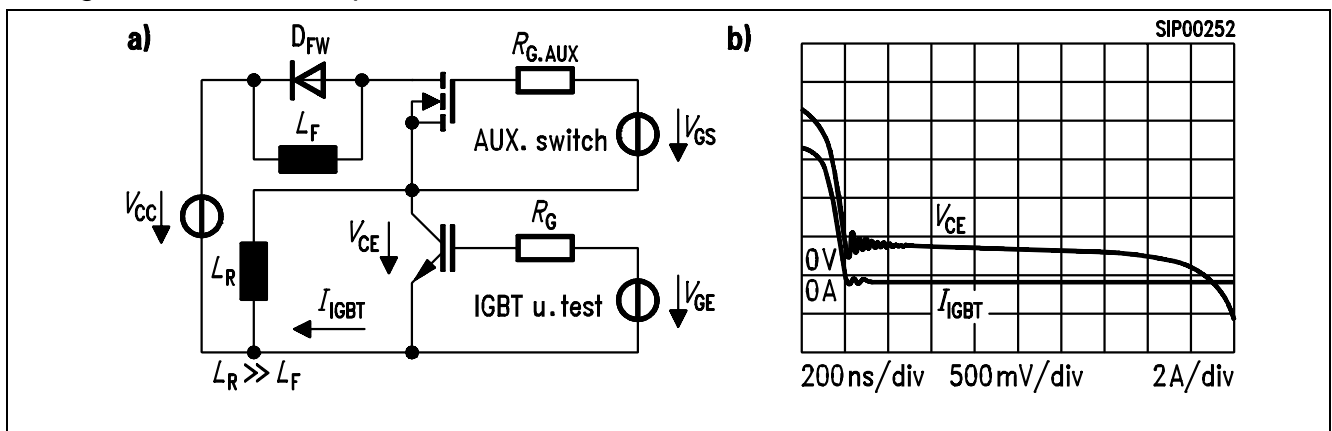


Figure 2
 a) Test Circuit;
 b) Reverse Commutation Process of a NPT-IGBT (Measured)

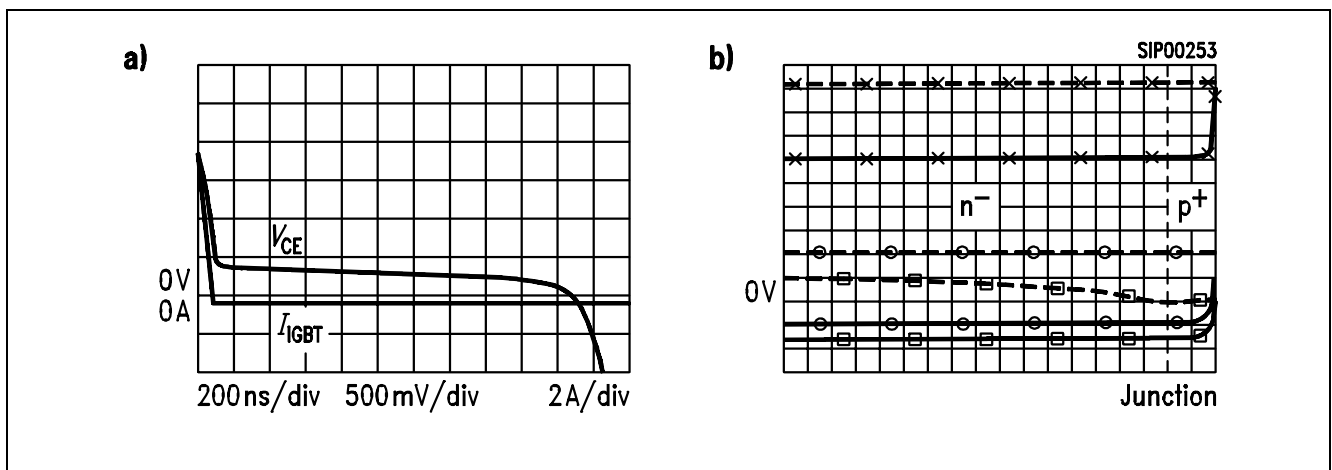


Figure 3
 a) Reverse Commutation Process of a NPT-IGBT;
 b) Inrefs of the Electrons (solid lines) and Holes (dashed lines) at Different Times as Indicated in (a) (MEDICI-simulation)

Test Cycle

In the steady state both switches of the test circuit are turned off. If the auxiliary switch turns on the current through the inductances L_R , and L_F increases to the required reverse current:

$$\Delta i_{L_R} = \Delta i_{L_F} \approx \frac{V_{CC}}{L_R + L_F} \times \Delta t \quad \text{equation 16}$$

By turning on the IGBT under test the current through L_R remains constant and the current through the IGBT and L_F (I_F) rises with:

$$\Delta i_{L_F} = \Delta i_{L_F} \approx \frac{V_{CC}}{L_F} \times \Delta t \quad \text{equation 17}$$

If the auxiliary switch turns off the current through the inductance L_F commutates to the free wheeling diode D_{FW} and the current through the inductance L_R commutates to the IGBT under test as a reverse current (I_R). The commutation rate is predicted by the gate resistance of the auxiliary switch $R_{G,AUX}$.

5 Measurement and Simulation

The investigations were carried out at NPT-IGBTs with a blocking capability larger than 1000 V. To meet the condition for equation 4 the ratio of forward and reverse current I_F/I_R has to be high. The commutation rate has to be high to prevent change of carrier distributions by recombination effects before reverse bias occurs.

Figure 2b shows measured traces of V_{CE} and I_{IGBT} of the reverse commutation process of a NPT-IGBT in its on-state from the turn-off of the auxiliary switch to the zero crossing of the voltage measured at the terminals of the IGBT under test. (It should be noted that after the IGBT current crosses zero, V_{CE} remains positive.) Actually the ratio I_F/I_R amounts to 7 A/0.4 A = 18 and the commutation time of 100 ns is much smaller than the life time of carriers.

To check the validity of the assumptions above the test has been simulated using a 2-dimensional MEDICI model of the IGBT. **Figure 3a** shows the calculated traces of voltage and current in comparison to the measurements (**Figure 2b**). **Figure 3b** contains the imrefs of electrons and holes near the collector terminal of the IGBT at different times indicated in **Figure 3a**.

Quantitative deviations are visible comparing measured (**Figure 2b**) and simulated traces (**Figure 3a**). They result from a slightly lower emitter efficiency of our collector in the measured IGBT and do not affect the formalism given in the **sections 2** and **3** qualitatively.

6 Results

The product of the reverse current I_R and the time between the zero crossings of current and junction voltage is equal to the whole charge removed from the IGBT. It includes the stored charge of the collector (equation 8) and the charge of the junction capacitance (equation 11) as well as the charge injected from the collector junction after the current zero crossing

(equation 15). The integral of the equations 8, 11, and 15 cannot be solved analytically, but numerically. However, the charges can be separated with an extrapolation of the removed charge under different reverse stress conditions.

Dependance on the Forward Current

As noted in **section 1** the whole removed charge is dependent on the forward bias before commutation. In **Figure 4a** the removed charges are plotted versus the impressed forward current. The shape of the traces show the expected resemblance with a square root relation like pointed out in (6). But Q_{REV} still contains the injected part of the charge and the parameters for the term of the storage charge cannot be extracted until the injected part is eliminated.

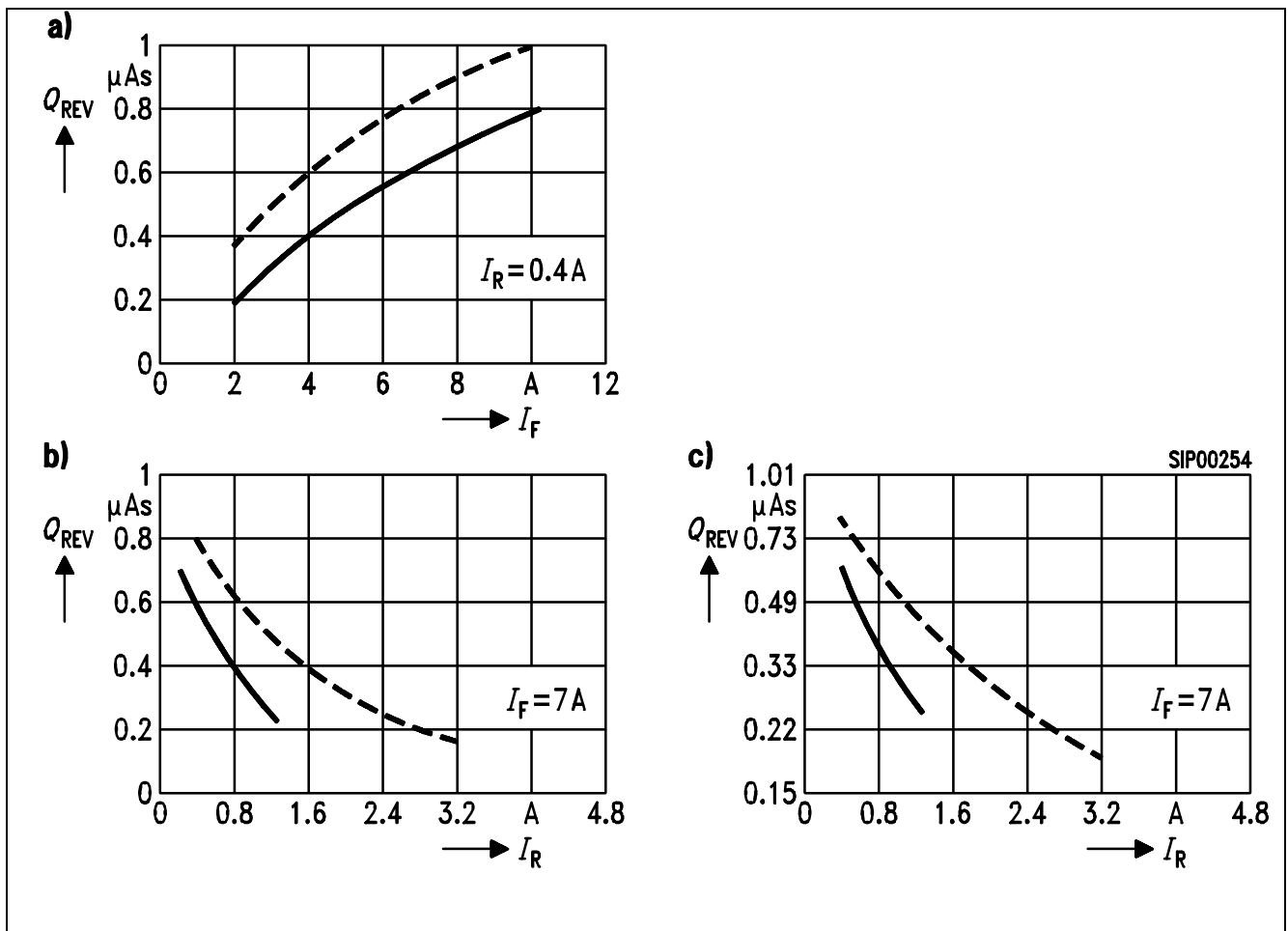


Figure 4

- a) From the IGBT Removed Storage Charge Versus the Impressed Forward Current for $I_R = 0.4 \text{ A}$;
- b) From the IGBT Removed Storage Charge Versus the Reverse Current for $I_F = 7 \text{ A}$;
- c) The same as in (b) in Semi-logarithm Plot; (solid lines-measurement, dashed lines - MEDICI simulation)

Dependance on the Reverse Current

After current zero crossing the injected part of the charge is the only one dependent on the reverse current. **Figure 4b** shows the removed charge versus the reverse current. An exact solution of the dependance appears impossible. The injection falls with decreasing junction voltage. The transient of the junction voltage is predicted by the RC-circuit formed from G_j and C_j . Both parts are non-linear and the properties of the branches cannot be determined analytically. Because the decrease of the voltage in respect to the time appears linear (**Figure 2b** and **Figure 3a**) an exponential term is expected to describe the relation between reverse current and injected charge.

Extrapolation of the Stored Charge

Figure 4c gives the results of **Figure 4b** in a semi-logarithm plot. The curve can be fitted with a function of the form:

$$y = B \exp(Ax) + C \quad \text{equation 18}$$

y , x are variables and can be replaced with Q_{REV} and I_{R} . The constants A , B and C have to be solved.

In reference to **section 2** it can be shown that the injection of charges decreases to zero, if the reverse current becomes very high. Then only the stored charge must be removed and the constant C in equation 18 has to be taken for the storage charge.

$$Q_{\text{REV}} = B \exp(AI_{\text{R}}) + Q_{\text{STOR}} \quad \text{equation 19}$$

The exponential term is the expression for the charge injected through the junction after current zero crossing. A , B and Q_{REV} can be extracted from the data of **Figure 4c** using a least-mean-squares algorithm.

The separation of the charges can be used to replace the extents of **Table 1** with a more quantitative marking. It will help designers to switch IGBTs with lower reverse stress and to obtain a higher circuit reliability.

Conclusions

Starting with an analysis of inverter circuits, the removable charge was pointed out as the essential parameter for the reverse self protection of IGBT. A model was built up describing the reverse biased IGBT with an equivalent circuit. Within the formalism reported it is not necessary to implement a model for the time dependent carrier distribution to describe the transient reverse behavior of the IGBT. Instead it is possible to calculate a consistent set of internal voltages, as well as the internal currents and carrier distributions for the time dependence of V_{CE} caused by a reverse IGBT current. According to the assumption of the model, a test circuit was realized. Measurements and simulations followed to extract the removable charge under different commutation conditions as well as the contents of the parameter Q_{REV} . The split of the parameter Q_{REV} makes it possible to find guidelines for designers applying IGBTs with low reverse stress.