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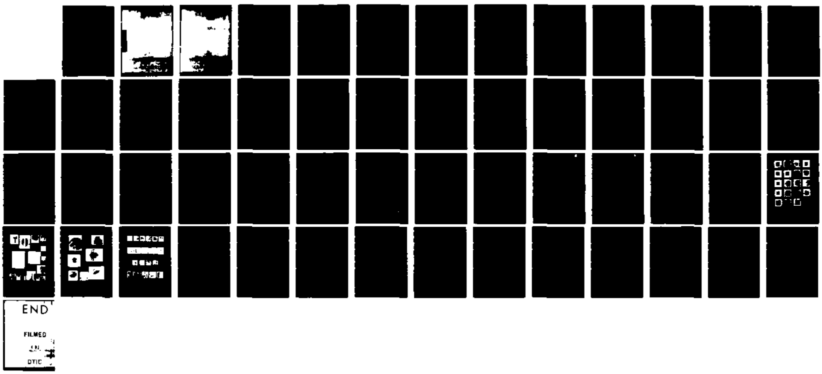

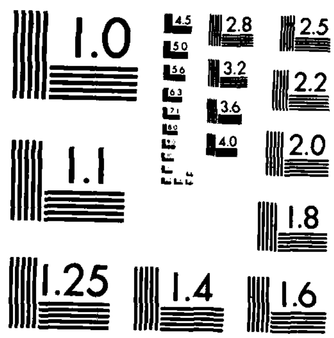

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The differences in the pulse hardness of several types of low-power transistors due to different designs (from different manufacturers) of each type were investigated. A knowledge of the differences that are possible is desirable for electromagnetic pulse (EMP) vulnerability analyses of electronic systems for which, in general, only the occurring device types but not their specific designs are known. The pulse hardness is characterized by the power of a 1-μs square pulse of voltage necessary and sufficient to cause failure or second breakdown in a reverse biased junction. This power was determined by the process of step stressing for both the emitter-to-base and collector-to-base junctions.

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20. Abstract Cont.

Two commercial types from 29 and 30 vendors, respectively, and four JAN types from a maximum of 6 vendors were investigated. Each commercial type occurred in 16 different designs. In one commercial type, the failure power of the collector-to-base junctions varied by more than four orders of magnitude, and the failure power of the emitter-to-base junctions varied by more than two orders of magnitude. In two of the JAN types investigated, a range of specimen failure powers of the collector-to-base junctions of more than three orders of magnitude was found; in one type, the mean values of samples (20 specimens per sample) varied by about a factor of 50. The variation of the failure powers of the emitter-to-base junctions in the JAN types investigated was negligible. Design-dependent variations of the failure levels of specimens of one type are thus possible that are orders of magnitude larger than previously thought, and consideration of these variations in systems analyses seems warranted.

The pulse failure power of emitter-to-base junctions, averaged over a sample, in general increases with chip area; no other correlation was found between the failure levels of devices and recognizable aspects of the device designs. The mean failure powers of the collector-to-base junctions of a commercial and JAN version of one transistor type, both versions having the same geometrical design, differed by more than one order of magnitude (the JAN version being harder).

For the 104 samples of devices (in combination of type, design, and junction), the report contains ranges and mean values of (1) voltage, current, power, and impedance that are charateristic of the failure level for a 1-μs reverse biasing square pulse and (2) capacitances and breakdown voltages of the junctions. Photomicrographs of the devices designs are provided.

FOREWORD

This work was conducted as part of a continuing effort to support electromagnetic pulse (EMP) systems analyses with information on component susceptibility to damage from electrical transients. The main objective of that effort is to clarify the relationships that must exist between aspects of the transient waveform and aspects of the device design for damage to result. The present work is not of this kind but was undertaken in recognition that there are other, rather practical limitations to our knowledge of component failure levels that need to be identified and dealt with. Preliminary results of this study were presented at the Defense Nuclear Agency System Hardening Seminar, Naval Ocean Systems Command, San Diego, CA, in August 1979. The inquiries received since then from the EMP community about further results indicated the interest that exists in the kind of information provided here.

The author gratefully acknowledges the contributions that Asa Williams of the Harry Diamond Laboratories made to this work by procuring devices, measuring device characteristics, and damage testing the emitter-to-base junctions of the devices.

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1. INTRODUCTION

Assessments of electromagnetic pulse (EMP) effects on electronic systems are a continuing challenge to systems analysts. The immediate results of such an assessment or analysis is a statement about the vulnerability or its opposite, the survivability, of a system in a specified EMP environment, and a certain accuracy and confidence level will be attributed to this statement. The EMP effects analyses of systems aim at an accuracy and a confidence level of survivability statements that minimize the possibility of a system's being hardened (at considerable cost if retrofitting is required) that is inherently hard or of a system's being fielded that does, in fact, not survive in the EMP environment. The achievable accuracy and confidence level of a survivability statement is limited by the uncertainties and the errors associated with the many factors that enter the analysis. Some of these uncertainties are simply measurement errors, like those occurring in experimental coupling studies, and can be quite small; others are considerably and undesirably larger. To identify all those limitations on the accuracy of a complete system analysis and, where possible, to reduce them to acceptable levels are of continuing concern. The present report deals with the identification of a major uncertainty in an EMP system analysis.

A system is vulnerable in an EMP environment when failure of system components is possible from the electrical transients occurring in the system during exposure. Information on the susceptibility to damage of components from EMP-induced transients is therefore indispensable to a system vulnerability analysis. Semiconductor devices are among the components most susceptible to damage from electrical transients, and their conditions for failure have been the subject of research for many years. Basically, the problem is that of being able to say what kinds of voltage transients (characterized by amplitude, aspects of waveform, and duration) are necessary and sufficient to cause damage in a device specimen that is available for detailed study (such as measurement of its electrical and other physical characteristics or of its responses to a standard type of transient). This ability to predict the failure thresholds of an individual device specimen is the basic test of one's understanding of the failure mechanisms and the way that they depend on the properties of a device. The state of this knowledge is less than satisfactory. (For a brief discussion of remaining problems, see Kalab.[1])

The total production of an electronic system usually consists of many identical units that are assumed to be equipped, in each stage,

[1] *Bruno M. Kalab, Damage Characterization of Semiconductor Devices for the AN/TRC-145 EMP Study, Harry Diamond Laboratories, HDL-TR-1915 (December 1980).*

with devices randomly drawn from production runs. Therefore, for applications to systems analyses, the information on the failure thresholds of a single device specimen must be broadened to include the distribution of the failure levels in large samples of devices of the given type. This distribution can be estimated, by using methods of statistics, on the basis of the conditions for device failure as determined on a small sample.

Two major uncertainties exist in present methods of providing the systems analyst with information on semiconductor device vulnerabilities. One uncertainty has been alluded to previously: efforts to understand the failure mechanisms in a specimen such that its response (failure or nonfailure) to an arbitrary electrical transient could be predicted have so far met with only modest success. The present method of predicting failure, widely used in the EMP community, is based on the so-called thermal failure model.[2] This model asserts that the junction area or, indirectly, the junction capacitance and the breakdown voltage uniquely determine the condition for failure of a junction from any kind of short-duration electrical transient. (A certain failure temperature also plays a role in this model. However, this temperature is the same in all silicon devices or all germanium devices and is therefore not essentially device dependent.) The analysis of this model then shows that the condition for failure of a given device is the reaching of a critical value of pulse power that depends only on pulse duration. For increased accuracy of failure prediction, rather than measuring the junction area or the junction capacitance, the pulse power for failure of a device can be determined in destructive testing (step stressing) by using a standard pulse waveform, usually a square pulse of a width of a few microseconds. A single value of power for failure from a forward biasing pulse and one from a reverse biasing pulse (obtained as a mean value from step stressing a sample of devices) allow one, according to the model, to predict junction failure from an arbitrary electrical transient, particularly in the time regime of interest to EMP studies. Since the introduction of this model in 1969, it has been recognized that many types of junctions do not respond as predicted by this model.[3] On this account, the systems analyst is often faced with a considerable degree of uncertainty about the conditions for system component failure, which is then reflected in the accuracy and the confidence level of a vulnerability statement.

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[2] *D. C. Wunsch and R. R. Bell, Determination of Threshold Failure Levels of Semiconductor Diodes and Transistors Due to Pulse Voltages, IEEE Trans. Nucl. Sci., NS-15 (December 1968), 244-259.*

[3] *DNA EMP (Electromagnetic Pulse) Handbook, Defense Nuclear Agency, DNA 2114H-2 (September 1975).*

The second major uncertainty about the failure thresholds of system components results from an often insufficient component identification. When fielded systems are to be analyzed, the system manuals provide the only information on a system and its parts. In these manuals, most electronic network components are identified only by their type (such as a 2N1613 transistor); for most purposes, including general repairs and replacement of parts, this identification is sufficient. However, for an EMP system study, a closer identification is desirable. Semiconductor devices of the same type but manufactured by different manufacturers can have a very different pulse hardness; variations by about a factor of seven in terms of pulse power for failure at a given pulse width (averaged over a sample) have been reported.[4] These differences, briefly referred to as intervendor variations, can be attributed to different designs or manufacturing processes that device manufacturers are free to select.

In view of such variations, the analyst conducting an EMP system study should have information on the failure thresholds of exactly the kind of devices that were used in the system. Unfortunately, the particular version of a component that was used in a system is in most cases untraceable and cannot be made available for the study of failure thresholds. The developer of a system may have procured a certain device type from more than one manufacturer, or, over a period of several years, a manufacturer may have changed the design of a device and sold out the original version; in fact, different designs of a device type, from the same manufacturer and with identical packaging and date code, were encountered in the present study. Thus, even inspection of a few units of a system and removal of components for study (an undesirable procedure in itself) need not lead to information on component failure levels that could be assumed to apply to the total production of systems. In general, the failure thresholds of a device type occurring in a system are determined on a sample from any one manufacturer, with a resulting uncertainty about the failure thresholds of the actual system components.

The situation described need not exist if the performance of a system in an EMP environment is being considered during the design stage of a system and suitable controls over the components to be used can be exercised. Where no such controls were in place when the system was built, it can become essential to at least know the limits within which the failure levels of a device type can vary due to different designs. The present study is aimed at detecting the maximum range of average failure thresholds due to different designs of a device.

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[4] *D. M. Tasca, Submicrosecond Pulse Power Failure Mode in Semiconductor Devices, General Electric Co. contract with Air Force Weapons Laboratory, 70SD401 (January 1970).*

The observation of intervendor variations referred to previously was made in early EMP studies and was followed by a few others during routine component damage testing for the analysis of specific systems (such as LANCE[5]). The variations observed in this later work were smaller, typically amounting to a factor of two in average pulse power for failure at a given pulse width. If intervendor variations do not amount to more than about a factor of seven, the largest variation previously observed, they may be ignored, considering that the pulse power for failure of specimens of the same type and design often vary by an order of magnitude. (Currently, these variations are assumed to be caused by manufacturing inhomogeneities.) Indeed, intervendor variations of component failure thresholds were not specifically accounted for in systems analyses. The manner in which the range of failure thresholds of individual devices, from any one vendor, is taken into account in systems analyses (discussed in detail by, for example, Miletta[6]) was thought to also account, to an acceptable degree, for possible intervendor variations.

Still, a certain dissatisfaction with the information on intervendor variations remained. The observation of such variations had been rather sporadic, also mostly involving only two or three manufacturers of a device type. A special study of intervendor variations seemed justified but appeared to be difficult. A systems analyst might wish to be able to say what the probabilities would be for the failure thresholds in any particular device type to differ by varying amounts, due to intervendor variations, from the value determined on a sample of devices from any one manufacturer. The design of a study that could provide this information is not believed to be straightforward, and a study of this kind could not be undertaken with the available resources.

An investigation of intervendor variations of the pulse hardness of devices will involve the study of samples of devices of at least one type and from different manufacturers. The problem is that of identifying the population (device types and manufacturers) from which samples are to be taken so that the statistical inferences to be drawn from the results will not be misapplied. Textbooks on statistics alert the student, more or less explicitly, to the fact that many important scientific studies using statistical methods in essential phases of the work were criticized for having generalized the results to populations

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[5]*Army Tactical Materiel Vulnerability and Hardening Program, LANCE Test Plan, Annex A, General Procedures, Harry Diamond Laboratories, AD 900 465L (April 1972).*

[6]*Joseph R. Miletta, Component Damage from Electromagnetic Pulse (EMP) Induced Transients, Harry Diamond Laboratories, HDL-TM-77-22 (November 1977).*

that were larger than or only part of the population that was the subject of the study. A study of the intervendor variations of the pulse hardness of devices could be particularly open to such criticism, because different designs of a device type cannot a priori be said to occur by chance, but nothing is known about the "mechanism" (that is, the motives of device manufacturers) by which they do occur. A study that solely consists of arbitrarily selecting a few types of devices, each from several manufacturers, and determining their failure thresholds carries the risk of adding nothing to our knowledge of the frequency of occurrence or the extent of intervendor variations in a larger population of device types.

The present study is of this kind, and it was undertaken with this risk in mind. However, it could be hoped that the particular selection of devices for this study would lead to a better recognition of the maximum range of average failure thresholds that can occur in a device type due to different designs. As discussed previously, at least a knowledge of this range is needed for an EMP analysis of many systems, especially if their survival in an EMP environment is critically important.

2. DEVICES AND TEST TECHNIQUES

2.1 Selection and Identification of Devices

The present study was spurred by the realization that devices of many different types are made each by a large number of manufacturers (up to 50). It could be expected that some of those sources would only package chips supplied by a smaller number of manufacturers. But even so, the greatest variety of different designs of a device type and with that the greatest differences in average failure thresholds would probably become apparent by studying a few of those types that are available from that many sources. A relatively small effort could thus be expected to yield an interesting result. Therefore, a first criterion for the selection of a device type for this study was that it be available from a large number of manufacturers.

It was considered important to this study to know something about the design that each manufacturer chose for a device type and to obtain this information directly from the procured devices rather than from the manufacturer. These considerations led to two further criteria for the selection of devices: they should be planar devices and they should be packaged in a metal can that could esily be opened, such as TO-5 or TO-18. (These first two criteria singled out transistors; no diodes were found to meet them.) Inspection of an opened device with a microscope would then show the size and the surface geometry of the chip. This information would make it possible to determine the failure thresholds only of the devices of any one type that are of different design, thus limiting the testing effort. Furthermore, although this was not an objective of the present study, this information on the design would later make it possible to look for a connection between the measured failure thresholds or other device responses and the size and the geometry of the chip. As discussed in the introduction, the relationship between the failure thresholds of devices and their physical and electrical characteristics still is not well established, and further experimental material that can shed light on this relationship should be useful.

Still other considerations in the selection of device types for this study were that the devices should be low-power devices, as those are most often found vulnerable in systems, and that JAN types as well as general commercial types should be included; both versions are used in military electronic equipment. The JAN devices were found to be offered by only a small number of vendors, from one to about seven.

From these considerations, the devices of tables 1 to 6 were procured. The abbreviations of the manufacturers' names in the tables are the same as the code letters of manufacturers used by D.A.T.A., Inc., in its Electronic Information Series[7] on semiconductor devices and are explained on page 13. For each device type, the manufacturers are listed in alphabetical order of the manufacturers' code letters as used by D.A.T.A., Inc.

The 50 devices of a type that were procured from each manufacturer who offered this type were inspected for possible external differences that might indicate different device designs. The only difference found was in the date code of the devices from some of the manufacturers. From each manufacturer, one device of each date code was then opened for inspection of its design.

In tables 1 to 6, the designs of the devices from the various manufacturers are given numbers beginning with 1 for the design of the first manufacturer. If the specimen from the second manufacturer in the Manufacturer column was of different design, the number assigned to its design is 2; had its design been identical to that of the first manufacturer, its number would also be 1, etc. The highest number in the Design column of a table then shows the number of different designs of the device type as identified in this process.

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[7] *Transistors, 42nd ed., 1, D.A.T.A., Inc., Pine Brook, NJ (1977).*

Code	Manufacturer
AMC	Ampower Semiconductor Corp., Long Island, NY
AMI	American Micro-Systems, Inc., Santa Clara, CA
CEN	Central State Industries, Inc., West Babylon, NY
CRI	Crimson Semiconductors, Inc., New York, NY
CSR	CSR Industries, Inc., East Farmingdale, NY
ESE	Elm State Electronics, Inc., Hamden, CT
ETC	Electronic Transistors Corp., Flushing , NY
FSC	Fairchild Semiconductor, Mountain View, CA
GSE	General Semiconductor Industries, Inc., Tempe, AZ
GTC	General Transistor Corp., Hawthorne, CA
IDC	International Diode Corp., Harrison, NJ
IDI	International Devices, Inc., Los Angeles, CA
MOTA	Motorola Semiconductor Products, Phoenix, AZ
NJS	New Jersey Semiconductor Products Co., Inc., Springfield, NJ
NTR	National Transistor Corp., Mountain View, CA
RCA	RCA Corp., Somerville, NJ
RTN	Raytheon Semiconductor, Mountain View, CA
SCA	Semicoa, Costa Mesa, CA
SES	Semitronics Corp., Freeport, NY
SGAI	SGS-ATES Componenti Elettronici S.p.A., Milan, Italy
SOD	Solitron Devices, Inc., Riviera Beach, FL
SPE	Space Power Electronics, Inc., Glen Gardner, NJ
SST	Solid State, Inc., Bloomfield, NJ
STI	Semiconductor Technology, Inc., College Point, NY
STR	Syntar Industries, Inc., Hicksville, NY
SWT	Swampscott Electronics Co., Swampscott, MA
TEC	Transitron Electronic Corp., Wakefield, MA
TIC	Transistor International Corp., Lake Park, FL
TII	Texas Instruments, Inc., Dallas, TX
TRS	Transistor Specialtys, Inc., Peabody, MA
TSC	Teledyne Semiconductor, Mountain View, CA
UPI	UPI Semiconductor, Paterson, NJ
UTS	Uni-Tran Semiconductor Corp., Lake Ariel, PA
WAB	Walbern Devices, Inc., Linden, NJ

TABLE 1. MANUFACTURERS OF 2N1613 TRANSISTOR

Manu-facturer	Date code	Design	Selection for testing
AMI	810	1	-
CEN	7713	2	S
CRI	7811	3	-
CSR	127	4	-
	215	3	-
	615	5	-
ESE	810	~4	-
ETC	7809	4	S
FSC	714	6	S
GTC	-	~4	-
IDC	644	~5	-
IDI	-	7	S
.)TA	339	8	S
NJS	7809	9	S
NTR	-	2	-
RCA	7810	10	S
RTN	7813	5	-
SCA	7810	11	-
SES	7810	~4	-
SGAI	87431	~4	-
	97745	~4	-
SPE	811	1	-
SST	452B	~9	-
	620B	11	S
STI	78-12	12	S
STR	97745	~4	-
SWT	-	3	S
TEC	7811	13	S
TIC	-	14	S
TII	407P	1	S
TRS	7801	3	-
UPI	7809	15	S
	7810	15	
UTS	7813	~5	S
WAB	810	16	S

TABLE 2. MANUFACTURERS OF 2N4237 TRANSISTOR

Manu-facturer	Date code	Design	Selection for testing
AMC	7811	1	S
AMI	810	2	-
CEN	7729	3	-
CRI	7715	3	-
CSR	7705	4	-
ESE	810	5	-
ETC	7808	6	S
FSC	822	7	S
GSE	7531	8	S
GTC	-	9	-
IDC	809	5	-
IDI	811	9	S
MOTA	826	10	S
NJS	7810	11	S
	7814	11	
NTR	625	5	-
SCA	7616	12	S
SES	7810	5	-
SGAI	7328	13	-
SOD	7749	14	S
	7622	14	
SPE	-	13	-
SST	7705	4	S
STI	78-12	15	S
STR	7604	3	S
SWT	-	13	-
TIC	-	8	-
TRS	7801	13	S
UPI	7640	5	S
UTS	7813	16	S
WAB	810	2	S

TABLE 3. MANUFACTURERS OF JAN2N1613 TRANSISTOR

Manufacturer[a]	Date code	Design	Selection for testing
<u>FSC</u>	7618	1	S
MOTA	K7714	2	S
<u>RTN</u>	H7730	3	S
<u>TEC</u>	P7643	4	S
<u>TII</u>	7749A	5	S
<u>TSC</u>	S7530	6	S

[a]Manufacturers using the same design for 2N1613 are underlined.

TABLE 4. MANUFACTURERS OF JAN2N2222 TRANSISTOR

Manufacturer	Date code	Design	Selection for testing
FSC	7729	1	S
MOTA	K7744	2	S
RTN	K7827	3	S
TEC	P7725	4	S
TII	7711	5	S

TABLE 5. MANUFACTURERS OF JAN2N2369A TRANSISTOR

Manufacturer	Date code	Design	Selection for testing
FSC	H7618	1	S
MOTA	K7804	2	S
RTN	K7746	3	S
TEC	7450	4	S

TABLE 6. MANUFACTURERS OF JAN2N2907 TRANSISTOR

Manu-facturer	Date code	Design	Selection for testing
FSC	H7602	1	S
MOTA	K7750	2	S
RTN	K7822	3	S
TEC	P7709	4	S
TII	7748	5	S

It was found that the designs of a device type from the different manufacturers can be put into three groups: (1) clearly different designs with respect to the geometry and the dimensions of the emitter metallization (which defines also the contour of the emitter-to-base junction), the base metallization, and the chip; (2) designs that are identical in the minutest discernible features of the previous characteristics; (3) designs that exhibit slight differences in these characteristics, indicating that the devices were made by using different, albeit very simlar masks. The terms "different" and "identical" used previously for device designs correspond to groups 1 and 2, respectively. A design that was found to be very similar but not identical to a previous one (that is, belonging to group 3) was given, in the Design column of tables 1 to 6, the number of that previous design preceded by the symbol "~"; only one design of two or more similar designs of a device type was tested.

Still other characteristics can properly distinguish a device design. For instance, identical designs (per the previous definition) can have a different arrangement of the wire bonding: a single wire from the emitter metallization to the device terminal versus two or more such wires bonded to different areas of the emitter. The different current distributions that these arrangements produce in a device can conceivably affect their pulse hardness. Such differences in the terminal arrangements of otherwise identical designs were observed in the 2N4237 transistor, but their effect on the failure thresholds has not been investigated here.

JAN versions as well as commercial versions of the 2N1613 transistor were included in this study (tables 1 and 3). The JAN2N1613 was available from all six manufacturers who make this device, and their designs were all different. From five of these manufacturers, the commercial version of the 2N1613 also was tested in the present effort.

Identical designs within a device type were not tested; however, identical designs were tested if they belonged to different device types. Table 7 shows the occurrence of identical designs among the device types and manufacturers selected for this study. Photomicrographs of the designs of the devices damage tested are provided in appendix A.

TABLE 7. DEVICE TYPES USING IDENTICAL DESIGNS

		2N1613							JAN2N1613	JAN2N2222	JAN2N2907	
Transistor	Manufacturer	CBN	FSC	MOTA	SST	TEC	TII	UTS	RTN	FSC	FSC	RTN
2N1613	NJS										●	
2N4237	UPI							●	●			
JAN2N1613	FSC		●							●		
	RTN							●				
	TEC					●						
	TII						●					
	TSC				●							
JAN2N2222	FSC		●									
	MOTA			●								
	RTN	●										●

For reasons explained in section 3.2, after damage testing of all devices and study of the data, the cans of all specimens of the 2N1613 and the 2N4237 were opened for inspection of the device designs. The samples from a few manufacturers were found to contain specimens of different designs, although packaging and data code were identical. These different designs are not reflected in tables 1 and 2, but are discussed in section 3.2. The identification of different designs as shown in tables 1 to 6 is based on the inspection of one specimen of a certain date code from each manufacturer at the beginning of the study.

2.2 Device Testing

For this study, a relative measure of the pulse hardness of a transistor junction is taken to be the average power of a nearly rectangular pulse of a 1-μs width that reverse biases the junction and is necessary and sufficient to cause second breakdown or device failure. Device failure is defined as a reduction of the direct current (dc) gain by 50 percent or more of the original value. This pulse power for second breakdown or failure is determined by step stressing of the junction with square pulses of a 1-μs width.

The process of step stressing to find the failure threshold of a device has repeatedly been described and discussed. Basically, it consists of applying single pulses of increasing open-circuit voltage to the device, recording both the voltage and current waveforms and measuring the device characteristics after each pulse application. The pulse power (averaged over pulse width) is derived from the recorded voltage and current. An aspect of this procedure as applied in the present study (but not a general requirement) is that the increase in pulse voltage from one pulse to the next (step size) was kept very small, typically about 10 percent of the preceding value but often much less than that. A step size of this magnitude leads in many cases to the occurrence of second breakdown close to the end of the applied pulse; this occurrence facilitates the extrapolation of the associated second breakdown power to that corresponding to a delay time of 1 μs. Such a normalization of all failure levels to one pulse duration or delay time is necessary for a comparison of the differences in pulse power for failure or second breakdown in different device specimens and, ultimately, in the samples of devices from different manufacturers.

During step stressing of many collector-to-base junctions, instantaneous second breakdown[1] occurred, making it difficult to even only approximately determine from this breakdown event the pulse power for second breakdown at 1 μs. In such cases, the average power of the

[1] *Bruno M. Kalab, Damage Characterization of Semiconductor Devices for the AN/TRC-145 EMP Study, Harry Diamond Laboratories, HDL-TR-1915 (December 1980).*

pulse immediately preceding the one that caused instantaneous second breakdown was taken to be the pulse power corresponding to a second breakdown delay time of 1 μs. In view of the small step size used in testing, the additional error of this pulse power, caused by this procedure, is small. The overall error of the pulse power for failure or second breakdown of a single test specimen, extrapolated to a pulse width or delay time of 1 μs, is estimated to be not larger than ±30 percent.

Both the emitter-to-base junction and the collector-to-base junction of the transistors were step stressed by using samples of 20 specimens for each junction. Before step stressing of a specimen, its dc gain, the breakdown voltage, and the capacitance at zero bias and at 3 V reverse bias of the junction to be pulsed were measured; they were measured for possible later comparison of the experimental pulse power for failure (or second breakdown) with that predicted by a model[8] using the junction capacitance and the breakdown voltage as model parameters.

3. RESULTS

3.1 General

The immediate result of the testing phase is a series of Polaroid photographs showing the voltage and current waveforms of the pulses applied to each of the 2080 specimens investigated. Of particular interest are the waveforms of the pulse causing device damage or second breakdown and, in many cases, of the pulse immediately preceding this event. The main information derived from these waveforms is the power of a square pulse causing failure or second breakdown of a junction at 1 μs; the pulse hardness of specimens and samples is expressed in terms of this power. Besides the power for failure of a specimen, the device impedance at the failure level also was derived from these waveforms. This impedance is defined as the quotient of average pulse voltage over average pulse current (averaged over the width of the pulse causing failure or second breakdown). The device impedance and the so-called surge impedance derived from it play a role in the device circuit model needed for circuit failure analysis. Therefore, the variation of this impedance in samples of devices of a given type but of different designs also is of interest to EMP systems analyses. The waveforms of the voltage and the current also show details of the device responses, such as the particular form or absence

[8] *D. C. Wunsch, R. L. Cline, and G. R. Case, Theoretical Estimates of Failure Levels of Selected Semiconductor Diodes and Transistors, Braddock, Dunn and McDonald, Inc., contract with Air Force Special Weapons Center, BDM/A-42-69-R (December 1969).*

of second breakdown. Such details may become useful to an analysis of the failure mechanism and device failure modeling but are not of interest to the present study.

The pulse voltages and currents and derived magnitudes for failure of the emitter-to-base junctions are for many samples scattered fairly closely around a mean value. For those samples (device type and manufacturer), a normal distribution may be assumed, and the data can be adequately reduced to a mean value and a standard deviation. However, in many other samples of emitter-to-base junctions and in most samples of collector-to-base junctions, although containing specimens of only one design (sect. 3.2), the voltages, the currents, and the pulse powers required for failure of the specimens and the associated device impedances are far from normally distributed. A reduction of the data on such samples is desirable, but a representation by a mean value and a standard deviation (which are defined for any set of numbers) might be misleading. For this reason, the particular formats of section 3.3 and of appendix A were chosen for all samples.

3.2 Detailed Device Inspection

A first analysis of the experimental device failure powers showed an often large range, of more than an order of magnitude, within a sample of devices from one manufacturer. Whenever such a difference in failure powers is observed in one device type of presumably the same design, a close comparison of the specimens with the lowest and highest failure powers is particularly interesting: how can such a difference be explained? (On the basis of the thermal failure model, one would have to expect an equally large difference in the junction areas.)

When the difference in failure power between the softest and hardest specimens in any sample of emitter-to-base junctions of this study amounted to more than a factor of five, these specimens were opened and their chips were inspected with a microscope. In this initial effort, it turned out that of two manufacturers of the 2N1613 and of two other manufacturers of the 2N4237, the specimens of lowest and highest failure powers were of different designs despite identical packaging. (However, the smaller failure power did not always correspond to the smaller chip area.) After this discovery, all specimens of the samples of emitter-to-base and collector-to-base junctions of both the 2N1613 and the 2N4237 were opened for inspection of their designs, and a still greater variety of designs of these device types used by the manufacturers referred to previously were found.

As mentioned in section 2.1, these designs are not reflected in tables 1, 2, or 7. However, in section 3.3 and in appendix A, the occurrence of these designs is taken into account, and data on the 2N1613 and the 2N4237 are reported for samples of one design only. The JAN types of any one manufacturer investigated in this study are not believed to contain different designs.

3.3 Results

For an immediate appreciation of the variations of the powers for failure in different designs of a device type, the ranges of the failure powers of samples of 20 specimens, for both the emitter-to-base and collector-to-base junctions, from the selected manufacturers are shown over a common logarithmic scale (fig. 1 to 6). The manufacturers' names are abbreviated as explained in section 2.1, and the number after the manufacturers' abbreviations is the chip area, in square millimeters, as determined in the procedure discussed in section 2.1.

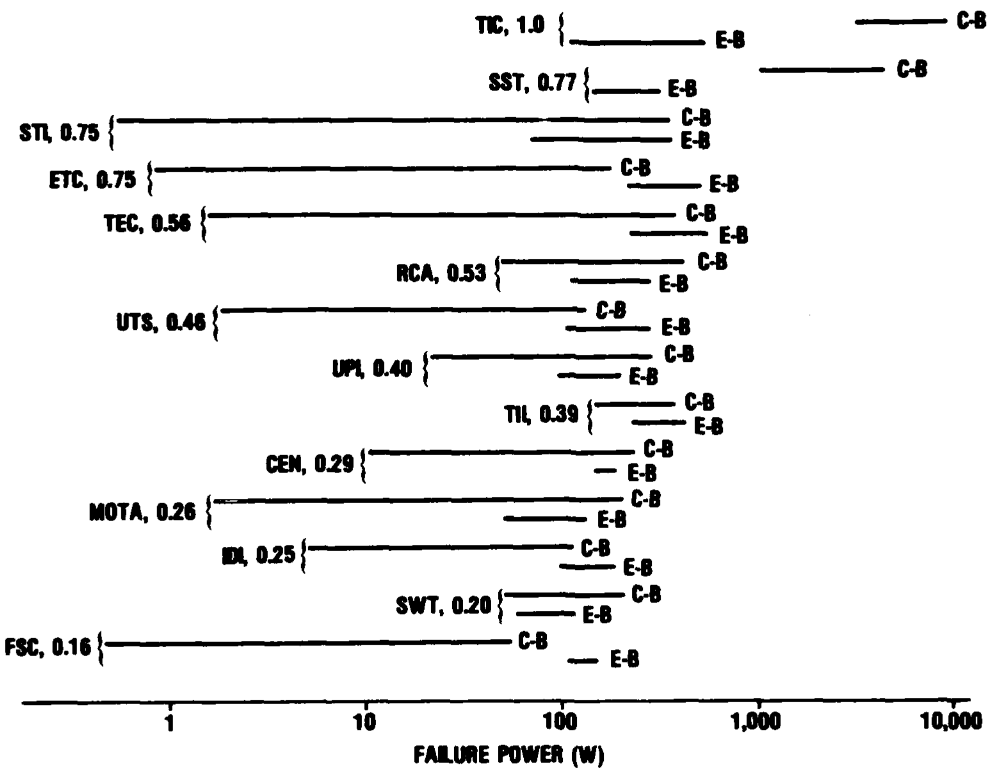


Figure 1. Range of failure powers (for reverse bias and 1-μs pulse width) of 2N1613 transistors from different manufacturers (20 specimens per sample).

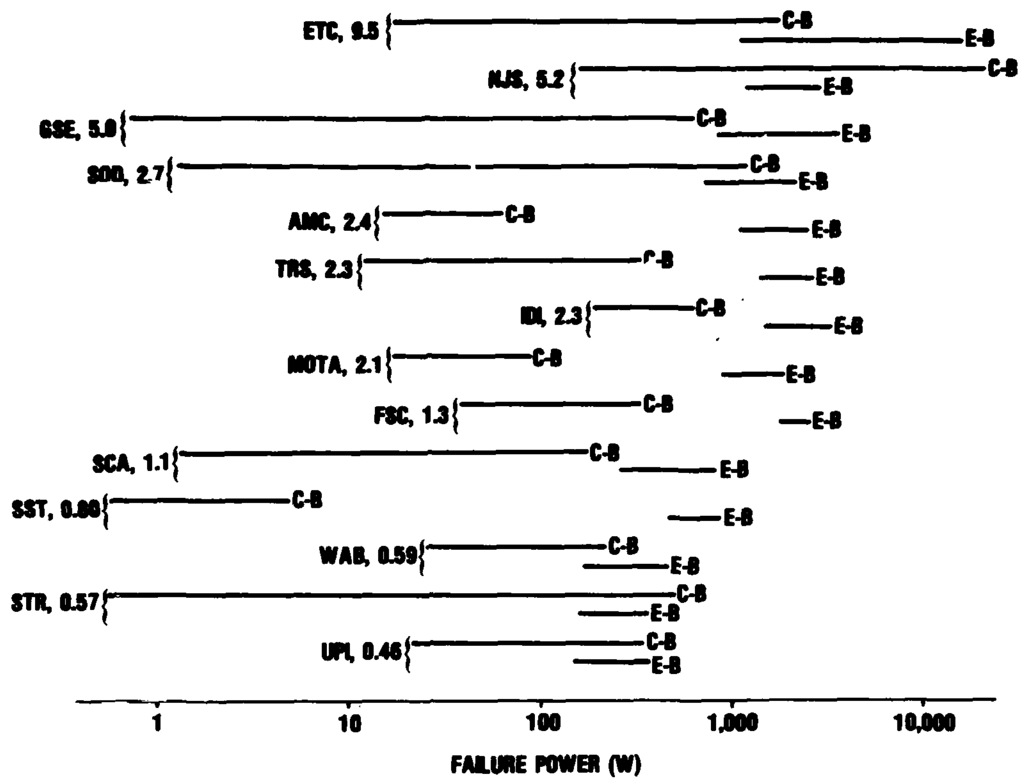


Figure 2. Range of failure powers (for reverse bias and 1-μs pulse width) of 2N4237 transistors from different manufacturers (20 specimens per sample).

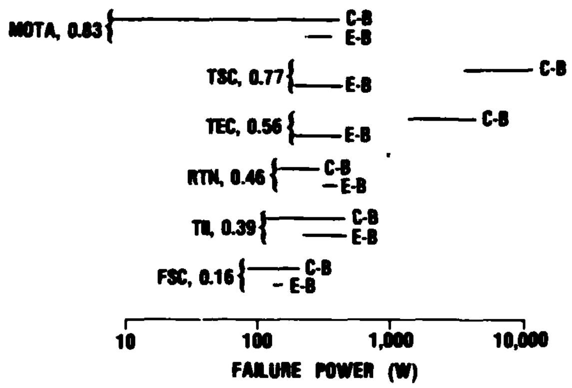


Figure 3. Range of failure powers (for reverse bias and 1-μs pulse width) of JAN2N1613 transistors from different manufacturers (20 specimens per sample).

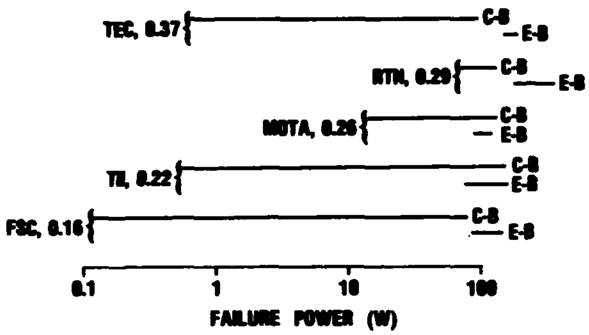


Figure 4. Range of failure powers (for reverse bias and 1-μs pulse width) of JAN2N2222 transistors from different manufacturers (20 specimens per sample).

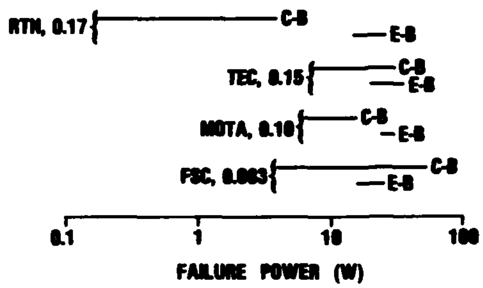


Figure 5. Range of failure powers (for reverse bias and 1-μs pulse width) of JAN2N2369A transistors from different manufacturers (20 specimens per sample).

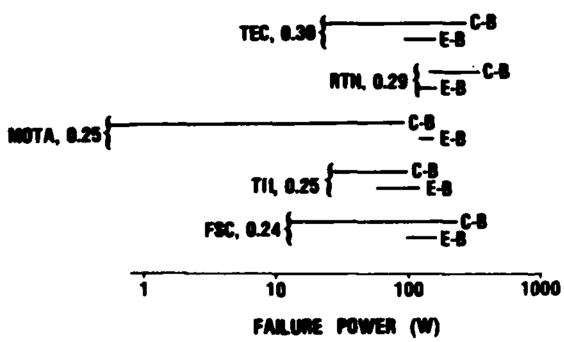


Figure 6. Range of failure powers (for reverse bias and 1-μs pulse width of JAN2N2907 transistors from different manufacturers (20 specimens per sample).

As pointed out in the previous section, the samples of several manufacturers of the 2N1613 and 2N4237 were found to contain specimens of different designs. The data on the samples from these manufacturers are excluded from figures 1 and 2 and presented in figures 7 and 8. The number of specimens of a specific design (with a total of 20 for all designs) in the samples of emitter-to-base and collector-to-base junctions is given in parentheses after the chip area.

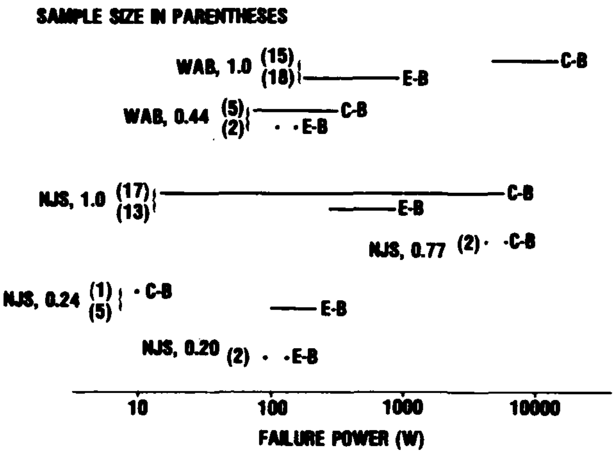


Figure 7. Range of failure powers of 2N1613 from WAB and NJS.

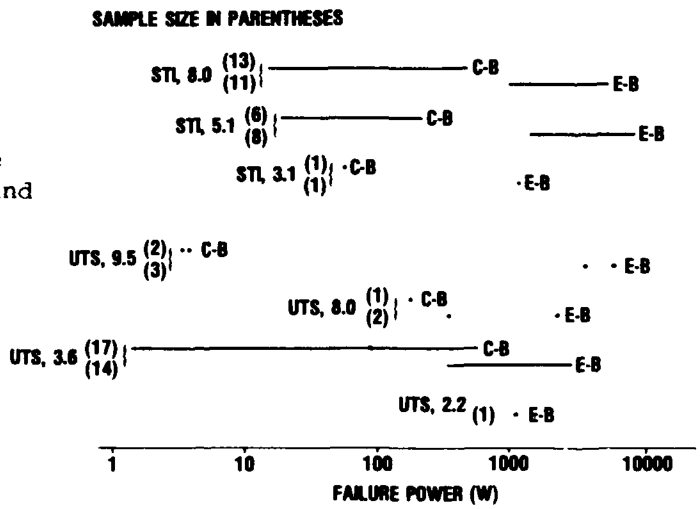


Figure 8. Range of failure powers of 2N4237 from STI and UTS.

It was believed desirable also to indicate how the failure powers are distributed over the respective ranges; the distribution is in many cases not even approximately normal. This distribution is indicated in figures 9 to 14 in the most simple form, that is, by disregarding the error interval of the failure powers of individual specimens and plotting the nominal values on a linear scale covering only the range for the particular sample. The data points are represented by a vertical bar of a certain length per specimen (see scale on figures).

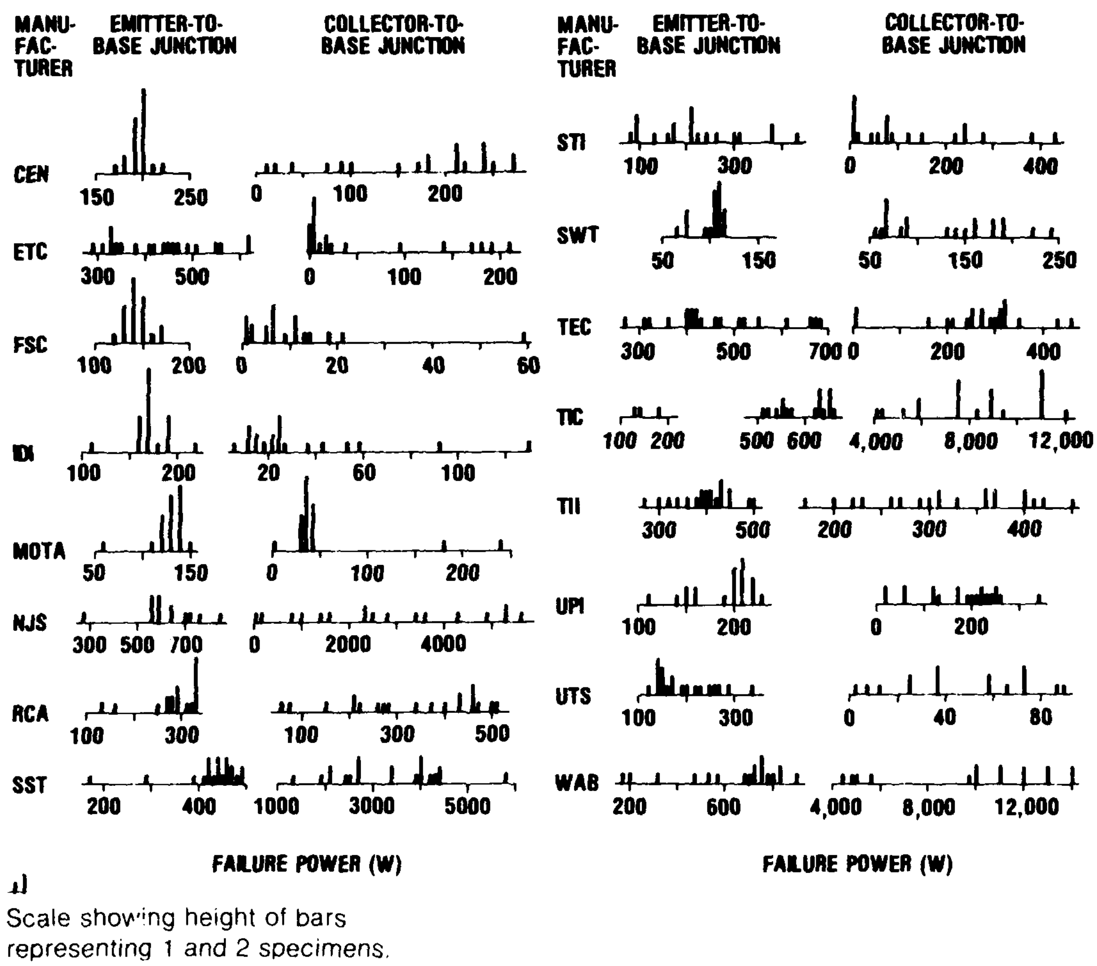


Figure 9. Distribution of failure powers in 2N1613 from different manufacturers.

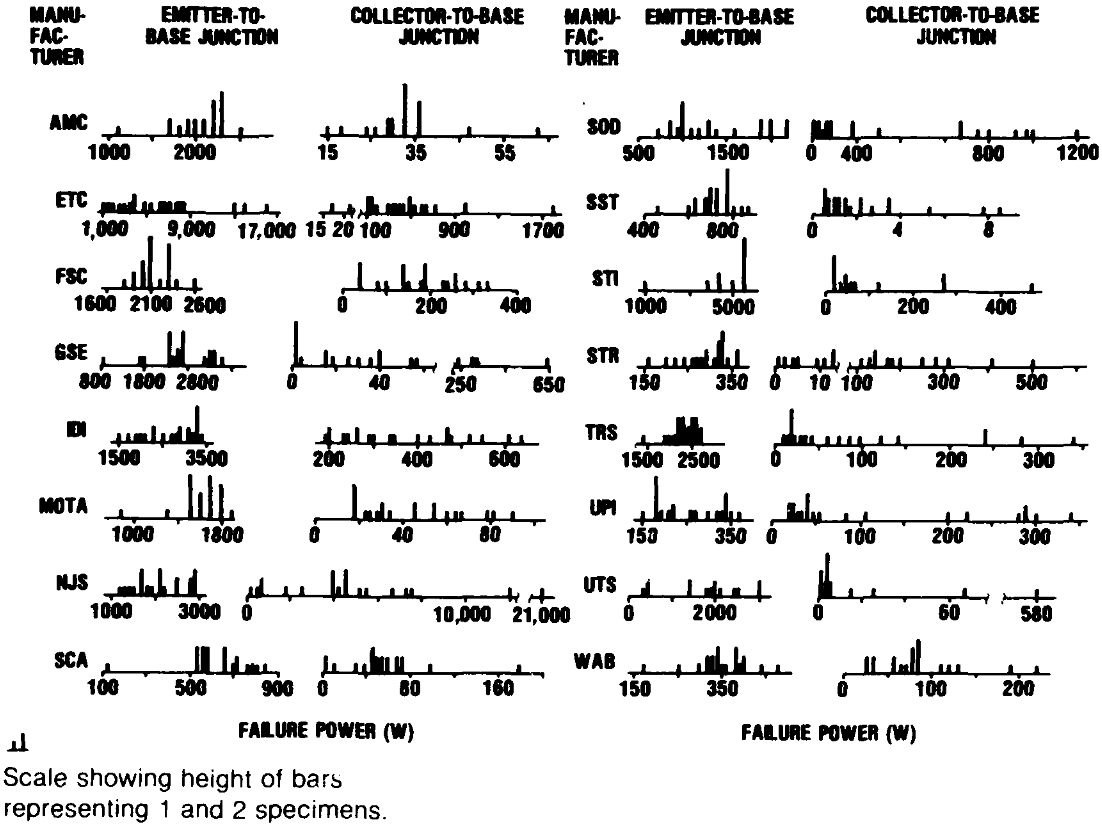


Figure 10. Distribution of failure powers in 2N4237 from different manufacturers.

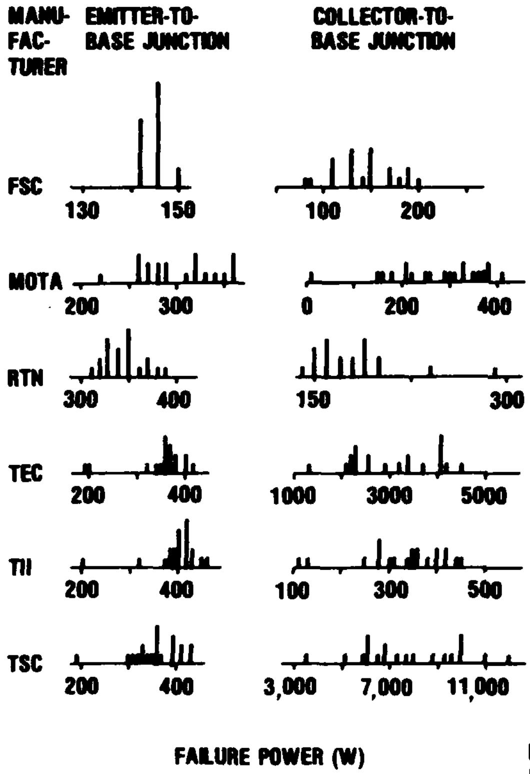
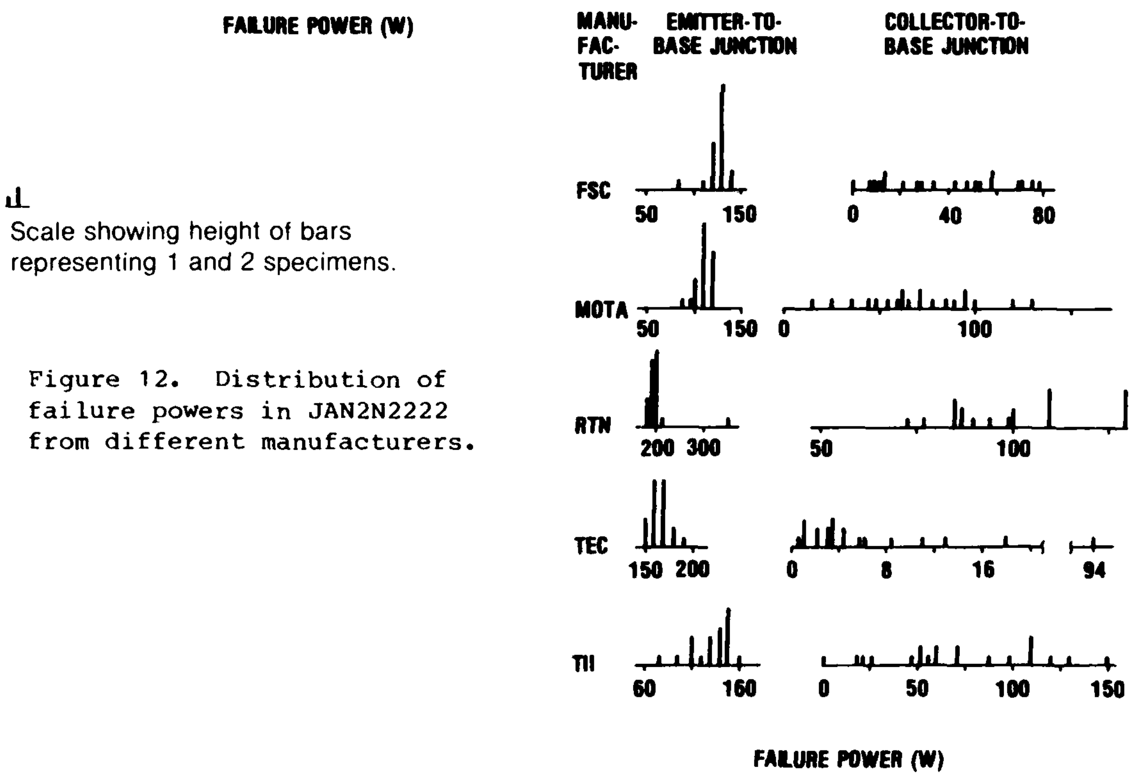


Figure 11. Distribution of failure powers in JAN2N1613 from different manufacturers.



Scale showing height of bars representing 1 and 2 specimens.

Figure 12. Distribution of failure powers in JAN2N2222 from different manufacturers.

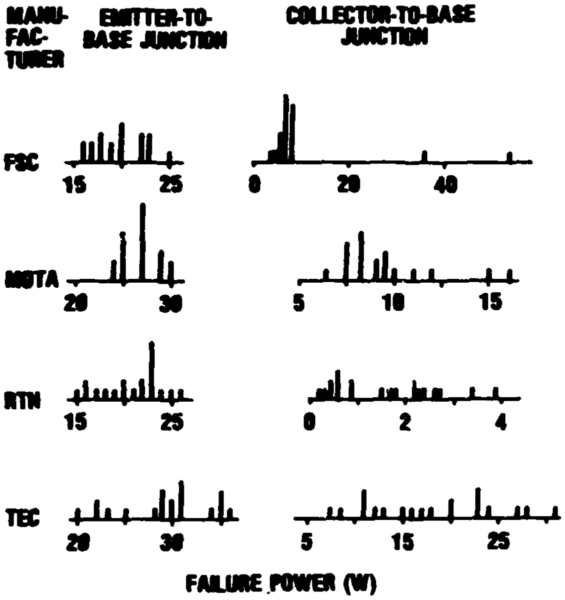


Figure 13. Distribution of failure powers in JAN2N2369A from different manufacturers.

Scale showing height of bars representing 1 and 2 specimens.

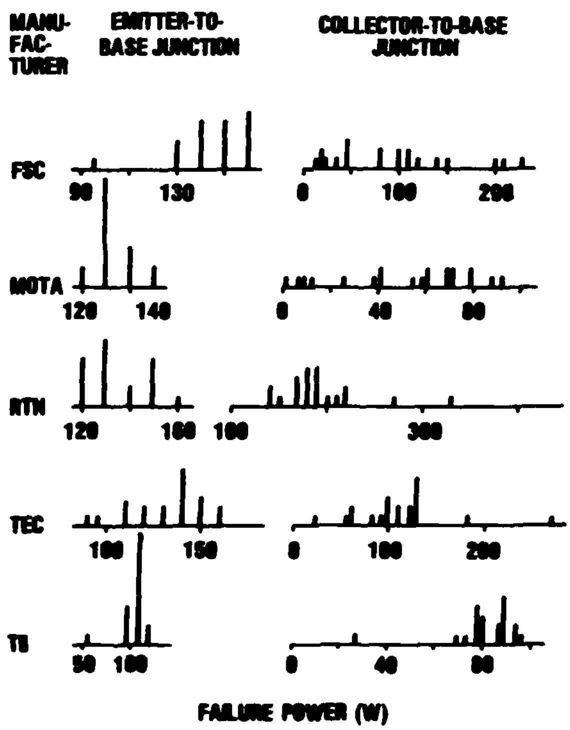


Figure 14. Distribution of failure powers in JAN2N2907 from different manufacturers.

In figures 9 and 10, the distributions of the failure powers of the 2N1613 and the 2N4237 from the manufacturers that used more than one design for these types are shown only for the designs that occurred in the greatest number of specimens. (As fig. 7 and 8 show, some of the designs from these manufacturers occurred in only one or two specimens.)

Finally, for the emitter-to-base and collector-to-base junctions of the device types of this study, appendix A contains tables containing the ranges and the mean values of (1) the voltage, current, power, and impedance that are characteristic of the failure levels of the device samples for a 1-μs reverse biasing square pulse and (2) the capacitances and the breakdown voltages of the respective junctions. Appendix A shows also the photomicrographs of the chips.

3.4 Discussion of Results

One of the surprising results of this investigation was the large number of different designs that are being used by manufacturers for the same device type. The designs not only differ in the pattern, but also differ considerably in the dimensions; in the 2N4237, the chip area varied by a factor of 20.

The variations of failure powers of collector-to-base junctions of individual specimens of a sample, as well as the variations of the mean value of such powers of samples of one device type from different manufacturers, also were found to be unexpectedly large. The failure powers of individual collector-to-base junctions of a single transistor type can vary by more than four orders of magnitude, which is the range previously thought to apply to transistors (of low and high powers) of all types.[3] The variations of the failure powers of emitter-to-base junctions, within a sample and between samples from different manufacturers, are generally smaller than those for collector-to-base junctions. Still, failure powers of the emitter-to-base junctions of a commercial transistor type can vary by two orders of magnitude. It will be the task of system analysts to consider the possibility of variations of this magnitude in EMP vulnerability analyses of systems.

From the point of view of device failure modeling, the results of this study suggest only one correlation between aspects of the device design and aspects of the threshold signal for failure: the pulse failure power of emitter-to-base junctions, averaged over a sample, increases with chip area. However this relationship is not strictly a proportionality and also does not hold without exceptions; furthermore, no such correlation exists for the collector-to-base junctions of the

[3] *DNA EMP (Electromagnetic Pulse) Handbook, Defense Nuclear Agency, DNA 2114H-2 (September 1975).*

devices studied. As a basis for a physical model of failure, if only of an emitter-to-base junction, this relationship is made even less promising by the fact that the emitter-to-base failure power of individual specimens of the same type and design can vary greatly; a variation by a factor of 5 is not uncommon, and in one sample a variation by a factor of 15 was observed. It is remarkable also that for many samples the average power for failure or second breakdown of the collector-to-base junctions is significantly smaller than that for the emitter-to-base junctionns.

Besides a comparison of the chip areas, no other quantitative comparison of the different designs of a device type was attempted (so that aspects of the design could be related to the device failure power). However, interesting differences in junction failure powers were observed in two device types, the 2N1613 and the JAN2N1613, both by TEC, that have the same design: the average failure power of the collector-to-base junctions of the JAN2N1613 is larger by more than one order of magnitude than that of the commercial version. To be relevant, a device failure model must be able to account for such a difference. A closer investigation of the devices from these two samples is planned.

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APPENDIX A. VARIABILITY OF DEVICE DESIGNS AND DESIGN-DEPENDENT VARIATIONS OF DEVICE CHARACTERISTICS AND AMPLITUDES OF 1-μs SQUARE PULSES REQUIRED FOR JUNCTION FAILURE IN SELECTED TRANSISTOR TYPES

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Tables A-1 to A-6 show, for the emitter-to-base and collector-to-base junctions of the device types of this study, the ranges and the mean values of (1) voltage, current, power, and impedance that are characteristic of the failure levels of the device samples for a 1-μs reverse biasing square pulse and (2) the capacitances and the breakdown voltages of the respective junctions. The samples for each device type are listed in alphabetical order of the manufacturers' abbreviation codes (in the main body of the report). The area of the device chip, in square millimeters, is given after the manufacturer's code. The range of any of the listed magnitudes (voltage, and so on) is followed, after a semicolon, by the mean value of that magnitude. The junction capacitance was measured with a capacitance bridge at zero bias and at 3-V reverse bias; entered in the tables is the value at 3-V reverse bias, which was found in most cases to be close to one-half of the zero bias value. The breakdown voltage is the voltage at which, in reverse bias of the junction, a current of 10 μA results. The numbers in the tables are rounded off to two significant digits.

For all but four manufacturers, the ranges and the mean values in tables A-1 to A-6 pertain to samples of 20 specimens. The exceptions are two manufacturers (NJS and WAB) of the 2N1613 transistor and two manufacturers (STI and UTS) of the 2N4237 transistor, which used several different designs; the ranges and mean values are shown for each design, and the number of devices in each sample can be seen in figures 7 and 8 in the main body of the report. The chip areas of each design will establish the proper correspondence between figure 7 and table A-1 and figure 8 and table A-2.

Figures A-1 to A-6 show, one for each device type, photomicrographs of the device chips from the various manufacturers. The magnification is the same for all chips of one device type; the size of a 1-mm reticle at the magnification used is shown in each figure. The chip area, in square millimeters, is given after the manufacturer's code. The first design of the four manufacturers that used more than one design for a device type, shown in figures A-1 and A-2, is the design seen in the initial design identification (sect. 2.1); the subsequent designs are those found in the device inspection discussed in section 3.2 in the main body of the report.

TABLE A-1. RANGES AND MEAN VALUES OF ELEC

Manufacturer	Chip area (mm^2)	Emitter-to-base junction: Voltage (V)	Current (A)	Power (W)	Impedance (Ω)	Junction capacitance (pF)
CEM	0.29	30-40;34	5.0-6.3;5.8	170-220;190	5.1-8.0;5.9	7.6-8.8;8
ETC	0.75	44-65;55	6.0-9.5;7.8	290-620;430	5.7-10;7.0	35-47;40
FSC	0.16	25-31;27	4.9-5.5;5.3	120-170;140	4.6-5.6;5.1	17-20;19
IDI	0.25	17-22;20	6.5-10;8.5	110-220;160	2.1-2.6;2.4	22-26;24
MOTA	0.26	35-43;39	1.4-3.6;3.3	57-150;130	10-29;12	18-19;18
NJS	1.0	43-100;72	6.2-10;8.6	270-850;620	6.9-12;8.4	32-52;40
	0.77					
	0.24	20-33;26	5.2-7.3;6.4	100-220;170	3.6-4.9;4.1	21-24;22
	0.20	26-30;28	3.4-4.2;3.8	88-130;110	7.1-7.6;7.3	17-18;17
RCA	0.53	36-62;51	3.6-6.7;5.5	130-330;280	7.1-12;9.2	24-30;28
SST	0.77	28-62;56	6.0-8.6;7.5	170-490;430	6.8-8.6;7.4	37-42;40
STI	0.75	18-78;35	1.6-10;6.3	80-430;220	3.1-16;5.3	36-49;42
SWT	0.20	19-31;27	3.3-4.5;3.9	65-130;110	5.6-7.7;6.9	16-19;17
TEC	0.56	30-47;39	9.0-20;12	270-680;460	1.7-4.4;3.4	36-52;44
TIC	1.0	30-90;68	4.2-8.4;7.3	130-660;520	6.5-13;9.3	37-42;40
TII	0.39	25-36;29	11-15;14	270-500;400	1.5-2.6;2.0	32-38;36
UPI	0.40	23-40;34	3.9-6.5;5.6	110-230;190	3.9-7.8;6.0	19-26;21
UTS	0.46	18-38;23	5.9-15;8.5	120-340;190	1.2-4.4;2.9	31-39;34
WAB	1.0	34-120;94	4.5-9.0;6.7	170-900;640	3.8-20;14	42-55;49
	0.44	24-28;26	4.6-5.3;4.9	110-150;130	5.2-5.3;5.3	22-25;23

Note: Junctions were reverse biased with 1-μs-wide square pulses.

TABLE A-2. RANGES AND MEAN VALUES OF EL

Manufacturer	Chip area (mm^2)	Emitter-to-base junction: Voltage (V)	Current (A)	Power (W)	Impedance (Ω)	Junction capacit (pF
AMC	2.4	34-65;58	31-39;35	1100-2500;2100	1.0-2.0;1.7	130-170
ETC	9.5	28-150;75	16-120;77	1,100-16,000;6,000	0.54-6.6;1.3	90-200;
FSC	1.3	39-48;44	42-59;48	1800-2600;2100	0.72-1.0;0.91	130-170
GSE	5.0	28-68;51	30-67;51	840-3600;2600	0.72-1.4;1.0	200-400
IDI	2.3	35-51;44	*44-69;60*	*1500-3400;2700*	*0.65-0.80;0.75*	230-280
MOTA	2.1	40-110;63	12-33;26	880-1900;1600	1.5-9.2;2.6	85-160;
NJS	5.2	29-55;44	28-60;47	1200-2900;2100	0.71-1.8;0.96	220-320
SCA	1.1	19-38;33	6.5-22;18	180-840;620	1.6-2.9;1.9	66-77;7
SOD	2.7	34-77;55	17-40;25	710-2200;1400	1.4-3.5;2.3	140-210
SST	0.80	20-28;26	23-32;28	460-870;720	0.78-1.1;0.94	56-75;6
STI	8.0	24-68;60	43-85;76	1000-5600;4700	0.56-0.84;0.78	720-780
	5.1	43-130;82	32-69;50	1400-9000;4500	1.1-2.0;1.6	300-380
	3.1	38	32	1200	1.2	200
STR	0.57	24-38;33	6.5-10;8.8	160-360;290	3.2-4.7;3.8	32-60;3
TRS	2.3	27-43;37	52-70;63	1400-2700;2300	0.46-0.69;0.59	220-320
UPI	0.46	24-44;37	4.1-9.8;7.1	150-370;260	3.4-10;5.9	16-42;2
UTS	9.5	35-83;64	23-75;49	810-6200;3600	1.1-1.5;1.4	460-550
	8.0	18-38;28	19-36;27	340-1400;870	0.95-1.1;1.0	820-110
	3.6	22-67;50	15-45;33	330-3000;1800	1.3-2.0;1.5	200-600
	2.2	40	28	1100	1.4	140
WAB	0.59	23-41;37	7.2-12;9.5	170-480;350	3.2-5.1;3.9	40-54;4

Note: Junctions were reverse biased with 1-μs-wide square pulses.

APPENDIX A

·1 OF ELECTRICAL CHARACTERISTICS AND FAILURE LEVELS OF 2N1613 TRANSISTOR

Junction ·apacitance (pF)	Breakdown voltage (V)	Collector-to-base junction Voltage (V)	Current (A)	Power (W)	Impedance (Ω)	Junction capacitance (pF)	Breakdown voltage (V)
·.6-8.8;8.2	20-23;22	130-190;160	0.080-1.8;1.0	11-270;70	83-1700;300	8.0-10;9.3	110-140;130
5-47;40	10-12;11	170-230;200	0.0050-0.95;0.26	0.85-210;55	210-30,000;11,000	20-27;23	73-220;170
7-20;19	7.2-8.0;7.5	130-190;160	0.0030-0.35;0.067	0.45-59;11	490-50,000;8,700	7.0-8.0;7.6	110-170;150
2-26;24	7.4-7.6;7.5	150-220;180	0.030-0.60;0.18	5.4-130;34	350-6000;1600	8.0-8.5;8.3	140-200;170
8-19;18	7.2-7.6;7.4	130-170;150	0.013-1.7;0.36	1.7-240;53	82-13,000;1,200	8.0-10;8.5	96-110;100
·2-52;40	8.8-11;9.7	180-650;300	0.080-17;9.1	14-5600;2800	17-2300;190	22-32;29	110-190;140
		400-490,450	10-12;11	4000-5900;4900	40-41;40	24-26;25	120-130;130
1-24;22	7.0-7.8;7.5	140	0.070	9.8	2000	9.9	130
7-18;17	7.6-8.0;7.8						
4-30;28	7.8-9.5;8.3	210-360;300	0.23-1.7;1.1	55-500;330	180-1000;340	15-20;16	86-150;140
17-42;40	7.5-10;8.6	420-600;550	3.2-9.6;6.0	1300-5800;3300	63-140;98	16-18;18	130-210;190
16-49;42	7.6-11;9.5	160-340;260	0.0030-1.6;0.46	0.54-430;120	150-60,000;6,900	9.0-20;14	100-240;190
6-19;17	7.2-7.5;7.3	140-170;160	0.35-1.4;0.80	56-240;130	110-490;260	7.5-8.0;8.0	110-120;110
16-52;44	7.4-11;8.5	160-460;320	0.010-1.2;0.80	1.6-460;260	250-23,000;410	11-31;15	110-230;170
17-42;40	9.6-10;10	330-630;520	11-20;16	4,100-12,000;8,300	25-53;34	27-30;29	90-130;120
12-38;36	8.0-9.0;8.3	280-350;330	0.52-1.3;0.98	170-450;320	270-630;360	10-11;10	150-180;170
9-26;21	7.8-11;8.6	180-350;260	0.12-1.1;0.65	23-340;170	200-1400;550	13-16;14	95-150;120
11-39;34	6.6-9.2;7.6	190-300;270	0.010-0.53;0.25	1.9-150;70	550-19,000;2,500	10-12,11	110-170;150
12-55;49	10-13;11	280-770;500	11-27;20	4,440-14,000;10,000	11-48;27	23-30;27	100-150;130
12-25;23	8.0-9.0;8.5	200-250;230	0.35-1.3;1.0	70-310;230	170-570;280	12-15;13	120-150;140

ES OF ELECTRICAL CHARACTERISTICS AND FAILURE LEVELS OF 2N4237 TRANSISTOR

Junction capacitance (pF)	Breakdown voltage (V)	Collector-to-base junction Voltage (V)	Current (A)	Power (W)	Impedance (Ω)	Junction capacitance (pF)	Breakdown voltage (V)
130-170;140	11-13;11	240-300;290	0.050-0.25;0.11	15-63;33	1000-5800;2900	45-60;50	160-250;230
90-200;150	5.4-29;12	150-280;200	0.090-6.5;2.2	17-1800;440	43-2100;270	200-270;230	50-170;91
130-170;140	8.6-11;9.7	290-440;370	0.10-0.88;0.45	38-330;180	420-3800;1200	25-35;29	50-310;270
200-400;290	6.5-15;11	100-300;210	0.0060-2.3;0.40	0.72-640;93	57-20,000;4,800	100-140;120	60-190;120
230-280;260	7.5-12;10	320-410;350	0.60-1.6;1.0	190-640;370	250-570;370	50-60;57	140-220;200
85-160;110	6.5-12;8.0	270-300;290	0.057-0.30;0.15	17-90;44	1000-5000;2600	55-120;70	60-290;240
220-320;290	6.5-10;8.6	320-490;410	0.40-42;12	160-21,000;5,000	12-970;110	100-120;110	120-410;310
66-77;71	11-13;12	160-300;230	0.0080-0.61;0.23	1.3-180;56	490-20,000;2,400	24-37;31	60-230;180
140-210;160	10-15;13	140-480;320	0.0080-2.9;0.97	1.1-1200;400	140-17,000;1,700	45-65;57	60-290;170
56-75;64	8.0-10;9.3	160-370;290	0.0020-0.023;0.0077	0.57-8.5;2.4	15,000-170,000;59,000	12-18;15	160-320;250
720-780;760	10-13;13	200-310;260	0.075-1.5;0.38	15-470;110	210-3100;1500	110-190;160	130-190;180
300-380;330	20-24;22	230-340;300	0.065-0.70;0.23	19-220;75	460-4500;2000	90-120;100	170-290;230
200	14	280	0.20	56	1400	60	220
32-60;37	9.4-11;10	120-300;220	0.0040-1.8;0.54	0.56-500;140	160-35,000;3,500	12-35;15	90-270;170
220-320;280	9.5-11;11	140-240;200	0.073-1.4;0.44	12-340;95	170-2300;970	60-80;73	90-160;130
16-42;29	8.2-9.2;8.5	130-240;190	0.10-1.6;0.62	21-340;120	130-2300;620	6.5-16;12	110-160;130
460-550;500	11-15;13	150-170;160	0.022	3.3-3.7;3.5	6800-7800;7300	190-210;200	40-60;50
820-1100;960	8.4-13;11	280	0.63	180	440	180	80
200-600;310	5.5-15;11	100-390;180	0.012-1.5;0.13	1.4-580;44	260-13,000;7,000	50-120;93	60-220;120
140	11						
40-54;46	7.4-8.8;8.2	210-260;240	0.10-0.86;0.36	25-220;86	300-2500;920	10-15;12	190-240;220

TABLE A-3. RANGES AND MEAN VALU

Manu-facturer	Chip area (mm^2)	Emitter-to-base junction: Voltage (V)	Current (A)	Power (W)	Impedance (Ω)
FSC	0.16	25-29;27	4.6-5.3;5.0	130-150;140	4.9-6.1;5.4
MOTA	0.83	30-38;34	7.4-10;8.8	220-360;300	3.6-4.1;3.9
RIN	0.46	31-40;37	8.7-12;9.4	310-390;350	2.6-4.4;4.0
TEC	0.56	30-46;40	6.5-10;8.7	190-420;350	4.0-5.3;4.7
TII	0.39	29-33;31	6.5-14;13	200-460;390	2.1-4.8;2.5
TSC	0.77	37-62;55	5.0-7.2;6.5	190-430;360	7.4-11;8.5

Note: *Junctions were reverse biased with 1-μs-wide square pulse*

TABLE A-4. RANGES AND MEAN VA

Manu-facturer	Chip area (mm^2)	Emitter-to-base junction: Voltage (V)	Current (A)	Power (W)	Impedance (Ω)
FSC	0.16	21-28;26	4.0-5.0;4.7	84-140;120	5.2-6.0;5.
MOTA	0.26	30-36;34	2.9-3.4;3.2	87-120;110	10-11;11
RTN	0.29	31-56;34	5.6-6.2;5.9	180-350;200	5.0-9.0;5.
TEC	0.37	25-29;27	6.0-6.7;6.3	150-190;170	3.8-4.6;4.
TII	0.22	22-36;30	3.4-4.8;4.4	75-160;130	5.1-8.4;6.

Note: *Junctions were reverse biased with 1-μs-wide square pulse*

TABLE A-5. RANGES AND MEAN VAL

Manu-facturer	Chip area (mm^2)	Emitter-to-base junction: Voltage (V)	Current (A)	Power (W)	Impedance (Ω)	J c
FSC	0.083	17-23;19	0.92-1.1;1.0	16-25;20	18-22;19	3.
MOTA	0.10	16-19;18	1.4-1.6;1.5	24-30;27	11-14;12	2.
RTN	0.17	19-24;21	0.80-1.1;0.98	15-26;21	19-24;22	3.
TEC	0.15	19-26;23	1.0-1.5;1.3	20-36;29	15-20;18	2.

Note: *Junctions were reverse biased with 1-μs-wide square pulses*

TABLE A-6. RANGES AND MEAN VAL

Manu-facturer	Chip area (mm^2)	Emitter-to-base junction: Voltage (V)	Current (A)	Power (W)	Impedance (Ω)
FSC	0.24	21-27;24	3.8-6.6;6.0	95-160;140	3.5-6.6;4.
MOTA	0.25	20-23;21	5.7-7.1;6.2	120-150;130	2.9-4.0;3.
RTN	0.29	19-23;21	5.8-7.4;6.4	120-160;130	2.8-3.6;3.
TEC	0.30	18-27;23	4.8-6.6;5.7	91-160;130	2.7-4.6;4.
TII	0.25	18-28;25	3.1-4.5;4.3	56-120;110	5.3-7.4;5.

Note: *Junctions were reverse biased with 1-μs-wide square pul*

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. RANGES AND MEAN VALUES OF ELECTRICAL CHARACTERISTICS AND FAILURE LEVELS OF JAN2N1613 TRANSISTOR

tter-to-base junction				Collector-to-base junction					
Power (W)	Impedance (Ω)	Junction capacitance (pF)	Breakdown voltage (V)	Voltage (V)	Current (A)	Power (W)	Impedance (Ω)	Junction capacitance (pF)	Breakdown voltage (V)
-150;140	4.9-6.1;5.4	14-15;14	6.9-7.9;7.4	190-250;220	0.38-0.85;0.65	80-200;140	240-600;350	5.5-6.5;6.0	120-160;140
-360;300	3.6-4.1;3.9	35-41;39	7.2-8.2;7.9	200-270;240	0.040-1.5;1.1	8.0-410;280	160-5000;460	11-13;12	140-160;150
-390;350	2.6-4.4;4.0	33-38;35	8.1-10;9.4	250-330;300	0.45-0.88;0.61	140-290;180	320-710;510	8.2-9.1;8.5	190-220;200
-420;350	4.0-5.3;4.7	38-49;44	7.5-9.1;8.1	200-380;300	6.4-14;10	1300-4500;3100	23-41;31	19-24;21	110-140;120
-460;390	2.1-4.8;2.5	29-30;29	8.2-9.1;8.7	280-340;310	0.40-1.4;1.1	110-450;330	210-710;320	7.2-8.6;8.0	150-200;160
-430;360	7.4-11;8.5	37-47;44	9.0-11;9.9	340-600;490	10-24;16	3,500-12,000;7,800	20-45;32	21-24;23	92-140;110

1-μs-wide square pulses.

-4. RANGES AND MEAN VALUES OF ELECTRICAL CHARACTERISTICS AND FAILURE LEVELS OF JAN2N2222 TRANSISTOR

ter-to-base junction				Collector-to-base junction					
ower (W)	Impedance (Ω)	Junction capacitance (pF)	Breakdown voltage (V)	Voltage (V)	Current (A)	Power (W)	Impedance (Ω)	Junction capacitance (pF)	Breakdown voltage (V)
-140;120	5.2-6.0;5.6	12-15;13	7.4-7.8;7.6	120-200;160	0.0010-0.50;0.24	0.12-78;49	280-120,000;7,200	4.6-6.3;5.5	100-180;150
-120;110	10-11;11	12-14;13	6.7-7.3;7.0	130-170;150	0.095-0.93;0.48	14-130;70	150-1600;420	5.8-7.2;6.2	86-100;97
-350;200	5.0-9.0;5.7	17-20;18	7.5-8.1;7.8	160-200;180	0.40-0.72;0.55	72-130;100	270-500;340	8.0-11;9.3	120-130;130
-190;170	3.8-4.6;4.2	13-16;15	6.6-7.1;6.9	110-220;180	0.0050-0.43;0.048	0.65-94;9.6	510-30,000;9,900	4.8-7.3;6.6	92-180;150
-160;130	5.1-8.4;6.8	13-16;14	6.8-7.4;7.1	110-140;130	0.0050-1.1;0.53	0.55-150;72	130-22,000;1,400	5.6-6.1;5.8	100-120;110

-μs-wide square pulses.

RANGES AND MEAN VALUES OF ELECTRICAL CHARACTERISTICS AND FAILURE LEVELS OF JAN2N2369A TRANSISTOR

er-to-base junction				Collector-to-base junction					
ower (W)	Impedance (Ω)	Junction capacitance (pF)	Breakdown voltage (V)	Voltage (V)	Current (A)	Power (W)	Impedance (Ω)	Junction capacitance (pF)	Breakdown voltage (V)
-25;20	18-22;19	3.0-3.2;3.1	5.6-5.8;5.8	52-65;58	0.070-0.90;0.18	4.0-54;11	67-810,470	1.9-2.8;2.1	45-58;52
-30;27	11-14;12	2.1-2.5;2.3	6.3-6.8;6.6	58-83;71	0.090-0.20;0.13	6.3-14;9.0	290-830;560	1.7-3.1;1.9	50-74;62
-26;21	19-24;22	3.2-3.5;3.3	5.8-5.9;5.8	74-100;88	0.0020-0.048;0.019	0.18-[illegible].9;1.6	1,700-45,000;10,000	3.2-4.0,3.4	52-64;60
36;29	15-20;18	2.7-3.1;2.9	6.0-6.4;6.2	60-85;70	0.10-0.47;0.27	7.3-31;18	130-850;340	2.6-3.2;2.8	50-63;56

μs-wide square pulses.

RANGES AND MEAN VALUES OF ELECTRICAL CHARACTERISTICS AND FAILURE LEVELS OF JAN2N2907 TRANSISTOR

tter-to-base junction				Collector-to-base junction					
wer W)	Impedance (Ω)	Junction capacitance (pF)	Breakdown voltage (V)	Voltage (V)	Current (A)	Power (W)	Impedance (Ω)	Junction capacitance (pF)	Breakdown voltage (V)
60;140	3.5-6.6;4.1	13-17;15	7.6-8.2;7.9	81-140;110	0.15-1.8;0.85	13-230;94	45-600;220	7.8-8.4;8.2	70-120;100
50;130	2.9-4.0;3.5	12-14;13	7.5-7.7;7.6	100-140;120	0.0050-0.79;0.42	0.55-91;51	140-22,000;1,500	5.4-6.4;5.8	90-120;110
60;130	2.8-3.6;3.3	14-16;15	6.6-8.8;7.7	120-160;150	0.93-2.1-1.3	140-330;190	62-160;120	8.4-10;9.1	90-99;94
60;130	2.7-4.6;4.0	11-16;14	7.2-8.4;7.9	90-140;110	0.27-2.5;1.0	24-270;110	44-330;140	7.6-11;8.4	70-130;110
20;110	5.3-7.4;5.9	10-13;12	7.4-7.7;7.6	95-120;110	0.28-0.88;0.76	27-97;82	110-340;150	6.6-8.5;7.6	90-110;100

1-μs-wide square pulses.

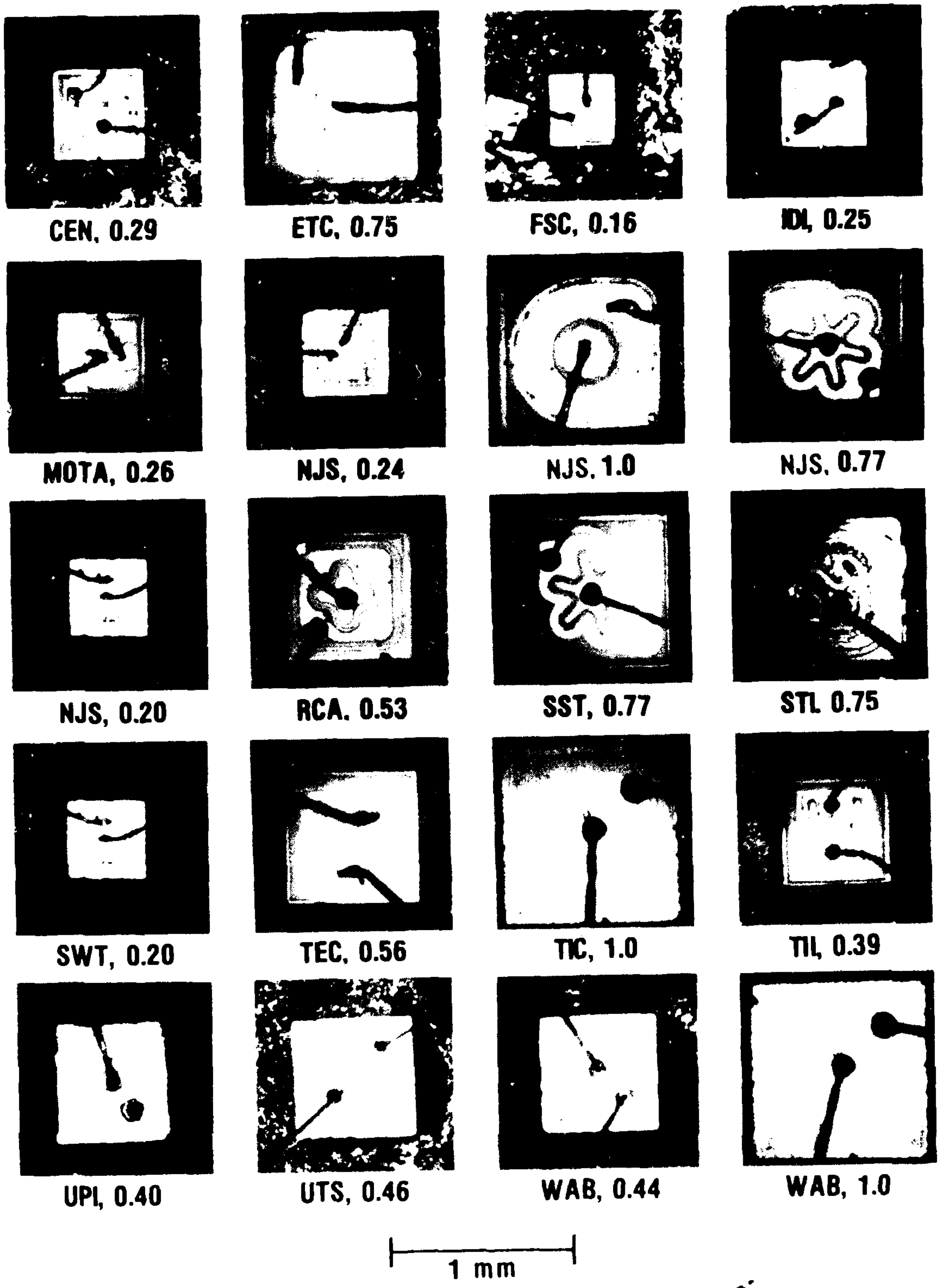

Figure A-1. Design variations of 2N1613 transistor.

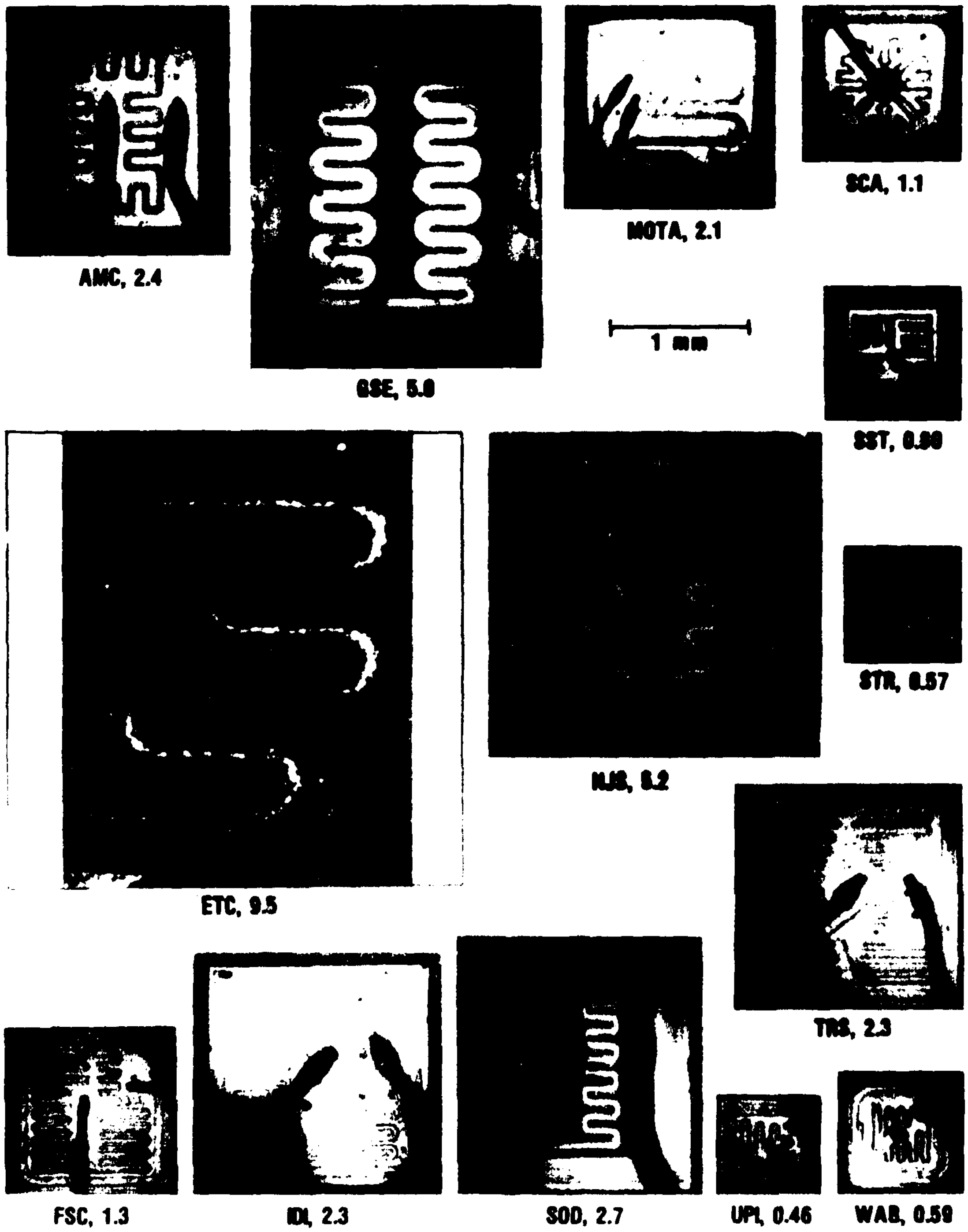

Figure A-2. Design variations of 2N4237 transistor.

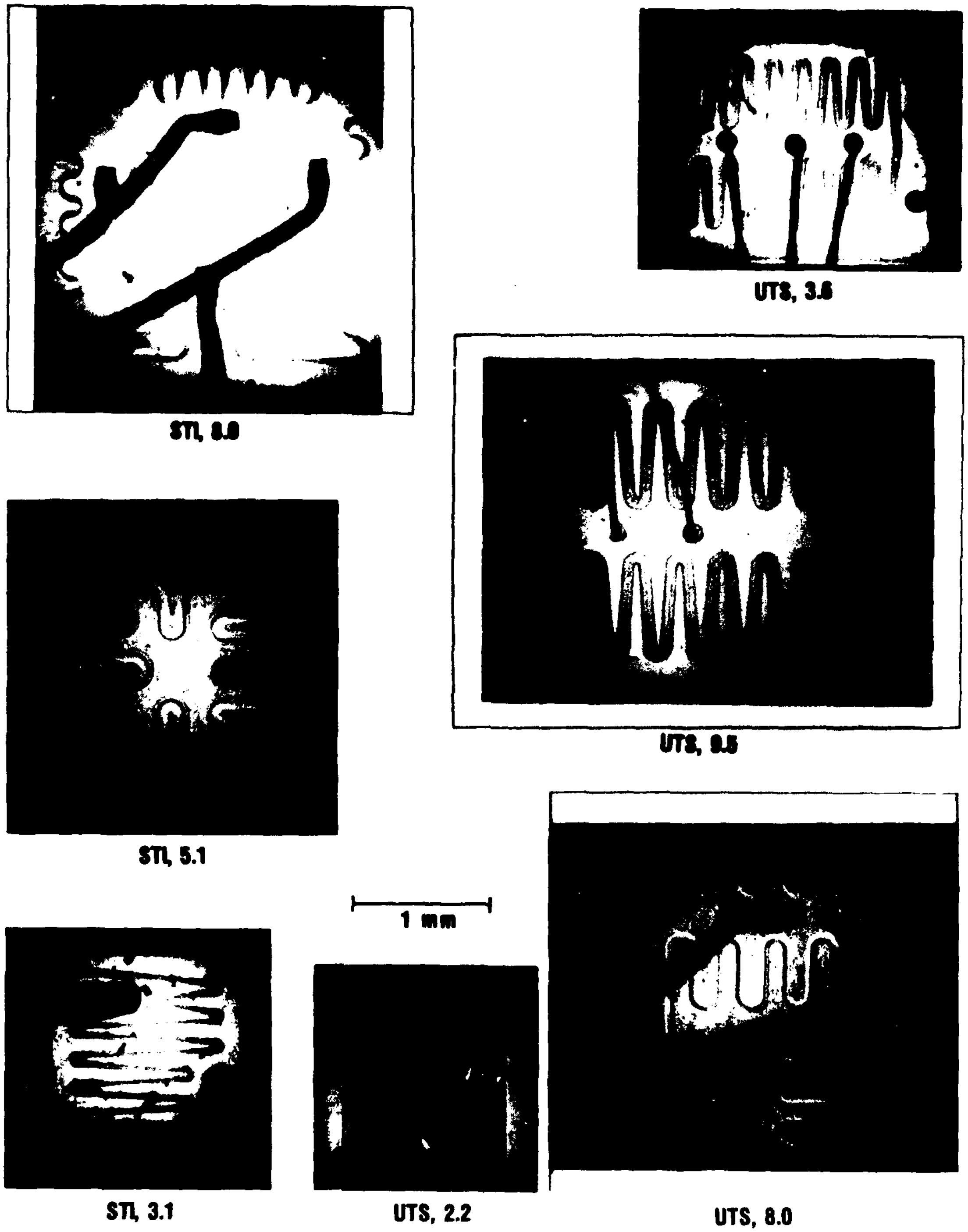

Figure A-2. Design variations of 2N4237 transistor (cont'd).

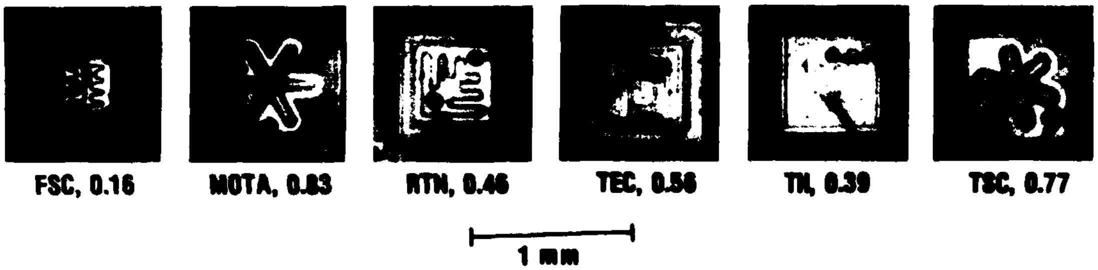

Figure A-3. Design variations of JAN2N1613 transistor.

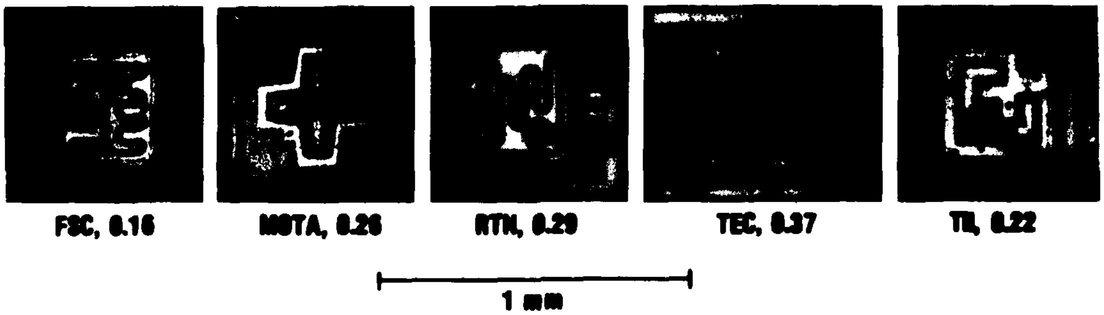

Figure A-4. Design variations of JAN2N2222 transistor.

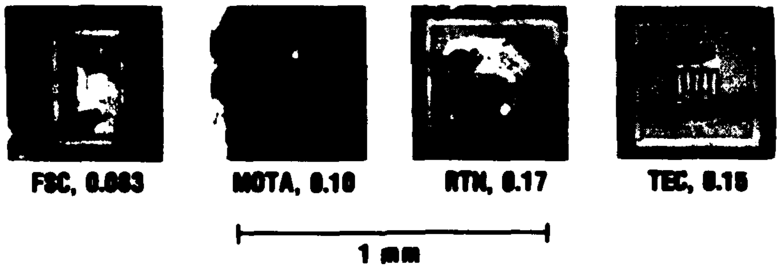

Figure A-5. Design variations of JAN2N2369A transistor.

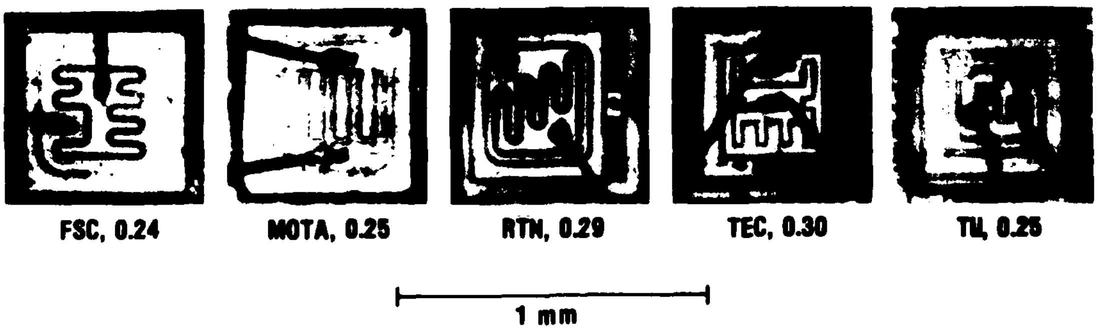

Figure A-6. Design variations of JAN2N2907 transistor.

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