An Approach to Microminiature Printed Systems

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T HE DAY is rapidly drawing near when digital computers will no longer be made by assembling thousands of individually manufactured parts into plug-in assemblies and then completing their interconnection with back-panel wiring. An alternative to this method is one in which an entire computer or a large part of a computer is made in a single process. Vacuum deposition of electrodes onto blocks of pure silicon or germanium and the subsequent diffusion of the electrode material into the block to form junctions is a most promising method. The successful development of this method would allow large numbers of transistors and all of their interconnecting wiring to be made in one operation. Vacuum deposition of magnetic materials and conductors to form coincident-current magnetic-core memory planes is a second promising method that will allow an entire memory to be made in one operation. The vacuum deposition of superconductive switching and memory circuits is a third method that will make possible the printing of an entire computer. The authors feel sure that the most significant milestone in computer component technology will be the announcement by one or more firms, in perhaps 2 years, that all of the technical problems of building a printed system have been solved, and that one of their engineers with his vacuum system can make a digital computer in an hour.

All three methods mentioned, as well as others not mentioned, involve vacuum deposition through a mask. A cleaned glass substrate or a semiconducting surface is placed in a vacuum system, and the air pumped out until the residual pressure is below 10^-4 atmosphere. A piece of metal near to the substrate is then heated and atoms of that metal evaporate. Some condense onto the substrate, forming a thin film. Between the source of atoms and the substrate a mask is placed to inhibit deposition of material outside the mask. A method is then employed to condense material onto the substrate through the mask. An alternative to this method is one in which the atom source is placed in a vacuum system and the substrate is moved relative to the source of material. A variant of this method is to deposit a material onto the substrate through a mask and then move the substrate to a second vacuum system where another material is deposited through another mask. The resulting product is a printed system with two or more layers of material.
tercept all of the atoms except those which pass through holes in the mask and condense onto the substrate. The pattern of holes in the mask therefore controls the pattern of deposited atoms in the film. By changing sources and switching masks, one can sequentially deposit conducting and insulating layers to form a circuit. The width of conductors in the circuit is no less than that of the holes in the mask. In practice, the minimum width is 0.001 inch.

The approach to microminiature printed systems that will be described has a line width of 0.1 micron as a goal (1,000 Angstrom units = 0.1 micron = 1/250 of 0.001 inch). If the goal is reached, it will then be feasible to make single-intersection cryotron circuits or other switching components which fit into a 1-micron square. Allowing 92% of the available area on a substrate for waste space and interconnections, the component density in a finished circuit could be 50 million per square inch per layer. Layers of cryotron circuitry can be isolated from one another by superconductive shielding and insulating layers to form a circuit. By changing sources and switching masks, described. The thin film which carries out a self-organization study in parallel, with many eventsocurring simultaneously as in an animal nervous system, would provide a much faster test of some of the rather ambitious models of "machines that think they can learn." By the time the techniques subsequently outlined reach reality, the models of neural networks will undoubtedly have changed.

To provide components for such large-scale tests of neural network models, at any rate, one of the present justifications for attempting to build components on such a small scale and in such large numbers. In addition, however, there are many fine physical experiments that can be performed on a 0.1-micron scale as soon as the building process is developed.

One can hardly justify work aimed at the manufacture of machines like present-day computers on such a small scale. If a present-day computer could be reduced to the size of a cigar box by one of the techniques mentioned in the first two paragraphs, there is little point in then reducing it to the size of a postage stamp. The computer would already be dwarfed by its own terminal equipment and, in the case of cryotron circuitry, its Dewar vessel. Man has ambitious plans for information-handling machines, however, and one can easily visualize a time, a decade from now, when truly vast numbers of components will be needed in a single machine. At present, there is a need for a large number of components to test models of self-organizing systems.\(^1\)\(^2\)

For an excellent review of neurophysiology see reference 6. Simulations of such systems on digital computers are relatively slow, and the number of neurons in a model of a neural network is presently limited to about 1,000. The slowness of a high-speed computer is a consequence of the step-by-step process by which it carries out a program and the small neural network size is a consequence of the limited amount of high-speed storage. A system of high-speed components that carries out a self-organization study in parallel, with many eventsocurring simultaneously as in an animal nervous system, would provide a much faster test of some of the rather ambitious models of "machines that think they can learn." By the time the techniques subsequently outlined reach reality, the models of neural networks will undoubtedly have changed.

The Resist-Forming Process

Specimen contamination due to the free-radical polymerization of hydrocarbon and siloxane vapors under the influence of electron and ion beams has long been a serious source of difficulty to electron microscopists.\(^8\)\(^9\)\(^10\)\(^11\) By purposely enhancing the effect, however, one can selectively deposit a "resist" onto an evaporated metal film that will protect areas of the film during the subsequent etching process. For example, tetraethoxysilane vapor, admitted to a high-vacuum system at a pressure of \(10^{-4}\) millimeter of Mercury (mm Hg), allows a silicon resist to be formed in one minute by an electron beam of approximately one milliampere per square meter in current density. The action of the electrons is to generate free radicals in the monolayer of siloxane which forms over the inside of the vacuum enclosure. A free-radical polymerization process then proceeds through its propagation phase, cross-linking the monolayer into a solid plastic which is effectively removed from equilibrium with its own vapor pressure. A second monolayer then forms and is likewise cross-linked. The nature of the termination phase of the polymerization reaction is not known, and the average molecular weight is also not known.

Ennos\(^11\) has studied carbonaceous and siliceous deposits up to 1,700 Angstrom units in thickness, formed in 100 minutes by an electron beam of 10 milliampere per square centimeter density, and he has followed the deposition rate as a function of temperature and beam density. Poole\(^12\) showed the existence of free radicals by removal of a lead mirror, a standard test for free radical hydrocarbons. The rate of formation of the resist appears to be independent of beam voltage. The resist forms nicely in an electron microscope with 100-KV electrons, and it was possible to insulate the anode of a diode with 20-volt electrons. Carr\(^14\) has used the resist formation process to trace trajectories for very low energy electrons.

The Etching Process

While still in the vacuum system, the areas of the thin film on which a resist has not been formed can be removed by vapor etching. Molybdenum films, for example, can be removed at a rate of about heated crucible, from a molten tip by electron bombardment, or from a water-cooled copper hearth by electron bombardment are also suitable means by which the thin film can be formed.
1,000 Angstrom units per minute by heating the film to 300 degrees C and admitting chloride at 10^{-4} mm Hg. Each metal has a different etchant and etching temperature. Ideally, the etching process will form a volatile compound of the metal so that not only will the film be etched, but the resulting compound will leave the substrate and be quickly pumped away. Some metals have a tenacious oxide which can be removed by a brief exposure to carbon tetrachloride vapor while hot. After removal of the oxide layer, a halide etch can then often be used. A siliceous resist can withstand a higher etching temperature than a carbonaceous resist.

**Insulation Between Layers**

A siliceous resist, when heated, becomes a high-silica glass, and can serve as a layer of electrical insulation between conducting films. The quality of the resist as an electrical insulator is not known. Tentatively, the plan is to deposit insulation selectively wherever a crossover is to be formed, as at a single-intersection cryotron, with the same process that forms the resist.

**Removal of Resist**

Hydrogen fluoride can be used to remove all exposed polysiloxane material (the resist) without appreciably affecting metallic surfaces. A convenient source of hydrogen fluoride (HF) in the vacuum system is a small amount of a metal acid fluoride which decomposes when heated, liberating HF. The resist must be removed whenever a metallic film on one layer must join a metallic film on another layer. After removing all of the resist with HF, it can be selectively replaced by the electron beam to form the insulation between films where needed.

**Resolution**

Electron microprobes 200 Angstrom units in diameter can be formed with a current density that will rapidly deposit a resist. In fact, the resist formation is the undoing of many microprobe attempts. Since the free-radical polymerization process is nearly independent of electron voltage, one must be particularly careful that secondary electrons do not cause the resist to form in a large area surrounding the point at which the beam intercepts the substrate. Electrons accelerated by 10KV have a range of 3,000 to 5,000 Angstrom units in materials of density 5 to 10, and 1,500 Angstrom units for heavy metals such as gold and wolfram. The range varies roughly as the square of the voltage, so that electrons accelerated by 2KV have a range of less than 200 Angstrom units. Fortunately, the region in which most of the electrons are stopped is well beneath the surface of substrate, so that the range of an electron probably gives a pessimistic estimate of the broadening effect of scattered electrons on the spot size.

The ultimate resolution of the etching process is not known. In one attempt to measure the resolution using polystyrene spheres of known sizes to form a shadow in the resist, a sharpness of shadow was observed in the etched film which suggested a 70-Angstrom unit resolution had been achieved.

The resolution which has been chosen as a target for component construction is 300 Angstrom units. Making conductors and insulators 0.1 micron in width should not be difficult if this spot size is reached. The goal of placing a component, such as a single-intersection cryotron, in a 1-square-micron area, then, consists of "drawing" that component with a 30-by-30 pattern of dots.

**Formation of the Electron Image**

A pattern of electrons can be formed in many ways. In an image tube, for example, a photocathode sensitive to X rays, light, or infrared radiation generates a pattern of electrons that can then be accelerated to strike a phosphor, and thereby produce an intensified image of the pattern which falls on the photocathode. The "snoperscope" is an example of an image tube. One could start in the drafting room with a set of drawings of the circuit to be formed, reduce that set of drawings photographically, and then generate a pattern of electrons for each stage of resist deposition by placing the appropriate photographic negative between the electron source and the resist. The pattern of electrons can be reduced electron-optically with either electrostatic or electromagnetic electron optics.

A second technique for generating a pattern of electrons is to form a mask by photoengraving, exactly as if the mask were to be used to control the deposition of evaporated atoms, but then to allow the mask to intercept all of the electrons except those which pass through holes in the mask. This technique is used to form the letters in the character tube. When using a mask, and when using electrostatic electron optics inside of the system containing the hydrocarbon or siloxane vapor, all parts on which a resist is not desired must be heated to 250 degrees C. At this temperature, the monolayer does not form, and the resist builds up at an exceedingly slow rate.

A scanning system for depositing the resist is one method by which the building process can be controlled electrically, possibly from another information-handling machine. When a large number of components are to be produced, the drafting of circuitry will become a burdensome task for all but strictly repetitive circuitry. Ultimately, therefore, the electron image must be formed by completely electronic means. Scanning is much slower than the simultaneous deposition of a reduced pattern, so a need exists for a means to accomplish the high-speed conversion of data from a computer into an electron image.

**Connections to a Microminiature Circuit**

The process by which narrow conductors are formed can be used to make conductors which become wider toward the edge of the substrate, eventually reaching a width of 25 microns. A 0.001-inch wire can then be soldered to the widened area, possibly by the pyrolytic decomposition of tetraethyl lead onto heated areas that correspond to holes in a reflective soldering mask. The power-supply connections and a limited number of information channels can thereby be made. Large numbers of input channels, such as a retinal field, pose a difficult problem. An optical input and output system involving photocathodes and electroluminescent "spots" make by the same 0.1-micron building technique is the best solution to date.

A retinal field would be focussed, using light optics, onto a pattern of 1,000 X 1,000 tiny photocathodes, which are formed at one place on the substrate. At the output region of the substrate, a pattern of 1,000 X 1,000 tiny electroluminescent spots might be constructed which will generate light to form an output image. If one takes a present-day light panel, and puts it under a microscope, he will find that all of the light comes from a large number of extremely tiny spots. The nature of the light-forming process is not completely understood. Field emission from the sharp corners of crystals may be the cause of the localization of light. In order to bring the hypothetical output device to reality, then, one will have not only to learn how to construct the spot on a 0.1-micron scale, but will also have to learn what it is that must be constructed.
Latent Images

The resist deposited by an electron beam is a latent image of the circuit to be etched. Many adjacent latent images can be formed, and the etching then done in a single step. The postponement of etching until many resist images have been deposited will almost certainly be necessary if a large number of components is to be assembled. In any one photographic field, the number of resolution units is fixed, usually by aberrations in the lenses. Electron lenses, particularly, have a large spherical aberration, and therefore the electron trajectories must be restricted to nearly paraxial paths by apertures. A circuit of approximately 1,000 components is perhaps the largest that can be handled at one time by the electron optical system, and therefore a number of latent images must be formed. Registration problems can be eased by wasting some area near the junction of two latent images. For example, a connection might be made between a horizontal conductor at the edge of one field and a vertical conductor at the edge of the other; considerable leeway in positioning can thereby be provided. In the case of cryotrons, one conductor can be a control element and the other a gate element, so that a cryotron that is half in one field and half in the other would provide the interconnection.19

Fortunately, the same electron optical system which reduces the image can be used to magnify the scattered electrons and give an electron-microscopic view of the construction process. A person can thereby serve as a part of the alignment feedback loop, or a system of photocells can replace him. At any rate, for small systems of components, one can watch the entire process. Time permitting, the person could even look first at the area on which the next image is to be formed to see if any bad imperfections exist in that area. Corrective means might then be taken to avoid regions having holes or bad spots.

Document Storage

If the 0.1-micron building scale is reached, a 10,000-line-per-millimeter photographic process will be available for the storage of documents such as texts, photographs, or maps. Electron optical reading has the advantage of high contrast. A second, and much more important advantage of electron optics over light optics is the very large depth of field and depth of focus of electron optics. In an electron microscope, the depth of focus is more than one foot. The large depths of field and focus result from the small numerical aperture that must be used in an electron optical system because the lenses have such large spherical aberrations. The specific energy density in an electron beam is exceeding high, however, so in spite of the small aperture, a high enough current density is usually available to produce chemical changes. A discussion of the beam current density versus demagnification is given by Cosslett and Haine.50 A reduction of 2,500 to 1 appears feasible with the electron-optical process described, but such a reduction would be all but impossible in a light optical system because of the demands placed on the mechanical design by the extremely small depth of field. The electron-optical system, of course, can also allow reduction to a scale far below the wavelength of light.

A scanning read-out system for the latent resist image would also be possible, so that etching of the metallic film would be unnecessary. The difference in secondary emission characteristics of the resist and the metallic film would provide an output signal. Such a system might be useful in telemetering space-probe photographs back to earth.

Summary and a Demonstration

One possible process for producing etched wiring on a 0.1-micron scale has been proposed. Fig. 1 shows an electron micrograph of a simple test of the process carried out by C. Crawford and A. Baker at Massachusetts Institute of Technology. The large dark lines are the wires of a 200-mesh electron microscope specimen screen. Corresponding points on the screen are separated by 0.005 inch. On this mesh was deposited a Parlodion film of about 800 Angstrom units in a vacuum system. The oxide film was then heated to 300 degrees C and chlorine was admitted to the vacuum system at 10⁻⁴ mm Hg. After one minute, the screen was placed in the electron microscope, and the molybdenum film was seen to be cut up into little squares about 0.001 inch on a side. Each square corresponds to a hole in the 400-mesh screen. Magnified pictures showed the edges of the film which were formed around pieces of stray material. The resolution is estimated to be finer than one micron.

The chemical reactions involved in the process appear to work. Many details must be explored and many techniques developed before the entire process becomes a practical reality and systems of information-handling components can be printed.

References

Organization and Retrieval of Records
Generated in a Large-Scale Engineering Project

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This paper describes the organization of a file and retrieval system developed for use on a large-scale engineering project, the development of the Electronic Recording Machine Accounting (ERMA) Mark I. ERMA, which was built by Stanford Research Institute for the Bank of America, is a large-scale computer and data-processing system designed to process bank checks automatically.

Although the authors have had no experience in the field of documentation as such, a useful and potentially efficient paper system was produced. The work on the file system was motivated by a respect and appreciation for the importance of a good retrieval system, not only in terms of the cost and efficiency of a research project, but also for its success as well.

The principles developed and utilized in creating this system should be useful to technical and research management and to others concerned with projects that can be systematized. Some research projects, in which only the broad outlines of the problem are initially understood, will not meet the specification of prior systematization. However, many engineering and research projects do meet this specification.

General Background

Crash programs are a significant characteristic of American industrial, commercial, and governmental operations. When such programs are hurriedly organized and executed, there is always the danger of inefficiencies arising from an inadequate information and record system.

The following is a partial list of situations and requirements that such an adequate system would serve to improve:

1. Training and orienting new personnel: Too often newly assigned people are thrown into the middle of a project without training or orientation or they are given "some kind of literature" to read for a week or so and then are expected to be familiar with the project. A simple information system designed to provide the trainee's needs for material and information already available will increase the efficiency of this orientation program.

2. Indispensable personnel: Frequently, vital information is carried in people's heads and, because it is not recorded, is often inconvenient and difficult to retrieve. The loss of such people due to illness or resignation may be catastrophic to the success of a project. An adequate information system designed to provide the trainee's needs for material and information already available will increase the efficiency of this orientation program.

3. Duplication of effort: It is wasteful, to have people working on one project duplicating the work of others on related projects, though this is sometimes unavoidable because of security or other reasons. But there is no legitimate excuse for duplication of effort within a project because of an inefficient information control system.

4. Action based on less information than is actually available: Often basic information has been generated within a project, but for some reason (usually because it has not been properly recorded and filed) it is not available to those requiring it. Under such circumstances, a duplicate program may be initiated to obtain the desired information lest decisions be made on the basis of insufficient information.

5. Patent preparation: Imnumerable man-hours are expended by patent attorneys in interviewing an inventor to obtain relevant information for purposes of disclosure and patent. Proper documentation and filing of patentable ideas would reduce this lost time.

6. Manufacturing information: Many "one-shot" projects include designers whose design paper is the "back of an envelope." One need scarcely emphasize that this is inadequate as a basis for translation to production specifications. Obviously, even this insufficient information is not filed.

7. Dissemination of information: Various types of information distribution systems exist (functioning with varying degrees of success). An adequate record system, explicitly designed to co-ordinate with a good distribution system, will keep appropriate personnel promptly informed of current project developments.

Performance Specifications

In attempting to avoid these potentially dangerous and inefficient situations, and, of course, in trying to keep an adequate record of the ERMA project, a set of performance requirements for a filing and retrieval system was developed. (During the development of the file system, these performance requirements were not actually recorded in detail as they are in this paper. Nor was the strategy actually detailed as it is here presented. With the benefit of hindsight, the authors recommend to readers intending to develop a similar file system, that performance requirements, strategy, and tactics be formalized and recorded in full detail during the course of the development.)

The performance requirements

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