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Memorandum M-1335

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D. A. Buck
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ELECTRICAL ENGINEERING DEPARTMENT
MASTER'S THESIS PROPOSAL

1. TITLE: AN INVESTIGATION OF FERROELECTRICS FOR DIGITAL INFORMATION STORAGE

2. BRIEF STATEMENT OF THE PROBLEM:

It is the intention of this thesis to investigate the application of ferroelectric materials to information storage systems; in particular to a two-dimensional memory for digital computers.

3. HISTORY OF THE PROBLEM UP TO THE PRESENT:

Engineers have long utilized the residual induction of a ferromagnetic material for information storage. Such devices as the magnetic-wire and magnetic-tape recorders, the magnetic-drum computer memory, the static magnetic delay-line, and more recently, the multi-dimensional magnetic memory all depend upon residual induction for their operation. The existence within a material of domains of permanent magnetic dipoles is a requisite for the phenomenon of residual induction.

Recently, materials have been discovered within which domains of permanent electric dipoles exist.[1,2,3,4] These materials, named ferroelectrics,

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[1] A. Von Hippel, "Ferroelectricity, Domain Structure, and Phase Transitions in Barium Titanate", Laboratory for Insulation Research Technical Report XXVIII, Massachusetts Institute of Technology, March 1950.

[2] W. J. Merz, "The Electric and Optic Behavior of $BaTiO_3$ Single-Crystal Domains", The Physical Review, Vol. 76, No. 8, pp 1221-1225, October 15, 1949.

[3] Development and Application of Barium Titanate Ceramics as Non-linear Circuit Elements, Final report contract No. W 36-039 sc 44-606 File No. 19028-PH-49-5 (4060), The Glenco Corporation, August 15, 1950.

[4] Dielectric Amplifier Fundamentals, Electronic Design and Development Division, Bureau of Ships, United States Navy, 20 August, 1951.

have been observed to exhibit residual displacement. Since residual displacement in an electric circuit is in many ways analogous to residual induction in a magnetic circuit, the possibility exists of using ferroelectrics in applications similar to those in which ferromagnetic materials are currently used.

Ferroelectric condensers are available which have hysteresis loops in the D-E plane with a shape similar to the hysteresis loops of the ferromagnetic materials in the B-H plane (Fig. 1).[5,6] Information can be stored in ferroelectric condensers in a way analogous to that used to store information in magnetic cores. Voltage sources, however, must be substituted for current sources as drivers, and current detectors must be substituted for voltage detectors when the stored information is being read (Fig. 2). In general, ferroelectric condensers can be used in circuits which are the dual of the circuits for their ferromagnetic counterparts.

The phenomenon of ferroelectricity has been observed in three groups of materials whose representatives are Rochelle salt, dihydrogen potassium phosphate, and barium titanate. It is planned in the course of this thesis to investigate all three of these groups, but at the outset the third group, represented by barium titanate, seems to be the most promising. Barium titanate, unlike the others, can be prepared in the form of a rugged ceramic which exhibits ferroelectricity over a wide temperature range,

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5. D. R. Young, "Temporary Enhancement of Hysteresis Loops in Barium Titanate Samples", The Journal of Applied Physics, Vol 22, No. 4, (April 1951).

6. H. Jaffe, "Titanate Ceramics for Electromechanical Purposes", Industrial and Chemical Engineering, Vol. 42, p. 264 (February 1950).

and which when compounded with other titanates can be tailored to a wide variety of electrical properties. All three of these materials are available commercially.

Having a method for storing and reading information, is but the first step in the design of a working memory. It has become increasingly clear as digital computers have developed that the most difficult problem for which to find an economical solution is that of selecting among the storage cells of a memory. Certain of the completed computer memories have found their solution in making _time_ one of the coordinates in the selection of memory cells. The mercury delay-line and the magnetic-drum memories fall into this category. For the attainment of truly high-speed computer operation, however, a random-access memory in which time is _not_ one of the selection coordinates is felt to be necessary. The electrostatic storage tube as used in the Whirlwind computer is one of the few working memories to fall into this latter category.

The possibility of locating the storage elements in a multi-dimensional matrix where selection is inherent in the storage elements themselves is a recent and most promising scheme for solving the selection problem.[7,8] This basic idea is being investigated for ferromagnetic storage using a matrix of small toroids at the M.I.T. Digital Computer Laboratory. In the next section of this thesis proporal, it will be shown how the same

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7. Jay W. Forrester, "Digital Information in Three Dimensions Using Magnetic Cores", Project Whirlwind Report R-187, (September 8, 1950), M.I.T. Servomechanisms Laboratory.

8. W. N. Papian, "A Coincident-Current Magnetic Memory Unit", Project Whirlwind Report R-192, (September 8, 1950), M.I.T. Servomechanisms Laboratory.

basic idea can be used for ferroelectric materials, as first suggested by Jay W. Forrester. The three-to-one selection scheme to be described was the outgrowth of work done by R. R. Everett.[9]

4. DESCRIPTION OF THE TWO-DIMENSIONAL MEMORY:

An economical method for selecting among N objects is to arrange them in a square matrix so that by the selection of one row and one column the object at the intersection of that row and column is selected. The selection problem is at once reduced from selecting among N objects to the problem of making 2 selections, each from among N objects -- one to find the proper row and one to find the proper column. How this method can be used to select among the storage elements of a memory, which in this case are ferroelectric condensers, will now be shown.

Consider the square n by n matrix of ferroelectric condensers shown in Fig. 3a. Having selected a single row and a single column, one may redraw the matrix as it is seen looking between this row and column. As can be seen (Fig. 3b), the selected condenser lies between the selected row and the selected column. In addition, condensers connect the selected row to each of the unused columns and the selected column to each of unused rows. Finally, there is a condenser between each unused row and each unused column.

Regardless of what voltages are applied to the selected row and the selected column the unused rows will all be, by symmetry, at the same potential, and the unused columns will likewise be at the same potential.

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[9] R. R. Everett, "Selection Systems for Magnetic Core Storage", Project Whirlwind Engineering Note E-413, (August 7, 1951), M.I.T. Servomechanisms Laboratory.

We can therefore, for this analysis, join the unused rows and sum the parallel condensers (Fig. 3c). Similarly, we can join the unused columns. We now see that a voltage applied between the selected row and the selected column will be directly across the selected condenser. In addition, this voltage will split among the three summed condensers, giving each of them a lesser voltage. The greatest of these lesser voltages is defined as the disturbing voltage, and the ratio of the voltage on the selected condenser to the disturbing voltage is defined as the selection ratio.

The summed condenser which joins the unused columns and the unused rows is (n-1) times as large as the other two summed condensers. If the unused rows and unused columns are left floating (Fig. 4a), a voltage appears across this large condenser equal to 1/(n-1) of the voltage across the selected condenser. Across the smaller summed condensers a voltage equal to (n-1)/(2n-1) of the voltage across the selected condenser appears. Thus the selection ratio is 1 : (n-1)/(2n-1). For a 2 by 2 matrix, this becomes 1 : 1/3 (three-to-one), and as n becomes large this rapidly approaches 1 : 1/2 (two-to-one).

Grounding the unused rows and unused columns (Fig. 4b) causes zero voltage to appear across the large condenser and a voltage of one-half to appear across the small condensers. The selection ratio is always 2 : 1 with this scheme regardless of the size of the matrix.

Presumably one would always be somewhere between these two cases, depending upon the internal resistance of the source used to apply voltage to the leads. For a matrix of size 16 by 16, the first scheme gives a selection ratio of 1 : 0.485 and the second a ratio of 1 : 0.5, a difference of 3%. It therefore appears that the internal resistance of the voltage source has little effect upon the operation of the matrix for sizes which at present seem to be desirable.

A third scheme for driving the matrix appears to be promising. Instead of letting the unused rows and columns float or be grounded, the selection ratio can be improved by driving the unused rows and columns to voltages such that the voltage across the large summed condenser just equals the voltage across each of the smaller summed condensers (Fig. 4c). Although this scheme involves additional driving problems, it makes the selection ratio 3 : 1 regardless of the matrix size. This means that the hysteresis loop of the ferroelectric need only be capable of discriminating between two voltages which bear a three-to-one relationship to each other, as will be explained in the following paragraphs.

Selection of a row and column allows us to apply a full voltage of either polarity to the ferroelectric condenser at the intersection while applying a lesser disturbing voltage to other condensers in the matrix. If we work with a ferroelectric having a hysteresis loop that is somewhat rectangular and then adjust the value of voltage applied to the selected condenser so that it just exceeds the knee of the hysteresis loop while the disturbing voltage is not quite out to the knee (Fig. 5), we can reverse the displacement of the selected condenser without reversing the displacement of the other condensers in the matrix. We thus have a means by which we can switch a selected condenser back and forth, moving from the top of the hysteresis loop to the bottom and back, without significantly changing the residual displacement in neighboring condensers.

We can now arbitrarily define one of the residual displacement points as a <u>one</u> in digital computer terminology, and the other as a <u>zero</u>. At random, then, we can write ones and zeros in the various condensers of the matrix.

To find out in which condition a given condenser lies, that is, to "read" from the matrix, we will apply a reference voltage which in effect is the same as writing a zero. If the selected condenser contains a one, the switching of the condenser as it traverses its hysteresis loop will cause a surge of current to flow into the matrix. If, on the other hand, the selected condenser contains a zero, no such switch will occur and only a small current will flow into the matrix to charge up the stray capacitances. To determine whether or not a surge of current flows into the matrix, we must be prepared to look for this current on each of the rows (or columns). This can be readily accomplished with the three-to-one selection scheme, the two voltage levels being used to operate diode gates. The diodes, tied to a common point, will connect this point to the selected row. Due to the internal resistance of the voltage source or an added resistance in series with each row, the current surge as the selected element switches will show up as a voltage pulse at the common point. Absence of such a pulse will imply that the condenser did not switch when the reference field was applied, and therefore that the condenser contained a zero.

Whether a one or a zero is read, the selected condenser will contain a zero after reading. Therefore after a one has been read, it must be rewritten into the selected condenser. This can be accomplished by reversing the polarity of all voltages applied to the rows and columns.

Ferroelectric circuits have at least two potential advantages over ferromagnetic circuits. First, because a magnetic field is a divergenceless field, a complete closed path is required for each magnetic circuit, whereas an electric field can terminate on a charge-carrying material; this fact relieves the electric circuit of the topological difficulties involved in obtaining flux-linkages, and therefore permits improvements in packaging. One possible packaging arrangement is to fire silvered electrodes on one side of a ferroelectric slab in the form of rows and on the other side in the form of columns (Fig. 6). The material at the intersection would then become the storage element. A second potential advantage is that the energy storage per unit volume in ferroelectrics is higher by about two magnitudes than in the ferromagnetic materials currently in use. This latter fact may make possible extremely compact storage.

5. PROPOSED PROCEDURE:

Before a matrix of ferroelectric condensers is assembled, more must be learned regarding the properties of the available materials, in particular the properties which affect the operation and operating speed of the proposed memory. The first step will be to construct equipment capable of pulsing a single condenser with voltage steps of alternating polarity and adjustable amplitude. The displacement current, as the condenser switches, will be observed as a voltage drop across a small series resistor. With this setup, the switching time of ferroelectric materials can be studied as a function of applied field strength and geometry.

Provision will be made to apply an variable number of disturbing voltages between successive positive and negative voltage steps, so that the ability of the material to retain a residual displacement in the proposed memory can be studied.

Experimental matrices will then be constructed and tested as memories, information being written and read in arbitrary patterns so as to evaluate the reliability of the memory. Consideration will then be given to the problem of finding the most practical scheme for selecting among the rows and columns and driving the selected row and column. At present a magnetic matrix switch described by K. H. Olsen[10] and its ferroelectric dual show promise of an economical solution to the problem.

6. EQUIPMENT NEEDS:

The equipment needed for testing the individual ferroelectric condensers is for the most part in existence and available in the form of a single-core (magnetic) pulse tester at the M.I.T. Digital Computer Laboratory. The tester is designed to drive current steps through windings on a magnetic core with provision for looking at the associated voltage waveforms on a

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[10] K. H. Olsen, "A Multi-Position Magnetic Switch and its Incorporation Into a Magnetic Memory", M.I.T. Digital Computer Laboratory Memorandum M-1282, (September 12, 1951).

synchronized oscilloscope. A voltage-source chassis will be constructed which will replace the pentode current sources with thyratron voltage sources, and the switching current of the ferroelectric condensers will be observed as a voltage drop across a small series resistor. Provision will be made for alternate-polarity voltages plus a small disturbing voltage, all adjustable.

The oven and facilities in the Dielectric Measurements Group of the M.I.T. Laboratory for Insulation Research have been made available for firing silver electrodes on the barium titanate slabs. The Glenco Corporation has indicated willingness to manufacture experimental barium titanate ceramics. The Electrical Ceramics Group of the M.I.T. Laboratory for Insulation Research, whose newly constructed ovens will soon be in operation, has indicated a similar willingness to manufacture experimental ceramics for this thesis.

The financial and technical assistance of the M.I.T. Digital Computer Laboratory in which the thesis work is to be done has been assured.

7. <u>ESTIMATED DIVISION OF TIME</u>:

(a)	Preparation of Proposal - - - - - - - - - - - -	40 hours
(b)	Further Study of the Literature - - - - - - -	25 hours
(c)	Experimental Work and Analysis - - - - - - -	210 hours
(d)	Correlation of Results and Formulation of Deductions and Conclusions - - - - - -	45 hours
(e)	Preparation of Thesis Report - - - - - - - -	40 hours
(f)	TOTAL	360 hours

8. <u>SIGNATURE AND DATE:</u>

Dudley A. Buck

Dudley A. Buck
November 23, 1951

9. <u>SUPERVISION AGREEMENT:</u>

The problem described here seems adequate for a Master's research. The undersigned agrees to supervise the research and evaluate the thesis.

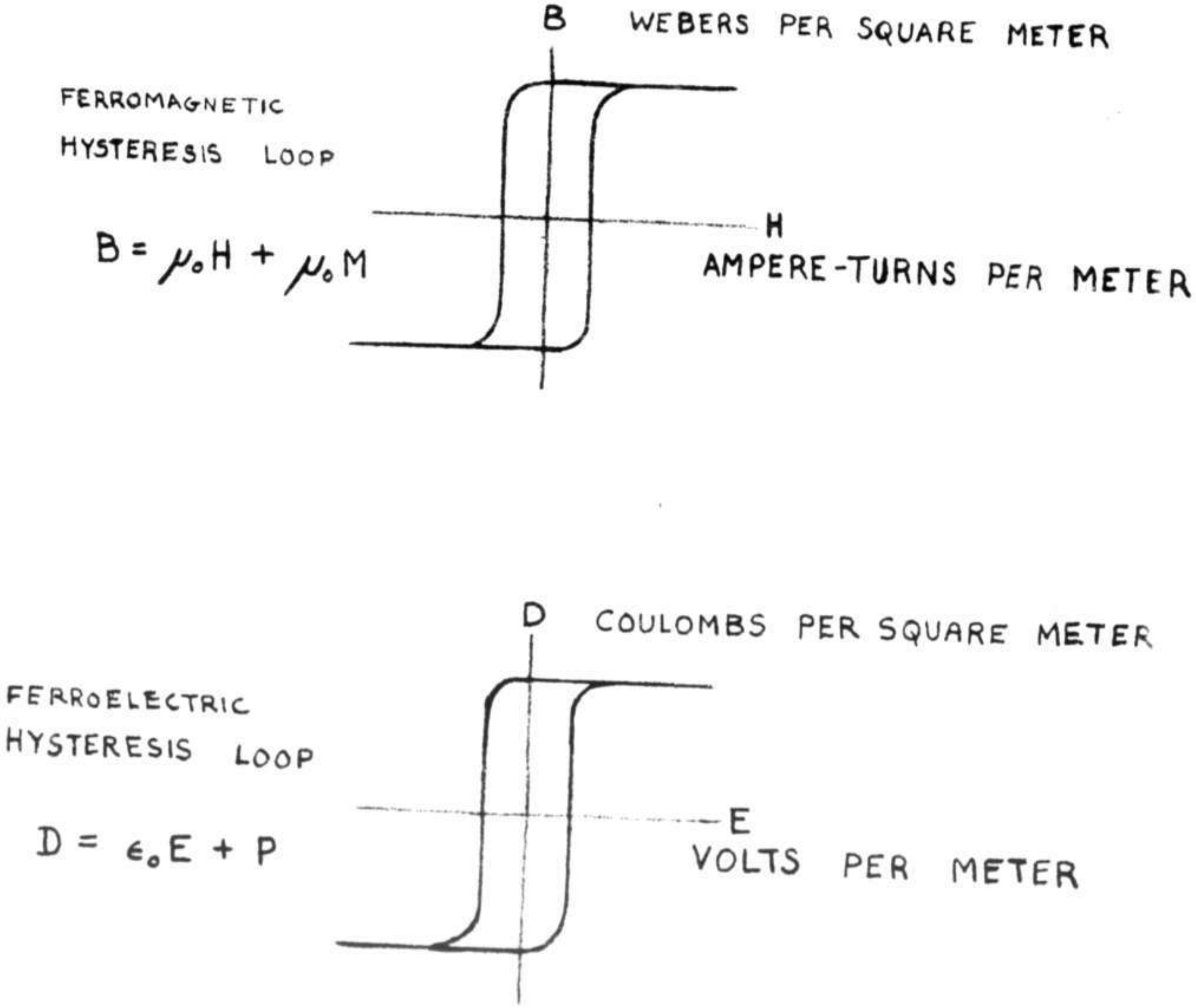
Arthur R. von Hippel

Arthur R. Von Hippel

DAB:kst

Drawings Attached:

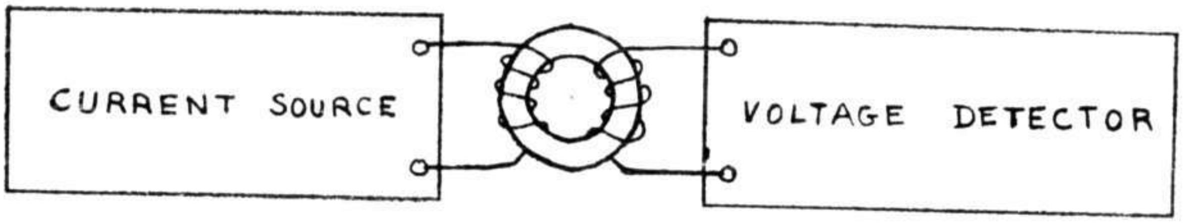
SA-50545	Figure 1
SA-50546	Figure 2
SA-50547	Figure 3
SA-50548	Figure 4
SA-50549	Figure 5
SA-50550	Figure 6



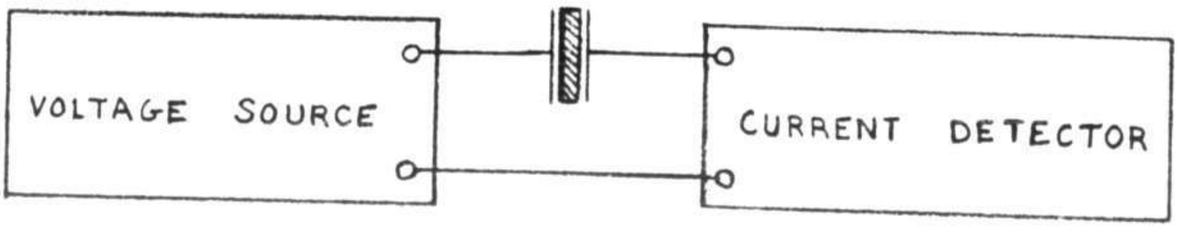
COMPARISON OF FERROMAGNETIC AND FERROELECTRIC HYSTERESIS LOOPS

FIG. 1

SA-. 2545



FERROMAGNETIC STORAGE



FERROELECTRIC STORAGE

A COMPARISON OF FERROMAGNETIC AND FERROELECTRIC STORAGE

FIG. 2.

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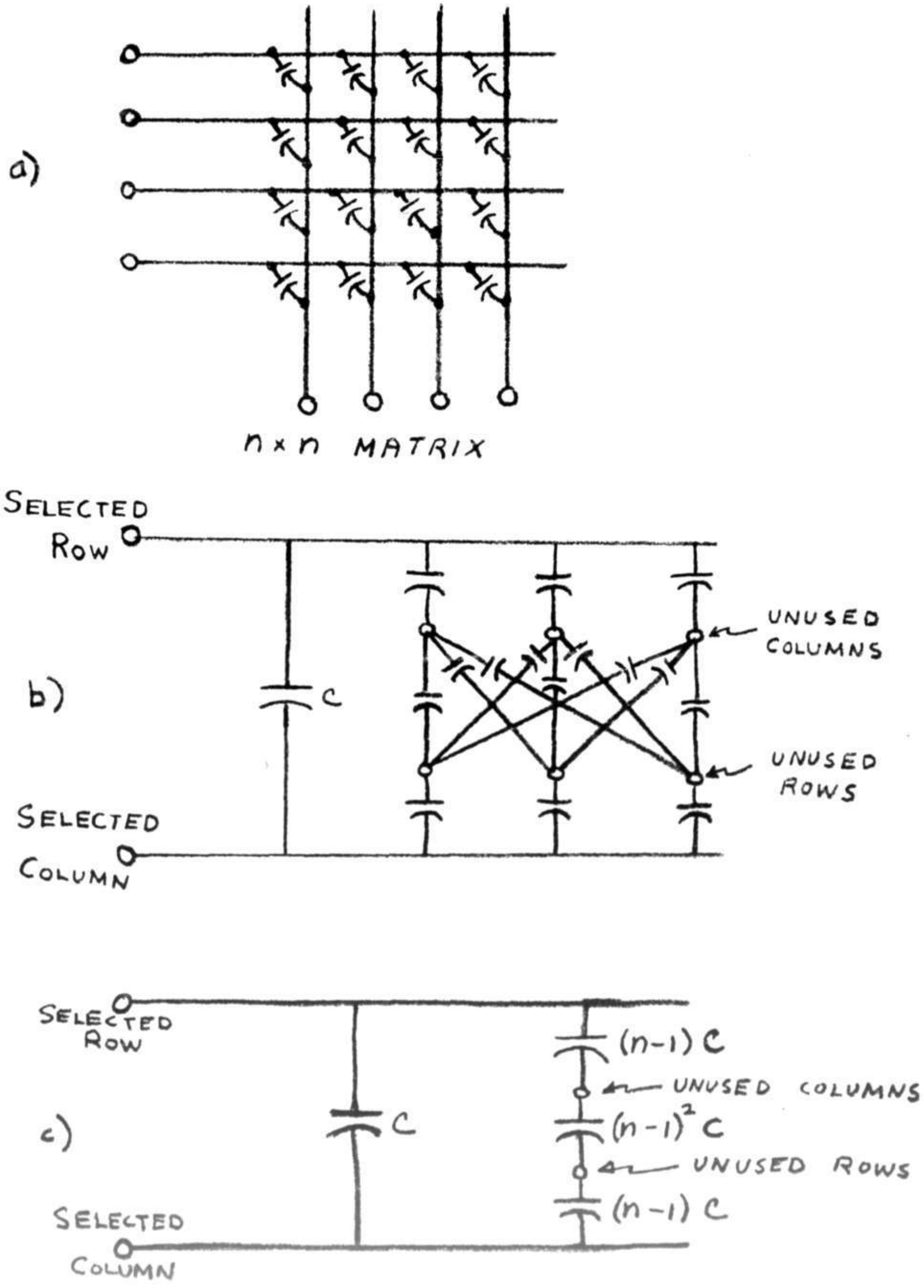

MATRIX REDUCTION

FIG. 3

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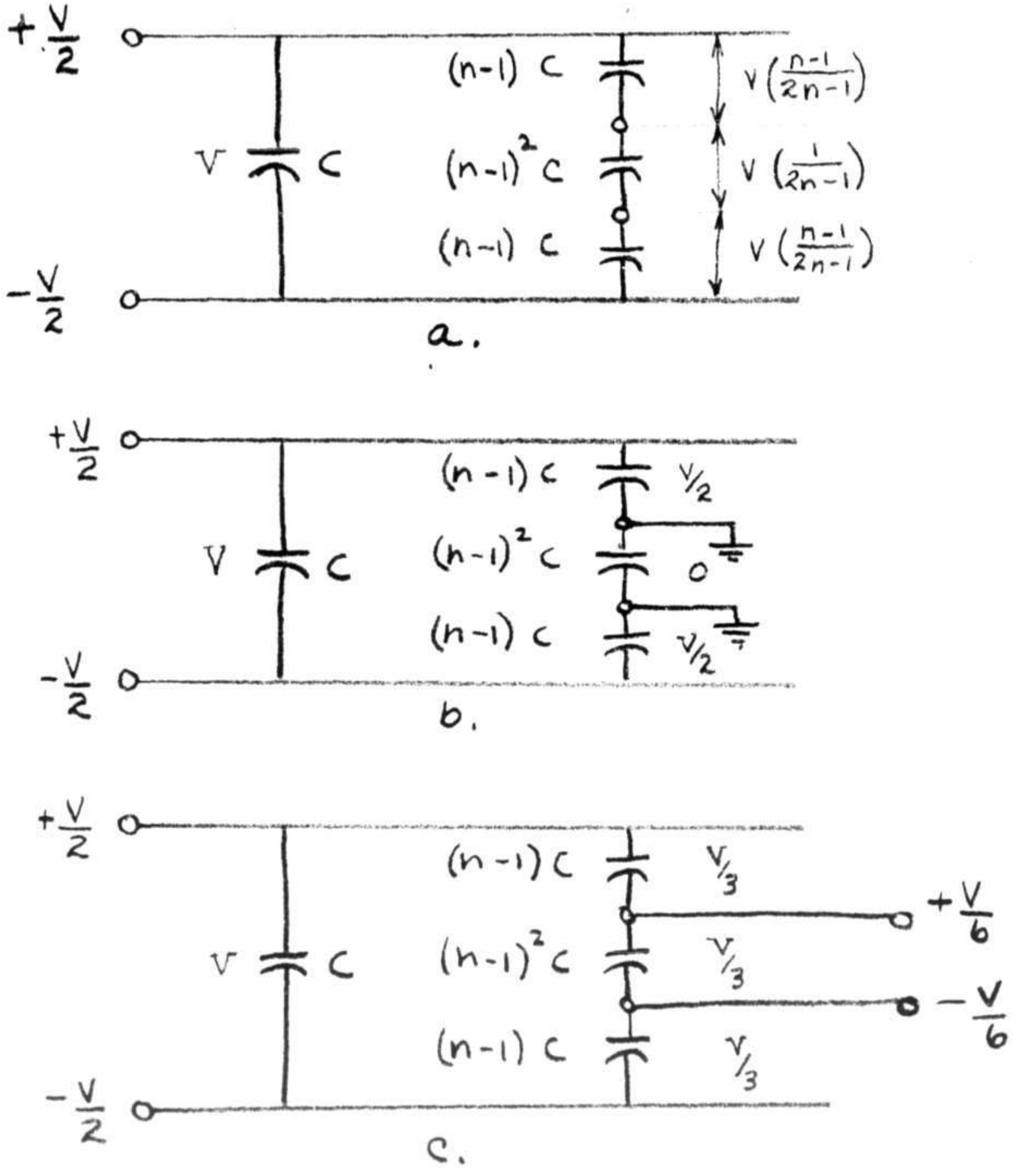

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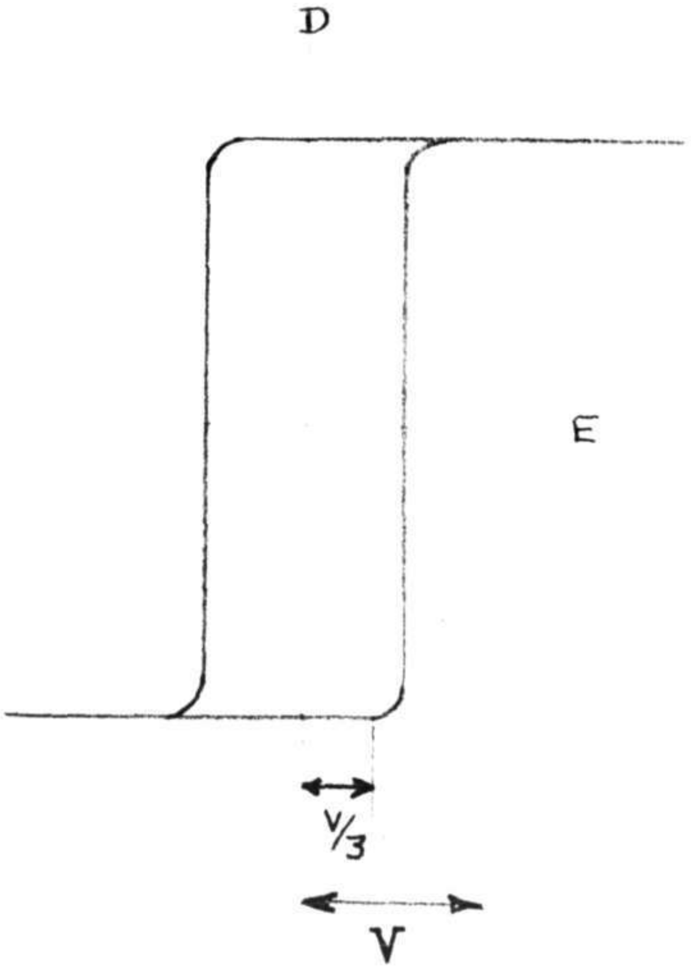
THREE DRIVING SCHEMES AND RESULTING DISTURBING VOLTAGE

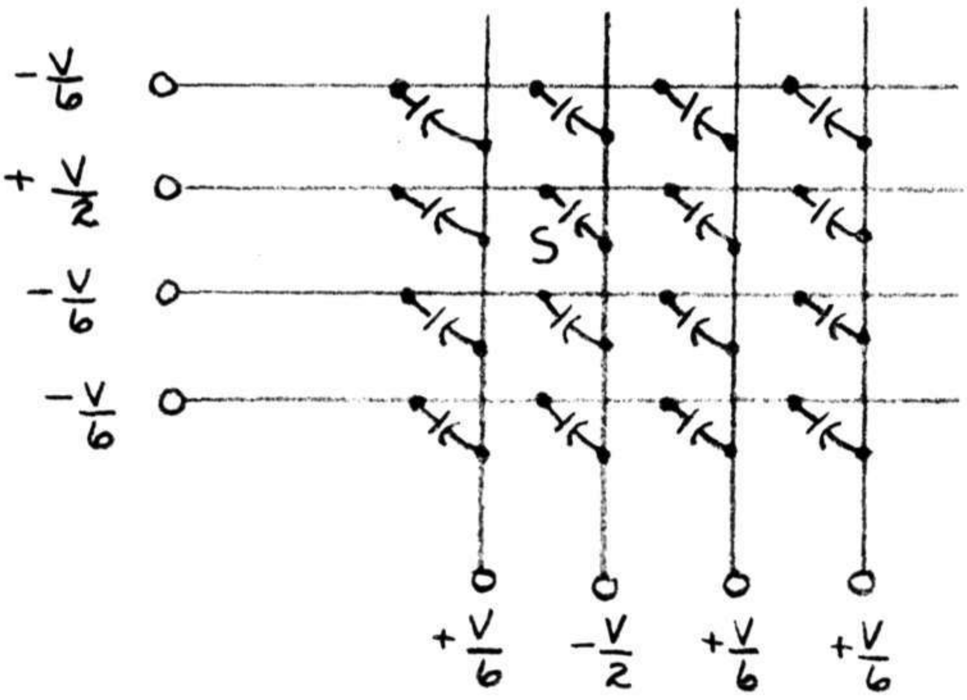
FIG. 4

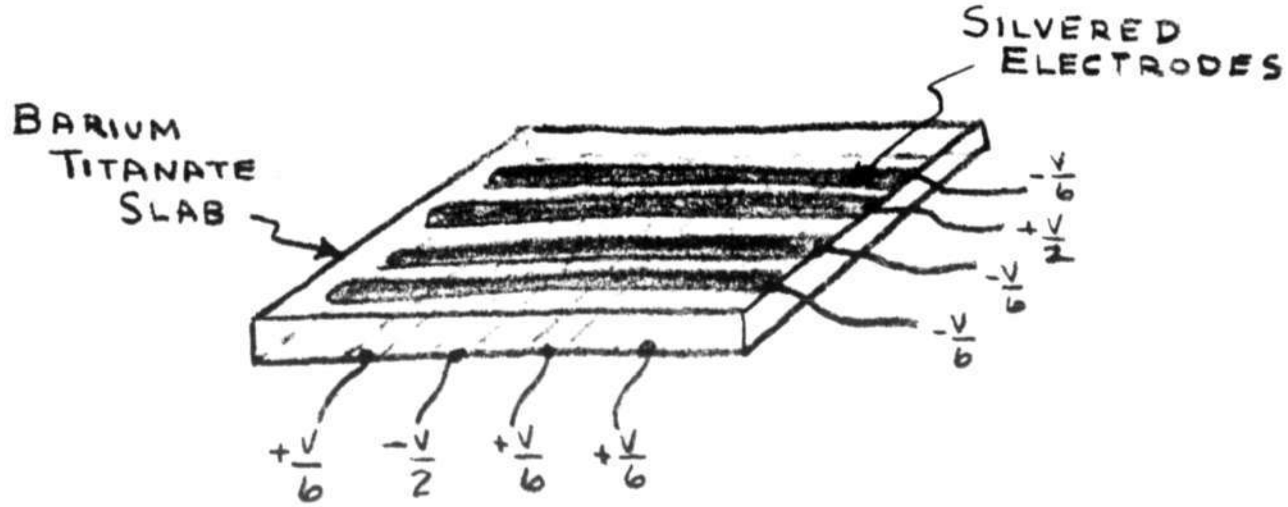


DISCRIMINATION BETWEEN TWO VOLTAGES
REQUIRED OF HYSTERESIS LOOP

SA 50579

FIG. 5





FERROELECTRIC MEMORY

FIG. 6

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