THE DEVELOPMENT OF A GaAs MMIC RELIABILITY AND SPACE QUALIFICATION GUIDE

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ABSTRACT

NASA, JPL, and DOD are collaborating with GaAs MMIC users, manufacturers, and international space agencies to develop the "GaAs MMIC Reliability and Space Qualification Guide." This paper discusses the need for a space qualification guide, provides a brief description of some common GaAs failure mechanisms, the approach that the NASA MMIC Reliability Assurance Program is following to develop the guide, and the status of the program.

INTRODUCTION

Direct broadcast television, interactive video services, telemedicine, mobile/personnel communications, and hubless VSATs are some commercial applications of satellites being proposed. In addition, the DOD and NASA will continue to use satellites for communications, global positioning, planetary exploration, and radiometry for the Mission to Planet Earth.

For applications below 2 GHz, Si circuits provide satisfactory RF performance, but for applications above 2 GHz, GaAs devices possess superior performance. Furthermore, GaAs MMICs are a promising and viable solution to the higher complexity, smaller size, and lower cost that are required in all of the proposed satellite systems. Specifically, multibeam antennas, phased array antennas, switch matrices, power amplifiers, and beam forming networks will all require MMICs.

An example of GaAs usage in satellites is the In Orbit Test Transponder (IOTT) shown in Figure 1 from the ITALSAT 1 satellite (Agenzia Spatiale Italiana, Italy) that was launched in January 1992. This IOTT employs a discrete GaAs FET power amplifier as a transmitter and a X-band GaAs FET MMIC driver amplifier. Other commercial satellites that are being planned or have recently been launched that use GaAs devices or circuits are ANIK (Telesat, Canada), AUSSAT (Australia), GSTAR (GTE Spacenet, US), INMARSAT, INTELSAT, N-STAR (NTT, Japan), PANAMSAT (Alpha Lyracom, US), SATCOM (GE Americom, US), SUPERBIRD (Space Communication Corp., Japan), TELSTAR (ATT, US), IRIDIUM (Motorala, US), ODYSSEY (TRW, US), and GLOBALSTAR (Loral Cellular Systems Corp., US). Some NASA missions that require GaAs MMICs are CASSINI, Pluto Fast Flyby, MESUR, and Space Station Freedom.

Although there are many GaAs circuits already in space, there is no standard space qualification procedure that is accepted by the GaAs community. Currently, each MMIC user negotiates with the MMIC manufacturer over the type of screens, the amount of testing, and the documentation necessary for each MMIC purchased. Often, screens and tests are used that were not developed from an experience with or a knowledge of GaAs but from Si IC failure mechanisms. Furthermore, new GaAs failure mechanisms are being recognized that are not properly screened. One example is the degradation of power output found in GaAs power devices after only a few hundred hours of operation. This failure mode was observed in solid state power amplifiers intended for INTELSAT, INMARSAT, and the Air Force DISC satellites.

The development of a reliability guide for GaAs MMICs that proposes strict qualification tests and standards is difficult. GaAs is still a young technology that is constantly evolving. GaAs MMIC manufacturers continuously change the device layout, material systems, and fabrication processes to improve the circuit performance and to reduce costs. This flexibility is critical for the manufacturers so that they may continue to develop higher performance and lower cost circuits which the customers require. It is also critical that both the manufacturers and the users of GaAs MMICs understand GaAs failure mechanisms and how qualification tests may be used to determine the reliability of the MMIC.

To address the need for a GaAs MMIC space qualification standard, NASA Code QW initiated a program to develop the "GaAs MMIC Reliability and Space Qualification Guide." NASA, JPL, and DOD are collaborating with GaAs

MMIC users, manufacturers, and international space agencies to develop the guide. This paper provides a brief description of some common GaAs MMIC failure mechanisms and discusses the approach that the NASA MMIC Reliability Assurance Program is following to develop the "GaAs MMIC Reliability and Space Qualification Guide."

GaAs MMIC FAILURE MECHANISMS

GaAs MMICs failures can be classified as either catastrophic failures or degradation failures. The exact mechanism that causes the failure is normally dependant on the material structure, processing methods, application, and stress conditions. The DC bias, RF input power, device channel temperature, passivation, and material interactions may all cause or contribute to different failure mechanisms. Furthermore, the handling procedures of the MMIC during wire bonding and packaging and the interactions of the MMIC with the package may also cause failures.

Some dominant failure mechanisms for GaAs MMICs include:

Metal diffusion:

Metals deposited onto the GaAs substrate to form ohmic and Schottky contacts must be stable over time and the operating temperature range. Failures occur when the metals diffuse into the semiconductor and the Ga and/or As diffuse into the contact. Metal diffusion is a primary failure mechanism for MMICs.

Diffusion is a function of the temperature, the material diffusivity, and the material concentration gradients. For perfect lattices, the diffusion rate at normal operating temperature is too slow to have an effect on device performance. However, when large grain boundaries or large numbers of vacancies exist, the diffusion rate can be fast (1).

For ohmic contacts that generally consist of Au/Ge or Ni/Au/Ge, the primary failure mechanism is Au diffusion into the GaAs and Ga diffusion into the metal contact. The Ga diffusion out of the GaAs creates lattice strain in the GaAs. Simultaneously, the Ga that has diffused into the metal contact reacts with the Au to form a Au-Ga eutectic (2-4). The result is an increase in the contact resistance.

Schottky contacts are also susceptible to diffusion of the gate metals into the GaAs, especially the Au layer that is often deposited on top of the refractory metal to reduce the gate resistance (3,4). Barrier metals are often used to inhibit the diffusion of the Au into the GaAs, but under thermal and electrical stress, diffusion can still occur. This failure mechanism is called the "sinking gate" because the Au metals that diffuse into the GaAs decrease the channel thickness. In addition, the Au ions in the channel change the effective channel doping. Gate metal diffusion results in a decrease in I_{dsat} and V_p.

Electromigration:

Electromigration is the movement of metal atoms along a metallic strip (5). The primary mechanism which drives the atom movement is not a concentration gradient but the continual transfer of momentum from the flowing electrons to the metal atoms. Since the mechanism is dependant on momentum transfer from electrons, electromigration is dependant on the temperature of the electrons and the number of electrons. Therefore, this failure mechanism is generally seen in narrow gates and in power devices where the current density is greater than $2x10^5$ A/cm^2 which is normally used as the threshold current density for electromigration to occur. Electromigration is a primary failure mechanism in microwave power devices.

The metal atoms that migrate along the line tend to accumulate at grain boundaries. The accumulation of metal at the end of the gate or the drain contact can create fingers of metal that can short the device. Simultaneously, the depletion of metal atoms creates voids upstream along the line. At the void location, the current density increases due to current crowding which further increases the temperature due to resistive heating. These effects increase the rate of electromigration which further increases the void size. Therefore, void creation is a self-accelerated runaway process. If the void formation occurs in the gate of the device, electromigration results in catastrophic failures due to the creation of gate open circuits. When electromigration occurs in the drain of a device, the voids result in increased drain contact resistance and associated device degradation.

Surface metal migration:

Metal can migrate across the surface of the GaAs wafer between two electrodes thus shorting them together. Although this failure mechanism is induced by high electric fields, it is also temperature dependant. It has been reported that lateral metal migration is directly proportional to the amount of As_2O_3 on the GaAs surface. Furthermore, it has been shown that migration can occur under the passivation layer (3).

Hot electron trapping:

Power transistors driven by large gate to drain voltages can create an electric field large enough to cause avalanche generation of electrons. Since the gate leakage current typically flows on the surface of the device, some energetic electrons are excited into the passivation layer and become trapped. The trapped electrons increase the depletion region on the drain side of the gate and therefore decrease I_{dsat} and increase V_{dsat} (6). These effects reduce the output power of the device leading to an effect commonly called the "power slump."

Humidity effects:

The effect of humidity on modern GaAs devices is not well established. It has been shown that Al corrodes when subjected to humidity and results in void formation and open circuits, but most MMICs no longer use Al. Reliability tests on MMICs using Au/refractory metal gates have shown no degradation due to humidity as high as 85 per-cent (7). This result was true for both passivated and unpassivated devices. Other tests have shown that ohmic contacts are susceptible to anodic Au corrosion leading to the formation of $Au(OH)_3$ (3).

Void formation due to Au-Al eutectic:

Devices with Au-Al contacts or Au wire bonds to Al pads can exhibit Au-Al intermetallic formation. Au migrates along the metal surface toward the Al where they react to form Au-Al intermetallics. This effect is called the "purple plague" due to the color of the predominant intermetallic, $AuAl_2$ (8). The accumulation of voids due to the Kirkendall effect under the Au-Al intermetallic causes increased resistance and bond lifting. Barrier materials have been shown to slow the rate of Au-Al intermetallic formation. This effect is accelerated with electrical bias and moisture. Purple plague related failures are not common with GaAs MMICs since Al contacts are rarely used.

Radiation effects:

An advantage of GaAs devices is the high tolerance to radiation exposure. The radiation resistance is due to the semi-insulating substrate and the lack of a gate oxide layer. Therefore, there is not the concern for the latch-up mechanism or device degradation due to charge accumulation at the gate oxide. If the radiation source is gamma rays or electrons with energies below about 0.6 MeV, doses greater than 10^8 Rad (Si) can normally be tolerated. Mobility and threshold voltage degradation may occur for exposures greater than 0.6 MeV (9). Also, neutron flux can cause threshold and pinch-off voltage shifts and mobility degradation due to displacement damage. Fluxes as low as 10^{14} Neutrons/cm^2 have been reported to cause significant damage (10).

GaAs devices are susceptible to long term transient effects when exposed to a pulse of ionizing radiation. Devices operating near threshold can be forced into pinch-off for several seconds after exposure to a pulse of 10^{10} Rad (GaAs). Long term effects are of concern for many GaAs applications where devices must operate in radiation burst environments, but these effects can be reduced with proper attention to the materials, design, and biasing of the GaAs devices.

NASA MMIC RELIABILITY ASSURANCE PROGRAM STATUS

NASA MMIC Reliability Assurance Program was initiated in October of 1992 by Code QW of NASA HQ. The program is managed by JPL. The main objective of the program is to develop a "GaAs MMIC Reliability and Space Qualification Guide" that GaAs MMIC customers and manufacturers can use as a starting point for negotiation of qualification methods. Another objective of the program is to increase the level of interaction and information exchange between MMIC users and manufacturers and to increase the awareness of GaAs MMIC reliability among system designers.

To achieve the goals of the program, two committees were established. The first is a working group consisting of representatives from JPL, NASA LeRC, NASA JSC (Shason Microwave), DOD's Rome Laboratory, and the Naval Surface Warfare Center. The working group is responsible for drafting the guide, organizing workshops on GaAs MMIC reliability, and coordinating activities relating to reliability with other organizations. The second committee is an advisory group consisting of representatives from the GaAs MMIC community. This group is responsible for giving technical guidance to the working group, reviewing drafts of the reliability guide, and keeping the focus of the working group on the reliability concerns that are important to the MMIC community. Since broad industry acceptance of the guide is needed, interaction between the advisory group and the working group is critical to the success of the program. Membership on the advisory board is voluntary and unrestricted. It currently consists of representatives from over 30 commercial and government organizations.

The "GaAs MMIC Reliability and Space Qualification Guide" is intended to provide both the users and manufacturers with a good understanding of GaAs reliability issues so that negotiation of the qualification methods is made prudently. Therefore, the "GaAs MMIC Reliability and Space Qualification Guide" will include sections on: basic GaAs devices and MMIC structures, basic failure modes and mechanisms, device modeling and characterization, MMIC design methodologies and verification, qualification methodologies, product acceptance, and testability and test structures.

The sections of the guide addressing qualification methodologies and product acceptance are the most critical to the program. They will describe accepted industry qualification tests, the rationale for the test, and how to decide if a test is value added. When differences exist between industry approaches regarding a particular test or screen, the working group and the advisory group will try to resolve the differences. When an agreement cannot be reached, the rationale for the different tests will be reviewed and the merits of each test will be discussed.

The program has made good progress since its conception eighteen months ago. An outline of the guide and a draft of the qualification methodologies section has been written. In addition, to facilitate interaction between the members of the GaAs MMIC community, a two-day workshop on MMIC reliability was held on August 31 and September 1, 1993 at NASA LeRC in Cleveland, Ohio. Approximately forty people attended the workshop with representatives from the American, French, and Japanese MMIC communities. A second workshop is scheduled to be held in cooperation with the Advanced Microelectronic Qualification/Reliability Workshop on August 16-18, 1994 in Boston, MA. Lastly, a GaAs Reliability Database has been established and is monitored by JPL (11). The database permits quick access to literature references related to GaAs reliability and is accessible for downloading via modem to all interested parties.

CONCLUSIONS

To address the needs of the GaAs MMIC community, the NASA MMIC Reliability Assurance Program was created. Its objectives are to develop the "GaAs MMIC Reliability and Space Qualification Guide" and to increase interaction between members of the GaAs community involved in reliability research and qualification methods. Additional information concerning the objectives of the program and participation on the advisory committee should be addressed to Sammy Kayali of JPL at 818-354-6830.

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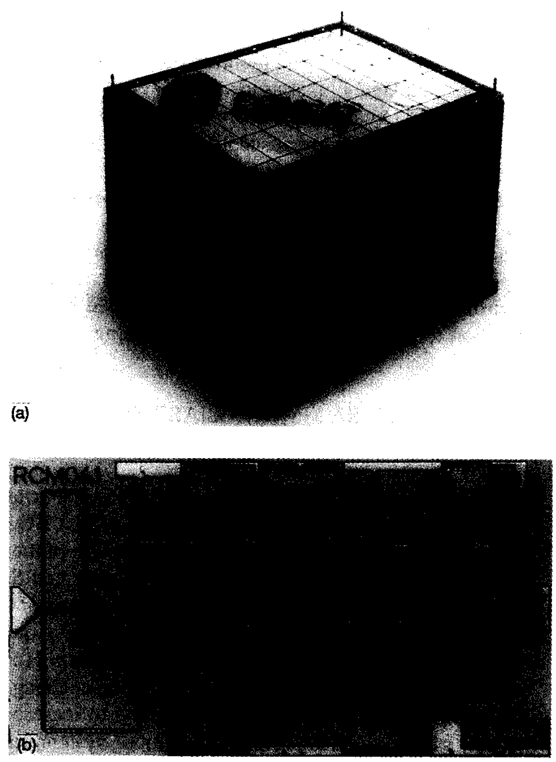

Figure 1.–(a) In orbit test transponder (IOTT) of ITALSAT that was launched in January 1992. (b) X-band (12 GHz)MMIC gain block for the IOTT (Courtesy of Mr. Dick Mott, Comsat Laboratories).