Radio Frequency Transistors

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Principles and Practical Applications

Second Edition

Norman Dye
Helge Granberg

Newnes
An imprint of Butterworth-Heinemann

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Library of Congress Cataloging-in-Publication Data

Dye, Norm, 1929–
Radio frequency transistors : principles and practical applications / Norman Dye, Helge Granberg.—2nd ed.
p. cm.
Includes bibliographical references and index.
ISBN 0-7506-7281-1 (pbk. : alk. paper)
1. Power transistors. 2. Transistor amplifiers. 3. Transistor radio transmitters. 4. Amplifiers, Radio frequency. I. Granberg, Helge, 1932– II. Title.

TK7871.92 .D96 2000
621.384′12—dc21 00-045618

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

The publisher offers special discounts on bulk orders of this book.
For information, please contact:
Manager of Special Sales
Butterworth-Heinemann
225 Wildwood Avenue
Woburn, MA 01801-2041
Tel: 781-904-2500
Fax: 781-904-2620

For information on all Newnes publications available, contact our World Wide Web home page at: http://www.newnespress.com

10 9 8 7 6 5 4 3 2 1

Printed in the United States of America

Dedicated to the memory of Helge Granberg,
who died suddenly in January, 1996

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PREFACE

This book is about radio frequency (RF) transistors. It primarily focuses on applications viewed from the perspective of a semiconductor supplier who, over the years, has been involved not only in the manufacture of RF transistors, but also their use in receivers, transmitters, plasma generators, magnetic resonance imaging, etc.

Since the late 1960s, Motorola Semiconductors has been at the forefront in the development of solid state transistors for use at radio frequencies. The authors have been a part of this development since 1970. Much information has been acquired during this time, and it is our intention in writing this book to make the bulk of that information available to users of RF transistors in a concise manner and from a single source.

This book is not theoretical; as the name implies, it is intended to be practical. Some mathematics is encountered during the course of the book, but it is not rigorous. Formulas are not derived; however, sufficient references are cited for the reader who wishes to delve deeper into a particular subject.

This book is slanted toward power transistors and their applications because much less material is available in the literature on this subject, particularly in one location. Also, RF power is the primary experience of the authors. One chapter is devoted to low power (small signal) transistor applications in an effort to cover more completely the breadth of power levels in RF transistors.

Chapters 1 through 4 discuss RF transistor fundamentals, such as what's different about RF transistors, how they are specified, how to select a transistor, and what the difference is between FETs and BJTs. Also covered are topics such as classes of operation, forms of modulation, biasing, and operating in a pulse mode. Chapters 5 and 6 lay the groundwork for future circuit designs by discussing such subjects as laying out circuit boards and mounting RF devices, as well as the importance of die temperature.

In Chapters 7, 8, and 9, the authors take the reader through various considerations in planning an amplifier design. Among the diverse topics covered are choice of circuit, stability, impedance matching (including computer-aided design programs), and the power amplifier output. Chapters 10 through 12 focus on wideband techniques.

Chapter 13 describes the many factors affecting small signal (low power) amplifier design. A variety of examples illustrate the concepts in an effort to make small signal amplifier design straightforward through a step-by-step approach.

About the Revision

The second edition of the book is being issued primarily to provide updated information on the newest transistor type to arrive on the RF power scene, namely LDMOS FETs. An entire chapter (Chapter 14) is devoted to this subject and takes the reader from die design, through modulation requirements of today's cellular radios, to the actual design of a high power amplifier using LDMOS FETs.

In addition, material has been added in Chapter 2 regarding selection of matched transistors, and in Chapter 7, a significant amount of material has been added on capacitors, inductors, and impedance matching. Finally, an example of the use of S-parameters in the design of a low power, low noise amplifier has been added at the end of Chapter 13.

ACKNOWLEDGMENTS

The authors wish to thank the many application engineers in the RF product operation at Motorola Semiconductors for their contributions to the book. Special recognition goes to Phuong Le for his assistance in low power applications, to Dan Moline for making available his recently introduced computer program for impedance matching with the aid of Smith Chart™ displays, to Bob Baeten for his assistance in computer-aided design programs, to Walt Wright for answering many questions about microwaves and pulse power applications, and to Hank Pfizenmayer for his advice and expertise in filter design. Special thanks also go to Analog Instruments Co., Box 808, New Providence, NJ 07974, for their permission to reproduce the Smith Chart in several diagrams in Chapter 13. And special thanks go to the management of the Communications Semiconductor Products Division within Motorola Semiconductor Sector, whose encouragement and support has made writing this book possible.

Both authors retired from Motorola Semiconductors in 1994. In order to give the reader the latest and best possible information about LDMOS transistors, Norm Dye enlisted, through the courtesy of Tom Moller, Vice President and General Manager of Ericsson, Inc., Microelectronics Division, the aid of the staff at Ericsson RF Power Products, Microelectronics Division to revise this book. Thus, Chapter 14 has been written primarily by Prasanth Perugupalli from the Ericsson Phoenix Design Center in Scottsdale, Arizona. Some of the material on LDMOS die was contributed by Jon Johansson, and information on die modeling was contributed by Qiang Chen, both located in Ericsson's transistor manufacturing facility in Stockholm, Sweden.

Some of the material on applications has also been contributed by Larry Leighton, manager of the Phoenix Design Center. Finally, comments and review of the technical material have been made by Nagaraj Dixit, also of the Ericsson Phoenix Design Center team. Special thanks to each of these gentlemen for their assistance, without which this second edition would not be possible.

Radio Frequency Transistors

1

Understanding RF Data Sheet Parameters

INTRODUCTION

Data sheets are often the sole source of information about the capability and characteristics of a product. This is particularly true of unique RF semiconductor devices that are used by equipment designers all over the world. Because circuit designers often cannot talk directly with the factory, they rely on the data sheet for their device information.[1] And for RF devices, many of the specifications are unique in themselves. Thus it is important that the user and the manufacturer of RF products speak a common language—that is, what semiconductor manufacturers say about their RF devices should be understood fully by the circuit designers.

In this chapter, a review is given of RF transistor and amplifier module parameters from maximum ratings to functional characteristics. The section is divided into five basic parts: D.C. specifications, power transistors, low power transistors, power modules, and linear modules. Comments are made about critical specifications, about how values are determined and what their significance is. A brief description of the procedures used to obtain impedance data and thermal data is set forth, the importance of test circuits is elaborated, and background information is given to help understand low noise considerations and linearity requirements.

D.C. SPECIFICATIONS

Basically, RF transistors are characterized by two types of parameters: D.C. and functional. The "D.C." specs consist (by definition) of breakdown voltages, leakage currents, h_{FE} (D.C. beta), and capacitances, while the functional specs cover gain, ruggedness, noise figure, Z_{in} and Z_{out}, S-parameters, distortion, etc. Thermal characteristics do not fall cleanly into either category since thermal resistance and power dissipation can be either D.C. or A.C. Thus, we will treat the spec of thermal resistance as a special specification and give it its own heading called "thermal characteristics." Figure 1-1 is one page of a typical RF power data sheet showing D.C. and functional specs.

A critical part of selecting a transistor is choosing one that has *breakdown voltages* compatible with the supply voltage available in an intended application.

ELECTRICAL CHARACTERISTICS (T_C = 25°C unless otherwise noted.)

Characteristic	Symbol	Min	Typ	Max	Unit
OFF CHARACTERISTICS					
Collector-Emitter Breakdown Voltage (I_C = 20 mAdc, I_B = 0)	$V_{(BR)CEO}$	16	–	–	Vdc
Collector-Emitter Breakdown Voltage (I_C = 20 mAdc, V_{BE} = 0)	$V_{(BR)CES}$	36	–	–	Vdc
Emitter-Base Breakdown Voltage (I_E = 5.0 mAdc, I_C = 0)	$V_{(BR)EBO}$	4.0	–	–	Vdc
Collector Cutoff Current (V_{CE} = 15 Vdc, V_{BE} = 0, T_C = 25°C)	I_{CES}	–	–	10	mAdc
ON CHARACTERISTICS					
DC Current Gain (I_C = 4.0 Adc, V_{CE} = 5.0 Vdc)	h_{FE}	20	70	150	–
DYNAMIC CHARACTERISTICS					
Output Capacitance (V_{CB} = 12.5 Vdc, I_E = 0, f = 1.0 MHz)	C_{ob}	–	90	125	pF
FUNCTIONAL TESTS					
Common-Emitter Amplifier Power Gain (V_{CC} = 12.5 Vdc, P_{out} = 45 W, I_C(Max) = 5.8 Adc, f = 470 MHz)	G_{pe}	4.8	5.4	–	dB
Input Power (V_{CC} = 12.5 Vdc, P_{out} = 45 W, f = 470 MHz)	P_{in}	–	13	15	Watts
Collector Efficiency (V_{CC} = 12.5 Vdc, P_{out} = 45 W, I_C (Max) = 5.8 Adc, f = 470 MHz)	η	55	60	–	%
Load Mismatch Stress (V_{CC} = 16 Vdc, P_{in} = Note 1, f = 470 MHz, VSWR = 20:1, All Phase Angles)	ψ *	No Degradation in Output Power			
Series Equivalent Input Impedance (V_{CC} = 12.5 Vdc, P_{out} = 45 W, f = 470 MHz)	Z_{in}	–	1.4 + j4.0	–	Ohms
Series Equivalent Output Impedance (V_{CC} = 12.5 Vdc, P_{out} = 45 W, f = 470 MHz)	Z_{OL}*	–	1.2 + j2.8	–	Ohms

Notes:
1. P_{in} = 150% of Drive Requirement for 45 W output @ 12.5 V.

* ψ = Mismatch stress factor—the electrical criterion established to verify the device resistance to load mismatch failure. The mismatch stress test is accomplished in the standard test fixture (Figure 1) terminated in a 20:1 minimum load mismatch at all phase angles.

FIGURE 1-1
Typical D.C. and functional specifications from a RF power data sheet. The references in the "Notes" above to a test fixture and "Figure 1" pertain to the data sheet from which this figure was extracted.

It is important that the design engineer select a transistor on the one hand that has breakdown voltages which will *not* be exceeded by the D.C. and RF voltages that appear across the various junctions of the transistor and on the other hand has breakdown voltages that permit the "gain at frequency" objectives to be met by the transistor.

Mobile radios normally operate from a 12-volt source, and portable radios use a lower voltage, typically 6 to 9 volts. Avionics applications are commonly 28-volt supplies, while base station and other ground applications such as medical electronics generally take advantage of the superior performance characteristics of high-voltage devices and operate with 24- to 50-volt supplies. In making a transistor, breakdown voltages are largely determined by material resistivity and junction depths (see Figure 1-2).[2] It is for these reasons that breakdown voltages are intimately entwined with functional performance characteristics. Most product portfolios in the RF power transistor industry have families of transistors de-

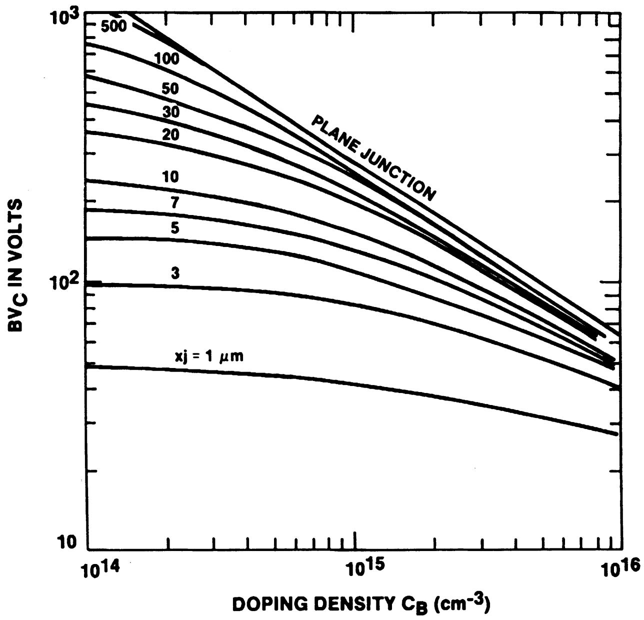


FIGURE 1-2

The effect of curvature and resistivity on breakdown voltage.

signed for use at specified supply voltages such as 7.5 volts, 12.5 volts, 28 volts, and 50 volts.

Leakage currents (defined as reverse biased junction currents that occur prior to avalanche breakdown) are likely to be more varied in their specification, and also more informative. Many transistors do not have leakage currents specified because they can result in excessive (and frequently unnecessary) wafer/die yield losses. Leakage currents arise as a result of material defects, mask imperfections, and/or undesired impurities that enter during wafer processing. Some sources of leakage currents are potential reliability problems; most are not. Leakage currents can be material-related, such as stacking faults and dislocations, or they can be "pipes" created by mask defects and/or processing inadequacies. These sources result in leakage currents that are constant with time, and if initially acceptable for a particular application, will remain so. They do not pose long-term reliability problems.

On the other hand, leakage currents created by channels induced by mobile ionic contaminants in the oxide (primarily sodium) tend to change with time and can lead to increases in leakage current that render the device useless for a specific application. Distinguishing between sources of leakage current can be difficult, which is one reason devices for application in military environments require HTRB (high temperature reverse bias) and burn-in testing. However, even for commercial applications—particularly where battery drain is critical or where bias considerations dictate limitations—it is essential that a leakage current limit be included in any complete device specification.

D.C. parameters such as h_{FE} and C_{ob} (output capacitance) need little comment. Typically, for RF devices, h_{FE} is relatively unimportant for unbiased power transistors because the functional parameter of gain at the desired frequency of operation is specified. Note, though, that D.C. beta is related to A.C. beta (see Figure 1-3). Functional gain will track D.C. beta, particularly at lower RF frequencies. An h_{FE} specification is needed for transistors that require bias, which includes most small signal devices that are normally operated in a linear (Class A) mode (see Chapter 4, "Other Factors Affecting Amplifier Design"). Generally, RF device manufacturers do not like to have tight limits placed on h_{FE}. The primary reasons that justify this position are:

a. Lack of correlation with RF performance
b. Difficulty in control in wafer processing
c. Other device manufacturing constraints dictated by functional performance specs (which preclude tight limits for h_{FE})

A good rule of thumb for h_{FE} is to set a maximum-to-minimum ratio of not less than 3 and not more than 4, with the minimum h_{FE} value determined by an acceptable margin in functional gain.

Output capacitance is an excellent measure of comparison of device size (base area), provided the majority of output capacitance is created by the base-collector junction and not parasitic capacitance arising from bond pads and other top metal of the die. Remember that junction capacitance will vary with voltage (see Figure 1-4), while parasitic capacitance will not vary. Also, in comparing devices, one should note the voltage at which a given capacitance is specified. No industry standard exists. The preferred voltage at Motorola is the transistor V_{cc} rating, that is, 12.5 volts for 12.5-volt transistors and 28 volts for 28-volt transistors, etc.

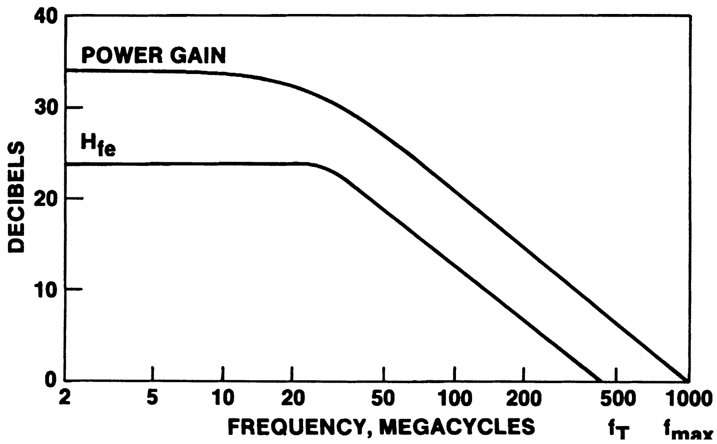


FIGURE 1-3

Relationship between transistor beta and operating frequency.

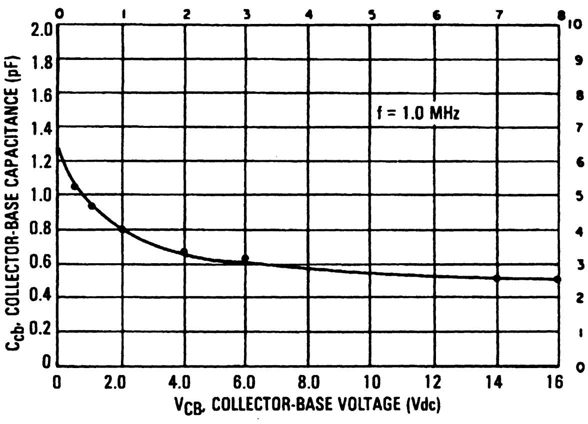


FIGURE 1-4

Relationship between junction capacitance versus voltage for Motorola MRF901.

MAXIMUM RATINGS AND THERMAL CHARACTERISTICS

Maximum ratings (shown for a typical RF power transistor in Figure 1-5) tend to be the most frequently misunderstood group of device specifications. Ratings for *maximum junction voltages* are straightforward and simply reflect the minimum values set forth in the D.C. specs for breakdown voltages. If the device in question meets the specified minimum breakdown voltages, then voltages less than the minimum will not cause junctions to reach reverse bias breakdown with the potentially destructive current levels that can result.

The value of BV_{CEO} is sometimes misunderstood. Its value can approach or even equal the supply voltage rating of the transistor. The question naturally arises as to how such a low voltage can be used in practical applications. First, BV_{CEO} is the breakdown voltage of the collector-base junction plus the forward drop across the base-emitter junction with the base open, and it is never encountered in amplifiers where the base is at or near the potential of the emitter. That is, most amplifiers have the base shorted or they use a low value of resistance such that the breakdown value of interest approaches BV_{CES}. Second, BV_{CEO} involves the current gain of the transistor and increases as frequency increases. Thus the value of BV_{CEO} at RF frequencies is always greater than the value at D.C.

The maximum rating for *power dissipation* (P_d) is closely associated with thermal resistance (θ_{JC}). Actually, maximum P_d is in reality a fictitious number—a kind of figure of merit—because it is based on the assumption that case temperature is maintained at 25°C. However, providing everyone arrives at the value in a similar manner, the rating of maximum P_d is a useful tool with which to compare devices.

The rating begins with a determination of thermal resistance—die to case. Knowing θ_{JC} and assuming a maximum die temperature, one can easily deter-

MOTOROLA
SEMICONDUCTOR
TECHNICAL DATA

MRF650

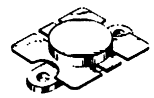
The RF Line

NPN Silicon RF Power Transistor

50 WATTS, 512 MHz
RF POWER TRANSISTOR
NPN SILICON

. . . designed for 12.5 Volt UHF large-signal amplifier applications in industrial and commercial FM equipment operating to 520 MHz.

- Guaranteed 440, 470, 512 MHz 12.5 Volt Characteristics
  Output Power = 50 Watts
  Minimum Gain = 5.2 dB @ 440, 470 MHz
  Efficiency = 55% @ 440, 470 MHz
  IRL = 10 dB
- Characterized with Series Equivalent Large-Signal Impedance Parameters from 400 to 520 MHz
- Built-In Matching Network for Broadband Operation
- Triple Ion Implanted for More Consistent Characteristics
- Implanted Emitter Ballast Resistors
- Silicon Nitride Passivated
- 100% Tested for Load Mismatch Stress at all Phase Angles with 20:1 VSWR @ 15.5 Vdc, 2.0 dB Overdrive



CASE 316-01

MAXIMUM RATINGS

Rating	Symbol	Value	Unit
Collector-Emitter Voltage	V_{CEO}	16.5	Vdc
Collector-Emitter Voltage	V_{CES}	38	Vdc
Emitter-Base Voltage	V_{EBO}	4.0	Vdc
Collector-Current — Continuous	I_C	12	Adc
Total Device Dissipation @ T_C = 25°C Derate above 25°C	P_D	135 0.77	Watts W/°C
Storage Temperature Range	T_{stg}	−65 to +150	°C

THERMAL CHARACTERISTICS

Characteristic	Symbol	Max	Unit
Thermal Resistance, Junction to Case	$R_{\theta JC}$	1.3	°C/W

FIGURE 1-5

Maximum power ratings of a typical RF power transistor, the Motorola MRF650.

mine maximum P_d (based on the previously stated case temperature of 25°C). Measuring θ_{JC} is normally done by monitoring case temperature (T_c) of the device while it operates at or near rated output power (P_o) in an RF circuit. The die temperature (T_j) is measured simultaneously using an infrared microscope (see Figure 1-6), which has a spot size resolution as small as 1 mil in diameter. Normally, several readings are taken over the surface of the die and an average value is used to specify T_j.

It is true that temperature over a die will vary typically 10 to 20°C. A poorly designed die (improper ballasting) could result in hot spot (worst case) temperatures that vary 40 to 50°C. Likewise, poor die bonds (see Figure 1-7) can result in hot spots, but these are not normal characteristics of a properly designed and assembled transistor die.

By measuring T_c and T_j along with P_o and P_{in}—both D.C. and RF—one can calculate θ_{JC} from the formula $\theta_{JC} = (T_j - T_C)/(P_{in} - P_o)$. Typical values for an RF power transistor might be $T_j = 130°C$, $T_C = 50°C$; $V_{cc} = 12.5$ V, $I_C = 9.6$ A, $P_{in}(RF) = 10$ W, and $P_o(RF) = 50$ W. Thus $\theta_{JC} = (130 - 50)/[10 + (12.5 \times 9.6) - 30] = 80/80 = 1°C/W$.

Several reasons dictate that a conservative value be placed on θ_{JC}. First, thermal resistance increases with temperature (and we realize $T_C = 25°C$ is NOT re-

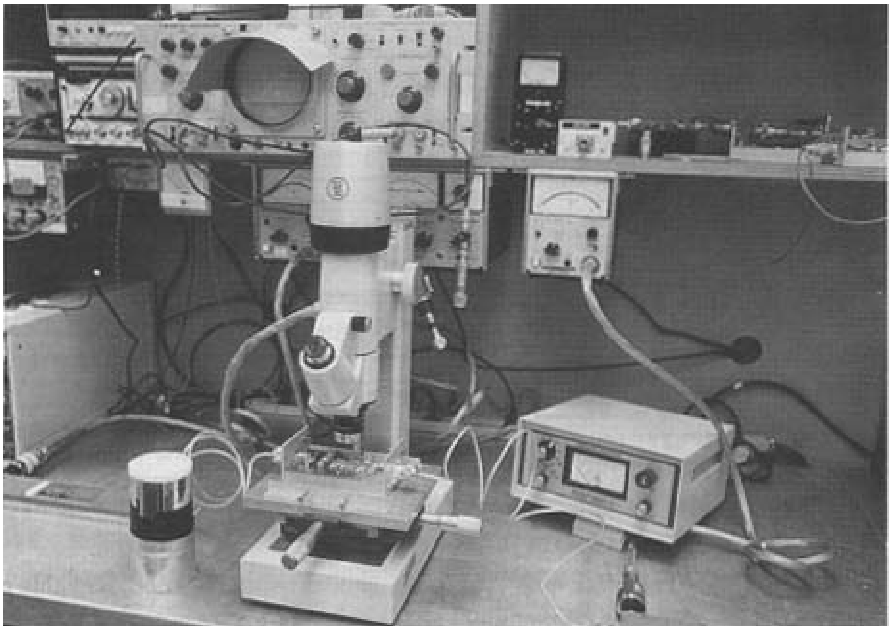


FIGURE 1-6
Measurement of die temperature using an infrared microscope.

alistic). Second, T_j is not a worst case number. And, third, by using a conservative value of θ_{JC}, a realistic value is determined for maximum P_d. Generally, Motorola's practice is to publish θ_{JC} numbers approximately 25% higher than that determined by the measurements described in the preceding paragraphs, or for the case illustrated, a value of $\theta_{JC} = 1.25°C/W$.

A few words are in order about die temperature. Reliability considerations dictate a safe value for an all-Au (gold) system (die top metal and wire) to be 200°C (see Chapter 5, "Reliability Considerations"). Once T_j max is determined, along with a value for θ_{JC}, maximum P_d is simply $P_d(\max) = [T_j(\max) - 25°C]/\theta_{JC}$.

Specifying maximum P_d for $T_c = 25°C$ leads to the necessity to derate maximum P_d for any value of T_c above 25°C. The derating factor is simply the reciprocal of θ_{JC}!

Maximum collector current (I_c) is probably the most subjective maximum rating on the transistor data sheets. It has been, and is, determined in a number of ways, each leading to different maximum values. Actually, the only valid maximum current limitations in an RF transistor have to do with the current handling ability of the wires or the die. However, power dissipation ratings may restrict current to values far below what should be the maximum rating. Unfortunately, many older transistors had their maximum current rating determined by dividing maximum P_d by collector voltage (or by BV_{CEO} for added safety), but this is not a fundamental maximum current limitation of the part. Many lower frequency parts have relatively gross top metal on the transistor die—that is, wide metal runners and the "weak current link" in the part is the current handling capability of the emitter wires (for common emitter parts). The current handling ability of

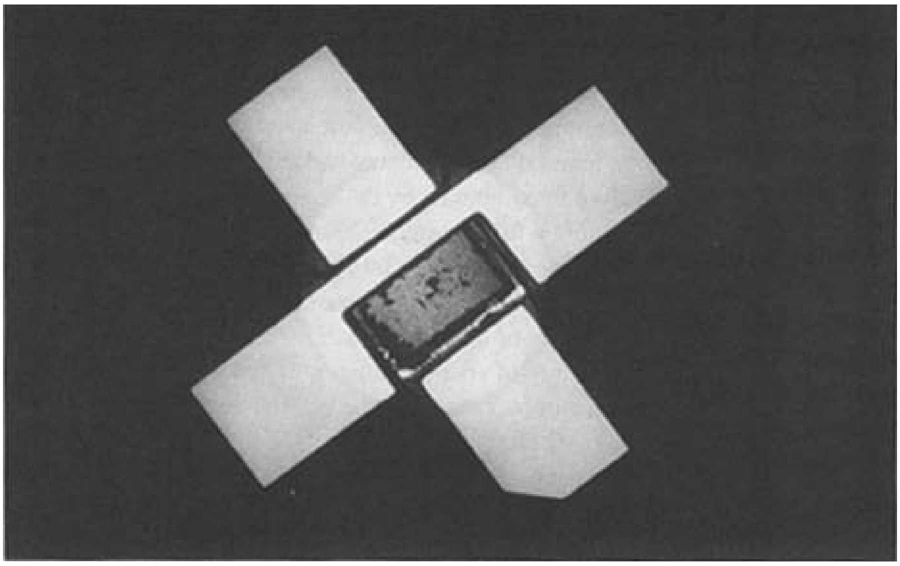


FIGURE 1-7

Voids appear as dark spots in X-ray photographs and will lead to "hot spots" in die temperatures.

wire (various sizes and material) is well known; thus, the maximum current rating may be limited by the number, size, and material used for emitter wires.

Most modern high frequency transistors are die limited because of high current densities resulting from very small current-carrying conductors, and these densities can lead to metal migration and premature failure. The determination of I_c max for these types of transistors results from use of Black's equation for metal migration,[3] which determines a mean time between failures (MTBF) based on current density, temperature, and type of metal. At Motorola, MTBF is generally set at >7 years, while maximum die temperature is set at 200°C. For plastic-packaged transistors, maximum T_j is set at 150°C. The resulting current density, along with a knowledge of the die geometry and top metal thickness and material, allows the determination of I_c max for the device.

It is up to the transistor manufacturer to specify an I_c max based on which of the two limitations (die or wire) is paramount. It is recommended that the circuit design engineer consult the semiconductor manufacturer for additional information if I_c max is of any concern in the specific use of the transistor.

Storage temperature is another maximum rating that is frequently not given the attention it deserves. A range of −55°C to 200°C has become more or less an industry standard. And for the single metal, hermetic-packaged type of device, the upper limit of 200°C creates no reliability problems. However, a lower high temperature limitation exists for plastic encapsulated or epoxy-sealed devices. These should not be subjected to temperatures above 150°C to prevent deterioration of the plastic material.