Short Papers

Use of Vacuum Tubes in Test Instrumentation for Measuring Characteristics of Fast High-Voltage Semiconductor Devices

DAVID BERNING

Abstract—Circuits are described that permit measurement of fast events occurring in power semiconductors. These circuits were developed for the dynamic characterization of transistors used in inductive-load switching applications. Fast voltage clamping using vacuum diodes is discussed, and reference is made to a unique circuit that was built for performing nondestructive, reverse-bias, second-breakdown tests on transistors.

INTRODUCTION

Recently, there has been a large increase in the demand for fast switching, high-voltage power transistors. Along with the increased use of these transistors has come the need for accurate measurement of the limits of safe operation for these devices. Reverse-bias second breakdown usually determines these limits for the transistors operating in a switching mode. Because of the large currents and voltages and the fast transients involved, there are numerous instrumentation problems in making controlled and repeatable measurements of the limits.

The devices being studied are used primarily for various types of power conditioning equipment including switching power supplies, motor controls, TV deflection circuits, and automotive ignition systems. In these applications, the transistor is usually required to turn off from a saturated condition with an inductive load in the collector circuit. The inductance causes the collector voltage to rise rapidly to a high value upon transistor turnoff. The voltage that the collector reaches is usually limited by a clamp diode that intended to prevent breakdown of the transistor switch. In testing these transistors, it is desirable to develop circuitry that will approximate the circuitry in which these devices are normally used, but to maintain additional control over various parameters such that accurate measurements can be made.

BACKGROUND

A circuit built for measuring the reverse-bias safe operating area (RBSOA) for high-voltage, bipolar, switching transistors is described in detail elsewhere [1]. This circuit was developed using some ideas from one built by Jahns [2]. The circuits perform second-breakdown tests by turning off the transistor under test (TUT) that has been in a saturated conducting state. The TUT has a load inductor in the collector circuit, and upon turnoff, the collector voltage rises rapidly until either the voltage is limited by a voltage clamp, the device reaches its reverse-bias sustaining voltage, or the device breaks down causing the voltage to fall rapidly to a low value. Both the circuits of Berning and of Jahns include a feature that allows second-breakdown measurements to be made, usually without destroying the TUT. The collector voltage collapse at breakdown is sensed and a shunt protection circuit removes the remaining energy stored in the inductor so that the energy absorbed by the TUT is minimized. If this energy is not diverted quickly, the transistor will be destroyed. The effectiveness with which the circuit can test and save devices is related to how fast the energy can be diverted from the TUT after it breaks down.

Manuscript received September 8, 1980. This work was supported in part by the NASA-Lewis Research Center, Cleveland, OH, under NASA Order C-32818-D.

The author is with the Electron Devices Division, National Bureau of Standards, Washington, DC 20234.

Fig. 1. Simplified diagram for a circuit used to test transistors for reverse-bias second breakdown.

One of the major differences between the two circuits is the capability of the protection circuit. The earlier circuit by Jahns uses high-voltage transistors to shunt the inductive energy away from the TUT, and a 350-ns energy removal time was reported. The later circuit uses pentode tubes and has an energy removal time of 40 ns. Vacuum tubes are faster than transistors for high-voltage applications because of the time involved in storing the charge required for conduction in transistors. The pentode tubes used for the protection circuit are type 6LF6, which is a high-perveance type intended for horizontal deflection in television receivers. In the protection circuit, 16 of these tubes are driven by low-voltage, high-speed transistors biased class A. In this configuration, the circuit can handle 1000 V and 30 A, with a slew rate of 5×10^4 V/ μ s. The circuit of Berning consistently permits hundreds of second-breakdown measurements to be made on a single transistor without destroying the device.

Numerous results using this later circuit have been published [3], [4]. The entire safe operating area has been generated and the effects of different base currents on the second-breakdown susceptibility has been shown, using a single device for all the measurements.

CIRCUIT DETAILS

A simplified diagram for the circuit described in [1] is given in Fig. 1. Before a test is initiated on a transistor, a clamp voltage, which can be set anywhere between 0 and 1000 V, is applied to the shunt protection circuit to isolate the TUT and the load inductor, L_3 , from the protection circuit by the reverse-biased clamp diodes, CR7 to CR9. This minimizes stray capacitance at the collector of the TUT. Three fast switching diodes are used in series for the clamping function to obtain the required voltage capability. The test for reverse-bias second breakdown is initiated by applying a base current to the TUT to turn it on for a period of time during which energy is stored in the load inductor. The TUT then receives a reverse-base current pulse to turn off the device, and the load inductor forces the collector voltage on the TUT to rise. The limits of the safe operating area are determined by measuring how much voltage the device can withstand before it breaks down. Since the safe-operating-area measurements are generally done for many different conditions of base drive on the same

device, it is desirable to save the device from destruction with each breakdown test.

A capacitor, $C1$, activates the shunt protection circuit when the collector voltage of the TUT collapses upon the onset of second breakdown. This capacitor consists of a short length of wire near the base of a sensing transistor internal to the shunt-protection circuit. This very small capacitance acts as a differentiator to detect only the very rapid fall in collector voltage associated with second breakdown as this voltage transition typically occurs in 10 ns. The collector voltage decrease associated with the collapsing inductor field after nearly all of the stored inductive energy has been dissipated is a slower voltage transition (occurring over about 1 μ s or more) and is ignored by the shunt-protection circuit.

When the TUT experiences second breakdown, the high-speed vacuum-tube protection circuit removes the stored energy remaining in the inductive load by shunting the clamp supply to the -140-V power supply. Additionally, when the protection circuit is activated, the clamp supply and the V_{CC} supply are turned off. An additional diode-resistor-inductor network, which consists of $CR1$ to $CR3$, $R1$, and $L2$, allows the clamp voltage to go negative for a short period of time after second breakdown has occurred and then decay to 0 V to overcome the inductance in the wire that connects the protection circuit to the TUT. Five power Schottky diodes, $CR10$ to $CR14$, are in series with the collector of the TUT to effectively open the collector lead when the clamp voltage is driven negative.

CIRCUIT IMPROVEMENT

In using the test circuit described above, it has been noted that some of the newer bipolar transistors measured have a very fast collector voltage rise time when large reverse-base currents are used. Voltage rise rates of 10^4 V/ μ s have been observed. The new power MOSFET devices also produce similar slew rates. The solid-state clamp diodes used for limiting the collector voltage are unable to turn on fast enough to prevent the voltage at the collector of these very fast transistors from going far beyond the desired clamp value during the test. Over 100 V of overshoot has been observed. Because it is very difficult to characterize devices accurately under such conditions, a vacuum-diode clamp was introduced into the circuit between the junction of $L3$ and $CR10$, and the clamp supply. This new clamp greatly reduces the overshoot. Fig. 2 is a photograph showing the collector voltage waveforms for both the solid-state and tube clamps. Most of the overshoot remaining in the tube clamp is caused by the inductance in the wires leading to the clamp. These wires could have been considerably shorter had this new added clamp been designed into the original circuit. The tube diodes used for the fast clamp are type 6CG3, which are designed for damper diode use in television receivers. Six were wired in parallel to handle a clamping current of 10 A.

There are some disadvantages in using the tube clamp. One disadvantage is the internal resistance which causes a voltage drop of about 45 V for 10 A through this six-diode clamp. This voltage drop decreases to approximately zero as the current decreases to zero, and the clamped voltage changes somewhat as the current through the clamp changes. This is not a serious problem because the data can be corrected for this effect if necessary. A second disadvantage is the added capacitance of the tube clamp. The six vacuum diodes and associated wiring add 150 pF from the collector circuit of the TUT to ground. Measurements have been made to determine the effect of 150 pF of additional snubbing to the collector circuit for the fastest transistors turning off 10 A. The rate of voltage rise is not significantly reduced, but there is a reduction in the collector current during the time in which the collector voltage is rising since the stray tube capacitance must be charged.

Often the collector voltage of the TUT is clamped momentarily, but the device experiences second breakdown before all of the collector current is diverted through the clamp. When the device breaks down under these conditions, there is a very large reverse recovery current from the solid-state clamp diodes before the protection circuit can take over. This surge of current does not occur with the tube clamp as there is no equivalent recovery time. The superior behavior of the

Fig. 2. Examples of overshoot using solid-state diode and vacuum-tube diode. The overshoot is 100 V for the solid-state diode and 50 V for the tube diode. The vertical scale is 100 V per division and the horizontal scale is 50 ns per division.

Fig. 3. Collector current for conditions of momentary clamping and subsequent second breakdown. The top trace is the collector current when the solid-state diode clamp is used, and the bottom trace is the collector current when the tube diode clamp is used. The scale factors are 5 A per small division on the vertical, and 50 ns per small division on the horizontal.

tube clamp under these conditions permits the collector current to be measured more accurately during second breakdown with less stress than with the solid-state clamp. Fig. 3 is a photograph that shows the difference in collector current at breakdown between the solid-state clamp and the tube clamp. It can be seen that the current appears to reach peak values of 30 and -20 A with the solid-state clamp. Since the bandwidth of the current probe used is only about 50 MHz, it is likely that the peak current is even larger than indicated in this figure as these transitions are very fast. With the tube clamp, only one large peak in the current is observed. This peak is caused by the discharge of the parasitic capacitance associated with the collector of the TUT. The other large current spikes are not present.

CONCLUSION

It has been found that some difficult measurements of high-voltage fast-switching transistors can be improved by the use of vacuum tubes in critical parts of the test circuits. The fast response of the tubes and freedom from recovery phenomena reduce voltage overshoot in voltage clamping and reduce uncontrolled current spikes normally generated in solid-state clamping diodes when measuring transistor second breakdown.

REFERENCES

- [1] D. W. Berning, *Semiconductor Measurement Technology: A Reverse-Bias Safe Operating Area Transistor Tester*. NBS Special Publ. 400-54, Apr. 1979.
- [2] T. M. Jahns, "Investigation of reverse-bias second breakdown in power transistors," Mass. Inst. Technol., Cambridge, MA, Dept. Electrical Engineering, M.S. thesis, May 1974.
- [3] D. L. Blackburn and D. W. Berning, "Some effects of base current on transistor switching and reverse-bias second breakdown," in *Tech. Dig., 1978 IEEE Int. Electron Devices Meet.* (Washington, DC, Dec. 4-6, 1978), pp. 671-675.
- [4] —, "Reverse-bias second breakdown in power transistors," in *Proc. Electrical Overstress/Electrostatic Discharge Symp.* (Denver, CO, Sept. 24-27, 1979), pp. 116-121.