Vol. 23 SEPTEMBER - OCTOBER, 1958 No. 7

CORNELL-DUBILIER ELECTRIC CORP.
Hamilton Boulevard, South Plainfield, N. J.

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FERROELECTRICITY AND ITS APPLICATIONS

The quest for amplifying and control devices which possess higher reliability than the vacuum tube has yielded many innovations. Some of these, like the transistor, have been immediately applicable to practical circuits. Others presently are in various stages of improvement or still are laboratory curiosities but give promise of early application.

One property which seems to be undergoing only slow utilization but very likely will yield intriguing components for the electronics of the future is **ferroelectricity.** Research in ferroelectricity is being advanced on many fronts and is receiving a great deal more serious attention than may appear on the surface.

Ferroelectricity Defined

What is ferroelectricity? Briefly, it is a property resulting from non-linear dielectric action. It is exhibited as the unusual characteristic that certain dielectric materials have of changing their dielectric constants with applied voltage. Linear dielectrics, such as the insulants commonly used in electronics, exhibit no such property — at least not to any marked degree.

Voltage-sensitive dielectrics are said to be ferroelectric. Among such materials which have been tested extensively in electronic development are barium titanate, titanium dioxide, guanadine aluminum sulphate hexahydrate (GASH), and triglycene sulphate. There, of course, are many other materials which are ferroelectric to some degree, not always useful. Some materials are both ferroelectric and piezoelectric.

There is no simple yet exact explanation of ferroelectricity outside of the realm of advanced physical chemistry. However, rudimentary physical pictures can impart a practical understanding of the effect. Perhaps, the simplest of these pictures is that an electrostatic field will align electric dipoles in a dielectric in much the same way that a magnetic field aligns magnetic dipoles in a magnetic material.

The mechanism is thought to result from the nature of the dielectric atom. In such atoms, there are very few free electrons. In fact, the number of electrons able to contribute to current flow is infinitesimal, this accounting for the insulating properties of the material. Most of them are bound tightly within the atoms. When an electrostatic field is applied to a dielectric, the atoms are strained or distended, as the bound electrons are pulled toward the positive electric pole. These stretched atoms, with their distorted shapes, are the **electric dipoles.** They line up along the electrostatic lines of force.

In non-linear dielectric materials, the number of aligned dipoles is not a direct function of the applied voltage. This accounts for the fact that the dielectric constant (K) of such materials varies non-linearly with voltage. At a given constant temperature, the K vs. E characteristic will resemble the plots given in Figure 1 (A and B).

The voltage sensitivity of non-linear dielectrics is a temperature-sensitive phenomenon. This can be either an advantage or disadvantage, depending upon the proposed application for the material. Figure 2 depicts the variation of dielectric constant with temperature, assuming a constant applied voltage. Note that the dielectric constant increases non-linearly with temperature up to a certain critical temperature known as the **Curie point**; and that beyond this point, K decreases as the temperature is increased further. The Curie point is at or near room

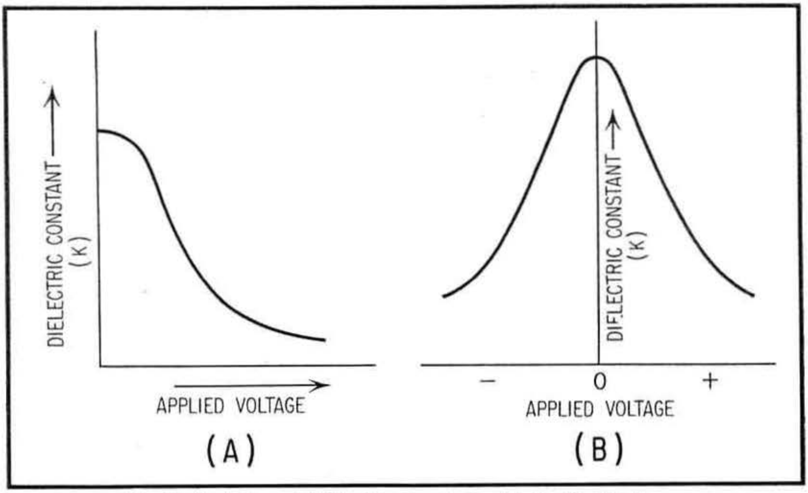

Fig. 1. Variation of Dielectric Constant with Applied Voltage.

temperature in some dielectrics, but many materials processed for ferroelectric applications provide Curie points at high temperatures well outside of the normal operating range.

Aside from the characteristics just discussed, ferroelectrics exhibit a hysteresis effect. This may be demonstrated with the setup shown in Figure 3. An a-c test voltage of desired frequency is applied to a ferroelectric plate (provided with flat parallel, plate-type electrodes) in series with a fixed capacitor, C. The capacitance of the latter is very high with respect to the capacitance of the ferroelectric. The internal sweep oscillator of the oscilloscope is switched off, so that the a-c source supplies a sine-wave sweep voltage. The voltage developed across capacitor C is proportional to the charge in the ferroelectric and is applied to the horizontal input. The pattern will resemble one of the shapes: Figure 4 (A, B, or C).

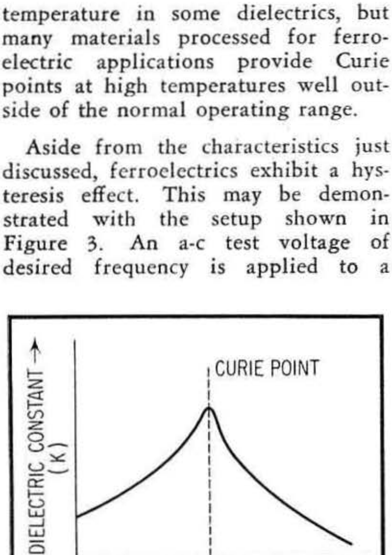

Fig. 2. Variation of Dielectric Constant with Temperature.

In Figure 4, the vertical axis represents charge in the ferroelectric, while the horizontal axis represents applied voltage. Response in all four quadrants is shown. The loops show the material to exhibit a saturation region at both positive (top) and negative (bottom) polarization, and rapid transition regions connecting the two.

When a ferroelectric possesses the severe square-loop hysteresis response

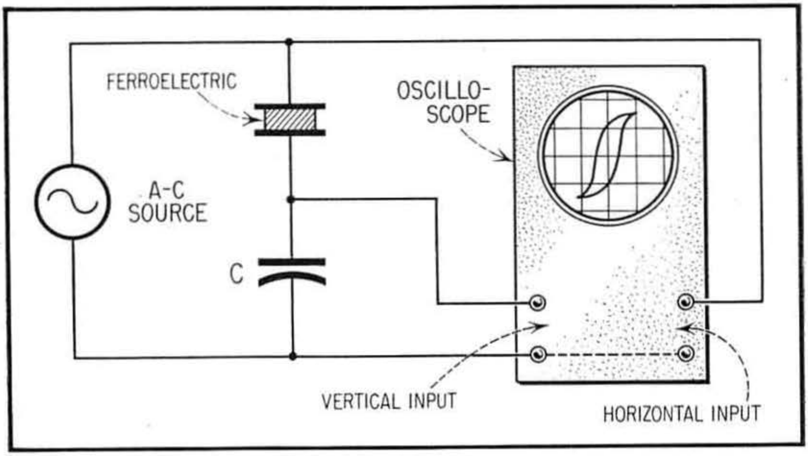

Fig. 3. Setup for Checking Ferroelectric Hysteresis.

depicted by Figure 4 (C), it has, in addition to other useful features, pronounced memory characteristics. That is, if it is polarized into one of its saturation regions by momentary application of a voltage of sufficient magnitude, it will remain so polarized indefinitely. If a voltage of the opposite polarity and correct magnitude subsequently is applied, the material will be polarized into the opposite saturation region where it will remain indefinitely. Thus, in Figure 4 (C), a positive voltage will flip the ferroelectric to 1, and a negative voltage to 2. Once the material has been saturated in the positive direction, further application of posi-

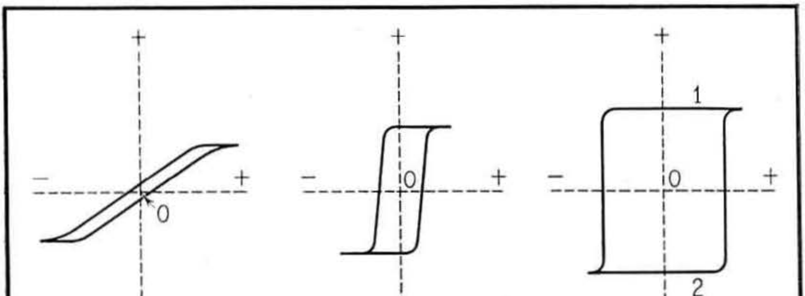

Fig. 4. Ferroelectric Hysteresis Loops.

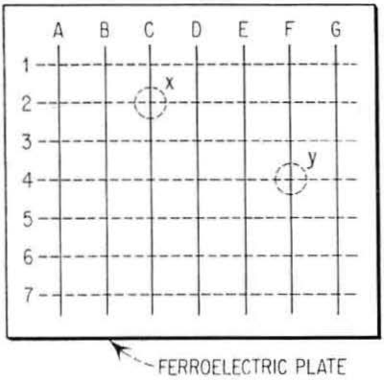

Fig. 5. Arrangement of Ferroelectric Memory.

tive pulses will have no effect. Similarly, when saturated in the negative direction, further negative pulses will have no effect. The effects discussed in this paragraph are possessed in lesser degree when the loops are not quite as square but more nearly resemble those shown in Figures 4 (B) and (A), in that order.

Electromagnetic Dual

The hysteresis loops given in Figure 4 are seen to resemble those of magnetic materials. The square loop (Figure 4C) is very desirable in magnetics, as it is in ferroelectrics. There are many applications of nonlinear magnetic effects which may be served also, to some extent at least, by similar ferroelectric circuits. In each instance, however, it is well to note that the two phenomena are duals. Thus, the non-linearity may be utilized for amplification, giving the magnetic amplifier in one case and the dielectric amplifier in the other. The duality in this example shows up in Table I below.

Ferroelectric Applications

In order to obtain uniformity of characteristics, single-crystal ferroelectric is employed in all exacting applications. Polycrystalline material is useful in many applications, however. Thin plates or slabs are cut or separated from the single crystals. These plates then are provided with flat, plate-type electrodes which are either fired or vacuum-evaporated on their flat, parallel faces. The result is a ferroelectric capacitor. Such capacitors are usable in amplifier, control, and flip-flop circuits having no tubes or transistors, and in special computer memory applications where a separate sub-subminiature ferroelectric capacitor is used for each memory cell.

In other applications; a large, single-crystal ferroelectric plate may be provided with a number of electrodes of suitable shape and size for the purpose of polarizing separately a number of tiny areas of the plate.

Computer Memory. An intriguing application which has attracted the interest of many workers with ferroelec-

TABLE I

Amplifier Type	Input Impedance	A-C Power Supply	Governing Reactance	Speed (Frequency Response)
Magnetic	Low	Low	Inductive	Slow (Low)
Dielectric	High	High	Capacitive	Fast (High)

tricity is the use of non-linear dielectric material as the basis of a simple, small-sized, static memory unit for digital computers. The basic principle of this device is illustrated by Figure 5. A thin plate of single-crystal, square-loop ferroelectric is employed. The electrodes consist of parallel metallic lines deposited by evaporation. One set of lines runs in one direction on top of the plate (as A, B, C, D, E, F, G in Figure 5) and the other set runs perpendicularly on the bottom of the plate (as 1, 2, 3, 4, 5, 6, 7). The point at which two perpendicular lines cross includes between them a small volume of the ferroelectric material. Thus, a tiny non-linear capacitor is set up at that point, as at x (the intersection of Lines 2 and C) in Figure 5. Forty-nine such intersections, and accordingly 49 capacitors, are shown in the Figure. The action of each capacitor is independent of its neighbors, although the dielectric is a single block.

Connections are made to external circuitry by attaching a lead to each of the metallic lines of the memory matrix or grid. Connections made to Lines 4 and F thus will utilize the capacitor formed at intersection y.

Memory action occurs in the following way. To "write" information into a particular memory cell (capacitor), pulses are applied simultaneously to the corresponding vertical and horizontal line-electrodes of the grid. For example, a pulse at 2 coincident with one at C will polarize the cell at the intersection of the lines at x. The dielectric at this point will be polarized to saturation and will remain in this state, thus "remembering" the pulse entry. Subsequent pulses of the same polarity can have no effect, since the cell now is filled. Information may be written digitally into the other cells in the same way.

To "read" information out of the memory, a cell must be examined (via the proper horizontal and vertical line-electrodes of the matrix) with coincident pulses of polarity opposite that employed in writing. If there is stored information, an output pulse will be obtained.

A distinct advantage seen for the ferroelectric memory is its large storage capability in small size. Many thousands of bits, for example, could be stored on a plate of 1 square inch size. Another advantage is the high impedance of this device, which makes it economical of power and renders it compatible with low-powered transistors which may be used as write-amplifiers. Disadvantages of the memory are the temperature-dependence of the ferroelectric material and the volatile nature of the memory action; i. e., the read-out is destructive of the information. A further disadvantage when barium titanate is employed as the ferroelectric, is the tendency of this material to fatigue in operation, becoming less effective as a memory material. Late work, especially at Bell Telephone Laboratories, show that GASH and triglycene sulphate exhibit little or no such fatigue.

Flip-Flop. Because of the bistable nature of the saturation characteristic of the ferroelectric, evident from Figure 4 and the attendant discussion, the ferroelectric capacitor in series with a suitable current limiting resistor will provide simple flip-flop action. The effectiveness is governed by the squareness of the hysteresis loop.

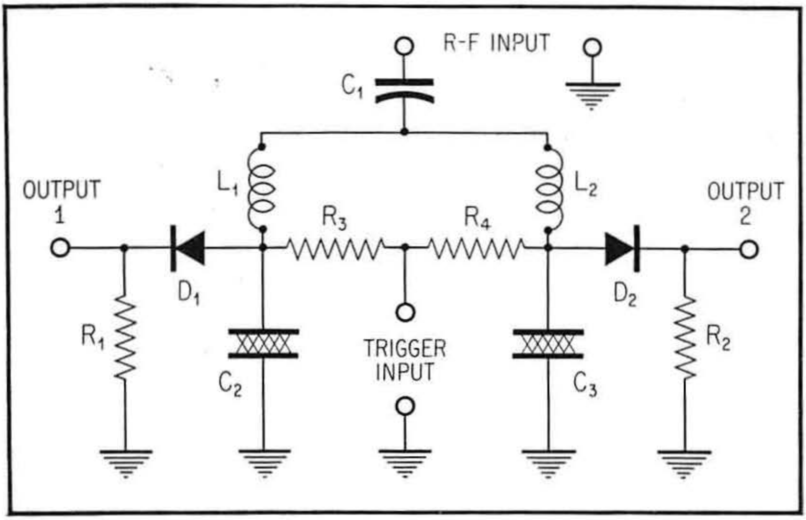

Fig. 6. Ferroresonant Circuit Employing Ferroelectric Capacitors.

A positive-going pulse of sufficient amplitude will polarize the capacitor (corresponding to binary 1 electrification). This state will be held. A subsequent negative-going pulse will depolarize the capacitor; or, if the pulse amplitude is sufficient, will polarize it in the opposite direction. This second stable state corresponds to binary O.

Flip-flop action may be utilized in the conventional manner to produce ring counters, shift registers, switches, and similar equipment.

Ferroresonant Circuit. The conventional ferroresonant circuit employs a non-linear inductor and conventional (linear) capacitor. This circuit has been applied to all well-known flip-flop uses, such as binary counters, ring counters, and shift registers. The functions may be shifted by employing a ferroelectric capacitor and conventional inductor, as shown in Figure 6.

Capacitor C_1 provides a common impedance for the two legs of the circuit. Its capacitance is very large with respect to that of the ferroelectric capacitors, C_2 and C_3. Conventional capacitors are in the latter position in the standard ferroresonant circuit. Linear inductors are employed at L_1 and L_2.

Upon application of a trigger pulse of suitable amplitude, the capacitance of C_2 is shifted sufficiently to switch the left leg of the circuit to its second stable state, and OUTPUT 1 is activated. Upon application of a subsequent pulse, the right leg is switched to its second stable state, OUTPUT 2 is activated, and the left leg is deactivated since both legs can not draw sufficient "firing" current simul-

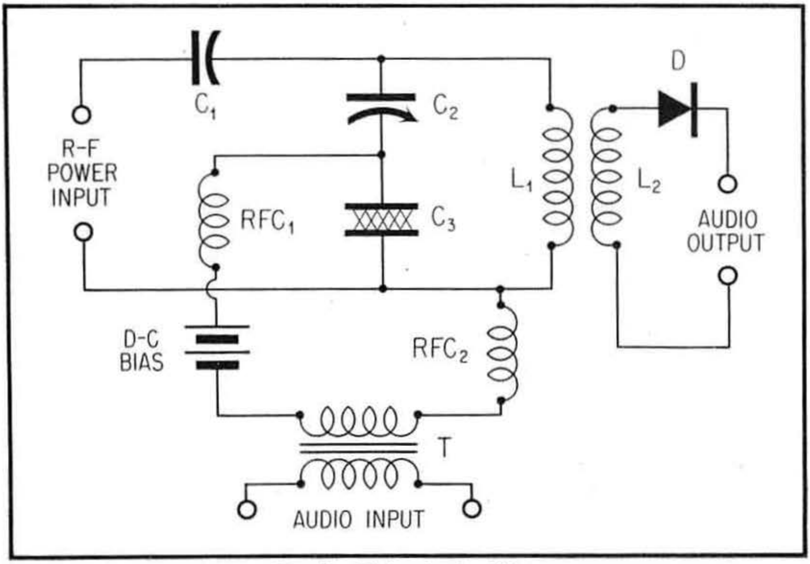

Fig. 7. Dielectric Amplifier.

taneously through the common impedance, C_1.

In all respects, this scale-of-2 circuit operates like the classic ferroresonant circuit except that the non-linear element in this instance is the capacitor rather than the inductor.

Dielectric Amplifier. Ferroelectric capacitors having hysteresis loops similar to that shown in Figure 4(A) provide useful amplification, both voltage and power, when operated in appropriate rf-powered circuits.

Figure 7 shows one type of dielectric amplifier for audio frequencies. The ferroelectric capacitor, C_3, is part of a radio-frequency tuned circuit. Inductor L_1 is tuned to the frequency of the r-f power supply by the conventional (linear) capacitor (C_2) and the ferroelectric capacitor (C_3) in series. Capacitor C_1 serves to block the d-c bias from short-circuit through L_1. The d-c bias sets the operating point along the non-linear curve (Figure 4A).

Input-signal a-f variations alternate the reactance of C_3, shifting the tuning of the L_1 tank above and below the operating point (carrier frequency of the r-f power supply). This produces an amplitude-modulated output wave. The audio envelope of this wave is recovered by the demodulator diode, D.

Considerable amplification is possible when the selectivity curve of the output tank circuit is steep and when the d-c bias is set for an operating point along the most linear portion of the curve. For a more detailed discussion of dielectric amplifiers, see C-D CAPACITOR, July 1954.