

## Conductivity-Modulated FETs-IGBT

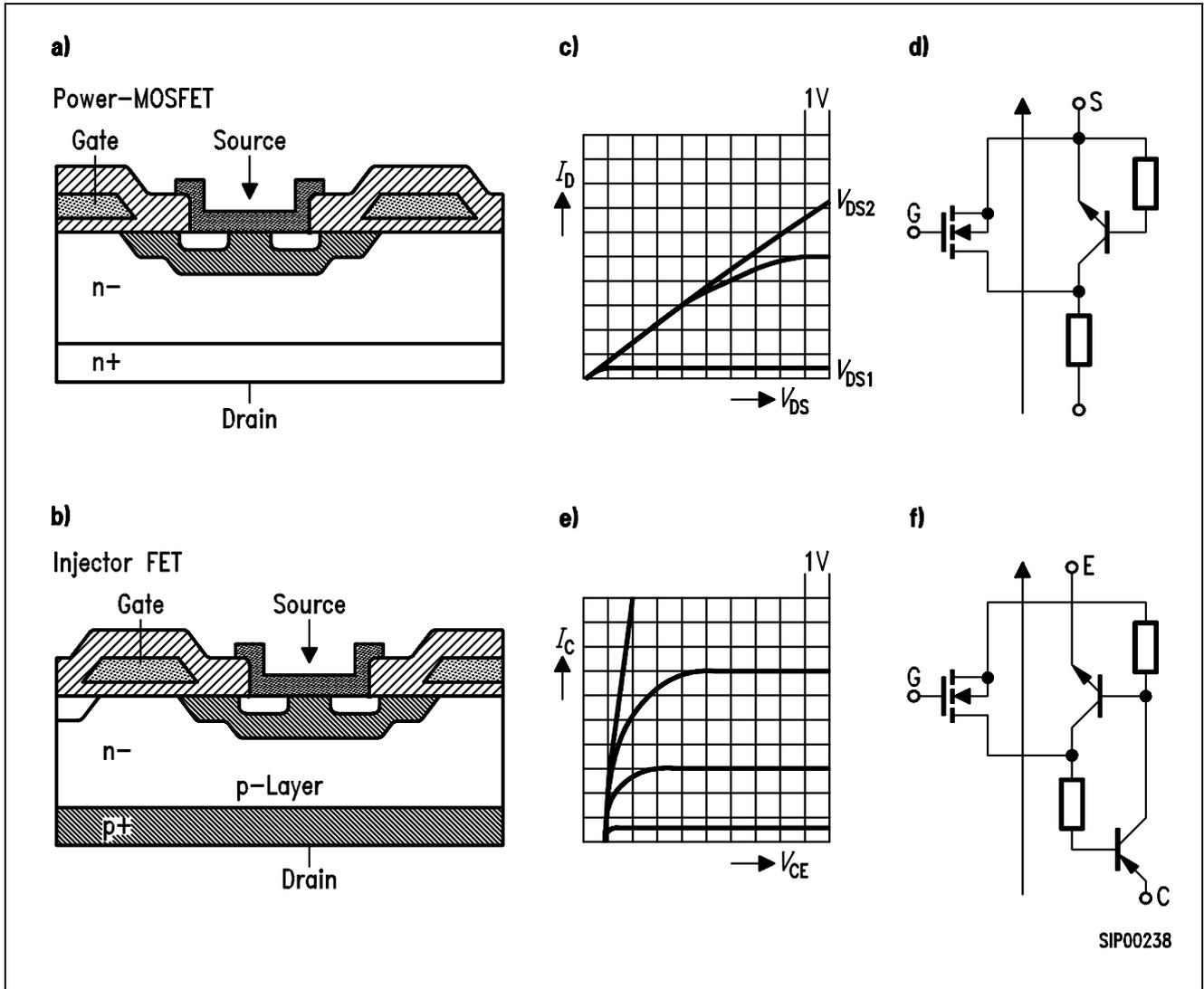
Up to a reverse voltage of  $V_{DS} \leq 200$  V, power MOSFETs are superior in all respects to any other switching devices components. With a supply voltage of  $V_B > 200$  V, the bipolar transistor has a lower saturation voltage ( $V_{CE\ sat} \leq V_{DSon}$ ) and is cheaper. In comparison with a bipolar transistor (assuming the same chip dimensions), a power MOSFET with a reverse voltage of  $V_{DS} = 1000$  V has significantly higher ON-resistance, and therefore high voltage drops and high static losses when switched on. The high ON-resistance of high-voltage MOSFETs can only be reduced by means of a larger chip surface. High-voltage MOSFETs are nonetheless used in application areas where their advantages represent a critical factor: short switching time, no storage time, easy to control the switching time, full SOA range, no second breakdown, short-circuit resistance, and ease of control.

The objective of component manufacturers is to develop a semiconductor switch whilst retaining the MOS characteristics, with a lower ON-resistance for the same chip surface. This basic concept gave rise to the development of the conductivity-modulated MOSFET (IGBT), the BIMOS switch, and the MOS-GTO.

### The IGBT

The high ON-resistance of existing high-voltage MOSFETs led to the development of this new type of transistor. It combines the characteristics of the power MOSFET with those of the bipolar transistor. The ON-resistance of the IGBT is lower than that of comparable MOSFETs of the same chip size, by a factor of 6 - 10.

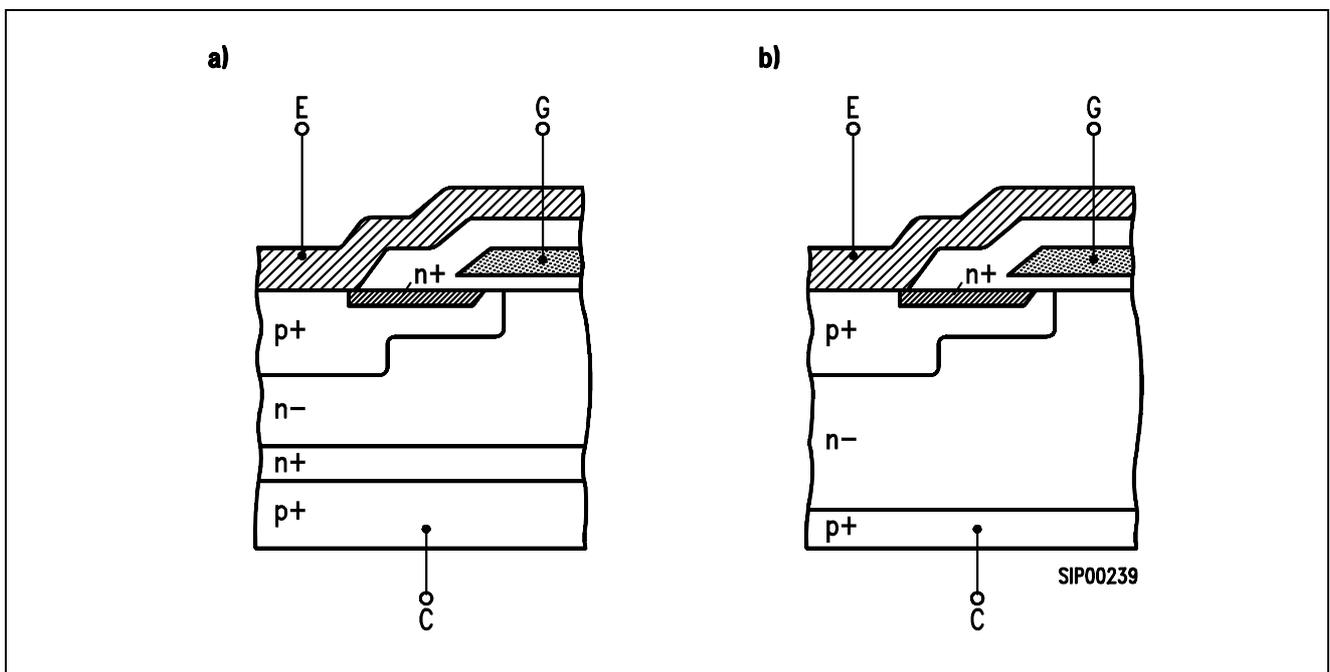
The conductivity of the epitaxial layer, and therefore the ON-resistance, is controlled by charge carrier flooding with electrons and holes. Hole injection is achieved by adding an additional  $p^+$  layer to the backside of the chip. **Figure 1** compares the semiconductor structures with electrical equivalent circuits and ON-resistance for both power MOSFET and IGBT. As can be seen from the semiconductor structures (**Figure 1a** MOSFET and **Figure 1b** IGBT), the only difference is the additional  $p^+$  layer on the IGBT.



**Figure 1**  
**Comparison of Power MOSFET and Conductivity-Modulated MOSFET**  
 a) Semiconductor Structure of the Power MOSFET  
 b) Semiconductor Structure of the IGBT  
 c) Output Characteristic Curve Range  $I_D = f(V_{DS})$  for the MOSFET  
 d) Electrical Equivalent Circuit for the MOSFET  
 e) Output Characteristic Curve Range  $I_C = f(V_{CE})$  for the IGBT  
 f) Electrical Equivalent Circuit for the IGBT

In order to exploit the many advantages of MOSFETs as power switches for even higher voltages, intensive development has been carried out into IGBT structures. It quickly became clear that a high-voltage structure offers much better conductivity if the n-channel transistor is located on p+ instead of n+ substrate. **Figure 2** shows the two most important examples of IGBT structures today. In both cases, the low-doped zone – as in a thyristor – is flooded with charge carriers when in a conducting state, thereby significantly increasing conductivity. After a number of initial problems, IGBTs have recently come onto the market offering the

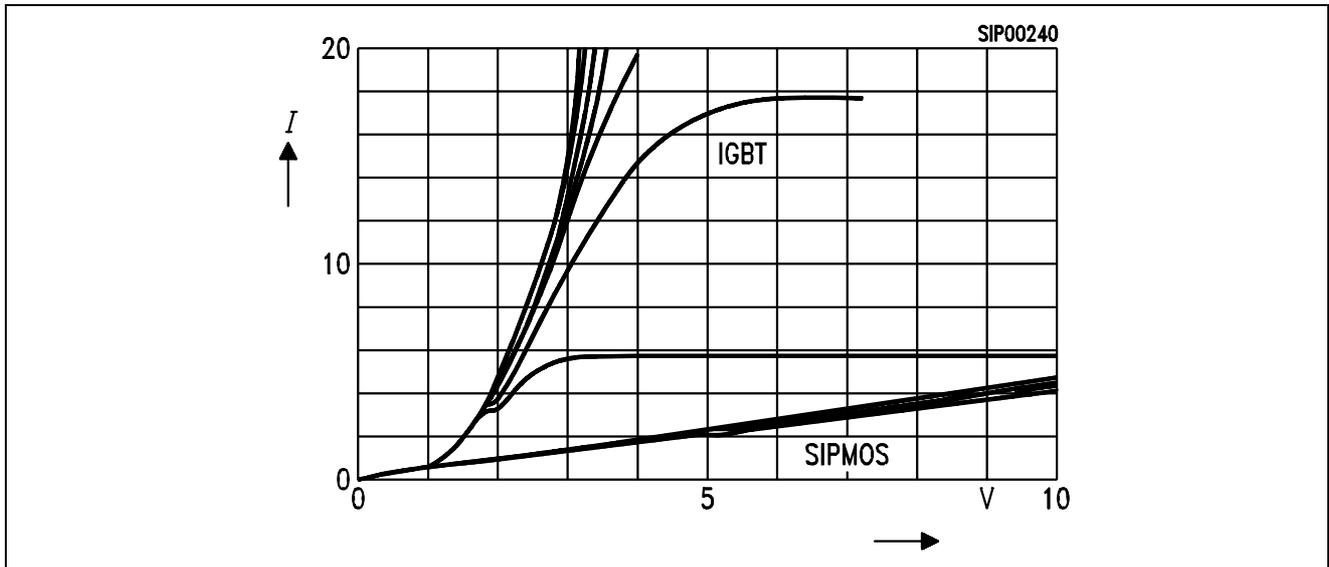
advantages of MOSFETs whilst completely eliminating the disadvantages of a high  $R_{DSon}$  in the case of high-voltage MOSFETs. Two different solutions are currently used to implement application-based IGBTs: the “epitaxy” structure (**Figure 2a**) and the “homogeneous” structure (**Figure 2b**) developed by Siemens. These are characterized by the  $p^+$  substrate and the  $n^+$  buffer layer, upon which the  $n^-$  layer and the cell structure are built. The charge carrier life is reduced by radiant exposure. With this design, as for the MOSFET, the dielectric strength is dependent on the thickness of the  $n^-$  epitaxial layer. However, the homogeneous structure is significantly simpler. It only requires a specially designed  $p^+n^-$  transition zone on the backside, and does not require epitaxy. In principle, this structure can be considered for any voltage, provided the boundary passivation is suitable.



**Figure 2**  
**Basic Semiconductor Structures for IGBTs**

- a) Epitaxy Structure
- b) Homogeneous Structure

The main advantage of using IGBTs for high-voltage applications is their superior current-carrying capacity, as shown in **Figure 3**. This diagram shows the characteristic curve range of a 42 mm<sup>2</sup> homogeneous structure, compared to an identically configured 1000-V MOSFET. Unlike the conventional MOS, a type of threshold voltage can be identified with the IGBT. This is caused by the pn transition of the collector terminal. As a result of this characteristic, ON-resistance can no longer be considered in the case of IGBTs.



**Figure 3**  
**Output Characteristic Curve Range of the IGBT and High-Voltage MOS Transistors**

In order to achieve minimum losses in the on state, the n-area (as with the saturated bipolar transistor) has to be flooded with charge carriers. However, this also means that the charge carriers must be removed when switching off. The result is an increase in switching losses due to the tail current. The charge carriers have to be reduced by recombination when disconnecting. There is a fixed relationship between the forward voltage drop in the on state and the tail current when disconnecting. Physical optimization is therefore required to combine the characteristics of good conduction and the requirements for appropriate switching speeds or timing frequency. Use of the homogeneous structure and special structure optimization have made it possible to reduce the tail losses at the same time as a good forward voltage drop.

In order to ensure the effective use of a power semiconductor component in power electronics final control elements, the following requirements must be met:

- Insensitive to parasitic reconnection when commutating
- Low forward voltage drop
- Low dynamic losses
- No latch-up response – extended SOA range
- Good short-circuit resistance on the component and disconnection control
- Parallel switching
- Insensitive to high  $di/dt$  and  $dV/dt$  values

The most important electrical characteristics of IGBTs are described below.

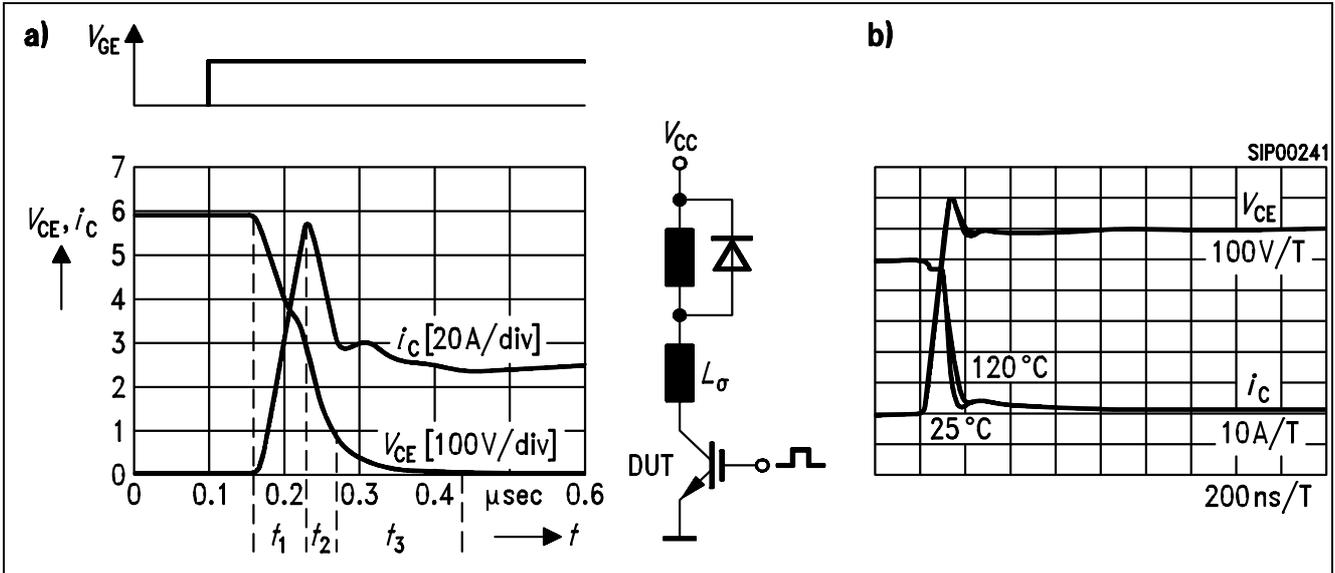
## Ease of Control

The threshold voltage of the IGBT was set specifically to  $V_{GEth} \approx 5 \text{ V}$ . This ensures that the IGBT is resistant to parasitic reconnection when these transistors are used in half-bridges or 3-phase bridge configurations, even with unfavorable conditions such as high-impedance input circuits and high  $dv/dt$  values. The rate of rise  $g_{fs}$  for the IGBT was set so that in short-circuit operation with full control voltage  $V_{GE} = 15 \text{ V}$  the current amplitude does not rise too far, so that the short-circuit resistance of the transistor is not threatened. On this basis, it is essential that the control voltage is  $13 \text{ V} \leq V_{GE} \leq 15 \text{ V}$  when switching inductive load with minimum turn-on losses. When switching on, it must in fact be ensured that the freewheeling diode of the transistor is not pushed into the pentode area during the recovery time. The switching times which can be achieved are in the same range as those of MOS transistors. The switching time itself can be controlled with a given control voltage by adding a gate resistor.

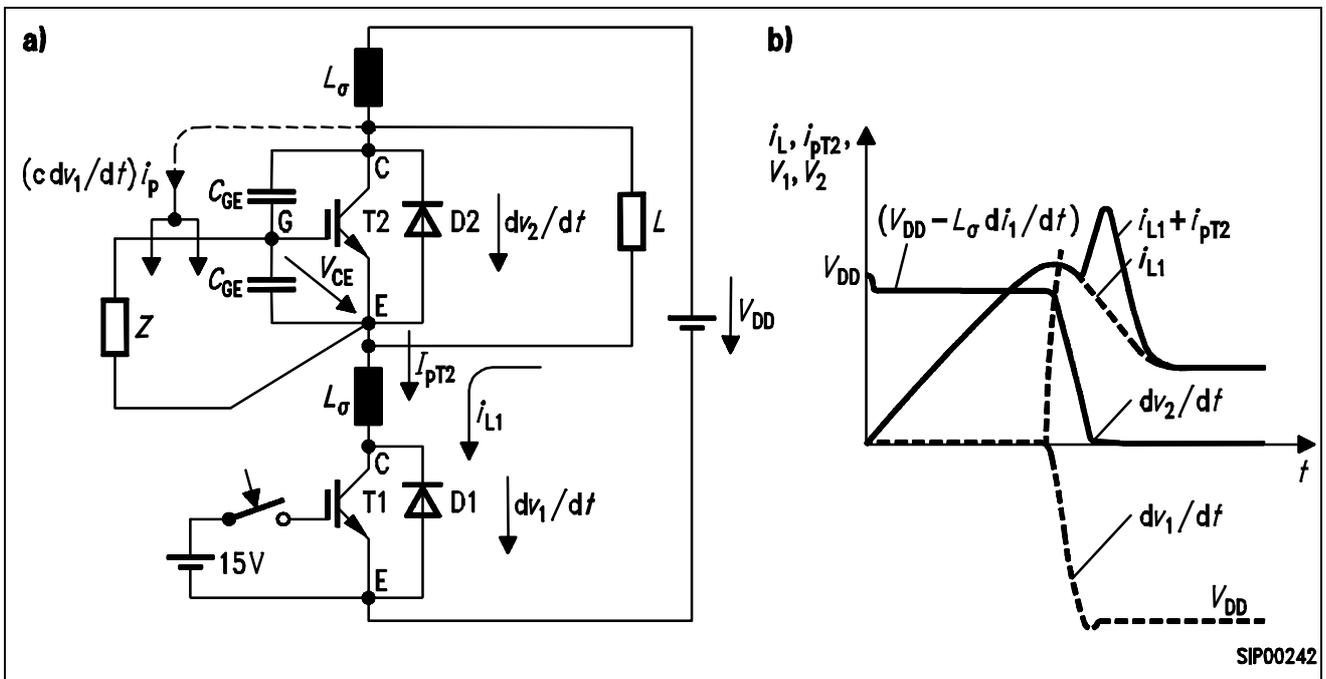
## Switching Performance of the IGBT

The IGBT turn-on performance is the same as that of the power MOSFET, with the exception of the dynamic saturation phase. The switching signal edge can be set easily and accurately by means of a gate resistor  $R_G$ . Like the bipolar transistor, the IGBT has a dynamic saturation phase. The dynamic saturation phase is required in order to flood the  $n^-$  area with charge carriers. **Figure 4a** shows the typical turn-on performance of an IGBT (50 A/1000 V). The turn-on operation is divided into 3 intervals. Interval 1 is characterized by the influx of the supply voltage due to the circuit inductance  $L_\sigma$  ( $v(t) = L_\sigma \times di/dt$ ). In Interval 2 the diode receives voltage. The  $dv/dt$  is determined by the diode response or/and the control characteristics of the IGBT. This  $dv/dt$  can be controlled via a gate resistor. Interval 3 is determined by the saturation phase. The turn-off performance is determined largely by the tail current. The tail charge has a considerable effect on the turn-off losses. Since the tail current for NPT IGBTs is set by the emitter efficiency level of the backside  $n^-p^+$  transition, the tail current is virtually temperature-independent. **Figure 4b** shows the turn-off performance of an NPT IGBT for two different temperatures.

High  $dv/dt$  values, such as those that can occur when commutating inductive load currents from the freewheeling circuit to the transistor being turned on ( $dv/dt > 5 \text{ kV}/\mu\text{s}$ ), can result in the anti-parallel transistor being switched into the conductive state, as shown in **Figure 5**. **Figure 5** shows the electrical equivalent circuit for an IGBT in its simplest form, with the input capacities and current flow when it is turned on. As soon as  $dv/dt$  values are applied to the transistor, parasitic dielectric current occurs at the transistor input due to the feedback capacitance, and this results in a voltage build-up and parasitic reconnection of the IGBT depending on the impedance. The parasitic reconnection can be clearly seen in the diode return. The  $dv/dt$  resistance of a freewheeling bridge branch is dependent on the threshold voltage level of the IGBT, the negative cutoff voltage  $V_{GE}$ , and the low impedance of the driver stage. In the case of high  $dv/dt$  values, it is advisable to ensure that the impedance of the driver stage is sufficiently low, or to allow for negative voltage when disconnecting.



**Figure 4**  
**Switching Performance of the IGBT**  
 a) Temporal Course of  $V_{CE}(t)$  and  $i_C(t)$  when Turning on, Divided into Turn-on Intervals  
 b) Temporal Course of  $V_{CE}(t)$  and  $i_C(t)$  when Turning off the NPT IGBT at 25 °C and at 125 °C



**Figure 5**  
**Parasitic Reconnection of the IGBT**  
 a) Electrical Equivalent Circuit Diagram with the Main Electrical Components  
 b) Temporal Course of Current  $i_C(t)$  when Turning on with Parasitic Resistance