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# A Current Source Method For $t_q$ Measurement of Fast Switching Thyristors

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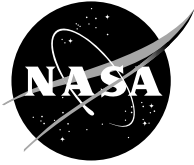
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# A Current Source Method For $t_q$ Measurement of Fast Switching Thyristors

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## Abstract

A current source driven circuit has been constructed to measure the turn-off time ( $t_q$ ) of fast-switching SiC thyristors. This circuit operates from a single power supply and a dual channel pulse generator to provide adjustment of forward current, magnitude and duration of reverse applied voltage, and rate of rise of reapplied forward voltage. Values of  $t_q$  down to 100 ns can be resolved.

## Introduction

This report describes the operation of a circuit developed to measure the so-called turn-off time ( $t_q$ ) of fast-switching thyristors. When a specified forward current through a thyristor is interrupted by a sudden application of a reverse voltage, a time  $t_q$  must elapse before the thyristor can recover its ability to block a reapplied forward voltage. Since the forward current conduction mechanism of a thyristor depends on minority carrier injection at internal junctions,  $t_q$  is a measure of the decay time of these carriers, after normal injection has ceased. Once the minority carrier density falls below a certain value, the regenerative action necessary for forward conduction cannot be maintained. Thus  $t_q$  depends on the magnitude of the forward current, the magnitude of the applied reverse potential that helps to sweep out the carriers and also on the rate of reapplication of forward voltage. The latter rate induces capacitive displacement currents and minority carrier injection. Bias conditions at the gate junction affect injection and hence also influence  $t_q$ . A superior  $t_q$  measuring circuit would provide for independent and perfect control of all influential magnitudes and rates. The circuit presented here is not superior in every way, but rather provides simplified control of forward current, magnitude and duration of reverse applied voltage and rate of rise of reapplied forward voltage, all from a single power supply and a single timing generator that drives a single MOSFET switch. For comparison, test circuits such as used by A. Frasca (ref. 1) need 2 transistor switches, 2 pulse sources and use 2 power supplies, making it more difficult to compact; however, a broader range of bias conditions can be obtained.

## Principles of Operation

The  $t_q$  of the thyristor under test (TUT) is measured repetitively in a cycle that consists of 3 phases. First, a gating pulse from a pulse generator turns on the TUT in order to establish a steady state forward current ( $\sim 1$  A). This current also stores energy in an inductor for use later in the cycle. Simultaneously, a 10- $\mu$ F capacitor gets charged to serve as the source of a reverse voltage, to be applied to the TUT during the next phase.

After a steady state current is achieved through the inductor and the TUT, a signal from a second channel of the pulse generator closes the MOSFET switch, starting the second phase. This action connects the precharged 10- $\mu$ F capacitor across the TUT, such that the sudden reverse bias cuts off its forward conduction current. A return path for the current is provided through this capacitor and the MOSFET, since the inductor enforces current continuity. The action of the current is to discharge the capacitor, but only a negligible amount during the short time (typically a  $\mu$ s or less) of the application of the reverse bias. At the start of the reverse bias, there is a fast-rising reverse current pulse that reaches a peak and decays, as the stored minority carriers in the TUT recombine and conduction ceases. The duration of the

reverse bias state is essentially the duration of the pulse that switches the MOSFET. Normally this duration is sufficiently long to avoid immediate turn-on of the TUT at reapplication of a forward voltage. Such conditions as magnitude of the reverse bias and rate of rise and limiting value of the reapplied forward voltage have a great effect on this minimum duration, which is essentially the  $t_q$ . For Si-based thyristors, the  $t_q$  is usually greater than a few  $\mu\text{s}$ , but for SiC thyristors, values below 100 ns have been observed (ref. 1). Times below 100 ns are difficult to resolve accurately with a circuit made of discrete components, because of the presence of spurious oscillations and the limits to switching speed ( $\sim 30$  ns) of MOSFETs. In that regard, the circuit presented here may have the advantage of improved response, due to compactness.

The final phase involves the application of a forward voltage at a controlled rate to the TUT to test whether or not it will spontaneously go into forward conduction. This phase is initiated by the turning off the MOSFET switch at the end of the switching pulse. Now the inductor does its job as a current source to feed some low value, selectable capacitors, thereby generating a voltage ramp across the TUT. The internal capacitance of the TUT, which can be significant, is of course included also. The voltage across the TUT will rise roughly linearly with time until either it causes the TUT to break down into forward conduction, or else a limit preset by transient absorbing Zener diodes (“tranzsorbs”) is reached. It may even happen that the TUT breaks down after a short lapse of time on the tranzsorb limited voltage plateau. For a given reapplied voltage limit and ramp rate and reverse bias voltage, the  $t_q$  is measured by progressively decreasing the reverse bias duration until the TUT breaks down into forward conduction. The time  $t_q$  is measured from the time when the forward current crosses zero, near the start of the reverse bias, to the time when the reapplied voltage goes positive (ref. 2), under incipient forward breakdown (c.f., the cursor lines in figs. 1 and 2).

A circuit diagram is drawn in the appendix. The additional circuit elements needed to control various details of circuit function are also described there.

## Sample Waveforms

The upper trace in figure 1 shows the current through an experimental SiC thyristor during a forward conduction, turn-off and re-triggering cycle and the lower trace is the simultaneous voltage across the device. Initially, a steady current of 1 A has been established. Closure of the MOSFET switch causes a very abrupt reversal of the current through the thyristor, in response to the suddenly applied reverse bias of about 80 V. This reverse bias has here a risetime of about 30 ns, due to the finite switching speed as well as thyristor and circuit capacitances. At least until the minority carriers recombine, the reverse impedance of the thyristor can be sufficiently low to permit a large reverse current pulse peak. The circuit presented here uses an adjustable resistor to limit this peak to safe values. In theory (refs. 3 and 4), the reverse current pulse has a step or plateau structure, not resolved in figure 1.

After about 250 ns, a forward voltage is reapplied, rising above zero at a controlled rate. The rate shown in figure 1 is roughly 250 V/ $\mu\text{s}$ . While climbing at this rate, the thyristor turns on again, when the forward voltage has reached 60 V. There is a brief current spike, perhaps due to capacitive effects, and then the current settles to 1 A again.

If the duration of the 80 V reverse bias had been longer than 250  $\mu\text{s}$ , then instead of retriggering on the slope, the reapplied voltage would have continued to rise up to a limit preset by the tranzsorbs. This critical duration of the reverse bias, indicated as 248 ns in figure 1, is the  $t_q$ , defined above as the time from the current zero crossing to the reapplied voltage zero crossing, when the device is just at the edge of re-triggering, as the duration of the reverse bias is gradually reduced.

The scenario in figure 2 is similar, except that now the thyristor re-triggers on the forward voltage plateau of 70 V, as set by the tranzsorbs. The increased  $t_q$ , shown as 604 ns, is to be expected, because the reapplied voltage was set to rise at a faster 670 V/ $\mu\text{s}$ .

## Discussion

The thyristor  $t_q$  measurement circuit presented here is an alternative to a more common arrangement that uses 2 sources of power and 2 coupled pulse sources to drive 2 MOSFET switches. Typical of a 2-switch circuit is the one used by A. Frasca (ref. 1), in a SiC thyristor dynamic characterization study. In such a 2-switch version, it is easier to obtain a wide range of forward current, reverse and reapplied forward voltages, but at the cost of increased equipment and switching complexity. Also, the switching from one MOSFET to the other has to be quick, but with no overlap. In contrast, the inductive current source circuit described here reduces peripheral equipment count and switching complexity by making a single MOSFET switch do the job. At high switching speeds, a more compact circuit has an advantage. It should be noted too, that instead of trying to minimize all inductive effects, this circuit makes good use of inductance to achieve its functions. Thus with substantial inductive energy storage, it is easy to obtain a linear ramp of reapplied voltage.

At present, this  $t_q$  circuit has been pressed into service, without much effort to correct some manifest problems. Thus a larger storage inductor would make for a steadier current source and a smaller inductor in series, based on a lower permeability core, might speed up the response. Also, the zero crossing behavior of reapplied voltage is better in figure 2 than in figure 1. The circuit elements controlling this function are mentioned in appendix A. And there is an annoying amount of spurious high frequency oscillation, which may be indicative of errors in wiring layout and grounding.

## References

1. A. Frasca, Wittenberg University, private communication.
2. *SCR Manual*, (The General Electric Co.), 6<sup>th</sup> Edition, Prentice-Hall, Inc., Englewood Cliffs, NJ, has an excellent diagram of the definition of  $t_q$  on p. 124.
3. S.K. Ghandi, "Semiconductor Power Devices," Wiley-Interscience Publishers, New York, 1977.
4. B.J. Baliga, "Power Semiconductor Devices," PWS Publishing Co., 1996.

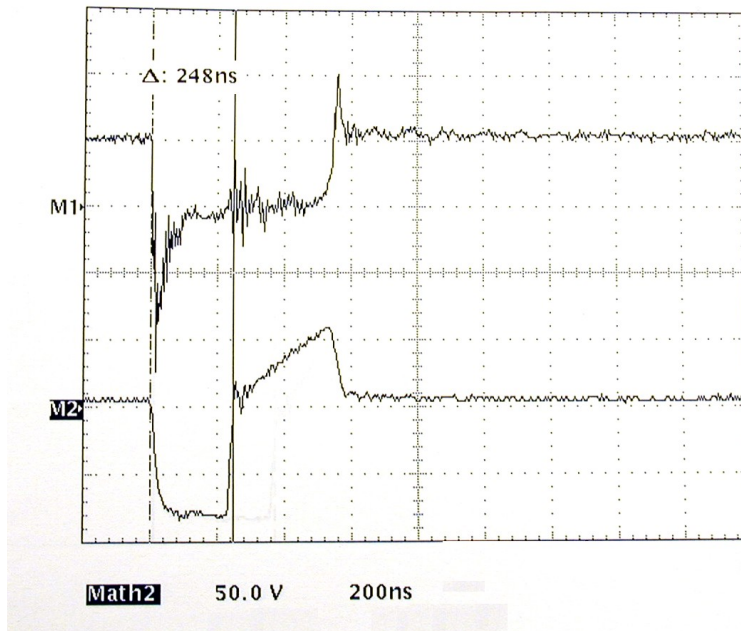


Figure 1.—Typical current (upper) and voltage (lower) waveforms observed during  $t_q$  measurement. Here the thyristor turns on spontaneously on the rising slope of the reapplied voltage. Except for the spurious oscillations, the reapplied voltage ramp starts at essentially zero volts.

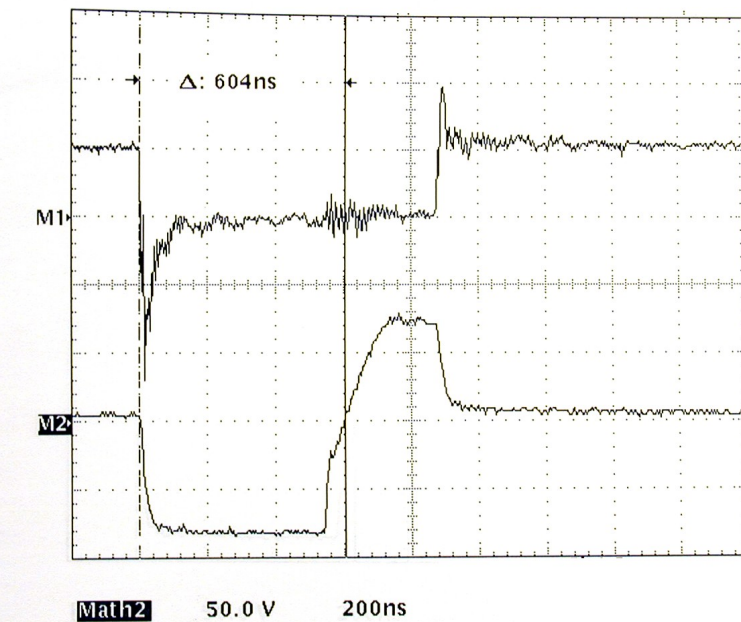


Figure 2.—Spontaneous turn-on of a thyristor on the plateau of maximum reapplied voltage. Due to the longer duration of the reverse voltage, the reapplied voltage ramp starts at negative values.



## Appendix A

### Details of the $t_q$ circuit

The diagram drawn in figure 1A, together with the descriptive comments on some of its elements, is sufficient for construction of the  $t_q$  measurement circuit. As shown, the circuit has been used with input voltages  $V_{in}$  from 50 to 100 V and forward currents up to 2 A. But depending on the current and voltage ranges desired, the ratings of some of the components may have to be altered.

#### List of components:

$C_1$	1000 $\mu$ F, 200 V, electrolytic capacitor
$C_2$	10 $\mu$ F, 100 V polypropylene film capacitor
$C_3$	ten selected ceramic disc and mica snubber type capacitors, ranging from 100 pF to 0.01 $\mu$ F each, connected by a 10-section DIP switch
$D_1$	Type BAV21 silicon diode (200 V, 250 mA)
$D_2$	type NTE580 fast recovery silicon diode (3 A, 600 V, $t_{rr}$ =250 ns)
$D_3$	type 1N6628 fast recovery silicon diode (2 A, 600 V, $t_{rr}$ =30 ns)
$D_4, D_6$	one section of Motorola type MGR2025CT gallium arsenide rectifier. (250 V, 10 A, $t_{rr}$ =12 ns)
$D_5$	in-house fabricated SiC Schottky diode ( $\sim$ 200 V, 0.5 A)
L	1.6 mH inductor, based on a Magnetics type 55436-M4 MPP core ( $\mu_r = 160$ )
$R_1$	350 $\Omega$ , 25W, wire-wound rheostat
$R_2$	1 k $\Omega$ , 1.5 W, 10-turn pot (Bourns ‘knobpot’ type 3600S-1-102, or similar)
$R_3$	2.7 k $\Omega$ , $\frac{1}{4}$ W, carbon resistor
$R_4$	1 M $\Omega$ , $\frac{1}{4}$ W, carbon resistor
$R_5$	2.7 $\Omega$ , $\frac{1}{2}$ W, carbon resistor
$R_6$	100 $\Omega$ , 1 W, 25-turn cermet trimpot (Bourns type 3252W-1-101, or similar)
$R_7$	270 $\Omega$ , $\frac{1}{4}$ W, carbon resistor
$R_8$	1.0 $\Omega$ , $\frac{1}{2}$ W, carbon resistor, trimmed to better than 5% accuracy
S	MOSFET switch (types IRFF 320, IRF720, or similar)
Z	series array of Zener diodes for transient power absorption (“tranzsorbs”), selectable by jumpers

#### Notes on component functions:

$R_1$  and  $R_2$ :

The adjustable  $R_1$ , together with the source voltage  $V_{in}$ , sets the steady state forward current of the TUT. Once  $V_{in}$  is set, the reverse bias voltage to be applied to the TUT is set by the tap on  $R_2$ , as a fraction of  $V_{in}$ . Hence to go to a higher reverse bias, the  $V_{in}$  may need to be increased. Consequently, the  $R_1$  will have to be increased in order to maintain the same forward current. This defines the setting of the forward current and the reverse bias voltage.

The switch S:

S is implemented by a fast-switching MOSFET, such as the IRFF 320. Best performance was obtained when using a gate driver IC, such as the type TC4425CPA. Power for this gate driver can be easily derived from  $V_{in}$  by means of a Zener diode to regulate the voltage.

$D_3$  and  $R_5$ :

The function of these elements is to ensure that  $C_3$  retains no positive charge when S opens and a voltage ramp is applied to the TUT. These elements add extra capacitance to the anode of the TUT and may not be needed.

D<sub>1</sub> and R<sub>3</sub>:

These elements serve to charge C<sub>2</sub> to a voltage that is to be the reverse voltage applied to the TUT. The value of this voltage is derived from V<sub>in</sub> by adjusting R<sub>2</sub> and is limited by V<sub>in</sub>. C<sub>2</sub> gets charged during the forward conduction time of the TUT.

D<sub>2</sub>:

This diode ensures that C<sub>2</sub> can never get charged reverse from normal.

R<sub>4</sub>:

This resistor provides a slow discharge path for C<sub>2</sub>.

D<sub>4</sub> and R<sub>6</sub>:

This combination of elements provides for essentially unimpeded current flow in the forward direction of the TUT. But in the reverse direction, the current is limited by R<sub>6</sub>. Thus R<sub>6</sub> controls the peak height of the reverse current pulse when S closes and a reverse bias is suddenly applied to the TUT. For this reason, D<sub>4</sub> should be a very fast recovery and low capacitance type. The specified gallium arsenide type power diode seemed to be acceptable.

C<sub>3</sub>, D<sub>5</sub>, R<sub>7</sub> and D<sub>6</sub>:

When S opens to end the reverse bias of the TUT phase, the only paths for the inductor current (still essentially the same as the initial forward current of the TUT) are the C<sub>3</sub> and the capacitances of the TUT and the Zener diode chain. This defines the anode voltage V<sub>A</sub> ramp. D<sub>5</sub> exists to keep R<sub>7</sub> from interfering with the linearity of this ramp. During the initial forward conduction of the TUT phase, C<sub>3</sub> has only a low positive charge (at most a few volts). But during the reverse bias phase, C<sub>3</sub> gradually acquires a negative voltage, since the reverse bias is also applied to C<sub>3</sub> in series with R<sub>7</sub>. Hence this effect depends on the C<sub>3</sub>R<sub>7</sub> time constant, as compared to the duration of the reverse bias. The effect is negligible in figure 1, but is evident in figure 2. A small amount of negative precharge on C<sub>3</sub> may be desirable at the end of the reverse bias phase, because that avoids the erratic zero crossing, due to oscillations, of the reapplied forward voltage ramp in figure 1. Possibly R<sub>7</sub> could be made adjustable, but this introduces complications. If R<sub>7</sub> is made too small, then there is risk of damage to the TUT when it breaks into forward conduction, with high positive voltage on C<sub>3</sub>. A better way to provide a small, negative charge on C<sub>3</sub> should be implemented. The extremely fast recovery SiC Schottky diode D<sub>5</sub> was found to be beneficial in reducing the high forward current spike when the TUT breaks into forward conduction under reapplication of voltage. In figures 1 and 2, the height of this spike is about 1 A above the 1 A steady state forward current. Capacitances other than C<sub>3</sub> contribute to this spike. Thus the fast recovery D<sub>6</sub> reduces the contribution coming from the capacitance of the power Zener diode chain Z.

R<sub>8</sub>:

The 1 Ω carbon resistor R<sub>8</sub> is used for sensing the current I<sub>AK</sub> through the TUT. All such sensing must be done differentially, as at high switching speeds, there may not be a uniform ground potential throughout the circuit.

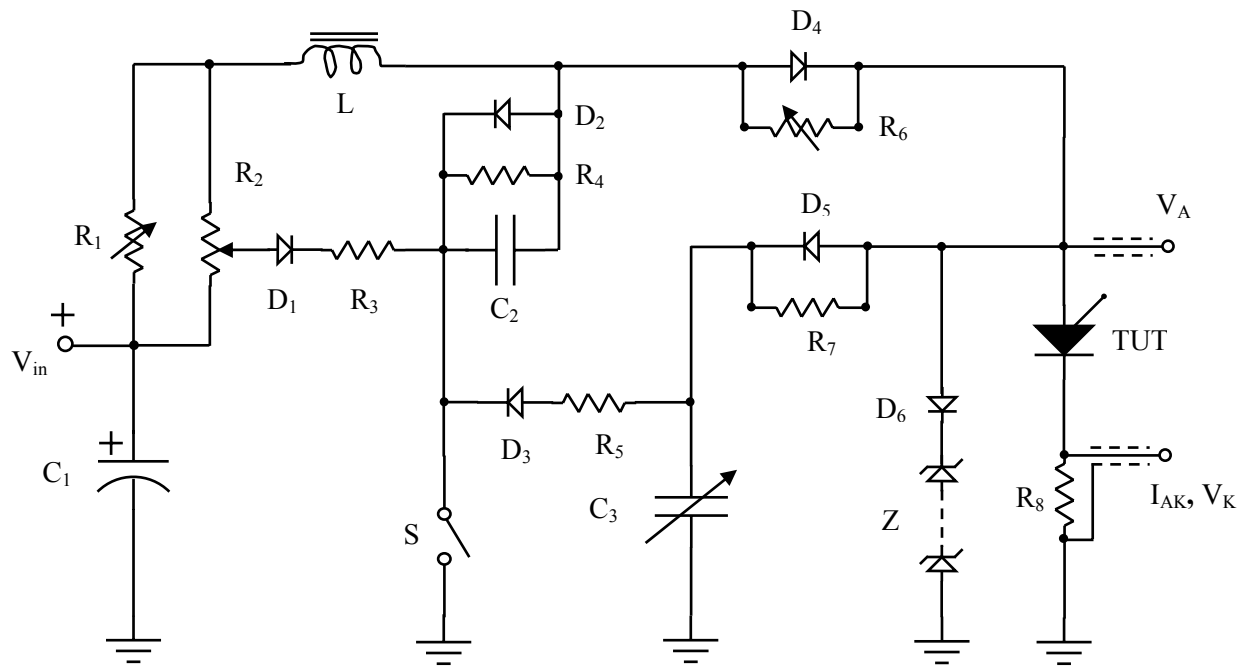


Figure 1A.—Diagram of the current source circuit for  $t_q$  measurement of fast recovery thyristors. Specific values are provided in the included list and particular functions are explained in the text.

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