THE SNAPPING DIPOLES OF FERROELECTRICS AS A MEMORY ELEMENT FOR DIGITAL COMPUTERS

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-SUMMARY-

A brief review is given of the memory properties of non-linear ferroelectric materials in terms of the direction of polarization.

A sensitive pulse method has been developed for obtaining static remanent polarization data of ferroelectric materials. This method has been applied to study the effect of pulse duration and amplitude and decay of polarization on ferroelectric ceramic materials with fairly high crystalline orientation.

These studies indicate that ferroelectric memory devices can be operated in the megacycle ranges.

Attempts have been made to develop èlectrostatically induced memory devices using ferroelectric substances as a medium for storing information. As an illustration, a ferroelectric memory using a new type of switching matrix is presented having a selection ratio 50 or more.

Introduction

High speed computing is, at the present, in a state of fermentation, and an intensive search continues for new computer and memory elements which are smaller and more reliable than those in present use.

All phenomena possessing two stable states are possible candidates for computer elements. The desirable characteristics of a computer or memory element may be summarized as follows:

1. High speed flip-flop (two stable states).
2. Small size per flip-flop or unit of information.
3. Low cost per unit of information.
4. Good memory properties without need for recycling.
5. Simple and reliable structure.
6. Convenient pulse operation.
7. Proper non-linearity of the flip-flop element such that very simple switching devices may be used.

The search for new computer and memory elements presents a two-fold problem if the elements are to be used in a switching matrix. First there is need for a material which meets the requirements listed in the second paragraph under Items 1, 2, 3, 4, 5 and 6; i.e. there is the problem of economical storage of information. Second, but of equal importance, is the switching problem. New computer and memory elements should have characteristics such that a random selection of the storage element could be easily performed. For this purpose Item 7 must be satisfied by providing the storage element with the "proper" non-linearity. It will be shown in this paper that the non-linearity of certain computer elements may be artificially increased by the use of proper circuit configurations.

Solid state physics presents many basic research opportunities in the growing field of high speed computing. This investigation was begun in 1940, when the "snapping dipoles" of ferroelectrics were proposed for memory devices in large scale digital calculators. It seemed clear however that a preliminary basic study of the significant properties of ferroelectric materials was necessary to confirm the practicability of this proposition. Proceeding along these lines, it was soon found (a) that the memory properties of ferroelectric materials in general, and $BaTiO_3$ in particular, had very promising features and (b) that there may be different approaches to the development of the use of these materials as memory elements. (1)* More importantly, it was recognized early in the investigation that the production of proper single crystals and a thorough understanding of the flip-flop action of snapping dipoles would be necessary prerequisites to the successful use of ferroelectrics in digital calculators.

*Numbers in parentheses refer to Bibliography at end of paper.

Snapping Dipoles of a Ferroelectric Material

A crystalline structure can be regarded as formed by as many uniform and parallel interpenetrating space lattices as there are ions in the unit cell. An electrostatic field causes a displacement of oppositely charged lattice centers from previous equilibrium positions. Thus different lattices of equal dipoles are induced. The response of ionic point lattices to an electric field depends on the constitution and microstructure of the lattice. (2)

The present investigation is concerned only with dipoles occuring in solids; three main types may be distinguished depending on nature of the displacement imposed on a particular atomic or molecular structure.

1. Dipoles may be induced by elastic displacement of an electronic or an ionic structure. In each case they exist only in equilibrium with an applied field. This type of dipole may be called simply, elastic dipole.

2. Dipoles which arise from binding forces between atoms in a molecule are permanent dipoles, and are inherent or firmly bound in equilibrium with the states of the material. Although material containing such dipoles may go through thermodynamic first-order transitions, they are not recognized as ferroelectric.

3. Recently a new type of permanent dipole was observed which arises from the very special intramolecular distance ratios of ionic spheres, which allow minute relative motion of ionic space lattices. Conditions for proper intramolecular spacing based on various considerations have been reported by many workers, as for example Mason and Matthias. (3)

Minute displacement of space lattices is accompanied by coupling of induced dipoles such that feed-back action may be visualized. Interaction of coupling and feed-back creates an intramolecular field which produces conditions such that two equilibrium states may occur in the structure. This type of dipole behaves like a free dipole in a solid; it may be called a "snapping" dipole, because, under the action of an external field, a network of dipoles jumps from one equilibrium position to another across the non-linear potential well. It has been recognized that if these snapping dipoles are in a single crystal structure a very fast "flip-flop" element would be possible with necessary properties for high speed operation needed in digital calculators.

Few materials possess snapping dipoles which may be identified as ferroelectric; barium titanate is one of these.

Signals Produced by Change in Polarization

For computer applications, a signal may be obtained from a condenser containing a ferroelectric dielectric. This signal is produced by change in polarization when a ferroelectric material is switched between its two equilibrium states. A physical picture of this action may be visualized as follows.

According to simple statistical considerations, when ferroelectric material is placed in an electric field N_1 cells assume one equilibrium condition and N_2 cells assume an opposite equilibrium condition. Knowing the dipole moment of one unit cell and the number of cells in particular equilibrium states, the remanent polarization may be computed, in the case of a single crystal, by:

$$P_r = (N_1 - N_2)\mu \qquad [1]$$

where P_r is the remanent polarization, and μ the dipole moment. If the material under consideration is a polycrystalline ceramic, μ is replaced by $\bar{\mu}$, the average dipole moment taken over all orientations of the polycrystalline material. Thus, if charges are applied to a condenser containing a ferroelectric dielectric in order to produce a polarizing field, a certain quantity of these charges are bound, i.e., the surface dipoles of the dielectric are in equilibrium with the bound charges.

As long as the ratio of N_1 to N_2 does not change, i.e., the polarization is in a stable remanent state as in the case of a ferroelectric dielectric, the bound charges cannot be removed. When change in polarization occurs, the quantity of bound charges is altered in such a way that during an increase in polarization the dielectric seems to absorb charges, and during a reduction in polarization the dielectric appears to liberate charges. Thus, a ferroelectric dielectric material resembles a storage battery. Charges (electric energy) can be stored by polarizing the dielectric remanently. The stored charge may be released by two methods: (a) by randomizing the alined dipoles, that is, by destroying the remanent polarization, (b) by changing the sign of the remanent polarization.

Figure 1 shows a family of hysteresis curves taken for different maximum values of electric field. Let it be assumed that the ferroelectric dielectric is originally in a random state (origin of coordinates). After the application and removal of each polarizing field a certain remanent polarization P_r, P'_r, P''_r, ... is obtained. These remanent polarizations bind on the condenser electrodes, certain quantities of charge Q, Q', Q'', ... If now, it is assumed that the total remanent polarization is completely randomized the charge Q, corresponding to P_r, is released and may be used to obtain a signal. Since the charge equals the product of remanent polarization and area and since it also equals the product of capacity and voltage, these equations may be combined with the simple equation for capacity with the following simple relation between field E, and remanent polarization P_r.

$$E = \frac{V}{\delta} = \frac{4\pi P_r}{\varepsilon} \qquad [2]$$

where ε is the dielectric constant of the ferroelectric dielectric, and δ the thickness of the dielectric material. Equation [2] shows that, if a remanent polarization P_r becomes randomized, a field can be obtained across the condenser. If a "flip-flop" action occurs the sign of the remanent polarization is reversed and the change in polarization is given by $2P_r$; thus twice the field is obtained.

If a signal is developed across a capacitive load, the charge released by randomizing is distributed on all capacities involved. Figure 2 is the equivalent circuit of a signal measuring apparatus developed for these investigations. Total capacity in the equivalent circuit is given by

$$\sum_i C_i = \frac{Q}{V} \qquad [3]$$

Since the voltage is distributed in inverse ratio to the capacities,

$$V_x = \sum_i C_i \frac{V_m}{C_x} \qquad [4]$$

where V_x is the voltage on C_x , the actual storage element (See Fig. 5). The remanent polarization is, therefore:

$$P_r = \frac{\sum_i C_i V_m \varepsilon}{4\pi \delta C_x} \qquad [5]$$

where V_m is the voltage measured on all distributed condensers and $V_m/\delta = E$, the field produced by $Q = P_r$ (units of charge per unit area), when P_r is randomized. Having obtained P_r , the free charge after randomizing will be $Q = P_rA$; when the sign of P_r is reversed the charge is given by $Q = 2P_rA$. Thus, the free electric charge does not depend on the thickness of the material but only on the area of the condenser.

Barium Titanate Storage Elements

It has been recognized for some time, that single crystal plates of $BaTiO_3$ are most desirable for any type of memory application, since in single crystals hysteresis loops may be nearly rectangular and stability of remanent polarization is superior to that of polycrystalline ceramics. Accordingly it was decided to attempt to produce single crystals. However, the work necessary for establishing crystal growth is taking a longer time than anticipated because several auxiliary devices for the high temperature oven had to be constructed in the laboratory.

Consequently, one of the present aims of the research is to produce practical memory devices with existing ferroelectric ceramic materials. It appears that the production of a highly oriented ferroelectric ceramic plate for this purpose is very promising, and successive improvements in obtaining highly oriented ferroelectric ceramics will increase the practicability of such ceramics for memory devices. If such a $BaTiO_3$ ceramic is made sufficiently thin (about 0.15 to 0.25 millimeters) and is subjected to crystallization conditions, some minute crystals tend to grow through the thickness dimension of the material.

Figure 3 is a photomicrograph of a thin sheet of Glenco ceramic, type X18 placed in front of a strong light source.* The thickness of the material is 11 mils. The small bright spots are crystal grains, some of which are presumably, single crystals. The abundance and scattered distribution of these crystal grains is clearly shown in the photograph.** The average dielectric constant of this material was found to be about 2500 at room temperature. Storage elements were formed by preparing condensers using silver paste electrodes placed on opposite sides of the ceramic plate. Capcity of specimen condensers varied from 50 to 180 micromicrofarads. Condenser areas varied between 1 and 4 square millimeters; a rather large surface was selected in the expectation that local effects of the irregularly distributed crystal grains would be obscured in an average integration of remanent polarization. To prevent voltage breakdown in the air surrounding the dielectric each condenser was encased by a protective plastic coating.

Figure 4 is a photograph showing the test condensers and several thin sheets of $BaTiO_3$ ceramics on which silver paste electrodes are fired.

Considerations in the Method of Measuring Remanent Polarization

Since no information was available on remanent polarization of ferroelectrics as function of amplitude and duration of applied field, it was decided to develop a standard method for comparative remanent polarization measurements. The time history, $P_r = f(E,t)$, (how the new steady state will be attained if E is a function of time) is a complicated statistical problem, particularly if a third parameter, decay of remanent polarization as a function of time, is also considered.

It has been found that while strongly polarized commercial polycrystalline barium titanate ceramic elements retain their remanent polarization for years, weakly polarized condensers lose polarization gradually; from this it would seem that a polycrystalline ceramic will not retain polarization for a long period of time. In single crystals, polarization occurs almost instantaneously in a group of cells (domains) and coupling and feed-back associated with the dipoles is sufficient to stabilize polarization. Although this research was designed to answer certain questions connected with decay of remanent polarization, it was believed that decay time is a function of overall crystal orientation.*** This indicated that, for memory purposes, development of highly oriented ferroelectric ceramics will be essential. It was hoped that if the orientation of a ceramic exceeds a certain critical value, practical stable signal storage would be possible.

* This material was manufactured by the Gulton Manufacturing Company.

** Courtesy of Dr. Dale C. Braungart, Department of Biology, Catholic University.

*** The overall crystal orientation may be defined as the ratio of the measured remanent polarization of a ceramic near breakdown to the maximum polarization obtainable in a single crystal (approx. 45,000 c.g.s.).

The desired information concerning remanent polarization includes:

a. Shortest pulse duration producing a desired amount of remanent polarization.
b. Rate of decay of remanent polarization as a function of pulse duration.
c. Rate of decay of remanent polarization as a function of applied field.
d. Information on breakdown voltage as a function of applied field and pulse duration.

The method of obtaining this information is indicated in Figure 5. The barium titanate condenser under inspection is acted upon by a d-c pulse, the sign of which may be reversed in order that a complete "flip-flop" can be obtained. The magnitude of remanent polarization of memory cell C_x under inspection may be determined by measuring the voltage developed by the memory cell as it is heated through the Curie temperature. The liberated charge is distributed on all capacities connected to C_x. Total load is then represented by C_L, the sum of C_1, C_s, and C_o. For the measurements taken, load capacity varied from 4,000 micromicrofarads to 120,000 micromicrofarads depending on the sensitivity desired. The insulation of each memory element including all connections was better than 500 megohms. Using this method, the randomizing action of heat, high frequency, etc., can readily be studied and remanent polarization can be measured without difficulty. This method was chosen for its simplicity and high sensitivity and because no circuit complication need be taken into account. Furthermore, remanent polarization caused by snapping dipoles could be studied in itself without elastic displacement disturbances. By this thermal randomizing method remanent polarizations of approximately 15 cgs units (an extremely low value) to 25000 cgs units and higher can be obtained with good reproducibility.

Instrumentation

Figure 6 shows a block diagram of the experimental arrangement for measuring remanent polarization. The units are described as follows:

1. Trigger unit. This unit simultaneously initiated the sweep of a cathode ray oscilloscope and a pulse generator. It can either deliver single 0.05 microsecond pulses or be driven at a repetition rate of 10 to 20,000 cps.
2. Pulse generator. The pulse generator delivers d-c pulses, variable in amplitude and in duration. The output impedance is of the order of a few hundred ohms. When short duration pulses of approximately 2 to 3 microseconds are needed, a blocking oscillator is connected to the 3E29 input of the d-c pulser; the blocking oscillator is fired by the trigger unit.
3. Blocking oscillator. This unit delivers a 0.01 microsecond trigger pulse at 1000volts.
4. CRO. An oscilloscope enables the operator to view the waveform of the pulse applied to the barium titanate condenser and gives a measure of duration and amplitude.
5. Electrometer. The Lindemann-Ryerson electrometer measures the voltage developed by the memory cell as it is heated through the Curie temperature. From the voltage indicated on the electrometer

the remanent polarization may be calculated by Equation [5]. The sensitivity of this instrument is an important factor if small values of polarization are to be measured. Thus the capacity of the input of the electrometer (C_x/C load) should be kept small when small values of polarization are to be measured.

6. Oven. The heat developed by the oven randomizes the polarized memory element. A 1-inch diameter alundum-tube oven is used for the heat bath. One end of the tube is sealed with a tefflon stop; the other end is open to receive the sample condenser. During randomizing, temperature is maintained constant at 140 degrees Centigrade. Provision is made in the stop for a thermometer to measure the temperature of the tube interior.
7. Specimen condensers. The condensers are permanently mounted on individual holders consisting of two wire arms -- one fastened to each end of an insulating mounting block by machine screws. Condenser leads are soldered to the supporting arms. The insulating block is held temporarily in a socket while electrical contact with the $BaTiO_3$ specimen condenser is effected by snap-spring terminals. (See Figure 4).
8. Switch. S_1 is a single-pole switch. If the electrometer is used to measure the polarization, S_1 is open in order to prevent the impedance of the pulser from being placed across the specimen condenser.

Grouping of Specimen Condensers

For the purpose of investigating remanent polarization of $BaTiO_3$ material as function of amplitude and duration of applied field, as well as for obtaining data on decay of polarization with time, fifty-three (53) condensers were prepared from the same sheet of Type X18 ceramic. During the preliminary measurements it was observed that the condensers varied widely in sensitivity although they were made from the same ceramic sheet. This indicated a need for determining some type of relative sensitivity measurement which would permit the selection of specimens with approximately equal ability to retain polarization. A "standard test", designed to give reliable reproducibility, was therefore devised. In the standard test the condenser was subjected to a 500 volt--500 microsecond d-c pulse, after which it was immediately randomized in the heat bath and measured for remanent polarization. The units assumed for this standard method of comparison are completely arbitrary; the method was intended to provide, as a first approximation, means for selecting condensers with approximately equal relative sensitivities.

Three groups of condensers were chosen for investigation. Capacities and "standard" sensitivities for the three groups are given in Table I.

Remanent Polarization Curves

Figure 8 shows representative curves of remanent polarization as a function of applied pulse voltage for several values of pulse duration. Data for these curves were obtained experimentally using condensers from Sensitivity Group 3. The remanent polarization coordinate of each plotted point in Figure 8 was obtained by averaging four measurements in which applied pulse polarity was alternately reversed. Thus, average remanent polarization of two complete "flip-flops" was taken to be the remanent polarization corresponding to the voltage of the applied pulse. Since the thickness of the condenser dielectric was known (11 mils) the field could be computed. Breakdown voltages are indicated by the change of solid lines to dashed lines, at about 950 volts or 37,000 volts per centimeter. This breakdown voltage is high compared to straight d-c breakdown voltage; this may be attributed to the fact that short pulses were used in the measurements.

These investigations established the fact that strong remanent polarizations in highly oriented barium titanate can be produced by single pulses in the microsecond range. The limiting factor in the time domain was not the response of the material but rather that of the instrumentation in use.

Decay Curves

Figures 9 and 10 show decay of remanent polarization with time for various pulse durations. Each curve represents measurements made on condensers from the three sensitivity groups for given values of pulse duration. Coordinate data for the curves were experimentally determined as follows:

1. All condensers of the three groups were subjected to 500-volt pulses for a given pulse duration.
2. Measurement of remanent polarization was made on one condenser from each group for each time lapse shown.

Thus three condensers, one from each group, were measured for remanent polarization at only one coordinate value of elapsed time.

Figure 11 shows decay of remanent polarization with time as a function of applied field, and indicates that even very low values of remanent polarization are stable for long periods of time.

It may be observed that these curves of loss of polarization with time are collectively and systematically associated in trend. The irregularity is thought to be due to random distribution of crystal grain orientation (Figure 3); the crystal grains are also clamped in different ways by the surrounding $BaTiO_3$ ceramic, with the result that the corresponding wall energies modify the total energy obtained when the dielectric is randomized.

However, the decay curves show conclusively that the polarization, following an initial loss during a short period immediately after pulsing, remains relatively constant for a very long period of time. Some of the test condensers were observed to have approximately 5,000 cgs units of remanent polarization even after three months.

Further work in progress will include:

1. Continuation of a study of decay of polarization in the 0 to 100-volt range with pulse durations ranging from 0.1 to 10 microseconds.
2. Construction of new instrumentation for measurement purposes.

Ferroelectric Bistable Circuit Elements

Results of this research have shown that ferroelectric materials may be used in small, inexpensive bistable circuit elements which possess good memory properties and high speed operation.

The dielectric hysteresis curve for $BaTiO_3$ shows that remanent polarization has two opposite limiting values. Switching of polarization from one limiting value to the opposite limiting value by an external field may be described as a molecular snap action and corresponds to the "flip-flop" operation desired in computing circuits. Because of this property the possibility of designing different computer circuit elements using ferroelectric material has been investigated.

Figures 12 and 13 show the basic circuit of a memory flip-flop element employing ferroelectric condensers. Figure 12 illustrates the use of an inductance and a resistance for load impedance. Figure 13 shows resistance-capacitance load impedances. Any type of series impedance may be used, selection being governed by type of circuit with which the basic element is to be used.

Assume that remanent polarization of the ferroelectric condenser in the basic memory circuit is minus P_r. If a positive pulse of sufficient amplitude is applied to the input terminals, the remanent polarization of the dielectric will be switched from minus P_r to plus P_r, causing a large displacement current to flow through the series load impedance. If a negative pulse is applied to the input terminals, the displacement current will be small, since the remanent polarization has the same sign as the applied pulse and no switching occurs. Thus the basic circuit element is capable of responding to pulses of predetermined polarity or of remembering the polarity of the pulse previously received. Such is the basic requirement of a counter or memory element.

For purposes of illustration simple types of indicating circuits are shown in Figures 12 and 13. A gas discharge tube, biased close to its ignition potential, is placed across the series load impedance. If an applied pulse causes switching of remanent polarization, the voltage drop across the series load impedance, caused by the displacement current, ignites or extinguishes the gas discharge tube depending upon polarity of the bias, direction of the displacement current, and initial condition of the gas discharge tube. Figure 13 is given to illustrate how a bistable transistor indicator circuit can be used to indicate the state of the ferroelectric "flip-flop."

These basic circuits have been tested and one microsecond operation obtained.

Ferroelectric Memory Matrix

In general it is assumed that memory properties must be inherently connected with sufficient nonlinearity to obtain simple switching of storage elements in a matrix type of memory device. This was the case when magnetic materials with rectangular hysteresis loops were proposed for digital information storage (4, 5, 6).

This same idea prevailed when $BaTiO_3$ single crystals, with rectangular hysteresis loops, were first suggested for use in a simple electrostatic memory matrix (7, 8). Figure 14 represents such an (n x n) ferroelectric memory matrix proposed at the beginning of this work. Without going into detailed discussion, it may be seen from the reduced matrix diagram of Figure 14 that the selected condenser, of capacitance C_{xy}, will be acted upon by the applied voltage V, while the groups of condensers connected to the leads x and y, of capacitance $(n - 1)C$, will be acted upon by a voltage somewhat less than V/2. Condensers located in the remaining part of the memory plane, of capacitance $(n - 1)^2C$, also produce a voltage drop; however this voltage drop is practically negligible. Thus the familiar 1:2 voltage ratio is obtained in the matrix. This ratio may be improved to about 1:3 by applying an electrostatic compensating potential to the unused rows and columns of the matrix.

Although it seemed that a memory matrix using single crystals would be a more simple arrangement, the favorable memory properties found for highly oriented ceramics suggested their use in a memory matrix even though this would present a more complex problem. The only disadvantage of ceramic material is the lack of "proper" non-linearity; that is, the lack of sharp breaks in the polarization characteristic curve.

However, it should be noted that a nonlinearity "sufficient" for the switching of the storage elements can be obtained by using a switching matrix with a high selection ratio. Remanent polarization curves shown in Figure 8 indicate that the relation between remanent polarization and applied field is approximately exponential as should be expected; this particularly so in the low voltage region. This exponential relation was also found by transient measurements (9). After recognizing this fact, it was decided to develop a switching matrix having a selection ratio of 50 or more. Since ferroelectric memory cells are voltage devices, the switching matrix should also be a voltage device. In such a matrix the switching and memorizing action would essentially be separated.

For illustration purposes assume a selection ratio of 50 and a simple square law relating remanent polarization and applied field. Further, assume a pulse which established a remanent polarization of about 1250 cgs units. It can now be seen that the disturbing polarization on the unselected matrix cross-points would be only 0.5 cgs units, a value well below the threshold of any remanent action in a highly oriented ceramic. Such a low level threshold should exist although no reliable measurements are yet available.

Principle of the High Selection Switching Matrix

The selection ratio in a switching matrix may be defined by the ratio of the potential acting on a selected cross-point to the highest potential appearing on any of the unselected cross-points. The basic problem was to find a method for compensating practically all disturbing potentials which appear on the unselected matrix cross-points. Many possible matrix combinations were systematically studied until a switching matrix using diodes as nonlinear elements was found which was capable of a high selection ratio.

Figures 15 and 16 illustrate schematically the principle of this new type of switching matrix. Figure 15 shows one cross-point; x and y represent one row and one column respectively and are connected through the resistors R_M to diodes D_1 and D_2. The diodes D_1 and D_2 are alternately connected through the corresponding switches to ground depending on whether writing or reading is desired. These switches, which may also be diodes, are common to all D_1 and D_2 diodes respectively. For a simple presentation, the usual switch symbols have been used in both Figures 15 and 16. The active diode in the cross-point is biased through the resistor R_c with a positive or negative potential, polarity depending on whether writing or reading is desired. C_F represents the ferroelectric memory cell. It should be noted that any other bistable element may also be used as a memory element such as a bistable transistor circuit, etc. R is the load impedance common to all memory cells; it may be a pulse transformer, integrating condenser, etc. A diode may be connected across the load impedance to act as a low resistance path during the writing period (Figure 16). The writing and reading steps are similar except for the polarity of the bias and the polarity of the applied pulses.

Operation of the selection matrix may be described as follows. For the writing cycle, diode D_2 at each matrix cross-point is biased in the forward direction (conduction) while diode D_1 is inoperative. If now a single negative pulse arrives at an unselected cross-point and the pulse amplitude appearing across the diode is slightly less than the bias voltage V_c, the diodes remain in a high conducting state. The potential drop across C_F is practically negligible due to low forward resistance of diode D_2 (about 70 ohms). On a selected cross-point two pulses coincide and drive diode D_2 into a low conducting state; a major part of the input pulse is now applied across the memory cell and switching action takes place. Thus the disturbances due to noncoincident pulses of amplitudes below the bias voltage are practically eliminated.

The selection ratio S_r may be computed from the expression:

$$S_r = \alpha \chi \qquad [6]$$

χ is a function of the operating point and characteristic curve of the diode and is defined as the ratio of the dynamic resistance of the diode in the low conducting state (high resistance) to the dynamic resistance in the high conducting state (low resistance). The term α contains the circuit parameters and is a function of the number of coordinates (coincidences) used. Due to the inherent symmetric conditions of the matrix all resistances are assumed to be equal; the pulse amplitude and bias voltage are also chosen to be nearly equal. Using these assumptions and the additional assumption that,

$$R + \rho \approx R,$$

α for a double coincidence matrix is given by

$$\alpha = \frac{2}{1 + \frac{3\chi\rho}{R} + \frac{2\chi^2\rho^2}{R^2}} \qquad [7]$$

where ρ is the dynamic resistance of the diode in the high conducting state (low resistance), and R is the value of the resistance connected to the matrix cross-point.

From this description it can be seen that triple, or higher order, coincidence memory matrices may be built, employing similar compensation. The dashed line in Figure 15 shows a three-dimensional matrix cross-point; perpendicular to the rows and columns a third switching conductor z has been added and connected through a resistor R_M to the cross-point. Triple coincidence on a cross-point is now needed for switching, enabling a random selection in three dimensions. Reading and writing operations are accomplished in the same manner as for the two-dimensional matrix.

The scanning devices are not shown since such circuits have already been described (10, 11); multicoincidence scanning switches may also be built on the principle described here.

Figure 16 illustrates schematically a two-dimensional matrix. The selection rows and columns are drawn with thick lines. The bias source for compensating the matrix is common to all memory cells and may be supplied in form of a long duration pulse; likewise the output is also common for all memory cells. Diode D_1 may be omitted and on each cross-point only one diode may be used. In this case in order to obtain a binary yes from the unswitched cross-points and a binary no from the switched cross-points, the reading step may be as follows:

1. The output comprises an anti-coincidence circuit, which combines in a bridge circuit a reading and signal pulse.
2. The same polarity pulses may be used for reading as for writing.
3. The stand-by condition may be reset by applying a reverse polarity bias pulse.

The equivalent circuit for the matrix in Figure 17 shows clearly that the impedance of all unselected cross-points connected to the selection rows or columns can be regarded as grounded. Thus the input resistance of a selected row or column will be primarily a parallel combination of the resistances of the unselected cross-points.

Figure 18 is a photograph of a working model of a 4 x 4 matrix of the type described. The diodes are type 1N56 and the resistances are 10,000 ohms.

Figure 19 shows the selection ratios obtained with operating conditions; however these curves do not represent optimum conditions but show merely preliminary results. It is clear from these curves that for each value of the compensating bias there exists an optimum applied pulse voltage corresponding to the highest selection ratio. The solid lines indicate the useful pulse amplitude on a selected cross-point as a function of applied bias and selection ratio.

The switching and memory matrix presented is only one of many possible applications of ferroelectrics in the computer field but it shows the potentiality of this new material.

Work extended on a three-dimensional memory matrix and other computer applications of ferroelectrics will be reported later.

Acknowledgment

The work here reported has been done with the financial support of the USAF Office of Air Research under Contract AF18(600)-106, E.O.R. - 468. The author wishes to thank Professor Frank A. Biberstein for his kind cooperation and for the enthusiastic assistance of Mr. George E. McDuffie, Jr. and Mr. Richard W. Young, members of the staff of the Electrical Engineering Department. The author also wishes to thank Dr. Jean S. Mendousse for the valuable discussions during this work and to acknowledge the assistance given by Mr. Louis Peselnick who assisted at the beginning of this project.

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Table 1 Condenser groups and their "standard" sensitivities.

Group No.	Capacitor No.	Capacity,	Sensitivity: P_r in cgs.
1	4	154	4200
1	5	169	4280
1	8	167	4510
1	9	167	4480
1	11	166	3990
1	27	124	4370
2	2	191	8520
2	19	107	8900
2	20	212	9300
2	24	174	8920
2	60	116	7650
2	65	126	10,580
3	22	134	21,900
3	33	238	22,000
3	41	250	22,200
3	44	171	22,000
3	48	208	21,900
3	55	152	21,900

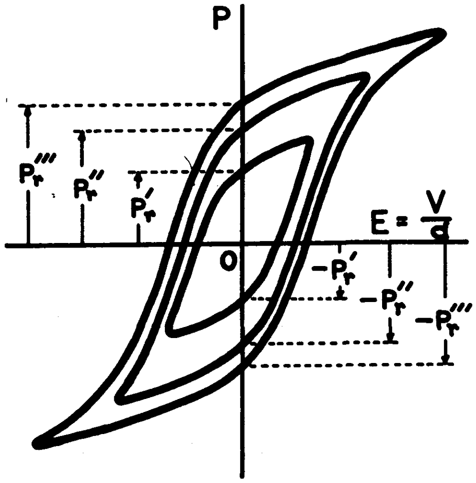
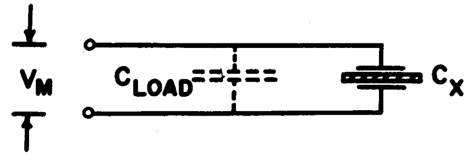


Fig. 1
Hysteresis curves obtained by different maximum values of electric fields.



C_{LOAD} = $\Sigma\, C_l, C_S, C_O$
V_M = MEASURED VOLTAGE

Fig. 2
Equivalent circuit of remanent polarization measuring apparatus.

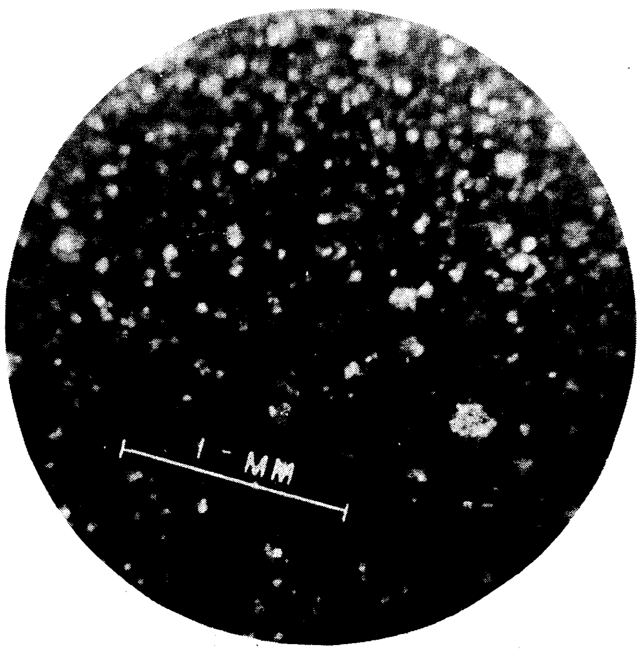


Fig. 3
Photomicrograph of a thin sheet of ferroelectric Glenco ceramic.

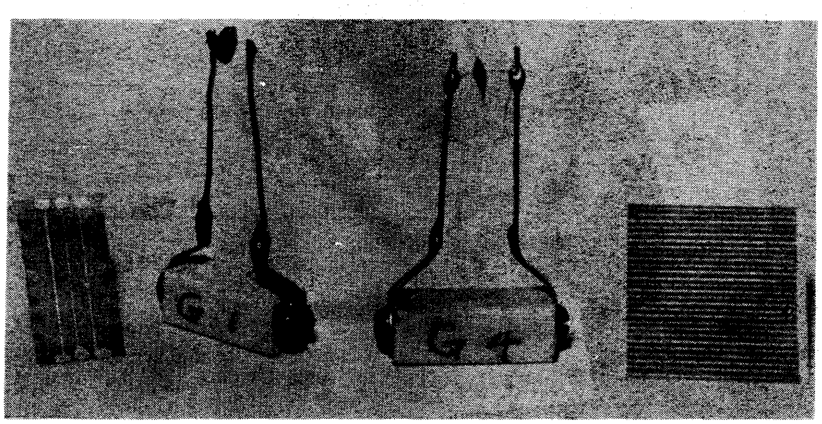


Fig. 4 - $BaTiO_3$ specimen condensers.

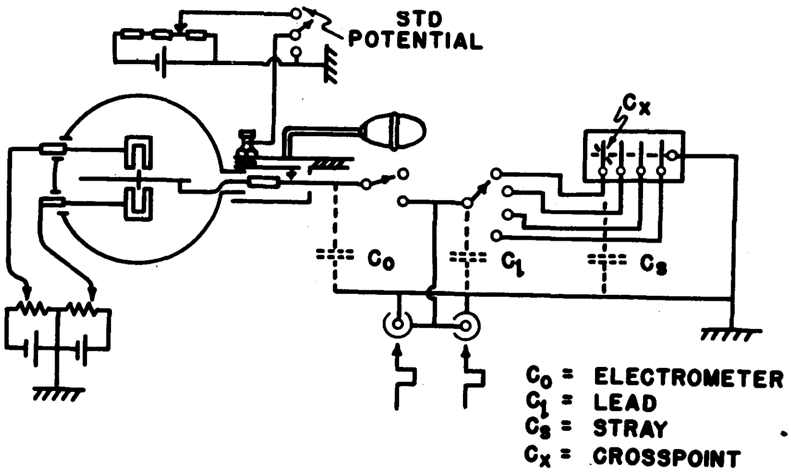


Fig. 5
Arrangement for obtaining data on remanent polarization.

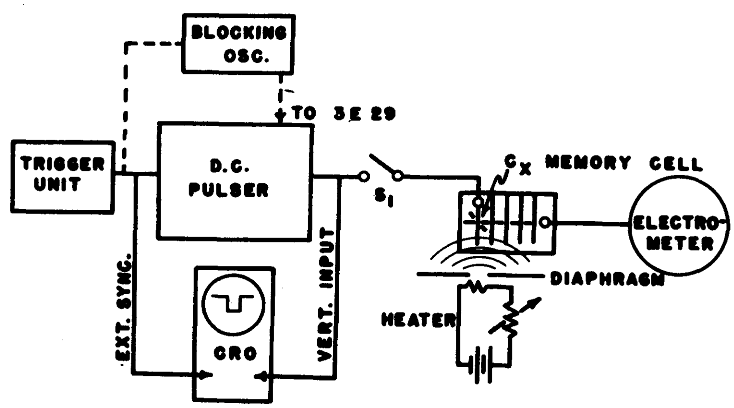


Fig. 6
Block diagram of the experimental set up for measuring remanent polarization.

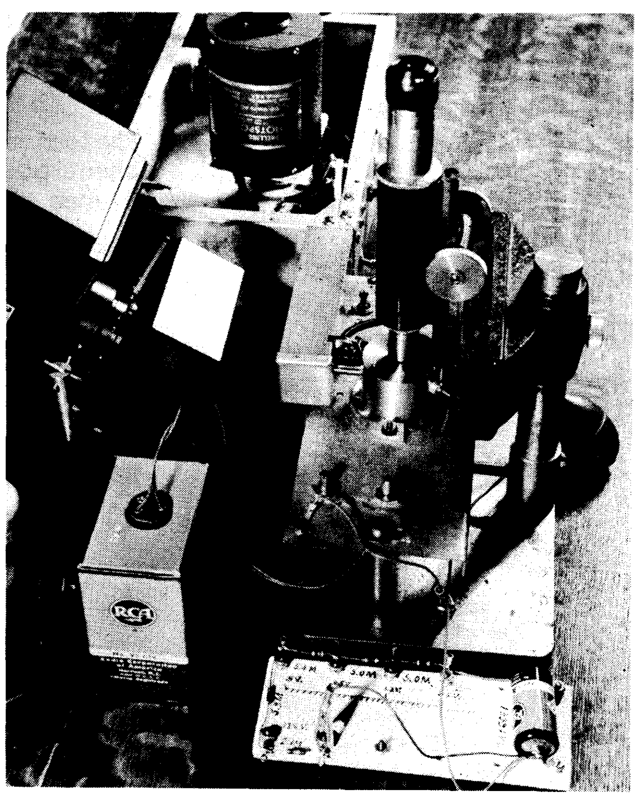


Fig. 7
The experimental apparatus.

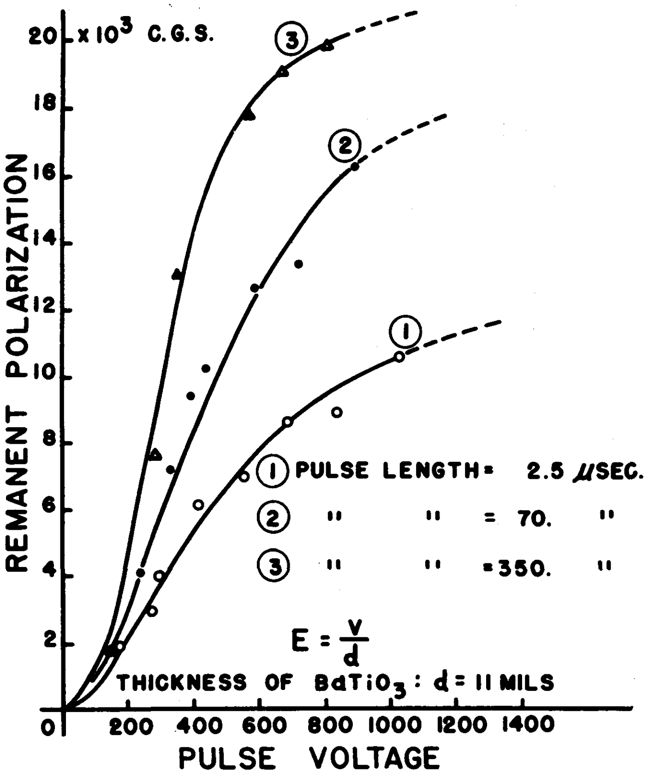


Figure 8 Remanent polarization curves.

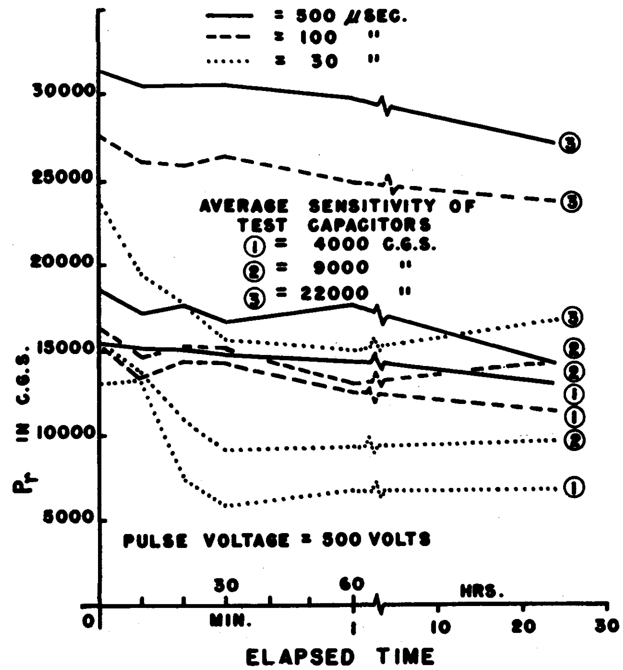


Fig. 9
Decay of remanent polarization in function of pulse duration.

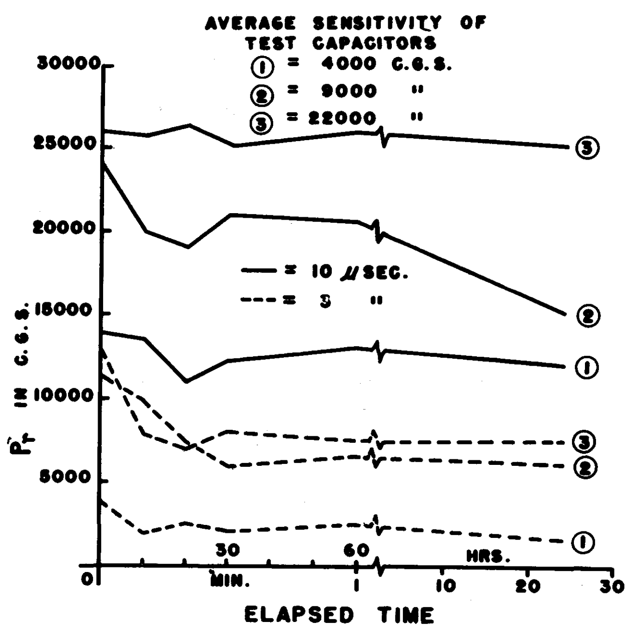


Fig. 10
Decay of remanent polarization in function of pulse duration.

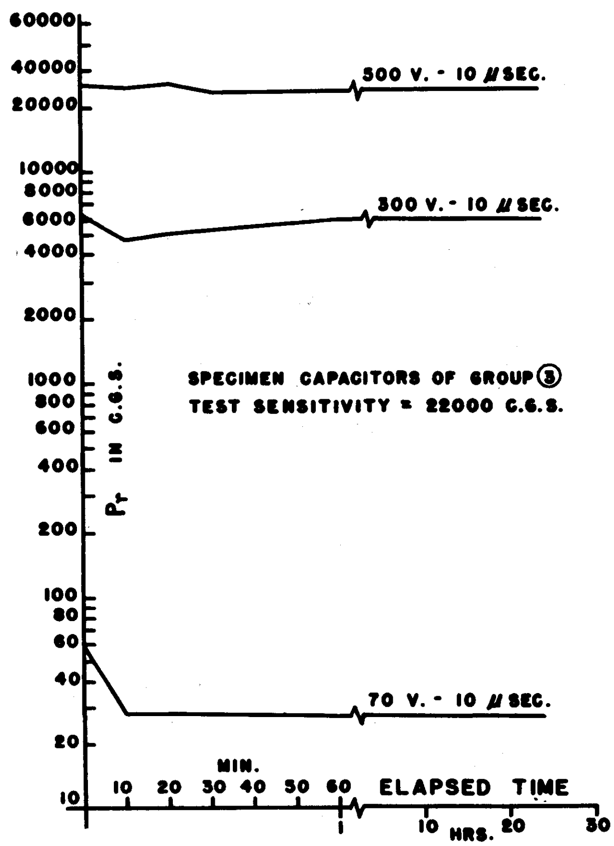


Fig. 11
Decay of remanent polarization in function of applied field.

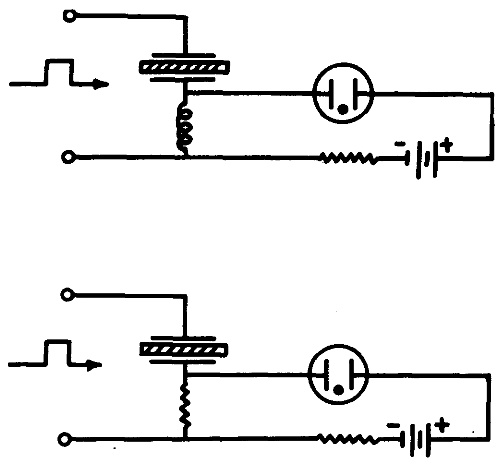


Fig. 12
Bistable ferroelectric circuit elements.

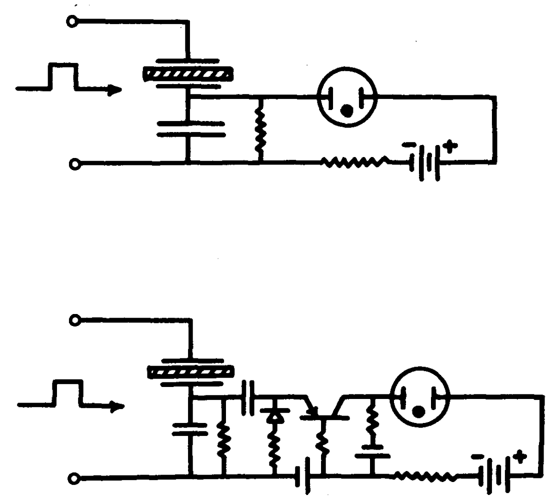


Fig. 13
Bistable ferroelectric circuit elements.

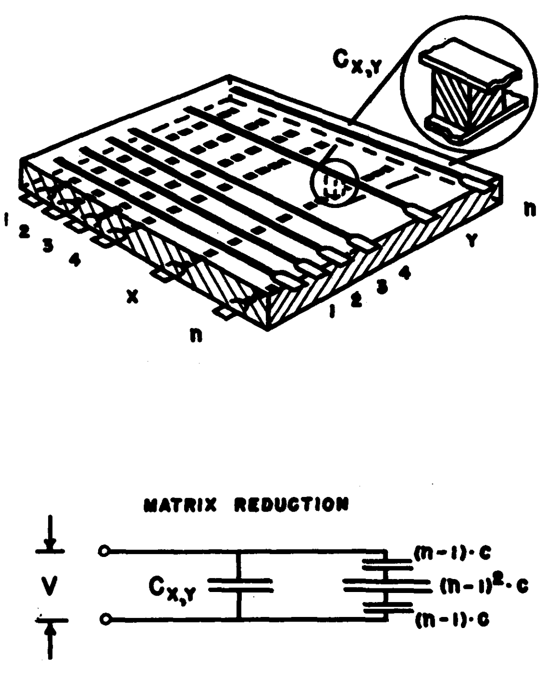


Fig. 14
Memory matrix on a single crystal ferroelectric plate.

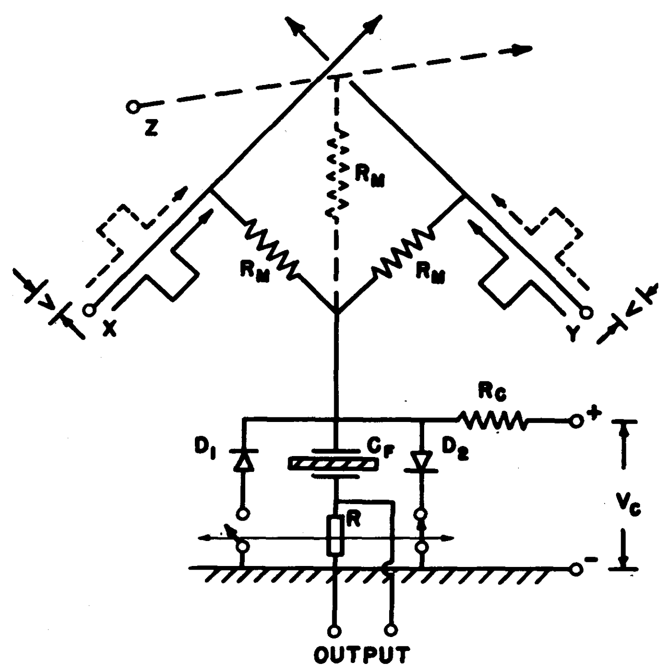


Fig. 15
One cross-point of the high selection switching and memory matrix.

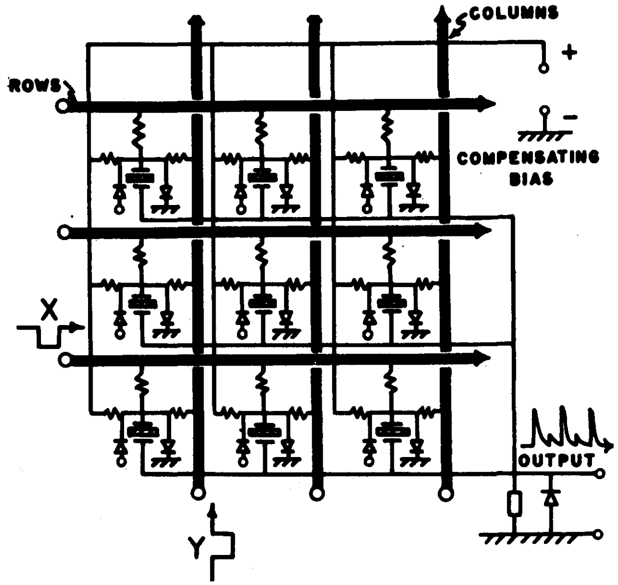


Fig. 16
Double coincidence memory matrix with compensated matrix disturbances.

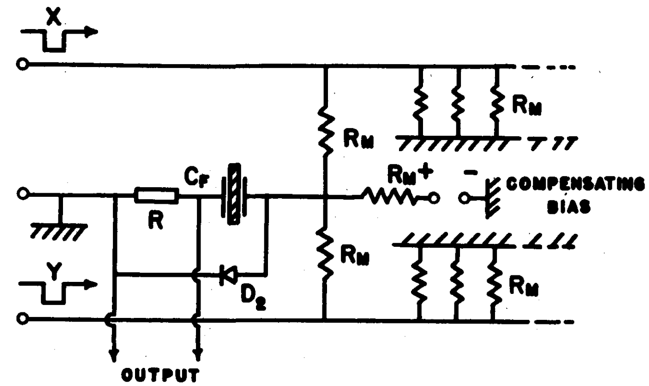


Fig. 17
Equivalent circuit for matrix shown in Figure 16.

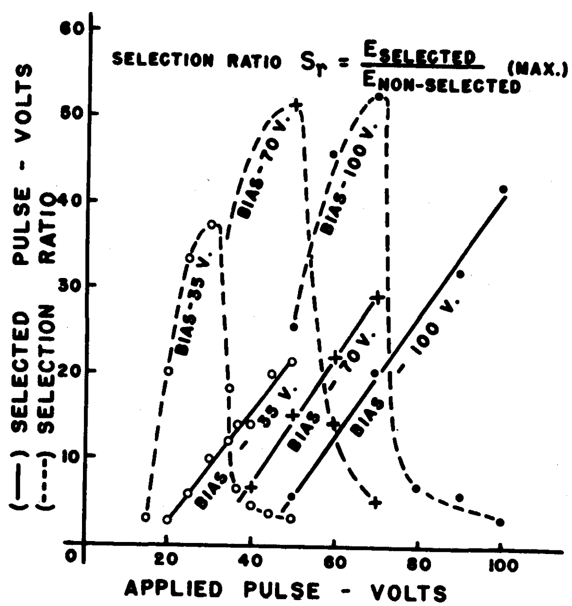


Fig. 18
Model of matrix shown in Figure 16.

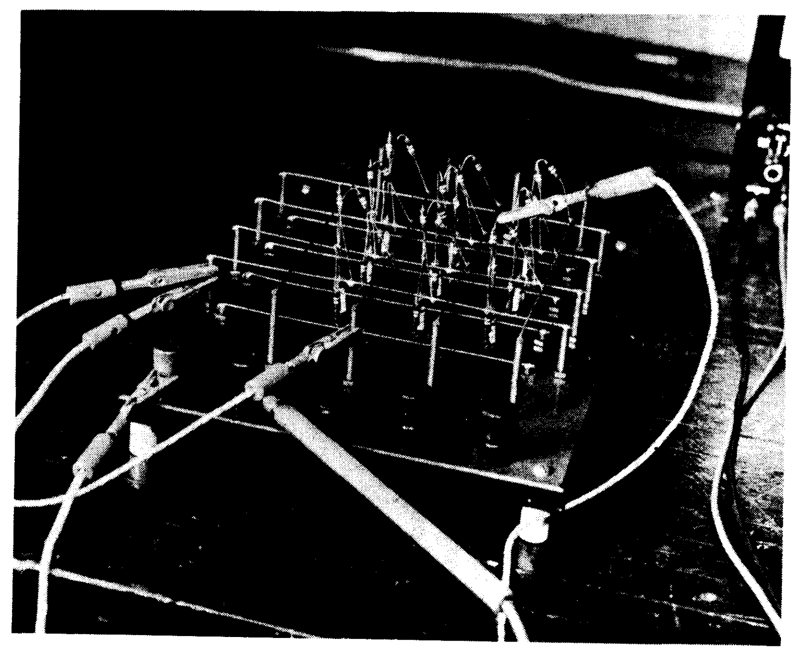


Figure 19 Selection curves.