Monolithic Microwave Integrated Circuits: An Historical Perspective

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Abstract —Monolithic microwave integrated-circuit (MMIC) technology as it exists today has evolved from events that occurred during the middle-to-late 1950's and early 1960's. These events are reconstructed through a review of the published literature, government contract reports and proposals, U.S. patents, and private communications with individuals directly involved in early MMIC development.

No single point in time can be viewed as that historical moment when the idea of an MMIC was formalized; rather, the idea evolved over a period of time as a direct result of the successful development of analog and digital IC's and the push by the military services (primarily the Air Force at Wright Patterson) to apply semiconductor technology in defense systems. The evolutionary period is presented in chronological order and includes a discussion of the role played by the Molecular Electronics for Radar Applications program. Early development activities were pursued with both silicon and GaAs used as the monolithic material. These activities, the early problems encountered with both materials, and the influence the problems had in molding today's technology are described.

I. Introduction

MONOLITHIC literally means "one rock" and, in electronics, has come to mean the processing of active and passive components *in situ* on a semiconductor slab and providing interconnections to the components to form an integrated circuit (IC). This method is substantially the concept Jack Kilby of Texas Instruments originated in July of 1958 and had reduced to practice by September 12, 1958 [1]. The first public announcement of the "Solid Circuit" (integrated circuit) was made at the IRE show in March of 1959.

The extension of the integrated circuit concept for microwave applications is a basis for a part of this paper. The progression from germanium to silicon and from there to gallium arsenide forms another part of the story. The sponsorship of the Air Force and its role in developing and exploiting the IC for microwave use is also covered.

We were privileged, in writing this paper, to be able to speak or correspond with a great number of the early-day participants in the microwave monolithic integrated-circuit (MMIC) developments, both in industry and in government. All who were contacted were extremely helpful and cooperative, which made the research for this paper a most pleasurable and memorable experience. We also had access to the papers, patents, conference proceedings, and a number of laboratory notebooks from within Texas Instruments, as well as a number of artifacts preserved by engineers and technicians from the MERA project.

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The professional historian is well aware of the blurring of events in tracing a particular series of developments. We all tend to measure a history by milestones and to forget or overlook the in-between transitions which led to the milestone events. These transitory events often are more important in acquiring a real perspective and true knowledge than the milestone events. The insights acquired in tracing the developments of the MMIC have allowed us, in particular, a unique and interesting view of the way our modern microwave industry has come to its present status.

It was also of great interest that most of the pioneer workers in MMIC's have tended to measure their contributions in light of advances since made. Several were somewhat apologetic because results weren't as good as the goals established or because they had labored over some aspect of their work that probably appears trivial in our time. The fact that some of these developments were industry firsts and, in essence, quantum steps of a sort has been of little consolation to them. This paper is a belated attempt to record some of the more significant contributions of those who paved the way for a rapidly expanding segment of today's microwave technology. In this sense, we apologize in advance for any contributions we may have overlooked or omitted.

II. The Evolutionary Era

The first to perceive the possibility of integrated circuits based upon semiconductor technology was G. A. W. Dummer of the Royal Radar Establishment in England, according to Kilby [1]. Dummer, in addressing the Electronic Components Conference in 1952, said, "with the advent of the transistor and the work in semiconductors generally, it seems now possible to envisage electronic equipment in a solid block with no connecting wires. The block may consist of layers of insulating, conducting, rectifying, and amplifying materials, the electrical functions being connected directly by cutting out areas of the various layers."

In the summer of 1956, a session on "Molecular Engineering" was organized by Professor Arthur R. von Hippel at the Massachusetts Institute of Technology with experts from science, government, and industry laboratories invited to participate. The resulting papers were collected as the last volume of a triology by von Hippel entitled *Molecular Science and Molecular Engineering* [2]. The underlying theme was that materials could be designed and tailored for specific applications, and, in doing so, one could obtain true criteria for ultimate performance. In von Hippel's preface, he states it thusly: "No longer shackled by available materials and empirical performance characteristics, we can dream up completely new devices." In this sense, von Hippel was continuing the theme he had established in his earlier work *Dielectrics and Waves*, where he had written: "For a number of years my demon has urged me to oppose the trend of specialization by helping to develop a knowledge that belongs not only to physics and chemistry but is also of vital importance for modern electrical engineering" [3].

In the early 1950's, perhaps as a result of Dummer's comments, and influenced in part by von Hippel's idea of molecular science and molecular engineering, the Air Force began to define an electronic technology approach which would be called "Molecular Electronics." This approach proposed to depart from the electronic circuits of the past and to develop new structures which would perform the desired functions more directly.

Westinghouse was perhaps the leading manufacturer in developing the molecular electronics approach to microminiaturization [4]. The Air Force had discussed this concept with Westinghouse in 1957 and 1958. A contract was awarded in 1959 and the program was funded at a $2 million per year rate over the strenuous objections of the other services [1].

In a 1961 paper by Stelmak *et al.* [5], the philosophy as developed at Westinghouse was expressed as follows: "The molecular electronics approach to microsystems considers the electronic function to be performed, then attempts to synthesize its performance within a suitable solid material. It is expected that this approach will lead to many new concepts in the realization of electronic functions." For this purpose, an electronic system was divided into more basic building blocks termed Functional Electronic Blocks (FEB). The realization of the FEB required the usual existing transistor processes and relied on an extensive use of photolithography. Germanium and silicon were the most commonly used materials. Generally, circuit functions were excluded which might require component designs that could not be realized within a semiconductor such as wound inductors, mechanically variable capacitors, and large values of capacitance. These functions were provided by making external connections to those components. Kilby noted that a quartz crystal was the preferred example of a molecular device, performing the functions of an inductance and capacitance without a part-for-part equivalence. Resistors were to be avoided because they wasted power.

The most extreme example of the Westinghouse molecular electronics approach was the germanium dendrite used for multiposition electronic switches. The dendrite was grown from solution using two Ge seed crystals spaced a small distance apart so that, as the dendrite was pulled from solution, a long flat strip was formed. In Stelmak *et al.* [5], a 50-position Ge dendrite switch is illustrated. Each of the fifty positions had a four region n-p-n-p area with two of the four regions being common to all positions. These types of switches were also fabricated using silicon.

The solid circuit concepts developed at Texas Instruments by Kilby departed radically from the molecular electronics approach in that the circuit functions were defined more directly. There was no intention of eliminating the interconnecting wiring, and resistors were included as a part of the circuit, even though they did waste power.

According to Kilby, the solid circuit caused a major debate within the Air Force as to whether these circuits fit the molecular electronics approach. Most of the strong Molecular Electronics supporters felt the solid circuit did not qualify since the goal was to eliminate circuits and particularly the resistors. Fortunately, a small group within the Air Force, led by R. D. (Dick) Alberts, was able to prevail. They felt the concept provided an orderly transition to a new era, and that by providing a systematic design approach, it would eliminate the need to invent the thousands of new devices that would be required for future equipments.

The Molecular Electronics Branch headed by Alberts provided a series of contracts to fund the development of solid circuits at TI. These were low-frequency developments, as were most of the Westinghouse FEB's, and were meant as replacements for vacuum tube logic, video, and IF functions.

According to the engineers at AFAL who were evaluating both solid circuits and FEB's, both types of circuits looked alike since they were packaged similarly and generally performed equally well. The main difference was in the philosophy of design and these were only discernible to a highly trained observer aware of the two philosophies. It is our view that since TI had no intention of eliminating the interconnecting circuitry, they were somewhat freer to concentrate on developing a planar technology.

Within the 1960–1962 time period, there was a general U.S.A.F. push to investigate the feasibility of converting almost all conceivable electronic circuit functions to integrated-circuit form. Most of this work was performed in Alberts's Molecular Electronics Branch and the bulk of it was supported by Howard Steenbergen, who headed the Integration Techniques section of Alberts's branch [4]. The other section under Alberts was the Phenomena Exploitation section headed after 1962 by William (Bill) J. Edwards. E. D. (Sonny) Maynard was hired into this section in 1961 as an Air Force Lieutenant and later assumed primary responsibility for microwave technology developments, reporting to Edwards [6].

Alberts had hired Edwards in 1962 with the assignment to give microwave direction to then a hodge-podge of small programs grouped under Phenomena Exploitation, none of which had anything to do with microwaves. According to Edwards, Alberts didn't have a specific direction in mind when he told Edwards to "do something with microwaves" [7].

It is significant that Alberts was insistent from the start on the use of "research vehicles" to demonstrate the emerging IC technologies, an approach still favored by the services [6]. Logic functions and low-frequency amplifiers had been variously demonstrated in IC form and were tied to use in military equipments. Westinghouse during the

1960–1963 time frame had demonstrated FEB's in experimental hardware, such as a military radio receiver (ARC-63) [8] and an IR search/track system [9]. TI had taken a similar path using a digital computer and telemetry encoder as research vehicles to demonstrate the solid circuit approach. Between 1962 and 1963, sufficient bandwidth had been achieved in analog IC amplifiers so that 30-MHz RF amplifiers could be implemented as IC gain stages on etched circuits by Westinghouse.

In view of the successes by Westinghouse in radio and other systems, and by TI in digital computers, radar now came to be seriously considered by AFAL as the next major research vehicle in which to demonstrate IC technology. It was expected by the Air Force that Westinghouse was in a leading position to develop FEB's for radar. Accordingly, Howard Steenbergen drafted the announcement which was published in the *Commerce Business Daily* of December 13, 1963. Firms having research and development capabilities *in the specific area of molecular electronics for radar applications* were invited to respond to the following tasks:

KEA4159-64-15A THE STUDY AND ANALYSIS OF THE TRANSFER FUNCTIONS REQUIRED AND THE OPTIMUM APPROACH TO ACHIEVE THESE FUNCTIONS THRU THE UTILIZATION OF COMPATIBLE MOLECULAR ENGINEERING AND SOLID STATE MICROWAVE DEVICE TECHNIQUES. The study and analysis shall include all transfer functions associated with RF generation and transmission, radiation, reception, and info processing as required for a typical radar of the terrain clearance type.

KEA 4159-64-15B DESIGN AND DEVELOPMENT OF ADVANCED INTEGRATED CIRCUITS capable of providing the required transfer functions as determined by the study phase.

KEA 4159-64-15C DEMONSTRATE THE COMPATIBILITY OF THE DEVELOPMENTAL INTEGRATED CIRCUITS AND SOLID-STATE MICROWAVE DEVICES, DEVELOPED UNDER SUPPORTING RESEARCH EFFORTS, in a continually evolving research vehicle which will ultimately become a demonstrable engineering model of the selected radar assembly.

Prior developments within TI before the Molecular Electronics for Radar Applications (MERA) announcement and which led to TI responding to the MERA requirements came from within two different divisions of TI [10]. The Apparatus Division, now known as the Equipment Group, had been engaged since 1957 in developing terrain-following radar for manned aircraft (the AN/DPW-19). In support of the radar activities, considerable emphasis had been put on developing solid-state microwave components in such areas as parametric amplifiers, mixers, varactor multipliers, YIG filters, and IF amplifier strips. The microwave area was emphasized in that significant cost, size, and weight reductions could be realized by developing solid-state components to replace the existing vacuum tube technology. The Semiconductor (SC) Division supported these efforts through the Semiconductor Research and Development Laboratory (SRDL). By 1960, a planar transistor technology had been developed in silicon and germanium, using the mesh and overlay designs. Silicon and gallium arsenide diodes had been developed with cutoff frequencies in excess of 200 GHz for use in paramps and multipliers. Considerable work had been done in developing GaAs bipolar transistors also.

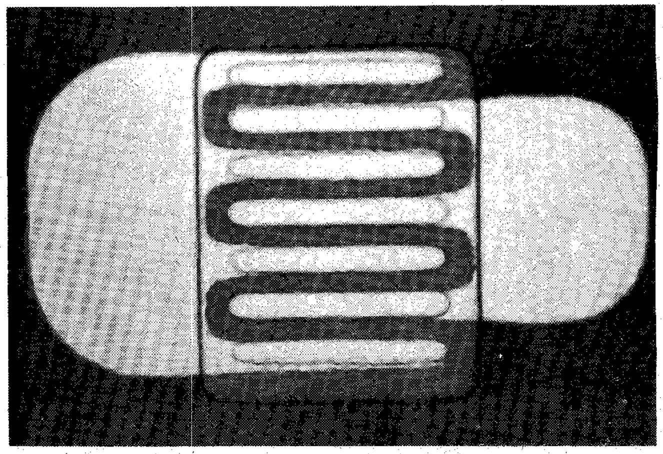


Fig. 1. TIX 3016 silicon planar transistor geometry.

In October of 1962, TI Corporate Management had started a company-funded program known as Microelectronic Circuit-Airborne Radar (MICAR) to support terrain-following radar using microelectronic integrated circuitry. The design approach was to examine a terrain-following radar system from a functional standpoint and evaluate each function that would benefit from conversion to thin-film or semiconductor networks. This program involved investigators from Apparatus and the SC divisions. The MICAR vehicle that evolved in late 1963 was essentially a redesigned AN/APQ-99.

One area in which TI was ahead of other companies was in high-frequency microwave-device developments which were needed to support the radar activities within the Apparatus Division. Roger R. Webster, Harry F. Cooke, and Andrew (Andy) J. Anderson were the investigators for high-frequency transistor developments in SRDL and by 1962 had made considerable advances using interdigitated planar topologies for Si bipolar transistors [11]. An example appeared in the MERA proposal and is shown in Fig. 1. The TIX3016, also known as the L-49, was a silicon device with seven interdigitated fingers of 0.1-mil width. Although better performance had been obtained using the mesa germanium transistor (the maximum frequency of oscillation $f_{\max}$ was in excess of 7 GHz), it was clear that better photomasking techniques and better control of shallow diffusions to lower the base resistance would be the best way to push $f_{\max}$ of silicon transistors to about 7 GHz. The interdigitated approach proved to be a good way to increase the power output. Fig. 2 shows a 65-stripe device, the 8307 transistor, which was developed for the MERA S-band power amplifier by 1965. The stripe width of about 0.1 mil represented the approximate limit for optical photomasks. A later device, the L-195, developed around 1968, had 195 stripes.

The MERA announcement in the *CBD* fit TI very well in the activities it had been pursuing. A proposal team headed by Phillip R. Thomas of SRDL was formed to respond, and team members were drawn from several different areas of the company. A major role was played by T. M. (Tom) Hyltin who was destined to become the MERA program manager [12].

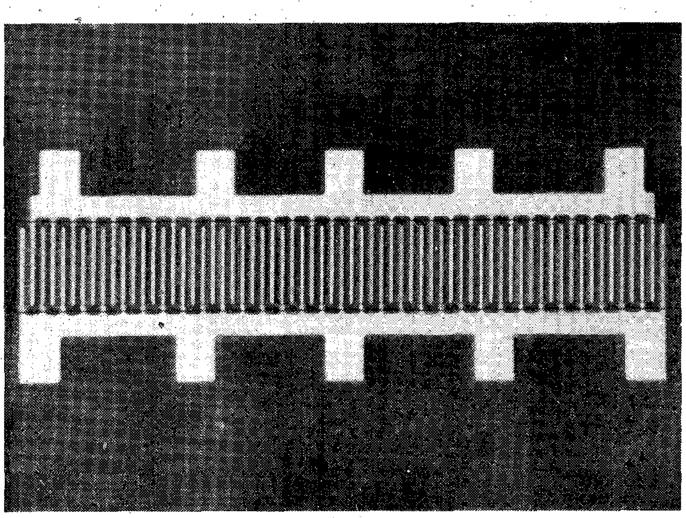


Fig. 2. The 8307 silicon transistor (65 Stripe—2 W at S-band).

Hyltin had developed, in 1960, the first completely solid-state multiplier chain using a silicon bipolar transistor as a fundamental oscillator and GaAs varactors to produce an L-band source. He subsequently was involved in several Apparatus microwave developments of which one was a multiport waveguide distribution feed for a prototype antenna array constructed in X-band waveguide. Hyltin, as the radar expert from Apparatus, began to press for a solid-state radar system, the approach finally proposed to AFAL.

The MERA proposal was quite detailed in the design approaches, probably because it was understood that Westinghouse had the leading position. The TI approach emphasized a distributive manifold to supply a 2250-MHz signal to an array of modules. Each module would, through a solid-state amplifying and multiplying chain, supply power to the antenna elements. These modules were identified as FEB's and were to have a peak pulse power output of 1 W at 9 GHz. A 100:1 pulse compression technique would be used to more effectively utilize the low peak power modules within the context of a higher peak power system. The system peak effective power output was to be around 50 kw (20 kw minimum), and the design goal was 100 kw. Digital phase shifters would be used at S-band to provide beam steering capabilities. A T/R switch was to be used at X-band to separate the transmitter and receiver functions. The number of modules could be increased to provide any desired power level and would be limited only by the size of the antenna array.

The MERA proposal, dated March 20, 1964, was submitted to the Integration Techniques Section at AFAL in early April of 1964. TI's proposed completely solid-state radar apparently went far beyond the expectation of some of the proposal-review team members [4]. Because of the combined low frequency and microwave developments involved, a joint evaluation ensued with personnel from Steenbergen's and Edward's sections. The MERA contract, AF33(615)-1993, was awarded to TI on September 30, 1964 for a one-year effort funded at around $600 K of 6.2 monies. This was for preliminary investigations, identified as Phase One. The Air Force interest in microwave technology sparked further investigations at TI into monolithic MIC's.

A number of patents were filed on September 18, 1964 by TI, in anticipation of the impending award from AFAL. These covered the initial work performed at TI and included the system as well as several component designs. U.S. Patent 3 454 945 by Hyltin covered the basic MERA system although it was entitled Modular Integrated Electronic Radar [13]. The system concept and the major components, including a switched-line phase shifter, were identified. Monolithic fabrication details were presented for the microwave circuits. Cooke, Hyltin, and Vincent also filed to cover antenna-related aspects of the system [14]. The antenna scan-control system was covered in another patent.

The remaining patents filed by TI on September 18, 1964 covered details of the mixer circuit to be used in the MERA module. The mixer was described as being monolithic and compatible with integrated circuits formed on high-resistivity silicon and gallium arsenide substrates. Kilby [15] had noted that some work to develop monolithic microwave integrated circuits had been in progress at TI prior to the MERA announcement, a viewpoint which is reflected in this series of patents further described below.

A significant point in Baird's patent on "A High Frequency Strip Transmission Line" is noted in references to integrated circuits [16] rather than solid circuits, the term previously used at TI. A reference to A. Uhlir's 1964 paper is cited [17] in Baird's patent. Edwards's recollection is that the term "integrated microwave circuit" was coined at Microwave Associates by Uhlir during a study completed by MA in late 1965 [7].

The microwave integrated-circuit mixer patent was filed by Thomas and Hyltin [18]. The surface-oriented diode for the mixer was covered in the patent awarded to Luecke [19]. Thomas also filed and was granted a patent for a stabilized integrated circuit which was to be used for high-gain amplifiers [20].

Preliminary work for monolithic microwave integrated circuits started in advance of the MERA award from AFAL. By August of 1964, according to entries found in laboratory notebooks, microwave transmission-line measurements were being performed on microstriplines on silicon by Hyltin with assistance from Vincent [21]. The measurements were in support of the monolithic X-band mixer development. Slices of p- and n-type silicon of various resistivities from 100 $\Omega\cdot$cm to 1500 $\Omega\cdot$cm were lapped and polished to 10-mil thickness. A range of line widths from 1 to 20 mils wide was measured using aluminum and silver metallizations in a thickness range from 10 to 500 μ inches. The problem in using substrates with finite resistivity is to stay below the intrinsic line over temperature. Hyltin demonstrated that 1500 $\Omega\cdot$cm (boron-doped) silicon could provide around 0.5-dB/cm loss over a temperature range from +5°C to +110°C. Welch and Pratt, in 1966, were unable to find any earlier references than Hyltin's paper and cited his work as having

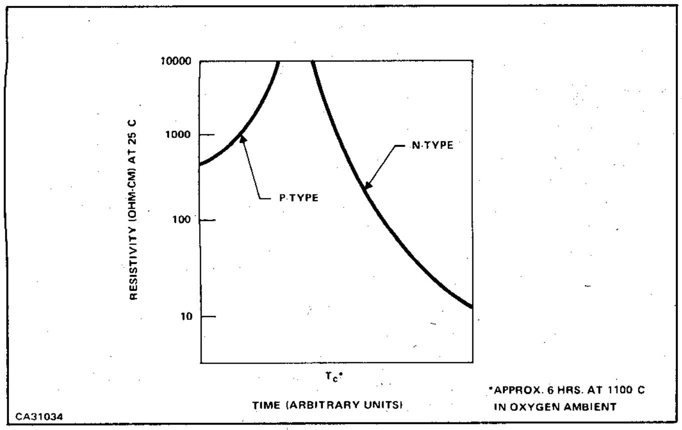


Fig. 3. Behavior of high-resistivity silicon during high-temperature processing.

the only available measured data [22]. Hyltin, in his paper, also refers to the use of semi-insulating gallium arsenide as a microstrip dielectric material and alludes to the resulting lower transmission-line loss relative to silicon; however, he did not report any measured data. Alumina was also measured for microstrip propagation but was not reported.

A number of experiments were performed during MERA Phase One with gold doping of high-resistivity p-type silicon (boron-doped) in order to minimize resistivity changes of the substrate with temperature [23]. Gold doping had been widely used in high-speed silicon switching devices to reduce lifetime. The amount of gold doping was in the range of the background doping, that is, between 10^{12} to 10^{14} atoms/cm^3. Highly doped n-type silicon (1 to 50 $\Omega \cdot$cm range) was also doped to obtain higher resistivity n-type but generally at the sacrifice of lifetime. Gold doping was used for most of the monolithic silicon MIC's investigated during the MERA program in attempts to reduce transmission-line attenuation variations over temperature and to reduce the lifetime for diodes.

The more critical problem encountered during the MERA developments of silicon monolithic MIC's was the conversion of high-resistivity p-type silicon to n-type lower resistivity silicon during the high-temperature processing sequences [24]. This is depicted in Fig. 3. This was thought to be due to the oxidation process in that silicon dioxide (used for masking in device processing) may act as a getter for boron so that surface states accumulated in the SiO_2 region and boron depleted from the substrate. It was generally noted that a highly doped phosphorus region in the silicon (or SiO_2 on the surface) appeared to getter the material causing the inversion; therefore a further speculation was that the inversion was due to a fast diffusing interstitial donor such as sodium or copper. Gold doping apparently aided in maintaining the high-resistivity characteristics during high-temperature processing, but was not extensively evaluated. No ready solution was found to the inversion problem in subsequent developments, and, generally, the device structures came to be designed with the idea of minimizing high-temperature processing steps. The background as outlined above was common to all the silicon monolithic MIC work attempted on MERA.

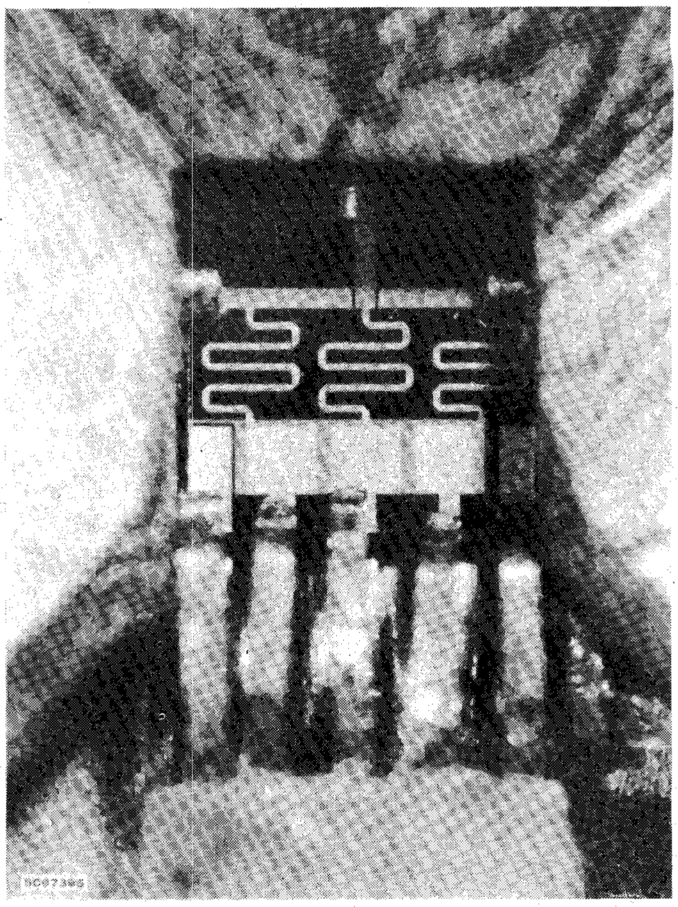


Fig. 4. The first monolithic silicon RF switch.

III. Silicon MMIC Development

The microwave circuits identified for monolithic integration for MERA were 1) an *X*-band T/R switch using PIN diodes, 2) an *S*-band mixer using a Schottky-barrier diode, 3) a $\times 4$ multiplier using planar varactor diodes, and 4) a 500-MHz IF amplifier using transistors in a two-stage design. High-resistivity p-type (boron) silicon was utilized as the microwave substrate and as host for the devices in all of the above designs.

The *X*-band T/R switch by Alfred Ertel is the earliest example of a silicon monolithic MIC [25]. A photograph of the TR switch mounted for testing is shown in Fig. 4. The surface-oriented diode was of the type described by Luecke and mentioned earlier in this paper [19]. A photograph of the seven-finger interdigitated surface-oriented p-i-n diode is shown in Fig. 5. The interdigitated structure was used to avoid deep diffusions in an attempt to minimize the inversion problem. An ohmic contact was used on the p-i-n diodes so that a shunt bias path was also established through the high-resistivity substrate to ground. This resulted in "conductivity modulation" of the substrate since uncombined carriers from the junction were injected into the substrate [26]. Conductivity modulation was due to the lack of a suitable isolation structure between the active

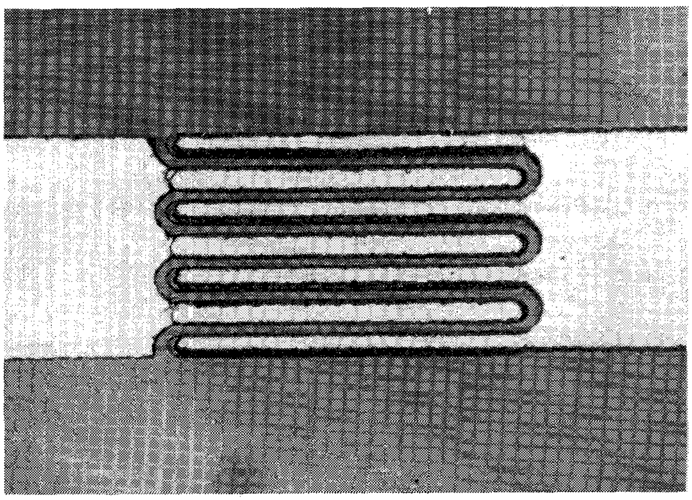


Fig. 5. Interdigitated surface-oriented p-i-n diode (TR switch).

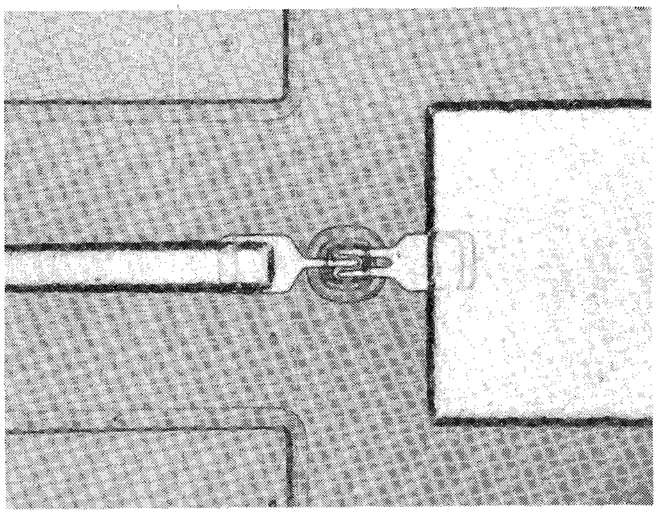


Fig. 6. Schottky-barrier diode in X-band mixer.

devices and ground, and was a problem for all monolithic MIC's. The isolation of the T/R switch was in the 25 to 27-dB range from 8 to 9 GHz, but the insertion loss of 1.5 to 2.0 dB was much too high for use in the MERA modules. A hybrid alumina T/R switch with an insertion loss of 0.5 dB was developed as an alternative and used in the MERA modules.

The X-band balanced mixer integrated circuit was first reported at the 1966 International Solid-State Circuits Conference in Philadelphia by Portnoy and Hyltin [27]. Single selective epitaxial deposition of low-resistivity silicon (0.025-Ω·cm n-type) was performed in etched pockets on the high-resistivity substrate. The principal difficulty was in nucleating the epitaxial deposits within the selectivity etched pockets to form deposits of uniform crystallinity and resistivity. The epitaxial growth also tended to "tip over" the edges of the pockets and so caused problems with the metallization patterns. A close-up of the Schottky-barrier diode pattern is shown in Fig. 6 (note particularly the circular pattern defining the etched pocket). A single-ended version of this mixer was reported later by Portnoy and

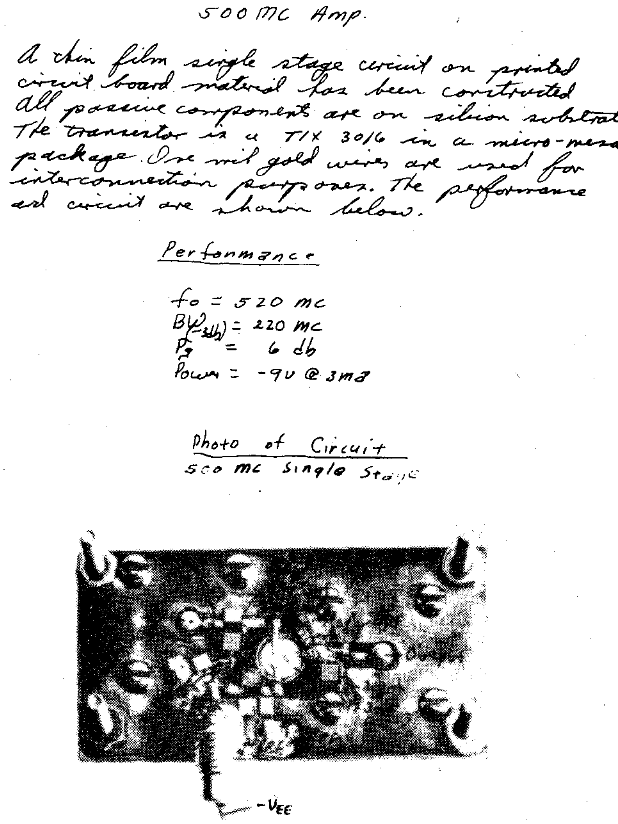


Fig. 7. 500-MHz IF amplifier prototype circuit (chips).

Leedy [28]. Portnoy and Leedy also noted the inversion problem since they had started with high-resistivity p-type (~800 Ω·cm) and ended with n-type of between 5000 to 17 000-Ω·cm resistivity. These mixers were not used due to the fabrication difficulties encountered.

Planar varactor diodes using the single epitaxial deposition within selectively etched pockets were to be used for a ×4 multiplier design. Very little progress was made on the ×4 multiplier due to the difficulties encountered with the mixer as outlined above.

The 500-MHz IF amplifier was the most difficult of the silicon monolithic circuits attempted. The first design started was a two-stage tuned amplifier using inductors and capacitors [29]. This was done on a silicon high-resistivity substrate, but chip transistors were used because of the difficulties in making the first chips. The transistor was to be a seven-stripe interdigital design and was to be fabricated using a double-selective epitaxial deposition into selectively etched pockets. A single-stage prototype circuit using chip components fabricated on a high-resistivity silicon substrate and chip transistors is shown in Fig. 7. A photograph of a completed version is shown in Fig. 8. (Chip transistors were used in this circuit due to transistor fabrication problems.) A video-type amplifier with wide bandwidth was next designed because of the difficulties experienced with the lumped-inductor tuning. This circuit was measured in March 1967 and had 5.5-dB gain and 12.0-dB noise figure. It was not developed further. Figs. 7 and 8 were taken from W. H. (Bill) Tulloch's lab notebook.

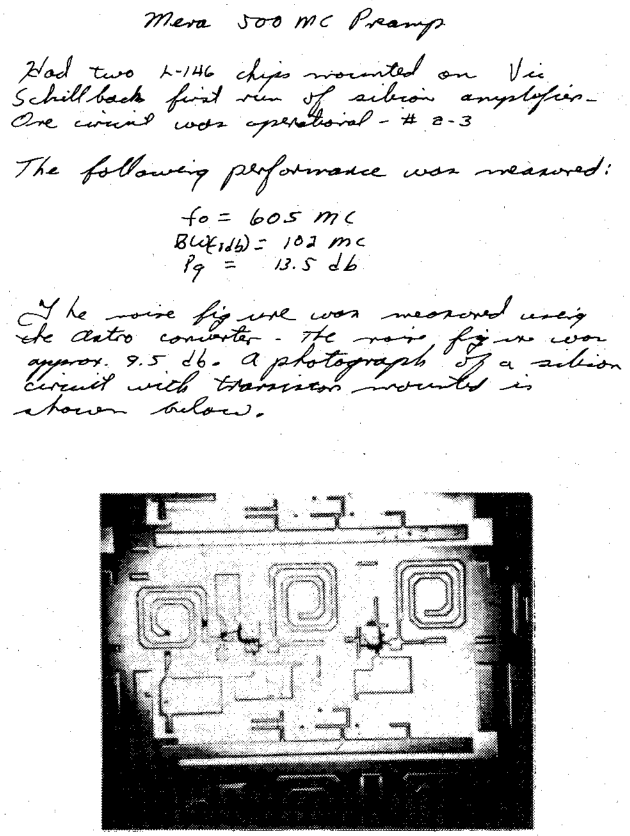
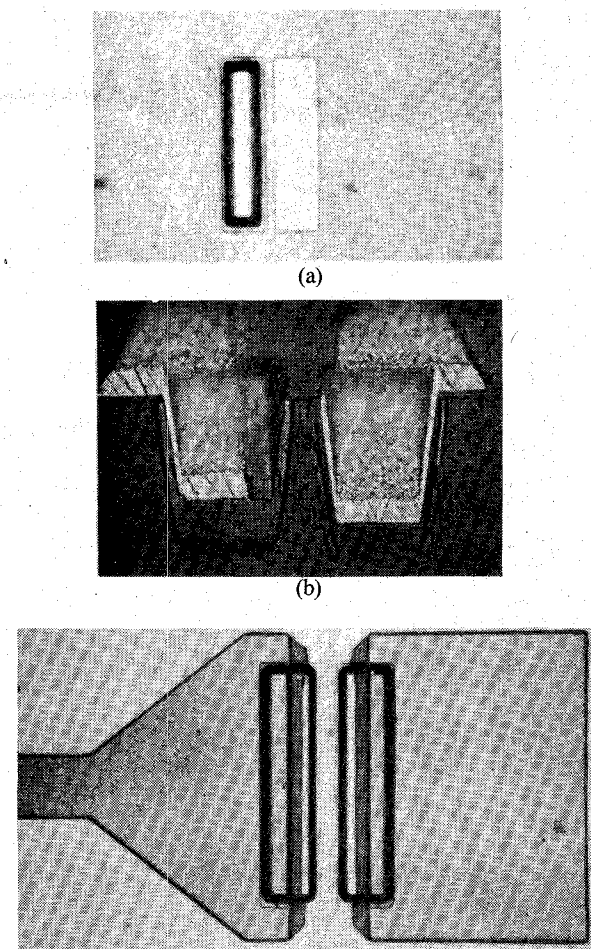


Fig. 8. 500-MHz IF monolithic amplifier with chip transistors.



(a) (b) (c)

Fig. 9. Pocket SOD structure (*Ku*-band phase shifter). (a) Top view before metallization showing etched pockets. (b) Bevel lap and vapor etch to show preferentially etched pockets and diffusion control. (c) Completed pocket SOD with contact metallizations.

The MERA array was completed in June of 1968. The array was composed of 604 modules with an average power output of 600 mW, which was less than the design goal of 1 W. All of the microwave components were fabricated using chip components on alumina microstrip circuits. The hybrid microwave integrated-circuit concepts were developed to achieve the small size required for the array.

One other significant silicon monolithic MIC development was performed at TI based upon a reflective three-bit phase-shifter design patented by Hyltin, Hoffman, and Austin [30]. The p-i-n diode was fabricated in pockets in order to minimize diffusion times and still be able to obtain a high-quality p-i-n diode. The pocket surface-oriented diode (SOD) had a total reverse capacitance of 0.034 pfd for a pocket width of 2 mils and length of 10 mils. The etched depth of the pocket was about 10 μm. The reverse voltage breakdown was in excess of 300 V. The diode structure is more fully described by Battershall and Emmons [24]. A photograph of the SOD with associated processing steps is shown in Fig. 9. The *Ku*-band phase-shifter development was performed under AF33(615)-67-C-1817 by F. E. Emery *et al.* [31]. A photograph of a completed phase-shifter slice is shown in Fig. 10. Inversion of the substrate was controlled successfully by using the pocket SOD approach to limit diffusion times. Starting material was 300 $\Omega \cdot$cm (p-type), and 1200 $\Omega \cdot$cm (p-type) was obtained for the final resistivity. Conductivity modulation was still a problem in that the insertion loss depended upon how many diodes were turned on. Gold doping was used to reduce the substrate lifetime and to improve the insertion loss.

Polycrystalline silicon was also investigated as a substrate material during the *Ku*-band phase-shifter project. Epitaxial deposition into etched pockets would have been used for the p-i-n diodes in order to obtain device isolation. This substrate showed a high microwave attenuation, 2 to 3 dB/cm, for microstriplines.

In order to avoid conductivity modulation of the substrate, silicon heteroepitaxy on either spinel or sapphire has long been under investigation. Low lifetimes, on the order of tens of nanoseconds compared to microseconds for bulk silicon, limit the choice to unipolar devices. Silicon MESFET's fabricated on silicon-on-sapphire (SOS) material have been combined with passive elements to produce MMIC's operating at the lower end of the microwave spectrum.

R. J. (Dick) Dexter, then at TI, explored the feasibility of producing buried insulating layers in high-resistivity p-type silicon (1000 $\Omega \cdot$cm) during the course of a monolithic MIC feasibility study performed in 1972 [32]. Nitrogen or oxygen was to be ion-implanted (150-Kev potentials) below the surface of the silicon substrate. The dose

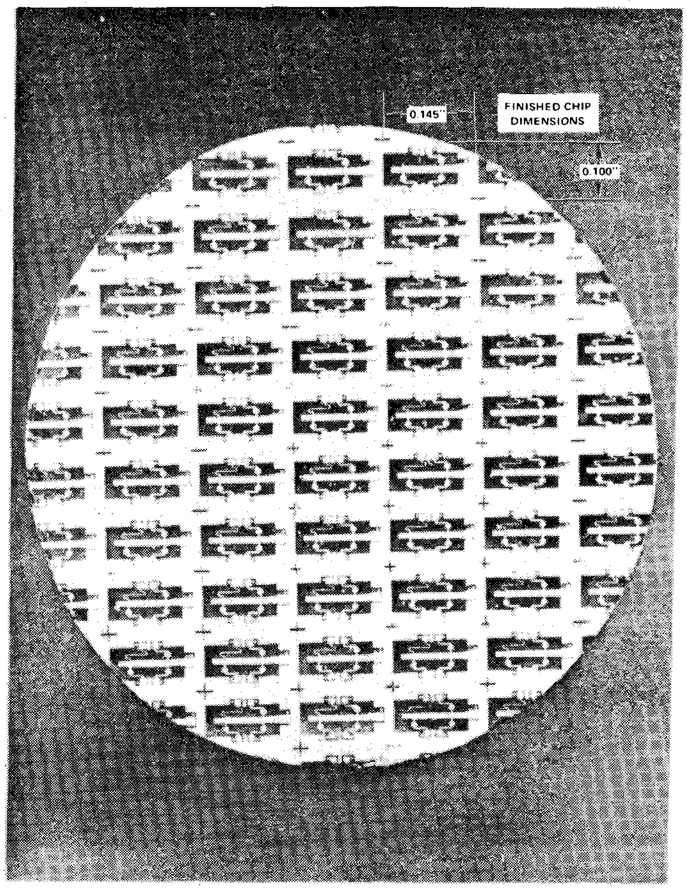


Fig. 10. Integrated *Ku*-band phase-shifter slice.

rates could be calculated to produce a stoichiometric layer of either Si_3N_4 or SiO_2 as much as 0.3 μm below the surface. The best results were obtained with Si_3N_4, which had a voltage breakdown of 30 V in one direction and >100 V in the other direction. The substrates were annealed at 1200°C for one hour to combine the buried ionized particles with silicon and to partially anneal the surface damage. Epitaxial high-resistivity silicon was deposited on the silicon substrate, but the stacking fault density was marginal for microwave devices. The technique appeared promising although it was not investigated further after the study was completed. No further silicon monolithic MIC work was pursued at TI after 1972.

As an interesting aside, Julius Lange was working at TI for Harry Cooke in 1968 when he invented his 3-dB hybrid coupler [33]. Lange was primarily involved in characterizing and evaluating silicon bipolar interdigitated transistors at that time.

IV. GaAs Emerges as the MMIC Material

GaAs was recognized early on as a suitable semiconductor material for MMIC fabrication. Uhlir, in his 1964 paper, describes how GaAs could serve as a high-quality dielectric and substrate for epitaxial deposition of germanium, in which transistors could be fabricated [17]. The germanium step was required because "gallium arsenide transistors are a problem." A patent covering the MERA system mentions a monolithic mixer circuit that could be fabricated on GaAs. Hyltin, in a patent application filed in 1966, described an MMIC consisting of a local oscillator (Gunn diode), microstrip transmission lines, and a balanced mixer, all integrated on a semi-insulating gallium arsenide substrate [34].

Two factors are primarily responsible for the major role played by GaAs in the development of MMIC's. First, the semi-insulating substrate serves as a nearly ideal medium for the dielectric required for microstrip transmission. The semi-insulating property of GaAs was discovered in the early 1960's. In 1964, G. R. Cronin and R. W. Haisty of TI first reported on the use of Cr doping to reproducibly achieve high-resistivity GaAs crystals [35], [36]. Using this approach, resistivities of 10^7–10^8 $\Omega \cdot$cm are routinely achieved. The second factor key to the dominant role of GaAs in MMIC's is the GaAs field-effect transistor (FET). The processing of the GaAs FET is very similar to that for Si transistors, and therefore, advances in Si processing technology and equipment have greatly benefitted the GaAs FET. This is particularly true in the area of lithography where the relatively small volume requirement for GaAs devices could not support the large investment required to bring lithography to its present highly advanced state.

The field-effect transistor was proposed by W. Shockley of Bell Laboratories in 1952 [37]. The cutoff frequency of early FET's was inferior to bipolar transistors, however. In 1966, C. A. Mead of the California Institute of Technology made the first Schottky-barrier MESFET using GaAs material obtained from L. Bailey and E. Mehal of TI [38]. While the geometry of this device was such that microwave operation was not possible, it demonstrated the feasibility of this approach. In 1967, W. W. Hooper and W. I. Lehrer of Fairchild reported on the first microwave GaAs FET [39]. This device had an f_{max} of 3 GHz, which was inferior to Si bipolar transistors available at that time, but this result helped to spur further FET development. In 1970, K. E. Drangeid *et al.* of IBM Zurich Research Laboratory reported on a GaAs FET with a 1-μm gate that had an f_{max} of 30 GHz, performance clearly superior to other transistors of any type [40]. This device had 6-dB gain at 10 GHz. In 1972, W. Baechtold, also of IBM Zurich, reported on the first *X*-band FET amplifier [41].

It was not until 1973 at the ISSCC that L. S. Napoli *et al.*, of RCA, and M. Fukuta *et al.*, of Fujitsu, reported on GaAs FET's designed for power operation [42], [43]. Fukuta reported on a 2-GHz device that had an output power of 1.6 W with 5-dB gain. The RCA device operated at 4 GHz with an output power of 250 mW at 4-dB gain. At the time these results were achieved, TI was working on an Air Force program to develop a low-cost module for phased-array radar applications [44]. GaAs IMPATT diodes were being developed for this purpose. In the summer of 1973, by mutual agreement between AFAL and TI, the program was modified to include an evaluation of the GaAs FET as a possible solid-state power source. L. S. Napoli presented a paper at the Workshop on Compound Semiconductors for Microwave Devices in Philadelphia in February 1974

[45]. During that presentation, he predicted that GaAs FET's would deliver 5 W at X-band in the future. This prediction was met with some scepticism and laughter by the audience. The first X-band power FET results obtained at Fujitsu and TI were well short of Napoli's prediction [46], [47]; however, in 1978, TI achieved 5.1 W at 8 GHz with 5-dB gain while working on another Air Force contract [48]. There have been several review articles on GaAs FET technology. C. A. Liechti wrote a comprehensive review of microwave FET's in the June 1976 Special Issue of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES [49]. DiLorenzo and Wisseman published a review article on GaAs power FET's in 1979 [50]. Recently, several books have been published on this subject [51]–[53].

The first work on GaAs monolithic microwave and millimeter-wave integrated circuits was carried out at TI in the late 1960's under Air Force sponsorship [54], [55]. The primary objective of this effort was the development of a monolithic 94-GHz receiver. The chip included a planar Gunn oscillator and planar Schottky-barrier diodes. Although a functional fully monolithic receiver was not demonstrated on this program, the work formed the base of future work on MMIC's.

It was not until 1976 that R. S. Pengelly and J. A. Turner of Plessey reported on the first GaAs X-band amplifier that was fully monolithic [56]. The amplifier had a single FET and lumped matching elements. The capacitors were interdigitated. The chip size was 1.8 mm by 1.2 mm, and the amplifier had a gain of 4.5 dB over the 7.5 to 11.5-GHz frequency band. The first power FET amplifier was reported at the 1979 ISSCC by V. Sokolov *et al.*, of TI, on an ONR sponsored program [57]. Both one- and two-stage amplifiers were developed using pairs of FET's connected in a push–pull configuration for each stage. The two-stage amplifier consisted of two 600-μm and two 1200-μm FET's on a 2.0-mm square chip. The amplifier had a gain of 10 dB at 9.5 GHz and an output power of 1.26 W. A photograph of the two-stage amplifier is shown in Fig. 11. Later in 1979, at the MTT-S Microwave Symposium, R. A. Pucel *et al.* of Raytheon reported on a single-stage, single-ended power FET amplifier that delivered 400 mW at 10 GHz [58].

Work at TI on multistage single-ended amplifiers began in 1979 under Air Force sponsorship. Preliminary results for a four-stage amplifier that operated at 3.5 GHz were reported in late 1979 [59]. Later, a four-stage X-band amplifier was developed that delivered 1 W with 27-dB gain over the 8.6 to 9.2-GHz frequency range [60], [61]. On a recent Air Force program, this four-stage amplifier was redesigned to operate at 7.5 GHz [62], [63]. The objective of the program was to develop an electronically steerable transmitter incorporating 150 monolithic amplifiers for satellite communications applications. The amplifier goal was 1.2 W with 30-dB gain with 20-percent efficiency over the 7.25 to 7.75 frequency band. The best performance achieved was 1.3 W with 32-dB gain and 30-percent efficiency. Over 400 monolithic chips capable of 1-W or more output power were supplied for packaging and use in the array. This is believed to be the first application of large quantities of "identical" monolithic chips at this or higher frequencies.

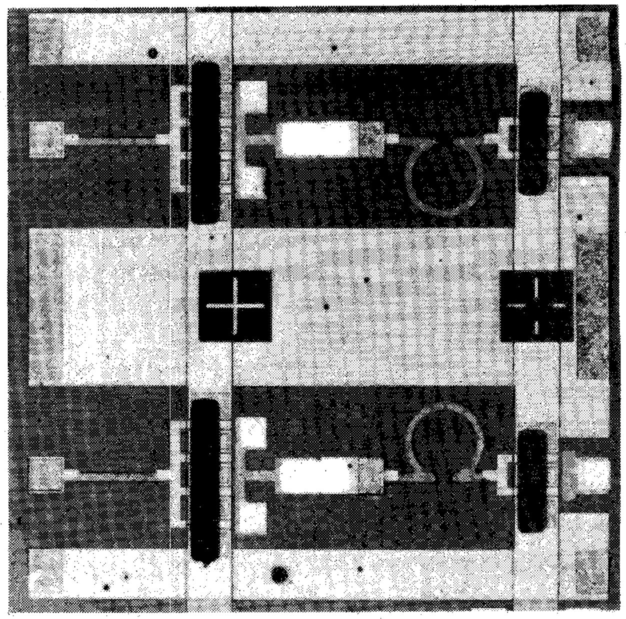


Fig. 11. The first monolithic GaAs power amplifier.

The emphasis of the above discussion has been on the development of power amplifiers since this work has led monolithic technology development and is believed to be key to volume applications. There have been extensive efforts on other monolithic components, however, including low-noise amplifiers, voltage-controlled oscillators, phase shifters, and couplers. Some of these developments were covered by R. A. Pucel in his review article (MTT National Lecture Invited Paper) [64]. MMIC's are also discussed in recent books on FET technology [52], [53].

During the past several years, work on monolithic technology has accelerated due in part to large DARPA sponsored programs at TI and Raytheon for the development of monolithic radar modules [65]. There has also been significant activity in the development of monolithic receivers for direct TV reception from communication satellites, particularly in Europe and Japan. One measure of progress in MMIC technology is the fact that two IEEE-sponsored annual Symposia have been organized on this subject: The GaAs IC Symposium and the Microwave and Millimeter-wave Monolithic Circuits Symposium.

V. SUMMARY

It is only fair to note that many were critical of monolithic MIC's and the MERA phased-array program, not only within TI and the services, but also throughout the industry. Harold Sobol, then at RCA, followed the MERA developments closely as evidenced by a paper published in 1967 [66]. His viewpoints were widely circulated and quoted during that time because cost effectiveness is an essential part of the innate conservatism of our engineering profession. In a later paper, Sobol developed this theme further, pointing out the real estate requirements of the devices are only a small percentage of the total circuit, and that cost is proportional to the yield, which was very poor at that time. It was not apparent at that time that the monolithic approach could offer any cost advantages over the hybrid MIC [67].

The cost advantages of monolithic MIC's are now becoming more apparent with the continual advances and refinements within the microwave industry. The inherent precision in monolithic processing, the elimination of tedious, exacting hand-assembly operations, and inexorably rising labor costs have forced a new look at all phases of monolithic MIC's. The microwave market has expanded significantly to provide the semiconductor manufacturer with good incentives to develop monolithic MIC's. It is significant that Avantek has recently introduced a silicon monolithic amplifier for up to 2-GHz applications.

A score of years has passed since the MERA proposal was submitted to the Air Force. Now, von Hippel's demon would be gratified at the large number of microwave practioneers who daily run the gauntlet of materials, processing, devices, circuits, and systems. It brings to mind the time when Hyltin, as the MERA program manager, would wander through the lab upon arriving at work. He would visit each bench, checking on the progress of the work and chatting with the technicians. When he was pleased with the progress, he would stutter in his characteristic way, "Ain't Science Wonderful!" Indeed, Tom, and it continues to be so.

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Reflection Charts Relating to Impedance Matching

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***Abstract* —A reflection chart is some grid of coordinates on which to plot an impedance locus over a frequency range. Taking as a reference a constant real impedance, one may construct contours of the reflection coefficient (or the related VSWR, reflection loss, etc.). The reference may be the wave impedance of a transmission line. This may be a line connecting radio equipment with an antenna, or it may be a standard line used in measuring the impedance. The reflection chart in widest use is the so-called "Smith Chart" proposed by Philip H. Smith in 1939. It is one form of the hemisphere chart, which was proposed, also in 1939, by Philip S. Carter. Its properties and uses are described. It has some limitations. A reference value must be assigned, after which the shape of a locus depends on this value. Also, a locus is crowded toward the rim of the chart. A logarithmic reflection chart has recently been proposed by the author, which overcomes these limitations but loses some desirable features of the hemisphere chart.**

I. Introduction

A REFLECTION CHART is a pair of coordinates on which to plot an impedance locus over a range of frequency. The complex impedance may be described in rectangular or polar coordinates. The impedance may be expressed by a ratio over a reference value (Z_0), which is customarily the constant real wave impedance of a transmission line or cable. Then this ratio determines the reflection loss in the transfer of power between a device having the general impedance and a device having the reference impedance.

The most widely known of reflection charts is the so-called Smith Chart, which was first published 45 years ago in 1939 [6]. It is one form of the hemisphere chart. On a circular area, there is an orthogonal grid of circular lines marked with the real and imaginary components of the impedance ratio. These cover the entire range of impedance with positive-real part. This feature is peculiar to any hemisphere chart.

There are various uses of the hemisphere cart. Smith emphasized its utility for computations with the aid of a radial scale pivoted at the center of the chart. Typical computations were series and parallel impedance, and the transformation of impedance through a section of line. The radial scale could be calibrated in any function of the reflection coefficient (ρ), such as the reflection loss at a junction or the voltage standing-wave ratio (VSWR $= S$) in a line terminated in the impedance. Carter, in his simultaneous publication [5], emphasized the use of the hemisphere chart with a standing-wave indicator to measure the impedance ratio of a load on a line. On the circular area, he showed a grid of circular lines marked with the magnitude and angle of the impedance ratio, corresponding to latitude and longitude on a hemisphere. The most advanced equipment for impedance measurement at high radio frequencies (say above 1 MHz) uses an automatic mechanical plotter on the Smith Chart, with an option of digital readout of the reflection coefficient (magnitude and angle) [25].

The hemisphere chart, by virtue of its orthogonal circular coordinates, offers much opportunity for displaying the frequency behavior of an impedance network and various relations, such as resonance. One common application is the wide-band matching of a load that has some limitation on its bandwidth, such as a resonant antenna.

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