Chapter 8. Qualification Methodologies

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I. Introduction

This chapter outlines a recommended procedure for the design, manufacture, and acceptance of space qualified MMICs. First and foremost, the reader must understand that although the methodologies recommended in this chapter may appear rigid and specific, they should not be viewed as such. In fact, it is the authors' intention that the qualification methodology not only permit but rather require the manufacturer and customer to determine many of the details. Instead of presenting specifications for reliability, this chapter presents the questions a MMIC user should ask of the manufacturer to assure a reasonable level of reliability, and at the same time it tries to present to the MMIC manufacturer the methodologies that have been accepted and practiced by some members of the industry in the hope that a standard qualification procedure may develop. This chapter, like the previous chapters, is also an educational guide. Furthermore, it should be used with the other chapters: The details of this qualification methodology depend on the type of circuit being fabricated and the devices incorporated into the circuit, along with the reliability concerns and failure mechanisms (Chapters 3 and 4), the testability of the circuit (Chapter 7), and the effect the package has on the MMIC reliability (Chapter 9).

The rationale for not publishing a strict qualification standard is derived from the fact that the GaAs industry is rapidly evolving, and, therefore, it would not be prudent to set limits on that evolution. In addition, it is not possible to guess the needs of every system being planned or the reliability requirements of every system. For example, MMIC users may request a relaxation of the recommended qualification methodology to lower the part cost, if the mission has a short expected lifetime or if the total satellite cost is small. Alternatively, very expensive satellites with a long projected lifetime will normally be qualified to a higher standard than even that recommended in this guide. The important point is that whenever reliability qualification is relaxed, either through the deletion of some tests, or screens, or a reduction in the number of parts tested, up-front MMIC costs are lowered at the price of increased risk of system failure.

A four-step procedure followed by most satellite manufacturers includes some practices recommended by the Qualified Manufacturers Listing (QML) programs [1] with screening procedures from more traditional qualification methodologies ; that procedure is recommended in this guide. The steps are (1) Company Certification, (2) Process Qualification, (3) Product Qualification, and (4) Product Acceptance, as summarized in Figure 8-1. Company Certification outlines the procedures and management controls the manufacturer should have in place to assure the quality of its MMICs. Process Qualification outlines a procedure the manufacturer should follow to assure the quality, uniformity, and reproducibility of MMICs from a specific fabrication process. Product Qualification encompasses a set of simulations and measurements to establish the electrical, thermal, and reliability characteristics of a particular circuit design. Lastly, Product Acceptance is a series of tests or screens performed on the deliverable that is normally practiced by GaAs MMIC manufacturers and their customers to satisfy high-reliability program requirements and provide specific reliability and qualification information pertinent to that particular product.

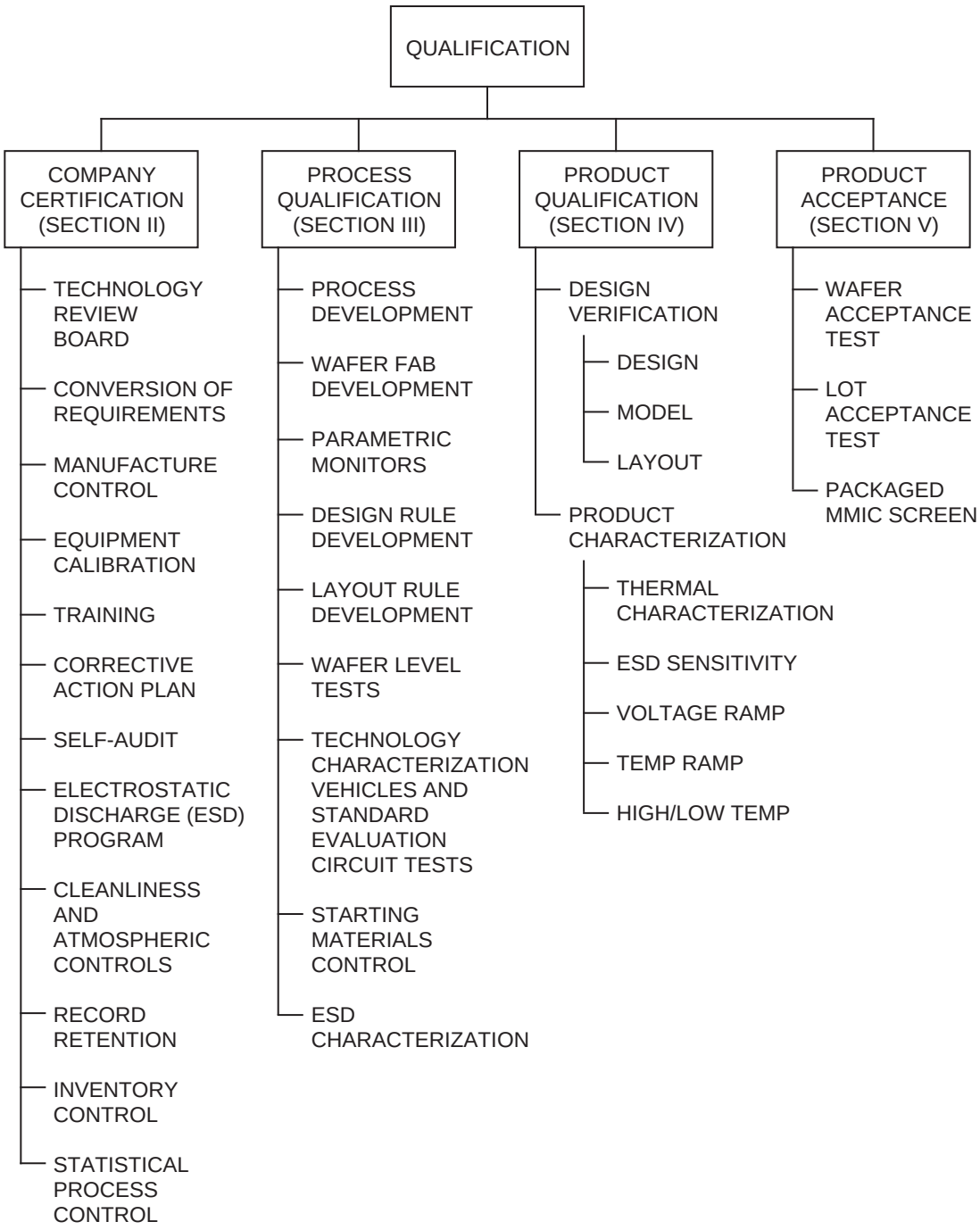

Figure 8-1. Recommended qualification methodology.

Before these four steps are presented in detail, a few important aspects of MMIC qualification must be discussed. First, although the manufacturer is ultimately responsible for delivering a reliable MMIC, the reliability of the total system rests with the MMIC user. Therefore, it is within both parties interests to understand the expected electrical performance requirements and operating environment of not just the MMIC, but the system itself. While this helps the manufacturer select the best technology for the MMIC and deliver a more reliable part, it requires the MMIC user to share information with the manufacturer. Furthermore, although the organization of the qualification

methodology is representative of what MMIC manufacturers and users currently use, the content of the qualification process is the essential ingredient. The MMIC user should not discount a manufacturer's proposal because the manufacturer does not organize its procedures in the same way or use the same terms and phrases offered in this chapter.

II. Company Certification

Procurement of MMICs is often the result of a long-term partnership between the customer and the manufacturer in which both parties add knowledge and experience to the process to assure reliability of the final circuits and satisfaction of the required performance specifications. This close, working relationship evolves after mutual trust is established. If the parties have never worked together, the MMIC user can still gain the necessary confidence in the manufacturer if the manufacturer can show that it has documentation, procedures, and management practices that control the facilities, equipment, design processes, fabrication processes, and personnel. These items are typically part of an overall Quality Management Program and outlined in a Quality Management Plan. This step of the qualification process is often referred to as "company certification" and is usually verified by the MMIC user through either a written or facility audit. It is recommended that the audit and company certification be completed before a contract for the purchase or development of an MMIC is established. The MMIC user may even consider this the first and most important criterion in selecting a company from which to buy parts. A company that cannot demonstrate a formal structure to address the issues of quality and reliability should not be used as a supplier of MMICs for high-reliability or space applications.

Since most of the information sought during company certification is based on established QML programs [1] and standard industry methodologies, the audit should be easy and inexpensive for both the user and manufacturer. In fact, most of the data sought in the audit should be compiled and available for distribution by the manufacturer. Furthermore, if the manufacturer has passed previous audits, either for other MMIC procurements or ISO 9000 certification, this step in the qualification process may be reduced to a simple updating of past audits, or eliminated entirely.

A simplified version of the audit is shown in Figure 8-2. The audit for a specific MMIC must be developed on a case-by-case basis. The major items in the Quality Management Program are presented in the rest of this section, but it must be remembered that this is only a partial list. As stated before, company certification is the first opportunity a MMIC user has to determine the credibility of a manufacturer's reliability program. This credibility should be established before a contract has been signed. Beyond the following list, the inclusion of additional items in the company certification procedure that are specific to the user's needs would be expected.

A. Technology Review Board

To assure the quality and reliability of MMICs, manufacturers will typically have a permanent committee or board in place with knowledge of the entire MMIC fabrication process and the authority to change the process if the quality of the parts is not maintained. This board is commonly called the Technology Review Board (TRB) from the QML program [1]. The TRB is responsible for

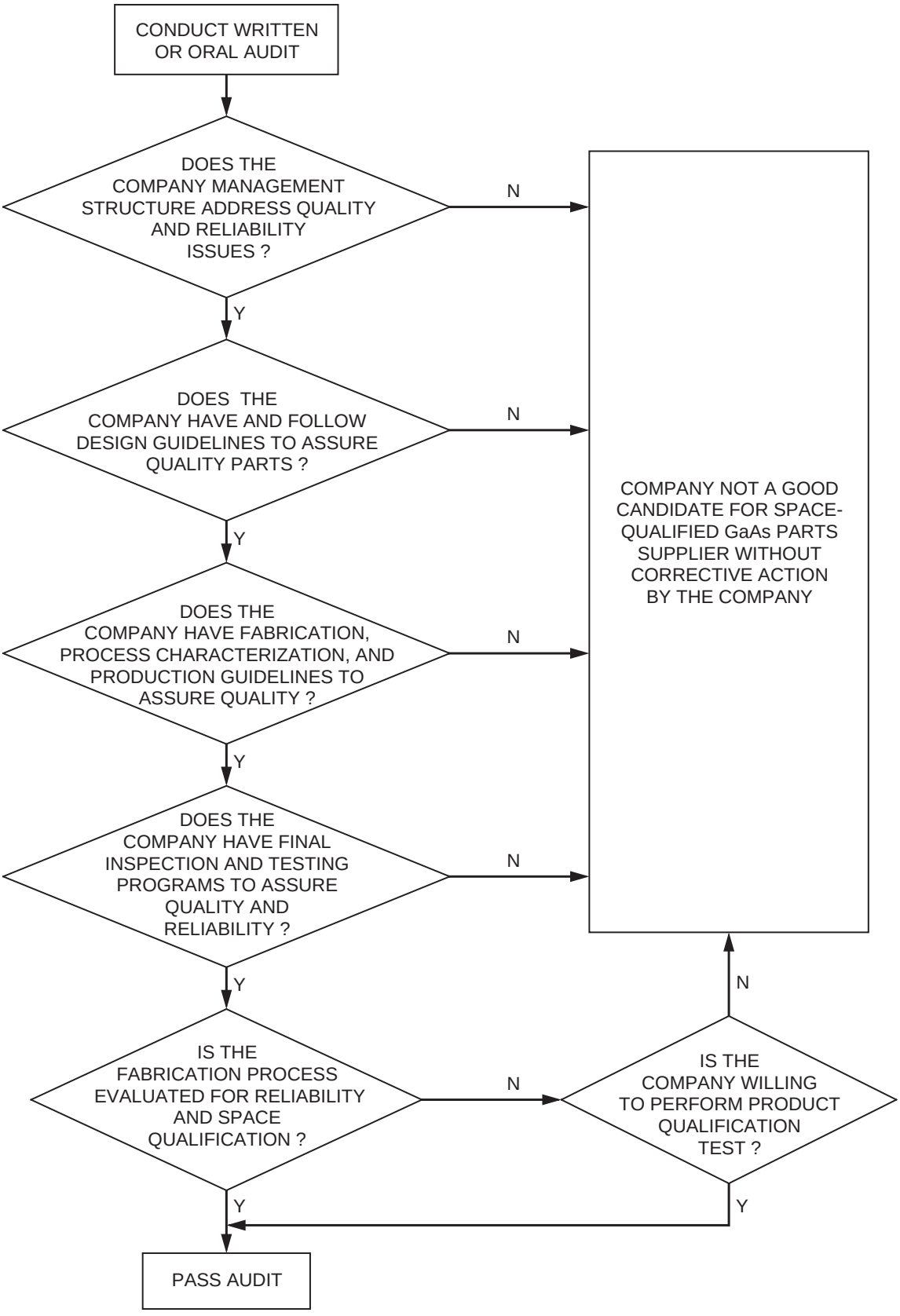

Figure 8-2. Reliability audit.

(1) The development, implementation, and documentation of the manufacturer's Quality Management Program and Quality Management Plan.

(2) The development, implementation, and documentation of the manufacturer's Process Qualification, Product Qualification, and Product Acceptance plans.

(3) Compiling and maintaining all records of the fabrication process, statistical process control (SPC) procedures, SPC data, certification and qualification processes, reliability data analysis, and corrective actions taken to remedy reliability problems.

(4) Examining standard evaluation circuits (SECs) and MMIC reliability data and establishing and implementing corrective actions when the reliability of the circuits decreases.

(5) Notifying customers when the reliability of a wafer lot is questioned and supplying the customers an evaluation of the problem and any corrective actions required.

(6) Supplying reliability data to customers.

Because of these great responsibilities that cover a broad area of knowledge, the members of the TRB should have good hands-on knowledge of device design, technology development, wafer fabrication, assembly, testing, and quality-assurance procedures. The members of the TRB are normally from the manufacturing company, but a customer requesting custom products may request a seat on the board for those products only.

B. Conversion of Customer Requirements

Not all customers express their specifications in the same way, and not all manufacturers publish MMIC performance specifications and operating guidelines in the same way. For example, a user will not normally specify the type of transistor, substrate thickness, or transmission lines they want in the fabrication of a circuit. Instead, they simply ask for an amplifier with 15 dB of gain and a maximum output power of 1 W at 10 GHz. For the MMIC manufacturer, these performance specifications are the starting point in determining the type of transistor, substrate, and transmission lines, among other things, required. Only after conversion from the customer's specifications to the manufacturer's specifications can the manufacturer bid on the contract and the user know what reliability questions to ask. It is recommended that the procedure by which customer requirements—as expressed, for example, in specifications and purchase orders—are converted into working instructions for the manufacturer's personnel be documented. A typical document will describe the procedures a company performs, the order in which they are performed, and the typical schedule. Some of the items commonly found in such a conversion are

(1) Relating customer circuit requirements to manufacturer circuit requirements.

(2) Converting circuit requirements to a circuit design, using controlled design procedures and tools (i.e., established geometric, electrical, and reliability design rules).

(3) Establishing a design review team.

(4) Selection of SECs and Parametric Monitors (PMs).
(5) Mask generation procedure within the controlled design procedure.
(6) Wafer-fabrication-capabilities baseline.
(7) Circuit-fabrication procedures in accordance with approved design, mask, fabrication, assembly, and test flows.
(8) Incoming inspection and supplier procurement document covering design, mask, fabrication, and assembly.
(9) Establishment of screening and traveler documents.
(10) Technology Conformance Inspection (TCI) procedures.
(11) Marking requirements.
(12) Rework procedures.

C. Manufacturing Control Procedures

MMIC manufacture is a very complicated process involving many materials and steps, all of which are critical to MMIC performance and reliability. Only a properly controlled manufacturing line can be expected to routinely produce quality MMICs. Thus, the customer should be assured that the manufacturer is using only certified processes and qualified technologies at every step in the manufacture of the MMIC—from the ordering of materials to the shipping of the MMIC. To obtain that level of assurance, the company certification audit should review the manufacturer's procedures for

(1) Traceability of all materials and products to the wafer lot.
(2) Incoming inspection to assure conformance to the material specification.
(3) Electrostatic discharge (ESD) control in handling the material in all stages of manufacturing.
(4) Conformance with design requirements at
    (a) Device procurement specification.
    (b) Simulation-model verification.
    (c) Layout verification.
    (d) Testability and fault coverage verification.
    (e) Electrical parameter performance extraction.
    (f) Archived data.
(5) Conformance of fabrication requirements at
    (a) Mask fabrication.
    (b) Mask inspection.
    (c) Wafer fabrication.
(6) Assembly and package requirements.
(7) Electrical testing.

Most of this information can be obtained if the MMIC user asks for documentation of the manufacturer's production flow.

D. Equipment Calibration and Maintenance

It would be difficult to maintain the quality of MMICs produced on equipment that is not properly maintained and calibrated. Therefore, all equipment used in the design, fabrication, and testing of the MMIC should be maintained according to the equipment manufacturer's specifications. In addition, the equipment should be calibrated on a regular basis. Documentation showing the maintenance and calibration schedule, deviations from the calibration and maintenance schedules, and any corrective action taken will normally be kept by the manufacturers. This documentation will also highlight any major discrepancies found in the calibration and maintenance of a piece of equipment since it may affect the reliability of the MMICs. The TRB will review this document to determine if any corrective action is required. Further information on equipment calibration and maintenance documentation can be found in [2].

E. Training Programs

Even well maintained and calibrated equipment cannot produce quality MMICs without skilled operators. To assure the skills of the personnel employed in the design, fabrication, and testing of the MMICs, each engineer, scientist, and technician should have formal training relative to their tasks. Furthermore, retesting and retraining should be provided regularly to maintain the worker's proficiency, especially if new equipment or procedures are introduced into the manufacturing process. It is therefore recommended that the work training and testing practices employed to establish, evaluate, and maintain the skills of personnel engaged in reliability-critical work be documented as to form, content, and frequency.

F. Corrective Action Program

One of the best ways to continuously improve the reliability of manufactured parts is to test and analyze failed parts—including returns—from all stages of manufacturing, and, based on the findings, make corrective actions to the manufacturing process or the education of the MMIC users. The plan that describes these corrective actions is normally documented. The corrective action plan should describe the specific steps followed by the manufacturer to correct any process that is out of control or found to be defective and the mechanism and time frame that a manufacturer will follow to notify customers of potential reliability problems.

G. Self-Audit Program

To promote continual quality improvement, manufacturers regularly review their manufacturing procedures through an internal, independent self-audit program under the direction of the TRB. The self-audit program should identify the critical review areas, their frequency of audit, and the corrective action system to be employed when deviations from requirements are found. Typical areas included in a self-audit are

(1) Calibration and preventive maintenance
(2) Fabrication procedures
(3) Training programs
(4) Electrical tests

(5) Failure analysis programs
(6) Test methods
(7) Environmental control
(8) Incoming inspection
(9) Inventory control and traceability
(10) Statistical Process Control (SPC)
(11) Record retention

The self-audit checklist, the date of the previous audits, and all findings from the audits are maintained typically by the TRB, which will use these findings to recommend corrective actions and prepare a self-audit follow-up.

H. Electrostatic Discharge Handling Program

Because of the catastrophic failure that normally follows ESD, all personnel that work with GaAs MMICs should be trained in the proper procedures for handling the devices. Furthermore, these procedures should be documented and available for reference. Typically, the procedures include the methods, equipment, and materials used in the handling, packaging, and testing of the MMICs. Further guidance for device handling is available in the Electronics Industry Association (EIA) JEDEC Publication EIA 625 [3] and MIL-STD-1686 [4].

I. Cleanliness and Atmospheric Controls

The quality of GaAs MMICs and the yield of the fabrication line is directly linked to the manufacturer's control over the cleanliness of the environment in which the parts are fabricated. Therefore, manufacturers often spend a large amount of their resources to assure that the MMICs are fabricated in ultraclean rooms where the atmosphere is tightly controlled. Since the yield of the fabrication process is so strongly dependent on the success of maintaining those conditions, regular measurements are taken to assure the temperature, humidity, and cleanliness of the fabrication areas. In addition, during transit and storage prior to seal, the die/wafer should be protected from human contact, machine overspray, or other sources of contamination. All of these procedures and measurements are recorded and compiled into a single document by the clean-room manager or alternate for future reference.

J. Record Retention

Documentation is the only method to gauge the reliability of MMICs fabricated today vs those produced last week or last year and to correlate changes in the reliability to variations in the processing steps. Although many sections in this guide recommend the documentation of certain data or procedures, it is helpful if a list of documents and the period of retention for each document is made. Furthermore, the list should contain a record of when each document was last changed, who is responsible for maintaining the document, and where the document is stored. The typical documents to be retained are relevant to

(1) Inspection operations (i.e. production processes, screening, qualification).

(2) Failure and defect reports and analyses.

(3) Initial documentation and subsequent changes in design, materials, or processing.

(4) Equipment calibration.

(5) Process, utility, and material controls.

(6) Product lot identification.

(7) Product traceability.

(8) Self-audit report.

(9) Personnel training and testing.

(10) TRB meeting minutes.

K. Inventory Control

The proper inventory of all incoming materials and outgoing parts is not only required for the management of a profitable company but also for the manufacture of reliable MMICs. Many materials and chemicals used in the fabrication of MMICs have shelf lives that must be adhered to if process yield and reliability are to be maintained. The tracking of in-process and completed MMICs is essential for the establishment of MMIC history, which is critical if failure analysis is ever necessary. Therefore, the methods and procedures used to control the inventory of all materials related to the MMIC manufacturing process should be documented. Typically documented inventory control procedures include

(1) Incoming inspection requirements and reports.

(2) Identification and segregation of non-conforming materials.

(3) Identification and control of limited-life materials.

(4) Control of raw materials.

(5) Data retention for required receiving reports, test reports, certification, etc.

(6) Supplier certification plan.

L. Statistical Process Control

The establishment of a statistical baseline for judging the continuous improvement of a manufacturer's processes is important. To establish that baseline, the manufacturer should develop an SPC program using in-process monitoring techniques to control the key processing steps that affect device yield and reliability. As part of the SPC process, every wafer lot typically has built-in control monitors from which data are gathered. The resulting data should be analyzed by appropriate SPC methods to determine the effectiveness of the company's continuous improvement plans. Additional information on SPC analysis can be found in the Electronics Industry Association JEDEC EIA 557A [5] and in MIL-I-38535 [1].

III. Process Qualification

A manufacturer who has standardized production around a single technology will often qualify the entire production line. In doing so, the manufacturer attempts to demonstrate that the entire process of designing and fabricating an MMIC using the stated technology is under its control. In addition, the manufacturer establishes an electrical performance and reliability baseline for all components fabricated using the process. This has advantages for both the manufacturer and the user of the MMIC. For the manufacturer, it saves costs and time on the fabrication of future MMICs, since the reliability and functional performance of the components constituting the MMIC have already been established. For the MMIC user, there is a certain level of comfort in buying parts from a production line with a history of supplying reliable MMICs, in addition to the reduced qualification time and therefore delivery time that should be possible.

The term usually applied to this procedure is "process qualification." Process qualification is a set of procedures a manufacturer follows to demonstrate that they have control of the entire process of designing and fabricating an MMIC using a specific process (e.g., MESFET, HBT, HEMT). It addresses all aspects of the process including the acceptance of starting materials, documentation of procedures, implementation of handling procedures, and the establishment of lifetime and failure data for devices fabricated using the process. Since the goal of process qualification is to provide assurance that a particular process is under control and known to produce reliable parts, it needs to be performed only once, although routine monitoring of the production line is standard. It is critical to remember that only the process and basic circuit components are being qualified. No reliability information is obtained for a particular MMIC design.

Although process qualification is intended to qualify a defined fabrication procedure and device family, it must be recognized that GaAs technology is constantly evolving, and this technology evolution requires the continual change of fabrication procedures. Furthermore, minor changes in the fabrication process to account for environmental variations, incoming material variations, continuous process improvement, or minor design modifications may be required. All of these changes in the process are permitted and frequently occur under the direction of the TRB. Thus, strict application of the commonly used phrase, "freezing the production process," does not apply.

The internal documents and procedures used by most manufacturers for process qualification are summarized in Figure 8-3. In addition, the QML program [1] provides guidelines for process qualification. The first step in the procedure is for the manufacturer to determine the family of devices to be fabricated and the technology that will be used in the fabrication—for example, a 0.5 μm, ion-implanted MESFET technology with Si_3N_4 MIM capacitors and NiCr resistors. Second, the manufacturer will establish a TRB to control the process qualification procedure. After all of the processing steps have been defined and documented, the workmanship, management procedures, material tracking procedures, and design procedures should be documented. The information contained in the documentation describes the process domain that is being qualified.

The qualification process also involves a series of tests designed to characterize the technology being qualified. This includes the electrical as well as the reliability characteristics of components fabricated on the line. Some of these tests are performed at wafer level and include the characterization of PMs, Technology Characterization Vehicles (TCVs), and SECs, which were all discussed in Chapter 7. Other tests require

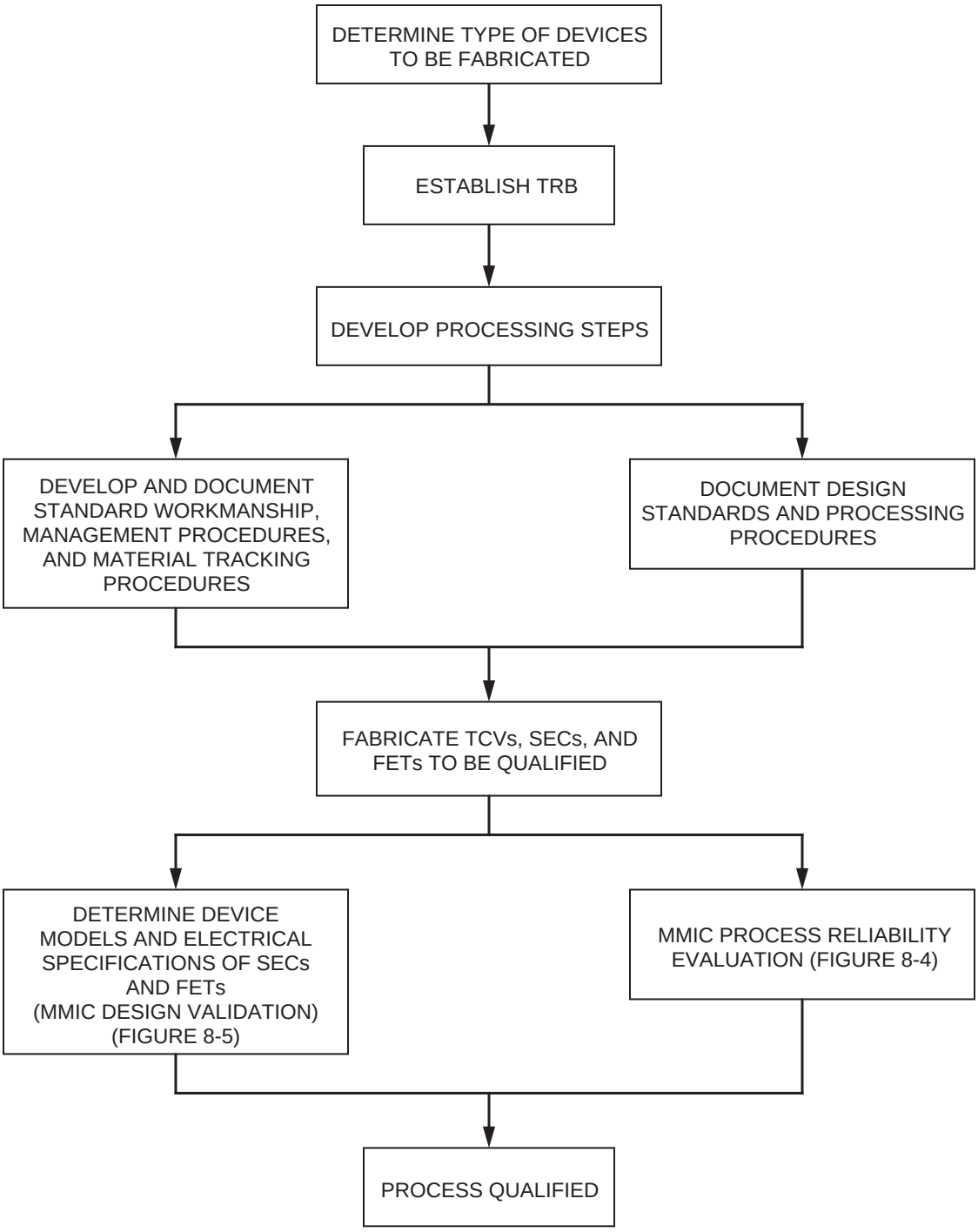

Figure 8-3. MMIC die process qualification.

the mounting of circuits or elements onto carriers. All of these tests and the applicable procedures are an integral part of the qualification program and provide valuable reliability and performance data at various stages of the manufacturing process. Figure 8-4 outlines a recommended series of tests for MMIC process reliability evaluation. The number of circuits or devices subjected to each test will normally be determined by the TRB and the rationale for their decision will become part of the process qualification documentation. In general, a higher level of confidence in the

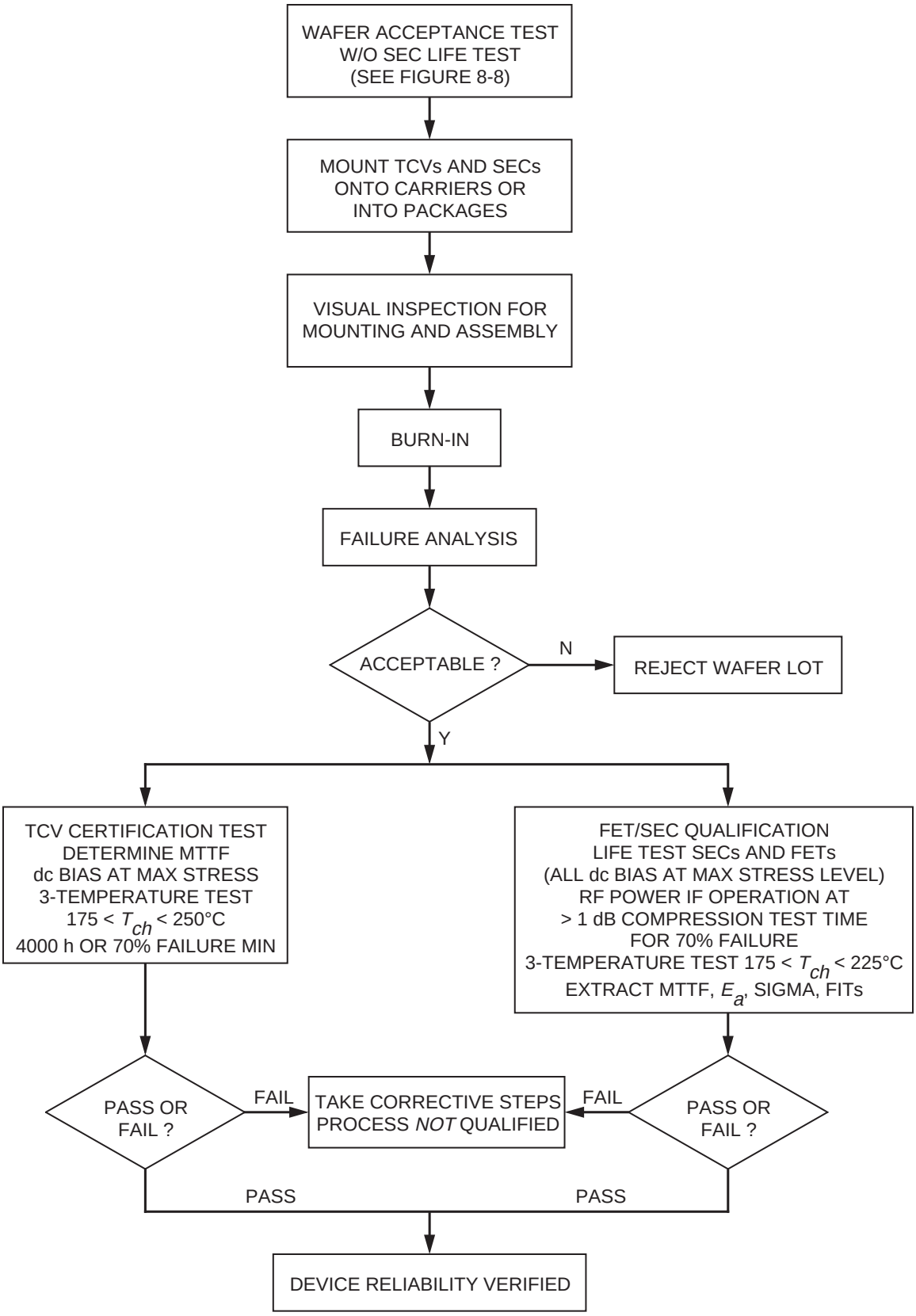

Figure 8-4. MMIC process reliability evaluation.

reliability data exists if more circuits are tested, but this is offset by the fact that after a certain level of testing, the incremental gain in confidence is minor compared to the cost of testing. Since the stability of the process is being determined as part of the process qualification, the manufacturer will typically fabricate and test components from several wafer lots. Figure 8-5 provides a series of tests that is recommended to characterize the electrical and thermal limitations of the devices or circuits. The performance limitations obtained from these tests often become the basis for limits incorporated into the design and layout rules.

Note that the process-qualification procedure is QML-like and therefore addresses topics similar to those of the company certification discussed in Section 8-1. The major difference is that company certification is performed by the customer, whereas process qualification is self-imposed by the manufacturer, often before customers are identified. Other items particular to process qualification are discussed below.

A. Process Step Development

Although all of the items described in Section 8-II are important to the process-qualification procedure, the actual process of turning a bare GaAs wafer into a MMIC by technicians in a clean room is often the only task associated with process qualification. Indeed, it may be the most critical step in the process and probably requires the most time and resources to develop. In addition, it is truly the fabrication procedures and the components fabricated on the line that distinguish one production line from another. Therefore, it follows that the first step in the process-qualification procedure is the development and documentation of the processing steps required to build a MMIC. Although all of the steps in the fabrication process, including wafer surface preparation, photolithography, active layer formation, passivation, and the metallization system and formation (Section 3-VIII), should be included in the documentation, the details are typically considered proprietary by the manufacturer. Therefore, the MMIC customer may expect to see a general list of processing steps or the process flow, but not the level of detail actually required to fabricate the parts.

B. Wafer Fabrication Documentation

Once a process is qualified, reliability concerns may still arise from minor variations in the process flow, environment, or starting materials. Therefore, all wafer fabrication steps and conditions will normally be recorded by the manufacturer in order to maintain repeatability of the product. Documentation of these steps and fabrication conditions should be maintained to trace any future quality or reliability concerns to a specific step. Although process travelers can be used to document the fabrication and manufacturing steps, they usually lack the detail necessary to trace quality or reliability problems to specific fabrication steps. The wafer fabrication steps themselves and the documentation describing them are usually considered proprietary by the manufacturer.

C. Parametric Monitors

Parametric monitors are essential for monitoring a production line's quality or continuous improvement. Parametric monitors were fully described in Chapter 7: they are mentioned in this section only to emphasize the fact that choice of the PMs is dependent on the process and technology being monitored. Therefore, this choice is a critical element in the process-qualification procedure. The complete list of PMs is

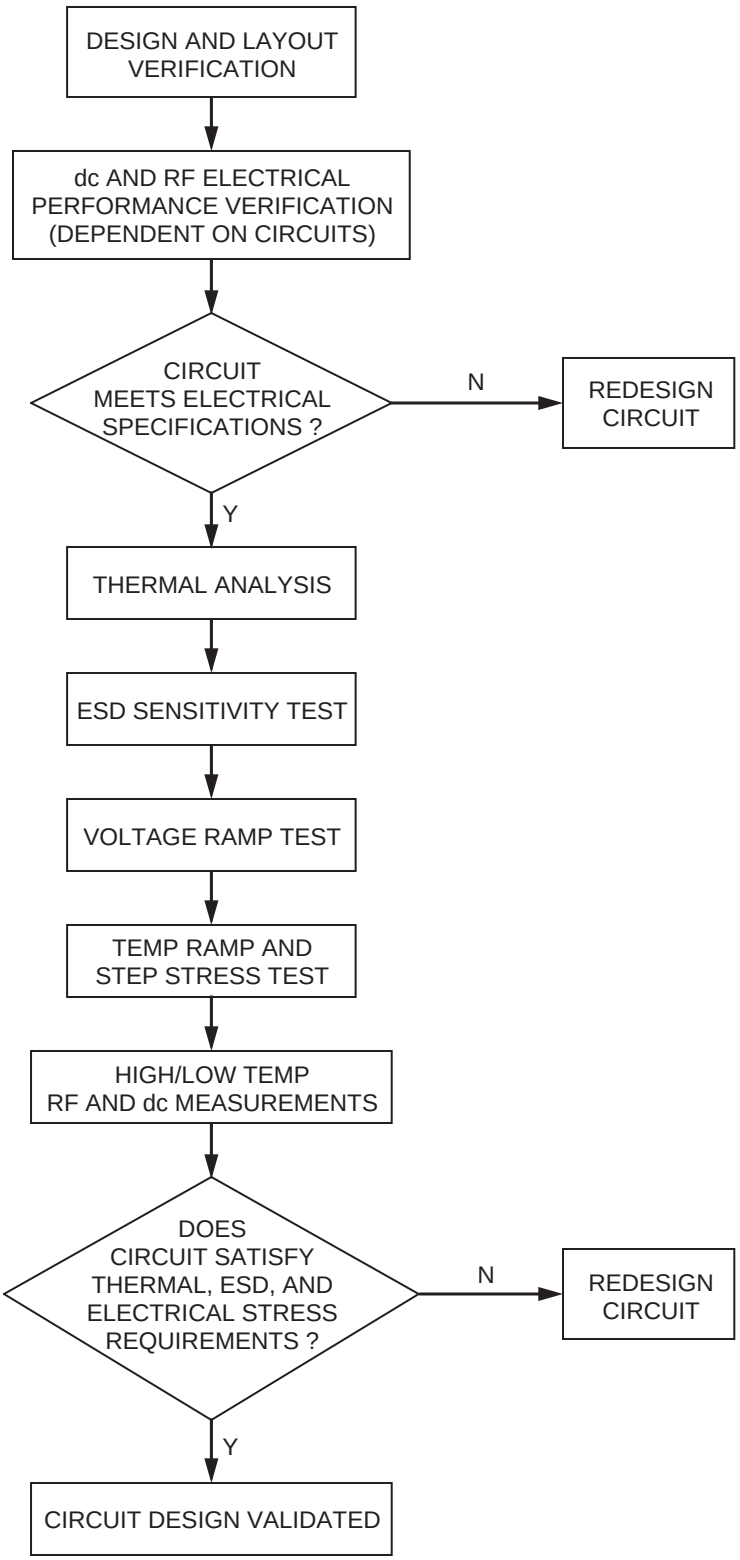

Figure 8-5. MMIC design validation.

usually combined into a single reticle that is included on all wafers. The data obtained from the PMs will normally be stored in a data base that permits the quick comparison of

each wafer fabricated on the line to all of the other wafers. This permits determination of process stability.

D. Design-Rule and Model Development

The reliability of MMICs fabricated using a qualified process will greatly depend on whether they are designed with qualified components and according to prescribed rules. In addition, the standardization of the component types also brings a certain degree of cost reduction. Therefore, part of the process-qualification procedure is to determine and document design rules that are specific to the process. Typical information included is the minimum resistor size, the maximum capacitance, the minimum air-bridge width, the maximum air-bridge length, the minimum separation between via holes, and the active device geometry. In addition to these characteristics, a list of rules relating to such issues of circuit design as the maximum power handling capability, maximum linear gain, and minimum noise figure of the devices should also be included. Finally, manufacturers will often develop standard cells or small circuits that perform specific functions, such as couplers, gain blocks, bias networks.

To fully use the standard components in circuit designs, models must be developed; although models contained in commercial software packages may be adequate, they often need to be adapted to fit the measured characteristics. Commercial software packages are available to extract the RF and dc characteristics from measurements and fit the model to the data. Once each of these components and cells is described and characterized, circuit designers can use them to increase the chance of first-time design success.

E. Layout-Rule Development

Layout rules should be followed in any circuit design to assure manufacturability and reliability. The layout rules may be specific to a particular process, and therefore, must be developed for the process being qualified.

F. Wafer-Level Tests

The GaAs industry strives to reduce production costs by shifting as much testing as possible to the earliest possible point in the production cycle—this to weed out bad wafer lots before more value has been added to them. The best strategy performs wafer-level tests that include dc and RF characterization, PM characterization data, and temperature performance. Limitations may exist in the level of test detail depending on the device design and the manufacturer's test capabilities discussed in Chapter 7. In general, wafer-level tests are performed, but they should be supplemented with other verifications, such as test fixture or in-package tests. Once agreement between the wafer level and the package-level tests has been established, the manufacturer may rely on the wafer-level tests for production monitoring.

G. TCV and SEC Tests

One of the most important steps in the process-qualification procedures is to determine the thermal, electrical, and reliability characteristics of devices fabricated within the domains of the process. This data is obtained through the characterization of

TCVs and SECs, as shown in Figures 8-4 and 8-5. Both of these test structures and the testing procedures for them were presented in Chapter 7. All data obtained from these tests should be gathered and stored by the TRB. In most cases, the success of a manufacturer in qualifying the process will depend on the data from these tests.

H. Starting Materials Control

The manufacturer should have in place a mechanism to assure the quality and characteristics of every starting material from the GaAs wafers and chemicals used in the processing steps to the shipping containers used for die/wafer transportation and storage, since they all have a direct impact on the quality and reliability of the final product. Analyses of the chemicals and gases used in processing GaAs is normally performed by the device manufacturer or the supplier of the chemicals. Traceability and documentation of the characterization results to the individual wafer process lot are essential in resolving any process variation questions or concerns. The facility audit program can be the vehicle used to determine the manufacturer's level of control.

Most GaAs device manufacturers procure the GaAs wafers from outside suppliers. Procurement requirements imposed by the device manufacturer identify the dislocation density, type of starting material, resistivity, and other characteristics that are very important to the device user. This information can help determine the suitability of the starting material to the process and the material's capabilities. The traceability and documentation of the procurement requirements and wafer characterization can be used to resolve any process variation concerns. Wafer preparation steps, such as initial surface cleaning, can also alter device characteristics and are an important aspect of process control.

Integral to the complete process flow is the mask preparation and the method of identification of any changes to the applicable mask set. The repeatability and quality of the masks should be assessed and documented prior to initiation of the fabrication process.

I. Electrostatic Discharge Characterization and Sensitivity

If not handled properly, several elements used in MMICs can be damaged by ESD. Damage may occur at tune-and-test, assembly, inspection, and other places, if proper precautions are not taken. Therefore, every process and design should be characterized to determine ESD sensitivity. Regardless of the test results, all GaAs-based devices should be treated as highly sensitive to ESD damage. An ESD handling and training program is essential to maintain a low level of ESD attributed failures.

Inspection, test, and packaging of MMICs should be carried out in static-free environments to assure that delivered products are free of damage. Devices should be packaged in conductive carriers and delivered in static-free bags. All handling and inspection should be performed in areas meeting "Class 1" handling requirements. Both the manufacturer and the user share the responsibility of assuring that an adequate procedure is in place for protection against ESD.

In general, the following steps can help reduce or eliminate the ESD problems in device manufacturing and test areas:

(1) Ensure that all workstations are static free.

(2) Handle devices only at static-free workstations.

(3) Implement ESD training for all operators.

(4) Control relative humidity to within 40 to 60%.

(5) Transport all devices in static-free containers.

(6) Ground yourself before handling devices.

IV. Product Qualification

A consumer expects the manufacturer to verify that his products are properly designed. A person buying a radio, for example, would expect it to receive RF energy in the AM and FM frequency bands and to convert that energy into a clear, audio wave. The consumer may also expect the manufacturer to specify the operating environment for which the product was designed. Again considering the radio, the consumer will want to know if it will work properly after storage in a shed in upper Michigan during the winter or on a boat during a summer sail of the Caribbean. The manufacturer can give these assurances and information only if he has tested the product after fabrication.

For MMICs, the process of obtaining this data is called product qualification or design validation, and, as implied above, every MMIC design should pass product qualification before it is sold. Because the data desired in product qualification is specific to a particular MMIC design, this applies as well to circuits fabricated on process-qualified fabrication lines. Figure 8-5 shows a product qualification procedure that addresses the issues critical to MMICs. The first step of design verification occurs before mask generation and includes design, simulation, and layout verification of the circuits. The rest of design verification includes full electrical characterization of the circuit to establish its operating performance, thermal analysis, and electrostatic discharge characterization, and verifies the results of the voltage ramp test, temperature ramp test, and temperature cycling tests. Although the sequence of the tests may be altered, it is recommended that design and layout verification be performed first, and this should be followed by electrical performance verification, since any out-of-specification parameters found during these tests will require a redesign of the circuit. This is a recommended approach, and all of the tests may not be required for some circuit designs. All participants in the MMIC design, manufacture, and end-product integration should be involved in deciding which tests are required.

The rationale for and a description of the steps recommended in the design validation follow.

A. MMIC Design, Model, and Layout Verification

One of the best ways of reducing MMIC engineering cost and improving reliability is to verify the design, model or simulation , and layout of the MMIC before fabrication begins. This critical step was addressed separately in Chapter 6. During the MMIC design cycle, these verifications are normally addressed through a series of design reviews that include representatives from all companies involved in the manufacturer and use of the MMIC. Furthermore, the representatives should come from all departments involved in the MMIC integration, including the MMIC designers, the fabrication staff, the RF metrology personnel, the packaging engineers, and the system designers.

Typically, the reviews are held before the circuits are sent to layout, after layout but before mask making, and after final MMIC characterization.

B. Thermal Analysis and Characterization

Thermal analysis determines the hottest part of the device during normal bias conditions and the temperature difference between the hottest point on the surface of the die and the case temperature; this is critical in determining the expected life of the MMIC. The analysis should be performed over the entire temperature range of the MMIC's intended application. Typically, this theoretical analysis is difficult and requires detailed knowledge of the power dissipation, geometry of the gold plating layers around the channel, method of attaching the die to the substrate, and the thermal boundary conditions of the substrate. A preferred method is actual thermal measurements using either liquid crystal or infrared scanning techniques.

C. Electrostatic Discharge Sensitivity Tests

GaAs devices are very sensitive to ESD damage, and therefore the ESD characterization given in [6] should be conducted to determine the sensitivity of the design. GaAs FET structures can be damaged by ESD voltages in the 20- to 2000-V range [4]. Thus, classification and treatment of the devices from the fabrication stage to the actual application as a Class 1 ESD-sensitive device is highly recommended. The device's normal electrical parameters should be used as a reference for degradation of performance due to testing.

Tests have shown that noncatastrophic damage can occur in the 50- to 75-V range for some devices. This damage is characterized by a slight increase in gate leakage current. As an example, typical leakage currents of 8 μA have been observed to increase to 30 to 40 μA after being subjected to 60- to 75-V ESD per MIL-STD-883 [6] test methods. The MMIC used in the test still operated properly and met all RF specifications, but catastrophic damage has been observed in the 50- to 200-V range.

Thin-film capacitors and resistors can be damaged by static charges of less than 2000 V and are therefore also "Class 1" devices. The voltages needed to damage these components are, however, much higher than those needed to damage FETs. Several hundred volts would damage these circuit elements; FETs are more susceptible to damage than capacitors and resistors.

Input and output blocking capacitors will not protect internal FETs from damage in most cases since ESD is usually present in the form of voltage transients and as such will be coupled through most capacitors. Therefore, it is recommended that all operators be careful when connecting these devices to RF test setups. Grounding the test technician prior to connecting the bias or RF leads is good practice.

It is not known what impact noncatastrophic damage will have on device lifetime. Tests on intentionally damaged devices have shown that they continue to operate for over 500 h at 85°C without further degradation. It is anticipated, however, that lifetime will be shortened when compared to undamaged devices.

D. Voltage Ramp

The sensitivity of an MMIC design to voltage overstress and the absolute maximum voltage ratings are determined during the voltage ramp test. Testing is normally done by ramping each device's power supply until a catastrophic failure occurs. Ramp rates and step duration are a function of the design limitations, but the test should allow thermal stabilization of the device at each successive step. After the test, an analysis to determine the exact failure site is recommended. Failure-point definition should be in conservative agreement with the device data sheet and design limits.

E. Temperature Ramp and Step Stress

Temperature ramping can serve more than one purpose. It can indicate which portion of the design is most sensitive to high-temperature operation, indicate the absolute maximum ratings applicable, give an indication of high-temperature operation characteristics, and it can determine the appropriate temperatures applicable for life tests. The test is normally done by ramping the temperature of the devices until catastrophic failure. Ramp rates and step duration should be designed to allow thermal stabilization of the devices at each successive step. Afterwards, failure analysis to determine the exact failure site is recommended. Failure point definition should be in conservative agreement with the device data sheet and design limits.

F. High/Low Temperature Tests

Data sheets will always specify the highest and lowest temperature at which an MMIC will operate, and it will give the percentage change in electrical parameters at the temperature extremes. The high/low temperature test is designed to obtain that data. The test temperature at both extremes may be obtained from step stress tests or from system requirements. Once the data have been measured for a specific MMIC design, the temperature limits and percent change in electrical parameters can be used in product acceptance screens.

V. Product Acceptance

Although an MMIC may be designed by highly qualified engineers, fabricated on a process qualified production line, and verified through measurements to meet the design goals, parts with poor reliability characteristics still exist. This may be due to variations in the fabrication process, or material flaws that were undetected, or, as is more often the case, to the MMIC package and stresses imposed on the MMIC during packaging. Regardless of the cause, these weak MMICs must be found and removed before they are integrated into the system. Therefore, manufacturers of all high reliability systems, including space systems, require the MMICs to pass a series of product acceptance screens, whose sole purpose is to increase the confidence in the reliability of the MMICs. Note that this step in the qualification methodology is the major difference between space qualified MMICs and commercial grade MMICs.

The level of testing performed under product acceptance is a function of the form of the deliverable. For example, the first level of acceptance testing, called "wafer acceptance test," is performed at the wafer level to assure the uniformity and reliability of the fabrication process through a wafer to wafer comparison. "Lot acceptance test for die" is a second level of testing that provides further reliability information, but only on a sample of the MMICs because of the difficulty in performing full characterization on

unpackaged MMICs. It is used if the MMIC user has requested the MMICs to be delivered in die form for integration into a larger module. This sample testing will provide the user with only an estimate of the MMIC's reliability. Furthermore, the user will not have an understanding of the MMIC's performance in the final package and any of the reliability issues that the package may cause. If packaged parts are requested though, a full 100% screening can be performed and the user should have assurance that the delivered parts are reliable. The acceptance testing procedure is summarized in Figure 8-6, where it is seen that the MMICs are not space qualified until they have passed the 100% screening tests, and the user takes responsibility for final space qualification screening if they request unpackaged parts.

The recommended product acceptance test for die deliverables is shown in Figure 8-7. Note there are three levels of testing within the procedure and each starts with the wafer acceptance test shown in Figure 8-8. The lowest level of testing is required for MMICs that have already been product qualified and have been manufactured on a qualified process line, whereas the highest level of testing is required for a new circuit design that is fabricated on an unqualified process line. Whichever level of testing is required, the same level of reliability assurance should be granted to the MMIC upon completion of the lot acceptance test. The cost and time advantage of buying MMICs from manufacturers with qualified processes and validated circuit designs can be large, and it is for this reason that manufacturers incur the cost of qualifying their processes.

A recommended flow chart for product acceptance of packaged parts is shown in Figure 8-9. It is assumed that a product acceptance of die deliverables is performed on the MMICs before they are inserted into the packaging process, or a subgroup of the parts can be removed from the packaged parts and life testing performed on them in a way similar to that recommended for the die deliverables. Thus, this screen adds further reliability information to the data obtained from the wafer and lot acceptance tests. As stated above, 100% of the packaged MMICs are recommended to be screened using Figure 8-9. Some of the steps require the selection of a particular screen, and this must be based on the intended application and device type.

Table 8-1 shows the recommended screening tests that can be used for MMIC packaged devices and the reference for the screen. This information is modified from MIL-PRF-38534 Class K requirements and should be applied after careful consideration of the applicability and the desired requirements.

Throughout the rest of this chapter, a brief description of and the rationale for product acceptance test or screen will be given.

A. Stabilization Bake

Some GaAs circuits have an initial period when their electrical parameters vary vs time. Most of the parametric variations decay to a steady-state value within 20 h, but during the initial life of the circuit, the variations can be large. Measured variations in I_{DS} of 20% over 2 h have been reported. The degree of instability varies between different manufacturers and between different fabrication processes at the same manufacturer. In fact, circuits from some manufactures do not exhibit any electrical parameter variations. It is therefore necessary to characterize the circuit performance over its early life to determine if electrical parametric variations occur. If they do occur, they must be eliminated before wafer acceptance, life testing, or product delivery can be made. If they are not eliminated, they will distort the life test results by shifting the "normal" operating parameters of the circuit; this will cause many circuits that are inherently good to appear defective.

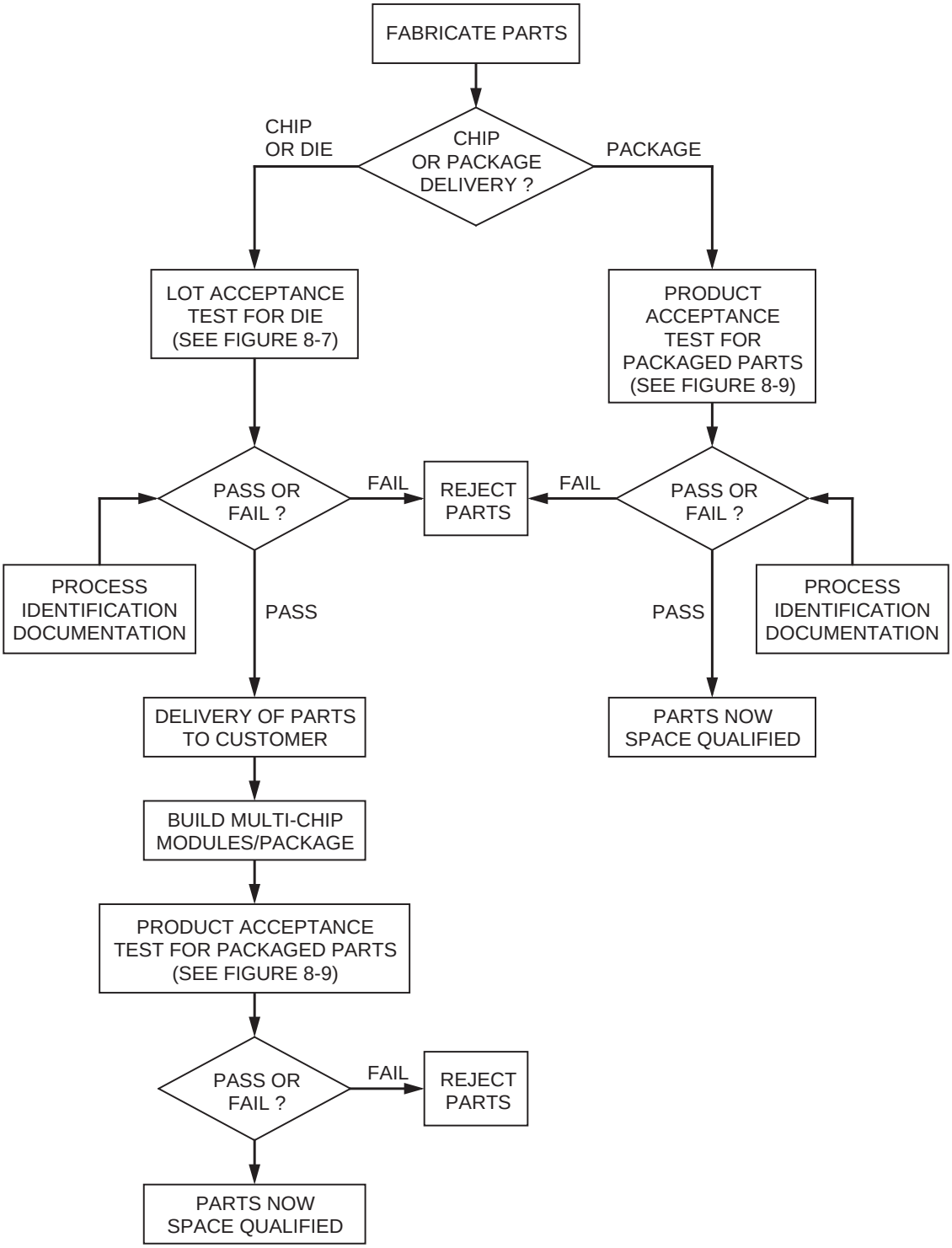

Figure 8-6. GaAs part qualification overview.

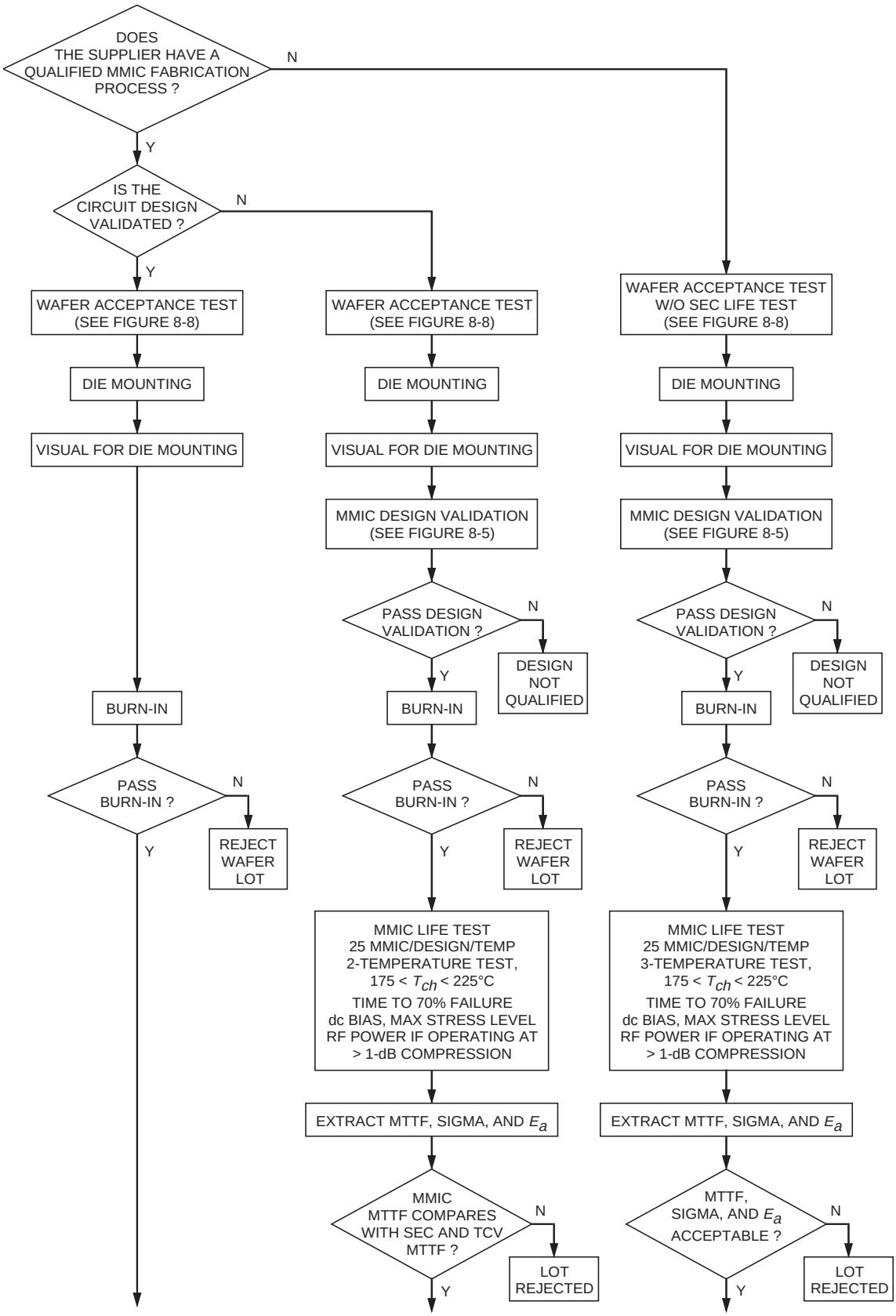

Figure 8-7. Lot acceptance test for die.

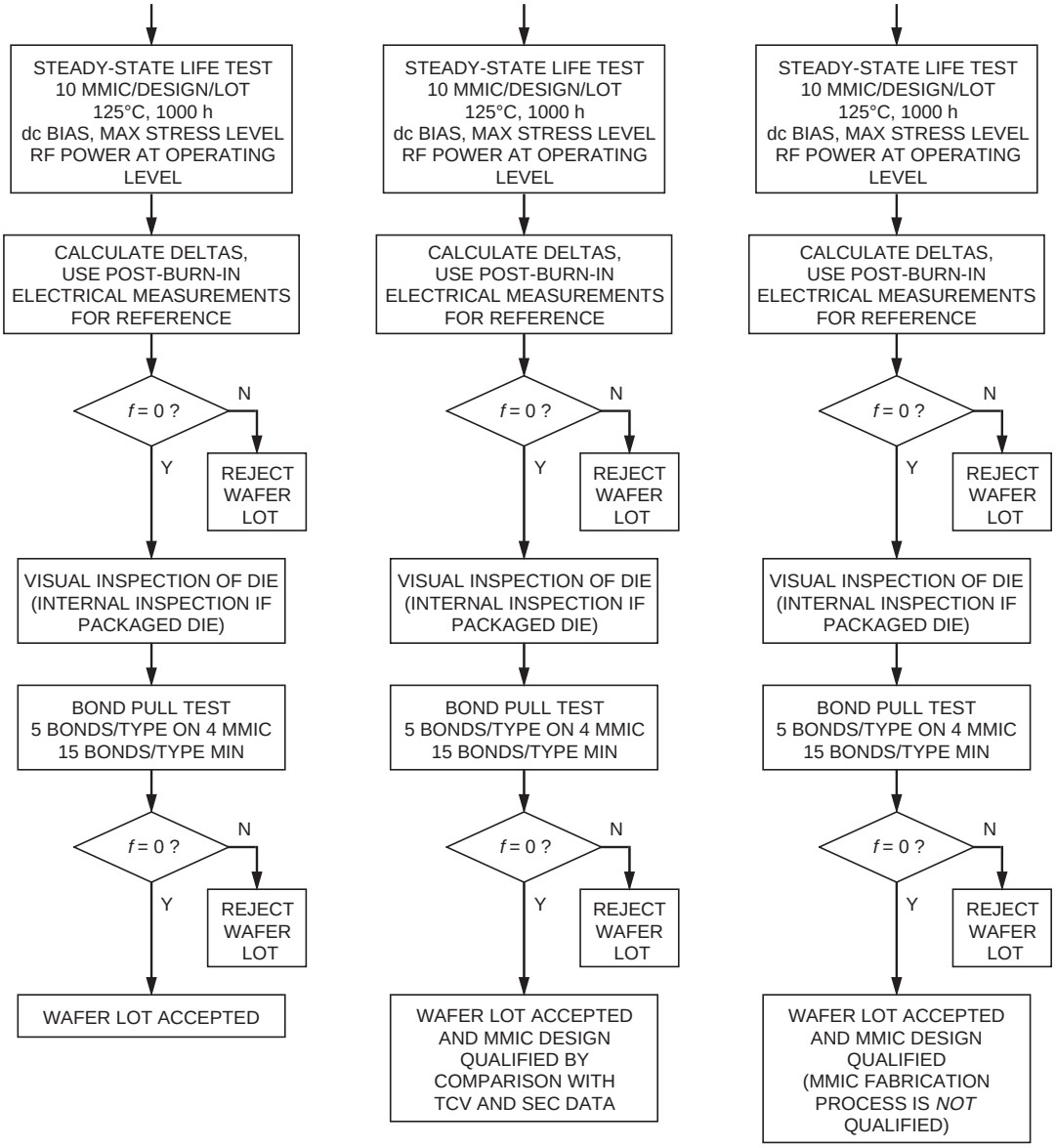

Figure 8-7. (continued)

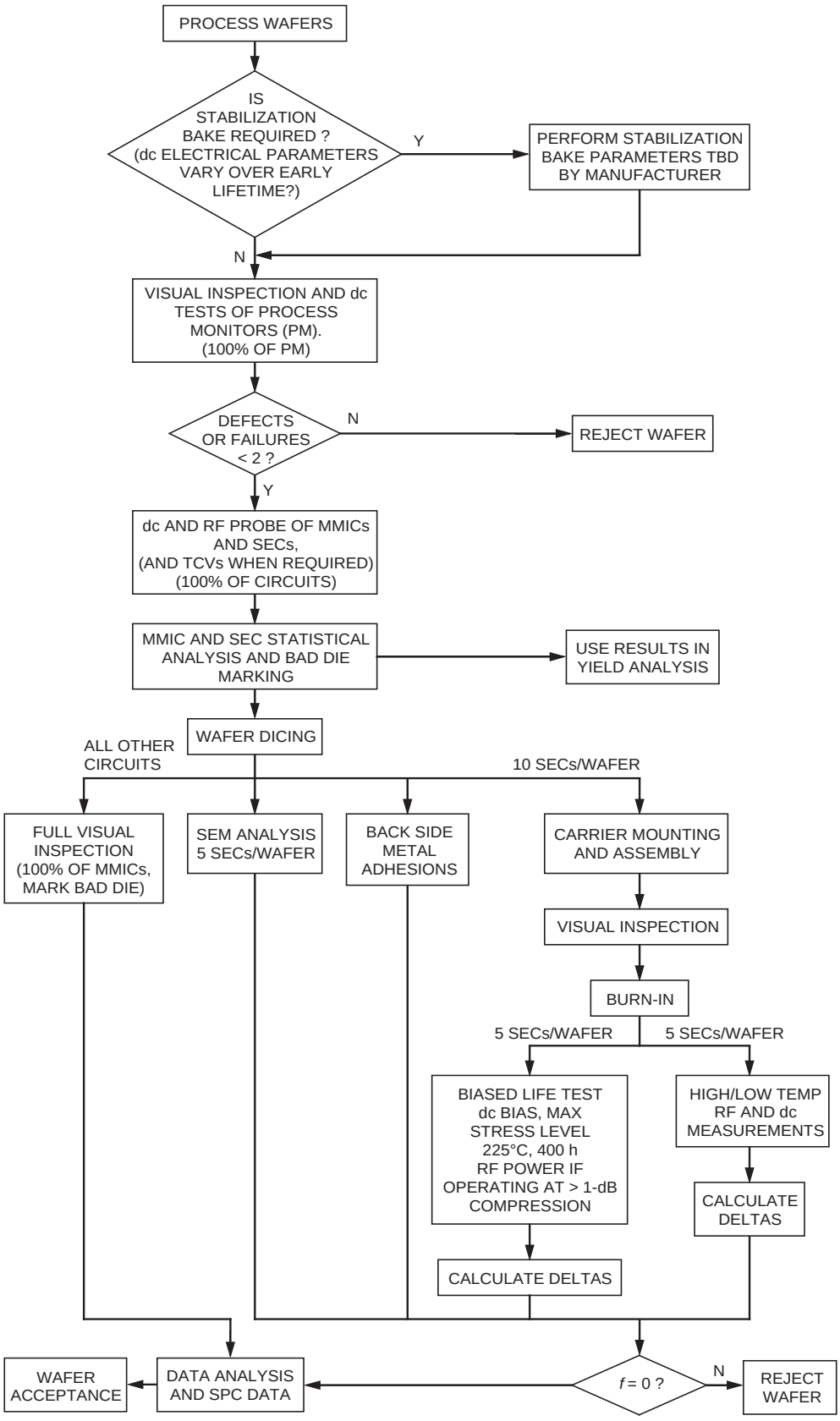

Figure 8-8. Wafer acceptance test.

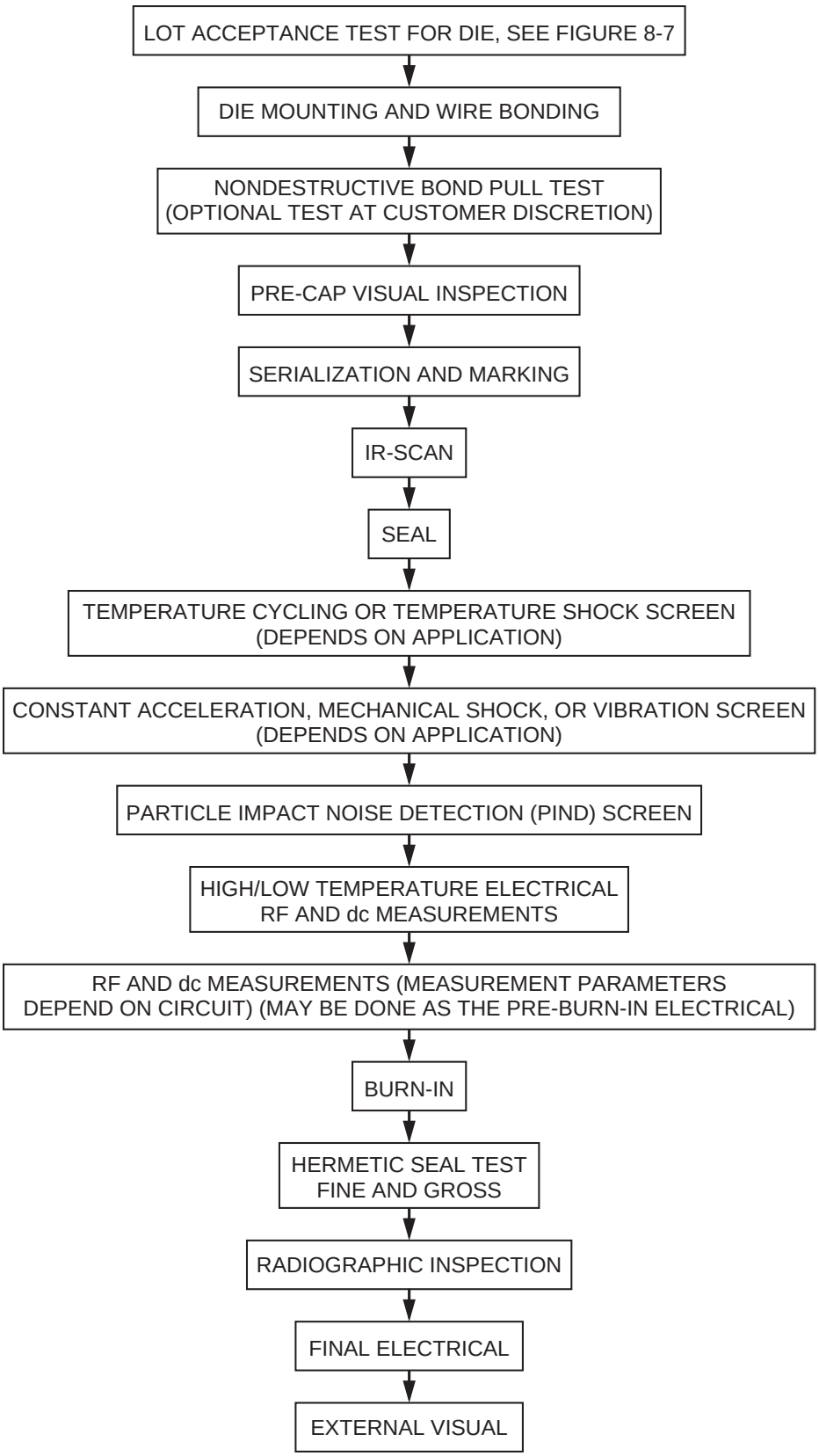

Figure 8-9. Screening process for packaged MMICs.

Table 8-1. Typical packaged device screening.

Test	Reference
Nondestructive bond pull	MIL-STD-883, Method 2023
Internal visual inspection	MIL-STD-883, Method 2017
IR-scan (prior to seal)	JEDEC Document JES2 [7]
Temperature cycling or Thermal shock	MIL-STD-883, Method 1010 MIL-STD-883, Method 1011
Mechanical shock or Constant acceleration	MIL-STD-883, Method 2002 MIL-STD-883 ,Method 2001
Particle impact noise detection	MIL-STD-883, Method 2020
Electrical	Customer's specification
Burn-in	MIL-STD-883, Method 1015
Electrical (high/low temp)	Customer's specification
Fine leak Gross leak	MIL-STD-883, Method 1014 MIL-STD-883, Method 1014
Radiographic	MIL-STD-883, Method 2012
External visual	MIL-STD-883, Method 2009

It has been shown that when parametric variations exist, the decay time is inversely proportional to the test temperature. In addition, it has been shown that a high-temperature bake may be used to stabilize the electrical parameters. These results may indicate that some of the fabrication processes, especially those that require bakes, are not adequately performed during fabrication. The alloying of ohmic contacts and the ion implantation activation bake are the two fabrication processes most often blamed. Another possibility is the development of mechanical stress in the GaAs lattice and in the metal deposited on the wafer during processing; this stress is relieved at high temperatures.

The bake performed to eliminate the parametric variations is called a stabilization bake. The stabilization bake is usually performed on the wafers immediately prior to dicing, but may be performed even before lapping and backside processing. The stabilization bake is an unbiased bake and should not be confused with the burn-in screen, which is a biased testing of the circuits at an elevated temperature. In addition, the stabilization bake is not the same as the Hi-Temperature Storage test, which some manufactures perform as part of the qualification process.

Although the stability of all electrical parameters is required before wafer acceptance, some manufacturers do not require a stabilization bake. Furthermore, some manufacturers who require stabilization bakes do not consider it a part of the wafer acceptance or reliability screening procedures, but rather a part of the fabrication process. Therefore, the stabilization bake may not appear in some manufacturers' reliability or product-acceptance procedures, while it does appear in others. Since the requirement for a stabilization bake is dependent on the manufacturer's processes, the bake temperature and time varies; typically, bake temperatures are between 200 and 300°C.

B. SEM Analysis

Scanning Electron Microscopy analysis can provide valuable information regarding the step coverage and quality of the metallization and passivation of GaAs devices. Thus, this tool is required as part of the wafer acceptance tests. Some accept/reject criteria are provided in MIL-STD-883, but they may need some modification to cover GaAs-device technology.

C. Nondestructive Bond Pull Test

The integrity of wire bonds cannot always be judged through visual and electrical tests. Therefore, some qualification procedures recommend the implementation of a nondestructive bond pull test of each bond. The pull force selected for this test is generally dependent on the material and wire diameter in question. MIL-STD-883, Method 2023, is normally used for this application. Obviously, selecting the required pull force is critical and must be decided by the manufacturer and the user.

Mechanical damage to good bonds as a result of this test is possible. Additionally, for microwave circuits, the wire bond's impedance can be changed when the shape of the wire loop is changed, which results in a change in the RF characteristics of the MMIC. Due to the problems associated with this test, some manufacturers have removed this step from their qualification and screen procedures and resorted to in-process controls and testing to provide the necessary information. The decision to require this test must be made by the MMIC user after careful consideration of the system application and the workmanship of the manufacturer.

D. Visual Inspection

Many defects in MMICs, such as metal voids, substrate cracks, poor wire bonds, and foreign materials, reduce the MMIC reliability. Small voids or cracks in the metallization will cause increased electrical resistance, increased current density, and an increased possibility of failure due to electromigration. Furthermore, microwave circuits radiate power at gaps and discontinuities in transmission lines. Edge chips and cracks created during wafer sawing or dicing easily propagate and cause circuit failures or die breakage during thermal cycling and wafer handling. This is especially true for GaAs monolithic circuits since GaAs wafers are more brittle than Si wafers and they are often thinned to 100 μm or less. The stray particles of GaAs created during wafer sawing or other byproducts of the circuit fabrication process may deposit themselves onto the wafer. Since GaAs is highly insulating, GaAs particles will usually not cause problems. However, other materials, especially metal particles, may adversely effect circuit performance. If the particles are on the gate of the transistors or on other circuit elements, the circuit performance will be degraded. This is especially true if the circuits have not been passivated. Since free particles may move during circuit testing, packaging, or in zero gravity space environments, even free particles away from the circuit elements may cause failures. During die attach, eutectic alloys and epoxies are used that may adhere to the sides or top of the circuit where it could short RF transmission lines and biasing pads to the ground plane. Lastly, the electrical connections between the package and the circuit must be made. These connections are usually made by ball or wedge bonds comprised of thin (typically 17 μm in diameter), gold wires attached to gold pads. The location and the quality of the bonds are critical for good MMIC performance and reliability.

These obvious defects and others not listed here in materials, construction, and workmanship must be eliminated since they degrade circuit performance and reliability. Furthermore, it is better to eliminate circuits with obvious defects before additional resources have been spent on them in bonding, packaging, and burn-in. Luckily, these defects are easily detected by performing a visual screen of every circuit with the aid of a microscope. The visual screen is performed during wafer acceptance tests for defects of the die and during the packaged MMIC screens for packaging and bonding defects.

E. IR Scan

Some defects such as substrate cracks and die-attach voids may not be visible, but they must be detected. Since these types of defects have a different thermal conductivity than the surrounding defect-free region, they may be detected through thermal mapping. The baseline for the comparison is the thermal profile of the MMIC that was made as part of the product or design verification step. For example, during design verification, it may have been determined that the final stage of an amplifier was the hottest part of the MMIC at 90°C, while the rest of the MMIC had a 15°C temperature variation. If a similar MMIC were thermally mapped and found to have a hot spot of 100°C or the wrong temperature variation across the die, a defect would be indicated. Typically, variations greater than 5°C are considered a reject. Thus, a simple comparison between the MMICs in the screening process and the MMIC thermal profile can be used to detect defects not visible to the eye.

Although infrared microscopes are expensive, require calibration, and have a minimum resolution of approximately 15 μm, they are the best method of mapping the MMIC's thermal characteristics since they do not damage the MMIC surface. Furthermore, the microscope can be computer controlled to scan the surface, make the required map, and perform the comparison to the thermal profile stored on file.

This screening step is not typically imposed as a requirement following MIL-PRF-38534. However, it is recommended for high-power devices and in applications that require good thermal stability. This step should be performed after die attach and before attachment of the package lid.

F. Temperature Cycling and Shock Screen

In the same way that electrical devices can be made to fail quicker at higher temperatures, mechanical devices can be made to fail quicker by applying thermal stress. These tests are used to detect flaws or weak points in the die attach, wire bonds, and package seals that would normally result in early failures. Temperature cycling consists of cycling the packaged MMICs between extreme temperatures many times. Typically, the temperatures used are -65 and 200°C, and the number of cycles is 15. The temperature shock screen is similar to the temperature cycle screen in that the test involves subjecting the packaged MMIC to extreme low and high temperatures (–65 and 150°C) over many cycles. The difference is a sudden change in temperature created by immersion of the parts into a bath, rather than the gradual change in air temperature used in the cycle test. Failure detection for both screens occurs during final electrical and visual inspections. Typically, only one of the screens is required, and the manufacturer and user decide on the appropriate screen for their application.

G. Mechanical Shock Screen

This screen is intended to detect weak parts that are required to undergo severe shocks during transportation, handling, satellite launch, or other operations. The test subjects the packaged MMIC to a number of short shock pulses with a defined peak. Failures are detected during final visual and electrical screens.

H. Constant Acceleration

This screen is intended to detect failures due to mechanical weakness by subjecting the packaged MMIC to a constant acceleration. Typical failures occur in the bonds and die attach, and these are detected during the final visual and electrical screens. Although this screen is typically required, it is not because of the forces caused during launch but rather as an effective tool to detect poor workmanship.

I. Particle Impact Noise Detection

During encapsulation, thermal stress screens, and mechanical stress screens, particles may break off the MMIC or package. These loose particles may mechanically damage the MMIC during handling, launch, or in operation, or they may cause short circuits. The particle impact noise detection screen is a nondestructive test used to find parts that have this defect. During the test, the part is vibrated and a sensor is used to detect anomalous noise. Failure criteria are given in the reference listed in Table 8-1.

J. Burn-In

Ideally, a well-controlled GaAs fabrication line, which employs proper wafer handling and fabrication procedures along with visual, dc, and RF screens, would eliminate circuits containing defects that result in the early failures that were discussed in Chapter 2. In fact, in some GaAs fabrication lines, the early failure rate is very small. However, in state-of-the-art circuits with 0.1- to 0.25-μm gate HEMTs, complex circuits with many air bridges, or packaged circuits with many wire bonds, latent defects may cause early failures at a higher rate. These are detected through the burn-in screen.

The burn-in screen stresses the circuits above their normal operating conditions to accelerate any early failures that would occur from latent defects. Although burn-in is often performed at elevated temperatures to shorten the time of the burn-in test, the temperature must be kept low enough so inherently good circuits do not fail due to failure mechanisms accelerated by the test. Also, since circuits that pass burn-in are used in either accelerated life testing or as flight deliverables, burn-in at too high of a temperature will distort the results of the accelerated life tests and reduce circuit lifetime during the mission. It is inevitable that the burn-in screen will use some circuit life, but if the circuit has an inherently long lifetime and the burn-in screen is not performed at too high of a temperature, only a few percent of the life will be lost. This small cost in circuit lifetime is accepted by the space industry, since the alternative is a failed mission or satellite.

To prevent creation of failures in inherently good circuits due to excessive stress conditions, burn-in should be performed only once on each circuit and appropriate test conditions should be selected. Circuits that fail burn-in should not be reworked and retested. If the circuits are to be delivered to another company for further processing or packaging, it is critical that the burn-in screen is coordinated to assure that it is not duplicated. An exception can be made if the system builder performs a burn-in on the

entire assembly, since assembly burn-ins are normally performed at lower temperatures and for shorter times than the GaAs die burn-in. Therefore, the total stress to the MMIC from the additional assembly burn-in is small and should not affect the circuit's lifetime.

It should be noted that only a small percentage of GaAs circuits fail the burn-in screen, and the burn-in screen increases the circuit cost. Furthermore, the increased handling of the circuits during the screening procedures increases the chance of creating failures in the circuits due to introduced mechanical, ESD, and handling defects. Therefore, most suppliers of commercial MMICs do not perform burn-in screens, but all satellite manufacturers require burn-in of all electronic parts.

The screen is typically performed at 125°C ambient temperature for 320 h with the circuits biased to their maximum stress levels. However, careful consideration of the resultant device channel temperature is recommended to avoid undue stress of the device during test and the introduction of thermally accelerated failure mechanisms. If the MMIC is classified as a large-signal (greater than 1-dB compression) device, RF energy should also be applied to the input port with the output port matched. Failure is usually specified as an electrical parametric drift from the initial conditions by a specified percentage. These conditions have been shown to be effective in removing weak MMICs.

K. Leak Test

There was considerable discussion in Chapter 4 about failure mechanisms that result from contamination and humidity. To eliminate these problems, MMICs, as well as all other electronic components intended for high-reliability applications, are sealed in hermetic packages, and the reliability of the MMICs is dependent on the integrity of these packages. To find weak packages that would result in loss of the hermetic seal, thermal and mechanical stress screens were performed. Although some gross package failures are visually detectable, most defects in the package require a leak test.

Fine leak tests consist of placing the packaged MMIC in a chamber pressurized with a known gas; some of the gas will enter cracks or defects in the package if they exist. Usually, helium or nitrogen gas with a small concentration of a radioactive isotope is used, since either is detectable in very small concentrations using standard, commercially available equipment. After a time, the chamber is cleansed by circulating air, and the packages are tested to determine if gas leaks from them. Although the use of radioactive isotopes sounds hazardous, it is the preferred method in high-volume production lines because it is easier to detect for a longer period of time. The disadvantage of fine leak testing is that the gas will leak from gross defects before it can be detected. Therefore, a gross leak test is required after the fine leak test. The principle of the test is the same except that a pressurized liquid bath is used instead of the gas.

L. Radiographic

The final screen is usually a radiographic “picture” of the inside of the sealed package taken in the same way that a doctor takes X-rays to image the skeletal structure of the human body. This nondestructive test uses radiation to penetrate the package walls and produce a shadow image on a photographic plate. It is useful for checking the location and position of wire bonds and for detecting loose particles that may have moved or broken off during the screening process. In some cases, this screen can also be useful in determining the presence of die-attach voids.

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