Celebrating 30 Years of Coverage

# Advances in Discrete Semiconductors March On

**By Steve Grossman**, Contributing Editor

The past three decades have heralded the introduction of MOSFETs, IGBTs, silicon, Schottky and silicon-carbide Schottky diodes, as well as continuing advances in high-voltage rectifiers.

It is really quite ironic, but we usually think of an invention as an ending to what is often an almost superhuman effort. But inventions are more like beginnings. Take for instance the transistor. Thanks to messieurs Bardeen, Brattain and Shockley, it had its beginnings in 1947. But it wasn't long before users bumped into a ceiling with regard to transistor performance, which in turn spawned the power MOSFET followed up by the IGBT. As we outlined in an earlier article, Hitachi invented what ultimately became the VMOS about 1969, then Siliconix introduced its VMOS in 1975 and International Rectifier unveiled the HEXFET in 1978.[1] So, let's pick up in the same decade, focusing on how the drive for less bulky power supplies brought on some extraordinary developments in what we know today as the power MOSFET (**Fig. 1**).

## The Early Days of the Power MOSFET

Nathan Zommer, who today is president and CEO of IXYS (Santa Clara, Calif.), recalls some of the power discrete devices when they were truly in their infancy. "In 1976, after pioneering work done by Signetics and people at Siliconix on V-Groove MOSFETs, the New Jersey division of Hewlett-Packard in Rockaway, N.J., which built power supplies, began their quest for a better discrete power device to support HP and IBM computers," says Zommer.

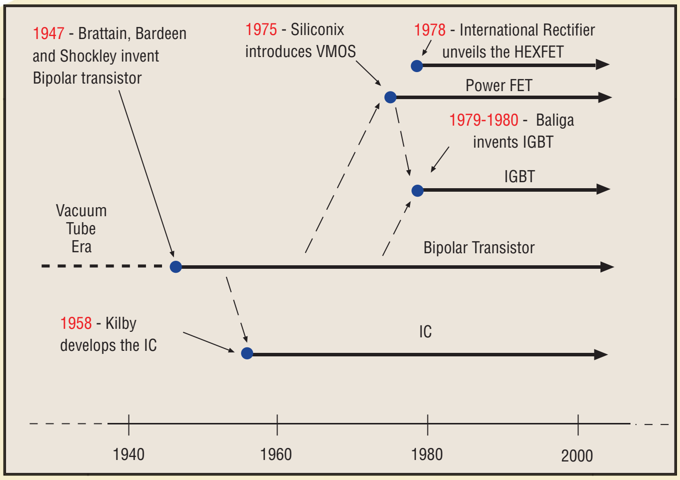


**Fig. 1** .*Chronology for some discrete power devices. Dotted arrows denote that various discrete power inventions descended from earlier solid-state devices.*

The New Jersey division contacted HP Labs in Palo Alto, Calif., as well as one of the giants of the power transistor world, John Moll, who at that time was the director of HP Labs. What they had in mind was raising the switching frequency of the switched-mode power supply from 20 kHz to 300 kHz, and they needed better performance than a bipolar device could provide.

HP Labs came up with the concept and Moll led the team that developed a version of the MOSFET, which became known as D-MOS, with the "D" standing for double-diffused. They began the project, doing the initial analysis at HP Labs, which at that time was closely associated with Stanford University.

"I did my Ph.D. at Carnegie Mellon on power transistors," says Zommer. "And HP's New Jersey division recruited me with the sole purpose to commercialize the power MOSFET. By the time I joined HP Labs in the spring of 1977, they already had fabricated prototypes of the DMOS," he says.

At HP, there were in fact two teams, one team going the DMOS route and the other team working on the V-Groove MOSFET. The DMOS team was able to demonstrate that the DMOS would win—and this was back in 1977. The team showed that the DMOS was superior with its lower on-resistance and higher breakdown voltage. Here is what was decisive: At that time, the V-Groove device could not reach much above 400 V. HP's power supply group had to have a device that would handle 450 V. So the DMOS team fabricated their DMOS devices and supplied them to HP Labs.

Zommer also helped B. Jayant Baliga commercialize the IGBT in the 1980 time frame. Zommer built the first IGBTs under the direction of Baliga, who invented the device at the General Electric R&D labs in Schenectady, N.Y. Together they delivered their first paper on IGBTs in 1981. Zommer eventually founded IXYS in 1983.

## Enter the IGBT

The IGBT combines the best of the bipolar transistor and the MOSFET—and by best, we mean low conduction losses at high voltages. An IGBT can be thought of as a MOSFET with a PNP embedded in it as depicted in **Fig. 2.**

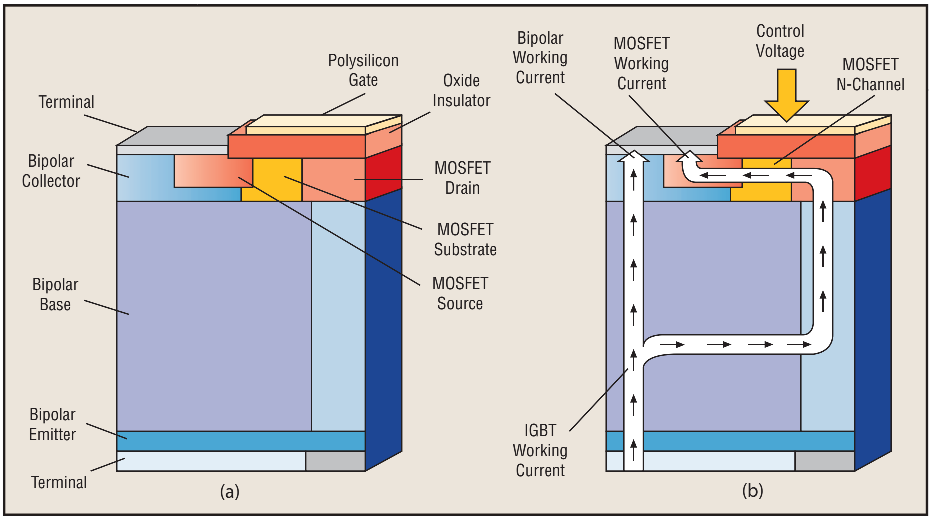


**Fig. 2.** *IGBT builds on bipolar and MOSFET design. An IGBT employs both bipolar and MOSFET building blocks (a); consequently, IGBT current, shown in IGBT ON state (b), comprises both bipolar and MOSFET currents.*

However, IGBTs have become faster and faster, and in some circuits have replaced power MOSFETs in motor-control and power-factor correction circuits. They can switch today in less than 100 ns, in contrast to 3 µs 20 years ago. Also, their efficiency has been enhanced over the years, thanks to a lower effective on-resistance. Before its speed was enhanced, it simply could not be used in circuits operating above 15 kHz.

Today, the issues relating to the choice of using which device—IGBT or MOSFET—centers heavily on voltage and frequency. Other issues are listed in the **table**, as well as typical applications for each device type.

## Another Viewpoint

"I go back to 1985, and that was the time that the

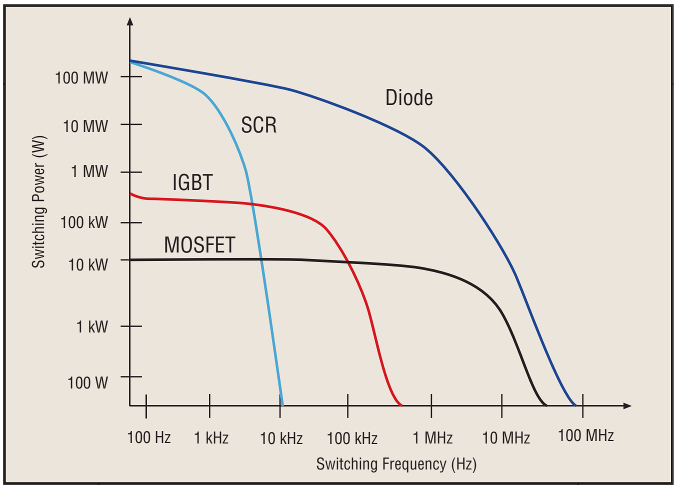


**Fig. 3.** *Curves of switched power versus switching frequency mark the boundaries of the deliverable power, to the left of each curve, of four of the principal discrete power devices. Although the IGBT is able to handle more power than the MOSFET, it falls short with regard to switching frequency capability, by about two orders of magnitude.*

transition from bipolar to MOSFETs was well underway," says Dhaval Dalal, technical marketing manager, power supplies, at ON Semiconductor (Phoenix). (ON Semiconductor was spun off from Motorola, so it has a legacy of Motorola power semiconductor devices that goes a long way back.) Dalal joined ON three years ago, but prior to that, while at Digital Equipment Corp., he and his colleagues were following MOSFETs and were impressed with how their reliability was clearly improving. Of course, from the start it was quite clear that MOSFETs were much easier to drive than bipolars.

In recent years, driven by Intel (Santa Clara, Calif.) and the advances in motherboard configurations, there has been a very high proliferation of low-voltage MOSFETs entering such designs. This has been driven by significant technology growth, by ON Semiconductor and other MOSFET suppliers who have brought down the $R_{DS(ON)}$ significantly—from hundreds of milliohms to single-digit milliohms, in many cases as low as 3 mΩ. This is particularly appealing for powering microprocessors in voltage regulator module (VRM) power.

There are some applications in which gate charge is more of an issue than on-resistance. Reducing the ohms per square (or milliohms per square) through process improvements and enlarging so that more cells are connected in parallel will always bring about a lower $R_{DS(ON)}$. However, with much larger dice, the gate charge can increase significantly, and that can bite you because of the increase in switching losses that occur due to the frequent on/off transitions.

In the late 1980s and early 1990s, it looked as if IGBTs would really take over from MOSFETs. But for a number of reasons, MOSFETs remained the favorite in the power conversion industry (**Fig. 3**). Obviously, IGBTs have done very well in motor drives and other applications where frequencies are relatively low. But in switched-mode power supplies, MOSFETs have retained their commanding position.

## High-Voltage and Schottky Diodes

Luigi Merlin, rectifier R&D director at International Rectifier (IR; El Segundo, Calif.), has been engaged in the development of rectifiers for 29 years. As he recalls, at the end of the 1970s and in the early 1980s, diodes were still being fabricated as 1.2-in. (30 mm) wafers. Back then, ion implanting was not yet available, so diffusing impurities in silicon relied solely upon diffusion processes. Early market applications included automobile alternators and welding applications. But IR was also delivering high current diodes for electric and diesel-electric locomotives that required delivering 120 A to 600 A in 1600-V to 2400-V operating conditions.

Today Schottky diodes are being designed into handheld equipment, particularly where holding the forward voltage ($V_F$) to very low values is essential. With 30-V devices, it is not uncommon to have $V_F$ as low as 0.33 V. In order to keep up with the increasing power density trends in handheld portables, one company has introduced Schottky diodes using the Chipscale concept where the die itself becomes the package in order to reduce the component size.

Another benefit delivered by Schottky diodes is higher switching speeds, since the Schottky is in fact a zero-time recovery device, unlike the traditional PIN diode in which minority carrier recombination slows the switching speed. But, on the other side is the limitation on overvoltage in conventional Schottky diodes, which is about 200 V.

Over the years, improvements in semiconductor process technology have shrunk the size of Schottky diodes. As an example, consider International Rectifier's IR140CSP: Described as a Flipky because of its flip-chip, surface-mount packaging, this 1-A, 40-V Schottky diode occupies a

| IGBTs Preferred | MOSFETs Preferred | IGBT Applications | MOSFET Applications |
|---|---|---|---|
| High duty cycle | Low duty cycle | Motor control | Switched-mode power supplies |
| Frequencies of 20 kHz or less | Applications of 200 kHz or more | Uninterruptible power supplies | Battery charging |
| Small line or load variation | Wide line or load variation | Welding | |
| High-voltage applications of 1000 V or more | Low-voltage applications of 200 V or less | Low power lighting | |
| Output power of 5 kW or more | Power outputs of 500 W or less | | |
| Junction temperatures of 100°C or more | | | |

**Table.** *IGBTs versus MOSFETs.*

total area of 2.25 $mm^2$ with a profile of less than 0.8 mm (**Fig. 4**). Contrast that with the first surface-mount, 1-A Schottky diode, introduced in the late 1980s, which required 15.4 $mm^2$ of board real estate.

## Silicon Carbide Energy Savings

Though Schottky diodes entered the marketplace about 35 years ago, the silicon-carbide version has only been on the market for about three years, according to Michael O'Neill, an applications engineer at Cree (Durham, N.C.). With regard to traditional Schottky diodes employing silicon, there are 200-V devices on the market, but typically their highest rating is up 100 V and that is as far as they go. But using silicon carbide, you can fabricate a Schottky diode that exhibits a higher electrical field breakdown, so that you can ultimately operate in the kilovolt region.

Cree is marketing Schottky diodes with operating voltages of 300 V, 600 V and 1200 V. The silicon carbide diode family that Cree markets has only become feasible in the last few years because pricing has diminished. Moreover, it's projected that prices will continue to decline. Currently, Cree is fabricating silicon-carbide diodes on 3-in. wafers, but they expect to move to 4-in. wafers over the next 12 to 18 months, almost doubling the area-per-wafer, which will enable a significant price reduction.

As the price drops, many more applications will become viable, including motor drives where, starting with a fixed-voltage and frequency from the power line, say 480 Vac and 60 Hz, you rectify it, turning it into 650 Vdc. And then, using an inverter, the dc is transformed back into a variable-voltage/variable-frequency ac driving source, which in turn drives the ac induction motor.

A typical inverter driving a three-phase motor comprises three half-bridges with IGBTs and companion free-wheeling diodes. The drive operates as a linear voltage-frequency controller beginning at 0 V, 0 Hz and rising to 60 Hz and 480 V, which plots as a straight line on a frequency-versus-voltage plot.

Here is the primary benefit that a silicon-carbide Schottky diode brings to a power-switching application when employed in a motor drive: There are free-wheeling diodes in the inverter section. When the IGBT in the lower part of the half-bridge turns on, the reverse recovery current is added to the current flowing in the IGBT portion of the switch. With the traditional PIN diode, there is an extra pulse of current that passes through the switch, whereas with a silicon-carbide diode you don't get that at all. So, the use of a silicon-carbide diode reduces the switching loss not only in the diode itself, but in the associated switch.

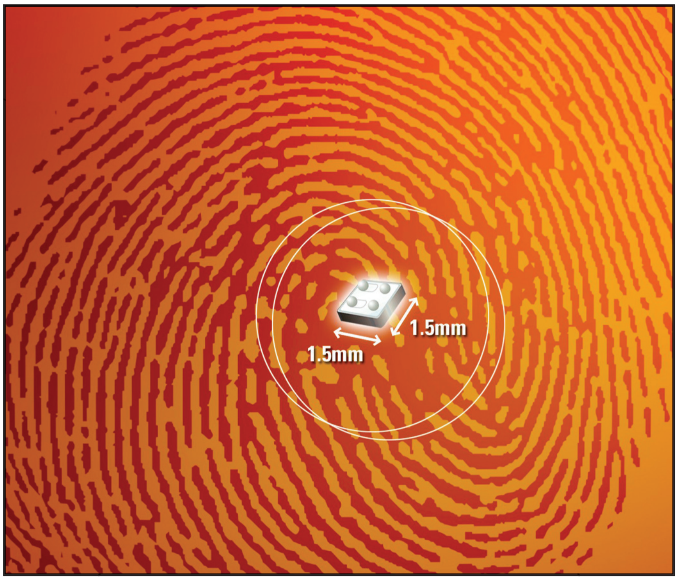


**Fig. 4.** *With its 1.5-mm x 1.5-mm footprint, International Rectifier's IR140CSP 1-A Schottky diode, shown here superimposed on a fingerprint, is nearly seven times smaller than the first surface-mount, 1-A Schottky introduced in the late 1980s.*

When you can control the voltage and frequency of the power supplied to a motor, you are varying the motor output, delivering only the power that you need rather than hanging the motor on the line and gearing it to whatever speed is needed. This means there is a huge amount of waste in motors that run flat out and are geared down to deliver the power required. But with the variable-voltage/variable-frequency drive in series with a motor, only the power required to drive the motor in its particular application is consumed. That is why variable-frequency drives are such major contributors to power savings.

As for the silicon-carbide diode, it will contribute about a 1% to 2% increase in motor-drive efficiency depending on frequency, which is really significant when you realize that over half of all power produced goes to driving motors. Today, more than 60% to 70% of all motors run right off the power lines, so only about 30% to 40% have drives controlling them. By adding more variable-voltage/variable-frequency driven motors that employ silicon-carbide Schottkys, the potential savings in electricity will indeed be huge. **PETech**

## References

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