Avalanche Transistor Selection for Long Term Stability in Streak Camera Sweep and Pulser Applications

S.W. Thomas, R.L. Griffith and A.T. Teruya

University of California
Field Test Systems Division, Electronics Engineering
Lawrence Livermore National Laboratory
Livermore, California 94550

ABSTRACT

We have identified the Motorola 2N4014 and 2N5551 and the Raytheon RS3944 as three transistor types that exhibit avalanche characteristics and have long term collector breakdown voltage stability superior to other transistors tested. Stability on all types has been improved by power burnin.

An automatic avalanche transistor burnin tester has been constructed to allow power burnin of up to 1008 transistors at a time. The tester is controlled by an IBM Personal Computer (PC) and can be programmed to acquire data, unattended, at any desired rate or period. Data are collected from each run and stored on a floppy disk in ASCII format. The data analysis software, RS/1, was used for analysis and display.

Data runs were typically 3 to 4 months long, with readings taken weekly. The transistors were biased into the avalanche or Zener region by individual current sources set to about 20% of the self-avalanche current for each type of transistor. Motorola, Zetex and National transistors were operated at 100 microamperes (μA), and the Raytheon units were operated at 20 μA. The electric field causes migration of material in the high field region at the surface near the collector-base junction, creating the voltage instability.

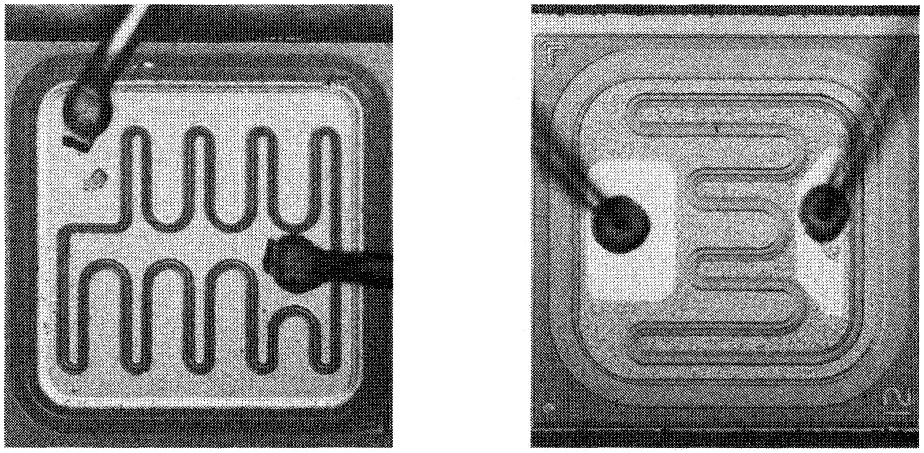
1. INTRODUCTION

We have used avalanche transistor circuitry for streak camera sweep voltage generation since 1970[1] and previously for other applications.[2] Since avalanche transistors, their characteristics and theory of operation have been described elsewhere,[3,4,5] this information will not be repeated here. Low trigger delay, simplicity of circuit design and fast rise time of avalanche transistor circuitry have led to its widespread use in the past decade. During this time an understanding of avalanche transistor operating limitations has resulted in vastly improved circuit reliability. Avalanching, also called second breakdown, occurs in a large fraction of some types of epitaxial transistors when the collector-base junction is allowed to break down with a current above a certain threshold. Avalanche characteristics are rarely specified by manufacturers and, for the same registered transistor type (those with 2N prefixes), differences among manufacturers' chip geometry and processing cause variations in avalanche characteristics. For example, Fig. 1 shows the chip geometries used by Fairchild and by National for the 2N3700 transistor and, while both can be used in the avalanche mode, the self-avalanche current for the Fairchild unit ranges from less than 50 μA to about 4 mA; for the National unit it is above 1 mA for nearly 100% of the devices. Additionally, optical triggering energy[1] for the Fairchild part is about 1% of that required by the National device. For these reasons, the manufacturer, as well as the transistor type, must be specified.

Trigger delay time has drifted in some of our streak camera applications, and pulse amplitude drift has been seen in pulser applications. This paper deals with solutions to these problems and concludes the avalanche transistor study described in Ref. 6.

2. AVALANCHE TRANSISTORS

Devices from Fairchild, Motorola, National Semiconductor, Raytheon, Zetex and several other companies have been evaluated for avalanche application. The yield of usable transistors was above 97% for the National 2N3700 (TO-18 version of the 2N3019), the Motorola 2N4014 and 2N5551, the Raytheon RS3944 (an RS3500 selected for self-avalanche current above 130 mA) and Zetex's ZTX653, ZTX300 and ZTX415. (Zetex acquired Plessey Semiconductor's transistor line on



Fairchild **National**

Figure 1. Photo showing two differing chip geometries of the 2N3700 transistor. The Fairchild transistor, shown on the left, triggers at a lower threshold, has a lower self-avalanche current and a more intricate design than the National device.

July 3, 1989. Plessey purchased the line some time ago from Ferranti. The transistors have always been made in England at the original manufacturing facility.) These transistors are shown in the photo of Fig. 2.

The collector voltage at which current just starts to flow is the collector-base breakdown voltage or Zener voltage (V_{Zener}). If the transistors are operated below this voltage so that the collector current is zero, the delay time from trigger-to-avalanche is longer than if even a few microamperes of bias current are allowed to flow. The reason for this is that current is the triggering mechanism for avalanching. Reaching the breakdown voltage must be achieved before current starts to flow, and this requires time to charge stray and transistor capacitances. If too much bias current is allowed to flow, the transistor will spontaneously avalanche. The current for spontaneous avalanching is called the self-avalanche current (I_{sa}), and it ranges from less than 1 μA to about 5 mA, depending on transistor type and base-emitter external circuit resistance. Our applications primarily require series strings of typically 4 to 26 avalanche transistors in order to achieve higher output voltage swings. Self-avalanche current for the National 2N3700 is about 5 mA with 200 ohms between the base and emitter. These units can be reliably operated in a biased string at about 20% of this current, or 100 μA. For the Raytheon RS3500, self-avalanche current varies from less than 1 μA to about 200 μA; they cannot be reliably used in a current-biased string without "free-running" or self-avalanching. For these transistors, there are two approaches to achieving stable operation. The self-avalanche current lower limit can be specified when ordering the transistors. We have used this approach with the Raytheon RS3944 units with satisfactory results, although a premium was added to the already expensive devices. The second and most common approach is to use zero bias current and operate the transistors very close to the breakdown voltage with a bias voltage established by a resistive divider or by Zener diodes. This requires careful selection and matching of the transistors to the divider or Zeners but does result in trigger delays comparable to those of a current biased string.

However, if the transistor collector-base breakdown voltage, V_{Zener}, changes, then the trigger delay and switching voltage will change to some extent. The switching voltage or output pulse voltage (V_{pulse}) is typically in the range of 70 to 90% of V_{Zener}. Construction of these transistors is such that the electric field between the collector and base regions is highest at the surface, and the breakdown voltage is probably controlled by surface characteristics.[7] The surface contains chemical elements used in processing. These elements physically drift or migrate in time scales of days to months in the presence of the high field, causing a change in surface conditions and, therefore, in the breakdown voltage. Such drifting should not recover with time. Another surface change is caused by "hole" drifting in the silicon dioxide surface passivation which affects the electric field at the surface and, thus, the breakdown voltage. The latter effect recovers after a month or two in the absence of an electric field.

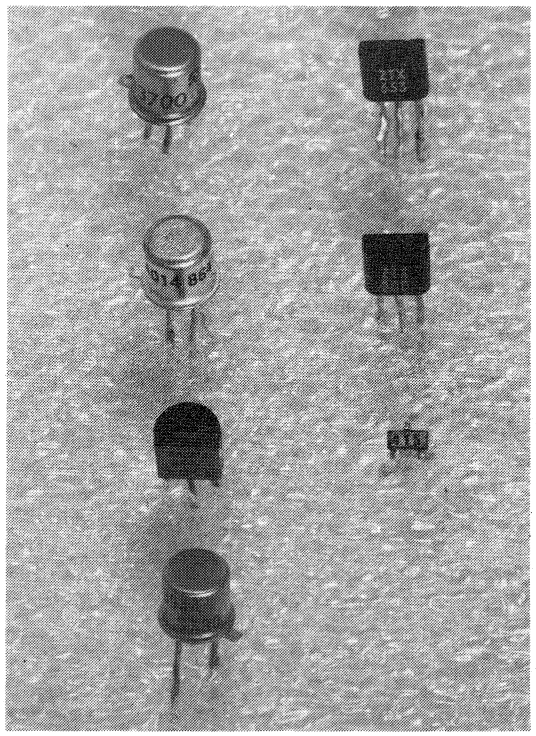


Figure 2. Seven transistors which exhibit avalanching characteristics. Only the RS3944 and ZTX415 are specified as avalanche transistors.

Avalanche transistors can be triggered into avalanche by an input between the base and emitter leads (base triggering) or by an input between the collector and emitter leads (collector or emitter triggering). Base triggering delay can be as low as four nanoseconds (ns) while collector or emitter triggering delay can be close to one ns, depending on the trigger amplitude and transistor type. Base triggering is more commonly used because it is usually easier to implement, requires a lower input current, and there is less disturbance to the triggering source when avalanche occurs as compared with collector or emitter triggering.

Since it is only the electric field which causes migration of the surface elements, transistors can be burned in with a constant voltage applied and need not be operated in pulsed mode. The units which exhibit satisfactory stability with time can be selected for use.

3. AVALANCHE TRANSISTOR BURNIN TESTER

An automatic avalanche transistor burnin tester has been constructed to allow power burnin of up to 1008 transistors at a time. Figure 3 shows a photo of the tester, and Fig. 4 shows the circuit block diagram. The tester consists of a control chassis, an eight test cell chassis (each of which can burnin 126 transistors at a time), a computer, a printer and a monitor. Only one test cell chassis was constructed and has proven to be adequate for our needs. The test cell chassis has space for 128 transistor sockets. Socket number one is removed and shorted to provide a ground or zero voltage reference while the second socket is removed and left open. The operator measures the power supply voltage (at open socket number two) and provides its value as input to the computer. The computer uses this value along with the values it reads from sockets one and two for automatic calibration of voltage readings during each run.

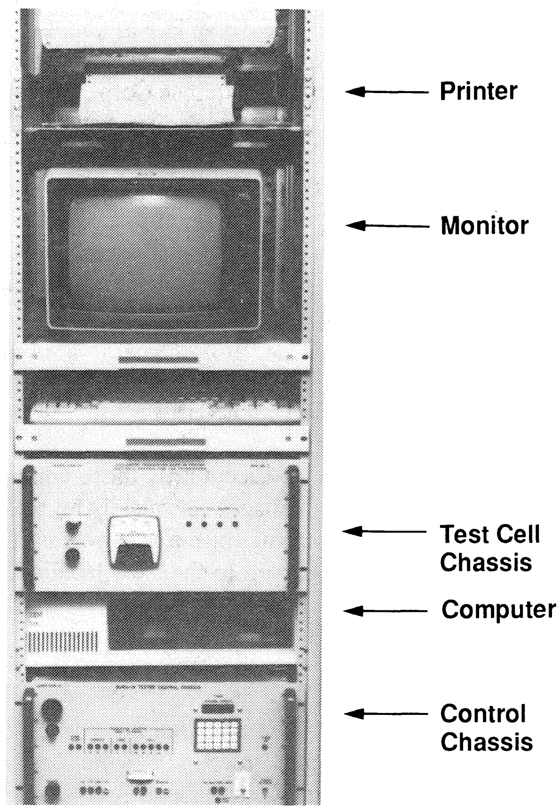


Figure 3. Photograph of the burnin tester.

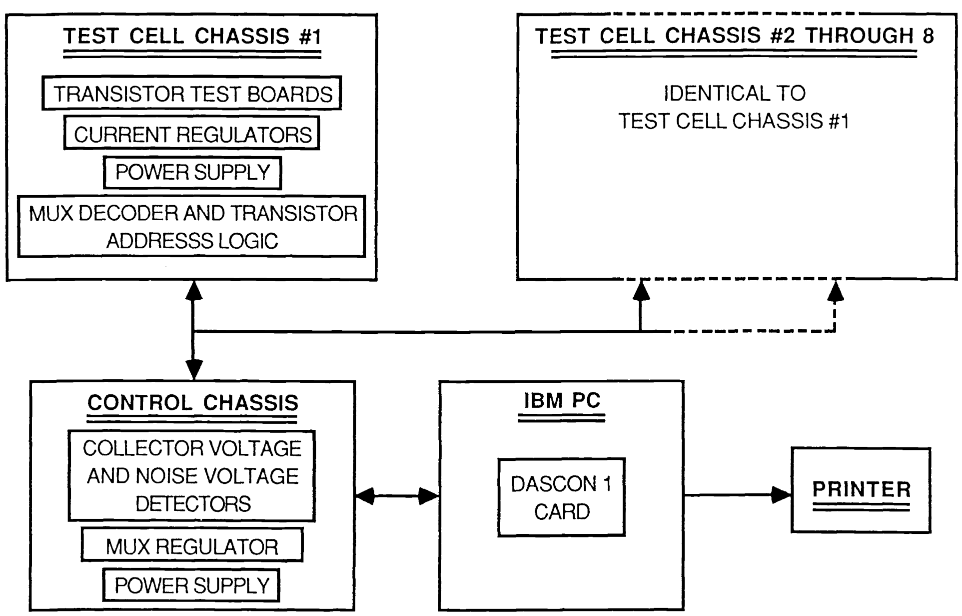


Figure 4. Schematic diagram of the burnin tester.

The control chassis contains a Model 416 Lawn Genie Electronic Sprinkler Timer (Garden America Corp.), which activates a relay, turning on the 117 Vac power to the IBM PC at the time a data run is to be executed. An AUTOEXEC.BAT file is used to run a BASIC data-taking program automatically on power up. The BASIC program acquires data, unattended, at any desired rate or period using a Metrabyte Corp., Dascon-1 data acquisition card installed in the PC. Data were taken at 3 a.m. to avoid disturbances from power-line transients and temperature variations from air conditioner cycling. The control chassis contains logic for addressing each transistor, and the test cell chassis contains the decoding logic and current regulators for the transistors besides providing sockets for testing 126 transistors at a time. Each transistor under test has a light emitting diode (LED) connected which flashes if the transistor spontaneously avalanches. The test cell chassis also contains a circuit that detects spontaneous avalanching of any of the transistors, lights a front panel LED to indicate in which section the bad transistor is located, and provides a flag so that the bad data can be identified and eliminated. Data are collected from each run and stored on a floppy disk in ASCII format. The data analysis software, RS/1 (BBN Software) was used for analysis and display.

4. TEST RESULTS

Before burning in the transistors, they are screened to accept only those which have low noise at the operating bias current, a sharp knee (i.e., a sharp transition at the V_{Zener} voltage), adequately high self-avalanche current, and to insure that they all avalanche. In the following figures, automatic scaling for the axes was used in order to present the data using the highest resolution possible. Therefore, attention must be paid to the axes labeling, particularly to the ordinant (Y-axis), since variations among the graphs are greatest there.

4.1 2N3700

The transistor type we have used exclusively in the sweep generator for the LLNL Laser Program's streak cameras is the National 2N3700. It is one of the devices from National's Process 12, which includes device types MPSA05, MPSA06, MPSA06-18, 2N3019, NSD106, TN3019 and TN3020, differing primarily from each other in packaging. Figure 5a shows the percent change in collector voltage from the start of the test as a function of time. The sample size is

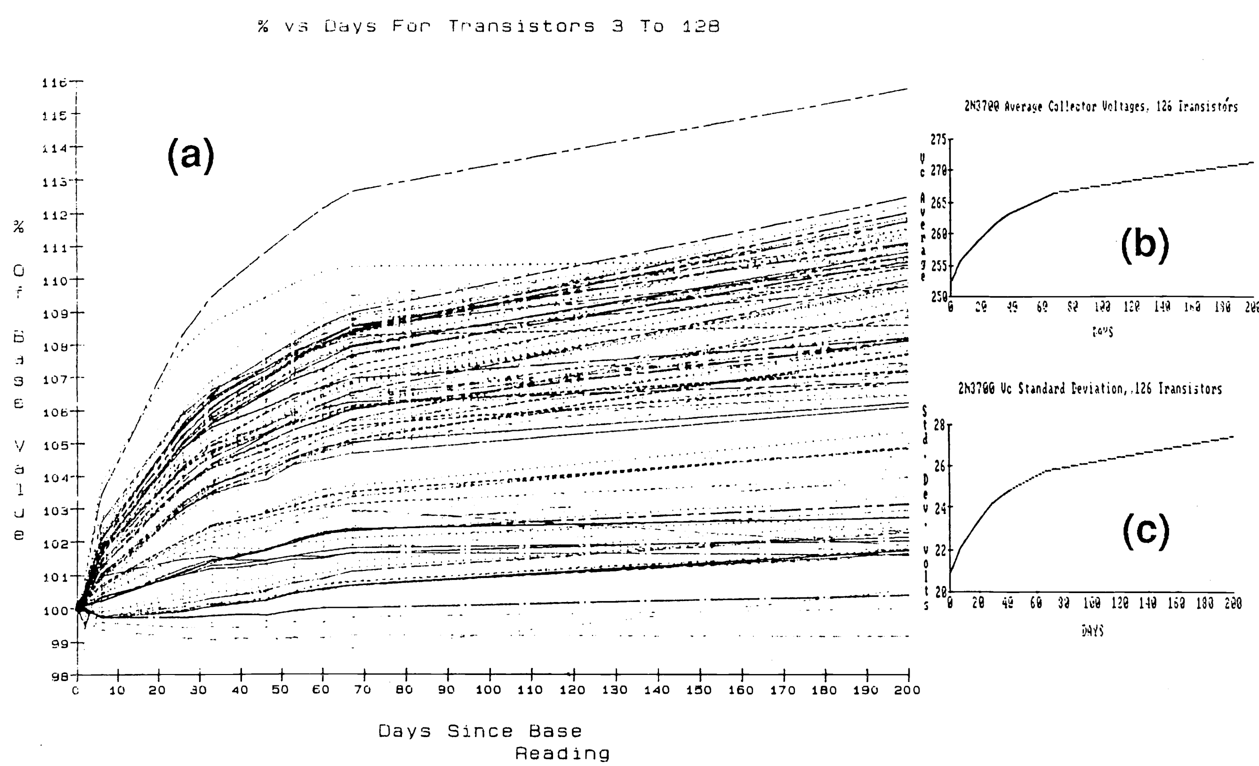


Figure 5. 2N3700. Collector voltage is shown as a percent of the starting value vs time in 5a and the average collector voltage and collector voltage standard deviation vs time are shown in 5b and 5c.

126 transistors. From previous tests, this transistor appeared to continue drifting and not to stabilize. Data were taken weekly for the first two months, and then one additional point was taken at a total of 200 days (about 6-1/2 months). Drifting did continue as expected, with the greatest change being +15% over the 200 days for one of the transistors.

Figure 5b shows the sample mean or sample average collector voltage as a function of time. This value drifts from 253 to over 270 volts during the 200-day test with a final drift rate of about 0.37%/month. It appears that drifting will continue indefinitely. Figure 5c shows the sample standard deviation as a function of time. Three standard deviations or ±75 volts about the approximately 265-V mean will contain 99.7% of the transistors; i.e., nearly all of the transistors will have collector voltages between 190 and 340 volts. The standard deviation is about 9.8% of the mean collector voltage. This parameter indicates the approximate variation in collector voltage which will have to be accommodated when the total voltage of a string is a consideration, or when resistor or Zener voltage bias is used.

4.2 2N4014

Although it is a lower voltage device, we have used this transistor in stripline pulser applications because of its short rise-time. Figure 6a shows the time history of the collector voltage of 30 2N4014 transistors. Drifting is less than a few

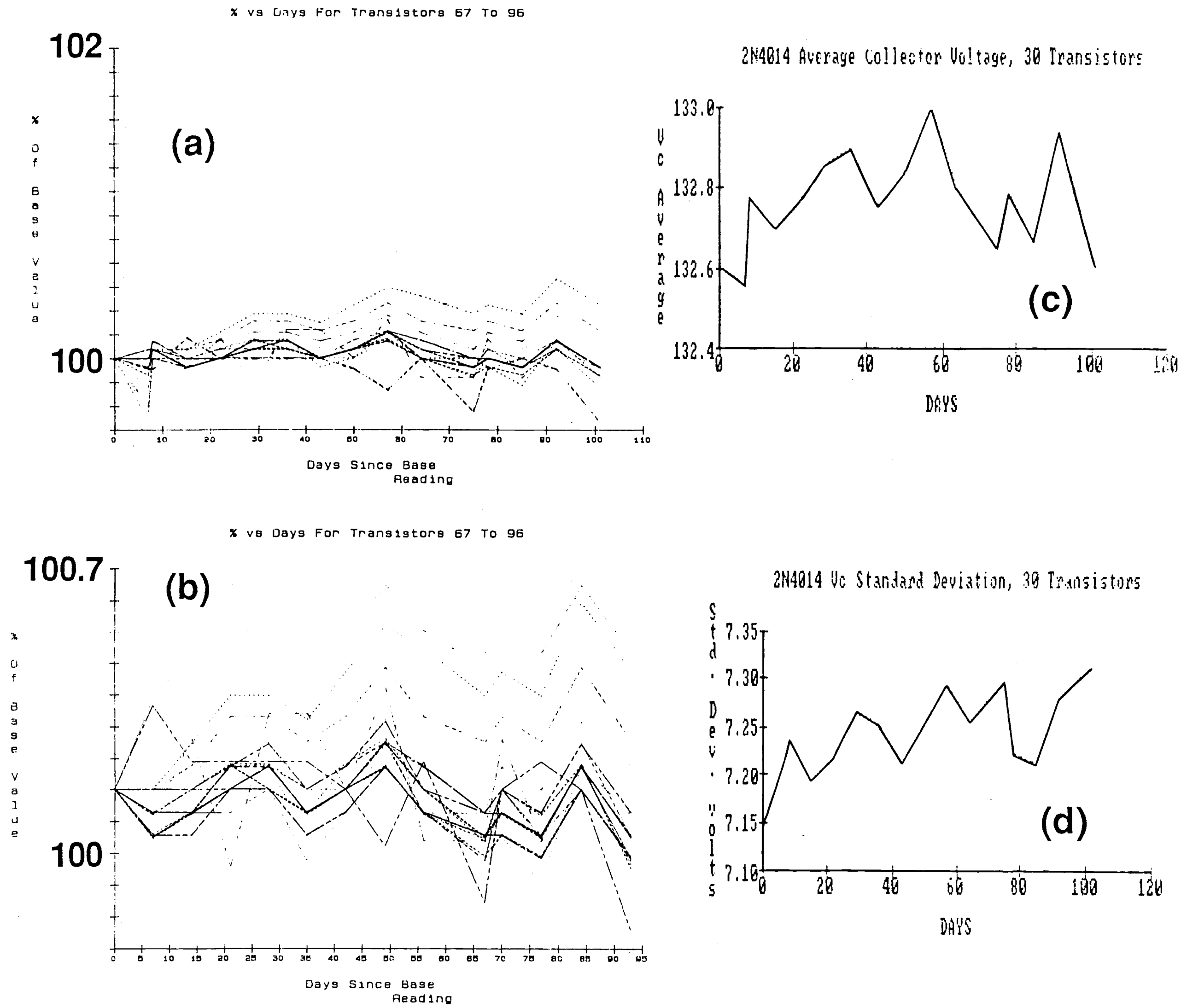


Figure 6. 2N4014. Collector voltage as a percent of the starting value vs time is shown in 6a. The data of 6a without the first week's data are displayed in 6b. The average collector voltage and collector voltage standard deviation vs time are shown in 6c and 6d.

tenths of a percent for the entire test duration, and there appears to be little indication of significant drift after the first 3 weeks. During the first week of the test, the power to the tester was inadvertently turned off, which caused the odd behavior indicated at that time in Fig. 6a. Figure 6b shows the data of Fig. 6a with first week's data deleted. Figure 6c shows the average collector voltage vs time, showing a drift rate of approximately 0.025%/month and indicating that variations caused by factors other than time are dominant. Figure 6d shows the standard deviation vs time, which is about 5.5% of the mean collector voltage.

4.3 2N5551

Figure 7a shows the percent voltage drift with time for 126 2N5551s. Only three transistors behaved differently from the rest of the group, and one of these drifted +11% during the test. Eliminating the three transistor which have excessive drift from the data and replotting the curves produces the results shown in Fig. 7b.

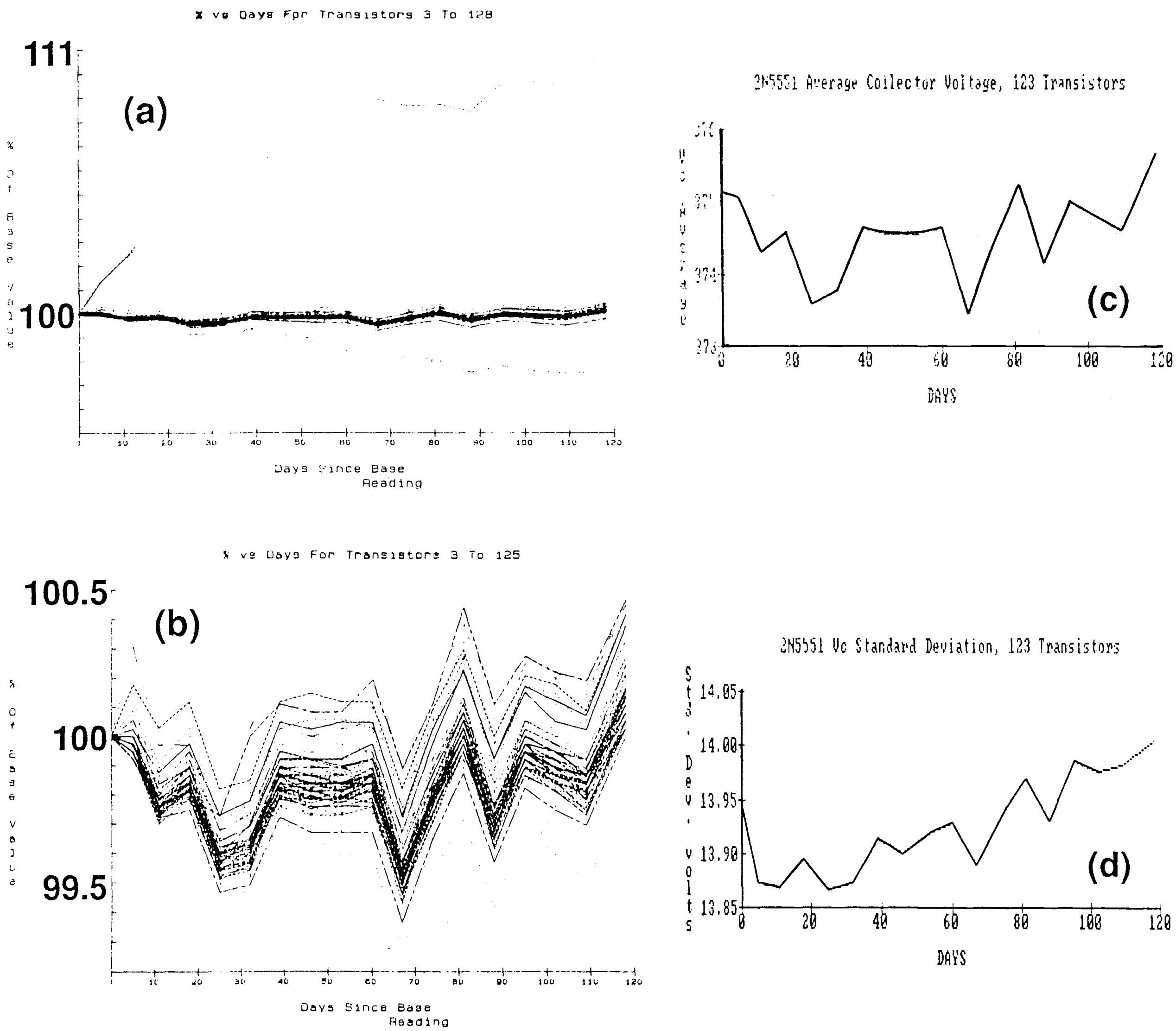


Figure 7. 2N5551. Collector voltage as a percent of the starting value vs time is shown in 7a. In 7b, the data of 7a are shown without the 3 transistors which diverge from the average, indicating the benefits of screening and removing those transistors with high drifting rates. In 7c and 7d, the average collector voltage and collector voltage standard deviation vs time are shown.

Figure 7c uses the data from Fig. 7b. It shows the small change in the average collector voltage with time (only about 0.07%/month) and that this transistor type has an average collector voltage of about 374.5 V, the highest of those tested. This means that fewer transistors will be required in a series string. Figure 7d shows the standard deviation, which is only about 3.7% of the mean collector voltage.

4.4 RS3944

The Raytheon RS3500 transistor is specified by the manufacturer as an avalanche transistor. The RS3944 is an RS3500 avalanche transistor selected for I_{sa} greater than 130 μA. It has a field plate (the base metalization is extended) covering the surface at the collector-base junction, which reduces the electric field at this point, causing breakdown to occur within the bulk material, and not at the surface. This should reduce the drifting caused by surface effects as seen with transistors which don't use a field plate. Figure 8a shows the collector voltage vs time for 93 of these transistors and, indeed, the drifting appears to be very low. Temperature or other effects appear to mask any drift with time.

The average collector voltage is shown vs time in Fig. 8b, indicating a drift of only about +0.045%/month. The standard deviation of collector voltage, displayed in Fig. 8c, is about 3.3% of the average collector voltage.

4.5 ZTX653

The drift of 61 samples of this transistor type is shown in Fig. 9a. The dashed, nearly horizontal line at 100% is the voltage measured at an empty socket, i.e., the power supply voltage, showing that the stability of the tester is better than 0.1% over the test duration.

The ZTX653 was tested at the same time as the 2N4014 described above and, therefore, displays the same discontinuity during the first week when the power was off. Figure 9a replotted without the first week's data is shown in Fig. 9b, and indicates continued drift is likely.

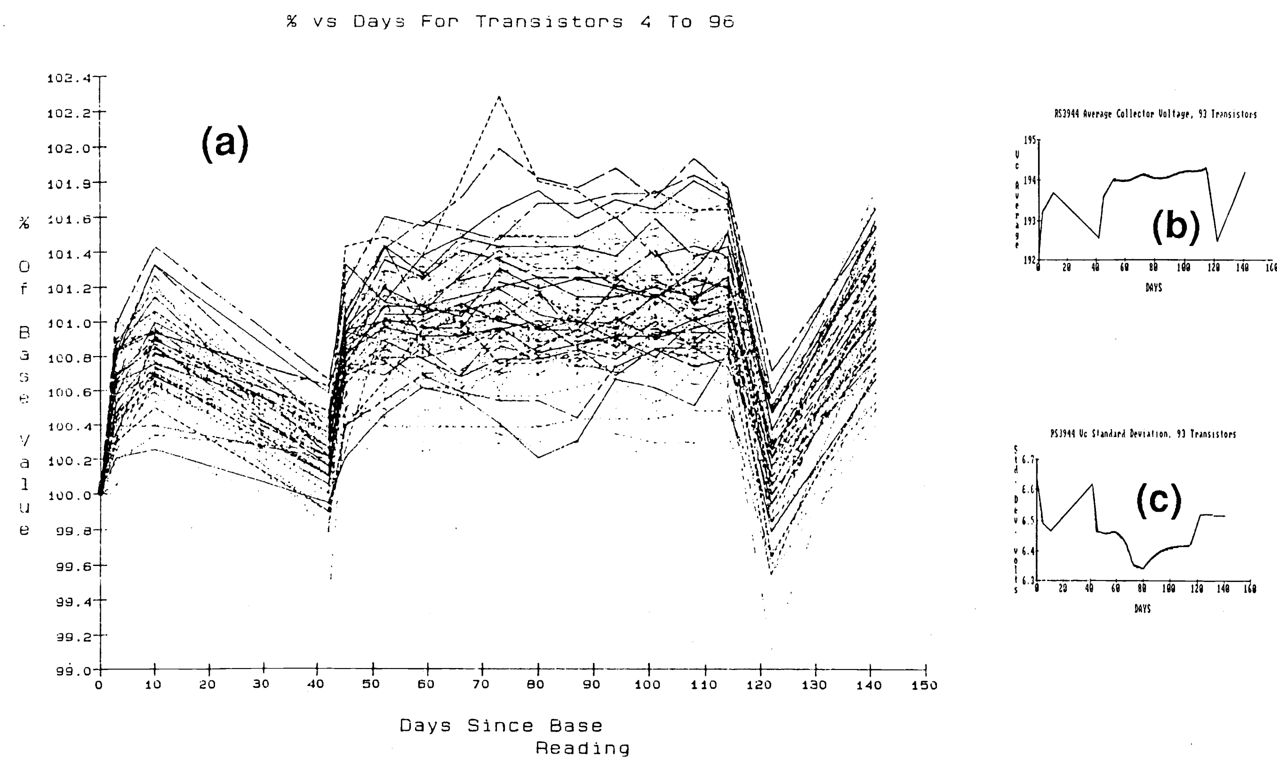


Figure 8. RS3944. Collector voltage as a percent of the starting value vs time is shown in 8a. In 8b and 8c, the average collector voltage and collector voltage standard deviation vs time are presented.

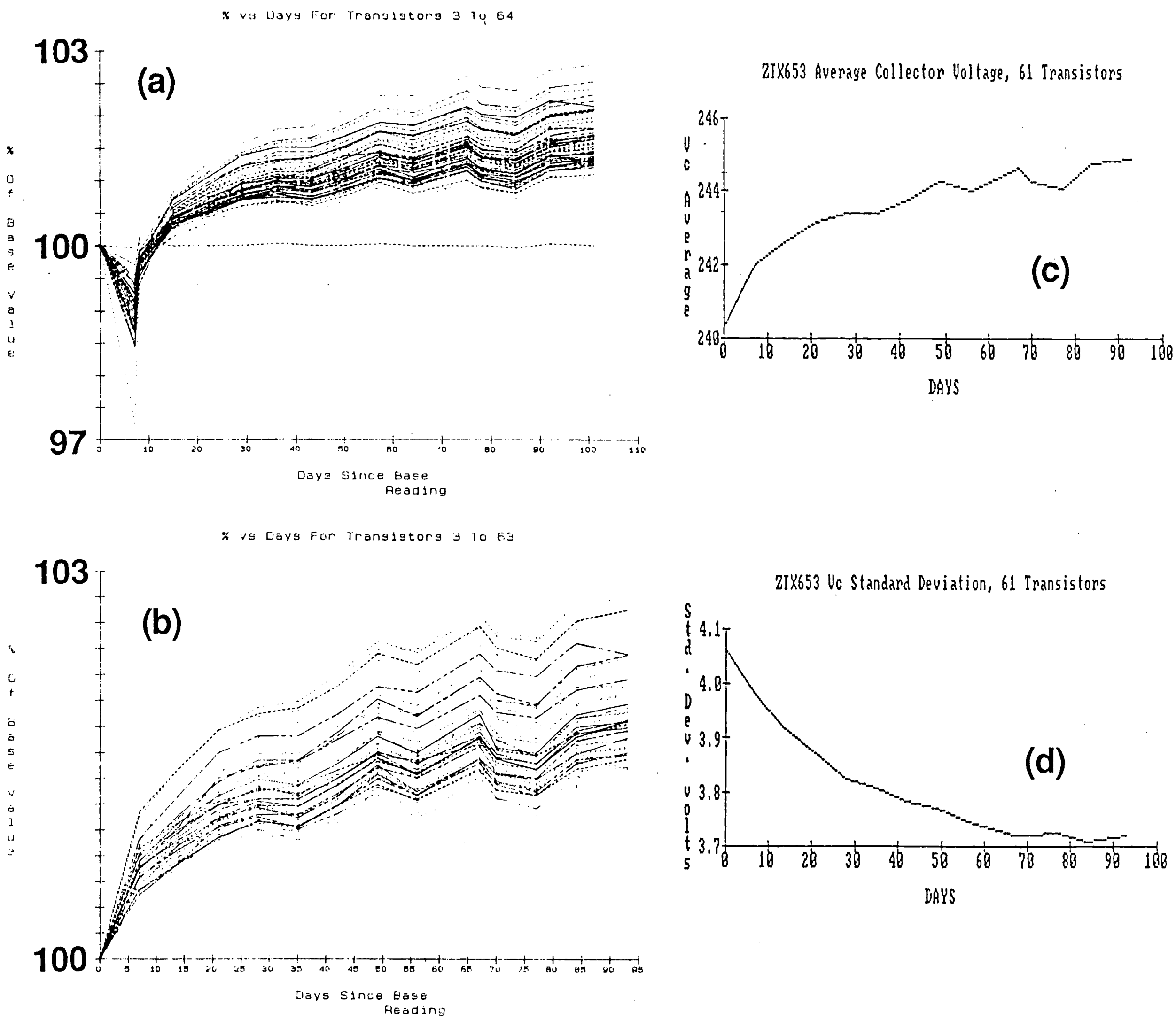


Figure 9. ZTX653. In 9a the collector voltage is shown as a percent of the starting value vs time, and 9b shows these data without the first week's data. Figures 9c and 9d show average collector voltage and collector voltage standard deviation vs time.

The average collector voltage vs time drifts about 0.12%/month (as shown in Fig. 9c) while the standard deviation, which is only about 1.5% of the mean collector voltage and the lowest of the transistors tested, is displayed in Fig. 9d.

4.6 ZTX300 and ZTX415

The ZTX300 transistor is currently being used in many pulser applications at LLNL because of its fast rise-time, very high output current capability, reasonably high output pulse voltage and reliability.

The ZTX415 transistor is relatively new on the market; we first tested it earlier this year. It is packaged in the surface mount SOT-23 case, which accounts for its extremely fast rise-time (less than 150 picoseconds has been seen) when fast pulse techniques and stripline geometries are used.

We plan on testing both of these transistors soon for stability with the burnin tester and will provide copies of the results on request.

4.7 TABLE 1

The following table summarizes data taken on the transistors and includes data from the manufacturers' data sheets.

Table 1. Summary of Avalanche Transistor Characteristics.

Type Mfg.	2N3700 National	2N4014 Motorola	2N5551 Motorola	RS3944 Raytheon	ZTX653 ZETEX	ZTX300 ZETEX	ZTX415 ZETEX
V_{cbo}	120 V	80 V	180 V	200 V	120 V	25 V	260 V
V_{Zener}	260 V	132 V	373 V	194 V	243 V	185 V	335 V
DRIFT	0.37	0.025	0.084	0.045	0.27	NM	NM
V_{pulse}	180 V	115 V	300 V	150 V	150 V	150 V	300 V
$\%V_{Zener}$	70	87	80	77	62	81	90
N	126	30	126	93	61	NM	NM
σ V	26	132.8	15.7	6.5	11.3	NM	NM
$\sigma \div V_{Zener}$	9.8	5.5	3.7	3.3	1.5	NM	NM
$I_{c\ min}$	1 A	2 A	0.6 Adc	1 A	6 A_{pulse}	0.5 Adc	0.5 Adc
I_{pulse}	20 A	20 A	28 A	20 A	20 A	20 A	60 A
I^2T	2×10^{-6}	2×10^{-6}	4×10^{-6}	2×10^{-6}	2×10^{-6}	62×10^{-6}	72×10^{-6}
$I_{self\ av}$	1–4 mA		>2 mA	>130 μA	1–4 mA	10–100 μA	>100 μA

V_{cbo} is the collector-base maximum operating voltage from the manufacturers' data sheets.

V_{Zener} is the measured collector-base breakdown voltage.

DRIFT is the value determined from the burnin tester data and is the time rate of change of collector voltage in percent per month after 3 or 4 months of power burnin.

V_{pulse} is the output pulse voltage we measured in the avalanche mode with a 100-ohm load.

$\%V_{Zener}$ is the ratio of V_{pulse} to V_{Zener}, expressed as a percent.

N is the size of the sample tested, i.e., the number of transistors. σ (sigma) is the sample standard deviation in volts.

$\sigma \div V_{Zener}$ is the ratio of the standard deviation to the collector-base breakdown voltage, an important parameter when selecting a transistor type for matching to a resistive or Zener voltage bias network.

I_c is the rated maximum collector current from the manufacturers' data sheets. In some cases, this current is the d.c. average where the peak is not given on the data sheet; otherwise, it is the peak value taken from gain curves or as stated in the data sheet as peak current.

I_{pulse} indicates absolute maximum pulse current levels determined for reliable operation with a 5-ns pulse width, except that for the ZTX415 this value is stated on the manufacturer's data sheet as the absolute maximum value for a 20-ns pulse.

I^2T is a measure of the power handling capability of the device. It provides the maximum safe operating value of the current (I) for a particular pulse width (T).

$I_{self\ av}$ or I_{sa} is the current we measured at which the transistor breaks into avalanching relaxation oscillation using a 200-ohm external base-emitter resistance. I_{sa} is a strong function of this resistance.

NM means not measured.

5. CONCLUSIONS

Consideration of collector-base breakdown voltage stability with time is important for long-term circuit stability in many avalanche transistor applications. It is not necessary to construct the elaborate tester we have described in order to achieve good stability. In fact, our first tester consisted of several sweep circuit boards mounted in a large, clear plastic box (for electrical safety) with a switching arrangement which permitted measuring the transistor voltages. Operating the tester was labor intensive, but it provided the needed data.

We have presented data to show that the Motorola 2N4014 and 2N5551 and the Raytheon RS3944 exhibit good stability. With a transistor type which exhibits generally stable operation, burnin to screen unstable units can be accomplished by constructing the desired circuitry, installing the avalanche transistors and operating the circuit for a period of 3 or 4 months while monitoring the collector voltages of each transistor one week and one month after the start of operation and again at the end of the test. This will provide enough data points for identification and elimination of those transistors which drift excessively.

6. ACKNOWLEDGEMENTS

Roy Hanks was the principal designer of the BASIC data taking and control code. He was assisted by Ulrica Kelly (Prairie View A. & M. University, Texas). Rex Booth provided both help and insight into the fundamentals of avalanche transistor use and testing.

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6.1 About the authors

Roger Griffith operated the tester and recorded all of the data throughout the many months of burning in the transistors. Alan Teruya selected the RS/1 data analysis software and wrote special procedures (macros) to tailor the presentations to our requirements. Stan Thomas designed the tester and managed the project.

7. REFERENCES

1. S.W. Thomas and L.W. Coleman, Laser-Triggered Avalanche-Transistor Voltage Generator for a Picosecond Streak Camera, *Appl. Phys. Lett.*, Vol. 20, No. 2, 15 Jan. 1972.

2. R.P. Rufer, Designing Avalanche Switch Circuits, *Electronics* (April 7, 1961).

3. W.B. Mitchell, National Semiconductor, Danbury, Ct., Avalanche Transistors Give Fast Pulses, Electronic Design 6 (March 4, 1968).

4. W.B. Herden, Application of Avalanche Transistors to Circuits with a Long Mean Time to Failure, *IEEE Trans. on Instruments and Measurements*, Vol. 25, No. 2 (June 1976).

5. H.M. Rein, Relationship Between Transient Response and Output Characteristics of Avalanche Transistors, *Solid State Electronics*, Vol. 20 (1977) pp. 848-859.

6. S.W. Thomas, R.L. Griffith and W.R. McDonald, Improvements in Avalanche Transistor Sweep Circuitry for Electrooptic Streak Cameras, *Optical Engineering*, Vol. 25, No. 3 (March 1986) pp. 465–470, and *Proc. 16th Int. Congress on High Speed Photography and Photonics, Strasbourg, France, Aug. 27–31, 1984.*

7. B. Iwanaka, "Overlay and Field Plates for the T730 Geometry," Raytheon Co., Semiconductor Div., 350 Ellis St., Mountain View, Calif., 94043, private communication.