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Evaluation of an Electronic Load for Pulsed Current Characterization of Power Semiconductors

by Timothy E. Griffin

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14. ABSTRACT

An electronic load was evaluated for outputting a pulse of a controlled value of current from a power supply, for consideration for measuring a device-under-test (DUT). A large Dynaload load containing insulated gate bipolar transistors (IGBTs) was used without a DUT but was rejected due to poor performance. In constant current mode, the load's pulses of $I(t)$ had undesirable off-state leakage. Its $I(t)$ pulse had slow rise, odd shape, and inadequate reproducibility for calibrated measurements. The load was rated merely 600 V, hence, during a pulse, could include a V_{DS} of less than 600 V.

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1. Introduction

Currently, silicon carbide (SiC) power metal-oxide-semiconductor field effect transistors (MOSFET) are still being developed and engineered, and as such they often do not have complete data sheets. Present state-of-the-art devices are rated for 1200 V and a conservative 50 A. In order to use a MOSFET properly, the gate drive must be properly designed. To do so, the gate drive requirements—the gate charge, Q_G, required to achieve a given V_{GS}—must be calculated. To calculate this value, the data must be measured for the device under test (DUT). This measurement can be achieved by supplying a known, constant gate current, I_G, along with a steady, and preferably pulsed, drain current, I_D. While a constant current I_G drive already exists, apparatus was needed to provide definitely constant I_D pulses that had well-defined edges and operated fast enough. The purpose of this study was to investigate the appropriateness of using an electronic load to select the needed I_D up to the full continuous current rating of the power SiC MOSFET, and perhaps, to its higher pulsed I_D rating. Since pulsing I_D reduces the time during which it dissipates energy, the pulsing I_D limits the heating of the DUT.

The $V_{GS}(Q_G)$ curve is typically specified at a $V_{DS,\,off}$ and usually either at an I_D or with a particular load resistance to limit I_D. The curve simplifies as an initial linear increase, then a plateau with a zero or small slope, then another linear increase to V_{GS} values, which turns the MOSFET on for use. The values needed to design a properly sized gate drive for operation of MOSFETs include Q_G for V_{GS} at 15 V and Q_G for V_{GS} at 20 V. In one leg of an existing module, the eight MOSFETs in parallel need a gate drive; a future module could have higher rated MOSFETs and/or more MOSFETs.

Measuring a MOSFET or other DUT requires one or more parameter values to be controlled and constant, including off-state V_{DS} from a stiffened power supply. The I_D pulse is also sought to measure $R_{DS\ on}$, or other parameters, to compare with data sheet measurements. Usually a constant-voltage power supply goes to an appropriately load arranged or controlled device, as available, to give this constant current. This load can be the positive terminal of an electronic load. The lower terminal of a load would be connected to the DUT's drain at V_{DS}, and the DUT's source would be at ground, as shown in figure 1. We measured current from an electronic load in its pulsed current mode and sought adequate performance. We included 10 min between pulses for cooling to room temperature and did not use a DUT.

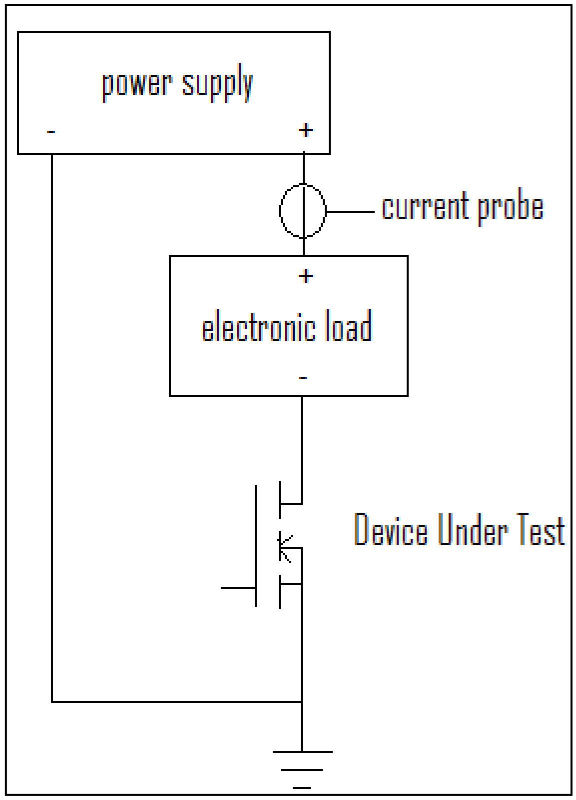

Figure 1. Circuit with supply and electronic load; DUT was not used.

A superjunction MOSFET for high V_{DS} is somewhat frail without a monitor to detect the onset of excessive current and the ability to turn off the MOSFET. Such a monitor for each MOSFET in parallel is not usual, hence superjunction MOSFETs are not placed in parallel in modules. The silicon power MOSFETs used in parallel have fewer tens of amperes and lower V_{DS}, less than 600 V, than do SiC. For power SiC MOSFETs, rated usually for at least 1200 V, our group was interested in such measurements using an I_D pulse of up to 50 A from an electronic load. A load rated for at least 1200 V was desired but the highest listed was 800 V, from the Dynaload division of Transistor Devices Inc. An electronic load rated for 600 V was tested; current went into its positive terminal and out its lower-voltage terminal, labeled negative. During the pulse, the V_{DS} of a DUT, if added below the load, could decrease by up to that rating.

2. Basics of Electronic Loads

Electronic loads are designed to absorb and measure the output of a power source, primarily to test it. Usually the complex, custom gate drive of a load turns partly on the load's MOSFETs or insulated gate bipolar transistors (IGBTs) by a controlled amount, so they have a voltage drop. The load can be in constant current mode, constant voltage mode, constant power mode, or constant resistance mode; in each, the controls specify that parameter's value. A load actively measured that parameter, and fairly closely and rapidly held it constant between its power terminals. The constant current mode had the highest performance. Each mode regulates by internal control of the gates of a load's power-dissipating IGBTs or MOSFETs. MOSFETs compared to IGBTs have less leakage especially at higher temperature, avoid saturation above V_{DS} of only a few volts and not 10 V, are faster, and turn off without tail current and its heat. IGBTs can handle more power and current.

An electronic load in the constant resistance mode is known for smaller series inductance than a resistor. A resistor as the load, other than working to zero voltage, would be undesirable. It would have a varying limit on I_D of $(V_{supply} - V_D)/R$ and on power of $(V_{supply} - V_D)^2/R$. Even a cooled resistor near full power has temperature; hence, resistance is only approximately constant. Ohmite TAP1000 resistors would increase this to 2% when warmed by 80 °C. Changing the resistance or current rating would require a physical rearrangement or replacement of the resistors.

A load has continual power dissipation capacity of hundreds to tens of thousands of watts; this must include during transitions of V_{DS} when its peaks have I_D. A load is water-cooled or air-cooled for a negligible temperature coefficient. A load has conveniently adjustable and familiar electronic operation, and a digitally selectable reconfiguration. This is unlike a tank of water made conductive with a chemical. A load operates with production-type rate and durability, and connects and disconnects with an electronic relay without mechanical wear. A load has an adjustable cut-off limit on its power dissipation alone, on its voltage alone within that power, and on its current alone within that power. A load usually has an output for a current monitor voltage. A load can select from different maximum values for a parameter; a smaller maximum would give a smaller value of its tolerance.

A load can have control by internal settings, external voltage, or the general purpose interface bus of a computer. Control includes setting the maximum rise/fall time for full scale, or similarly, the slew rate. The parasitic inductance's $L\mathrm{d}I/\mathrm{d}t$ voltage and ringing are a limit on slew rate and are reduced by longer rise/fall time. Known loads do not have separate control of rise and fall slew rates.

A pulsed load would heat the DUT with conduction losses only during the pulse, keeping the DUT junction temperature closer to specification during measurement of on-state V_{DS} and transconductance. Large bypass capacitors are recommended for stability (*1*). Measurement within the pulse's middle or second half would be away from transients. For a DUT example of a IRF540 power MOSFET rated 100 V, the bypass capacitors recommended are C_{DS} of 0.3 μF (about 1000 times that of the MOSFET) to slow the increase in DUT V_{DS} to prevent DUT high-frequency oscillation and C_{GS} of 82 nF (about 40 times that of the MOSFET). This implies that use of electronic loads is not as fast, stable against oscillations, or flexible as wished for this measurement; we did not explore this. A non-saturated load can pulse a current with adequate compliance and with controlled rise/fall time, seeking clean and well-controlled waveforms.

Considering stray inductance, a pulse of tens of amperes needs the rise and fall speed to be achieveably constant and, especially, not faster than optimum. For our work, a power supply was too slow to change or recover (i.e., when a switch closes); after a current change of 50% of the rated amount, an Agilent 6692A rated 60 V and 110 A had an output voltage recover within 0.1% within 100 µs.

The voltage from the load's positive terminal to its lower-potential terminal is the V_{DS} of load MOSFETs or V_{CE} of load IGBTs, hence it must be positive or zero. The lower terminal of the load used can be electrically floated above earth ground by up to 2200 V (*2*). This is at presumably less than 1 Hz, too much slower than our pulses. Floating was not used, and even after consulting the factory, a rapid rise up to floating may not be permitted. The lower terminal clearly cannot be pulsed to float to a majority of that 2200 V within ten times the desired tens of microseconds. Also, known loads have slow and usually unrepeatable $I(t)$ pulsed from zero, so two loads in series and pulsed simultaneously could not be used for more voltage rating. When any DUT used would be turned on, its drain at the lower terminal of the load used should near ground. This would permit the load's positive terminal to be up to 600 V, so we could float the lower terminal to only 600 V.

3. Examples of Loads

The American Reliance (Amrel) load PLW, large like the Dynaload, listed a load of MOSFETs with complex gate drives and on a water-cooled heat sink between 28 °C (above the condensation of humidity) and 50 °C. Constant current minimum rise/fall time was 50 µs; the slew rate was up to 6 V/µs.

An Agilent load N3305A rated 150 V, 60 A, and a small 500 W avoids saturation with 3 V or more across it, at which it has a slew rate to 5 A/µs and a smaller minimum pulse width of 50 µs.

The Hewlett Packard load 6060B is rated 300 W, 60 A, and 60 V; it states saturation of its load MOSFET could widen the pulse by 15 µs (*1*). To avoid saturation, one can add a minimum 3 V power supply in series with a diode across the load. When a DUT MOSFET with adequate V_{GS} receives V_{DS}, the DUT flows a value of I_{DS} limited by the rest of the circuit; load current programmed above that limit would make the load act as a non-regulating switch.

A parametric analyzer/curve tracer has too small a V_{DS} capacity when sourcing $I_D(t)$ but gives $I_D(t)$ with less leakage and perhaps a more constant value than does an electronic load with a power supply. An Agilent B1505A with dual high-current source measurement units could pulse for 50 µs or more at up to 40 A and up to 20 V. The 20 V can float on up to 42 V DC, which probably cannot be varied anywhere nearly as rapidly as the pulse.

4. Electronic Load Used for Pulsed Current

We considered a load to measure a DUT MOSFET drain charge with current much greater than the load leakage current. The load used was a Dynaload model WCS488SYS35-60016 with a master unit and a slave unit in parallel. Ratings were to 600 V implying to 26.7 A, to 200 A implying to 80 V, and to 16000 W limiting the other two; a 5% higher value disconnects the load's electronic output relay. The voltage ranges were to 600, 300, and 60 V, and current ranges were to 200, 100, and 20 A. The load IGBTs were on a heat sink, which after reaching a designed temperature would flow its water cooling, but the single pulses used here did not heat up to that threshold.

Operation of the load needed at least 0.4 V across it. Before the control pulse, the load's transistors were off; hence, it was undesirably saturated and slow. The lowest practical load current rating range is recommended for fast pulsed current response (implying the number of IGBTs used is proportional to the current range's rating). If the load selects any baseline current, it would be continual and would have any pulse on top of it. The instruction manual of the load used also recommended using a baseline current at least 10% of the full-scale rating to prevent the IGBTs from becoming electrically saturated (*3*). This 10% level is probably needed for the slew rate to reach 10 µs; slew rate is listed selectable from 10 to 4000 µs, but the programming menu offered merely as fast as 50 µs. Baseline current was avoided as being continuous. The slave half was not mechanically disconnected to reduce current rating and hence leakage.

Pulse control was done through the external (remote) analog programming terminal, which accepted a customized signal from 0 V to up to 10 V, from an Agilent 33220A arbitrary function generator. Each signal was rectangular with a rapid 10-µs rise/fall, except for a few, which showed they could not reshape the current pulse to be more rectangular. The Xantrex 60-46 power supply used was rated to 60 V and 46 A and was stiffened adequately by an 1100-µF capacitor Cornell-Dubilier 550C rated 500 V.

If manual triggering were repeated within several seconds, it heated up the load used and notably changed the observed pulse $I(t)$. For example, a hump in $I(t)$ appeared after turnoff, in a later pulse it moved earlier and was larger, and it could make the very end of the pulse increase rapidly. Hence, a delay of 5 to 10 min between pulses let the load used be initially cool near the room temperature of 15 °C; pulse shape reproducibility was improved but not always acceptable. The $I(t)$ was smooth but had inadequate control of its amplitude as a function of time and inadequate repeatability, and a slower rise and far more overshoot than desired. Slowing the menu's slew rate from 50 to 500 µs slowed the $I(t)$ turn-off. Selecting a 3000-µs slew rate limited the initial rise and the fall from 40 to 10 A, and the fall was slower after that.

With the menu slew rate of 50 µs, the rise of a current pulse was slow. Changing the current range from 20 A to at least 100 or 200 A gave a more stable pulse. In figure 2, a pulse commanded 40% of the maximum for 2 ms, while the load used had 200-A current range, a menu limit of 50 A, a slew rate of 50 µs, and a supply of 59 V. Channel 1 was the control pulse, channel 2 was load $I(t)$, and channel 3 was power supply voltage. Note: Please ignore text labels at the upper left of the oscilloscope screen.

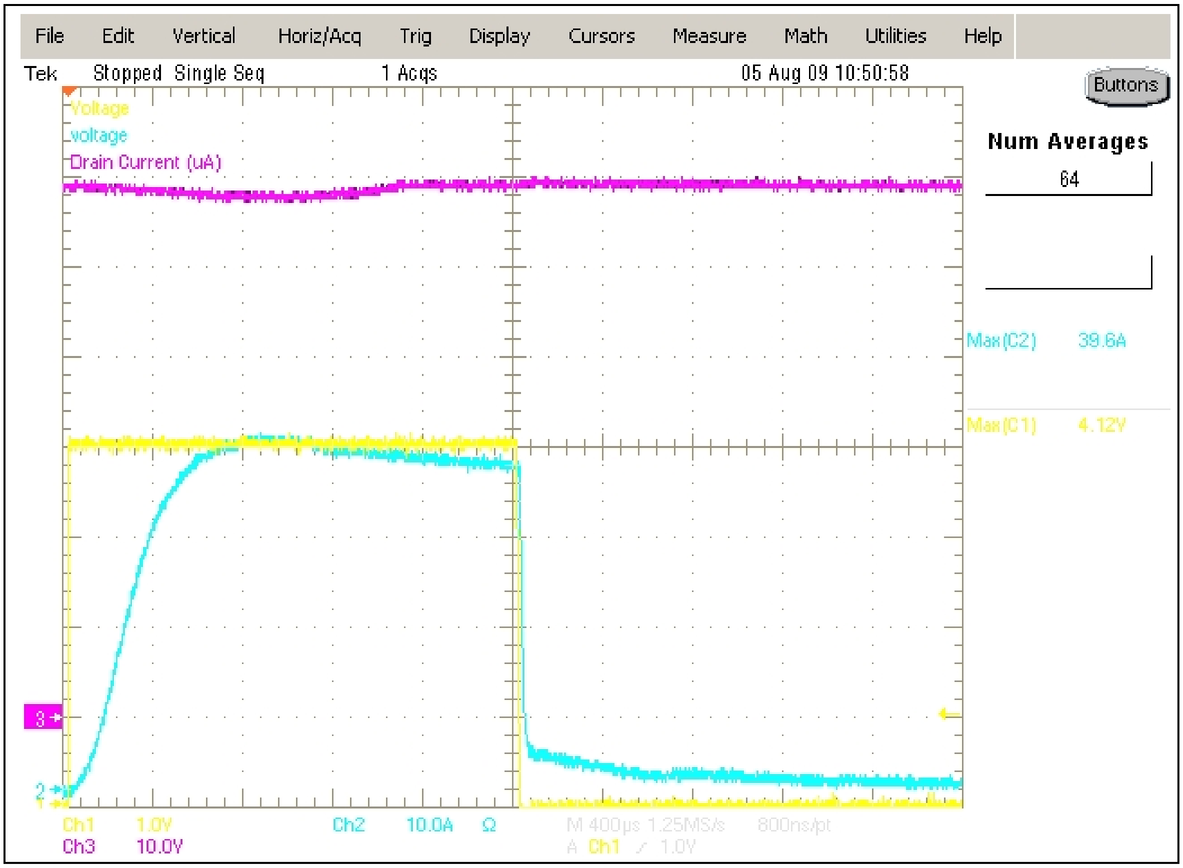

Figure 2. A good example of a current pulse.

The $I(t)$, at 7 µs after the control voltage rose, began rising at 20.3 µs to 0.4 A, at 155 µs to 10 A, at 370 µs to 30 A, and near 870 µs to 38.8 A. This rise time and especially overshoot by this fraction were less than most others. The current then decreased slowly to reach at 1.981 ms, 36 A. From there, the $I(t)$ began its commanded fall, averaging 1.18 A/µs to at 2.002 ms, 10 A. This fall rate approached the listed slew rate of 50 µs for the full menu scale, since internal control has a simple and obtainable goal to turn off the IGBTs at the slew rate. The decrease in $I(t)$ averaged 0.54 A/µs to reach at 2.04 ms, 4 A, which was 90% complete. $I(t)$ at 2.39 ms reached 2 A and at 3.3 ms, 1 A.

Observed $I(t)$ over the many pulses was random enough to need to be recorded each time. A 2-ms pulse sometimes had half of a previous pulse's amplitude or rose only during its final one-third and to 0.7 as large. After the control voltage ended, the pulse sometimes had a hump; one pulse started rising again 5 ms afterwards. For the 200-A current range with menu current limit of 10 A, one 8-ms pulse was from 1 to 6 ms at 12.5 to 14 A, and then fell to around 7 A, so the menu current limit had an imprecise and delayed effect. Some pulses had smaller $I(t)$, reaching, for example, three quarters of their usual current at too late in the pulse. One first pulse was 20 A and not the usual 40 A.

The conductor inductance in μH is about 7.9 times the round-trip length in meters of the round wire for the power supply; flat bus bar would have less inductance. My 6.7 m of twisted-together AWG6 was calculated to be 53 μH, too small to cause the slowness of rise. During only the tens of μs, while $I(t)$ fell faster than 0.5 A/μs, the inductance might be noticeable. However, odd features of $I(t)$ occurred before that and much after that, and for far longer. The length of wire was reduced by half, but enough had been learned.

5. Leakage and Measurement Considerations

Load leakage, of course, is not precisely constant with time, and is likely to be smaller for a load with a smaller rating. For loads similar to the load used but with from half to five times the power rating, the manual lists a representative normal 20 mA of off-state leakage even near 0 V. The load's leakage at 5 V DC was measured by a current probe Tektronix TCP312 as more than 4 mA, and at 40 and 60 V as 4.8 mA; this was much larger than for any DUT, hence was basically not tolerable. When the positive terminal of the load used would just begin to be at the power supply voltage but before the current pulse, if a DUT were there, the load leakage would unacceptably increase its V_{DS} to the supply voltage in milliseconds.

To short out the load leakage around the DUT until measurement, one could add a circuit in parallel with it. Suggested is a resistor of hundreds of ohms in series with a shorting MOSFET rated for more voltage than the power supply and much less current. The shorting MOSFET would be usually turned on but would be turned off just before the pulse commanding the load's positive terminal to increase towards the power supply voltage; then after this control pulse and measurement the load would go to its near-zero current. Finally the shorting MOSFET would be turned on again. For the complexity, the performance would not be optimal for all users.

The pulsed load produced a current waveform with different values as to measure $V_{DS}(I_D)$. During a current pulse, a digitizing oscilloscope could record in an Excel spreadsheet a list of a MOSFET's $V_{DS}(t)$ and of $I_D(t)$, preferably in a time range of $I_D(t)$ fairly constant away from the ends of the pulse. Then from a plot of the Excel $V_{DS}(t)$ as abscissa and $I_{DS}(t)$ as ordinate, $V_{DS}(t)/I_D(t) = R_{DS}$ could be calculated then the results could be examined for consistency.

6. Conclusion

The electronic load used gave an $I(t)$ pulse that was not repeatable and desired, and so did not fit the needs for device characterization. The $I(t)$ pulse had a slow rise, often an odd shape, and unrepeatable performance. This performance sometimes included a rise again after the end of the control signal. A small fraction of pulses had fairly desirable characteristics. The suggestion of a parallel capacitor about 1000 times the C_{DS} of the DUT and a capacitor 40 times the C_{GS} to prevent oscillations indicates that an electronic load is not as stable as wished nor does it have the desired performance. The load rating was far less than the 1200 V rating of the DUT. Measurement of $Q_G(V_{GS})$ would use a specified V_{DS} to a load and prefers the load to give a specified I_D. Load leakage could be less and/or circumvented by timing and usually shorted by a resistor and MOSFET. If this procedure had worked, measurements in the more constant middle to later in the I_D(t) pulse with current closest to the desired current would have been examined for useful and consistent results. An alternative method to measure and calculate $Q_G(V_{GS})$ is needed.

7. References

1. *Pulsed Characterization of Power Semiconductors Using Electronic Loads*, Application Note 1246, Hewlett Packard, June 1993
2. Dynaload's CE testing, conversation with Matt Wishbauer, 2009.
3. Dynaload WCL488 Series Water Cooled Electric Loads, Operation, and Programming Manual, TT*i*: Huntingdon, United Kingdom, p. 34, http://www.tti2.com/dynaload/dyna-watercooled.pdf.

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