MOLECULAR ELECTRONICS

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EFFORTS to elevate air and space craft to new plateaus of capability are continually made more difficult through a technical paradox. As we make these craft more sophisticated through the use of advanced electronic gear, the risk of failure among components and connections grows. And as we add this more complex electronic equipment it becomes more difficult to provide for its weight and size. The problems of improvement of reliability and reduction or weight and size of electronic equipment may be approached in several ways. But such techniques as better quality control on components and connections, and miniaturization, while exploiting modern technology, do not yield maximum reliability.

In the recent past, a substantial part of Westinghouse research and development effort has been focused on a new approach to both problems. It exploits a new concept in the design and function of electronic systems. In fact, it is a broader concept of electrical engineering which we call "molecular electronics" to indicate its dependence on phenomena occurring within or between domains of molecules in the solid state. In this programme a variety of molecular electronic "function blocks" are now being produced, three of which are shown in Fig. 1, as solid-state elements that achieve,

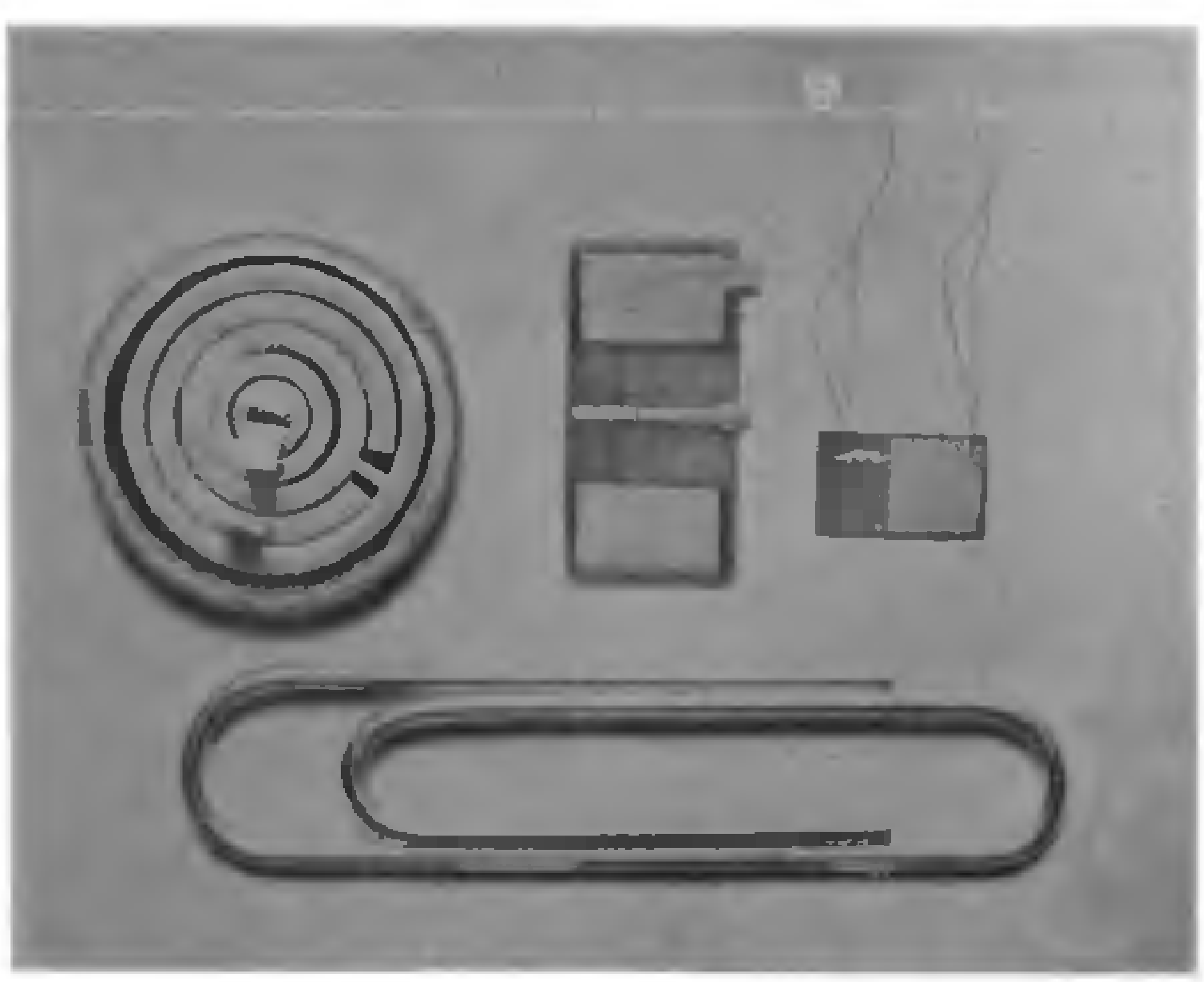

FIG. 1. Three of eight molecular electronic function blocks demonstrated as subsystems. Device bearing concentric arcs is an audio amplifier at centre is a free running multivibrator, and at right, a two-stage video amplifier.

entirely within themselves, electronic results such as have been gained only by assembling many, varied items of electronic hardware. Because of this, these elements are not intended as "components", as we think of transistors and tubes, but rather as "subsystems" since each of the function blocks has the ability to achieve an electronic result which is essential if all the subsystems in the entire system are to work together effectively. These function blocks perform such electronic operations as amplification, oscillation, telemetering, etc.

Because there are no internal connections or components, and the only external connections needed are those for coupling inputs and outputs to the complete system, it is possible to build subsystems whose risk or failure should be equal to or less than that of familiar solid-state devices and perhaps one-thousandth of that for a subsystem built of many parts for the same purpose. This ability of molecular electronics to reduce the number of components and connections required is illustrated by a comparison of three designs for a light telemetering subsystem, Fig. 2. When designed to use electronic tubes, this subsystem required 16 components and 18 soldered connections; when designed to use transistors, it required 14 components and 15 connections. In contrast a molecular electronic subsystem developed to achieve the same purpose needed but one component and two connections. Also, because their internal functions involve distances of the order of a few atomic spacings, these function blocks are almost microscopically small and virtually weightless. For example, weight of the light telemetry subsystems was reduced from about one ounce to one quarter of an ounce, the weight of the monolithic element to about seven-tenthousandths of an ounce.

As the basis for these molecular electronic subsystems, we have a very substantial knowledge of solid state phenomena developed over the past thirty years. It is simple now to create materials having excessive positive or negative electrical charges and, by placing these materials in physical contact with related materials, to bring about such phenomena as rectification or amplification, as in diodes and transistors. Also, we can readily take advantage of the ability of radiation to cause charge paths to occur in a semiconductor material along which current will flow when the material is irradiated.

Effects of this general type are used in molecular electronic blocks by creating—usually in single crystals—a number of distinct operative domains. The domains border one another at

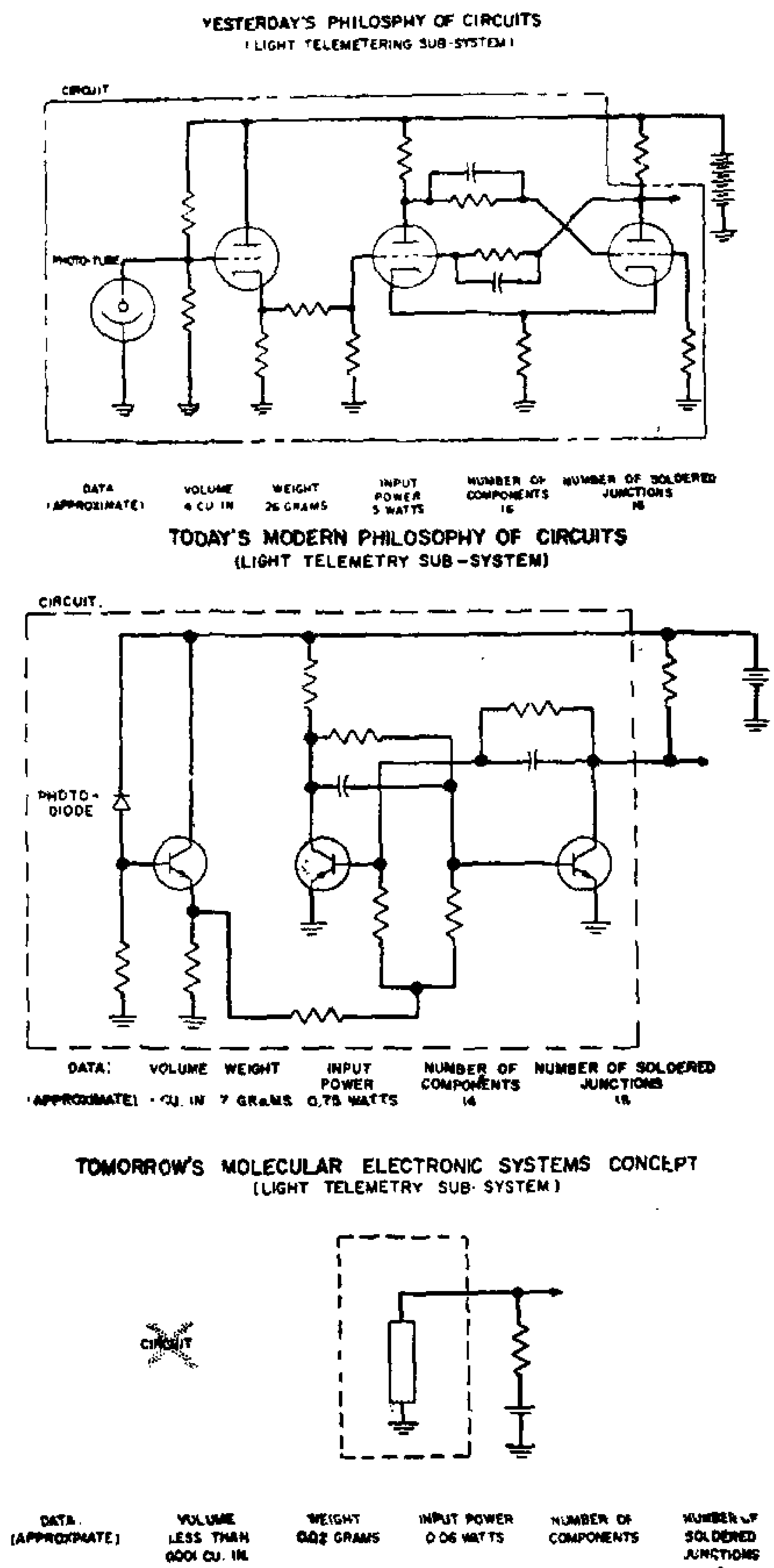

FIG. 2. Schematic drawing of light telemetry subsystems showing extent of circuitry required for systems using (1) electronic tubes, (2) transistors, and (3) molecular electronic element.

boundaries called interfaces where phenomena different from those occurring inside the molecular domains are initiated.

As a simple example in the element diagrammed in Fig. 3 we see that it is composed of two domains which meet physically at one interface. One of these domains is composed of a resistive material selected and shaped to present a resistance R_1 to the passage of current; the other domain is also resistive, but is so planned that it has a resistance R_2. At the interface, the interaction between domains causes a capacitive effect. Thus, in one tiny element we have a subsystem equivalent to a time-delay circuit.

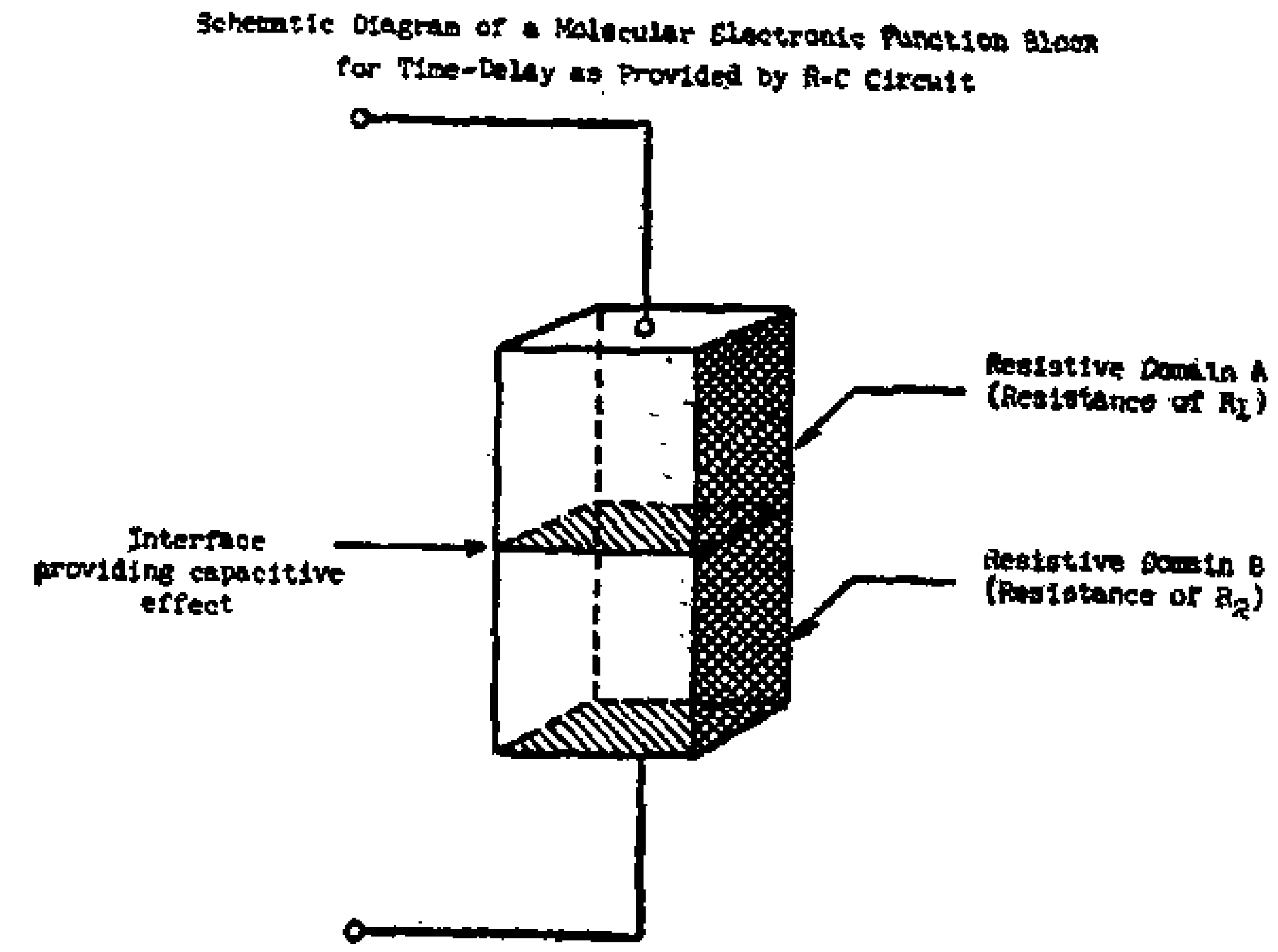

FIG. 3. Schematic drawing of function block of two resistive domains and one capacitive interface, whose total effect is that of an RC or time-delay circuit.

Another illustration of the uses of domains and interfaces is a function block designed as an ac-to-dc power supply for transistor circuits. It makes use of the Seebeck effect for the thermoelectric generation of electricity to convert 110-volt alternating current to 9-volt direct current power. In contrast, the conventional circuit, Fig. 4, requires five individual

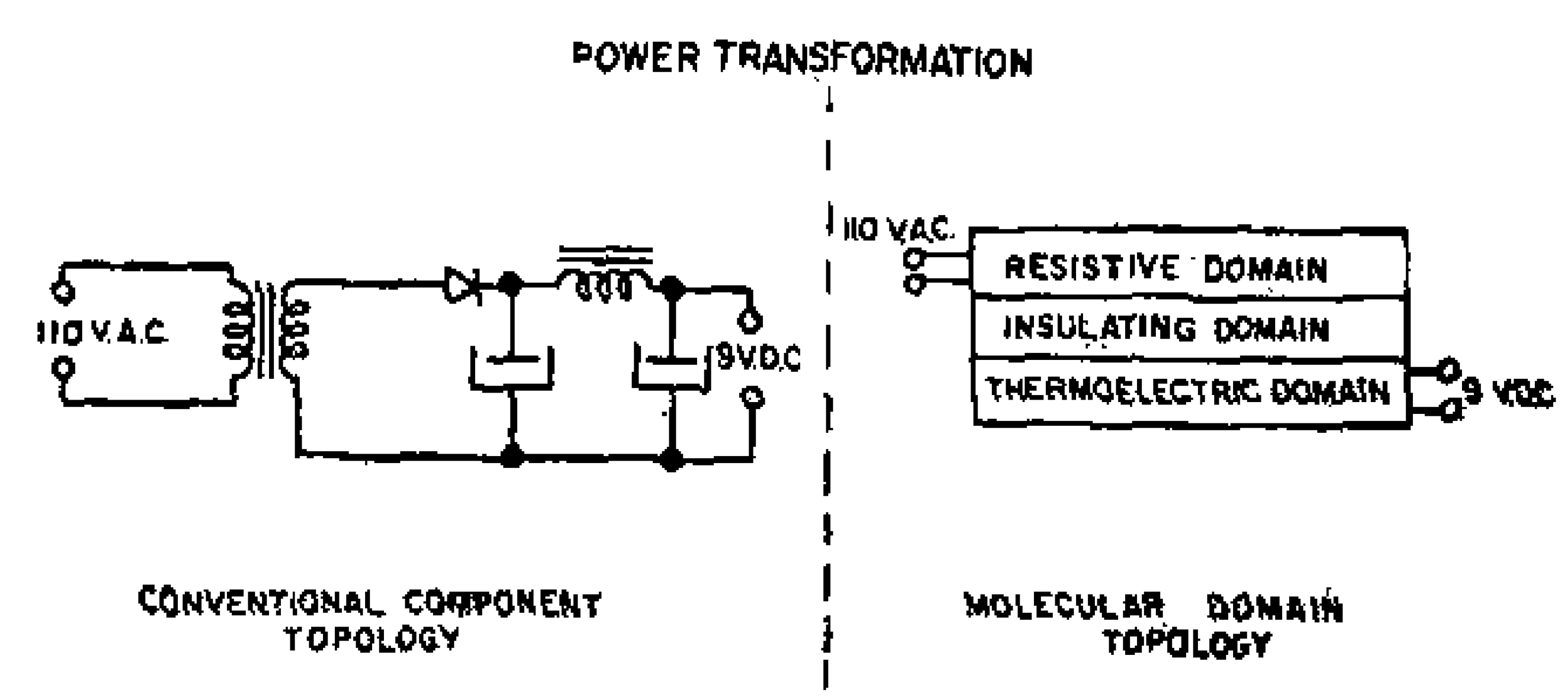

FIG. 4. Schematic drawing of a-c to d-c power supplies showing (1) molecular element with resistive, electrical-insulating, and thermoelectric domains and (2) conventional method using transformer, diode, and filter circuit.

components—a transformer, a diode, and the inductive and capacitive elements making up the LC filter circuit. To accomplish this same purpose with electronic methods, we have a function block comprising three separate domains. When a-c power is applied to the resistive domain, the heat that is generated passes through the domain at the centre—this domain is an electrical but not a thermal insulator—and into the thermoelectric domain where the energy is converted into electrical energy by the Seebeck effect. By proper control over the materials used, we provide the 9-volt d-c output we desire. An interesting aspect of the power supply is that elimination of ripple as an undesirable variation in voltage is inherent since heat flows from the resistive domain to the thermoelectric domain at practically a constant rate.

As these two examples suggest, the concept of molecular electronics makes no use of the traditional circuit-and-component approach to electronics. Instead, the objective is to use our knowledge of the structure of matter to synthesise monolithic function blocks whose arrangement and composition permit each to serve as a substation to perform an electronic function in the control or transformation of energy.

To achieve function blocks with this capability, a number of effects and phenomena of the solid state are available. The only firm limitations on choice are that the effect must not react adversely on system reliability and must lend itself to consistent results when included in a function block. Methods typical of practice so far include: solid state phenomena, such as the Seebeck generation, Peltier cooling, and Hall-effect multiplication; the use of PN semiconductor junctions arranged to produce a result which would otherwise require numerous individual components; and when necessary, fabrication of circuit elements within a function block. Although such phenomena will be most often used for the control of electrical signals, they will also be suitable when quantities like electromagnetic radiation, heat, and mechanical displacement are inputs or outputs.

The design of a subsystem begins with the designer's analysis of the requirements of the system, to establish the functions to be performed by the function block. After logic processes are determined and suitable physical effects settled upon, a topologist—a mathematician who works with shapes—determines the structure of the block by designing, on paper, the arrangements of domains and interfaces that is to control the flow of energy in the block. The block is then produced by the materials engineers who use germanium and silicon as the basic semiconductor materials.

In producing these blocks we do not assemble them from various tiny components. Rather, we start with a basic semiconductor wafer and produce the necessary domains and interfaces by techniques used in the production of conventional semiconductor devices, including diffusion, plating, electron beam machining, etching, cutting, radiation, alloying and photographic processes. Although the function block so produced can now perform its function, additional processing steps are required to encapsulate the block, protect it against shock and vibration, and make it stable under the conditions of temperature and radiation it will encounter.

One important illustration of the contributions made by materials scientists is the development of a method for the rapid production of semiconductor crystals in a form that requires no removal of material to make them into suitable wafers for use as transistors or as the basic elements of molecular electronic elements. This is the dendrite process in which germanium crystals in the form of ribbons about one-eighth of an inch wide and a few thousandths of an inch thick, are produced by drawing them from a molten mass.

The dendritic method is essentially a continuous process in which the germanium ribbon grows at the rate of 6 to 12 inches per minute and in the precise direction of crystal growth we require for application.

Now, although this dendritic method has immediate usefulness in molecular electronics today, we are confident that its greatest significance is its ability to bring about a number of new processes for producing fundamental blocks. We are now most interested in a recent modification which makes it possible and practical to carry out diffusion, plating, and evaporation processes directly on the crystal as it grows from the furnace melt. With this technique, we are able to create semiconductor devices ready for the attachment of leads. One of the first uses has been to grow transistors in the form of a long germanium crystal.

When the ribbon-like crystals are cut into segments, only simple processing is needed to produce transistors at a yield very near 100%. By this method we have produced lengths of ribbon along which small multiple-junction subsystems are distributed, Fig. 5. Since these ribbons can be easily processed to become a long series of tiny amplifiers, it is not at all facetious to say that this ribbon can be snipped into lengths to give us amplifiers of whatever gain we desire.

A more recent and extremely significant achievement resulting from our research is that we have now discovered how to grow multizoned

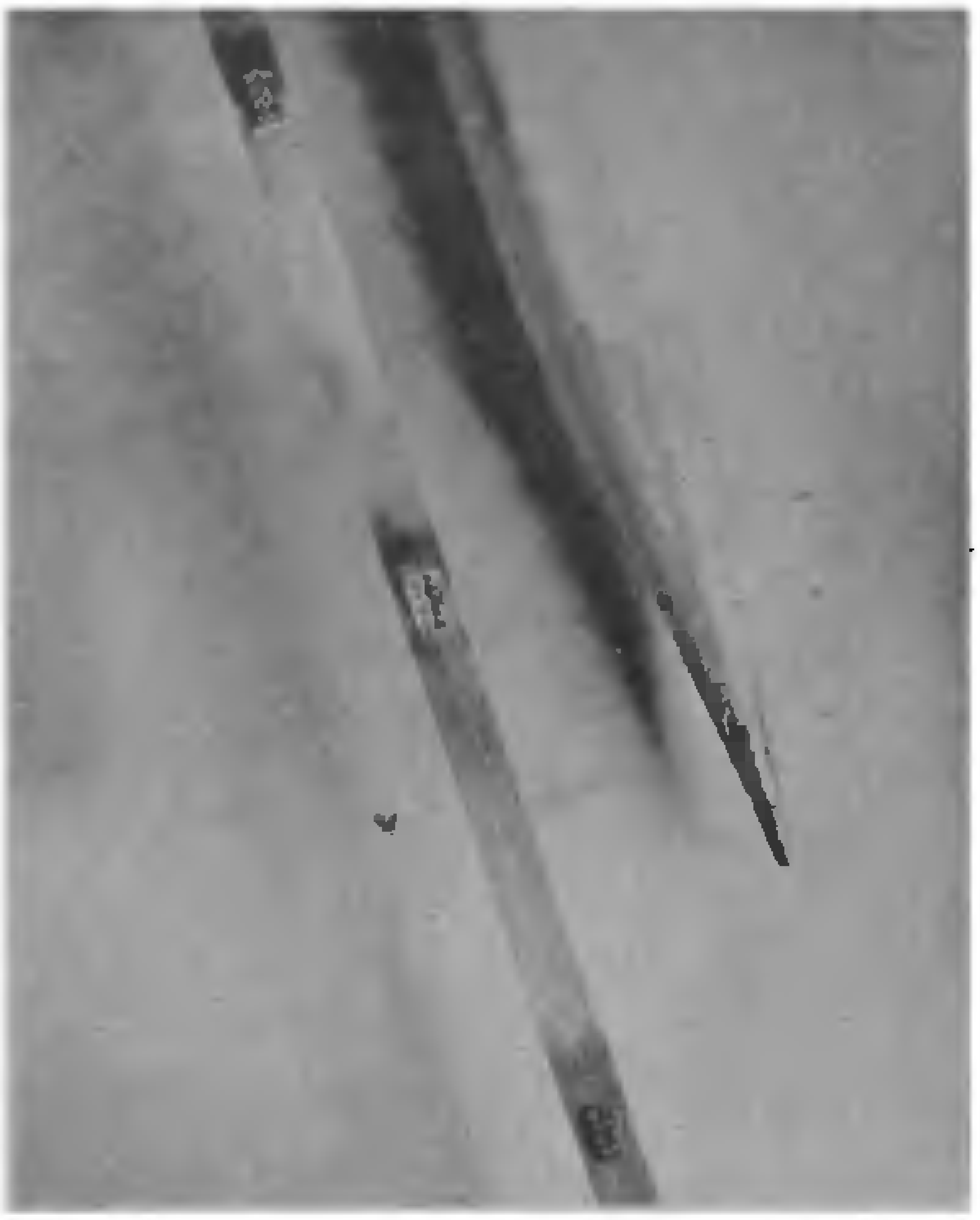

FIG. 5. Ribbon bearing multiple-junction systems on germanium crystal produced by dendrite process.

crystals as dendrites, directly from the furnace melt. We regard this development as a major event in new technology of molecular electronics. It makes available to us basic building blocks having at least three layers of zones and two interfaces. Thus it will no longer be necessary to perform many operations to create multizone elements.

In considering the implications of this basic method for crystal growth, one most interesting possibility is that it will prove practical to combine our ability to grow multizoned crystals with our ability to perform operations on the crystal at the time it is growing in the furnace. Admittedly, to achieve near-automatic production of semiconductor devices and molecular electronic function blocks is a long-range objective, but it is probable that we will eventually be able to "grow" from a pool of molten semiconductor materials some items of electronic equipment that today are of the order of complexity of radio receivers and amplifiers.

Although there was a 20-year interval between the invention of the vacuum tube and its first significant application, and an 8-year interval between the development of the transistor and its first uses, it is almost certain that no such delay is likely for molecular electronics. It is very likely that in three to five years we will see the molecular electronic concept widely applied in air space electronic systems for such important applications as telemetering, fire control guidance, communications, etc.

OBITUARY

SIR K. S. KRISHNAN

WE deeply regret to record the death of Sir K. S. Krishnan, Director, National Physical Laboratory, New Delhi, on Wednesday, the 14th of June, 1961.

Krishnan was born on the 4th December, 1898. He graduated from the Madras Christian College and later migrated to the University College of Science at Calcutta where he studied for two years. Sir C. V. Raman chose Krishnan for a position as Research Assistant in his laboratory and sponsored his promotion to the various positions held by him in later years; Reader in Physics at the Dacca University; the Mahendra Lal Sircar Professor at Calcutta in 1933 and University Professor of Physics at Allahabad in 1942. Sir C. V. Raman also proposed him for the Fellowship of the Royal Society to which body he was elected in 1940. Krishnan was appointed as the first Director of the National Physical Laboratory at New Delhi in 1947. This position he held till his death.

In his earlier years, Krishnan was closely associated with Sir C. V. Raman in his investigations. After the discovery by Sir C. V. Raman of the effect known by his name, Krishnan and later on, other workers also in the laboratory, assisted in following up the consequences of that discovery. At about the same time, systematic researches on magnecrystallic action were initiated by Sir C. V. Raman and were first carried on by Bhagavantam at Calcutta. These were subsequently continued by Krishnan at the Dacca University and formed the basis of his election to the Fellowship of the Royal Society.