AN ANALOG MEMORY DEVICE[1]

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Summary. The analog memory device is a combination of a bipolar and a MOSFET device which stores information in analog form for several hours or more with no degradation of data. The emitter base junction of a bipolar transistor is covered with an SiO_2 layer and a voltage is applied to this point. With zero volts applied, the unit acts as a bipolar transistor. Increasing the voltage at this point increases the emitter injection efficiency of the bipolar transistor, which in turn increases the current gain of the device. An SiO_2 layer with no leakage paths can retain the charge applied to it for long periods of time; thus the gain will remain at this level as long as the charge remains on the oxide layer. A large number of such devices can be fabricated on a single chip. Such devices combined with other integrated circuits can be used, for example, for automatic equalization of transmission lines, echo suppression, and correlation detection.

Introduction. Solid-state devices have important functional[2] properties, such as the negative resistance characteristics of tunnel diodes and 4-layer diodes, which have not been fully utilized in the past. The tunnel diode can be used as a bistable or astable element as well as a linear amplifier due to its stable negative resistance region, whereas the 4-layer diode can be used as a bistable and astable element, but not as a linear amplifier due to its avalanching property in achieving the negative resistance region.

Lack of understanding of the physical aspects of solid-state device operation has prevented most application engineers from fully utilizing the functional properties of such devices. This paper will introduce an important device which has an analog information storage capability. These two important properties are achieved by combining two well-known functions of solid-state devices, namely, the properties of bipolar transistors and the modulation effects of oxide used in MOSFET devices. Such a device can perform any function which requires analog data storage.

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[1] This paper is based upon work performed by the author prior to joining COMSAT Laboratories.

[2] Vasil Uzunoglu, "Some Future Aspects of Microelectronics," WESCON Convention Record, Los Angeles, California, August 1966.

Device. Figure 1 is a physical layout of a bipolar transistor. Its emitter efficiency is[3]

$$\gamma = \frac{1}{1 + (\sigma_b/\sigma_e)(L_p/L_n)(\tau_n/\tau_p)} \quad (1)$$

where
- σ_b = conductivity of the base region
- σ_e = conductivity of the emitter region
- L_p = average diffusion length of holes
- L_n = average diffusion length of electrons
- τ_n = average lifetime of electrons in a n-type region
- τ_p= average lifetime of holes in an p-type region

From equation (1) it can be deduced that, in order to increase σ_e, the conductivity of the emitter region must be high compared to that of the base region. Also the diffusion length of the base must be short, and the lifetime of electrons in the base region must be high. Since equation (1) deals with a given emitter area, it is also evident that increasing the injection emitter area will increase the gain

Next a device which possesses these properties will be introduced. The properties of an oxide layer on a MOSFET device are well known. Figure 2 is a physical layout of such a device. It has two N^+ regions imbedded in a P region, with an SiO_2 oxide layer on top of the gate region. The device of interest is an enhancement-type device so that, with no voltage applied to the gate, there is no channel between the source and the drain. Channeling or modulation is achieved by applying a positive voltage to the gate so that the P-region underneath the oxide is depleted of holes and becomes an N region. This N region forms a channel between two N^+ regions and is modulated with the variation of the voltage applied to the gate. Since modulation[4] is a requirement for gain or amplification, an amplifying device has been achieved, namely, a MOSFET device.

Now the same concept will be applied to a bipolar device with an oxide on top of the emitter-base junction, as shown in Figure 3. It is assumed that the oxide layer is perfect and void of positive ions and that the region beneath it is in its normal mode. As soon as a positive voltage is applied to the oxide layer, the region beneath it becomes depleted of holes and portions of the base region next to the emitter region become an N region, as shown by the dotted line in Figure 3. With this condition, the desired goals have been achieved; that is, the emitter injection area has been enlarged and the distance for the

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[3] H. Kroemer, "Zur Theorie des Diffusion and Des Drift Transistors," Arch. Elekt. Übertragung, Vol. 8, May 1954, p. 223.

[4] Vasil Uzunoglu, "Evolution of Solid State Amplification and Its Limitations," IEEE Transactions on Education, Vol. E-10, No. 3, September 1967.

electrons to travel from the emitter to the collector has been shortened, which implies less recombination of carriers and increased gain. It should be remembered that most of the carrier injection to the base occurs beneath the surface area. In addition to these effects, the goal of increasing the conductivity of the emitter region has been achieved, hence decreasing the conductivity of the base region. Positive voltage on the oxide attracts more electrons to the effective emitter injection area, which increases the number of electrons and consequently σ in equation (1).

The opposite effect occurs in the base region. That is, the region adjacent to the emitter region is converted to an N region, but the area further to the right, which has remained a P-type region, has decreased its conductivity due to removal of holes away from the surface. Thus, σ_b is decreased and equation (1) is satisfied.

If it is assumed that the oxide inserted on the top of the emitter base junction is perfect, the charge applied to it will be retained for an indefinite period of time. Of course, there is always a finite leakage present so that the charge will be retained for a finite period of time which determines the time constant of the storage.

The equivalent circuit of Figure 3 can be represented as shown in Figure 4.The I_c-V_{CE} characteristics are given in Figure 5.

In the normal mode of operation, as shown in Figure 4, with no voltage applied at X, the operating point lies at point A. With a positive voltage applied to X, the operating point is switched to point B. With a higher voltage applied to X, the operating point is brought to point C.

The device shown in Figure 3 has the following properties:

a. current gain,
b. storage or memory, and
c. weighing capability.

Weighing means that the storage or normal gain can be increased externally by varying R_B or V_{BS} on R_B. Also the R_B point can be used as a second input, which simplifies circuit design for many requirements.

At this point it should be noted that this device should not be confused with a charge coupled device (CCD). In a CCD the information is stored in potential wells and moved sequentially or transferred by external clocks from one well to the next. In an analog storage device there is no transfer of information and the device acts on its own as a memory element using the oxide.

Several of these analog information storage devices have been fabricated and tested individually as memory elements. With SiO_2 as an oxide layer, the unit has a storage time of over one hour with no appreciable degradation of information. It is assumed that silicon nitrate can greatly increase this time. An area which requires further testing is the linearity of gain versus voltage applied to the oxide. Results of these tests will determine whether the design of the device will require extra precautions.

Application. The device in its simplest form is an analog information storage device. Thus, it can be used whenever analog information must be stored.

As a simple example, consider the circuit shown in Figure 6. It consists of a shift register (SR) #1 which sequentially feeds the information to the memory devices. This shift register is driven by clock #1 at frequency ω_1, for example. A second shift register (#2) recovers the stored information at a later time and combines it on an operational amplifier (OA), where the data, which are in sampled form, are reassembled. Shift register #2 is driven by clock #2 at a speed ω_2 which may be different from ω_1 as long as both satisfy the Nyquist criterion.

The information to be stored is a 2-period sine wave. According to the Nyquist criterion, four points are needed for identification of the information. Thus, the shift registers and the storage elements have four stages. In addition to storing analog information, the device is also capable of feeding and recovering the data from the system at different speeds. For the preceding application, only the storage property of the device was used. If the device is used as a correlator, its second input is also used, namely, R_B or the voltage applied to R_B may be used as a variable. In both cases the current gain of the device can be changed.

In autocorrelation, for example, the function is multiplied by itself at a later time and the similarities of the two functions are identified within a given period of time. In this case information is stored on the oxide layers and the delayed information is applied to the R_B's as V_{BS} voltages. Next the product of information applied to the oxide and the R_B's should be maximized so that the information applied to R_B must be inverted, and the operational amplifier should be replaced with a level detector.

In a correlation detector,[5] in which incoming information must be compared with all possible available data stored in the receiver, this device is ideal. Incoming information is stored on the oxide layers and all possible information levels are recycled through the R_B's at a rate determined by available levels of information.

Conclusion. The examples introduced herein represent only a part of the functions which can be accomplished with the analog storage device. Lack of such a device has

[5] Vasil Uzunoglu, Analysis and Design of Digital Systems, Gordon and Breach, 1974, p. 38.

complicated circuit design in the past and information has been changed to digital form to be stored. The present device accomplishes this important storage function, and its inclusion in the family of integrated circuits is in accordance with the present philosophy. In fact, a complete memory device with several hundred information levels can be built on a single chip.

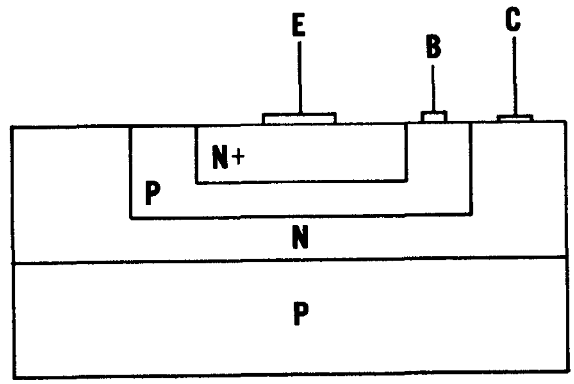

Figure 1. A Bipolar Transistor

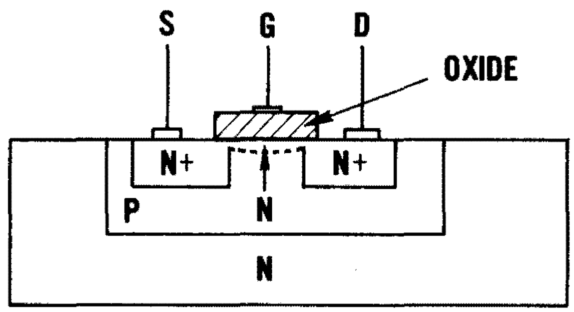

Figure 2. A MOSFET Device

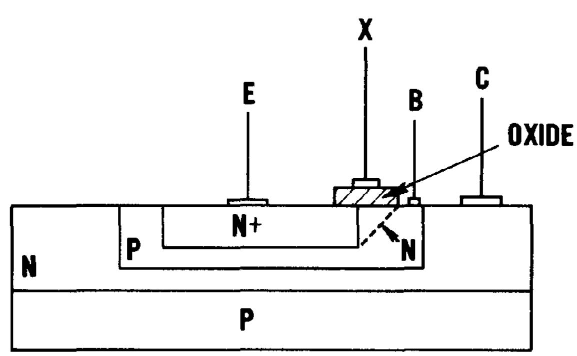

Figure 3. Memory Device

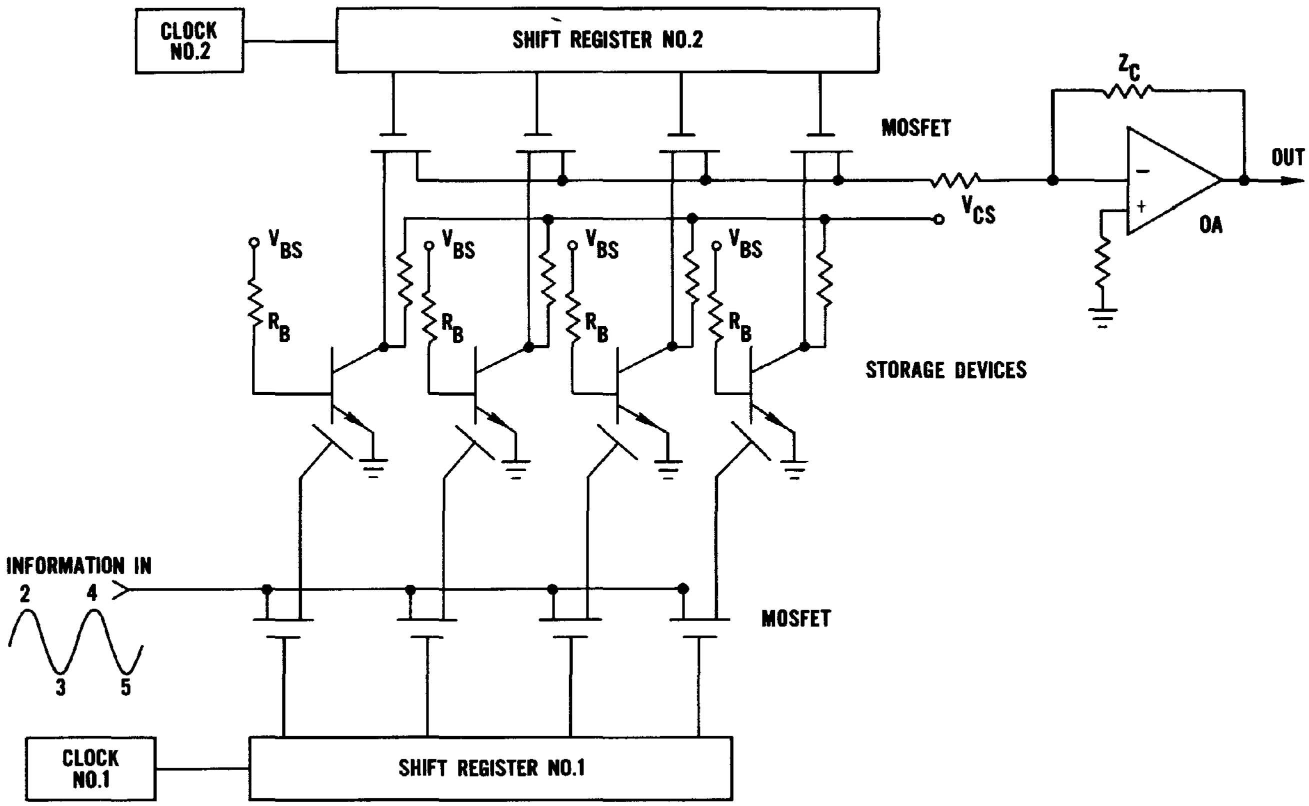

Figure 4. Analog Memory System

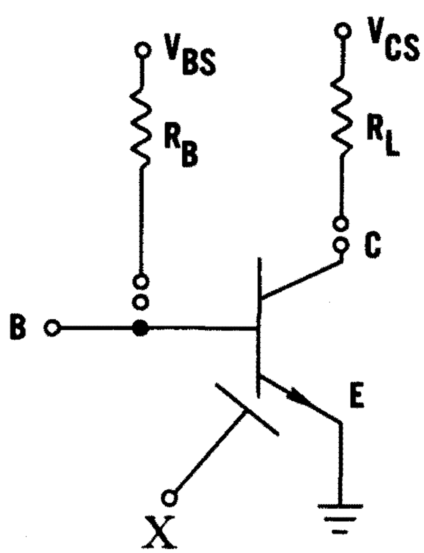

Figure 5. Equivalent Presentation of a Memory Device

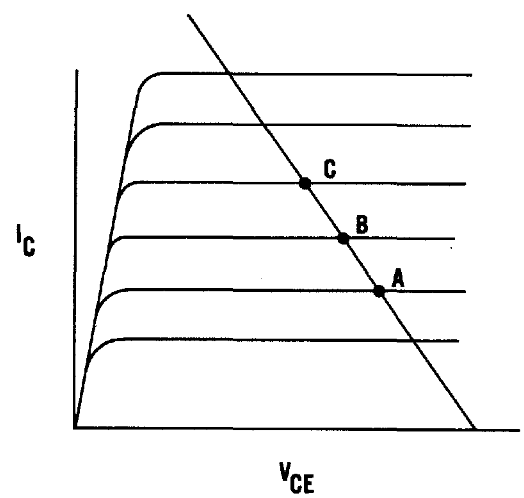

Figure 6. V_{CE}-I_c Characteristic