High-voltage GTO thyristors streamline power-switching circuits

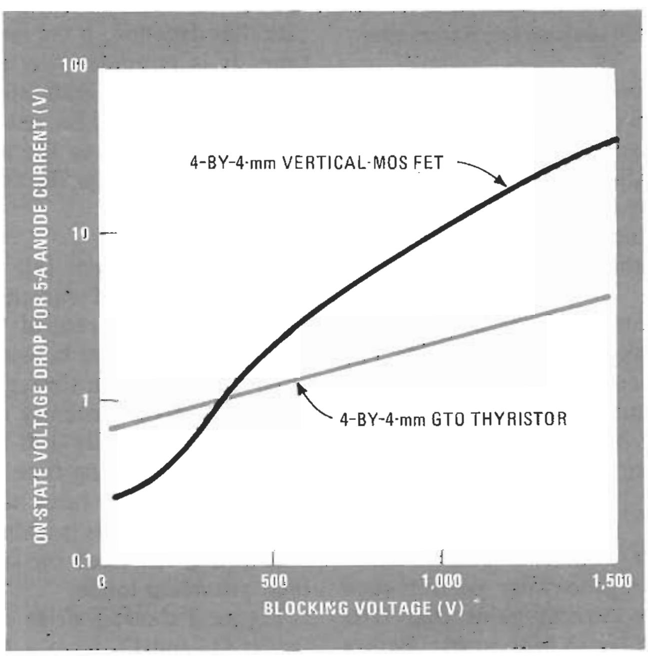
Advanced processing produces gate-turn-off devices with high yields as well as high reliability

by Arthur Woodworth, *NV Philips, Power Semiconductor Division, Stockport, UK*

☐ High-power, high-frequency switching is beyond the reach of most power semiconductors, even vertical-MOS field-effect transistors. Yet the number of applications in which high voltages as well as high currents must be switched is on the rise—for instance, in preventing line pollution due to phase control or in switch-mode systems and in TV horizontal deflection circuits.

A new gate–turn-off thyristor supplies this need. Its use of 5-volt, 200-milliampere drive circuitry makes it especially appealing for use with microprocessors. Moreover, up-to-the-minute processing and circuit-design techniques enable it to be produced in volume with high yields and hence microprocessor-compatible prices—$2 each in quantities of 10,000 or more.

Unlike other thyristors, GTOs not only switch on fast but also switch off fast. Unlike bipolar transistors, they can handle current surges and high voltages without burning out, yet their switching speed is comparable and their drive circuitry about as simple.



1. High voltage. On-state voltage drop of V-MOS power transistors forbids high-voltage ratings in a small chip, while GTO thyristors can block 1 kV with tolerable on-state losses. Voltage drop is lower because both electrons and holes carry current.

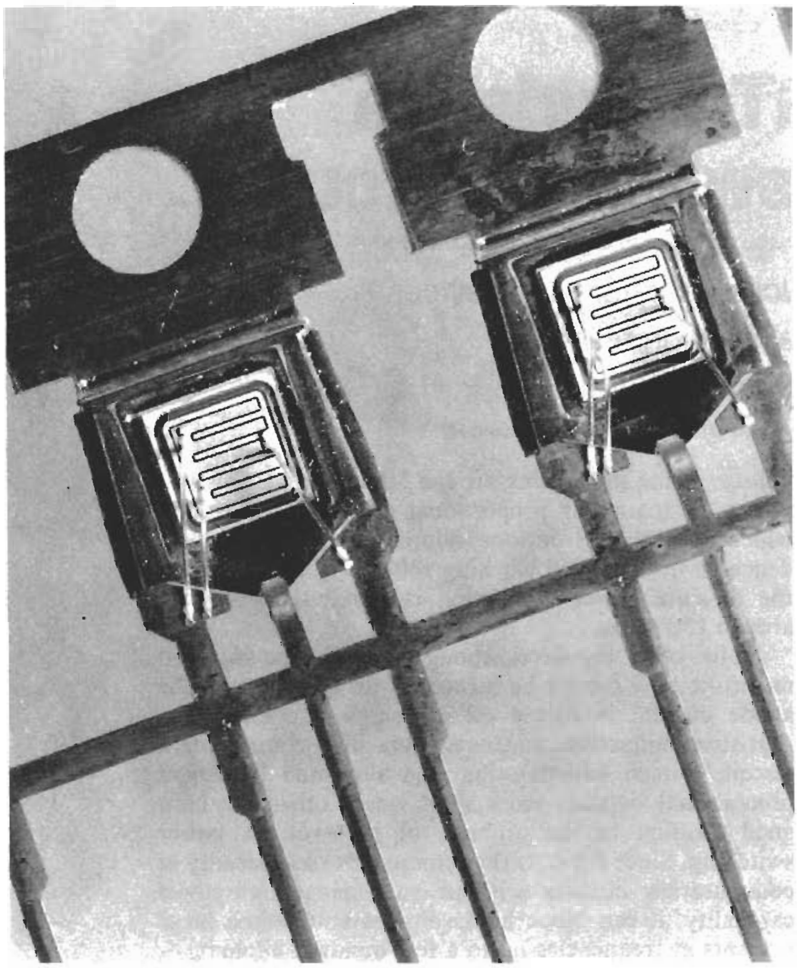
The GTO's nearest competitor is the V-MOS FET, which switches much faster and requires only a low drive current. But unless expensively large, V-MOS FETs have a much higher on-resistance, in the region of several ohms, at voltages above 400 V.

As in other thyristors, the GTO structure is filled with minority carriers of both polarities in the on state. Since both electrons and holes participate in conduction, a thyristor allows a high current density with a relatively low voltage drop, as compared to MOS devices. For example, a 4-millimeter-square, 1,500-V GTO thyristor such as the new BTW58 passes 5 amperes with about a 3-V drop, whereas a V-MOS device of the same size and voltage rating would drop around 30 V (Fig. 1). On-state power dissipation is proportional to the on-resistance, which for the MOS devices follows a power-law dependence on the designed blocking voltage. In this example, the on-state power dissipation is prohibitively high—around 150 watts.

As for other thyristors, though they can be switched on easily, they cannot be turned off using the gate. The anode current is forced off by employing additional thyristors, inductors, and capacitors in a commutation circuit. Forced commutation is a slow and inefficient process that detracts from what would otherwise be a good solution to the problem of high-voltage power switching. Since the GTO thyristor avoids the necessity of commutation circuits without sacrificing high-power capability, it can block high voltages and switch large currents at frequencies up to a few hundred kilohertz—comparable to bipolar transistor speeds.

The GTO thyristor is an npnp structure that can be analyzed in terms of merged npn and pnp transistors with common-base current gains of α_n and α_p. Gate current injected into the center p-type region—or base—drives the npn device; this current multiplied by the gain of the npn device drives the pnp transistor, where it is multiplied by this device's gain and fed back to the npn unit—and so on, in a regenerative loop.

The transistor current gains are small at low currents, so a certain minimum anode current must be established through the device before the positive feedback condition is met. This minimum defines the gate turn-on current. Once the anode current is such that $\alpha_n + \alpha_p > 1$, the device latches and the gate cur-



2. Small and rugged. Philips BTW58—a 5-A GTO thyristor—fits on a 4-by-4-mm chip. The interdigitated gate pattern visible in this cut-away view contributes to the gate–turn-off capability and lowers the gate's resistance. The small TO-220 package keeps costs down.

rent can be removed without losing conduction.

In other thyristors, $\alpha_n + \alpha_p$ is made as large as possible to reduce the on-state voltage drop and the turn-on current. Because of the high gain, it is impossible for the available gate current to halt conduction; switching a larger gate current requires the additional turn-off circuitry that has to employ other thyristors as well as passive components.

With GTO thyristors, current gains are controlled so precisely that their sum only slightly exceeds unity. The gate current required to switch off the device can then be provided by a simple drive circuit. In the case of the BTW device, advanced processing techniques and strict process monitoring achieve the necessary control over these crucial device parameters.

Precision processing

Recent advances in device processing permit such tight control of the thyristor current gains that GTO devices are now being produced with high yields. Before processing begins, computer modeling of the device's switching behavior establishes the optimal current gains for the component transistors, for it is on the careful balancing of the npn and pnp transistors' current gains that GTO thyristor reliability depends.

To achieve this balance in practice, proper doping profiles must be obtained. Neutron doping of the starting ingots adjusts the background resistivity to within a narrow window, so that subsequent ion implantation of the wafers sliced from it will consistently produce the required profiles.

Finally, glass passivation of power-switching chips is essential to their stable, high-voltage performance at high temperatures. By incorporating techniques similar to those used on triacs and thyristors, GTOs are being produced with a mean time before failure of more than 100,000 hours.

Fast switching

Careful processing also minimizes the GTO thyristor's turn-off time within the constraints of the desired blocking voltage, current density, and on-state resistance. The turn-off time has two components: the storage time and the fall time. In the storage phase, the conducting channel is squeezed down to a narrow filament connecting anode and cathode.

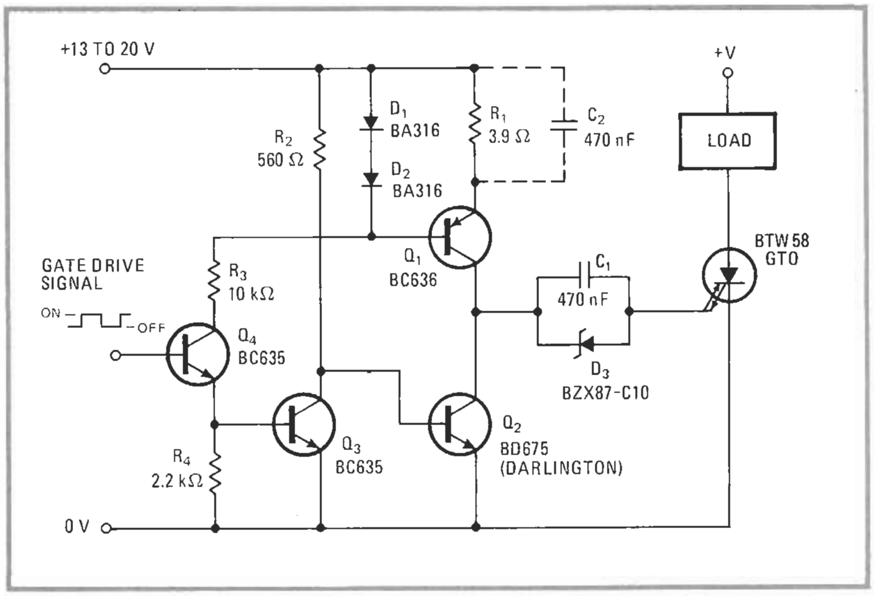
Two strategies minimize this delay. First, the cathode is formed as a pattern of long narrow fingers over the gate region, giving a low-resistance path out of the p base (Fig. 2). Fine-line photolithography is required to produce this interdigitated pattern, which allows the gate to exert strong control over the anode current, enhancing the gate–turn-off capability. Second, the cathode-gate junction is made to withstand 10 V or more before breakdown, since a larger applied field during turn-off allows larger anode currents to be turned off. The optimal base doping level is dictated by the tradeoff between low resistance and high breakdown voltage.

When the filament joining cathode and anode breaks, the device current falls and the anode voltage rises at a rate that depends on the load. This is the start of the fall time. It is minimized by providing shorts between the anode and the pnp transistor's n-type base. This internal base, which otherwise has no direct connection to the outside, is shorted to the anode by masking the boron-diffused region under the cathode fingers.

Drive circuit

The anode current fall time depends heavily on the size of the turn-off current supplied to the gate of the device. A gate current of 1 A on the BTW58 turns off 5 A of anode current in less than 1 μs. If the drive signal pulls the gate down through such a low impedance that the gate current instantly equals the anode current, the fall time is typically 100 ns—comparable to a bipolar transistor's switching time. In this unity-gain mode, the device can tolerate rates of change of the anode voltage of up to 10 kV/μs without spurious turn-on, thereby eliminating the need for snubbing networks along with their attendant losses.

Figure 3 shows a drive circuit for the BTW58. Transistors Q_1 and Q_2 form a high-current push-pull output stage driven by Q_3 and Q_4. A positive gate signal at the base of Q_4 turns on current source Q_1, which turns on the GTO via capacitor C_1. In turning off, Q_2 sinks a large current from the thyristor gate, rapidly halting conduc-

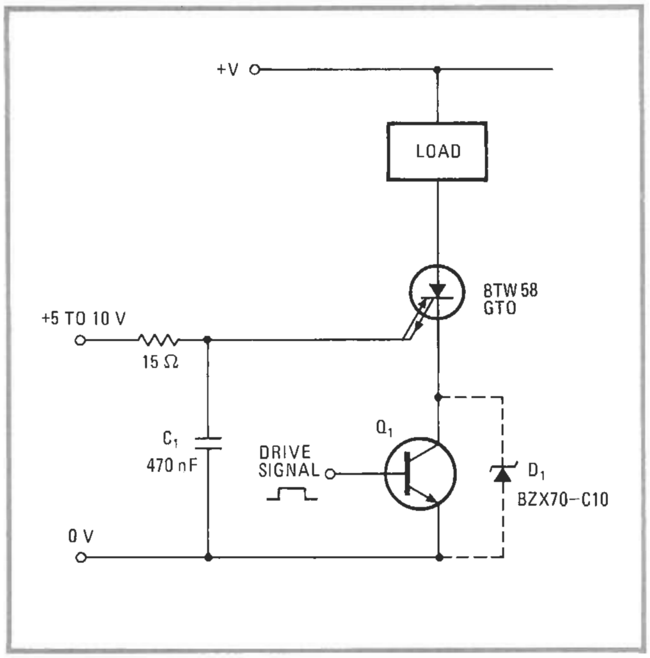


3. GTO driver. Unique gate–turn-off capability allows a single drive circuit to switch a GTO thyristor on and off. The need for extra commutation circuitry is eliminated, boosting speed and lowering parts count.

tion. Capacitor C_2 is included to reduce turn-on losses when the rate of change of the anode current is high.

An even simpler unity-gain drive circuit uses a variation of the well-known cascode configuration (Fig. 4). When Q_1 is turned off, the anode current is forced to leave the device through the gate, charging C_1. The GTO blocks the high voltage, but the drive requirements and switching speed are largely determined by Q_1, which may be a low-voltage bipolar or MOS transistor. A zener diode is included to protect Q_1 from high voltages.

Other possible gating circuits include transformer drives and switching to a negative supply line. In all cases, a properly driven GTO thyristor offers the circuit designer the usual advantages of thyristor switches—high voltage blocking and high current in a small and reliable device—plus the added advantages of gate–turn-off capability: low drive power, simple drive circuits, and switching speeds of 100 kHz and more.



4. Cascode drive. A simple GTO drive circuit uses a power transistor in series with the thyristor. Although the GTO blocks the high voltage, switching speed and drive power are set by Q_1. A zener diode protects the low-voltage cascode drive transistor.

Line pollution

The number of applications requiring high-voltage switching of large currents at high frequencies is increasing. A full-wave ac controller using a single GTO thyristor reduces the line pollution for which phase controllers are notorious. Such a chopper controller selects portions of the ac waveform to deliver a higher power factor and lower harmonic content to the load. In addition, it can work as a fast-acting trip to turn off the load at any point in the cycle.

Most switching power systems use diode-capacitor input circuits, which also pollute the ac line. Under threats of legislation, engineers throughout Europe are looking for ways to design converters with low harmonic content and low radio-frequency interference. Resonant systems, such as the series resonant inverter, show the most promise. In such a resonant circuit, the switch must withstand several times the line voltage—something a GTO thyristor is well able to do. Another familiar resonant circuit is found in TV horizontal deflection controllers. The BTW58 can handle 1,500 V of flyback voltage, and its small size and low drive power requirements make it a viable alternative to existing solutions.

The speed of three-phase induction motors can be controlled from a variable-frequency three-phase pulse-width-modulated inverter. The choice of power switches for such an application has, in the past, been between relatively expensive high-voltage bipolar transistors and thyristors. Although themselves inexpensive, thyristors required other components for switching off. But, since the GTO thyristor can be turned off with the same drive circuit that turns it on, these power switches are now more economical than bipolar transistors in many applications. Furthermore, they show excellent promise of scaling up to higher current levels, since the die sizes are relatively small at the present 5-A current level. □