

**Table 4.3** Characteristics of several commercial IGBTs

Part number	Rated maximum voltage	Rated average current	$V_F$ (typical)	$t_f$ (typical)
Single-chip devices				
HGTP12N60A4	600 V	23 A	2.0 V	70 ns
HGTG32N60E2	600 V	32 A	2.4 V	0.62 $\mu$ s
HGTG30N120D2	1200 V	30 A	3.2 V	0.58 $\mu$ s
Multiple-chip modules				
CM400HA-12E	600 V	400 A	2.7 V	0.3 $\mu$ s
CM300HA-24E	1200 V	300 A	2.7 V	0.3 $\mu$ s
CM800HA-34H	1700 V	800 A	3.3 V	0.6 $\mu$ s
High voltage modules				
CM 800HB-50H	2500 V	800 A	3.15 V	1.0 $\mu$ s
CM 600HB-90H	4500 V	900 A	3.3 V	1.2 $\mu$ s

the expense of a somewhat increased on-resistance. The current gain of the effective PNP transistor can also be minimized, causing  $i_1$  to be greater than  $i_2$ . Nonetheless, the turn-off switching time of the IGBT is significantly longer than that of the MOSFET, with typical turn-off times in the range 0.5  $\mu$ s to 5  $\mu$ s. Switching loss induced by IGBT current tailing is discussed in Section 4.3.1. The switching frequencies of PWM converters containing IGBTs are typically in the range 1 to 30 kHz.

The added  $p-n$  diode junction of the IGBT is not normally designed to block significant voltage. Hence, the IGBT has negligible reverse voltage-blocking capability.

Since the IGBT is a four-layer device, there is the possibility of SCR-type latchup, in which the IGBT cannot be turned off by gate voltage control. Recent devices are not susceptible to this problem. These devices are quite robust, hot-spot and current crowding problems are nonexistent, and the need for external snubber circuits is minimal.

The on-state forward voltage drop of the IGBT can be modeled by a forward-biased diode junction, in series with an effective on-resistance. The temperature coefficient of the IGBT forward voltage drop is complicated by the fact that the diode junction voltage has a negative temperature coefficient, while the on-resistance has a positive temperature coefficient. Fortunately, near rated current the on-resistance dominates, leading to an overall positive temperature coefficient. In consequence, IGBTs can be easily connected in parallel, with a modest current derating. Large modules are commercially available, containing multiple parallel-connected chips.

Characteristics of several commercially available single-chip IGBTs and multiple-chip IGBT modules are listed in Table 4.3.

#### 4.2.5 Thyristors (SCR, GTO, MCT)

Of all conventional semiconductor power devices, the silicon-controlled rectifier (SCR) is the oldest, has the lowest cost per rated kVA, and is capable of controlling the greatest amount of power. Devices having voltage ratings of 5000 to 7000 V and current ratings of several thousand amperes are available. In utility dc transmission line applications, series-connected light-triggered SCRs are employed in inverters and rectifiers that interface the ac utility system to dc transmission lines which carry roughly 1 kA and 1 MV. A single large SCR fills a silicon wafer that is several inches in diameter, and is mounted in a hockey-puck-style case.