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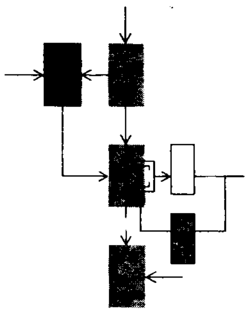

PART I
COMPUTER-AIDED ELECTRONIC CIRCUIT DESIGN

PART II
CONDUCTION PROCESSES IN THIN FILMS

Status Report

June 1, 1966 - November 30, 1966

Electronic Systems Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY, CAMBRIDGE, MASSACHUSETTS 02139

Department of Electrical Engineering

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(PART I)

COMPUTER-AIDED ELECTRONIC CIRCUIT DESIGN

and

(PART II)

CONDUCTION PROCESSES IN THIN FILMS

Status Report

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ABSTRACT

Research in On-Line Computer-Aided Design of Electronic Circuits has continued along several directions. Computational algorithms for the static and dynamic problems of CIRCAL-1 were investigated and compared both theoretically and experimentally. CIRCAL-1 was also used to study through lumped-network modelling the switching behavior of semiconductor diodes under neutron radiation. Results of this experiment, along with experience accumulated from the overall CIRCAL-1 effort, were used in the planning and preliminary development of CIRCAL-2, the next generation of on-line circuit design programs. Central features and capabilities of CIRCAL-2 have been defined and have led to the more detailed development phase, currently in progress.

The investigation of the feasibility of constructing a thin-film solid-state analog of the vacuum triode has continued, using an aluminum grid with a cadmium sulfide film as the conduction medium. Controlled evaporations of CdS films have been made using a low-power electron-beam gun evaporator, and also directly-heated-crucible methods.

Research in the application of coincident-radio-frequency techniques to a thin-magnetic-film memory was concluded with an examination of drive-current amplitude and phase conditions during radio-frequency writing. Writing was found to depend on a critical combination of phase and amplitude conditions, demonstrating that radio-frequency writing techniques do not appear to have any significant advantages over more conventional pulse-writing techniques.

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(PART I)

COMPUTER-AIDED ELECTRONIC-CIRCUIT DESIGN

A. INTRODUCTION

Research in On-Line Circuit Design was pursued along the following directions: First, several computational algorithms were proposed, studied, and tried within the experimental forum provided by CIRCAL-1. The main objective of this activity has been the acceleration of the analysis process known as the "static problem solution." Second, the CIRCAL-1 program has been used extensively to find a network model for the diffusion process in semiconductor diodes under radiation. Finally, a significant portion of the plans for CIRCAL-2 have been completed.

The algorithmic developments in CIRCAL-1 are discussed in some detail, while the use of CIRCAL-1 is presented very briefly. A more detailed report now being prepared will appear under separate cover. The CIRCAL-2 planning activities also are briefly reported; detailed documentation will be forthcoming here also at a later date.

B. CIRCAL-1 DEVELOPMENTS

Professor M. L. Dertouzos

Mr. H. L. Graham, and
Mr. C. W. Therrien
Research Assistants

Two different approaches to network analysis, the state-space approach and the simulation approach, were investigated and compared with regard to speed of computation, applicability to nonlinear networks, and flexibility in the context of on-line simulation.

1. The State-Space Approach[1*]

This method involves writing the network equations in the form:

$$\frac{d\underline{x}(t)}{dt} = \underline{f}(\underline{x}(t), \underline{z}(t)) \tag{1a}$$

$$\underline{g}(\underline{x}(t), \underline{z}(t)) = 0 \tag{1b}$$

*Superscripts refer to numbered items in the References on page 4.

The components of $\underline{x}$ and $\underline{z}$ are tree voltages or link currents, or linear combinations of these. The components of $\underline{x}$ are derived from the graph variables corresponding to the energy storage elements (capacitor voltage or charge, and inductor current or flux), while the components of $\underline{z}$ are related only to voltages and currents of the resistors. The procedure is to eliminate $\underline{z}$ from Eq. 1a and then to integrate the vector differential equation. Once the variables $\underline{x}$ and $\underline{z}$ are known for all time, any network variables of interest can be obtained through a linear combination of $\underline{x}$ and $\underline{z}$.

When Eq. 1a is linear, its solution can be written immediately in terms of a matrix exponential. This function can be computed in a variety of ways.[1]

When Eq. 1a is nonlinear, the solution can be evaluated by any of the standard numerical integration routines.[2] However, the use of nonlinear techniques can waste computation time and effort, because many components of $\underline{f}$ may be linear. Therefore, methods were investigated for separating the equations into linear and nonlinear parts, and applying analytic techniques to the linear parts in order to reduce computational effort.

The state-space method has a distinct advantage for linear networks. Here, the solution need not be stored for each point in time, since it can be obtained at any time point by direct evaluation of a function. For nonlinear networks, one disadvantage of the state-space approach is that functions $\underline{f}$ and $\underline{g}$ are in general difficult (and in some cases impossible) to obtain, even though the network has a unique solution.

2. The Simulation Approach

The second method of network analysis is the simulation approach. Here each network element with memory (each energy-storage element) is replaced by an equivalent memoryless element and a state in the form of a voltage source or a current source. By proper augmentation techniques, the resulting static networks can be made to contain only elements whose i-v characteristics are monotonic. Such networks are termed quasilinear. The emphasis in this area has been on the development of algorithms for the solution of these quasilinear networks. The algorithms investigated can be divided into two groups: (1) modifications of Newton's method, and (2) methods for increasing the rate of convergence of the CIRCAL-0 algorithm.[3]

An algorithm representing a modified Newton's method can be stated as follows:

(a) Assign two sets of node voltages v_1 and v_2 to the network.

(b) Replace all circuit elements by linear elements passing through these two points.

(c) Solve the linear network by matrix inversion to obtain a new voltage vector v_3.

(d) Repeat the procedure described above, computing at each iteration v_{n+1} from v_n and v_{n-1} until some error criterion is met.

The purpose of modifying Newton's method is to simplify the linearization of the network elements. Convergence is quadratic, as with Newton's method; however, convergence is not guaranteed in the large if a network element has a v-i characteristic in which the second derivative changes sign. No method has yet been found to force this algorithm to converge in such instances.

In the case of linear networks, the CIRCAL-0 algorithm converges exponentially to the solution. An additional algorithm was designed to speed up the CIRCAL-0 algorithm; it is based on the assumption that the convergence of each node voltage is approximately exponential. This approach was programmed and compared with the plain CIRCAL-0 algorithm and also with a matrix inversion algorithm for a number of linear networks. Although this algorithm reduced significantly the computing time for the CIRCAL-0 algorithm (by up to an order of magnitude), it still took far more time than was required for matrix inversion.

Other schemes for improving speed of convergence of the CIRCAL-0 algorithm were investigated both theoretically and experimentally. These involved using a weighted set of convergence constants (one for each of the nodes) in the CIRCAL-0 algorithm, and using this method in conjunction with the foregoing three-point algorithm. For some of the networks tried, this procedure showed an improvement in convergence speed by two to three orders of magnitude over the CIRCAL-0 scheme. However, for linear networks, matrix inversion was about 10 times faster than this accelerated CIRCAL-0 approach.

3. References

1. Zadeh, L.A., and Desoer, C.A., Linear Systems Theory, McGraw-Hill, New York, N.Y., 1963.

2. Traub, J.F., Iterative Methods for the Solution of Equations, Prentiss-Hall, Englewood Cliffs, New Jersey, 1964.

3. Dertouzos, M.L. and Therrien, C.W., "CIRCAL: On-Line Analysis of Electronic Networks," M.I.T., Electronic Systems Laboratory Report ESL-R-248, October, 1965.

C. USE OF CIRCAL-1

Professor K. Zander

Mr. C. W. Therrien
Research Assistant

CIRCAL-1 has been used to study the switching behavior of semiconductor diodes under neutron radiation, using lumped network models for the simulation. The accuracy of lumped models to illustrate the diffusion and drift processes in distributed semiconductor elements, such as diodes and transistors, depends of course on the number of lumps used in the model. By using a reasonable number of lumps (12 in these studies), the behavior of this model approximates adequately the behavior of the corresponding distributed system.

The CIRCAL-1 program provides a convenient and proper way to design a lumped model which allows the study of the injection and ejection processes of minority carriers in diodes under different conditions. These conditions include low and high carrier injection from voltage or current sources with different waveforms, simple diffusion processes, or those combined with drift currents caused by built-in electrical fields. Ejection carrier transient response was examined for a wide range of ratios between reverse and forward currents, and with and without rejecting built-in fields, such as those encountered in storage switching diodes.

The effect of these variables has been examined for varying lifetimes and decreasing diffusion lengths of the minority carriers due to neutron radiation according to the relationship:

$$1/\tau = 1/\tau_o + k\,\Phi t$$

where:

τ = effective lifetime

τ_0 = lifetime before radiation

Φt = absorbed particle dose

k = radiation damage constant

On-line computer simulation using CIRCAL-1 techniques offers several advantages in the investigation of the lumped models. It is possible to define (1) nonlinear elements, such as resistors, and diodes with material-independent knee-voltages for matching built-in fields, (2) dependent and independent voltage and current sources, for matching the boundary conditions, and (3) voltage-dependent resistors, for matching the carrier lifetime to different carrier densities. Also, digital techniques avoid the problems of resolution in measuring or representing low voltages or currents, which limit accuracy when using oscilloscopes and other equipments in analog networks. The ability to request sample pictures of dynamic processes at any desired time and with any time increment using these computer-aided techniques allows a considerable improvement in precision.

The results for switching behavior of diodes obtained from the 12-lump model investigations agree with measurements of distributed elements within a few percent of error, even for carrier lifetimes varying over a range of three orders of magnitude. Moreover, it seems possible to include the influence of surface recombination processes in one-dimensional as well as in three-dimensional models. Simulation of lumped-network models for field-effect transistors may be possible using programming techniques to be made available later, such as the CIRCAL-2 program, which can model voltage-dependent energy-storage elements.

D. CIRCAL-2 PROGRESS

Professor M. L. Dertouzos

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Research Assistants
Mr. J. Stinger
Graduate Student

Considerable research effort was expended during the reporting period in formulating plans for CIRCAL-2, a system of programs for on-line circuit design for use by practicing circuit designers. Listed below are the main features of CIRCAL-2, which capitalize on the experience gained from CIRCAL-1.

1. System Objectives

The following list describes the central objectives to be satisfied by CIRCAL-2, both in its executive program and within its subroutines.

a. Modularity. The system consists of a central executive program which accepts a broad class of commands for inputting and defining elements and for testing network performance under a variety of conditions. The executive program functions are deemed essential for any network class--linear, nonlinear, or time-varying. All other functions associated uniquely with specific classes of networks, or with specific operations, which may be improved or modified in the future, are isolated into distinct, identifiable and replaceable modules. Thus, for example, if the network is linear, a special linear-network analysis module is called to operate on the network data structure. Although the network can be analyzed as well through a nonlinear analysis module (e.g., the one used in CIRCAL-1), a significant efficiency and speed improvement is achieved by the use of special subprograms which are intended for use in corresponding special cases. Moreover, within the nonlinear analysis subprogram, the programs that accomplish the static and dynamic problem decomposition are each modular, hence, replaceable if more efficient algorithms are developed in the future.

b. Growth Capability. In CIRCAL-1, the ability of the system to grow is made possible by the way elements and waveforms are defined. In CIRCAL-2, besides these approaches, it also is possible to define new system commands. This capability is explained further below, and permits, among other applications, the use of CIRCAL-2 for optimization of networks, as long as the designer can formulate unambiguously the optimization process. In addition, CIRCAL-2 permits definition of dynamic elements (i.e., elements with memory) other than capacitors and inductors, and interrelation of any system variables through functions introduced by the designer.

The CIRCAL-2 system consists of a fixed portion deemed essential for all users and a growth portion which is adapted to the needs specified by the user. Thus, for example, although two CIRCAL-2 systems may start at the same level, they may be entirely different from each other after some use by two different user groups, e.g., power-system designers and communications engineers.

c. Convenience. The growth in complexity of CIRCAL-2 must under no circumstances affect the convenient use of the system by designers of varying levels of sophistication. Toward this goal, CIRCAL-2 has the following features:

(1) Format check. A capability for checking user statements and notifying him of errors in format, and suggesting desired corrective actions.

(2) Status identifiers. At any stage of the design process the user may request and receive a brief description of what already has been accomplished and what steps are allowed in the future.

(3) Brief reminders of commands. A simple command permits the user to request instructions regarding what format to use in order to effect a desired command.

(4) A command-indexed, up-to-date, detailed manual is available to the user through the system. A user may thus start with a minimum set of sufficient commands and progressively acquire sophistication at his own pace.

(5) A high-speed, minimum-interaction mode, which an experienced user of the system may employ to avoid the reminders and explanations named above that would only delay

him, so that he can proceed with maximum efficiency toward his goals.

2. System Features

Besides the commands of CIRCAL-1, which input, edit, and analyze a network and/or define network elements and excitations, CIRCAL-2 also has the following features:

(1) The ability to name elements and to postpone assigning parameters to them until analysis is undertaken. For repeated analyses, values of any element may be changed. Between analyses it is only necessary to change those values which are of interest. Elements and parameters may be assigned numerical values, or may be related to other system variables or to user-controlled "factors" through any algebraic expression. For example, all resistors may be defined as having value $R_i(1+K)$ where R_i is the nominal value of each resistor and K is a factor the user wishes to control.

(2) Any network may be nested into an element with several external nodes. After nesting, the composite element is identified by a name and any relevant parameters, e.g., transistor β's. Any instances of this nested element then may be used in a larger network, each instance possibly having different parameters.

(3) In addition to the usual input, edit and define commands, CIRCAL-2 is equipped with a command that can form sequences of other system commands, some of which already may be composite commands. For example, a command:

$$PD(R,t)$$

may be defined by the user for calculating the power dissipation across resistor R at time t, by saying:

$$PD(R,t) = v_R(t) \cdot i_R(t)$$

where v_R and i_R are the resistor voltage and current respectively.

Thereafter, use of:

$$PD(R16, 9)$$

would give the power dissipated in resistor R16 at $t = 9$.

Besides this ability it is possible in CIRCAL-2 for the program to "examine" results and to make "decisions." For example, it may be desirable to define a command:

POWER ADJUST (R, t, P)

to do the following:

If PD(R, t) exceeds a power level P, increase R until the power dissipated in that resistor is P then stop.

Or it may be desirable to define a command:

PLOT MAX POWER (T_1, T_2, ... T_n)

to display a graph of the maximum power dissipated (over time) in transistors T_1, T_2, ... T_n versus transistor index number. Thus a small class of easily-understood defining commands can create for each class of users any number of commands with special meaning to their particular class of problems. These commands can be made common to all users of that class as permanent parts of CIRCAL-2. Such commands can be deleted when they become obsolete.

(4) Each network created by the user becomes an input file stored temporarily in the secondary storage of the computer system. Upon completion of the design session the network is deleted unless the user wishes to store it permanently. Once stored, the network is available for further improvement in future design sessions, or for use as a nested element in a larger network.

(5) Dynamic elements, which possess memory, include hysteresis-type devices, relays, and thermal phenomena which exhibit heat capacity. These memory devices can be modeled in CIRCAL-2 via a provision for defining dynamic elements which corresponds to the provision for defining elements without memory in CIRCAL-1.

E. PUBLICATIONS OF THE PROJECT

1. Current Publications

a. Reports

"Computer-Aided Electronic-Circuit Design," M.I.T. Electronic Systems Laboratory Status Report No. ESL-SR-274, Part I, June, 1966.

b. Technical Papers and Conference Papers

Dertouzos, M. L. and Graham, H. L., "A Parametric Graphical Display Technique for On-Line Use," presented at Fall Joint Computer Conference on November 8, 1966. Published in the Conference Proceedings of the FJCC.

Therrien, C. W. and Dertouzos, M. L., "CIRCAL: On-Line Design of Electronic Circuits," presented at the NEREM Show and published in NEREM record November 9, 1966.

Notes: (1) Professor Dertouzos was Chairman of the Computer-Aided Electronic-Circuit Design Session at the NEREM 1966 Conference, Boston, Massachusetts.

(2) CIRCAL-1 was used from Munich, Germany via TELEX, June, 1966.

c. Theses

Gertz, J. L., "A Graphical Input-Output Program for Digital System Simulation," S. M. Thesis, Department of Electrical Engineering, Massachusetts Institute of Technology, June, 1966.

Graham, H. L., "A Hybrid Graphical Display Technique," S. M. Thesis, Department of Electrical Engineering, Massachusetts Institute of Technology, June, 1966.

Meltzer, J. R., "CIRCAL: An Input for Nonlinear Elements," S. M. Thesis, Department of Electrical Engineering, Massachusetts Institute of Technology, June, 1966.

Taubman, C. N., "Computer Analysis of Electrical Analog Distribution Systems," S. M. Thesis, Department of Electrical Engineering, Massachusetts Institute of Technology, June, 1966.

Walpert, S. A., "An Output Program for Representing Electrical Signals," S. M. Thesis, Department of Electrical Engineering, Massachusetts Institute of Technology, June, 1966.

2. Past Publications

a. Reports

Computer-Aided Electronic Circuit Design, Status Report ESL-SR-225, December, 1964.

"Computer-Aided Electronic Circuit Design,"Status Report ESL-SR-245, June, 1965.

Dertouzos, M. L. and Therrien, C. W., "CIRCAL: On-Line Analysis of Electronic Networks," Report ESL-R-248, December, 1965.

Dertouzos, M. L. and Santos, P. J.,Jr., "CADD: On-Line Synthesis of Logic Circuits," Report ESL-R-253, Electronic Systems Laboratory, M.I.T., December, 1965.

"Computer-Aided Electronic Circuit Design," Part I, Status Report No. ESL-SR-256, Electronic Systems Laboratory, M.I.T., December, 1965.

b. Technical Papers

Reintjes, J. F. and Dertouzos, M. L., "Computer-Aided Design of Electronic Circuits," WINCON Conference, February, 1966, Los Angeles, California.

Reintjes, J. F., "The Role of Computers in Modern Design Technology," Conference on Computer-Aided Design, University of Wisconsin, May 3-4, 1966.

c. Motion Picture

CIRCAL: Computer-Aided Electronic Circuit Design, January 1966.

d. Theses

Dvorak, A. A., "An Input-Output Program for Electronic Circuits Using a CRT," Bachelor of Science thesis, Department of Electrical Engineering, Massachusetts Institute of Technology, June, 1965.

Santos, P., "CADD, A Computer-Aided Digital Design Program," Master of Science thesis, Department of Electrical Engineering, Massachusetts Institute of Technology, June, 1965.

Therrien, C. W., "Digital-Computer Simulation for Electrical Networks," Master of Science thesis, Massachusetts Institute of Technology, June, 1965.

Fluhr, Z. C., "Single-Threshold Element Realizability by Minimization," S. M. Thesis, Massachusetts Institute of Technology, Department of Electrical Engineering, August, 1965.

Olansky, K. J., "A Low-Cost Teletype-Operated Graphical Display," S.M. Thesis, Massachusetts Institute of Technology, Department of Electrical Engineering, August, 1965.

(PART II)

CONDUCTION PROCESSES IN THIN FILMS

A. A COINCIDENT-FREQUENCY MEMORY USING THIN MAGNETIC FILMS

Professor A. K. Susskind

Mr. W. S. Nicol
Staff Member
Mr. M. Blaho
Technician

During the previous reporting period the investigation of coincident-radio-frequency techniques for nondestructive readout of magnetization from thin magnetic films was concluded successfully. However, an investigation of coincident-pulse techniques for writing had led to difficulties from domain boundary creep. Therefore, it was decided to try coincident-radio-frequency writing to determine whether this could minimize creep.

Coincident-radio-frequency writing had been found to be possible under certain conditions of phase between a 20-Mc/s field applied in the easy axis direction (the bit-steering field), and 20-Mc/s and 40-Mc/s fields applied in phase along the hard axis direction. It was found necessary to apply in addition a small d-c bias field along the easy axis direction to ensure writing.

Investigation during the present reporting period has concentrated on an examination of the amplitude and phase of r-f driving currents during conditions of writing and nonwriting. Also, the effect of inducing an asymmetry in the amplitudes of the two phases of the 60-Mc/s outputs by applying a d-c magnetic field of approximately 100 oersteds during readout was again confirmed for several films. Pulse writing measurements were not conducted.

1. Phase and Amplitude Conditions for Coincident-Radio-Frequency Writing

Sinusoidal currents of between 100 and 300 mA peak-to-peak at 20 Mc/s and 40 Mc/s were applied in-phase to separate, parallel striplines to produce sinusoidal magnetic fields along the hard axis of a film. A 20-Mc/s signal was applied to an orthogonal stripline so that its magnetic field acted as a steering field along the easy axis of the film.

As described in the previous report, ESL-SR-274, it is necessary that the two 20-Mc/s signals should be applied in phase, or 180° out of phase in order to have writing take place by the rotational switching mode. These signals, together with the 40-Mc/s signal, should have sufficient amplitude so that the locus of the resultant applied field will pass outside the critical switching curve, into the region of rotational switching. If any one of the three signals is not applied, the locus will remain inside the critical curve and switching will not occur.

The locus of the applied field in the plane of the film was plotted for conditions of switching and nonswitching (that is, writing and nonwriting) from oscillograph displays of the three drive currents. A simple scalar relationship was assumed between each applied field and its corresponding drive current. With a stripline width of 20 mils, and a separation of 41 mils between the stripline and the ground plane, the field calculated at the position of the magnetic film is approximately 12.5 oersteds per ampere. The films used have an average H_c of 2.1 oersteds. Therefore, a d-c digit (steering) line current needed to switch the films by domain wall motion alone should be about 160 mA, if the simple scalar relationship assumed between current and field strength is valid. The d-c steering current of the sense/digit line necessary to switch the films was found to be approximately 200 mA.

At radio-frequencies, however, the simple scalar relation presumed between the drive current and the resultant magnetic field within the film was found to be totally invalid--the currents actually required to switch the film would, according to this relation, have provided fields about three or four times greater than those required at d.c. It was noted that large r-f drive currents of approximately 800 mA peak-to-peak can be applied to the sense/digit line without any alteration in the magnetized state of the film. Simultaneous currents of 100 mA peak-to-peak applied to the transverse drive lines do not alter the magnetization. The addition of a very small d-c bias field along the easy axis will, however, change the state of magnetization according to the direction of this bias field. Although it is suggested that the mode of switching is through domain wall creep (the transverse field in this case being a radio-frequency one instead of the pulsed one which has been employed in most investigations of creep), it is important to note that it was also necessary to apply the sense/digit radio-frequency field for switching to occur.

2. Creep Writing Using D-C Bias Alone Along the Easy Axis

Radio-frequency drive signals of 20-Mc/s and 40-Mc/s were applied in phase and of equal amplitude to produce fields along the hard axis direction in conjunction with a d-c field applied externally from Helmholtz coils to produce a d-c bias field along the easy axis direction. Beginning with values of 30 mA peak-to-peak for the hard axis r-f driving currents, the external d-c bias field was increased in both directions until switching of the magnetization was observed. The switching was then repeated for successively larger values of the drive currents. A value was eventually reached at which the magnetization was completely unstable in one state even with no externally applied field. The earth's magnetic field along the easy axis direction was taken into account during this experiment. From the resultant field locus it is possible to obtain: (a) the domain wall creep boundary, and (b) the sensitivity of the nondestructive readout to an external applied field in the easy axis direction.

3. Conclusions and Recommendations for Future Investigations

The application of radio-frequency techniques in the 20 Mc/s to 40 Mc/s frequency range proved very successful in obtaining nondestructive read-out at low drive-current amplitudes from a thin magnetic film. Their application to coincident-frequency writing, on the other hand, did not appear to have any significant advantage over creep writing by a coincident-pulse technique. In addition, writing by a coincident-frequency method was found to depend critically upon the relative phases of the drive currents. (By way of comparison, it is to be noted that the read-out signal does not depend on the relative phase of the drive current.) Also the sense/digit line drive current amplitude required during writing was of the order of 800 mA peak-to-peak. Although a coincident-mode of radio-frequency writing was achieved, it is apparent that much further work would be required to develop a useful system. Even then, the advantages over conventional pulse techniques cannot clearly be seen. Thus, research on the coincident-frequency memory using radio-frequency techniques will be discontinued. A more detailed account of the research findings will be issued in a separate report.

It is suggested that any further investigation of these techniques for writing should include the following:

1. The use of drive line widths less than 20-mils wide in order to reduce the magnitude of the drive currents as well as to increase bit densities on the film.

2. The use of metal substrates so that the stripline-to-ground-plane distance will be much smaller, and the induced magnetic fields thereby increased.

3. Gating of the radio-frequency drive currents to observe the duration necessary to assure writing, as part of a more thorough investigation of the r-f write mode, which now is believed to be a creep writing mode.

4. The investigation of effects of the d-c bias field along the hard axis.

B. THIN FILM ACTIVE DEVICE INVESTIGATION

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Staff Member
Mr. M. Blaho
Technician

The objective of this research is to obtain a thin-film active device which will operate in a space-charge-limited current mode. The particular device which has been under investigation uses the Wright concept,[1] wherein a metal grid is insulated and imbedded between two layers of semi-insulating material. During the previous six-month period research was conducted on: (1) the feasibility of forming an insulated grid structure of aluminum over sulphur-diffused CdS surfaces, and (2) evaporation techniques for CdS films. During the present reporting period, work has concentrated on (1) further study of evaporation of CdS films, and (2) the fabrication of complete triode structures.

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*Superscripts refer to numbered items in the References on page 22.

1. Evaporation Studies of Thin CdS Films

Previous investigations into the conduction mechanisms in CdS films revealed the effect of various post-evaporative treatments on the films. A detailed account is contained in Report ESL-R-272, June, 1966. Space-charge-limited current behavior has been found over a restricted range of values of the electric field applied to the film. It was suggested in the report that a study of the conditions for the growth of high-resistivity and high-mobility CdS films would be a more worthwhile area of research than such post-evaporative treatments as ion bombardment, annealing, sulphur or copper diffusion, or re-crystalization. This suggestion was based on the observation that the composition and form of the CdS evaporant itself was important in determining the resistivity of the deposited film.

For example, luminescent-grade material had been observed consistently to produce highly nonstoichiometric films, compared with laboratory purified grade material. However, differences in the packing of the CdS in the crucible also were suspected to be a factor in producing nonstoichiometric films.

During research carried out during this reporting period, three requirements were imposed upon the evaporation source: (1) greater amounts were to be evaporated than before without exhausting the source, (2) high evaporation rates, though not necessarily high condensation rates, would be achieved, if needed, and (3) the CdS would be evaporated from a pellet form, all pellets to be compressed identically. The requirement of a high evaporation rate is derived from a common feature of several methods for growing high-resistivity CdS films which require a relatively high vapor pressure of CdS within the vacuum system. A baffle between source and substrate can prevent a high deposition rate.

a. Evaporation from a Boron Nitride Crucible. Evaporations were made from a circular Boron Nitride (BN) crucible, 5/8-inch in diameter by 1-inch high. The crucible was heated directly by a 7-mil-thick tantalum filament. The CdS was used in compressed pellet form. Initially, films were deposited on microscope-slide glass substrates at a temperature of 160°C, from compressed pellets of CdS alone. Later, films were evaporated from pellets having sulphur added to the CdS before being compressed. The pellets containing excess sulphur were first fused by heating in a separate vacuum chamber, and then transferred to the main vacuum evaporator.

Films were evaporated with a baffle placed directly in front of the substrate--between the substrate and the source. These films were uniformly coated on both sides of the substrate, achieving resistivities greater than 10^5 ohm-cm. It was not determined whether the coating took place on both sides because of surface diffusion, or due to deposition taking place from the vapor at the relatively high pressure of 10^{-4} torr.

b. Evaporation of CdS Films by Electron Beam Heating. The electron beam evaporation of thin CdS films has been reported by Avis, Boesman, and Readey,[2] and by R. Weber.[3] An electron beam evaporator was constructed during the reporting period, as shown in Fig. 1. Mechanical design was based on a simple scheme used by Weber, and the gun was constructed using techniques developed at M.I.T. by C. K. Crawford.[4] The filament is a 30-mil-diameter thoriated tungsten wire in a 0.5-inch-diameter single loop. The crucible is a water-cooled copper block. Surrounding the filament is a stainless-steel shield open at both ends. The evaporated vapor passes through the open ends of the shield. An etched stainless-steel grid at the top open end confines the electric field to the anode side of the shield. Beam power required for CdS evaporation is in the range of 7.5 watts to 50 watts. Anode voltages range from 1 kv to 2.5 kv, with beam currents ranging from 5 mA to 20 mA. Higher currents were possible, but were found unnecessary for CdS evaporation. The CdS was used in compressed pellet form.

The electron beam evaporator has been mounted so it can be used for coevaporation in conjunction with any one of six directly-heated filament sources. This permits all film layers of a triode to be deposited in one pump-down of the vacuum system.

Figure 2 shows resistivity in the plane of the CdS films as a function of substrate temperature, as measured between two evaporated indium electrodes. Previously, luminescent-grade cadmium

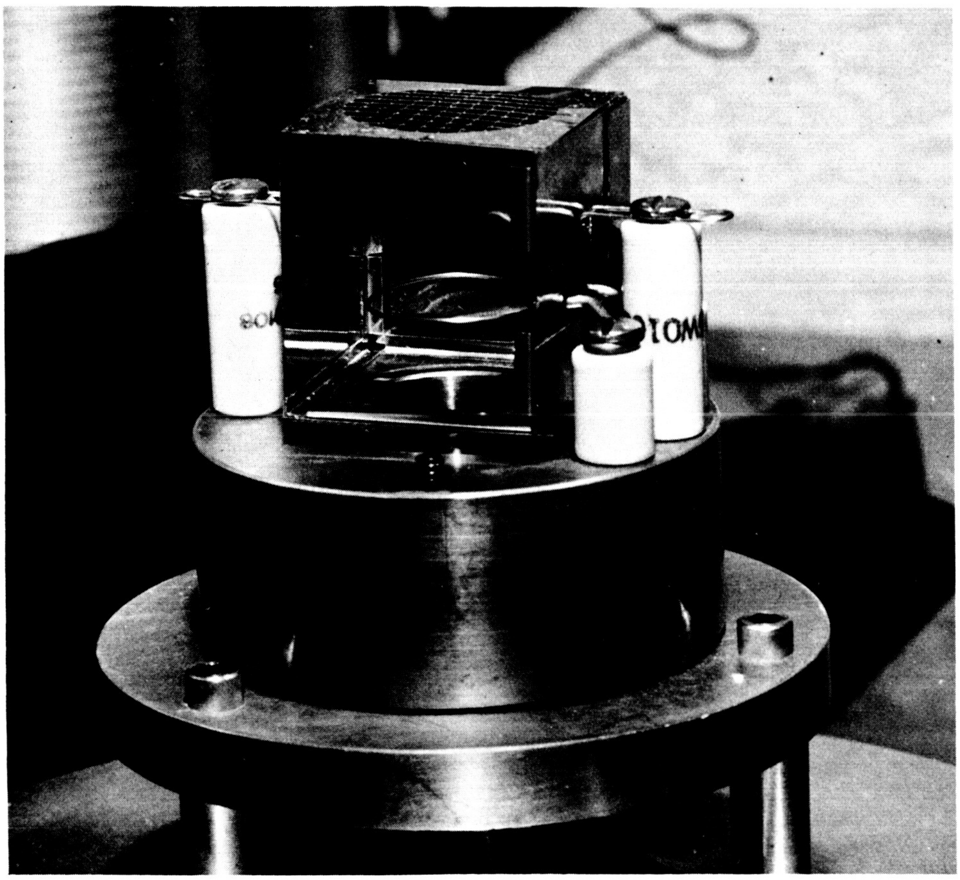

Fig. 1 Electron Beam Evaporator

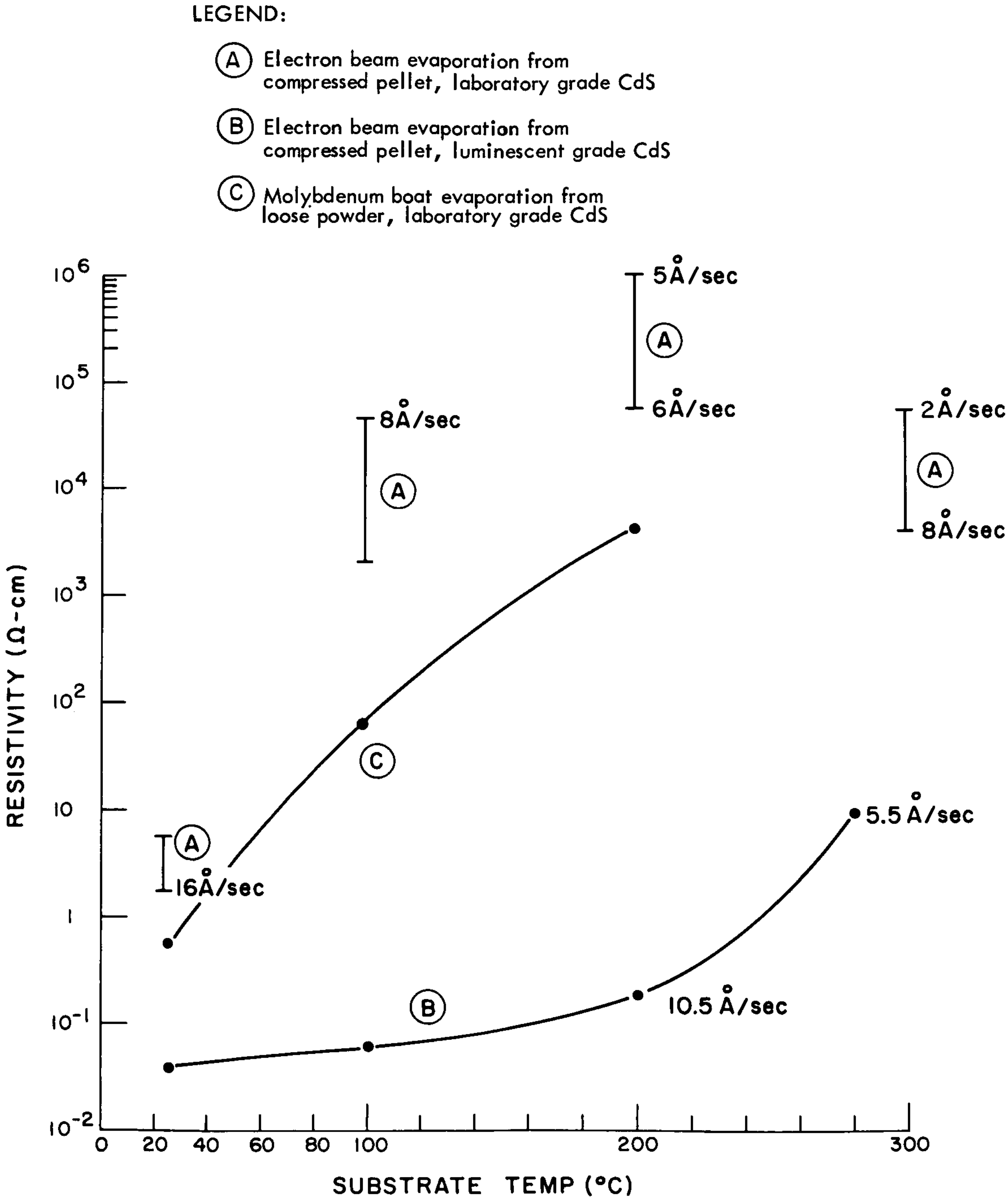

Fig. 2 Variation of CdS Film Resistivity with Substrate Temperature

Note: The spread in rate of deposition for data points (A) prevent construction of a curve joining points of equal rate.

sulfide had been found to yield nonstoichiometric films of resistivity 10^{-1} ohm-cm when evaporated from a molybdenum boat, while films evaporated from laboratory-grade CdS power had been found to give resistivities of the order of 10^2 to 10^4 ohm-cm. One significant finding confirmed with this evaporator and shown in Fig. 2 is that, using identical beam power conditions for CdS powder of laboratory grade and of luminescent grade, luminescent-grade powder still produces highly nonstoichiometric films. Note also that the rate of deposition has no bearing on this conclusion.

2. Fabrication of Thin-Film Triodes

The fabrication of a series of CdS triodes with an imbedded aluminum grid, isolated on the emitter side by evaporated sulphur and on the collector side by aluminum oxide, is now underway using CdS evaporated by the electron beam gun. These isolation techniques were described in the previous status report, ESL-SR-274. Preliminary results indicate that modulation of the conductivity by the grid voltage is possible, but the grid-to-collector leakage currents remain excessive, and must be reduced.

3. Future Investigations

Recent improvements in evaporation techniques for CdS have resulted in highly stoichiometric films, indicating that it is worthwhile pursuing further research using this material. However, major effort at this laboratory will be directed to investigating other materials which will support space-charge-limited currents, and which can be grown, if possible, in single-crystal thin-film form by evaporation techniques.

The proposed program will include:

1. An investigation of the techniques of formulation of evaporated, single-crystal films of III-V compounds, favoring GaAs. Crystalline as well as amorphous substrates will be used.

2. The measurement of the electrical properties of these films, including resistivity, mobility, and trapping energy level measurements, and also the influence of various evaporated metal contacts.

3. Examination of the structure of the films by electron diffraction.

4. Fabrication of triode devices which will permit modulation of space-charge-limited currents in order to examine various electrode configurations.

5. Continued investigation of the feasibility of the Wright concept of grid modulation, using the electron microscope to examine the grid structure.

4. References

1. Wright, G. T., "A Proposed Space-Charge-Limited Dielectric Triode," Journal of the British I.R.E., Vol. 20, pp. 337-355, May 1960.

2. Avis, G. G., Boesman, W. C., Readey, D.W., "Vacuum-Deposited Cadmium Sulfide Thin Films," Harry Diamond Laboratories, TR-1297, July 1965.

3. Weber, R., "Electron-Bombardment Technique for the Deposition of CdS Film Transducers," Review of Scientific Instruments, Vol. 37, No. 7, p. 955, July 1966.

4. Crawford, C. K., "Improved Series of Ion Gun Parts," Review of Scientific Instruments, Vol. 36, No. 6, p. 844, June 1965.

C. PUBLICATIONS OF THE PROJECT

1. Current Publications

a. Reports

"Conduction Processes in Thin Films," M.I.T., Electronic Systems Laboratory Status Report No. ESL-SR-274, Part II, June 1966.

Gottling, J. G., Nicol, W. S., "Electrical Conduction Processes in Thin Films of Cadmium Sulfide," M.I.T., Electronic Systems Laboratory Report No. ESL-R-272, June 1966.

b. Article

Gottling, J. G., Nicol, W. S., "Double-Layer Interference in Air-CdS Films," Journal of the Optical Society of America, Vol. 56, No. 9, p. 1227, September 1966.

c. Thesis

Teicher, S. N., "The Fabrication of Thin-Film Triodes," B. S. Thesis, Department of Electrical Engineering, M.I.T., June 1966.

2. Past Publications

a. Reports

"Conduction Processes in Thin Films," M.I.T., Electronic Systems Laboratory Status Report No. ESL-SR-225, Part II, December , 1964.

Aponick, A. A., Jr., "An Investigation of Thin-Film Gold Structures on CdS," M.I.T., Electronic Systems Laboratory Report ESL-R-237, May, 1965. (Also published as a Master of Science Thesis, May, 1965.)

"Conduction Processes in Thin Films," M.I.T., Electronic Systems Laboratory Status Report No. ESL-SR-245, Part II, June, 1965.

Aponick, A. A., "A Study of CdS Thin-Film Vacuum-Analog Triodes," M.I.T., Electronic Systems Laboratory Technical Memorandum ESL-TM-247, December, 1965.

"Conduction Processes in Thin Films," M.I.T., Electronic Systems Laboratory Status Report No. ESL-SR-256, Part II, December, 1965.

b. Theses

Aponick, A. A., Jr., "An Investigation of Thin-Film Gold Structures on CdS," Master of Science Thesis, Department of Electrical Engineering, Massachusetts Institute of Technology, June, 1965.

Gajda, W. J., Jr., "Hole Conduction in Thin Films of CdS," Master of Science thesis, Department of Electrical Engineering, Massachusetts Institute of Technology, June, 1965.

Jenssen, H. P., "De-excitation of CdS Films by High Electric Fields," Bachelor of Science thesis, Department of Electrical Engineering, Massachusetts Institute of Technology, June, 1965.

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