The Impact of the U.S. MIMIC Program On MMIC Technology and Applications

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Abstract

The primary objective of the U.S. Department of Defense Microwave and Millimeter Wave Monolithic Integrated Circuits (MIMIC) program is the development of high performance, affordable, and available microwave and millimeter wave technology for building electronic systems. This paper describes the advances made under program sponsorship, during the past six years, in the areas of material growth, computer aided design capabilities, microwave monolithic integrated circuit (MMIC) manufacturing, MMIC circuit capabilities, multi-chip packaging, and automated testing. MMIC technology use in systems is also discussed.

Introduction

The U.S. Department of Defense Microwave and Millimeter Wave Monolithic Integrated Circuits (MIMIC) program is now entering its final year. The primary objective of the program has been and continues to be the development of high performance, affordable, and available microwave and millimeter wave technology for building electronic systems. Program products and processes continue to find increasing acceptance and use in both military and commercial applications. The MIMIC program has established a solid infrastructure for microwave monolithic integrated circuit (MMIC) technology. Two U.S. substrate vendors are profitable and are selling material worldwide. Two computer aided design (CAD) vendors are profitable and dominate the world market for microwave CAD. More than six MIMIC program participants are providing MMIC foundry services to multiple customers worldwide. RF test equipment developed under MIMIC program sponsorship defines the state-of-the-art. Several package vendors are now available to support the MMIC industry. The numerous products and capabilities now becoming available as a result of the program have been made possible through comprehensive, planned technology development in every area related to MMICs. Examples of these products and capabilities are described below.

Materials

In the substrate materials area, boule size has increased dramatically. Current boules yield greater than 100 substrates each compared to 20-40 substrates/boule at the inception of the MIMIC program. Typical gallium arsenide wafer diameters have increased from 2 inches at the start of the first development phase of the program in 1988 to 3 and 4 inches. Six inch diameter material is now becoming available in limited quantities and is under evaluation. Even more important, wafer characteristics and uniformity have greatly improved during the past few years. A portion of the success in this area must be attributed to the ARPA sponsored Intelligent Processing of Material-Gallium Arsenide (IPM) program carried out by General Electric Research and Development in conjunction with Airtron, one of two U.S. commercial gallium arsenide material suppliers. Under the IPM program, recipes for growing uniformly high quality gallium arsenide substrates were determined, computer programs used in conjunction with in-situ sensors were developed to accurately control growth parameters, and extensive modeling of the growth process was carried out. Results of the program were also shared with M/A-COM, the other U.S. commercial gallium arsenide supplier. Another completed MIMIC effort provides a capability for nondestructive optical characterization of defects and impurities in gallium arsenide wafers. All of these activities have contributed to establishing profitable, world-wide suppliers of gallium arsenide substrates.

The MIMIC program is also helping to establish commercial supplies of pre-qualified, production grade epitaxial material, particularly for use in fabricating advanced device structures such as high electron mobility transistors (HEMTs) and heterojunction bipolar transistors (HBTs). Related work has included development of an in-situ growth monitor using near-threshold photoemission oscillation, establishment of techniques to improve control of substrate temperature, and development of techniques to minimize oval defects occurring in molecular beam epitaxially (MBE) grown material. A program on metal-organic chemical vapor deposition (MOCVD) growth process technology has also been conducted, and a program to achieve cost reductions and quality improvement of MBE material is currently underway. The latter program has a goal of reducing the cost of pHEMT epitaxial structures from about \$40/cm^2 to \$14-18/cm^2 by 1994.

Computer Aided Design

A major focus of the MIMIC program has been upon the development of advanced CAD capabilities. This effort has yielded enhanced design tools, improved circuit models, increased the population of microcell and macrocell libraries that can be used in the design of complete MMIC circuits, and improved availability and use of collections of information from computer databases. One of the major advances achieved during the current portion of the MIMIC program is the ability to greatly reduce the area of gallium arsenide required to perform a given electrical function. This "compaction" of circuits has resulted in substantial cost reductions through much more effective use of gallium arsenide "real estate." For example, between December 1991 and mid-1993, the cost of a low noise amplifier produced by M/A COM was reduced from \$80 to \$13.50, a 6 times improvement. Although part of this cost reduction can be attributed to improved fabrication yields, the major savings have occurred because four amplifiers are now being produced in the space previously needed for one. Design centering and electromagnetic simulation are reducing the number of design iterations and increasing the yield of "good" chips. Software libraries of design microcells developed under the impetus of the MIMIC program at M/A-COM, Hughes, TriQuint, Martin Marietta and Texas Instruments have become available for use in computer aided design systems. These are marketed by EEsof as part of the Smart™ Library. These new, expanded microwave circuit libraries make it possible to achieve further significant savings in the cost and time of developing MMIC circuits. In addition, statistical design methodology is finding increasing use. This approach to design permits the establishment of data-based relationships between the most important requirements for a particular application (specifications) and the most significant manufacturing variables. The result is designs that are optimized for yield, leading to minimal production costs using existing manufacturing capabilities. Work is also in progress to increase the speed at which electromagnetic simulation of circuit performance can be carried out. This includes both development of new, more efficient algorithms for circuit analysis and the use of parallel processor arrays to speed up the execution of the design programs.

Devices and Circuits

The range of available device types has also dramatically increased over the past few years. At the inception of the MIMIC program, most circuits were fabricated using ion implantation technology to form active device layers. Minimum feature size was 0.5µm and the only commonly available device type was the MESFET. During the current phase of the MIMIC program, MESFETs and HEMTs with minimum feature sizes as low as 0.1µm and HBTs with 2µm emitters have been produced with increasingly good yields. HEMTs are being used in circuits such as W-band (94 GHz) amplifiers with noise figures of between 3 and 4 dB and a single stage gain of several dB, and power HEMTs and HBTs have both been used to develop power amplifiers having between 4.5 and 6 watts of output at X-band (8-10 GHz) and up to 40% power added efficiency. In addition, increasing numbers of circuit functions are now being integrated onto a single gallium arsenide chip. One of the most impressive demonstrations of increased per chip functionality is a 25 function synthesizer chip designed by Northrop and fabricated by TRW. It operates at frequencies up to 20 GHz. Another example is a complete FM-CW radar transceiver on a single chip, designed by Hittite and fabricated by Triquint. This C-band circuit includes a local oscillator, amplifier and mixer.

Manufacturing Advances

The MIMIC program has emphasized the establishment, maintenance, and use of manufacturing process databases and statistical process control (SPC). As a result, many MIMIC fabrication contractors are making effective use of information from comprehensive manufacturing parameter databases to reduce design errors and increase both circuit yields and the probability of "first pass" circuit fabrication success. Some organizations use speech recognition capability to allow visual inspectors to instantly incorporate MMIC inspection results into the manufacturing process database.

Module assembly has become highly automated with the introduction of high speed, accurate robots that perform placement of MMIC die, their interconnection to substrates and to other circuit elements. Batch processing for die and substrate attachment and automated wire bonding of full module assemblies have both greatly reduced module production cost. Even higher levels of automation will become economically feasible with increasing demand for MMIC products. This will result in still shorter design-production times and further reductions in MMIC component costs.

Packaging

In the packaging area, considerable progress has been made toward the goal of providing plentiful supplies of multi-chip packages that are fabricated from metal matrix composites such as copper tungsten, iron-nickel (Alloy 46), and aluminum-silicon carbide (AlSiC). These materials offer light weight, high thermal conductivity, and lend themselves to the tailoring of their coefficient of thermal expansion to match that of GaAs by varying the ratio of their constituents. Of the preceding options, AlSiC provides the lightest weight with the best thermal properties. However, until recently, typical costs for packages fabricated from this material were much too high. This year, under MIMIC program funding, the cost of AlSiC packages, including feedthroughs, has dropped to below $30 even for relatively small quantities (approximately 1000). The cost of packages made from Fe-Ni has now dropped by about a factor of 5, from $50 to $10 each, in large quantities. Other advances have been made in the development of housings and interconnection layers made from low temperature co-fired ceramics (LTCC). Work is also in progress to develop low-cost millimeter-wave packages using electroforming. The electroforming process is an automatic, controlled batch method that consists of electroplating metal onto a soluble mandrel that is fabricated in exactly the desired package shape. Batch dissolution of mandrels leaves accurate, net shape metal housings available for immediate use.

Testing

In the test area, significant progress has been made in the development of both on-wafer test probes and high speed module testers. During the past year, Cascade Microtech has begun marketing a 75-100 GHz on-wafer probe system developed under MIMIC program funding. Previously, this company developed a similar 50-75 GHz on-wafer probe system, also under MIMIC funding. Technology has advanced so rapidly during the course of the MIMIC program, that the performance and loss characteristics of the 75-100 GHz probe system are superior to those of the previously produced 50-75 GHz probes in spite of the more demanding circuit requirements at high frequencies. In another MIMIC program sponsored tester development, Scientific Atlanta has substantially improved their commercially available test station that is used for microwave characterization of both modules and MMIC die on-wafer. This system has reduced time for module testing and automated data collection from many minutes to a few seconds for a very complete range of RF and DC parameters. This, of course, eliminates a commonly encountered production bottleneck and results in dramatically reduced module costs. A M/A-COM produced pulsed power test system has provided an additional greatly needed, rapid and inexpensive testing capability. Testing has traditionally been one of the largest components of both MMIC and transmit/receive (T/R) module costs.

Applications

All of the above technology developments have resulted in the increasing ability of MMICs to compete successfully for use in both military and commercial system applications. A recent commercial application, using processes developed under MIMIC program funding, is the Forewarn™ radar system that is currently being installed in school buses. This system is produced on a flexible production and assembly line that is also used for military radar T/R module production and assembly. It uses an adaptation of Hughes Aircraft Company X-band MIMIC radar chips, produced in the same MMIC foundries that fabricate military ICs, to warn school bus drivers of the presence of children within the "blind" areas surrounding buses. This product has generated enormous interest in the U.S. and is a precursor of similar obstacle warning systems for all classes of ground vehicles. Another MMIC consumer product, announced late in 1993, is a cordless telephone produced by AT&T. This telephone operates in the 900 MHz frequency band and uses frequency hopping, spread spectrum techniques to prevent undesired interception of transmitted information. An additional benefit of this telephone is its range, which is 4 times greater than that of lower frequency, older design telephones. The circuitry of this telephone was designed by RF Micro Devices (RFMD). It incorporates HBTs produced by TRW on fabrication lines developed under MIMIC program funding. Other tangible commercial market successes for MIMIC products include Raytheon HEMT chips and TRW HBT chips that are being produced and sold in Europe and Asia for direct broadcast satellite receiver applications. Raytheon is also supplying MMICs for the U.S. Iridium™ satellite transmitters and receivers. Iridium™ will provide worldwide cellular telephone service by the late 1990s. M/A-COM and Alpha Industries are also selling many thousands of MMICs worldwide, including parts produced by ITT and marketed through Alpha, for a broad variety of military and commercial applications.

Conclusion

In summary, the solid technology base developed under the MIMIC program has brought microwave monolithic circuits from experimental proof-of-concept demonstrations carried out in research and development laboratories to the status of the high yield, low cost, readily available products of today that are produced on highly automated fabrication lines. Much work remains to be accomplished to drive costs down further, extend product successes to higher frequencies (e.g., millimeter waves) and integrate larger numbers of functions on single chips. This will include development of still more advanced material structures, increased CAD capabilities, better models, more complete circuit libraries, more agile manufacturing lines, cheaper and higher performance multi-chip assemblies, and improved testing methodologies. However, a viable U.S. microwave monolithic integrated circuit industry has indeed been established which will serve the needs of the microwave community for many years to come.

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