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Power Transistor Switching Characterization

D. L. Blackburn

Electron Devices Division
Center for Electronics and Electrical Engineering
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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

Table of Contents

List of Figures

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ABSTRACT

The results of the first year of an experimental investigation of the switching characteristics of power transistors are discussed. The devices studied were housed in TO-3 cases and were of an n^+-p-n^--n^+ vertical dopant structure. The effects of the magnitude of the reverse base current and temperature on the reverse-bias second breakdown characteristics are discussed. Brief discussions of device degradation due to second breakdown and of a constant voltage turn-off circuit are included. A description of a vacuum tube voltage clamp circuit which reduces clamped collector voltage overshoot is given.

INTRODUCTION

This report covers activities during the first year of the National Bureau of Standards (NBS) Power Transistor Switching Characterization project being sponsored by The Lewis Research Center, National Aeronautics and Space Administration. The purpose of this work is to develop improved methods for characterizing the switching properties, particularly the reverse-bias safe-operating-area limits, of power transistors. Ideally, the methods would be circuit-independent.

The tasks to be undertaken the first year were:

<u>Task 1</u> - Complete the study of the effect of base current magnitude on the switching characteristics of power transistors.

    A. Study variable base current during turnoff.

    B. Study the influence of device construction on the base current variation of second breakdown voltage.

<u>Task 2</u> - Begin study of the influence of device temperature on switching characteristics.

    A. Design and construct a heat sink with low electrical capacitance and select and purchase an electrical controller for the test apparatus.

    B. Initiate study to determine the effect of case temperature on switching characteristics and reverse-bias second breakdown.

Task 3 - Initiate study of degradation mechanisms of second breakdown.

    A. Incorporate "controlled delay" into second breakdown protection circuitry.

    B. Study the effect on device parameters of permitting device to to "stay" in second breakdown for varying lengths of time.

Task 4 - Develop constant-voltage base turn-off circuitry to aid in developing a circuit-independent method for establishing the reverse-bias safe-operating-area limits.

ACCOMPLISHMENTS

The power transistors investigated in this study have an n^+-p-n^--n^+ vertical dopant density profile and are housed in TO-3 packages. An example of the dopant profile as determined by spreading resistance [1,2] for an actual device is shown in figure 1. Transistors of this structure are used in applications that require the device to be switched on and off rapidly, to dissipate substantial energy, and to support high voltages.

Most of the measurements described have been made using the nondestructive reverse-bias safe-operating-area test system developed previously at NBS [3]. Some of the important characteristics of this system are listed in table 1. The most important feature is that all power can be removed from the transistor under test within 40 ns of the occurrence of reverse-bias second breakdown (RBSB). Because of this, the devices that have been tested in this work (TO-3 housed) have experienced RBSB many times (in most instances, over 100 times) with no measurable degradation of their electrical properties.* Most such devices exhibited no change in either their open base, collector-emitter leakage current, I_{CEO}, or their open emitter, collector-base leakage current, I_{CBO}, after experiencing RBSB. In prior work, before the power removal circuit was optimized, some devices were degraded during RBSB testing. The degradation was first evident as an increase in leakage currents.

Task 1

An extensive study of the effect of reverse base current, I_{BR}, on the switching characteristics and RBSB behavior of power transistors was performed. Measurements for both constant and variable I_{BR} were made. Examples of the RBSB behavior as a function of I_{BR} for three different devices are shown in figure 2. Each data point represents the measured voltage at which second breakdown occurred, V_{SB}, for a constant I_{BR}, with a

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*The TO-3 housed devices usually have a chip area of less than 0.4 cm^2. Larger area devices (~3 cm^2) housed in "stud-mounted" packages have degraded electrically after experiencing RBSB in the test circuit. As with the TO-3 encased devices, all power was removed within 40 ns of RBSB. The degradation may occur because as the device area is increased, the collector capacitance is also increased. When RBSB occurs, the energy internally discharged increases as the collector capacitance is increased. The protection circuit cannot reduce this discharge of internal energy. If larger area devices are to be studied, this problem must be investigated further.

Figure 1. Typical dopant profile as determined from spreading resistance of a high-voltage n^+-p-n^--n^+ power transistor.

Table 1.

Parameter	Limits
Device Type	npn
Collector Voltage (V_{CE})	0 to 1100 V (clamped)
Collector Current (I_C)	0 to 30 A
Forward Base Current (I_{BF})	10 mA to 15 A
Reverse Base Current (I_{BR})	50 mA to 15 A
Reverse Base-Emitter Voltage (V_{BER})	2 to 15 V (clamped)
On Time (τ_{on})	1 μs to 0.1 s
Protection Time (τ_p)	<40 ns after RBSB

Figure 2. The measured voltage at which RBSB occurred, V_{SB}, for a collector current of 10 A for various values of reverse-bias current, I_{BR}, for three devices, A, B, and C.

maximum collector current, I_C, of 10 A. In Appendix A, it is shown that the variation of V_{SB} with I_{BR} depends upon the behavior during turnoff of the reverse-bias sustaining voltage, $V_{CEX}(SUS)$,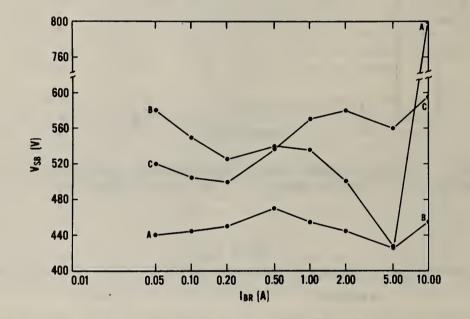 and also that the variation can be qualitatively explained by the theory of avalanche injection [4]. The mechanism of avalanche injection is commonly thought to be the dominant initiating mechanism of RBSB [5,6].

However, the theory of current focusing to the center of the emitter fingers [5,6], in conjunction with the theory of avalanche injection, fails to accurately predict the values of V_{SB} for a given I_{BR} and I_C during sustaining operation. The theory of avalanche injection predicts that RBSB should occur whenever the electric field in the collector is large enough for significant carrier multiplication to occur and:

$$j_e(0) \geqslant q \cdot v_\ell \cdot N_C , \qquad (1)$$

where:

$j_e(0)$ = peak emitter current density (A/cm^2),
q = electronic charge (1.6×10^{-19} C),
v_ℓ = scattering limited drift velocity ($\sim 10^7$ cm/s), and
N_C = collector doping density (cm^{-3}).

The value of $j_e(0)$ can be computed from the theory of current focusing for any values of I_C and I_{BR} for a particular device. According to this theory, the value of $j_e(x)$, the emitter current density at any point x along the emitter width, is given by [5,6]:

$$j_e(x) = j_e(0) \; \text{sech}^2 \; (x/L_B) , \qquad (2)$$

where:

x = position along emitter width (cm) and
$j_e(x)$ = emitter current density at any point x along the width of the finger (A/cm^2).

The expression for L_B is:

$$L_B = \left[\frac{2 \cdot V_t \cdot G}{R_{SB} \cdot j_e \cdot (0)} \right]^{1/2} , \qquad (3)$$

where:

R_{SB} = base sheet resistance under the emitter (Ω),
G = I_C/I_{BR}, and
V_t = kT/q,

where:

k = Boltzmann's constant (1.38×10^{-23} J/K) and
T = temperature (K).

The total emitter current is given by:

$$I_E = j_e(0) \; Z \cdot L_B \cdot \tanh \; (L_E/L_B) , \qquad (4)$$

where:

I_E = emitter current (A),

Z   = total device emitter perimeter (cm), and

L_E = half of the emitter width (cm).

The value of $j_e(0)$ can be found by solving eqs (3) and (4) simultaneously.

The collector voltage and current waveforms for a device whose voltage reaches $V_{CEX}(SUS)$ prior to V_{SB} are shown in figure 3. Second breakdown occurs at $I_C \cong 1.5$ A and $V_{CE} \cong 650$ V. The value of I_{BR} was 0.10 A. In table 2 are listed the values of the various parameters required to compute $j_e(0)$ for this device as well as how those parameters were determined. Also listed is the value of N_C, which is required to compute the right side of eq (1). For sustaining operation, the equality sign in eq (1) holds. The value of $j_e(0)$ computed is 13 A/cm^2, whereas the value of the right side of eq (1) is 128 A/cm^2. Thus, the requirement as stated by eq (1) that $j_e(0)$ be at least as large as the product of $q \cdot v_\ell \cdot N_C$ for RBSB to occur is not satisfied. This failure in agreement has been found to be the case for nearly all devices during sustaining operation.

For the devices studied, the qualitative RBSB behavior as a function of I_{BR}, case temperature (discussed later), and energy dissipation (discussed in Appendix A) is in agreement with the theory of avalanche injection. It is thought at this time that the failure of eq (1) to accurately predict the RBSB behavior during sustaining is a result of a failure of the theory of current focusing to accurately predict the peak current density. It is speculated that either a mechanism similar to thermal instability [7] or the inability of the transistor to turn off uniformly spatially due to its emitter or base structure may cause the current density to be greater than predicted by the theory of current focusing. These ideas are being actively investigated at this time.

Measurements were also made for a variable reverse base current in order to simulate circuit operating conditions for which I_{BR} cannot be held constant. The reverse base current waveform for these measurements is shown in figure 4. If the second step is applied at any time during the traditional current storage time (and often any time before the collector voltage has reached 100 V or so), V_{SB} depends only upon the magnitude of I_{BR} at the end of the turnoff (I_{BR2}) and not at all upon the magnitude of the initial I_{BR} (I_{BR1}). Some examples of the effect of such a variable I_{BR} on V_{SB} are shown in table 3. The first column lists the constant values of I_{BR} used and the second column, the values of V_{SB} for these I_{BR}. The third and fourth columns list the values of V_{SB} for which the initial value of I_{BR} was set equal to 1 and 5 A, respectively, but the second step was adjusted so that the final I_{BR} value was the same as listed in column 1. The second step was arbitrarily applied when the collector voltage reached about 10 V. In each instance, the value of V_{SB} depends only upon the final value of I_{BR}. These results are consistent with the theory of avalanche injection in that it is assumed that the instantaneous value of I_{BR} determines the magnitude of $j_e(0)$ which determines the magnitude of V_{SB}.

Figure 3. Collector voltage and current waveforms for a device which reaches $V_{CEX}(SUS)$ prior to RBSB. The occurrence of RBSB is noted on the voltage waveform.

Table 2.

Parameter	Value	Method
Base Sheet Resistance, R_{BS}	798 Ω	Spreading Resistance
Emitter Perimeter, Z	14.1 cm	Metallurgical Microscope
Emitter Half Width, L_E	0.014 cm	Metallurgical Microscope
Collector Current, I_C	1.5 A	Oscilloscope
Base Current, I_{BR}	0.1 A	Controlled by Circuit
Collector Doping, N_C	8×10^{13} cm^{-3}	Spreading Resistance

Figure 4.   Reverse base current waveform for variable current.

Table 3.

I_{BR2} (A)	V_{SB} (V)		
	($I_{BR1} = I_{BR2}$)	$I_{BR1} = 1$ A	$I_{BR1} = 5$ A
0.05	490	490	490
0.1	480	480	480
0.2	460	460	460
0.5	450	450	450
1.0	450	450	430
2.0	430		410
5.0	300		300
10.0	>900		

No correlation has been observed between the RBSB behavior as a function of I_{BR} and the construction of the transistors studied. As noted in Appendix A, devices of identical construction (same part number, manufacturer, and date code) have exhibited a variety of different behaviors as a function of I_{BR}. The major difference in construction between the devices studied is in the dopant profile at the transition region between the collector and substrate. For some devices, the transition is smooth; in others, it is step-like. An example of the step-like collector profile as determined by spreading resistance measurements is shown in figure 5. This is in contrast to the smooth transition shown in figure 1. No significant variation in the RBSB behavior as a function of I_{BR} has been observed which can be attributed to this difference. Different collector doping profiles and small differences in the base width or base doping density may have an effect on the value of V_{SB} for a given I_{BR}, but no significant differences have been observed in how V_{SB} varies as I_{BR} is varied as these parameters are changed.

At this time, it is difficult to study the effects of device construction on RBSB behavior. It has been demonstrated that apparently identical devices display a variety of different behaviors. It appears that obvious differences in construction may not be as important as the more subtle, as yet unknown, differences. An understanding of these differences apparently must await a more in-depth understanding of RBSB itself.

The conclusions drawn from this phase of the study are:

(1) The RBSB behavior of a transistor in sustaining operation as a function of I_{BR} depends upon the variation of $V_{CEX}(SUS)$ as the device is turning off. The voltage at which RBSB may occur either increases or decreases as I_{BR} is increased, depending upon how $V_{CEX}(SUS)$ behaves.

(2) The theory of avalanche injection qualitatively explains the V_{SB} behavior with varying I_{BR}.

(3) The theory of current focusing in conjunction with the theory of avalanche injection does not accurately describe the RBSB behavior during sustaining. Because avalanche injection describes qualitatively the behavior as a function of I_{BR} as well as a function of temperature and energy, it is concluded that the theory of current focusing may be in error.

(4) It is the magnitude of I_{BR} at the end of turnoff that is important for determining the value of V_{SB} and not the value early in the turnoff.

(5) Although device construction may influence the relative magnitude of V_{SB} for various I_{BR}, the variability of behavior for seemingly identical devices makes it difficult at this time to attribute to differences in construction any variation in the functional dependence of V_{SB} on I_{BR}.
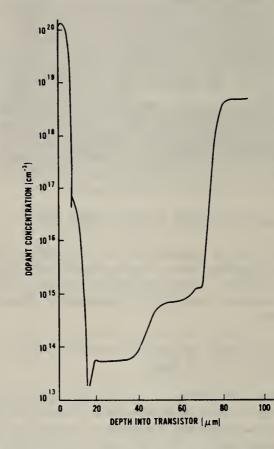
9

Figure 5. Dopant profile for a device with a step-like transition between collector and substrate.

Task 2

The influence of the temperature of the transistor on its RBSB behavior was studied. The results of this study are discussed in Appendix A. It was found that as temperature increases, the voltage at which RBSB occurs also increases. These results are in agreement with the avalanche injection theory of RBSB; i.e., the value of V_{SB} increases as T is increased.

In order to make these measurements, a temperature-controlled heat sink was designed and built. The heat sink is an adaptation of the commercial test fixture used in previous studies. The temperature is sensed with a Type K thermocouple inserted in the heat sink directly beneath the transistor being tested and insulated from the device by a thin layer of Thermal Film 1 (Thermaloy Corp.).* The heat sink is heated by four strands of coiled nichrome resistance wire inserted in four holes drilled through the heat sink. Cooling is achieved with forced air. Both the power supplied to the heating resistor and the volume of forced air are under the control of a temperature controller. The temperature range of the heat sink is 25°C to 100°C. The heat sink has very low thermal capacitance and therefore has short heating and cooling response times. More importantly, it features low electrical capacitance and thus the switching times of the transistor under test are not adversely affected.

Task 3

A study of the degradation of transistors due to RBSB was begun. To do this, the ability to introduce a controlled delay into the RBSB protection circuit has been implemented. The delay can be varied between 10 ns and 1 µs in 10-ns increments. Thus, transistors can be "taken into" RBSB and be allowed to remain in the low-voltage (<200 V) high-current density state associated with RBSB for up to 1 µs. Because of the length of time they can remain in this state, the electrical properties of the devices can be degraded.

The device parameters that seem to be most sensitive to numerous or extended RBSB excursions are the leakage currents, either I_{CEO} or I_{CBO}. It was found that for the lowest values of I_{BR} (0.05 A in this work), some devices may "stay in" RBSB for the entire 1-µs limit and experience no apparent degradation. This occurs when the device reaches its reverse-bias sustaining voltage, $V_{CEX}(SUS)$, prior to RBSB and the collector current subsequently decays to a small value ($\approx$1 A) before RBSB occurs. For larger values of collector current, device degradation usually begins after only a few (only one for large currents) extended excursions into RBSB.

The collector voltage has been observed to experience two distinct "collapses" after the onset of RBSB. The first collapse occurs within the first 10 ns after RBSB is initiated. In the devices studied, the voltage collapses to about 200 V. The voltage then decays to a value near 0 V ($\widetilde{\gtrsim}20$ V) in

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*Certain commercial equipment, instruments, or materials may be identified in order to adequately specify or describe the subject matter of this report. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

11

about another 30 to 40 ns. These events can be observed because the firing of the protection circuit, which is normally activated some time during the initial collapse, can be delayed as discussed above. The reason for the two periods of collapse is not known. Oscillographs of these events for two different temperatures, 25° and 100°C, are shown in figure 6. The initial collapse is slower at the higher temperature, but the second collapse is faster at the higher temperature. The reasons for this behavior is also unknown.

Task 4

A constant reverse base voltage circuit was developed which permits the device being tested to be turned off with a constant voltage of 0.05 V to 5 V through a resistance of 0.1 Ω to 50 Ω. The power supply of the constant reverse base current circuitry was altered to supply a constant voltage. This modification will be used in the study to compare the effects of the constant current and constant voltage turn-off conditions on transistor turn-off and second breakdown.
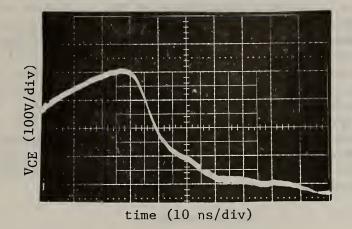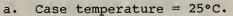
Other Accomplishments

A new collector voltage clamp circuit has been developed, which, when added to the measurement system, reduces or eliminates the voltage overshoot for extremely fast-rising collector voltage waveforms.
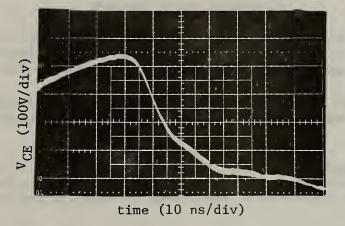
When a transistor which has an inductive load at its collector terminal begins to turn off, the voltage at the collector rises as the inductor attempts to maintain a constant current. For high-voltage, fast-switching transistors, the voltage can rise rapidly, perhaps as much as 500 V in 100 ns. In most applications for these devices, the maximum voltage rise is limited by a voltage clamping circuit connected to the collector. Usually, the voltage clamp consists of a solid-state diode in series with a voltage source (clamp voltage) arranged in such a manner that the bias on the diode is equal to the difference between the collector voltage and clamp voltage. When the collector voltage is lower than the clamp voltage, the diode is reverse biased. When the collector voltage rises slightly above the clamp voltage, the device is forward biased, the current is shunted from the transistor, and the collector voltage is held constant at the clamp voltage minus the voltage drop across the diode.

The diode in the clamp circuit cannot instantaneously go from a reverse-bias condition to a forward-bias condition. Even the fastest solid-state diodes must have time for the depletion region to collapse, which delays the forward biasing of the diode. This results in an overshoot of the collector voltage above the clamp voltage for a short period of time (~50 ns) for fast-rising collector voltages. The overshoot has been observed to be over 100 V for some very fast bipolar transistors tested on the nondestructive NBS test circuit. Because of the overshoot, the devices appear to experience second breakdown at lower clamp voltages than they would if no overshoot occurred. There is no overshoot for slower rising voltages.

To reduce the overshoot on the NBS circuit, a vacuum tube diode clamp circuit has been constructed which can replace the solid-state diode. The vacuum

a. Case temperature = 25°C.

b. Case temperature = 100°C.

Figure 6. Collector voltage waveforms during RBSB. The
time base has been delayed to eliminate most of the por-
tion of the waveform prior to RBSB.

tube has no reverse recovery time and thus has a shorter delay time in assuming its conducting state than does the solid-state diode. The result has been to eliminate overshoot in some instances and to substantially reduce it in others.

Two disadvantages of the vacuum tube clamp are that the vacuum tube can have a substantial voltage drop, about 45 V for 10 A of current, and that it introduces an increased parasitic capacitance at the collector of the device being tested. The first disadvantage is overcome by merely accounting for the extra voltage when recording the clamp voltage. The second does present a problem in that the collector current can droop substantially during the early stages of the collector voltage rise as the extra clamp capacitance is charged. Measurements have indicated that this may have an effect on the second-breakdown characteristics of the device being tested. The vacuum tube clamp is only used when voltage overshoots are a problem, and at other times the solid-state diode clamp is used. The effect of the current droop on the second-breakdown characteristics is being investigated. A paper describing the new clamp circuit as well as some of the other "vacuum tube" features of the circuit is included as Appendix B.

Acknowledgment

The spreading resistance measurements were made by Dr. James R. Ehrstein.

Dissemination of Results

Published - An Experimental Study of Reverse-Bias Second Breakdown, D. L. Blackburn and D. W. Berning, *Technical Digest, 1980 International Electron Devices Meeting,* Washington, D.C. (December 1980).

Associated talk - An Experimental Study of Reverse-Bias Second Breakdown, D. L. Blackburn and D. W. Berning, 1980 International Electron Devices Meeting.

Submitted for publication - Use of Vacuum Tubes in Test Instrumentation for Measuring Characteristics of Fast High-Voltage Semiconductor Devices, D. W. Berning, submitted to *IEEE Trans. on Measurement and Instrumentation.*

Tour - Tour of laboratory conducted in December 1979 for attendees of 1979 International Electron Devices Meeting ($\sim$80 participants).

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AN EXPERIMENTAL STUDY OF REVERSE-BIAS SECOND BREAKDOWN*

D. L. Blackburn and D. W. Berning

Electron Devices Division
National Bureau of Standards
Washington, DC 20234

ABSTRACT

Experimental results showing the influence of reverse-base current, case temperature, collector inductance, and peak collector current on the reverse-bias second breakdown (RBSB) behavior of high-voltage $n^+-p-n^--n^+$ power transistors are presented. The results are in qualitative agreement with the theory that avalanche injection initiates RBSB. The inductance and peak collector current results are in conflict with the theory that RBSB is initiated at a critical temperature. It is concluded that for these devices for the condition studied, RBSB is not initiated at a critical temperature. It is shown that the theory of current focusing, in conjunction with the theory of avalanche injection, does not accurately predict the RBSB conditions during device sustaining. It is proposed that other mechanisms in addition to current focusing contribute to the nonuniformity of current during transistor turnoff.

INTRODUCTION

The reverse-bias (turn-off) characteristics of high voltage, fast switching power transistors have become more important as these devices are used in increasing numbers as high speed switches in power conditioning applications. Research to improve the device and circuit operating characteristics [1-3] and to better model and understand their operation [4,5] is continuing. Perhaps the most severe impediment to this research is the continued lack of documented experimental results on which to base device design changes and with which to compare and improve the prediction of models. The scarcity of experimental data results primarily because of the difficulty in obtaining repeatable, accurate measurements in the presence of the large voltage and current transients that occur during transistor turnoff and because of the destructive nature of reverse-bias second breakdown (RBSB). The phenomenon of RBSB determines the reverse-bias limits of safe operation, but the physical mechanisms of RBSB are only partially understood.

The purpose of this paper is to present experimental results of the RBSB behavior of high voltage, fast switching power transistors obtained using the nondestructive reverse-bias safe operating area test circuit developed at the National Bureau of Standards (NBS) [6]. Earlier results have previously been reported [7,8]. This paper reports results of measurements of the RBSB behavior of $n^+-p-n^--n^+$ power transistors as a function of the reverse-base current, case temperature, collector load inductance, and peak collector current. It is anticipated that the new results will be valuable to device and circuit designers and modelers for testing and improving their designs and models. In addition to helping to develop a better understanding of the switching and RBSB characteristics of power transistors, the objective of the NBS work is to develop a basis for the improved characterization of these devices.

THEORETICAL BACKGROUND

It is generally believed that the mechanism of avalanche injection is the dominant initiating mechanism of RBSB in $n^+-p-n^--n^+$ high-voltage power transistors [4,10]. This theory assumes that the collector current density becomes large enough locally that the charge density in some region of the collector is comprised primarily of the free, current-carrying charges. The net effect of this is that the peak electric field in the collector occurs at the collector-substrate (n^--n^+) interface rather than at the base-collector ($p-n^-$) junction. If the field is peaked at the collector-substrate interface and is simultaneously large enough for significant carrier multiplication by impact ionization to occur, avalanche injection will be initiated [9]. This forces the device to operate in a negative resistance region (current density increases as voltage decreases) which is inherently unstable [11]. The instability manifests itself as RBSB. The electric field peaks at the collector-substrate interface whenever

$$j_c \geq q \cdot v_1 \cdot N_C , \qquad (1)$$

where
j_c = collector current density (A/cm^2),
q = electronic charge (1.6 x 10^{-19} C),
v_1 = scattering-limited drift velocity ($\sim$10^7 cm/s), and
N_C = collector dopant density (cm^{-3}).

The large current density required for avalanche injection to occur is thought to be achieved as a

result of focusing of the emitter current to the centers of the emitter fingers [4, 10]. When the transistor is turned off from a saturated operating condition, the charges that have been stored in the base and collector regions are extracted via the base terminal. Because the active base beneath the emitter acts as a resistive component from and through which most of the stored charge is extracted, a voltage gradient is created along the width of the base-emitter junction. The gradient is such that the center of the emitter is more strongly forward biased than the edges and thus injects a larger current density. Expressions which have been developed for calculating the current density as a function of position along the emitter width [4, 10] predict that the current density at the center of the finger, $j_e(0)$, increases as emitter current, I_E, or reverse-base current, I_{BR}, is increased.

EXPERIMENTAL RESULTS

All of the results to be discussed were generated for the transistor being turned off with an inductive load at its collector terminal. Unless otherwise noted, the magnitude of the reverse-base current, I_{BR}, was held constant during turnoff. The test circuit and conditions were the same as have been described previously [6-8].

Measurements were typically made for both clamped and unclamped conditions. The clamped condition is one for which a circuit external to the device does not allow the collector voltage to rise above a specified value, and the unclamped condition is one for which the voltage is allowed to rise with no clamping external to the transistor. Because the only significant difference observed in the RBSB behavior between clamped and unclamped conditions is in the magnitude of the collector voltage at which RBSB occurs, V_{SB}, and not in the functional dependence of this voltage on other parameters, only unclamped results are presented.

The occurrence of RBSB manifests itself as a sudden collapse of the collector voltage of the transistor from the maximum voltage achieved to about 200 V. The collapse occurs in less than 10 ns, and in this work the voltage is reduced to zero within an additional 40 ns by the protection circuit [6]. Because of these short transition times, RBSB is observed on most of the oscilloscope traces presented in this work as an abrupt halt of the collector voltage waveform with an apparent discontinuous transition to zero voltage.

The results presented in this paper represent a sampling of results of numerous measurements on numerous devices. Each of the oscilloscope tracings presented shows the results of several measurements made on a single device. Typically, between 10 and 100 similar measurements have been performed on each of these devices. The repeatability of these measurements is within the resolution of the oscilloscope presentation. The large number of RBSB measurements is made possible by the protection circuit that is used [6]. For the device types discussed in this paper, hundreds of RBSB measurements can be made on a single device

with no apparent degradation of the device's electrical parameters.

Temperature

The temperature of the transistor may have a strong influence on its RBSB behavior. The collector current and voltage waveforms for a device for the case temperature T_C equal to 25°, 50°, 75°, and 100°C are shown in figure 1. It has been observed that in almost every instance, for all operating conditions, as T_C is increased, the voltage at which RBSB occurs, V_{SB}, is increased. This behavior is consistent with the avalanche injection theory of RBSB. Because the ionization coefficients for electron and holes decrease as the temperature is increased, the critical electric field required for significant impact ionization to occur is increased. This requires that the collector voltage at which the critical field is reached is also increased, i.e., V_{SB} is increased.

Reverse Base Current - I_{BR}

The magnitude of I_{BR} has a strong but varied effect on the RBSB behavior of high-voltage transistors. The measured V_{SB} is shown as a function of I_{BR} for three devices in figure 2. The variation of V_{SB} with I_{BR} can be partially explained with the aid of collector voltage and current waveforms for these same devices, which are shown in figure 3. For some values of I_{BR}, the collector voltage reaches the reverse-bias sustaining voltage, $V_{CEX(SUS)}$, prior to V_{SB}. The sustaining condition is evident in figure 3 as the voltage reaching a plateau and the current decaying at a relatively slow rate and approximately linearly with time. Because of the time scales of figure 3, it is not obvious for devices A and B at $I_{BR} = 0.2$ A and device C at $I_{BR} = 1$ A that the voltage reaches $V_{CEX(SUS)}$. By expanding the time scale for these waveforms, as done for figure 4 for device C, it can be seen that the devices do reach the sustaining condition for a brief time prior to RBSB.

Sustaining Conditions

If the device voltage reaches $V_{CEX(SUS)}$ prior to RBSB, as I_{BR} is increased, V_{SB} may either increase or decrease. For devices such as device A which remain in the sustaining condition for only a short time prior to RBSB and for which $V_{CEX(SUS)}$ is constant in time (does not change as I_C decays), V_{SB} will usually increase as I_{BR} is increased for sustaining conditions. Most often, though, $V_{CEX(SUS)}$ is not constant with time, but tends to increase as I_C decays during the sustaining condition. Devices of this type tend to remain in the sustaining condition for a rather long time prior to RBSB for the lowest values of I_{BR}. For these devices, examples of which are devices B and C, as I_{BR} is increased for sustaining operation, V_{SB} usually decreases. The V_{SB} of device C experiences both types of behavior, first decreasing and then increasing as I_{BR} is increased. The reasons for the differences in the sustaining behavior of these devices are not known. Devices A and B are identical devices made by the same manufacturer with the same
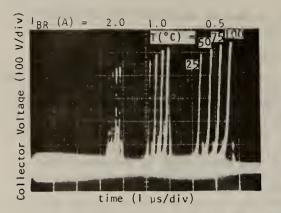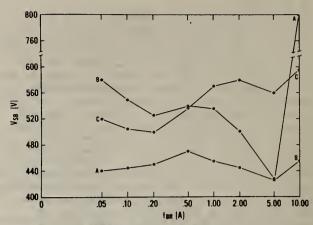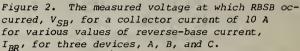
Figure 1. The collector voltage waveform for a device for three values of reverse-base current and the case temperature at 25°, 50°, 75°, and 100°C. For each I_{BR}, increasing T is from left to right. RBSB occurs at the peak of each voltage waveform for which the waveform abruptly halts.

Figure 2. The measured voltage at which RBSB occurred, V_{SB}, for a collector current of 10 A for various values of reverse-base current, I_{BR}, for three devices, A, B, and C.

a. Device A.   b. Device B.   c. Device C.

Figure 3. The collector voltage and current waveform for the same devices as in figure 2. RBSB occurs when the voltage waveform appears to halt and discontinuously goes to zero.

Figure 4. The collector voltage waveform at an expanded time scale for device C, $I_{BR} = 1$ A. The voltage collapses to about 200 V after RBSB. The voltage waveform after RBSB is determined both by the device and the protection circuit.

Figure 5. The collector voltage and current waveform for $I_{CM} = 10$ A, $I_{BR} = 0.1$ A, and L = 0.5 mH and 1.0 mH.

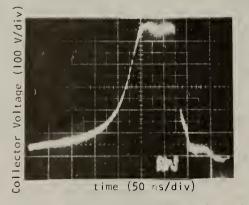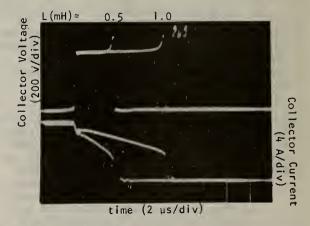date code. Device C is of similar construction to A and B, but was made by a different manufacturer. For sustaining conditions, the variation in V_{SB} with I_{BR} is not a predictable function.

By using the expression developed for calculating $j_e(0)$ [4,10], it is possible to test the quantitative predictions of the theories of current focusing and avalanche injection for sustaining conditions. For small I_{BR} compared to I_C ($I_E \approx I_C$) and for sustaining conditions, eq (1), the criteria for RBSB to occur, becomes

$$j_e(0) = q \cdot V_l \cdot N_C . \qquad (2)$$

The device physical parameters required for computing $j_e(0)$ can be determined from spreading resistance measurements and emitter dimension measurements. Typically, for the smallest values of I_{BR} and for sustaining operation, it has been found that the computed values of $j_e(0)$ for the observed second-breakdown conditions, such as shown in figure 3, are less than 10 percent of those necessary to satisfy eq (2). Also, for the devices and conditions studied, the theory of current focusing predicts that during sustaining, as I_C is decreasing, $j_e(0)$ is also decreasing.* Thus, the theories of current focusing and avalanche injection predict that if the device does not experience RBSB before sustaining begins, RBSB will not occur and the device will safely turn off. The results in figure 3 show this not to be the case. One reason for these discrepancies may be that other mechanisms in addition to current focusing can cause the current to constrict to a locally high density. More will be said about this later. Also, because the device may be dissipating a significant amount of energy during the sustaining condition, the possibility was investigated that a thermal mechanism rather than avalanche injection might initiate RBSB. These measurements will also be discussed later.

Nonsustaining Conditions - For values of I_{BR} such that the voltage of the device does not reach $V_{CEX(SUS)}$, the behavior of V_{SB} with varying I_{BR} is as predicted by the theory of current focusing and avalanche injection. That is, as I_{BR} is increased, for a given emitter current, $j_e(0)$ should increase. This causes RBSB to occur at a decreased voltage. Eventually, though, as the magnitude of I_{BR} approaches that of the maximum collector current, I_{CM}, the magnitude of the maximum emitter current, I_{EM}, approaches zero because:

$$I_{EM} = I_{CM} - I_{BR} . \qquad (3)$$

As $I_{EM} \to 0$, $j_e(0) \to 0$. Because the emitter effectively is turned off and there is no current focusing, the breakdown voltage increases and can approach V_{CBO}, the open emitter, collector-base breakdown voltage. This occurs for $I_{BR} = 10$ A for all three devices of figures 2 and 3.

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*A correction for variation in the effective base sheet resistance due to changing injection levels was made in performing these calculations.

Energy Dissipation

There is ample evidence that for devices of different structures and for different operating conditions than those studied here, RBSB may be initiated by a thermal mechanism [12]. When this mechanism dominates, RBSB should be initiated when the device locally reaches a critical junction temperature. Because the energy dissipated may be significant, measurements have been made to determine if a thermal mechanism is responsible for the RBSB behavior for high-voltage devices during the sustaining condition.

Inductance - If RBSB is initiated at a critical junction temperature, if only the collector load inductance L is varied, the total energy dissipated by the transistor prior to RBSB should not change. This energy is given by:

$$Energy = \int_{t_o}^{t_{sb}} I_C(t) \, V(t) \, dt = \int_{I_{CM}}^{I_{sb}} L \, I_C(t) \, dI \qquad (4)$$

where t_o is the time that turnoff begins and t_{sb} is the time RBSB occurs. The collector voltage and current waveform for L = 0.5 and 1.0 mH are shown in figure 5. From these waveforms, the calculated energy dissipated prior to RBSB is about twice as great for L = 1.0 mH as for L = 0.5 mH. This indicates that the temperature at which RBSB occurs is significantly greater at L = 1.0 mH than at L = 0.5 mH. Although this is not in agreement with the concept of RBSB being initiated at a critical temperature, the results are in qualitative agreement with the prediction of the theory of avalanche injection. That is, L should have almost no effect on the magnitude of V_{SB}. The slight increase in V_{SB} for L = 1 mH in figure 5 is probably due to the higher temperature at which RBSB occurred.

Peak Current - Another test of the critical temperature theory is the RBSB behavior as I_{CM} is varied, with all other parameters held constant. The energy dissipated prior to RBSB for different I_{CM} should be about the same if RBSB occurs at a critical temperature. The collector current and voltage waveforms for several values of I_{CM} are shown in figure 6. As I_{CM} is increased, the energy dissipated prior to RBSB also increases until $I_{CM} = 15$ A for which the device no longer reaches the sustaining condition, but experiences RBSB first. Neither the varying energy dissipation with I_{CM} nor the sudden change in behavior at 15 A can be explained by the critical temperature theory of RBSB.

The results of figure 6 can be explained by the theory of avalanche injection if it is assumed that some other mechanism in addition to current focusing contributes to the generation of a high-current density. The discontinuity in behavior can occur as I_{CM} is increased to ~ 15 A if the value of $j_e(0)$ at the instant the device reaches the sus-

I_{CM} (A):

15 6   9   11 13

Collector Voltage (200 V/div)

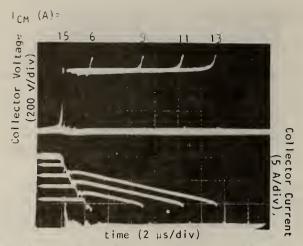Collector Current (5 A/div),

time (2 μs/div)

Figure 6. The collector current and voltage wave-
form for various values of I_{CM} and I_{BR} = 0.1 A,
all other parameters held constant. When I_{CM} = 15 A,
the device no longer sustains prior to RBSB.

taining condition satisfies eq (1) with the equal-
ity sign. If I_{CM} is increased further, the in-
equality in eq (1) is satisfied and RBSB occurs
prior to sustaining. Below I_{CM} = 15 A, when
the device reaches the sustaining condition $j_e(0)$
does not satisfy eq (1). As the sustaining condi-
tion continues, other mechanisms in addition to
current focusing may cause the current to begin to
localize within the transistor. Perhaps a phenome-
non similar to the thermal instability [13] that is
known to occur for forward-bias operation causes
the current to begin to localize, or perhaps some
regions of the transistor do not "turn off" as
readily as others because of their location with
respect to the base or emitter leads or because of
the device geometry. If such mechanisms do occur,
then the effective active area of the transistor
may begin to decrease and the current density in-
crease even though the total emitter current is de-
creasing during sustaining. This can cause $j_e(0)$
to increase and eventually become large enough to
satisfy eq (1).

CONCLUSIONS

Measurements showing the influence of reverse-base
current, case temperature, collector inductance,
and peak collector current on the reverse-bias
second-breakdown (RBSB) behavior of n^+-p-n^--n^+
high-voltage power transistors have been presented.
The inductance and peak collector current results
are in conflict with the concept that RBSB may be
initiated at a critical temperature. It is con-
cluded, for these devices and for the operating
conditions studied, that the theory that RBSB is
initiated at a critical temperature is incorrect.
All of the results are in qualitative agreement
with the theory of avalanche injection as the ini-
tiating mechanism of RBSB. The quantitative pre-
dictions of the theory of current focusing during
sustaining are shown not to be accurate in predict-
ing the RBSB behavior. It is speculated that other
mechanisms contribute to the nonuniformity of the
current during this type of operation.

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APPENDIX B

USE OF VACUUM TUBES IN TEST INSTRUMENTATION FOR MEASURING CHARACTERISTICS OF FAST HIGH-VOLTAGE SEMICONDUCTOR DEVICES*

David Berning
Electron Devices Division
National Bureau of Standards
Washington, DC 20234

Circuit techniques are described that permit measurement of fast events occurring in power semiconductors. These techniques 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 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 is 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 [B-1]. This circuit was developed using some ideas from one built by Jahns [B-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

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21

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 rapidly fall 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.

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/μs. 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 [B-3,B-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 reference [B-1] is given in
figure B-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 pro-
tection circuit to isolate the TUT and the load inductor, L_3, from the pro-
tection circuit by the reverse-biased clamp diodes, CR7 to CR9. This mini-
mizes 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
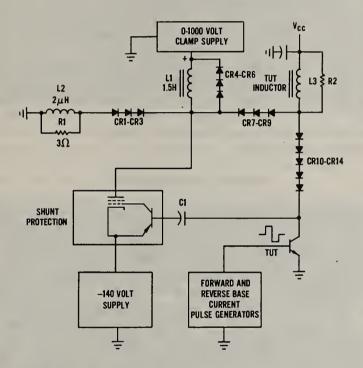device, it is desirable to save the device from destruction with each
breakdown test.

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

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 μs 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/μs 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. Figure B-2 is a photograph showing the collector voltage waveforms for both the solid state and tube clamp. 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
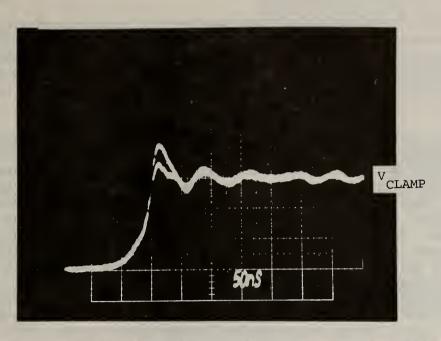
24

Figure B-2. Examples of voltage overshoot using solid-state diode and vacuum tube diode. The overshoot is 100 V for 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.
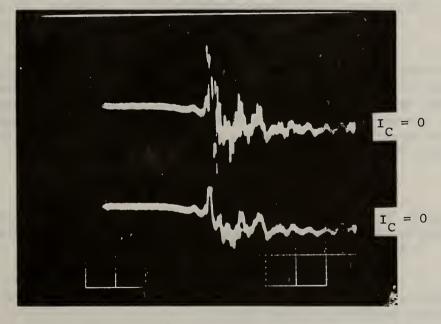

Figure B-3. Collector current for conditions of momentary clamping and subsequent second breakdown. The top trace is the collector current when the solid-state diode clamp is used, and the bottom trace is the collector current when the tube diode clamp is used. The scale factors are 5 A per small division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

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 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. Figure B-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 A 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.

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15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The results of the first year of an experimental investigation of the switching characteristics of power transistors are discussed. The devices studied were housed in TO-3 cases and were of an n^+-p-n^--n^+ vertical dopant structure. The effects of the magnitude of the reverse-base current and temperature on the reverse-bias second breakdown characteristics are discussed. Brief discussions of device degradation due to second breakdown and of a constant voltage turn-off circuit are included. A description of a vacuum tube voltage clamp circuit which reduces clamped collector voltage overshoot is given.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Base current, reverse; degradation; reverse bias; second breakdown; switching; temperature; transistors, power.

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