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SURVEY OF MICROMINIATURIZATION OF ELECTRONIC EQUIPMENT

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SUMMARY

Rapid advances in microminiaturization of electronic equipment will affect missile and space vehicle electronic design within a short period of time. To assess the potential impact of the new techniques, a field and literature survey of current progress has been made.

Approximately 150 firms in the electronic equipment and parts industry are energetically engaged in microminiaturization research, development, and technical support. A wide variety of techniques are employed.

Some manufacturers are fabricating microelements of thin films deposited on very small glass or ceramic wafers; these microelements are then stacked, interconnected, and encapsulated into complete circuits. One firm has deposited complete 14-part circuits on 1/4 square inch of surface. Various semiconductor manufacturers have developed complete circuit modules on silicon or germanium material no larger than a conventional transistor. Other approaches utilize molecular techniques to obtain circuit effects from a single block of material without identifiable electronic parts. Additional firms use resistance welding and small encapsulated printed circuits for high-density packaging of very small parts. Still another organization is developing an evacuated ceramic thermionic circuit module for high-temperature use. Rapid progress is being made.

A wide variety of fabrication techniques are used, ranging from vacuum, electrical, and chemical depositing of thin films to the growing of semiconductor ribbons. Among methods used are spectrographic plates for photo resists, screen and photolithographic printing, micromachining, air abrasion, ultrasonic machining, and electronic etching.

Microminiature circuits of some types are expected to be available soon for limited applications. Improved performance, resistance to environmental extremes, and increased reliability can be anticipated. Reduced size will eventually permit satellite payloads with highly sophisticated instrumentation and completely redundant control systems.

I. PHILOSOPHY OF MICROMINIATURIZATION

Electronic equipment has been reduced in size and weight over a period of some 40 years in a series of progressive steps resulting from increasingly efficient design and advances in technology. Present developments, which will result in even smaller and lighter equipment, are collectively designated as microminiaturization.

A. Definition

Microminiaturization, the packaging of electronic circuits in units so small that handling by manual methods and identification of individual component parts is almost impractical, is commonly defined as the fabrication of electronic equipment at least a full order of magnitude smaller than present-day equipment. Compared with present-day subminiature equipment, which may utilize 25,000 to 35,000 electronic parts per cubic foot, microminiature equipment is capable of utilizing the equivalent of 250,000 to 10,000,000 parts per cubic foot.

Microminiaturization may be further defined as a group of techniques involving the following:

1. Use of thin metallic films, semiconductors, solid state materials, and other devices made possible by application of recent developments in physical science.

2. Design of integrated modular circuits, such as multivibrators, inverters, amplifiers, and counters, which can be used as building blocks for a complete electronic system.

3. Increased volumetric efficiency by elimination of bulky, inert, and nonfunctional protective coverings, insulation, and cases of individual electronic parts. Only the essential operating core of the part is used.

B. Considerations

Much more is expected to result from microminiaturization than mere size and weight reduction. Basic considerations include the following:

1. Improved circuit speed and efficiency will be provided by closer physical location of circuit elements and elimination of wiring leads and connections which often result in undesired side parameters.

2. A more uniform product, more closely controlled processes, and elimination of human error inherent in hand-made items will result from use of automatic machinery necessitated by the requirement for small elements, including many of microscopic size.

3. Heat, a major factor in circuit breakdown, can be substantially reduced by use of more efficient circuit elements.

4. Greater resistance to shock, vibration, and acceleration conditions will be provided.

5. Smaller size allows for more efficient utilization of space. The same amount of available space can be used for the performance of an increased number of functions in missile and space vehicles. Completely redundant standby systems can be provided in the same volume used by present-day equipment.

6. Fabrication of such items as resistors, capacitors, diodes, and similar electronic parts as individual component parts will virtually be eliminated.

7. Electronic equipment manufacturers primarily engaged in assembly of purchased parts may find their role in the industry declining rapidly.

8. Radical redesign of present-day circuitry will be required to take full advantage of new characteristics, performance, and properties.

9. Highly trained engineering scientists, who possess the combined approaches of the electronics engineer, mechanical engineer, physicist, and chemist, will be required to design microcircuits and microminiature equipment.

10. Automated machinery and highly mechanized equipment will be needed for electronic fabrication, assembly, and testing.

11. Improved reliability may be anticipated. Fewer interconnections, more closely controlled fabrication methods, and reduced size, weight, power, voltage, and heat dissipation can result in electronic equipment better able to withstand operating and environmental conditions.

12. Although microminiature equipment will be almost impossible to repair or service, thus forecasting the use of expendable units, these disadvantages will be largely offset by longer life expectancy of the units.

Microminiaturization is the next step forward in electronics, made possible by the vastly increased knowledge of modern physics, by new materials and techniques exploiting solid state physical phenomena, and by the continuing demand for progressive reduction in size and weight of equipment.

II. OBJECTIVES OF INVESTIGATION

The purpose of the STL microminiaturization survey is to determine the state of the art and to evaluate potential effects of the new techniques, with emphasis on electronic design for missile and space vehicle applications.

Specifically, the investigation has sought to discover the following:

A. Progress

An attempt has been made to learn the various approaches taken toward microminiaturization and the concepts on which they are based. This has included study of the techniques, materials, and processes used to achieve the desired results, as well as accomplishments in fabricating experimental or prototype microminiature circuits or modules. Preliminary test data, indicating electrical performance of circuits and ability to withstand environmental conditions, have been particularly desired.

B. Program

Information has been sought on the estimated time scale required for development of microminiature equipment. The length of time devoted to research by each organization and accomplishments to date have been used to estimate when circuits and modules may be expected to be available for testing and evaluation. Estimates have also been sought on test programs, design of complete equipment utilizing microminiaturization techniques, tooling, and availability of production models.

C. Present Activity

The investigation has attempted to determine the present nature of microminiaturization activity in an effort to evaluate the potential results of research and development work, types of circuits on which work is being done, problems encountered, and applications which appear most promising for microminiature circuitry. The survey also included evaluation of ability to handle developmental contracts as well as to observe work on existing military contracts.

D. Capabilities and Resources

Information has been sought on the comparative abilities of organizations engaged in microminiaturization work. Related experience, the numbers and types of personnel engaged in the work, equipment available for laboratory and production programs, test equipment, and supporting facilities have been studied for this purpose.

E. Reports and Literature

As a part of the survey, STL has attempted to gather available technical reports and other literature covering various phases of microminiaturization.

F. Coordination and Standardization

Information has been sought on requirements for coordination and standardization in the field of microminiaturization as a possible basis for specifications in future development work.

G. Areas for Development

Of particular importance in the investigation has been the evaluation of those areas requiring development to permit best use of the new techniques in meeting requirements for electronic equipment.

III. EVALUATION AND DISCUSSION

A. Basic Approaches and Concepts

Efforts to achieve electronic equipment a full order of magnitude smaller than existing subminiature designs may be grouped generally into seven basic microminiaturization approaches.

Active development work is being conducted on the following concepts:

1. Microelement and Micromodule Approach

Individual electronic parts, for the most part fabricated by vacuum depositing of thin metallic films, are mounted on thin ceramic, glass, or plastic wafers of standard size and shape. These wafers, called microelements, are then stacked, interconnected, and encapsulated with a potting material to form a micromodule which contains a complete functional electronic circuit.

This micromodule approach at the present time is the largest single effort in the field of microminiaturization, with approximately two dozen companies participating in the program under a leader contractor for the U.S. Army Signal Corps.

Wafers on which typical microelements are mounted are approximately 0.3 inch square and 0.01 inch thick. Resistors and capacitors are thin films deposited on the wafer substrate material. Diodes and transistors are bare parts cemented or otherwise attached to the wafers and then covered with a protective coating. Inductors are made of wire wound on ferrite cores and then bonded to the standard size wafers. In some instances, multiple resistors, resistance-capacitance units, and inductance-capacitance units have been fabricated on single wafers.

Micromodules are being fabricated for the Signal Corps program in a standard 0.35-inch-cube size, with the length dimension somewhat flexible to allow for more complex circuitry. Interconnections between microelements are made by means of round riser wires fitted into notches along the edges of the microelements. An epoxy resin is used as the encapsulating material.

Several experimental devices potentially useful for analog computers have been fabricated, as well as a miniature sawtooth generator transmitter.

5. Thermionic Integrated Micromodules

One concept of microminiaturization involves a vacuum-tube-type device. This device, known as a thermionic integrated micromodule, is a complete circuit contained in a stacked evacuated titanium and ceramic module designed for operation only at extremely high temperature.

Thermionic emissions are produced by cold cathodes in high ambient and high internally generated heat. Resistors and capacitors are built into the unit. Film-type resistors are reportedly stable at high temperatures, and synthetic mica capacitors are stable within 5 percent over a wide temperature variation.

An operating circuit density of 250,000 parts per cubic foot is possible with this type of module with a much greater theoretical packing density.

6. High-Density Packaging

Although not usually considered microminiaturization, an order of magnitude reduction in the size of electronic assemblies can be achieved with high-density packaging of the newer electronic parts developed for use with transistor circuitry.

One such method has resulted in completely encapsulated packaged circuits containing very small electronic parts mounted on printed circuit boards. These packaged circuits have been widely used in commercial television receivers.

Another high-density packaging method uses commercially available electronic parts stacked closely and welded into circuits with nickel ribbon bus wire. Entire modules are then encapsulated. This method has been used for missile guidance computer applications, and can provide packaging densities up to 260,000 electronic parts per cubic foot.

sliced, inlaid with complementary materials, and used as substrates for film-deposited electronic parts to produce complete microminiature solid circuits in the space occupied by an ordinary transistor.

Utilizing these methods, one transistor manufacturer is working on developing microminiature solid circuits suitable for use in computers. Experimental bistable flip-flops, NOR's, phase shift oscillators, logic blocks, inverters, and gate circuits are in process. Work is also being accomplished on linear stages and devices. Interconnections are made using a conducting grid of mylar tape. Similar work has been done in England by a contractor for the Royal Radar Establishment.

A complete circuit measuring 1/4 by 1/8 inch and 1/32 inch thick can be fabricated on a bar of silicon or germanium. This permits a packing density of the equivalent of 30,000,000 electronic parts per cubic foot, without allowing for interconnections.

4. Molecular Circuitry

Development of functionally complete circuits rather than an assembly of components is the objective of reseearch under way in molecular circuitry. This concept eliminates such electronic parameters as individual resistances and capacitances by utilizing the distributed constant parameters of a complete circuit.

One such method which offers the possibility of achieving promising results involves the vacuum mixing of pure metals in a vapor form and depositing the mixture on a suitable substrate. The alloy characteristics of the metal determine the properties of the circuitry. Utilizing magnetic and electrostatic fields by employing equipment resembling a multigun cathode ray tube, the metallic vapor mixtures can be beamed into desired patterns.

Another method makes use of electrical fields within a semiconductor to perform circuit functions, achieving results by use of charges and spins on the molecular level. Using only PN junctions and eliminating other types of components, transfer effects are obtained. Another recent development is the dendritic crystal process which is being investigated for use in molecular electronic programs.

Micromodular circuits fabricated to date include mixers, RF amplifiers, limiters, crystal oscillators, discriminators, IF amplifiers, AF amplifiers, dividers, gates, time modulators, sawtooth generators, oscillators, pulse shapers, output amplifiers, clippers, and pulse generators.

Experimental equipment constructed by this method has attained a practical parts density of 600,000 parts per cubic foot.

2. Two-Dimensional Microminiature Circuits

The two-dimensional (2-D) approach to microminiaturization has resulted in complete microminiature circuits fabricated of thin films deposited on a single wafer.

Originally developed by the U.S. Army Diamond Ordnance Fuze Laboratories more than two years ago, work on the 2-D approach is presently being conducted by several companies under Army contract.

Five-part circuits have been built on 1/4-inch-square wafers approximately 1/50 inch thick. Fourteen-part circuits have been placed on 1/2-inch-square wafers. Circuits suitable for use in digital computers have been fabricated, including binary counters, AND, NOR, and astable circuits.

Various techniques are used for depositing the thin films on the wafer substrates. These include vacuum, chemical, and screening techniques, photolithography, ultrasonic drilling, and air abrasion etching. Resistors, capacitors, and conductors are fabricated by these methods. Transistors and diodes are uncased commercial types fastened by adhesives into recesses in the wafers.

A theoretical packing density of the equivalent of several million electronic parts per cubic foot is possible with the 2-D microminiaturization approach.

3. Microminiature Solid Circuits

By an extension of techniques commonly used in transistor manufacture, oxidized bars of silicon or germanium material can be diffused, etched,

7. Electronic Etching

An advanced development approach on which a limited amount of experimental work has been accomplished involves etching of circuitry on thin metallic film using a monitored electron beam to produce extremely fine lines, possibly no more than 70 angstrom units (0.0000007 centimeter) wide.

This differs from other work with thin films in that such fine lines of metallic material pass the energy of only a small number of electrons. Practical consideration of this effort is several years away, but the possibilities for data storage and memory devices, as well as other circuitry, are worthy of consideration. With this technique, it is theoretically possible to place the equivalent of 100,000,000 electronic parts on a square inch of surface.

B. Program Time Scale

It is apparent from the STL microminiaturization investigation that considerable effort is being expended by a number of companies on an accelerated program schedule, inasmuch as the first suppliers of microminiature electronic equipment will have an important advantage in obtaining contracts for equipment which may profoundly affect the future of the entire electronic industry.

Many factors complicate any effort to estimate a time schedule for microminiaturization. Molecular electronics, for example, is relatively new in comparison with thin film microminiature circuits. Deposited metallic film electronic parts have been in common usage for years, and experience exists in the fabrication techniques and electrical characteristics. Similarly, circuitry for thin film fabrication is relatively well known. For the most part, these circuits are similar to others using diodes and transistors assembled in the conventional manner. These factors make it likely that thin film circuits and micromodules using thin film components will be available at an early date.

Solid and molecular circuits, on the other hand, although relatively new concepts with much research and development remaining to be accomplished, may not require as much time for perfecting fabrication, control, and assembly techniques as the intricate thin film circuits.

Models of some thin film microelements and micromodules are available now (at only moderately high prices) for evaluation and testing purposes. Others are expected to be available within the current year. These, however, are experimental samples produced on a laboratory scale and cannot be expected to have the characteristics of production units.

Considerable work remains to be done before microminiature units can be considered feasible for design purposes. Full-scale test programs are required to determine high- and low-temperature characteristics, resistance to vibration, shock, and acceleration environments, moisture resistance, effects of altitude and pressure, aging effects, anticipated life, and reliability. In addition, full testing of electrical characteristics is required before actual design applications can be considered.

Most experimental microminiature circuit samples fabricated to date have been low-power, digital-type signal circuits of a few simple types which can hardly be expected to fulfill very many of the needs of electronic equipment. Careful evaluation is required to determine possible uses for these micromodules and to design the associated circuitry required even for incorporation into digital-type computers.

Despite difficulties, microminiature circuits of some types will displace conventional circuitry within a very few years, possibly as few as two or three, for some limited applications. First usages will probably be for such equipment as computers, digital instrumentation, programmers, and complex switching devices.

Before full application of microminiature circuits to electronic equipment, it will be necessary to have reasonably complex, accurate, and carefully controlled production equipment. The very small size of the circuitry virtually precludes laboratory or manual fabrication of the units to any degree of uniformity. Once microminiature circuits are satisfactorily developed, some delay will probably be necessary for the design and fabrication of the production machinery.

C. Present Activity

Approximately 400 individuals were determined to be engaged in microminiaturization in some 15 organizations. Since some microminiaturization work is being conducted by almost every major supplier of electronic parts and by many electronic equipment and systems manufacturers, a conservative estimate of the number of persons engaged in microminiaturization study, research, and development work would be at least several thousand persons.

This activity is impressive considering that direct effort on microminiaturization is hardly more than two or three years old. None of the firms visited by STL has been directly engaged in microminiaturization for more than three years, and some have programs barely a few months old.

At the present stage of microminiaturization development, the services of physicists, chemists, and materials and processes engineers, are being employed with some assistance from electronic design engineers. For the more advanced solid state and molecular electronics approaches, physicists with special training in solid state and atomic physics are needed. Obtaining qualified scientific personnel, preferably with advanced degrees, was mentioned as a problem at a number of the organizations visited during the STL investigation.

For laboratory research on thin film deposition, several organizations visited are apparently equipped with little more than a vacuum electrodeposition machine, photo-resist masking equipment, ordinary electronic test equipment, and means for microscopic examination of the thin films. From an equipment standpoint, the companies best qualified for product research and development appear to be manufacturers of semiconductors and other electronic parts. These firms have available such facilities as microhandling and micromachining equipment, materials test equipment, and full facilities for control and examination of the product.

As microminiaturization research becomes more complex, involving new materials and new processes, highly specialized equipment will be needed. Equipment needs mentioned during the STL investigation included such items as electron microscopes and an extremely fine-line etching device using multigun cathode ray tube techniques.

D. Review of Literature

Only a limited number of articles, papers, and reports (see Appendix B) relate directly to the topic of microminiaturization. However, the number of such publications is growing rapidly, promising considerable literature within a short time. New technical reports describing work accomplished under various government contracts, as well as journal articles and papers describing new developments prepared for professional and scientific societies, are expected within the coming year.

The subject of microminiaturization incorporates much of the research work presently being accomplished in electronics. For specific information on various topics possibly having significant bearing on microminiaturization, it is necessary to consult literature listed under the headings of semiconductor compound formation, ferroelectric and ferromagnetic devices, tunnel diodes, cryotrons and cryogenics, electroluminescence, and thermoelectric power and devices. For techniques useful in development, literature exists on vacuum, chemical, and screening methods used in thin film deposition work, including results obtained using magnetic, conductive, dielectric, and semiconductive materials.

The book Microminiaturization of Electronic Assemblies, the proceedings of a symposium sponsored by the Diamond Ordnance Fuze Laboratories, published in 1959, contains a summary of background material.

E. Circuit Technology

Design of microminiature circuits and the design of equipment incorporating these devices both require new skills and originality by the electronic design engineer.

The present state of the art of microminiaturization requires that design of circuits be as simple as possible and contain a reduced number of parts and circuit elements. Difficulties in testing internal electrical performance limit the first microminiaturization efforts to easily understood circuits.

Experimental units have been largely transistor-resistor logic circuitry, such as AND, NOR, flip-flop, binary counter, and similar digital types. These permit use of low operating power levels and allow individual parts to be designed for broad tolerance parameters.

Types of parts used in experimental circuit design are presently limited to those easily fabricated in the laboratory. Even though film capacitors and film-type toroids of some values have been deposited successfully on substrates, it is best to avoid larger capacitors and inductors in circuit design wherever possible.

The circuit elements most easily fabricated are film resistors. These have been made of metals, metal alloys, and other materials. Metal alloy film resistors have been successfully produced with values as high as 1/4 megohm exhibiting stable characteristics. Several types of capacitors have likewise been produced for both general purpose and precision use. Thin film tantalum capacitors with values to 0.25 microfarads, and single- and multiple-layer ceramic capacitors with values to 40 micromicrofarads have been fabricated. Transistors and diodes apparently can be placed directly on substrates, but the small size of uncased production units makes it more practical to attach these to microwafers by means of adhesives. Difficulties have been experienced in obtaining satisfactory inductances, although several solutions have been found. Toroid windings on ferromagnetic cores have resulted in microminiature IF transformers for use at frequencies between 455 kilocycles and 10.7 megacycles. One organization is said to have successfully fabricated inductors using deposited film methods. Several different metals have been satisfactorily deposited for conductors and a special conductive adhesive has been used for both internal leads and interconnections.

The design of equipment incorporating microminiature circuits requires special care. Transducers, inputs, outputs, read-out devices, and antennas require special selection or special design to function with low-power digital-type microminiature circuits. In order to utilize circuits economically without excessive special design and fabrication, it is advisable to reduce circuits to a limited number for standardization purposes and to use these for maximum performance.

If the full possibilities of microminiature circuitry are to be realized, it is necessary to reduce the number of interconnections required between modules. Otherwise, more space will be occupied by interconnections than by actual functioning circuits.

Testing of microminiature circuits is a problem requiring a great deal of consideration. Conventional test equipment permits electrical testing of inputs and outputs only. Designing of test points into extremely small devices to permit use of test probes is impractical. Even if such test information on internal parts were available, however, its usefulness would be limited since repair or replacement of circuit elements cannot be easily accomplished. Test equipment is being studied which can monitor the internal working of the circuitry, utilizing only electrical input and output information.

F. Fabrication Techniques

Techniques used experimentally in fabrication of microminiature assemblies range widely from the deposition of thin films to the alloying of metals and the use of grown semiconductor junctions.

These methods for circuitry fabrication more closely resemble those used heretofore in the manufacture of electronic parts than the methods used in assembly of electronic equipment and systems. A listing of some processes and materials includes the following:

1. Photo Resists

Use of photo resists for fabrication of thin film circuits is similar in principle to techniques used for fabrication of printed circuit boards. For design of microminiature circuits, however, refined techniques are needed to achieve extremely fine lines. Use is made of recently developed spectrographic photo plates which achieve high resolution, high contrast, maximum sharpness, and minimum granularity. These plates permit use of as many as 1000 lines per millimeter. Resists or other methods of masking are required for most thin film deposition methods.

2. Photolithographic and Screen Printing

Photolithographic offset and screen printing methods are used for the accurate placement of photo resists at microscopic dimensions in design and fabrication of thin film circuits.

3. Deposition Methods

Thin films of conductive, dielectric, semiconductor, and magnetic materials are deposited on substrates by vacuum, chemical, and electrical methods. Vacuum deposition is accomplished by vaporizing the material in a vacuum by heating, then allowing the vapor to condense on cool surfaces. Sputtering, a variation of this process, involves intermittent heating and deposition of material in a succession of steps. Electrodeposition and chemical deposition are accomplished in a manner similar to ordinary electroplating and chemical plating.

4. Air Abrasion, Ultrasonic Machining, and Etching

Air abrasion, ultrasonic machining, and etching on suitably masked substrates are used to remove undesired surface material and provide a fine-line, thin-film pattern. Air abrasion is similar to sandblasting using finely divided abrasive materials, and ultrasonic machining is accomplished through use of a soft metal tool in an abrasive slurry.

5. Substrates

Substrate materials on which thin film circuitry can be placed include microscope glass, various plastics, and such ceramic materials as barium titanate, quartz, alumina, forsterite, and steatite. Characteristics of each of these materials have an important bearing on the design of individual microminiature circuits.

6. Micromachining

In the fabrication of circuits, a number of micromachining processes are used. Microgrinding, for example, is used to bring film deposited resistors within tolerance. Other techniques involved in circuit design include sawing, drilling, and scribing and breaking.

7. Connections

Connections between microwafers, microcircuits, and micromodules are made by means of soldering, resistance- and capacitance-discharge welding, and use of conductive adhesives. In some cases, pressure-type contacts are used. Connections have presented troublesome problems in development work, and more satisfactory methods are being sought.

IV. AREAS FOR DEVELOPMENT

From the applications engineering standpoint, involving the actual incorporation of microminiature circuitry into electronic systems and equipment, the STL survey has indicated that considerable work remains to be done before these techniques are feasible. For missiles and space vehicle applications where improved size, weight, and reliability characteristics are important, it will be advantageous to use the capabilities of these circuits as soon as practicable.

Ten areas for applications engineering study and laboratory development in the field of microminiaturization have been indicated. These are as follows:

A. Interconnection Techniques

To solve the problem of interconnecting microminiature devices into complete electrical circuits and equipment, several approaches have been used, none of which is completely satisfactory. For the microminiaturization approach utilizing microwafers containing a single electronic part, the problem is particularly important since interconnections are required for internal micromodule circuitry. For module-to-module connections and for connection of microminiature circuits into conventional electronic equipment, evaluation of connection materials and methods is required, including the use of solders, welding processes, bus bars, external leads, pressure contacts, and conductive adhesives. For adhesives composed of metallic silver in an epoxy base material, the possibility of silver migration must be considered.

B. Thermal Considerations

In laboratory work to date, insufficient emphasis has been given to thermal considerations. Use of closely spaced encapsulated electronic parts, even for low power circuits, creates a problem of internally generated heat. Dissipation of internal heat, the effects of conducted and radiated heat on materials and circuit performance, and characteristics of circuits at high and low temperatures are among the problems for evaluation. Electronic cooling, known as the Peltier effect, is one method suggested which may be worthy of consideration.

C. Linear Circuit Applications

Further investigation is required into the use of microminiaturization for linear circuit applications together with circuit requirements for IF and RF use. To date, most work in microminiaturization has been devoted to digital circuitry because of the simplicity of functions, wide electrical tolerances, and quantity production possibilities of circuits used repetitively in computer applications. Microminiature techniques for analog applications and for linear circuitry require careful study. Whether or not it develops that microcircuits cannot be adapted for closely held parameters, study of methods of designing around these parameters will be useful.

D. Missile and Space Vehicle Applications

Because of the obvious space, weight, and reliability advantages, specific applications of microminiature circuits to missile and space vehicle electronics require early consideration. Possible uses include airborne and space programmers, switching matrices, instrumentation, and computers, as well as ground support equipment. Extensive laboratory testing is needed to determine the ability of the equipment to withstand missile and space vehicle environments. Particularly for advanced programs involving long lead times, substitution of microcircuits for conventional devices may result in significant additional performance capability.

E. Integration Into Present Circuitry

Integration of individual circuits into conventional electronic equipment at the soonest practical date for important space, weight, and performance savings will permit maximum advantage to be obtained from microminiaturization development. Completely microminiaturized equipment at an early date is not likely; instead, a transition period in which portions of equipment would be microminiaturized seems more feasible. Problems of integration include study of associated circuitry, input requirements, and the use of microminiature signal outputs for application of power.

F. Active Circuit Elements

Uncased transistors and diodes in microminiature circuits and thin film semiconductors deposited directly on substrate material raise problems of electrical performance and contamination requiring laboratory evaluation. Solid circuits in which all electronic parts are intrinsic with the semiconductor material or deposited on the surfaces require laboratory testing before application of these devices can be seriously considered.

G. Passive Circuit Elements

Before incorporating microminiature thin film resistors, and capacitors into critical circuits, a full laboratory test program seems advisable. The test program would consist essentially of all performance and environmental testing required for military specification qualification approval for conventional electronic parts.

H. Environmental Protection

A major improvement in reliability is one of the advantages anticipated for microminiature circuitry. Whether this increase in reliability can actually be achieved is still to be determined. Information is required on modes of failure and types of malfunctions to be expected. Study is required on life expectancy, including such wear-out factors as possible disintegration and dissipation of material. An adequate repair and maintenance philosophy, with procedures for testing and replacement of defective circuits, would be of value in establishing reliability of equipment.

I. Evaluation of Progress

In a field in which technology is advancing so rapidly, continuous surveillance of progress and evaluation of new developments is required for successful applications engineering. As new devices, materials, circuitry, and processes are developed, study is required to determine possible usefulness for rapid incorporation into equipment.

APPENDIX A

REPORTS ON ORGANIZATIONS SURVEYED

To assess the progress of microminiaturization and its potential impact on electronic development, representatives of the Product Engineering Department of Space Technology Laboratories, Inc. have visited some 15 organizations engaged in work in this field.

Reports on these field visits indicate that extensive activity is under way with considerable progress being accomplished in a relatively short period of time. Several hundred professional personnel, both engineers and scientists, are engaged in microminiaturization effort. Although the work generally falls into two categories, thin film deposition and solid state circuits, each organization visited is exploring some original phase of methods, materials, processes, or circuits.

For the most part, work in microminiaturization is presently in the research and development phase. However, some devices and circuits will be available commercially for test and evaluation purposes within the coming year. Completely microminiaturized equipment appears to be several years distant at this time.

In addition to the firms and research organizations visited, questionnaires were sent to numerous others. Altogether, it appears likely that several hundred firms are engaged in microminiaturization work to some greater or lesser extent. Displacements within the industry of the relative positions of the parts and equipment manufacturers which will result from microminiaturization are apparently of considerable concern. These potential effects are spurring independent development work.

Quite understandably, many developments in this field are regarded as proprietary company information, not ready for disclosure at this time. For the most part, information of this nature was withheld from STL representatives, and a conscientious effort has been made to delete proprietary information which was disclosed from the company reports which follow. The companies visited are as follows:

1. Radio Corporation of America, Camden, New Jersey
2. Diamond Ordnance Fuze Laboratories, Washington, D.C.
3. Texas Instruments, Inc., Dallas, Texas
4. Westinghouse Electric Corporation, Air-Arm Division, Baltimore Maryland
5. Varo Manufacturing Company, Garland, Texas
6. Philco Corporation, Philco Research Laboratory, Philadelphia, Pennsylvania
7. International Resistance Company, Philadelphia, Pennsylvania
8. Motorola, Inc., Military Electronics Division, Phoenix, Arizona
9. Fairchild Semiconductor Corporation, Palo Alto, California
10. Hughes Aircraft Company, Culver City, California
11. Lockheed Aircraft Corporation, Missiles and Space Division, Palo Alto, California
12. Stanford Research Institute, Palo Alto, California
13. Denver Research Institute, University of Denver, Denver, Colorado
14. Naval Research Laboratory, Washington, D.C.
15. Burroughs Corporation, Paoli, Pennsylvania

RADIO CORPORATION OF AMERICA, Camden, New Jersey
Contract DA 36-039 SC-75968
<u>Microminiature Modules</u>

The micromodule program, originated by RCA in mid-1956 and operating under Army Signal Corps contract since April 1958, is the most ambitious microminiaturization program now under way. Phase I of the program development of microelements and micromodules, is scheduled for completion in 1960. Phase II, subassemblies and equipment, has begun and will continue through 1961. Phase III, design of production machinery, is anticipated for 1960-1962. The program has been widely publicized, and industry-wide participation is being attempted for development of suitable electronic parts, materials, and processes. Approximately 125 to 150 people are working on the program including approximately 80 professional engineers and scientists.

Highlights of the RCA program are as follows:

1. Encapsulated 0.35-inch-cube micromodules have been fabricated comprised of wafers measuring 0.35 x 0.35 inch and 0.02 inch thick. Most micromodules contain a complete building-block type of circuit (crystal oscillator, IF amplifier, RF amplifier, discriminator, and others for a total of approximately 16).

2. A number of the micromodules are now available in limited quantities for evaluation and testing.

3. With participation of electronic part manufacturers in the program (Sprague for capacitors, Hoffman for diodes, Philco for transistors, and numerous others), RCA now has the principal types of parts on standard size wafers which can be combined in conventional circuits.

4. Wafers are interconnected by soldering along four sides of the module. After testing, the assembled modules are potted into a solid block with leads protruding from two sides.

5. Resistors are made by depositing evaporated nichrome films onto wafer surfaces. Capacitors are made from barium titanate wafers or by multiple layers of evaporated films. Transistors and diodes are hermetically sealed into standard size wafers.

6. A small radio receiver with a super-regenerative superheterodyne circuit tuned to a single frequency has been fabricated in a package approximately 1.75 x 3 x 0.5 inches.

7. Actual packaging density, with allowances for interconnections, will be approximately 250,000 parts per cubic foot. Part density, however, is 600,000 per cubic foot.

8. Reliability information on RCA micromodules is expected to be released early in 1960. Failure rates to date have been 0.133 per 1000 hours. A rate of 0.02 is expected to be achieved shortly. Pilot production is being conducted at Sunnyvale, California.

9. A major advantage of the RCA approach compared with other types of deposited circuitry is that wafers, normally containing a single circuit element, can be individually tested for desired performance before interconnection into a micromodule circuit.

DIAMOND ORDNANCE FUZE LABORATORIES, Washington 25, D.C.
U.S. Army Ordnance Corps
Microminiature Circuit Development

Fabrication of microminiature electronic assemblies using thin films deposited on thin wafer substrates, a program generally known as the two-dimensional (2-D) approach, was started at DOFL in May 1957. At present, eight professional engineers and scientists in the passive components, semiconductor, and circuit-systems groups are working on the program. Complete passive circuits are deposited on a single wafer.

Highlights of the DOFL program are as follows:

1. The equivalent of 14 electronic parts have been placed on a wafer 1/2 inch square and approximately 1/50 inch thick. Five-part circuits have been built on 1/4-inch-square wafers, usually of steatite ceramic material. Binary counters, AND, NOR, and astable circuits suitable for use in digital computers have been fabricated.

2. Work is in progress on a 30-megacycle IF strip with a bandwidth of approximately 10 megacycles. The circuit, including a toroidal transformer, is mounted on a 0.6-inch-square wafer.

3. A 100-diode matrix mounted on a 1/4 inch square is being developed. Yield of the diode matrix is approximately 80 percent for individual diodes; peak inverse voltages of 30 to 50 volts may be used.

4. Nichrome film resistors with values to 4700 ohms per square have been fabricated. Chemically deposited nickel film resistors are being developed with values up to 1000 ohms per square.

5. Capacitors have been vacuum deposited using silicon monoxide and fuzed silica for dielectrics and gold film plates. Film thicknesses are 5000 to 10,000 angstroms. An electrical pulse across the electrodes burns open short circuits between capacitor plates resulting from pin holes. Capacitance values in the range of 0.01 microfarad have been achieved on a square centimeter of surface.

6. Techniques used include: photolithography; vacuum, chemical, and screening techniques for thin film deposition; use of conductive adhesive for connections; and ultrasonic drilling and air abrasion etching.

7. Work is sufficiently advanced so that the methods could probably be developed for mass production within a 12-month period.

TEXAS INSTRUMENTS, INC., Dallas, Texas
Contract AF 33 (616)-6600
Microminiature Solid Circuits

Employing techniques and equipment used in diode and transistor manufacture, Texas Instruments is developing microminiature solid circuits capable of use in computers. Work has been in progress for several years, actively since early 1957, with a military contract received in June 1959. The firm expects to double the dozen professional staff menbers working on the program.

Features of work at Texas Instruments are as follows:

1. Two parallel strips are cut through the completely oxidized outer surface of a bar of germanium or silicon measuring 1/4 x 1/8 inch and 1/32 inch thick. In these strips, a complementary material is laid to form the collector and emitter of a transistor. The bar perpendicular to the strips is sliced into several smaller bars, and leads are attached to form resistors. Film depositions, properly placed, form distributed capacitance. In this manner, complete circuits may be fabricated. Technical details are considered proprietary.

2. Computer circuits which may be manufactured by this method include: bistable flip-flop, NOR, phase shift oscillator, logic block, inverter, and gate circuits. Work on linear stages and devices is also in progress.

3. Interconnection of multiple stages, as many as 10 or 20, are made using a conducting grid of mylar tape. Several layers may be attached, with proper connections made to each grid.

4. Techniques are those employed in manufacture of transistors. Semiconductor fabrication facilities are used for microminiature circuitry.

5. Capabilities for actual production appear to exist at TI. It was estimated that material cost of circuits will be two to five times that of conventional circuits in mass production.

6. A delivery date of 9 months was estimated for a countdown timer consisting of 20 flip-flops plus 30 gating circuits.

7. Under this concept, it is felt that complete circuits and equipment should be designed and fabricated by the manufacturer of solid circuits. Unlike conventional electronic parts, it is not considered practical to sell modules to other electronic manufacturers for assembly into equipment.

8. The solid state circuits permit a packing density equivalent to 30,000,000 electronic parts per cubic foot.

9. Reliability data is scheduled to be released in early 1960.

WESTINGHOUSE ELECTRIC CORPORATION, Air-Arm Division,
Baltimore, Maryland
Contract AF
<u>Molecular Electronics</u>

Westinghouse believes that a substantial advance in the state of the art has been achieved with a major breakthrough in solid state circuitry or, as Westinghouse people prefer to call it, molecular electronics. Active work on government contract has been in progress since the latter part of 1958, with previous work in this field extending back to 1954. Approximately 50 professional personnel are working on the program with others to be added as rapidly as they can be obtained.

Highlights of the Westinghouse approach are as follows:

1. Solid state circuitry development at Westinghouse has resulted in a variety of prototype circuits useful for analog as well as digital computers, for infrared sensing amplifiers, for relays, commutators, and other related applications. Transistor fabrication experience has been fully utilized. This approach uses PN junctions, eliminates parameters such as resistors and capacitors, and simulates various transfer functions.

2. Using a circular wafer with one or two junctions, a sawtooth generator has been fabricated which is sensitive to light intensities. Utilizing the harmonics created by this device, it has been possible to transmit amplitude modulated frequencies for short distances to a conventional AM receiver.

3. An AM-FM device which can separately transmit AM and FM frequencies is also available for demonstration. Much effort is being devoted to various other circuits using these techniques.

4. Details of construction were not disclosed, although demonstration was made and the input and output characteristics were discussed. The new technique involves the fabrication of dendrite crystals by a process which greatly facilitates control of quality.

5. Because of greater complexity, control of solid state circuits is probably more difficult than the transistor control problem. To date, only silicon and germanium have been evaluated, but the technique is not limited to these materials.

6. The feeling was expressed that molecular electronics is at relatively the same state of development as transistors were 2 years after discovery, with much work remaining to be done. Units may be available for evaluation late in 1960.

7. It was pointed out that mass production of solid state electronic equipment is unlikely. Since each circuit must be tailored to meet special requirements, Westinghouse expects to produce complete equipment based upon customer input and output characteristics rather than supplying individual circuits for assembly into systems.

8. The opinion was expressed that solid state circuit devices might be available on the commercial market within 5 years, with equipment for military usage following commercial applications.

VARO MANUFACTURING COMPANY, Garland, Texas

Contract N (onr)-1075(00)

Microcircuitry

For a computer being fabricated by Litton Industries for evaluation purposes under an Office of Naval Research program, Varo is producing all necessary microminiature modules with the exception of the memory drum. Utilizing laboratory techniques, the seven professional engineers and three technicians comprising the microcircuitry staff fabricate the required circuitry using a vacuum deposition chamber. The program was started at Varo in January 1957.

Features of the Varo program are as follows:

1. A 100-megacycle FM transmitter, a broadcast band transmitter, and a countdown circuit consisting of several bistable circuits have been fabricated.

2. The complete computer equipment, using 5000 parts, is scheduled for completion in early 1960. Flip-flops, write-read amplifiers, gates, and other related circuits are being produced.

3. Passive networks of resistors and capacitors are deposited on barium titanate substrates 1 inch square and 0.012 inch thick. Nichrome films are used as resistors providing values to 2000 ohms per square with considerable stability. The 10,000 ohms per square resistors fabricated to date are not adequately stable. Capacitors are developed in the base plate by depositing a gold conductive layer on a metered area on both sides of the plate. Capacitance values of 0.01 microfarad have been achieved.

4. Uncased mesa transistors and diodes are attached to finished circuit plates with solder or conductive ink. Circuit plates are finished with a protective coating.

5. Several circuits can often be placed on one standard base plate. Packing densities equivalent to 1,000,000 parts per cubic foot can be achieved.

6. Inductances present problems.

7. Future plans call for placing multiple layers of material on one substrate, permitting multiple stages per unit.

8. The company desires to obtain development contracts for building additional microcircuits. At present, capabilities are limited to production of hand-tailored laboratory samples utilizing the considerable experience accumulated to date.

9. No information was disclosed on the work that Varo is reportedly doing in molecular circuitry. This involves the vacuum mixing of pure metals in gaseous atomic form and depositing on a substrate. With this approach, the alloy characteristics determine the electrical properties of the circuit, supposedly because of the morphology of the materials. The gas mixture is beamed into patterns by a technique similar to that of multigun cathode ray tube which creates the proper magnetic or electrostatic fields. No mention was made of work in this area.

PHILCO CORPORATION, Philco Research Laboratory, Philadelphia Pennsylvania
Contracts DA 49-186-500 ORD-732, AF 19 (604)-5522, and AF 19 (604)-5537
Microminiature Circuits

Laboratory samples of digital-type microminiature circuits on wafers of the Diamond Ordnance Fuze Laboratories type can now be supplied to special customer requirements by Philco. A staff of 30 persons is participating in microminiaturization which has its beginning at Philco in the latter half of 1957. Work is also in progress on solid state techniques, an extension of Philco's work as a transistor manufacturer.

Features of Philco's program include the following:

1. Extensive work has been accomplished in development of sputtered film-deposited resistors, capacitors, and conductors. Work on film-deposited capacitors has been in progress for 2 years. Almost a year has been devoted to the microminiature approach to complete digital-type circuits.

2. By using available diodes and transistors together with film-deposited resistors, capacitors, and conductors, Philco has no great problem in fabricating microcircuitry. Type 2N502 transistors without the can are cemented onto pyrex glass substrate carrying the passive components.

3. Experiments are in progress in laying down semiconductor material by film deposition as an approach to solid state techniques. This method does not eliminate individual circuit parameters, such as resistors and capacitors; it is felt that a sacrifice in performance would result from using semiconductor material with PN junctions only.

4. Philco is also conducting a metallurgical studies program.

5. Capacitors are made by depositing films of silica, aluminum oxide, barium titanate, and tantalum oxide on glass substrates.

6. Conductors are aluminum covered with silver film. If silver migration becomes a problem, gold will be used.

7. Satisfactory resistors are made of tantalum films with values up to 1 megohm in an area of 5 by 2.5 millimeters. Work to improve the yield is continuing.

8. The problem of achieving inductances has been avoided to date by designing around their use.

INTERNATIONAL RESISTANCE COMPANY, Philadelphia, Pennsylvania
Contract DA 18-119 SC-729
Microminiature Thin Film Circuit Elements

Development of microminiature thin film circuit elements at IRC is a direct outgrowth of the manufacture of conventional deposited film resistors over a period of years. Research leading to microminiature circuit elements has been in progress since 1951, with active work since the fall of 1958.

Features of microminiaturization work at IRC are as follows:

1. Metal film resistors have been deposited on glass substrates in 0.0002-inch widths with resistances up to 1000 ohms per square, ±15 percent tolerances, and 50 to 100 parts per million temperature coefficients.

2. Evaporated single film capacitors, with values of 0.1 microfarad per square inch, ±10 percent tolerance, and 50-volt breakdown voltages, have been manufactured with a yield of better than 80 percent.

3. Bistable multivibrator circuits have been fabricated on glass wafers measuring 5/8 x 5/8 inch and 0.06 inch thick. The smallest available semiconductors have been mounted on the same size wafers. An adder circuit is now under development.

4. Methods are being studied for depositing semiconductive films with a monocrystalline structure for active elements.

5. Several different approaches are being studied as possible solutions to the problems of interconnection and interaction between wafers.

6. Attempts are being made to use ion beams for depositing passive elements, thus avoiding the shields required for evaporation techniques.

7. Although most of the work to date has involved digital-type circuits, some effort is being devoted to develop linear circuitry.

8. Capabilities in the manufacture of conventional deposited film electronic parts provide IRC with the necessary experience and facilities to produce microcircuitry in quantity.

MOTOROLA, INC., Military Electronics Division, Phoenix, Arizona

Microelectronics Development Work

Motorola is conducting a program in film deposition techniques, preliminary to development of functional electrical circuits. The microelectronics laboratory with a staff of eight persons was started in mid-1958, and maintains a close working relationship with Motorola's Solid State Division.

Capabilities of the program are indicated by the following:

1. Capacitors are made on a substrate with successive layers of sputtered or evaporated tantalum, followed by tantalum oxide film produced by controlled anodizing, and finally a film of sputtered gold. Mica is also used as a dielectric. Capacitors with values to 250,000 micromicrofarads, capable of withstanding 25 to 50 volts, have been fabricated.

2. Low-value resistors are made by evaporation of tantalum or chromel; high-value resistors are made by phase deposition of tin oxide. By doping the tin oxide with antimony, electrical characteristics are changed through wide limits. Resistances to 25,000 ohms per square have been achieved.

3. Inductance effects are possible by combining a low Q capacitor with a PN semiconductor active element.

4. Transistors are stripped down Motorola silicon mesa units. Crystals are cemented to the base plate with a special arsenic sulphide glass which covers the crystal to provide mechanical protection and act as a moisture barrier. The glass is somewhat ductile, which releases strains, and is claimed to improve the surface characteristics of the crystal.

5. Packing densities of 2,000,000 parts per cubic foot are obtainable with the Motorola approach. The firm is actively working on new magnetic materials and single-crystal semiconductor solid circuits. Evaporation of barium titanates has not been successful because of voltage breakdown. Anodizing tantalum foil also has not been successful because of crystallinity.

FAIRCHILD SEMICONDUCTOR CORPORATION, Palo Alto, California

Microminiature Circuit Modules

Microminiaturization effort at Fairchild is pointed toward producing a complete circuit module in a configuration similar to a conventional transistor package. Two scientists are presently working on the program which began late in 1958, with more to be added shortly.

Highlights of the program are as follows:

1. A complete d-c coupled flip-flop circuit module, consisting of four uncased transistors and two resistors, have been placed on an aluminum oxide disk 1/4 inch in diameter and 0.02 inch thick. This circuit is capable of 20-megacycle pulses with a rise time in the vicinity of 10 to 15 millimicroseconds. The module is protected by an evaporated coating and can be placed in a can 1/3 inch in diameter and 5/16 inch thick. Connections are made by means of six conventional-type leads.

2. The size of the model, which is smaller than most standard micro-element wafers, was described as larger than actually required. Size, however, may be determined by requirements for handling and connections.

3. Only a few of these units have been made, and testing is in progress. Fabrication techniques are extensions of methods used for transistor manufacture.

4. The d-c coupled flip-flop circuit module is expected to be available early in 1960.

HUGHES AIRCRAFT COMPANY, Culver City, California

Microminiature Development Work

Hughes Aircraft Company was not ready to disclose more than rudimentary information on development work in progress since early 1957. Approximately a dozen persons in the computer department are engaged in microminiaturization. Full reporting of progress, however, was expected to be made shortly.

Features of the Hughes program include the following:

1. A two-dimensional approach involving use of evaporation techniques for development of passive functions is being used.

2. Packing densities equivalent to 1,725,000 to 3,500,000 conventional electronic parts per cubic foot are anticipated.

3. The program has been planned for computer application. All prototype computer modules will be ready for environmental testing by early 1960. This will be followed by a study of characteristics for application feasiblity. Actual computer equipment production is not anticipated before 1962-3.

4. Studies have been started on difficulties involved in the interconnection problem.

5. With the techniques presently used in development work, frequencies under 1 megacycle offer no difficulties.

6. Development work is sufficiently advanced to permit the acceptance of contracts in the field of microminiaturization.

LOCKHEED AIRCRAFT CORPORATION, Missiles and Space Division,
Palo Alto, California
Microsystem Electronics

Extensive work in microsystem electronics, as the program is called at Lockheed, was started in early 1959, continuing previous efforts in solid state electronics since 1952. Approximately 50 scientists, most of whom have advanced degrees, are working on the program. The nature of the Lockheed effort is being withheld at the present time.

Information concerning the Lockheed approach includes the following:

1. Emphasis is being placed on accomplishing transfer functions through synthesizing materials rather than utilizing the parameters of present electronic parts and functions. The basis of the transfer function approach is that various materials treated differently operate on certain charges or transformation of electrical energy with end results similar to those of commonly known circuitry.

2. Electroluminescence was mentioned as a method of interconnection. This technique may be used to facilitate transfer of information through photoelectric methods, thus decreasing or eliminating the need for interwiring connections.

3. It is apparent that the Lockheed approach is designed for long-range theoretical effort. Mathematical analysis plays a considerable part in the program.

4. No reports are available, and no prototypes are ready for demonstration.

STANFORD RESEARCH INSTITUTE, Palo Alto, California

Advanced Microscopic Etching Development

The effort at Stanford Research Institute is aimed at achievement of microscopic etching techniques and instrumentation far beyond any existing requirements, permitting use of measurements as small as 70 angstrom units (0.0000007 centimeter) in microminiature circuitry. If successful, this could lead to a new field of molecular electronics. Work has been in progress since late in 1958, with one scientist and one technician engaged in the program.

Objectives of the SRI program are as follows:

1. A monitored electron beam like that in an electron microscope will be used for developing an etch resist pattern on a metal film deposited on a ceramic substrate. The pattern has a resolution of approximately 300 angstrom units, considerably finer than can be achieved by any other known technique. Ultimate resolution is said to be 70 angstrom units.

2. By a suitable etching technique, it is possible to remove background metal not covered by the resist pattern, resulting in a circuit configuration of great compactness and precision.

3. The process is potentially useful for producing cryotron circuits and data storage elements.

4. Once the techniques are satisfactorily mastered, advance in the state of the art is expected to follow easily. Distributed parameters, such as transmission line effects, will be investigated rather than conventional parameters, such as resistance and capacitances. Active elements of the field emission effect or tunnel diode type may be used as well as electrostatic parameters. The use of distributed parameters and active elements will result in duplicating the majority of present-day circuits.

5. Emphasis is placed on deriving devices insensitive to changes in temperature. For stability, materials such as tungsten and aluminum oxide will be tried, since these are not prone to migration.

6. Power consumption will be extremely low.

7. The program is still in the hypothetical and experimental stage. An electron optical system analogous to an electron microscope is being designed. When fully developed, these techniques would theoretically permit placing the equivalent of 100,000,000 electronic parts on a square inch of surface.

DENVER RESEARCH INSTITUTE, University of Denver, Denver, Colorado

Microminiature Circuitry

Mastery of the techniques of vacuum metal evaporation for fabrication of microminiature circuits is the objective of the four engineers engaged in the program at Denver Research Institute since January 1959. The effort is presently concerned with research rather than development work.

Results of the DRI work include the following:

1. An astable circuit was fabricated using two commercial transistors mounted on a thin barium titanate wafer on which resistors and capacitors were deposited. The multivibrator was operated over a 200-hour span.

2. Tellurium and nichrome have been studied for resistors. Resistors with values to 3000 ohms per square were fabricated, but exhibited negative temperature coefficients; drifts of 30 percent per month have been noted in some cases. Ceramic, glass, and plastic substrates have been used. To overcome oxidation, an impervious coating was laid before depositing the tellurium. Some work has been done using manganese.

3. For capacitors, 0.02-inch-thick barium titanate disks were used. By placing aluminum on both sides of the disk, capacitance values to 400 micromicrofarads have been obtained.

4. Diodes have been fabricated by film depositing indium and gold and then diffusing the junction.

5. Best results for connections have been obtained with evaporated copper. Migration and polarization problems caused trouble where silver was used. Aluminum was also tried; however, rectification trouble was encountered.

NAVAL RESEARCH LABORATORY, Washington, D. C.

Semiconductive Thin Films

An experimental program involving work with semiconductive thin films leading to microminiature circuitry has been under way at NRL since spring of 1959, with three scientists assigned to the program. First efforts have been largely devoted to establishment of laboratory facilities and outlining of a 2-year program.

Objectives of the NRL program are as follows:

1. Monocrystalline films of germanium and silicon will be attempted on suitable substrates to fabricate transistors and diodes for electronic circuits.

2. These films, deposited by vacuum evaporation techniques, will be processed by heat treatment, electron bombardment, and various other ways to facilitate growth of polycrystalline structure.

3. Considerable effort will be devoted to mastering techniques, such as X-ray diffraction, for examining the structure of deposited films.

4. Efforts will culminate in determination of approaches and evaluation of achievements possible in the field of thin semiconductive films.

BURROUGHS CORPORATION, Paoli, Pennsylvania

High-Density Packaging Methods

Although Burroughs has done development work in thin magnetic film deposition, the high-density packaging studies presently under way stress the use of small commercially available electronic parts in computer design.

The Burroughs approach is typified by the following:

1. Packaging densities approaching 1,000,000 parts per cubic foot may be attained using the smallest available commercial electronic parts and newly developed packaging techniques.

2. Although these techniques are not true microminiaturization in the commonly accepted sense, they should prove valuable for computer equipment where extreme size and weight reduction are not essential but where a decrease in size of one order of magnitude would be useful.

3. Extremely high equivalent electronic part densities may be obtained with film deposition and molecular electronic techniques, but these achievements may be defeated by the volume required when many of these microminiature units are contained in a complete package.

APPENDIX B

MICROMINIATURIZATION BIBLIOGRAPHY

A comprehensive bibliography on microminiaturization is not necessarily limited to literature published since the spring of 1957, when the word "microminiaturization" was introduced to describe efforts to reduce electronic equipment by another order of magnitude below the previous "subminiature" packaging techniques. A complete bibliography would encompass all of the literature covering the fields which will make microminiaturization possible. These contributing and related topics might include all solid state electronics, semiconductors, vacuum deposition, thin film components, molecular electronics, tunnel diodes, and numerous other related fields.

The bibliography presented here, however, lists only material published since 1957 relating directly to research and development effort leading to the fabrication of electronic circuits and equipment on the microminiature scale.

To date, the only book which resembles a textbook is a collection of papers entitled "Proceedings of the Symposium on Microminiaturization of Electronic Assemblies," sponsored by Diamond Ordnance Fuze Laboratories, the complete contents of which are listed here.

With the entire electronic industry now taking an active interest in microminiature development, this literature is growing rapidly. Each month can expect to see reports, announcements, and articles describing new progress. Professional electronic and related scientific societies are placing microminiature development on the agendas of meetings and conventions, which will produce a wealth of new papers and journal articles. Government contracts for microminiaturization development also will inevitably result in a series of new technical reports covering various phases of the subject.

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APPENDIX C

MICROMINIATURIZATION ACTIVITY

The extent of present activity in the field of microminiaturization is indicated by the number of organizations participating in various efforts, by the government contracts for research and development, and by the number of government agencies taking an active interest in the work. The following lists, which are by no means complete, have been compiled as an indication of this widespread activity.

1. GOVERNMENT AGENCIES INTERESTED IN MICROMINIATURIZATION

Air Force

Air Force Cambridge Research Center, Bedford, Massachusetts
Wright Air Development Center, Wright-Patterson AFB, Ohio
Rome Air Development Center, Griffiss AFB, New York
Andrews Air Research and Development Center, Washington 25, D.C.

Army

Army Signal Research and Development Laboratory, Fort Monmouth, New Jersey
Army Ordnance Missile Laboratories, Redstone Arsenal, Alabama
Diamond Ordnance Fuze Laboratories, Washington 25, D.C.
Army Research and Development Laboratories, Fort Belvoir, Virginia
Frankford Arsenal, Philadelphia, Pennsylvania
Army Ballistic Missile Agency, Redstone Arsenal, Alabama
Army Rocket and Guided Missile Agency, Redstone Arsenal, Alabama

Navy

Office of Naval Research, Washington 25, D.C.
Bureau of Aeronautics, Washington 25, D.C.
Bureau of Ships, Washington 25, D.C.
Naval Electronics Laboratory, San Diego 52, California
Naval Research Laboratories, Washington 25, D.C.

Other

National Bureau of Standards, Washington 25, D. C.

Central Radio Propagation Laboratories, Boulder, Colorado

Armed Services Electro-Standards Agency, Fort Monmouth, New Jersey

National Security Agency, Fort Meade, Maryland

Lincoln Laboratories, Lexington, Massachusetts

Sandia Corporation, Sandia Base, Albuquerque, New Mexico

2. MILITARY CONTRACTS FOR MICROMINIATURIZATION RESEARCH AND DEVELOPMENT

Microminiature Modules, Radio Corporation of America, DA 36-039 SC-75968

Work consists of providing a new and broad potential to enable construction of microminiature electronic equipment reduced in size by an order of magnitude. The micromodules will integrate with other micromodules and with associated components to provide equipment subassemblies and equipments. The micromodules are to be consistent with machine production and utilize available knowledge and capabilities.

Among the companies supplying materials, microminiature parts, or related research and development work to RCA under this contract are:

Corning Glass Works, Corning, New York

Centralab Division of Globe-Union Inc., Milwaukee, Wisconsin

P. R. Mallory & Co., Indianapolis, Indiana

Daven Company, Livingston, New Jersey

Aerovox Corporation, Olean, New York

Sprague Electric Company, North Adams, Massachusetts

Philco Corporation, Lansdale Tube Division, Lansdale, Pennsylvania

Pacific Semiconductors Inc., Culver City, California

General Instrument Corp., Newark, New Jersey

Hoffman Electronics Corporation, Semiconductor Division, Evanston, Illinois

Ceramics for Industry Corporation, Mineola, New York

American Lava Corporation, Chattanooga, Tennessee

Daystrom-Weston Instruments, Division of Daystrom Inc.

Microcircuitry, Varo Manufacturing Company, N(onr)-1076 (00)

Feasibility is being studied of producing electronic devices based on the end functional requirements of the circuits themselves in preference to considering the requirements of each component irrespective to its relationship to the over-all circuit function. Entire circuits are to be fabricated in a vacuum chamber using vacuum deposition of a multiplicity of materials on a suitable substrate.

Microminiature Solid Circuits, Texas Instruments, Inc., AF 33(600)-6600

Microminiature solid circuits capable of use in computers are being developed by use of bars of silicon or germanium material which are oxidized, etched, diffused, sliced, and inlaid with complementary materials using transistor manufacturing techniques.

Microminiature Thin Film Circuits, International Resistance Company, DA 18-119 SC-729

Microminiature thin film circuits are being developed on suitable substrates. Techniques and methods are being studied for depositing semiconductive films with suitable crystalline structures for semiconductor circuit elements. Attempts are being made to use ion beams for depositing materials on substrates.

Microminiature Circuits, Philco Corporation, DA 49-186-500 ORD-732, AF 19 (604)-5522, and AF 19 (604)-5537

Film deposition of semiconductor materials on suitable substrates is being studied together with work on sputtered resistors, capacitors, and conductors. Objective is the development of microminiature digital-type circuits.

Microminiature Solid State Circuits, Westinghouse Electric Corporation

Development work is being conducted on solid state electronic circuits involving the growing of dendrite crystals employing new fabrication techniques. This approach utilizes transfer functions in solid state circuitry rather than such circuit parameters as conventional resistances and capacitances.

Printed Circuit Research, Haloid Xerox, Inc., AF 19 (604)-1736 (AFCRC), AF 19 (604)-5508

Conducting units and passive components are fabricated in place by Xerographic techniques. Films are deposited by screen stencil, chemically, by vacuum evaporation, and electrostatically. The effort is primarily on forming circuit units in place on refractory substrates.

Thin Film Electronic Components, Armour Research Foundation, AF 33 (616)-5720 (WADC)

Research is being conducted on deposition of metal, dielectric, and insulating films by pyrolytic methods. Study of the structure of these films and plates, the nature of molecular deposition of multiple layers, the degree of adhesion to substrate, and the physical and electrical properties will be accomplished through application of solid state theory.

Ferromagnetic Films, Remington Rand Univac, AF 19 (604)-2659 (AFCRC)

Properties of thin ferromagnetic film are being studied to determine methods, other than vapor deposition, which lead to optimum performance in memory devices.

Solid State Circuit Functions, Georgia Institute of Technology, AF 33 (616)-6028 (WADC)

Experimental data are to be provided whereby the single or multiple functions performed by lumped parameter circuits can be integrated into single elements. Work includes survey of known solid state physical phenomena and effects, and provision of both general and exact mathematical expressions for each effect.

Solid State Phenomena and Circuit Functions, Pennsylvania State University, AF 33 (616)-6029 (WADC)

Work consists of derivation of mathematical expressions for circuit and system functions, including input and output characteristics together with a study of the combination of various expressions for solid state phenomena to perform the derived functions.

Evaporated Magnetic Memory Matrix, Servomechanisms, Inc., AF 33 (616)-3039

Equipment was developed (ending September 1957) for evaporation of ferromagnetic and insulating materials by electronic bombardment. Attempts were made to fabricate magnetic memory units using laminated films. Work indicated no limit to the ultimate thickness to which an evaporated laminated film could be fabricated. Regular and toroidal transformers were made using evaporated films.

3. ORGANIZATIONS ENGAGED IN MICROMINIATURIZATION WORK

The following list contains names of some organizations engaged in microminiaturization activity. In some cases, this may represent broad research activity, in others, a particular specialty such as fabrication of materials or a single type of part.

Aerovox Corporation, New Bedford, Massachusetts, and Olean, New York
American Lava Corporation, Chattanooga, Tennessee
American Bosch Arma Corporation, Arma Division, Garden City, New York
American Machine and Foundry Company, Alexandria, Virginia
Amphenol Borg Electronics Corporation, Broadview, Illinois
Applied Physics Laboratory, Johns Hopkins University, Silver Spring Maryland
Allen-Bradley Company, Milwaukee, Wisconsin
Airborne Instruments Laboratory, Mineola, New York
Armour Research Foundation, Illinois Institute of Technology, Chicago, Illinois
Autonetics Division of North American Aviation, Inc., Downey, California
Avco Corporation, Crosley Division, Cincinnati, Ohio
ARF Products, Inc., River Forest, Illinois

Battelle Memorial Institute, Columbus, Ohio
Bell Telephone Laboratories, Murray Hill and Whippany, New Jersey
Bendix Aviation Corporation, Radio Division, Towson, Maryland
Bendix Aviation Corporation, Research Laboratories Division, Detroit, Michigan
Boeing Airplane Company, Pilotless Aircraft Division, Seattle, Washington
Borg Warner Corporation, BJ Electronics, Santa Ana, California
Burroughs Corporation, Detroit, Michigan, and Paoli, Pennsylvania

Cannon Electric Company, Los Angeles, California
Centralab Division of Globe-Union Inc., Milwaukee, Wisconsin
Ceramics for Industry Corporation, Mineola, New York
Chicago Telephone Supply Corporation, Elkhart, Indiana
Cleveland Metal Specialties Company, Cleveland, Ohio
Cinch Manufacturing Corporation, Chicago, Illinois

Collins Radio Company, Cedar Rapids, Iowa
Coors Porcelain Company, Golden, Colorado
Cornell Dubilier Electric Corporation, New Bedford, Massachusetts
Corning Glass Works, Corning, New York

Dale Products, Inc., Columbus, Nebraska
Daven Company, Livingston, New Jersey
Denver Research Institute, University of Denver, Colorado
Diamond Ordnance Fuze Laboratory (U.S. Army) Washington, D. C.
Douglas Aircraft Company, Inc., Los Angeles and El Segundo, California
Dow Corning Corporation, Midland, Michigan

Electro-Optical Systems
Elgin National Watch Company, Micronics Division, Elgin, Illinois
Emerson Radio Corporation, New York, New York

Fairchild Semiconductor Corporation, Palo Alto, California
Fairchild Engine and Airplane Company, Wyandanch, New York
Federal Telecommunications Laboratories, Nutley, New Jersey
Food Machinery and Chemical Corporation, San Jose, California

General Electric Company, General Electric Laboratories, Schenectady, New York
General Electric Company, Light Military Electronics Department, Utica, New York
General Instrument Corporation, Newark, New Jersey
Georgia Institute of Technology, Atlanta, Georgia
Glass Products Company, Santa Barbara, California
Gulton Industries, Metuchen, New York

Haloid Xerox Inc., Rochester, New York
Hewlett-Packard Company, Palo Alto, California
Hoffman Electronics Corporation, Semiconductor Division, Evanston, Illinois
Hughes Aircraft Company, Culver City and Fullerton, California

International Business Machines Corporation, Kingston, New York
International Resistance Company, Philadelphia, Pennsylvania

JFD Manufacturing Company, Brooklyn, New York
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

Key Resistor Corporation, Gardena, California
Kellogg Switchboard and Supply Company, Chicago, Illinois

Lear, Inc., Santa Monica, California
Lind Corporation, Princeton, New Jersey
Litton Industries, Beverly Hills, California
Lockheed Aircraft Corporation, Missiles and Space Division, Palo Alto, California

Magnavox Company, Fort Wayne, Indiana
Maico Co., Minneapolis, Minnesota
P. R. Mallory and Company, Indianapolis, Indiana
Martin Company, Baltimore, Maryland, and Orlando, Florida
McDonnell Aircraft Company, St. Louis, Missouri
Mellon Institute, Pittsburgh, Pennsylvania
Melpar, Inc., Falls Church, Virginia
MF Electronics, New York, New York
Massachusetts Institute of Technology, Cambridge, Massachusetts
Minnesota Mining and Manufacturing Company, St. Paul, Minnesota
Minneapolis Honeywell Regulator Company, Minneapolis, Minnesota
Microdot, Inc., South Pasadena, California
Midland Manufacturing Company, Inc.
Motorola, Inc., Military Electronics Division, Phoenix, Arizona

National Cash Register Company, Hawthorne, California
National Beryllia Corporation, Haskell, New Jersey
Naval Research Laboratory, Washington, D. C.
Norden Ketay Division, United Aircraft Corporation, Commack, New Jersey
Nortronics Division, Northrop Corporation, Hawthorne, California

Ohmite Manufacturing Company, Skokie, Illinois
Onandago Pottery Company, Onanadago, New York

Philco Corporation, Philco Research Laboratories, Philadelphia Pennsylvania
Philco Corporation, Lansdale Tube Division, Lansdale, Pennsylvania
Pacific Semiconductors, Inc., Culver City, California
Pennsylvania State University, State College, Pennsylvania

Radio Corporation of America, Camden, New Jersey
Remington Rand Univac, St. Paul, Minnesota
Rutgers University School of Ceramics, New Brunswick, New Jersey
Raytheon Manufacturing Company, Waltham, Massachusetts

Sanders Associates, Inc., Nashua, New Hampshire
Servomechanisms, Inc., Goleta and Hawthorne, California
Space Technology Laboratories, Los Angeles, California
Speer Carbon Company, St. Mary's, Pennsylvania
Sperry Gyroscope Company, Great Neck, New York
Sprague Electric Company, North Adams, Massachusetts
Sippican Corporation, Marion, Massachusetts

Stackpole Carbon Company, St. Mary's, Pennsylvania
Stanford Research Institute, Menlo Park, California
Stromberg Carlson Company, Rochester, New York
Sylvania Electric Products, Inc., Needham and Woburn, Massachusetts, Mountain View, California

Texas Instruments, Inc., Dallas, Texas
Transitron Inc., New York, New York

Union Thermoelectric Corporation, Forest Park, Illinois
United Shoe Machinery Corporation, Boston, Massachusetts
U.S. Semiconductors, Inc., Phoenix, Arizona

Varo Manufacturing Company, Garland, Texas
Virginia Institute for Scientific Research, Richmond, Virginia
Vitro Laboratories, West Orange, New Jersey
Vitramon, Inc., Bridgeport, Connecticut

Westinghouse Electric Corporation, Air-Arm Division, Baltimore, Maryland
Weston Instruments Division of Daystrom, Inc., Newark, New Jersey

Yardney Electric Corporation, New York, New York

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Rapid advances in microminiaturization of electronic equipment will affect missile and space vehicle electronic design within a short period of time. To assess the potential impact of the new techniques, a field and literature survey of current progress of approximately 150 firms has been made. Micro-miniature circuits of some types are expected to be available soon for limited applications. Improved performance, resistance to environmental extremes, and increased reliability can be anticipated. Reduced size will eventually permit satellite payloads with highly sophisticated instrumentation and completely redundant control systems.

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