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DEVELOPMENT OF AN INHERENTLY DIGITAL TRANSDUCER

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16. Abstract

The term digital transducer normally implies the combination of conventional analog sensors with encoders or analog-to-digital converters. Because of the objectionable characteristics of most digital transducers, a program was instituted to investigate the possibility of producing a transducer that is inherently digital, instead of a transducer that is digital in the usual sense. Such a device would have improved accuracy and reliability and would have reduced power and bulk requirements because two processes, sensing and conditioning, would be combined into one process.

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SUMMARY

The term digital transducer normally implies the combination of conventional analog sensors with encoders or analog-to-digital converters. Because of the objectionable characteristics of most digital transducers, a program was instituted to investigate the possibility of producing an inherently digital transducer, instead of a transducer that is digital in the usual sense. Such a device would have improved accuracy and reliability and would have reduced power and bulk requirements because two processes, sensing and conditioning, would be combined into one process.

The intuitive acceptance of an inherently digital transducer hinges on the point of view taken toward the classification of natural phenomena. For example, the magnetic induction–magnetic field strength (B-H) magnetization curve appears to be grossly continuous (analog) in nature. However, the Barkhausen effect is indicative that the magnetic dipoles of a ferromagnetic sample are not oriented in a smooth manner. Although currently not considered feasible for transducer applications, the Barkhausen effect is a naturally occurring discontinuous process that provides an intuitive appreciation of the goal of this development program: to use discontinuous or quantized phenomena occurring in nature which will provide information about the condition of a physical stimulus.

A Curie-point-temperature sensor is described that represents realization of the stated goal. Also, a metal-insulator semiconductor is described that does not conform precisely to the program goals but that appears to have applications as a new and interesting transduction device.

INTRODUCTION

A classification of transducers, based on the combination of the available choices of sensor techniques and electronic manipulations, has evolved informally. The following list represents some of the commonly accepted terminology used in the classification of transducers (ref. 1).

1. Direct digital transducers

2. Indirect digital transducers

3. Quasi-digital transducers

4. Analog-to-digital transducers

Direct digital transducers provide an instantaneous coded output, proportional to the sensed stimuli, without the use of any intermediate mechanisms or signal processing. Indirect digital transducers include the shaft encoders, nuclear disintegrations, and so forth. Examples of quasi-digital transducers are the rotating-vane flowmeter and the vibrating-string pressure transducer that have frequency output, pulse, and pulse rates. Both direct digital transducers and transducers that do not comply fully with any of the previous definitions will be discussed. In the noncompliance case, if the sensor is considered separate from the transducer, and if the output of the sensor is discontinuous, then this sensor will be referred to as "inherently digital."

AVAILABLE DIGITAL TRANSDUCERS

No attempt will be made to discuss all of the available digital transducers. However, an example of a direct digital transducer, also called a true digital transducer (ref. 2), will be given to illustrate a variety of phenomena that will conform to the scope of this report. Also a liquid-level measurement system will be described to introduce a particular type of output signal (quasi-digital) that is essential for an appreciation of the reported work.

Photoelasticity

Photoelasticity is one phenomenon that has been investigated for application as the transduction mechanism for a direct digital transducer. Operation is based on the changing of the index of refraction of an optically transparent material resulting from application of a mechanical stress. An illustrative device can be constructed by mounting several photoelastic sections on a flexure (fig. 1) with a light source and optics arrangement which focuses light through each section to separate detectors. A variation of logical 1's and 0's results at the output when the force applied to the photoelastic sections is varied, causing a change in the light levels falling upon the detectors.

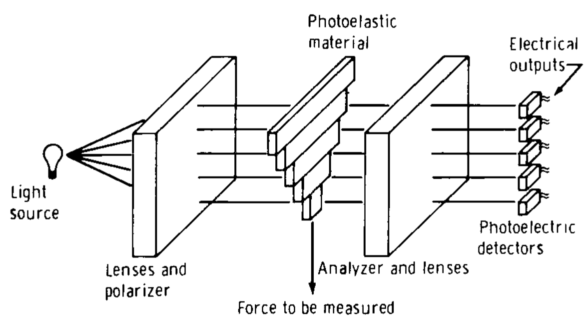
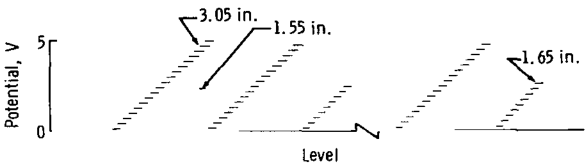


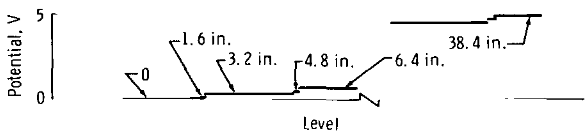
Figure 1. - Photoelastic force transducer.

Liquid-Level Probe

The liquid-level probe is illustrative of a variety of analog-to-digital transducers and can be used to introduce the idea of a quasi-digital signal, which is relevant to concepts that are to be discussed. The basic sensor is composed of two cylindrical, concentric capacitances in which the measured liquid constitutes the dielectric. Changes in capacitance, caused by lowering or raising the liquid, are sensed by comparison with fixed capacitors in a bridge arrangement. Bridge balance is maintained with an electronic servosystem that electronically switches in binary-weighted-balance capacitances. Parallel binary read-out is accomplished by sensing the status of counters. Also, the counter outputs are combined into another output that provides two quasi-digital voltages, a fine voltage (fig. 2(a)) and a coarse voltage (fig. 2(b)), suitable for telemetering. This system involves conventional digital techniques; therefore, this system does not conform to the scope of this report. However, the quasi-digital signal output of this device introduces a digital concept that cannot be identified strictly with the usual analog or digital output signal.



(a) Fine-scale output (0. 1-inch scale).



(b) Coarse-scale output (3. 2-inch scale); note half steps.

Figure 2. - Liquid-level probe, digital-analog output.

THE QUASI-DIGITAL OUTPUT SIGNAL

To explore some of the advantages of quasi-digital output signals, the present trend in the design of large data systems will be considered. In these systems, only changes in data are recorded, as opposed to the continuous recording of data that change infrequently or slowly. In designing these systems, the instrumentation or systems engineer must determine the minimum data of interest rather arbitrarily. This minimum level determines the resolution of the system and amounts to a fixed quantity of information. The fabrication of a basic sensor that responds with a preselected change in output level to a change in stimulus would be an obvious and logical advantage. By using this basic sensor, accurate information could be obtained by counting steps or by measuring the approximate voltage level of accumulated steps.

It is constructive to compare the data change of interest to the least significant bit of a binary system. This bit limits or defines the resolution of the system and is chosen on the basis of precision required, bandwidth, economy, and so forth. Also, resolution divides the range of data into a given number of increments. Thus, the number of steps in the described stairstep outputs could be selected in a fashion that could be compared with the selection of the number of bits to be used in a data system.

Output signals of the variety referred to as quasi-digital can be produced uniquely by a sensor that requires no electronic manipulation. Another device will be described that produces a stairstep output voltage in response to an analog voltage input through the use of metal insulation semiconductor (MIS) devices. It is suggested that sensors producing quasi-digital signals can combine some of the best aspects of analog and digital transducers and, further, can provide many of the desirable characteristics found in digital data systems. Analog and digital transducers have applications for which substitutes may not exist; but this quasi-digital concept offers another alternative.

REQUIREMENT FOR RESEARCH

Over the past several years, the use of analog-to-digital and other varieties of digital transducers by the process industries and some testing facilities was indicative that the predicted increased benefits of digital systems were realizable. This realization was of paramount significance in the evolution of digital data systems for use in spacecraft. However, it was obvious that suitable hardware was lacking, primarily because of the stringent power, weight, and volume requirements. It was assumed that technological evolution would correct the problem. However, the NASA Manned Spacecraft Center (MSC) determined that conditions were right for encouraging new approaches to the development of measurement devices. No significant advances had been made in measurement techniques for some time, and new technologies were being developed in thin films and microcircuits. Also, predicted technological needs for extended space missions necessitated a combination of unique requirements that would be difficult to satisfy with conventional techniques.

RESEARCH PRELIMINARIES AND RATIONALE

In June 1965, a "NASA Research Topics Bulletin" (appendix) was generated and widely circulated; inquiries were received from several universities. A proposal was submitted by the University of Texas at Austin. Because the intent of this proposal coincided with the goals of the MSC effort, negotiations were begun to define a mutually beneficial research program. These negotiations resulted in the awarding, by the NASA to the University of Texas in June 1966, of a grant for the support of basic research entitled Theoretical and Experimental Investigations in Digital Transducers. To clarify the rationale for the ensuing effort, it is necessary to begin with a discussion of the heart of a measurement system, the sensor or the transducer.

Transducer Apparatus

In ordinary applications, a transducer converts sensed physical stimuli into a form compatible with a data-acquisition system. This means that the transducer provides an electrical signal that is proportional to, or related to, a measured quantity or condition. Numerous transduction apparatus are available for accomplishing this transformation. Among these apparatus are bonded or unbonded strain gages, piezoelectric crystals, variable reluctance devices, differential transformers, potentiometers, encoders, and so forth. From these examples, it is clear that transduction processes rarely use the physical properties of materials (as in thermocouples), but usually require that the quantity measured provide relative displacement in a mechanism. This displacement alters electrical circuitry, producing a voltage (output) that varies as a function of the displacement.

Direct Digitization

A review of measurement processes reveals a need for a straightforward process to achieve the required input-output relationship. Environmentally induced changes that can be detected readily in the properties of materials could hopefully provide information concerning the magnitude of the environmental factors. In addition, the possibility of direct digitization through the use of discontinuous phenomena occurs. Thus, the expression "inherently digital," as used in the present context, is meant to convey the idea of naturally occurring digital phenomena, as opposed to electronically or artificially induced digitization. To clarify the present concept further, consideration of some fundamental aspects of the measurements process would be constructive.

Measurement Process

The measurement of a quantity with a transducer requires that energy be absorbed by the measuring device. A question exists: is the measurement process analog or digital? Experience reveals the process to be analog, but the ultimate answer depends on the point of view, macroscopic or microscopic, because the microscopic view indicates that energy absorption is quantized. These quanta are generally much too small to be detected by conventional means, forcing consideration to be given to larger quanta or bundles or energy. Consistent with this concept, energetic particles or other quantized or discrete processes (such as interference fringes, nuclear disintegrations, or domain phenomena) might be included. Currently, interference fringes and radioactivity are being investigated by a number of researchers; however, the resultant devices do not appear to be in an advanced stage of development.

PRELIMINARY RESULTS

The following list of concepts was made during the previously discussed negotiations for the University of Texas grant.

1. Photons
2. Electrons
3. Atoms
4. Magnetic flux (observed in superconductivity)
5. Particles
6. Magnetic domains
7. Electric domains
8. Cycles

Although some of these concepts seem to be of questionable practical use in attaining the goals of the project, wide latitude was encouraged. Initially, ultimate practicability was disregarded pending the development of insights for directing subsequent efforts.

Photons are difficult to detect unless they are extremely energetic. In addition, in order to be meaningful, statistical considerations require that a large number of photon-detector interactions be observed. Ordinarily, individual photons have little or no meaning when considered alone.

Electrons and holes are plentiful in nature and are quantum in character; however, individual electrons are difficult to detect. Normally, detection is limited to evacuated volumes in which special detectors such as photomultipliers can be used.

Atoms, molecules, and other larger particles appear to be suitable from a quantum viewpoint. However, detection is difficult because a gaseous or liquid state generally is required in order to make such observations. Because of the problems associated with gases and liquids, the properties of atoms, molecules, and larger particles were considered to be less interesting than the properties attributable to a solid material.

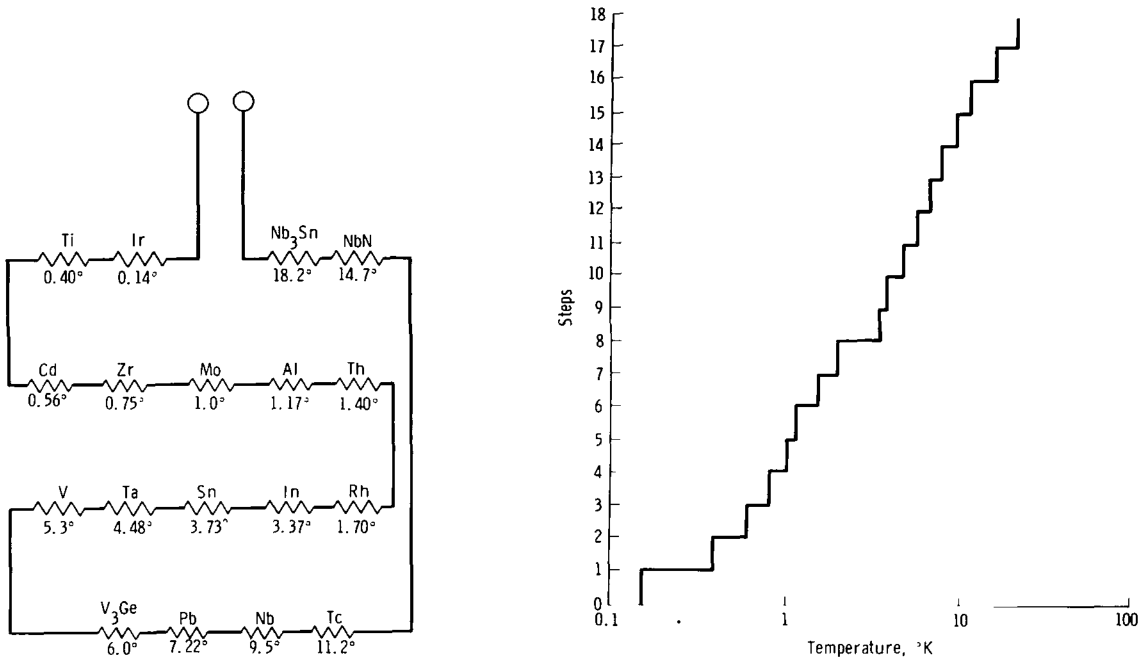
Because an individual oscillation is a detectable quantum change, as in a frequency shift, many detection devices have been conceived. These devices are somewhat hindered by the limitations attributed to transducers in general: the requirement of a mechanism and rather extensive signal conditioning or electronic manipulation.

Of the items in the list, magnetic and electric domains were thought to have the greatest promise in advancing the state of the art in transducers. Practical applications could result from the presence of the polarization domains that are characteristic of ferromagnetic and ferroelectric materials. These domains have the property of changing polarization direction as a domain unit. The change in polarization direction usually takes place suddenly, with the involved atoms changing simultaneously. The best known example of sudden domain changes in polarization is the Barkhausen noise observed in ferromagnetic materials. The problem with domains is finding ideal materials and controlling "flipping" action in a reproducible manner (nonhysteretic). Because of this problem and the subsequent consideration of more interesting phenomena, the items in the list have received reduced emphasis. However, the phenomenon of magnetic flux provides one means of producing a digital cryogenic-temperature transducer.

Inherently Digital Cryogenic-Temperature Transducer

Superconducting transitions in materials provide a measurable step response to temperature in a well-defined manner. Therefore, a series string of superconducting materials may be assembled to provide a stairstep type of electrical response to varying cryogenic temperatures. Furthermore, options are available in the construction of such a device (ref. 3). For example, discrete portions of the required material could be assembled, or thin-film depositions could be used. Selective alloying of materials, use of appropriate geometry, or correct deposit of successive layers of material would provide the adjustment needed to present uniform resistance steps. A schematic of an

18-step device that operates in the 0.14° to 18.2° K range is shown in figure 3(a). The output (fig. 3(b)) is similar to that output produced by conventional digital techniques (fig. 2). Although this transducer has not been produced, there are few technological obstacles to fabrication.



(a) Transducer schematic.

(b) Plot of discontinuous nature of temperature transducer between 0.14° to 18.2° K.

Figure 3. - Cryogenic-temperature resistance digital transducer.

Advantages of the Inherently Digital Cryogenic-Temperature Transducer

Once the inherently digital cryogenic-temperature transducer is fabricated and an operational check that is equivalent to a calibration is performed, recalibration is never necessary because the transition temperatures are functions of the compositions of the materials, the properties of which are invariant. This feature is important for the success of long-duration space missions wherein the constraints of inaccessibility of components and unavailability of facilities are imposed.

Metal-Insulator-Semiconductor Digital Transducers

Research into the characteristics of the MIS has resulted in the identification of features that appear to be promising for digital transducer applications. The construction technique in this MIS research was to form an insulating film over a silicon wafer by means of polymerization of diffusion-pump oil with 350-volt electrons (ref. 3). Then, a small metal terminal or field plate was vapor deposited onto the polymer to complete the MIS sandwich.

The conduction mechanism for the MIS appears to be a combination of several effects such as tunneling and Schottky emission. The observed saturation effect results from the depletion of surface charge on the semiconductor.

A plot of the log of current compared with applied voltage for MIS devices that have several dielectric thicknesses is shown in figure 4. The position of the step or break is a controllable function of dielectric thickness. Thus, a given range of voltage can be divided into an arbitrary number of steps. This statement does not imply that an external bias is always required, because a piezoelectrically generated voltage is adequate at these current levels. Connecting several of the MIS devices in parallel (fig. 5(a)) would yield the stairstep characteristics shown in figure 5(b), again achieving a quasi-digital output similar to that output previously described.

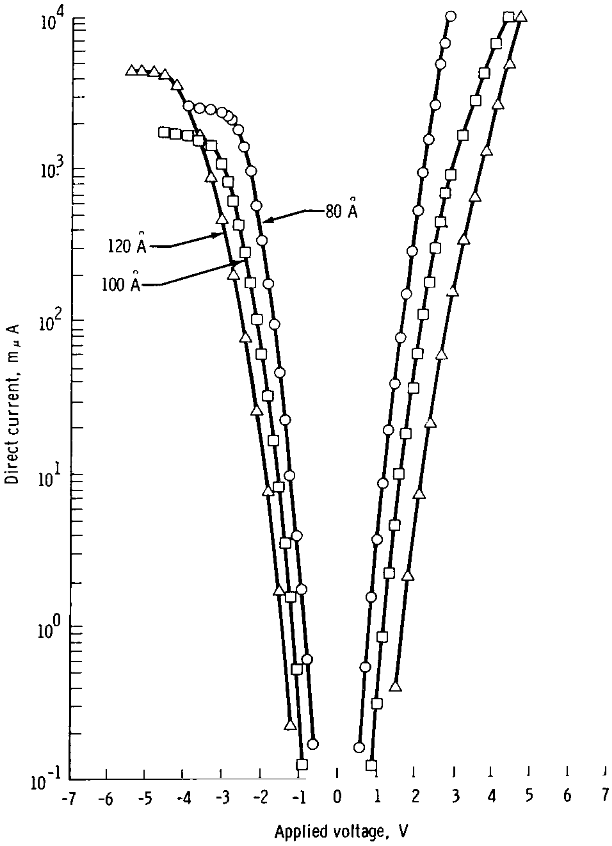
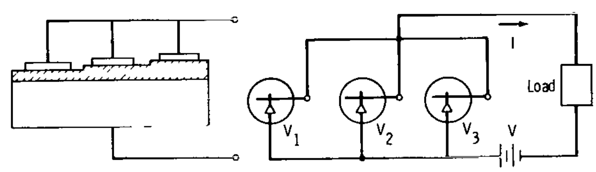
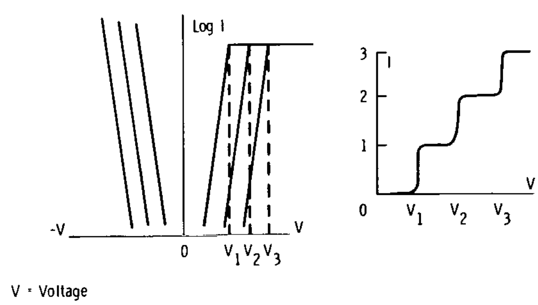


Figure 4. - The MIS tunneling.



(a) Three MIS devices on one substrate.



(b) Transfer characteristics of parallel MIS devices.

Figure 5. - Parallel MIS devices.

The MIS does not comply with the basic precepts of the research. However, this device does provide a potentially significant step in simplifying both digital transducer construction and signal processing.

Curie-Point-Temperature Sensor

It appears to be a common belief that Curie-point temperatures, the point at which ferromagnetic properties of a material are no longer observable, are too high to be of interest. This assumption is an extrapolation from the well known Curie temperature for iron (760° C). The breakdown of ferromagnetic properties is caused by molecular agitation of the material to the extent that a coherent dipole alinement is no longer possible. Instead of the Curie temperature occurring at high temperatures for all metals, it is observed that the breakdown occurs in materials from temperatures approaching absolute zero through room temperatures to temperatures of approximately 1000° K (ref. 4).

Considerable research has been conducted into the properties of magnetic materials such as manganese germinide (ref. 5). This alloy takes the form

$$Mn_{5-x}Fe_xGe_3$$

where x varies between zero and 0.5. This material has been formed into samples having Curie temperatures that bracket room temperatures at increments of 0.1° C. A plot of the relative inductance as a function of temperature for a sample of manganese germinide formed into a solenoid of small diameter is shown in figure 6. The sharpness of the break in the curve may not be obvious until it is realized that there is a 70-percent drop in relative inductance over a span of 4° C. It is known that this slope can be sharpened.

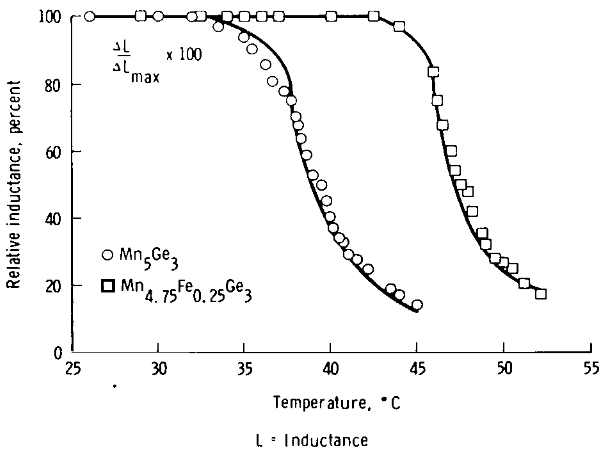


Figure 6. - Relative inductance as a function of temperature for a sample of manganese germinide.

One configuration of a transducer involving this Curie phenomenon would consist of a number of solenoids of perhaps 5/1000-inch diameter that are pulsed in computer memory fashion. In series, one pulse would suffice. Responses would come from those solenoids at temperatures below the Curie point, providing a true digital read-out. The number of cores could correspond to the number of resolution elements of a conventional digital system. A judiciously chosen number of points within a given temperature range could be selected for greater practicality.

Once calibrated, the Curie-point-temperature sensor would never require recalibration because the transfer function is a property of the material and is invariant. The device would be virtually indestructible, could operate in a passive mode requiring no power, and would be competitive in size with conventional temperature sensors. No regulated power is required and there are no parameters to drift, change, or otherwise become uncertain. With a modicum of conditioning, this transducer would be competitive in all characteristics with conventional digital devices.

INVESTIGATIVE TERMINOLOGY

With the presumption that work in this field of research would continue, an attempt has been made to organize some of the generated thoughts and concepts to facilitate further study and discussion (ref. 3). This attempt resulted in a list that is indicative of a substantial advancement. This list is presented first in its entirety for consideration; then, each idea is discussed individually.

1. Exhaustion phenomena
2. Cooperative phenomena
3. Unstable phenomena
4. Geometry-limited phenomena
5. Ordering and phase transformation in metals
6. Resonance and relaxation phenomena
7. Dipole orientation
8. Bandgap effects and optical transparency

Exhaustion Phenomena

Exhaustion phenomena include those phenomena that cause a discontinuity because of exhaustion of the stored charge. The exhaustion of space charge in thermionic diodes is a familiar example. As the plate voltage is raised, the plate current tends to saturate at a value set by the cathode temperature.

A less familiar example is the exhaustion of surface-charge states in semiconductors. This effect has been studied extensively in thin-film tunneling configurations and is the basis of the MIS device.

Cooperative Phenomena

Cooperative phenomena include those threshold phenomena that have a quality of coherence. One example is a Q-switched laser in which a light-pulse output is obtained when a reflecting mirror or prism has reached a chosen position. The condensation of normal electrons into superconducting pairs with opposite spins is another example.

Josephson tunneling is another aspect of superconductivity that is suited to digital transducer action. The effect is a zero-voltage transport of charge across a very thin insulating film between two superconducting films. This component of current flows in addition to the familiar tunneling current that consists of single electrons. This effect is the basis of a new class of cryotrons, as shown recently by Matisoo (ref. 6). The Josephson-tunneling transition is very rapid, and switching times are much less than a nanosecond. The transition is the removal of the Josephson component of current by the magnetic field generated by a control current in an adjacent superconductor. There is no transition from the superconduction to normal states as in the previously discussed transducer (fig. 3). The Josephson digital transducer consists of several junctions, in series or parallel, with each one switched at a preset value of an external magnetic field. The transitions are sharp and reproducible, but the entire concept is limited by the low-temperature requirement.

Unstable Phenomena

Unstable phenomena include avalanche effects having a threshold (such as Zener breakdown in p-n junctions). Multiple discontinuities in the voltage-current characteristics have been observed and may become of use in a digital transducer mechanism if the external influence is developed sufficiently.

Geometry-Limited Phenomena

There are numerous examples of discontinuous behavior determined by a moving boundary reaching discontinuity in a device (for example, a depletion zone in a semiconductor crystal widening until it encounters a surface that has higher or lower conductivity). This effect may prove to be a means of building a multiple-step transducer in which the first step terminates by a depletion zone reaching its limit and other steps continuing until they terminate successively. This concept is a possible means of commutation of several transducers and is the basis for digital response. Geometry-limited phenomena are being considered in conjunction with the surface-state exhaustion studies.

Ordering and Phase Transformations in Metals

Ordering and phase transformations in metals are a broad and complex class of phenomena in solids that may include some others in this list. This category contains a restricted group of behaviors in metals that are reflected in the specific heat, magnetic behavior, and resistive behavior of the metals with respect to temperature and pressure. The subject is discussed by Seitz (ref. 7) and in numerous other recent texts. It is a class of behavior that is hysteretic and slow in reaching completion. A rearrangement of atom positions, such as the alpha-gamma phase transition in iron or the change from disorder to order in the arrangement of atoms of CuPd or Fe_3Al, is not a phenomenon that has reversible characteristics. Although the discontinuities are evident and understood, they do not seem particularly attractive for digital transducers.

The antiferromagnetic and ferrimagnetic effects differ from ferromagnetism in the alinement of electron spins. Antiferromagnetism is characteristic of crystalline compounds, like manganese oxide, in which the manganese ions are arranged with antiparallel spins. At some sufficiently high temperature, called the Ne'el temperature, the paired-spin configuration breaks down completely. Above this temperature, the compounds behave as normal paramagnetic materials.

Ferrites are a special group, being ionic crystals of metal atoms plus iron and oxygen, such as $MeFe_2O_4$. The unit cell has 24 iron atoms, of which 16 are trivalent and eight are divalent. The eight divalent atoms have alined moments that give the crystal a net moment and an incomplete antiferromagnetic-spin arrangement. Although these materials are interesting, no application to a novel digital transducer is known.

Resonance and Relaxation Phenomena

Many natural resonance and relaxation phenomena have a true digital pulse-type response. Magnetic resonance, paramagnetic relaxation effects, and nuclear resonance, that reflect a complex susceptibility, are examples of the numerous frequency-dependent magnetic effects. In a high-frequency magnetic field, Gorter (ref. 8) observed that the buildup of magnetization could be represented by the equation

$$\frac{dM}{dt} = \frac{\left(M_e - M\right)}{\tau}$$

where M is magnetization, M_e is the equilibrium value of magnetization, and τ is an equivalent relaxation time. This phenomenon has an analog in dielectrics, leading to a complex permittivity. In each behavior, the relaxation time is best represented by a distribution of relaxation times.

The paramagnetic phenomena are best understood by considering a material that contains a randomly oriented group of free magnetic dipoles. If a uniform external magnetic field is applied, the dipoles will precess about the magnetizing vector $\vec{H}$ but will not orient themselves permanently. The only way the dipoles will add to the magnetization is by exchanging energy with their surroundings. The relaxation occurs as a spin-lattice or spin-spin mechanism. The essential difference between these mechanisms may be noted by comparing the magnitude of the applied field H_a with the magnitude of the local field set up by neighboring dipoles H_i. For H_a, much less than for H_i, precession about $\vec{H}_i$ is shifted to a slightly different direction. There is an energy exchange between each dipole and the field, but there is no exchange with the lattice. Spin-lattice relaxation occurs when H_a is much greater than H_i, and the field direction is determined by H_a. If the magnitude of H_a is changed, the number of dipoles in parallel orientation and the number in antiparallel orientation are shifted toward new equilibrium values by exchange of energy with the lattice.

Because atomic nuclei have a magnetic moment associated with their angular momentum, there is a nuclear analog to the paramagnetic relaxation. Nuclear magnetic resonance is well known and is the basis for numerous measuring instruments. As frequency and magnetic field are tuned to their proper values, the sharp response for the measured material is suggestive that the resonance and relaxation phenomenon is an attractive digital-transducer phenomenon.

Dipole Orientation

Dielectric materials have a variety of properties that make them interesting for digital-transducer applications. Orientation of dipoles, electrostriction, piezoelectricity, ferroelectricity, optical and electro-optical phenomena, and tunneling are some of the properties that are not found in metals.

In an external electric field, dipole orientation in some materials occurs at the freezing point; in other materials, dipole orientation occurs below the freezing point. Molecules that have permanent dipoles become oriented along the electric field vector $\vec{E}$ just above critical temperature; below this temperature, rotation is hindered.

Electrostriction and piezoelectricity are properties of numerous crystalline solids such as quartz, Rochelle salts, ammonium dihydrogen phosphate, and potassium dihydrogen phosphate. Contrasted with sodium chloride, these materials have low crystalline symmetry and have a polarization-strain behavior that is the basis for numerous analog-digital transducer possibilities.

Ferroelectric materials, such as barium titanate and potassium niobate, polarize spontaneously when subjected to strain. The polarization propagates by means of domain flipping, similar to ferromagnetism in iron. This analogy is nearly complete because the ferroelectrics have hysteresis and Curie temperatures above which the effect disappears.

A digital transducer is conceivable by using the dielectric-constant discontinuities of several materials. A capacitor that has discontinuous changes in capacity as a function of temperature can be constructed by applying this effect. This phenomenon has been studied, and the results leave much to be desired. Although discontinuities are evident for materials examined so far, hysteresis and an intolerable analog drift between discontinuities also are evident.

The successful use of dielectric materials is dependent upon the use of combinations of properties. Such a concept might be implemented by allowing one effect to provide transducer action and by allowing another effect to inject the discontinuity.

Bandgap Effects and Optical Transparency

Semiconductors are transparent to wavelengths longer than hc/E_g, where E_g is the bandgap energy, and are opaque to much shorter wavelengths. Considering that the optical transparency changes 2 decades for a change of less than 8 percent in the wavelength of light incident on germanium at 300° K, the transition region shown in figure 7 is more abrupt than is at first apparent.

The bandgap is not only a function of temperature (as shown in fig. 8) but it is also a function of pressure. Rindner and Braun (ref. 9), studying shallow p-n junctions, demonstrated that anisotropic elastic stress caused completely reversible resistance decreases of several orders of magnitude. Substantial reduction of the breakdown voltage can be observed. Also, piezoresistance of homogeneous semiconductors has been studied extensively by Keys (ref. 10). The suggested digital-transducer concepts involve both strain and temperature modulation of the bandgaps of selected semiconductors.

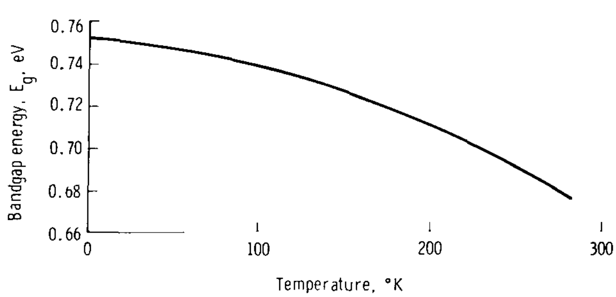


Figure 7. - Variation of the energy gap of germanium with temperature.

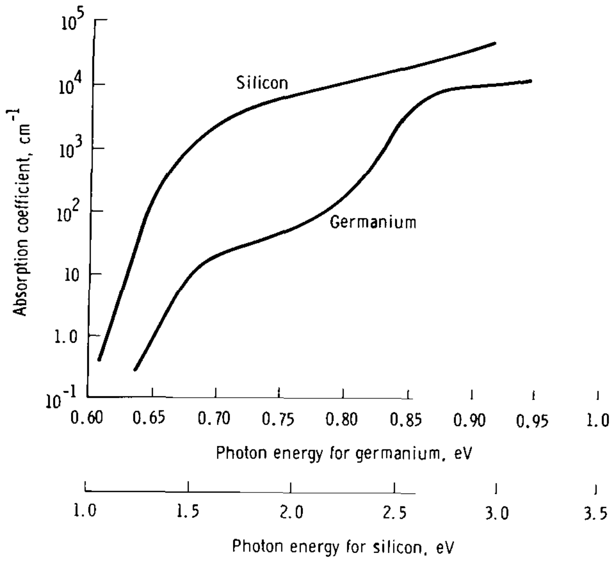


Figure 8. - Absorption spectra of silicon and germanium at 300° K.

CONCLUSION

An inherently digital temperature transducer in the strictest sense can now be produced. Furthermore, a choice of conventionally coded or arbitrary, quasi-digitally coded output is available. With the metal-insulation-semiconductor device, reduction of any analog-voltage phenomenon to a stairstep or discontinuous relationship makes it possible to obtain a quasi-digital output for stimuli other than temperature. The metal-insulation semiconductor and the inherently digital cryogenic-temperature transducer provide new approaches to digitization, facilitating new developments for transducers and measurement systems. With a minimum of signal conditioning, outputs of these devices can be made to provide a conventional digital output. Techniques appropriate for producing first-generation space hardware and for exploring new materials and phenomena for application to direct digital measurement will be refined in future work.

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908-10-13-14-72

REFERENCES

1. Schuler, A. E.: Digital Transducers — Types and Trends. Instrumentation Technology, vol. 16, no. 12, Dec. 1969.

2. Anon.: Force Transducers. Electro-Technology, May 1967, pp. 69-70.

3. Hartwig, W. H.: Research on Digital Transducer Principles. First Semiannual Report, The University of Texas at Austin, Texas, vol. I, July 1 to Dec. 1, 1966.

4. Anon.: Bibliography of Magnetic Materials and Tabulation of Magnetic Transition Temperatures. Report ORNL-RMIC-7, National Laboratory, Oak Ridge, Tenn., Mar. 1968.

5. Tchernev, D. I.; and Collier, T. E.: Magnetic Materials for Digital Transducers. Biannual of Electronics Research, no. 10, AFOSR-70-TR, Electronics Research Center, The University of Texas at Austin, Texas, Nov. 15, 1969.

6. Matisoo, J.: The Tunneling Cryotron — Superconductive Logic Element Based on Electron Tunneling. Proc. IEEE, vol. 55, no. 2, Feb. 1967, pp. 172-180.

7. Seitz, F.: The Modern Theory of Solids, McGraw-Hill, New York, 1940.

8. Gorter, E. W.: Saturation Magnetization and Crystal Chemistry of Ferrimagnetic Oxides. Philips Research Reports, vol. 9, no. 4, Aug. 1964, pp. 295-320.

9. Rindner, W.; and Braun, I.: On the Effects of Elastic and Plastic Deformation on p-n Junctions in Semiconductors. Paper presented at 5th International Conference on the Physics of Semiconductors (Exeter, England), July 1962.

10. Keys, R. W.: Solid State Physics. Vol. 11. Academic Press, 1960.

APPENDIX

The NASA Research Topics Bulletin informs the broad scientific community about NASA research interests. This bulletin provides a basis for planning related research. A NASA Research Topics Bulletin on Digital Transducer Research is paraphrased as follows.

The safety of a spacecraft is dependent on the performance of measuring systems. Most of the measuring is performed by sensors and transducers that have an electrical output that is analog in nature. Most requirements are met by the use of analog signals, but digitized data offer many advantages. Therefore, research in the area of digital transducers is being emphasized. Proposals for support in a related research study should be submitted.

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