EXECUTIVE SUMMARY

NASA
RCA-PRRL-82-CR-18

ADVANCED III-V SEMICONDUCTOR TECHNOLOGY ASSESSMENT

M. Nowogrodzki
Project Coordinator

RCA LABORATORIES
Princeton, New Jersey 08540

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center
Contract NAS 3-22884

1 Report No	2 Government Accession No	3 Recipient's Catalog No
NASA CR-168102		

4 Title and Subtitle ADVANCED III-V SEMICONDUCTOR TECHNOLOGY ASSESSMENT	5 Report Date February 1983 6 Performing Organization Code
7 Author(s) M. Nowogrodzki	8 Performing Organization Report No RCA-PRRL-82-CR-18 10. Work Unit No
9 Performing Organization Name and Address RCA Laboratories Princeton, New Jersey 08540	11 Contract or Grant No NAS3-22884 13 Type of Report and Period Covered Final Report Executive Summary
12 Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546	14 Sponsoring Agency Code

15 Supplementary Notes

Project Manager, Alan N. Downey, Space Communications Division, NASA Lewis Research Center, Cleveland, Ohio 44135

16 Abstract

Against a background of an extensive survey of the present state of the art in the field of III-V semiconductors for operation at microwave frequencies (or gigabit-rate speeds), likely requirements of future space communications systems were identified, competing technologies and physical device limitations were discussed, and projections of difficulties in implementing emerging technologies were made. On the basis of these analyses, specific research and development programs required for the development of future systems components were recommended.

17 Key Words (Suggested by Author(s))	18 Distribution Statement
Space communications components III-V technology Microwave transistors Gigabit-rate logic Spaceborne transponders	Unclassified -- unlimited

19 Security Classif (of this report)	20 Security Classif (of this page)	21 No of Pages	22 Price
Unclassified	Unclassified	16	

N-305

N83-21988#

EXECUTIVE SUMMARY

Under Contract NAS-3-22884, the impact of the state of the art in the area of III-V semiconductor materials employed in microwave solid-state components on future space communication systems was studied. Following the program format outlined by NASA, the study was pursued in terms of distinct tasks, as follows:

Task 1: Space Communications Applications

Task 2: Present Status of Technology

Task 3: Competing Technologies

Task 4: Fundamental Limits

Task 5: Problems in Implementation

Task 6: Recommendations for Implementation

In general, the investigations followed the plan developed in the original proposal. The two deviations from that plan concerned Tasks 1 and 2.

In Task 1, it was originally envisaged that future space communication systems could be identified on the basis of existing planning documents in sufficient detail to make possible the development of broad component "specifications," which would then serve as the background for Tasks 3, 4, and 5. This did not prove feasible, since few plans offering sufficiently precise projections - in terms of frequency, concept, or system architecture - could be gleaned from the literature. Thus, instead of very specific component specifications, the needs identified in Task 1 were broader in scope, based on subjective projections of what technical innovations future systems might contain, either in terms of evolutionary progress from present thinking (e.g., "large structures") or as a result of basic changes in technical approach (e.g., "reconfigurable transponders").

Although originally planned as one of a number of "coequal" tasks, it became apparent that Task 2 (Present Status of Technology) could well serve as the single most important task, central to the study. We therefore allowed (with the concurrence of the contract monitor) the expansion of this effort in terms of both scope and allocated time.

TASK 1: SPACE COMMUNICATIONS APPLICATIONS

The original intent was to define future space communications applications in detail sufficient to make possible the development of component specifications

- in terms of such parameters as frequency, function, mechanical characteristics, and reliability - to serve as a basis for the study. This did not prove feasible because of the lack of existing planning information on which such specifications could be based. It would, of course, have been possible to invent "future systems" solely for the purpose of defining the components they might require. Based on the program objectives, as discussed during an early planning meeting with NASA/LRC personnel (in September 1981), namely, the preparation of recommendations for NASA sponsorship of new broad technology development programs (rather than those for specific components) for future space communication systems, it was judged more productive to attempt to project future systems in terms of their more general characteristics and to extract new technological needs for systems so defined.

As a result of literature searches, meetings with personnel from technical and operating activities both within and outside RCA, and personal interviews with various individuals, the projections of future systems fell into three main categories:

(1) Systems that were logical extensions of systems currently being planned for the 1985-1995 time slot.

(2) Systems in which new types of modulation schemes would be employed.

(3) Novel system concepts that may strongly impact future space communications.

Evolutionary systems concepts considered in the study were (a) large antenna systems; (b) satellite crosslinks; (c) single-sideband systems; and (d) digital communication systems. Spread-spectrum techniques and quadrature-amplitude modulation are examples of advanced modulation approaches that might be used in future systems. Transponders that can be reconfigured by Earth command to change their electrical characteristics (e.g., from linear multi-carrier to saturated operation) and a concept originally proposed for the Solar Power Satellite involving a distributed antenna in which solar cells are placed on one side of a "space blanket" so that they can provide dc power directly to the antenna elements placed on the other side were considered as examples of novel concepts for future systems.

TASK 2: PRESENT STATUS OF TECHNOLOGY

In this section of the report, emphasis has been placed on materials and discrete device technology since this forms the basis of microwave and digital integrated circuits. We have attempted to project future trends and have included a subsection on the exploratory development that is being undertaken in many laboratories.

The field of III-V compound microwave and gigabit-rate logic technology is currently very active. We have tried to include most of the results published up to early 1982. The trends discussed in this section are believed to be reasonably accurate. The extensive literature references provided are representative rather than complete or in historical order.

We believe that a major change is occurring in III-V compound technology. The major attraction of GaAs for microwave and gigabit-rate digital ICs until recently was due mainly to the superior semiconducting properties of GaAs and not to its fabricating technology. New materials growth techniques such as molecular-beam epitaxy (MBE) and metal/organic chemical vapor deposition (MOCVD) now permit an unprecedented complexity, flexibility, and diversity in III-V compound growth. This technological strength, in addition to superior fundamental semiconducting properties, promises to make III-V compound research an exciting and useful endeavor in the mid-1980 to 2000 time frame.

The major topics reviewed in this section are:

1. Materials technology, including bulk growth of substrates, epitaxial crystal growth, and ion-implantation doping techniques.
2. Microwave solid-state discrete active devices, including two-terminal and three-terminal devices.
3. Multigigabit-rate GaAs digital integrated circuits.
4. Microwave integrated circuits, including both hybrid and monolithic circuits.
5. Exploratory developments currently being pursued, including GaInAs devices, heterojunction devices, and quasi-ballistic devices.

TASK 3: COMPETING TECHNOLOGIES

The main topics discussed in this section of the report are (a) rf power generation; (b) filter structures; and (c) microwave circuit fabrication. Each of these will profoundly influence the communication systems of the future.

In the area of power generation, the present trend of replacing thermionic devices with solid-state amplifiers in the spacecraft transponders is likely to continue, certainly at the lower frequencies. Various types of solid-state sources (FETs vs IMPATTs, GaAs vs Si) are likely to be used for transponders operating at different frequencies and power levels. Active antenna arrays, in which large numbers of antenna elements whose power is combined (in space) for fixed-, switched-, or scanning-beam systems are a very probable means of future generation of large amounts of power.

In the filter area, miniaturized active filters and new materials employed in dielectric resonators are expected to replace the present bulky and relatively heavy channel filters.

There are three distinct ways in which microwave circuits can be fabricated: In the conventional hybrid technology, active devices (packaged or in chip form) are mounted in custom-made microwave matching circuits, employing either distributed (transmission-line segments) or lumped-constant (capacitors, inductors) elements. In monolithic circuits, both active and passive circuit components are fabricated at the same time. In an emerging technology employing miniature hybrid circuits, the passive circuits are batch-fabricated and therefore quite cqst effective, while the active elements (e.g., FETs) are later placed in the circuits, possibly employing automated bonding methods. This latter technology may prove superior in systems where fully monolithic approaches may not be justified, for either technical or economic reasons.

TASK 4: FUNDAMENTAL LIMITS

The solid-state devices discussed in this section of the report can be functionally characterized to fit into two categories: linear devices and logic devices. Linear devices include both low-noise and high-power devices for transponder applications; logic devices are mostly for baseband signal processing.

For future applications, the transponder carrier frequency is likely to be higher than it is now - 20 GHz and above - because of the crowded lower--frequency spectrum. On the other hand, the trend of baseband signal processing may be expected to head toward complex, multifunctional processing to facilitate on-board switching functions.

In this task, we concentrated our study on the fundamental limits in high-frequency microwave monolithic integrated-circuit (MMIC) devices and in high-density logic devices. The fundamental physical limits such as electrical, thermal, and physical-dimension limitations are presented. Research areas in new device concepts as well as technology development that will affect the limits are also identified.

TASK 5: PROBLEMS IN IMPLEMENTATION

The recently completed major effort by RCA to develop, space-qualify, and transfer to a manufacturing operation an all-solid-state transponder for use in a commercial communication system provided valuable insights into the problem of implementing a new technology for a critical operation. These experiences - in terms of both manufacturing and test approaches and reliability-proof considerations - are reviewed in this section of the report. In addition, a new type of solid-state amplifier, the GaInAs MISFET, which may well provide linearity properties superior to those in present-day GaAs units, is discussed, as are the existing technology limitations in realizing high-speed digital monolithic circuits.

TASK 6: RECOMMENDATIONS FOR IMPLEMENTATION

This section contains recommendations on how to take advantage of the technical capabilities of III-V compounds so as to enhance the performance of future space communication systems. The following is noted:

(a) The recommendations are for technology-development programs, as opposed to specific mission-related programs. The RCA SSPA development for the SATCOM system may serve as an illustration: The technology of GaAs power FETs operating at 4 GHz was considered "ready" for exploitation several years ago. It took considerable skill, tight planning, a sizable commitment of funds, and several important ancillary programs - such as reliability proof, automated testing, "transfer of technology" to a manufacturing group, and the establishment of quality-assurance procedures - before this "ripe" technology could be utilized in spaceborne transponders.

(b) In estimating costs, it was assumed that most of the technology development would be done under contract. Contract administration and technical monitoring costs are NOT included in the projections, which are in 1982 dollars.

(c) III-V laser components are not included in the study. Also, programs that have been judged adequately covered by present NASA-sponsored effort were not included in the recommendations. As an example, ongoing and presently planned effort in the area of switches and switch matrices will likely result in components adequate for future space systems.

To focus more precisely on the recommended technology-development programs, classes of applications and their component needs were examined and tabulated. The results are presented in table VII-1 of the report.

The following is a list of programs recommended for implementation:

1(a) Antenna Module Technology (Monolithic)

2(b) Antenna Module Technology (Miniature Hybrid)

1(c) Antenna Module Technology (SMART)

2(a) Adjustable Transponder Components (Switched)

2(b) Adjustable Transponder Components (Electric)

3 Ternary-Compound Linear Amplifiers

4 High-Speed Digital Circuit Technology

5(a) Millimeter-Wave Device Investigations (Ternary Compounds)

5(b) Millimeter-Wave Device Investigations (Permeable-Base Transistor)

5(c) Millimeter-Wave Device Investigations (Quasi-Ballistic)

6 High-Efficiency, Lightweight, Miniature Ground Transponder

CONCLUDING REMARKS

Future space communication systems are likely to show technical advances that, for purposes of analysis, can be grouped into three categories: (1) extensions of present systems; (2) systems in which new types of modulation will be employed; and (3) novel system concepts based on progress in components technologies. The study described in this report examined microwave components based on III-V compounds that require development to fill these future system requirements.

Large antenna structures employed in future systems will require quantities of antenna modules which - depending on the frequency of operation and antenna characteristics - could be fabricated in either monolithic or miniature-hybrid form. To achieve better utilization of the crowded spectrum, "super-linear" amplifiers will be likely to replace units in the currently used frequency region. The concept of a transponder with characteristics (bandwidth, linearity) changeable on command from Earth offers a flexibility not obtainable with present-day systems. Intersatellite links of the future may well operate at millimeter wavelengths, possibly doing away with primary power distribution problems by the use of solar cells to power amplifier modules directly. Digital systems will require high-speed monolithic ICs.

Advances in III-V materials technology (molecular-beam epitaxy, organometallic epitaxy, the use of vapor-phase epitaxy for growing ternary and quaternary compounds) have made new transistor geometries possible. These show promise of outperforming conventional planar GaAs FETs at microwave and millimeter-wave frequencies. This may be a particularly fruitful area of research.

The conclusions of the study are contained in a number of specific recommendations for research programs aimed at components to be employed in the identified applications.

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