Electronic Materials: Functional Substitutions

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One of the most dramatic of recent technological achievements is the hand-held electronic calculator. In its simplest versions, costing only a few dollars, it performs all the functions that were previously performed by the electromechanical desk-top calculator. In more sophisticated versions it does much more, performing comparably to what formerly required moderately sized computers. Quite apart from its primary purpose of making increased mathematical capabilities more widely available, the savings in materials relative to older equipment are obvious. So the question arises, whether such kinds of technological developments could help us to meet some of the limitations on supplies of natural resources that may lie ahead. The answer is of necessity open-ended; nevertheless, the needs for more in-depth studies of some of the factors—resources, technical, economic, and social—raised by this question warrant further attention.

The hand calculator is only a recent, well-publicized example of the revolution that is being steadily brought about by solid state electronics. While some solid state devices existed in the 1920's and 1930's, such as the original cat's whisker diodes and selenium rectifiers, the solid state revolution really had its beginnings in the discovery of the transistor in 1947. This three-terminal device essentially opened up the whole of electronics technology, previously based on vacuum tubes, to solid state components. The substitution of the transistor for the vacuum tube was immediately seen as a materials- and energy-saving substitution in addition to the improved technical performance it made possible. In many ways, the transistor did for man's brain what the earlier invention of the steam engine had done for man's brawn. It can be regarded as the instigator of the Second Industrial Revolution.

The transistor led, in turn, to the development of integrated circuits in which not simple discrete electronic components are linked together but in which the whole circuit, often consisting of thousands of transistors, resistors, capacitors, and interconnections, is fabricated essentially as one, highly processed, minute piece of material. These integrated circuits, nowadays the heart of nearly all electronic equipment, including the hand calculators, also seem to offer enormous material and energy savings over their older counterparts.

Functional Substitutions

The sort of substitution represented by transistors for vacuum tubes, and by integrated circuits for calculating machines, is often referred to as a functional substitution (as distinct from a material substitution). In these substitutions, a completely different approach to performing a needed function is found. For example, adhesives can be used instead of nuts and bolts for joining. Jet engines replace piston engines and propellers in aircraft. Telephones can replace mails for transmitting information. Nuclear reactors replace boilers fired by fossil fuels. Functional substitutions can lead to the revision of consumption patterns for materials and energy and can inspire the creation of entirely new industries.

The transistor, for example, has led to technological development of computers, missile-control systems, and a broad range of industrial, medical, and leisure products. And in nearly every case, the substitution of solid state electronics for older techniques appears to have led to considerable savings in the amounts of material needed for manufacture and the energy required to operate the equipment. To some extent the new development can be regarded as the substitution of light industry for heavy industry, of information technology for machinery.

Nature of Electronic Materials

Increasingly, electronic materials are included alongside metals, ceramics, and polymers as a major material division in the field of materials technology, in spite of the different ways in which electronic materials are used. Whereas metals, ceramics, and plastics are nearly always used in structural parts that have mechanical functions, electronic materials (as their name implies) are used to perform electromagnetic, including optical, signal processing functions. In the hand calculator, the calculation is performed electronically; in the older desk calculator it is performed mechanically via levers, shafts, and gears. Likewise, electronic mechanisms are replacing mechanical ones in watches. The overall functions are the same, but an electronic technology has been substituted for a mechanical one.

Stemming largely from the transistor discovery, and as indicated in Fig. 1 by the schematic tree (*1*), there is a growing variety of electronic materials, a term that can be taken to embrace semiconductors, conductors, superconductors, magnetic metals and crystals, dielectrics, piezoelectrics, pyroelectrics, ferroelectrics, lasers, electrooptical and magnetooptical materials, luminescents, and others. Their names often belie their main functions. They can be made to perform a vast range of information or signal-handling operations, such as signal generation, modulation, detection and amplification, memory and display, switching, and logic. And in performing such functions they provide a gold mine of technological options for the development of, for example, communications, computers, and control systems.

If we accept for the present that electronic materials and solid state electronics offer prospects of significant materials and energy savings and in so doing may be more part of the solution to materials scarcity problems than a cause, two principal questions arise: (i) Are electronic materials themselves vulnerable to scarcities of raw materials? and (ii) In which technological sectors can electronic materials mitigate problems of materials scarcity?

Effects of Materials Scarcities on Solid State Electronics

With regard to the first question, most of the elements in the periodic table are used in some kind of electronic equipment. In the telephone alone, 42 of the 92 elements provided by nature (Table 1) are present as constituents of 35 types of metals and alloys, 14 types of plastic, 12 varieties of adhesives, and 20 different semiconductor devices. Supplies of many of the elements used in the telephone, as in other electronic equipment, can be considered as vulnerable either to worldwide shortages

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← *Courtesy General Electric Research and Development Center, Schenectady, New York* (mercury and tin, for example) or vulnerable to the export policies of foreign nations (gold, palladium, chromium, for example).

Offsetting these vulnerabilities, however, is the fact that the quantities used in electronic equipment are usually relatively small. Furthermore, compared with other uses for materials, electronics usually carries a large value-added factor so that relatively large, scarcity-driven increases in materials prices can be more readily carried than in many other technologies. For example, finding a substitute for soldering tin may prove very difficult whereas substitutes may be found for tinplate in containers and for bronze alloys in bearings. Thus if tin becomes scarce and relatively too expensive, the substitute products would leave the available tin for more critical electronic uses.

But what if it does become necessary to find a substitute for one of the materials used in electronic equipment or in integrated circuits? Such items are usually assemblies of intimately interacting materials, each material being carefully chosen and developed to optimize the overall performance of the component. In consequence, even a minor change in one of the materials used within a complex component might have a major effect on the overall quality or performance of the component. In such circumstances, substitution of one material for another may be difficult or even impossible. This is particularly true for equipment in which materials performance has been pushed to the limit.

As a general rule, the simpler the application, the easier it is to find a substitute material. If a society's needs are sufficiently simple, the thesis of infinite substitutability might be tenable—materials are likely always to be available for simple products such as utensils for cooking and eating, for clothing, and for simple dwelling structures. But the more a society depends on complex and sophisticated equipment, the more vulnerable it is to scarcities of certain key materials, even if these are used in very modest amounts. Nevertheless, among the more sophisticated technologies, electronic equipment will often retain an advantage over other technological sectors because of the relatively small amounts of material it requires.

There are some materials for which the electronics and electrical industries are the dominant consumers. Copper, for example, is the electrical conductor material par excellence. The electronics and electrical industries account for 54 percent of U.S. consumption. But we are likely to experience shortages of copper over the next 50 to 100 years, even though, in the nearer term, domestic resources are large, worldwide reserves appear to be good, and the multiplicity of sources minimizes the U.S. vulnerability to actions by foreign governments. Also, a strong and well-established recycling technology for copper exists. But perhaps most important for the longer term, there is an abundant substitute, aluminum. While the substitution of aluminum for copper in wires and cables is by no means as straightforward or inexpensive as many people might think, nevertheless it is possible. There is an energy penalty, however; the energy required to produce aluminum can be several times that required to produce the same weight of copper.

Other metals for which the electronics and electrical industries are the dominant users in the United States include beryllium (62 percent), gallium (> 80 percent), germanium (60 percent), indium (85 percent), tantalum (55 percent), and yttrium (86 percent). In addition, there are several elements which find some critical use in these industries and whose abundance or source of importation (or both), along with a lack of domestic reserves, may cause concern. The general supply of these elements is summarized in Table 2. Some of the major applications in the electronics and electrical industries for these elements and also some possible substitutes are listed in Table 2.

Examination of the data shown in Tables 2 and 3 leads to the reassuring conclusion that, overall, the electronics industry is not very vulnerable to materials shortages. No sudden, dramatic shortages are foreseen for any of the key elements; besides, in many cases, the quantities required for electronics are modest. Furthermore, material or functional substitutes are available in many instances.

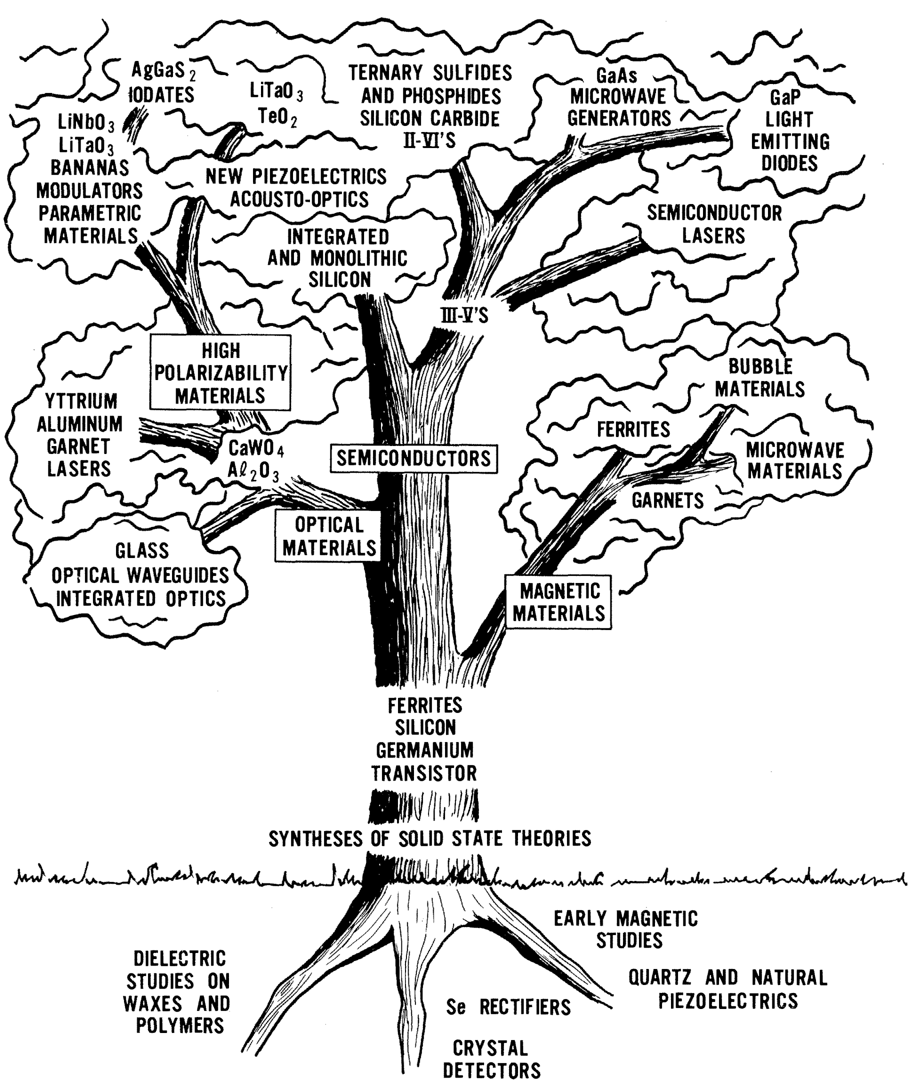

Fig. 1. The electronic materials tree. Representing progress in electronic materials, the roots lie in the basic sciences and in early studies of materials; the trunk signifies the development of the transistor; the branches represent those areas of current electronic materials progress—semiconducting materials more complex than those used in early transistors, magnetic materials now being used in computer memories, and optical materials for use in light-emitting, transmitting, and modulating devices.

For the integrated circuit, which is the heart of electronics, the prospect seems even more reassuring, because it is based on silicon—the most abundant of all elements except oxygen. And since such small quantities of silicon are needed, this suggests that man can plan on using solid state electronics extravagantly and indefinitely. However, there may be, eventually, other constraints regarding some of the more exotic materials used in conjunction with the principal semiconductor materials, the chemicals used for processing them, and the methods used for preparing the necessary ultrapure materials.

Except for certain special applications, a substitute for silicon is neither likely nor necessary. Rather, emphasis will be the other way round. In comparison with other semiconductor materials silicon always offers a relatively simpler technology—"If you can do it with silicon, you will." However, other semiconductors, particularly compounds of group III elements in the periodic table, such as gallium, aluminum, and indium, with group V elements, such as antimony, arsenic, and phosphorus, offer many optoelectronic and microwave properties that silicon cannot. But again, the quantities of material envisaged are relatively small, and overall it appears that shortages of basic semiconductor materials will not occur for the foreseeable future.

While substitution may not be a pressing problem with the semiconductor materials, it may become more so with some of the other electronic materials. As judged from the following examples, substitution, at least up to a point, would appear possible in many of these cases.

Electronic-grade mica is one of the scarcest of all materials. Traditionally it has been used in capacitors and as insulating supports in vacuum tubes. Nowadays there are various other materials suitable for these functions, but if a material were needed closely comparable to mica in its dielectric and mechanical properties, including its cleavage capabilities, such a material appears available. It is potassium niobate, a material that can be prepared by the same Czochralski pulling technique used for growing silicon crystals. Its mica-like properties were discovered as a by-product of an exploratory program in which new, nonlinear optical materials for electrooptical devices were being sought.

Brazil has been essentially the sole source for electronic-grade quartz used in piezoelectric frequency standards and filters. At present, such quartz is not used directly for making devices, but is crushed and used as nutrient for the hydrothermal growth of "synthetic" quartz. Recently, the price of Brazilian quartz was raised more than tenfold. This action stimulated searches for alternative sources of quartz of suitable quality, but again, in the hypothetical situation that this material became completely unavailable, it is reassuring to know that there are potential substitutes sitting on the shelf. Among the best of these is lithium tantalate, another crystal that can be grown by the Czochralski technique. Piezoelectrically it is even more efficient than quartz and has excellent temperature stability. Like potassium niobate, it was a spin-off from the optical material exploratory program. But single-crystal piezoelectric materials are not the only means of making electromechanical resonators. A feasible alternative is to use thin film oxide (such as zinc oxide) piezoelectric transducers mounted on metal resonator blocks.

Magnetic alloys are used in many varieties of electromagnetic switches and relays and in certain memory devices. Although the principal ingredient is usually iron, customarily cobalt and nickel are used in these alloys together with other elements such as vanadium, niobium, molybdenum, and chromium. Again, substitutes in the form of ferrites (oxides of iron), or other substances, such as yttrium, are potentially available although, in most cases, considerable equipment redesign would be necessary to incorporate them. Various ferrites are already used widely in electronics for high-frequency transformer and inductor cores, computer memory cores, and for magnetic recording tape.

Precious metals are important to a number of electronic components and integrated circuits. Gold is frequently used for leads and thin film conductor strips in integrated circuits because, among other properties, it has long-term stability and corrosion resistance qualities that are particularly important in microcircuits where dimensional or compositional changes on even the microscopic scale can be serious problems. However, other metals, such as aluminum, can be used for thin film conductors if suitably protected from corrosive environments.

Palladium offers an instructive case history of substitution. In electronic equip-

Table 1. Elements in the telephone handset (*3*).

Element	How used
Aluminum	Metal alloy in dial mechanism, transmitter, and receiver
Antimony	Alloy in dial mechanism
Arsenic	Alloy in dial mechanism
Beryllium	Alloy in dial mechanism
Bismuth	Alloy in dial mechanism
Boron	Touch-Tone dial mechanism
Cadmium	Color in yellow plastic housing
Calcium	In lubricant for moving parts
Carbon	Plastic housing, transmitter steel parts
Chlorine	Wire insulation
Chromium	Color in green plastic housing, metal plating, stainless steel parts
Cobalt	Magnetic material in receiver
Copper	Wires, plating, brass piece parts
Fluorine	Plastic piece parts
Germanium	Transistors in Touch-Tone dial mechanism
Gold	Electrical contacts
Hydrogen	Plastic housing, wire insulation
Indium	Touch-Tone dial mechanism
Iron	Steel, magnetic materials
Krypton	Ringer in Touch-Tone set
Lead	Solder in connections
Lithium	In lubricant for moving parts
Magnesium	Die castings in transmitter, ringer
Manganese	Steel in piece parts
Mercury	Color in red plastic housing
Molybdenum	Magnet in receiver
Nickel	Magnet in receiver, stainless steel parts
Nitrogen	Hardened heat-treated piece parts
Oxygen	Plastic housing, wire insulation
Palladium	Electrical contacts
Phosphorus	Steel in piece parts
Platinum	Electrical contacts
Silicon	Touch-Tone dial mechanism
Silver	Plating
Sodium	In lubricant for moving parts
Sulfur	Steel in piece parts
Tantalum	Integrated circuit in Trimline set
Tin	Solder in connections, plating
Titanium	Color in white plastic housing
Tungsten	Lights in Princess and key sets
Vanadium	Receiver
Zinc	Brass, die casting in transmitter, ringer

ment its major use is as a contact material for the electromagnetic relays used by the millions in telephone networks. On account of the high cost of palladium relative to other metals, suitable substitutes have been sought since the 1920's; but the only acceptable one so far found is an alloy of 60 percent palladium and 40 percent silver. (Silver is of the order of 1/20 the price of palladium, reflecting its relative availability.) All of the countless other metals and alloys investigated over the last 50 years or more have been shown to be less satisfactory in some physical, chemical, or engineering respect as a direct substitute for palladium. This is not to say that contacts made with other metals would not work, but that their performance and reliability would generally be inferior.

The electromagnetic relay or switch will be useful in communications systems for many years to come, but at the same time newer electronic switching systems, which do not rely on relays, will be steadily taking over, eventually eliminating this need for palladium.

This brief review of some examples of materials substitution in electronic technology, both current and potential, reinforces the impression that this technology is not particularly vulnerable to materials shortages either because of the relatively minute amounts of material used or, more importantly, because of the enormous versatility and adaptability of the science of electronic materials.

Table 2. Elements important to the electronics and electrical industries, listed in decreasing order of percentage of all consumption accounted for by these industries. Data from (*4*).

Material	Electronics use (%)	U.S. annual consumption		Sources of U.S. imports		U.S. reserves/ U.S. annual consumption (years)	World reserves/ annual production (years)	Ratio of world resources to reserves
		Total (tons)	Percent imported	Country	Percent			
				Elements				
Yttrium	86	92	?	Australia	53	?	150	Probably very large
				Malaysia	44			
				Other	3			
Indium	85	?	?	Canada	44	?	25	>2
				U.S.S.R.	14			
				Peru	11			
				Japan	9			
				Other	22			
Gallium	>80	~20	80	Switzerland	72	?	7,500	Very large
				United Kingdom	4			
				West Germany	4			
				Other	20			
Beryllium	62	312	20 (1969)	Brazil	64	?	?	?
			75 (1973)	Republic of South Africa	13			
				Argentina	7			
				Uganda	5			
				Other	11			
Germanium	60	20	17 (1969)	U.S.S.R.	40	?	?	?
			33 (1973)	Belgium	17			
				Japan	13			
				Czechoslovakia	9			
				Other	21			
Tantalum	55	600	100	Canada	30	~0	85 (Non-Communist source)	Limited
				Brazil	22			
				Zaire	14			
				Other	34			
Copper	54	2,350,000	25	Canada	31	35	50	~3
				Peru	27			
				Chile	22			
				Republic of South Africa	6			
				Other	14			
Platinum group	39	60	~100	United Kingdom	39	2	120	2-3
				U.S.S.R.	32			
				Republic of South Africa	12			
				Other	17			
Mercury	33	2,000	~85	Canada	59	7	20	~0
				Mexico	17			
				Spain	8			
				Italy	5			
				Other	11			
Cobalt	28	9,400	100	Zaire	45	3	100	~2
				Belgium	29			
				Norway	8			
				Canada	6			
				Other	12			
Gold	27	250	~85	Canada	51	10	23	?
				Switzerland	24			
				Burma	9			
				United Kingdom	3			
				Other				

Solid State Electronics: Materials Conservation via Miniaturization

While conventional electronic components—from cathode-ray tubes to crossbar switches, from klystrons to magnetic disk and tape memories—may not figure as massive consumers of materials when compared with, say, transportation equipment, they are nevertheless significant consumers of certain materials, as was discussed above. But a salient lesson of the substitution of transistors for vacuum tubes is the enormous potential that functional substitutions with solid state devices present for materials and energy conservation through miniaturization.

Fresh examples of miniaturization in solid state electronics continue to occur. Nowadays, an integrated circuit based on a silicon chip less than a quarter of an inch square may incorporate many thousands of transistors and associated circuit elements. This is a far cry from the early, discrete transistor of 20 years ago. Yet further miniaturization of integrated circuits, enabling even higher packing densities, is still expected. For example, the widths of conductor stripes, now typically a few micrometers, may eventually be reduced approximately tenfold by the development of ion and electron beam methods and plasma processing methods to replace the photographic techniques now commonly employed.

Other new devices, largely based on in-

Material	Electronics use (%)	U.S. annual consumption		Sources of U.S. imports		U.S. reserves/ U.S. annual consumption (years)	World reserves/ annual production (years)	Ratio of world resources to reserves
		Total (tons)	Percent imported	Country	Percent			
Silver	25	5,000	55	Canada	58	>7	18	>3
				Peru	20			
				Mexico	8			
				Honduras	5			
				Other				
Tin	15	56,000	~100	Malaysia	64	0.1	17	?
				Thailand	27			
				Other	9			
Aluminum	14	6,600,000	10	Canada	76	?	Abundant	Abundant
				Other	24			
Nickel	12	195,000	~90	Canada	82	1	65	Large
				Norway	8			
				Other	10			
Tungsten	10	7,750	56	Canada	61	10	30	~2
				Peru	9			
				Australia	5			
				Mexico	5			
				Other	20			
Antimony	7	39,500	50	Mexico	18	2	60	1–2
				China	16			
				Japan	13			
				United Kingdom	13			
				Other	40			
Lead	6	1,550,000	20	Canada	29	35	40	~1000
				Peru	21			
				Australia	21			
				Mexico	12			
				Other	17			
Rare earths	4	13,700	13	Australia	53	370	700	3–4
				Malaysia	44			
				Other	3			
Niobium	<4	1,000	0	Brazil	62	0	600	?
				Canada	16			
				Nigeria	14			
				Other	8			
Manganese	~2	1,900,000	85	Gabon	35	0	60	Very large
				Brazil	33			
				Republic of South Africa	7			
				Zaire	7			
				Other	18			
Zinc	—	1,520,000	40	Canada	48	20	20	~40
				Australia	10			
				Japan	9			
				Peru	8			
				Other	25			
				Other materials				
Mica (sheet)	~95	2,800	~100	India	79	~0	?	?
				Brazil	14			
				Malagasy Republic	3			
				Other	4			
Quartz (crystal)	100	150	100	Brazil	95	?	?	Limited
				Other	5			

Table 3. Some principal uses of elements important to the electrical and electronics industries and some possible materials substitutes.

Material	Uses in electronics	Materials substitutes
	Elements	
Yttrium	Color television phosphors	Other rare earth phosphors
	Magnetic materials	Some other rare earths
Indium	Semiconductors	
	Solders	Tin, lead, bismuth, cadmium
Gallium	Semiconductors (particularly, light-emitting diodes)	No equivalents
Beryllium	Electrical connector alloys	Phosphor bronze
	Springs	Phosphor bronze, spinodal copper alloys
Germanium	Semiconductors	Silicon
	Optical glass	Boron
Tantalum	Solid electrolytic capacitors	Aluminum, niobium
	Thin film circuitry	Hafnium
Copper	Signal transmission lines	Aluminum, glass optical waveguides
	Electrical conductors	Aluminum
Platinum group	Contact materials	Silver, gold, and their alloys
	Thin film conductors	Aluminum, tungsten
Mercury	Wetted contact relays	None satisfactory
	Arc rectifiers	None satisfactory
	Batteries	Various
	Lamps	Sodium
Cobalt	Magnetic alloys	Nickel, iron
	Ferrites	
Gold	Platings, contacts	Various, but inferior
	Thin film conductors	Tantalum, aluminum
Silver	Contact alloys	
	Conductors	Copper, aluminum
	Conductive paste	
Tin	Solders	Lead (partial)
	Copper alloys	Aluminum bronzes, stainless steel
	Superconductors	Other A-15 compounds
Aluminum	Conductors	
	Insulating ceramics	Various
Nickel	Magnetic alloys	Cobalt, iron
	Spring alloys	Various
	Ferrites	
Tungsten	Light filaments	
	Evaporator filaments	
	Metallizations	Aluminum
Antimony	Semiconductors	
	Fire retardants	Halogenated aromatics
	Solders	Tin, lead, bismuth, cadmium
	Cable sheathing	Calcium
	Batteries	Calcium
Lead	Batteries	Nickel-cadmium, and others
	Cable sheathing	Polyolefins
	Solders	
Rare earths	Magnetic crystals	Various rare earths
	Optical crystals	
	Phosphors	
Niobium	Magnetic alloys	Iron, nickel, cobalt
	Superconductors	Other A-15 compounds
Manganese	Ferrites	
	Magnetic alloys	
Zinc	Ferrites	
	Spring alloys	Various
	Batteries	Various
	Other materials	
Mica (sheet)	Dielectric	Potassium niobate
Quartz (crystal)	Filters, transducers	Lithium tantalate Mechanical resonators

tegrated circuit technology but which portend materials savings, include bubble domain memories, charge-coupled devices, and Josephson junction logic circuits. These devices or circuits are able to process and store bits of digital information. In the bubble domain device, a bit is represented by the magnetization state of a small region, or domain, of a crystalline or amorphous metal magnetic material. By suitable arrangements of externally applied driving fields, these domains can be moved about and used to perform sequential and associative memory and logic operations. Including associated circuitry, bubble domain memories have already been built which offer nearly half-a-million bits storage capacity in a few cubic centimeters, a considerable reduction in volume (and weight) from that required to achieve the same capacity using magnetic drums or disks.

Charge coupled devices (CCD), in which the information is stored as an excess or absence of electronic charge under a given electrode on a semiconductor, offer similar dramatic reductions. By means of suitable sequences of driving voltages, the charge state can be transferred along an array of semiconductor junctions thereby allowing the device to be used as a sequential or shift register. In a comparison of the potential of CCD's with magnetic drums, it has been estimated that for a usable capacity of more than 8 million bits, the CCD's offer approximately a tenfold reduction in weight (and volume) and nearly a hundredfold reduction in the required operating power. The CCD's also promise another dramatic development—a miniature television camera—in which an optical image is focused onto the CCD junction array and the impressed charge pattern is read out sequentially as in a television raster. Such a camera, with an FM (frequency modulation) transmitter making it a portable "walkie-lookie," need be no bigger than ordinary photographic cameras.

Josephson junction devices that exploit the peculiar switching properties of thin film superconductor structures potentially offer further increases in operational speed and packing density over integrated circuits. They present the possibility of another way of performing computer and logic operations that may be close to fundamental lower limits in power requirements.

An area in which functional substitution by solid state electronic components is rapidly occurring concerns electric indicator lights. Light-emitting diodes and liquid crystal displays are substituting for incandescent lights in a widening range of alpha-numeric and visual display applications, again with a much lower material content and operating power requirement.

Just as the transistor substituted for the vacuum tube at lower frequencies, so at microwave frequencies we see the relatively small Gunn and Impatt diodes substituting for much more massive components such as klystrons, magnetrons, and traveling wave amplifiers.

And hard on the heels of integrated circuit technology is optical electronics, which promises to establish this technology as a major factor in electronics. Information is transmitted as optical rather than electrical signals. The signals are generated and detected by semiconductor junction devices—lasers, light-emitting diodes, and photodetectors—and transmitted along optical fiber light guides. The light guides, made of very pure glass, no thicker than a human hair, functionally substitute for the signal-carrying purposes of copper wires and coaxial cables. Light guides will probably find an increasing array of applications, from interoffice trunk lines in telephone networks to high-speed digital links in computers and large switching machines, from communication and control systems on board aircraft and ships to wide-band local services to telephone subscriber premises. Besides potentially offering improved performance and costs relative to conventional transmission methods, optical fibers are attractive in that their principal ingredients are silicon and oxygen, the two most abundant elements on the earth.

Increasing the Productivity of Electronic Equipment

The above examples of current and potential functional component substitutions reaffirm the conclusion that such substitutions for more conventional components can offer considerable materials and energy savings in the components themselves. But another very significant way in which such savings can occur is by increasing the productivity of electronic equipment. Telecommunications networks illustrate this point.

It would be impossible to provide today's volume of telecommunications traffic if it all had to be carried by wires and cables—the requirements for copper alone would be prohibitive, let alone the associated needs for additional switching machines and buildings in which to house them. As the volume of trunk-line traffic increases, it becomes advantageous to multiplex many signals on to a single transmission line rather than provide separate lines for each signal. Further productivity can be obtained by time division in which a given frequency band is shared in a rapid, repetitive sequence by several different signals. Voice signals, converted into a series of digital pulses can be compressed, timewise, and transmitted as a short pulse train. At the receiving end the pulse train is expanded again and converted to analog to reconstitute a voice signal. By means of such compression and time-sharing, the productivity of transmission lines can be increased many times over what it would be if they carried simple, real-time analog signals alone. Another promising way of squeezing more productivity out of transmission lines is to avoid sending redundant signals along them; for example, in transmitting a video signal, the requirement for transmission capacity can be considerably reduced if only the changing elements of the picture are transmitted.

These and many other tricks with transmission techniques often exploit large bandwidths, available to signal propagation by radio links rather than cables. The higher the bandwidth the higher the transmission capacity, a relationship that is quantitatively defined. However, frequency space, which can be regarded as another type of "natural resource," has very definite, quantitative limitations, thus setting fundamental limits to the growth of communications capacity. These limits have already been reached—from low frequencies up to radio frequencies—as evidenced by the familiar interference effects encountered in radio broadcasting. There is some room left at ultrahigh frequencies, but it is rapidly being used up. Higher frequencies, microwave and beyond, still offer considerable transmission capacities.

The choice of the most economical transmission frequency and technology depends very much on the traffic volume. Roughly speaking, as the volume increases, the trend changes from simple wires to coaxial cables to radio and microwave transmission. It is interesting that, at the same time, the materials impact of these technologies trends downward. Likewise, on a per-channel basis, various high-frequency transmission systems under development are relatively economical in their materials requirements. A buried 2-inch (5-cm) copper-lined steel pipe will carry a quarter of a million voice channels simultaneously. Microwave transmission via satellites requires materials only in the satellites and the ground stations. And optical fibers, as was discussed earlier, depend principally on inexhaustible materials.

It will be apparent that the increasing sophistication of transmission techniques depends heavily on signal processing in the central offices and terminals. The relatively less materials-intensive switching technology is substituting for transmission technology, a trend that has been given enormous impetus by the integrated circuit which is doing for switching what it is doing for calculators. And as switching and logic actions are increasingly controlled by stored programs, another form of substitution can be seen under way—that of software substituting for hardware.

Functional Opportunities for Solid State Electronics

Electronic materials, through solid state electronics, have become intimately and inextricably involved in virtually every area of technology. But weaving through the maze of applications are two broad themes that can have considerable significance for materials usage.

1) As is frequently recognized, in the primary roles of telecommunications and information handling, solid state electronics can provide alternative forms of communication. Video transmission could substitute for some personal travel, whether for employment, business, personal, educational, recreational, cultural, or other purposes. Likewise, facsimile transmission could substitute for some mail services, and credit card "readers" can be used to record and process financial transactions. "Communicating to work rather than commuting," the "wired community," and the "cashless society" are familiar phrases that convey some of the potential that electronics has for providing new services to society. Such substitutions could make positive contributions to materials conservation by lessening society's dependence on materials-intensive transportation and construction technologies (for vehicles, roads, offices, and the like).

2) Perhaps less direct but with even more potential for materials conservation overall, is the use of solid state electronics to sense, monitor, and advise on the real-time performance and reliability of equipment. For example, sensing devices coupled to microprocessors or minicomputers might provide a direct display of the fuel performance of automobile engines, information which can be used to ensure its efficient use. Sensors monitoring room occupancy could be used to control lighting and heating. Sensors that could reliably monitor structural fatigue or reveal defects could reduce the ignorance that leads to materials extravagance and overdesign in order to meet desired safety and reliability standards.

Health monitoring combines many of the features described above. Sensors attached to patients, for example, for taking blood pressure or electrocardiograms, can be used to transmit information over the telephone network to doctors (or computers) who can then interpret the signals so received and advise on appropriate actions.

These various elements of electronics technology are capable of moving us closer to the era of intelligent machines, or "robotics," in which apparatus made up of sensors, microprocessors, and servomechanisms will be able to take over many functions normally performed by humans. Some of the possibilities that can be foreseen include the following (*2*).

▶ Automated intelligence system. In concept this is a general augmenter of human intelligence, capable of automatically monitoring ongoing streams of input data, coordinating facts, and making logical inferences to obtain insights.

▶ Talking typewriter. This voice-operated typewriter would be capable of converting spoken language into typewritten form at the speed of normal speech, and with an error rate about equivalent to that of a human typist.

▶ Voice-response order taker. Capable of handling spoken questions about orders for merchandise, this system would make up orders on request, look up catalog information, and inform the user with audible messages.

▶ Automatic identification system. Using voiceprints, fingerprints, or facial matching, this system would automatically recognize individuals, performing a unique personal identification.

▶ Automatic diagnostician. Based on biological tests and on questions answered by patients, this system would interactively or automatically supply medical diagnoses.

▶ Industrial robot. Using both visual and manipulative skills, this type of robot would perform product inspection and assembly in a wide variety of automated factory working environments.

▶ Robot tutor. This would not be simple-minded programmed learning but complex interaction near the level provided by a human teacher. Given an appropriate data base, it would accept verbal and biological responses from the student and individually tailor the course of instruction.

▶ Universal game player. Capable of operating at skill levels from novice to master, this machine would play such games as chess, checkers, Kalah, Go, bridge, Scrabble, and Monopoly.

▶ Computer-controlled artificial organs. These devices would be capable of replacing human hearts, livers, lungs, and other organs, while maintaining overall balance of body function. Present-day experiments with feedback-controlled heart pacemakers, and satellite life-support systems can be viewed as first steps toward the development of such artificial organs.

Vision and Some Problems

Electronic materials have established themselves throughout man's technological fabric. They are now as ubiquitous as iron and steel. The above examples of further developments that may be within technical reach give some idea of the enormous potential of functional substitutions via electronic materials for substituting light industry for heavy industry, thereby reducing overall needs for metals, ceramics, plastics, and energy. More quantitative studies need to be made of the net materials and energy savings that would accrue from these functional substitutions, but there is evidence that they could be significant in, for example, the substitution of telecommunications for personal travel. In view of the enormous versatility of solid state electronics it is reasonable to expect that man's ingenuity will continue to find new ways to exploit its materials- and energy-saving potential throughout all technology. It might also be noted that so far, nearly all progress in information technology has been based on inorganic materials. The future may have in store expansion into organic information materials, akin to those used in the human's information handling organs—the nervous system and the brain.

Such is the vision. But there are also many problems—material resources, technical, economic, and sociological. Among the material resource aspects, one that is frequently overlooked is that although the material content of the final solid state device may be minuscule, considerable quantities of a surprisingly large variety of processing chemicals, some relatively exotic, are often needed in its manufacture. It could well turn out that the principal material constraint on the availability of electronic devices will not be the electronic material itself, but the availability of the necessary processing chemicals. Also, it should be kept in mind that the small quantities of electronic materials often represent not insignificant expenditures of energy in obtaining them.

Foremost among the technical problems is reliability, both of hardware and software. The vaster and more complex that electronic systems become, the more reliable must their individual components or subsystems be. On the hardware side this particularly implies improved understanding of the physical and chemical mechanisms of materials failure and improved nondestructive means for detecting microscopic defects. Regarding software, there is an urgent need for practical methods for characterizing and detecting program errors.

Concerning economic matters, the relative abundance of electronic materials may tend to encourage extravagance. However, practical constraints are likely to be set by capital requirements. Electronic systems are highly capital-intensive, reflecting the relatively high, value-added factors. For example, nationwide investment in computers and communications in recent years has accounted for approximately 20 percent of all new capital available. Clearly, and especially in the face of increased demands for capital by the energy sector, massive and rapid increases in investment in electronics cannot be anticipated.

The chief problems facing the full and widespread implementation of the information age are, however, not so much technical or economic, but sociological. Electronics technology is likely to be in abundant supply, little affected by materials shortages, and this could, in principle, generate extravagant demands for it up to limits set mainly by economic considerations. However, man's attitudes, both individually and collectively, can severely hamper the introduction of enormous electronic computer, communications, and control systems.

Most people are, as yet, unfamiliar with information technology, especially two-way interactive technology, although the hand calculator may prove to be one of the most successful ways of introducing the general public to it. Nevertheless, the mass learning process will probably be much slower than the pace that technological advance alone could set. This is all the more true as the technology becomes larger, more complex, and sophisticated. Some systems can become so large and complex that very few individuals can comprehend and manage them. Breaking them down into more manageable subsystems eases some of the problems but does not eliminate them; there always have to be some individuals and organizations that can understand and manage the whole assembly of interacting subsystems.

References and Notes

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