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SPIN RESONANCE STORAGE SYSTEM

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FIG. 1

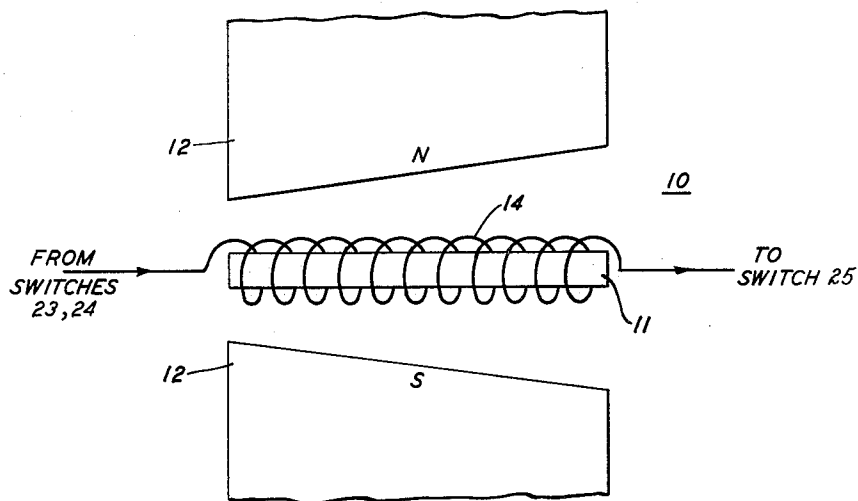
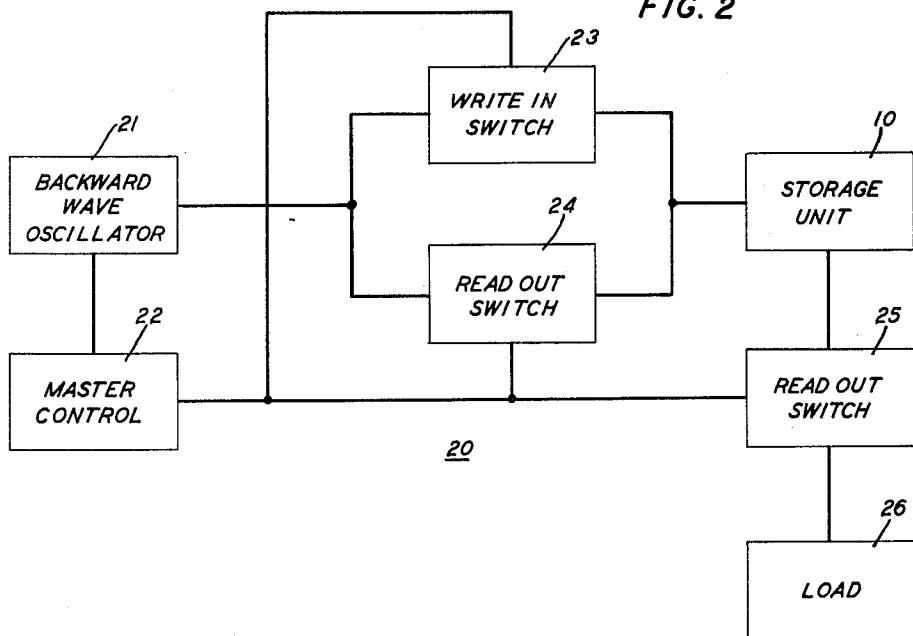


FIG. 2



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SPIN RESONANCE STORAGE SYSTEM

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7 Claims. (Cl. 340-173)

This invention relates to apparatus which employs the electron spin resonance phenomenon. More particularly, it relates to apparatus in which electron spin resonance in paramagnetic materials is utilized as a means of storing information.

It is known from the study of paramagnetic resonance that the normal population distribution among the energy levels of unpaired spinning electrons may be altered by applying to the system wave energy having a frequency which corresponds to the separation between two given levels. The relation between the frequency and the separation is expressed by Bohr's equation

$$\nu = \frac{E_2 - E_1}{h}$$

where h is Planck's constant. It is characteristic of a system in thermal equilibrium that the population of the lower energy levels is greater than that of the upper levels. By applying a signal of the proper frequency and amplitude it is possible to disturb the equilibrium distribution. Such distribution will tend to remain disturbed for a time which is described as the spin lattice relaxation time. During such time, the medium will offer less absorption to applied wave energy of the corresponding frequency than otherwise. In fact, if the equilibrium distribution has been inverted by the initial application of wave energy, as is possible under known conditions of operation, the medium will be stimulated to emit radiation on the subsequent application of wave energy of the appropriate frequency.

The invention is based upon my realization that based on the occurrence or nonoccurrence of absorption of an applied signal at the resonant frequency the existence or nonexistence of a population disturbance between two particular energy levels, and hence the previous history of the two particular energy levels, may be advantageously employed to store information.

An object of the present invention is new and improved apparatus for storing data.

A feature of applicant's invention is a storage medium which includes a collection of paramagnetic ions and which is disposed in a magnetic field to provide a collection of electron spins each characterized by a pair of discrete energy levels, the collection providing a system exhibiting a plurality of electron spin resonant frequencies.

Another feature of the invention is an arrangement for providing to the storage medium described a first sequence of resonant frequencies for the storage of information and a second sequence of resonant frequencies for the read-out of information. Either or both of the sequences may be random.

The invention is suitable for use in high speed digital computers, either as a buffer store or as the main digital store. Flexibility with respect to function is due to the wide range of storage times which may be attained by appropriate choice of the resonant medium.

In an embodiment in accordance with the invention, a paramagnetic storage medium is positioned in an inhomogeneous magnetic field to create a plurality of centers having different resonant frequencies. A backward wave oscillator is used to supply the input information to be stored to a microwave circuit which surrounds the storage medium. The frequency of the backward wave oscillator is varied in accordance with the information to

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be stored. There is interposed between the oscillator and the microwave circuit a switch which is under the control of signal information to insure that the oscillator is effectively connected to the microwave circuit when a signal corresponding to a piece of information is to be stored. Reading out of the stored information is achieved by the use of the oscillator to generate a frequency corresponding to the particular piece of stored information to be recovered and the application of the resulting wave energy to the microwave circuit. Such microwave energy will be absorbed by the medium in the absence of any previously stored piece of information at that frequency but will be little attenuated in the presence of a stored piece of information at that frequency.

The invention will be more fully understood from the following more detailed description, taken in conjunction with the accompanying drawing, in which:

FIG. 1 shows apparatus suitable for use as a memory unit according to the principles of the invention; and

FIG. 2 depicts schematically an illustrative arrangement of a data storage system in accordance with the invention.

Referring now more specifically to the drawing, there is shown an electron resonance memory unit 10 comprising a solid storage medium 11 including therein a collection of paramagnetic centers which is situated between the poles of a magnet 12. In accordance with the principles of the invention, the storage medium 11 includes therein many paramagnetic centers having different resonant frequencies so that a plurality of pieces of data may be stored in each unit. A broad band microwave circuit 14, shown in the drawing as a helix, is coupled to the storage medium 11 so that signals corresponding to the various resonances and representing separate pieces of information may be applied thereto and abstracted therefrom.

A large number of different spin resonances can be attained in a sample of a particular paramagnetic compound by placing it in an inhomogeneous magnetic field as shown, since the strength of the field determines the Zeeman splitting between pairs of energy levels. In substances where the resonant frequencies vary with the orientation of crystalline axis in a magnetic field, a powder of randomly oriented paramagnetic crystallinities may be used as the storage medium to widen further the storage band. Additional bandwidth may be attained by utilizing as the storage medium an intimate mixture of several types of paramagnetic centers having different resonant frequencies. The widest band is achieved by combining all three techniques.

The storage capacity of a memory unit of the type shown in FIG. 1 depends principally upon the maximum permissible number of spins per cubic centimeter of the storage medium and the width of the frequency band required for rapid write-in and read-out of each piece of information. The density of spins should be high enough to give a read-out sufficiently above the noise level for faithful recovery but low enough to avoid spin-spin coupling which results in an undesirable broadening of the various resonances and limits the capacity of the medium. A density of about 10^{15} for each resonant frequency is suitable. Actually each resonant frequency will be a narrow band of frequencies.

In most applications it will be desirable to insert and remove a particular piece of information without disturbing the others stored in different "cells" in the medium. It will be convenient to refer to each group of spins of a particular resonance band as a storage cell. To this end, the extended frequency range available for storage of data in the memory medium will generally be divided into discrete narrow bands, each of which will be of a bandwidth sufficient to write in and read out a piece of in-

formation without substantially lapping over into the adjacent bands of the spectrum which correspond to other storage cells. It can be seen that the speed of operation will affect the number of available bands and hence tend to limit the capacity of each storage unit. A very high speed application of the device may, for example, utilize a read out signal which builds up in about 10^{-8} seconds. Such a burst contains components spread out over a 30 megacycle frequency band. To avoid overlapping it might be desirable to allocate about twice this bandwidth, or 60 megacycles, to each storage cell.

Speed of operation also affects sensitivity of read-out, since the magnitude of the amplification experienced by the sensing burst depends to some extent upon the duration of its interaction with the inverted spin system.

A wide range of memory times can be achieved by the use of various suitable materials as storage media. Thus phosphorous-doped silicon at liquid helium temperatures is capable of storing a bit for about one minute. This material provides a spin concentration of about 10^{17} per cubic centimeter so that about 100 storage cells, each containing 10^{15} spins can be attained in an element of reasonable size. Other paramagnetic materials are known which provide spin concentrations as high as 10^{19} per cubic centimeter with relaxation times between one millisecond and one second. Such materials include alkali-halides bombarded for the introduction of paramagnetic color centers therein, as is disclosed in application Serial No. 618,864, filed October 29, 1956, by G. Feher, now abandoned.

In the data storage system 20, shown in block schematic form in FIG. 2, a backward wave oscillator 21 is employed as the source of write-in and read-out signals. An advantage of such a device is that its output frequency can be conveniently and rapidly varied by controlling the voltage applied to its slow wave structure for fixing the velocity of its electron beam. Thus the data input and program information is translated into a voltage wave form and is conducted from the master control unit 22 of a computer or data processing system, to the control oscillator 21 to control the frequency of its output.

The output of the oscillator 21 is supplied to the microwave circuit of the storage unit 10 through a selected one of the traveling wave tubes 23 and 24, utilized in the illustrated system as microwave switches. The storage unit 10 is as described in FIG. 1. In this capacity the traveling wave tubes serve to isolate the storage unit from the oscillator 22 while the latter is being swept to the frequency at which a piece of information is to be inserted or withdrawn. Thus the power output of the oscillator 22 is allowed to remain steady while the switches prevent the intermediate frequencies covered during its sweep from affecting the storage cells having resonances at such intermediate frequencies.

The traveling wave tube switches 23 and 24 are conveniently opened and closed by a voltage wave form sent out by the master control 21. In the diagram, the switch 23 has been designated as the write-in switch. Advantageously, it is adapted to transmit a relatively high power while the read-out switch 24 is adapted to transmit a relatively low power. This is so that the write-in signal will saturate the appropriate energy transition in the storage unit 10 while the read-out signal will be sufficient merely to sense whether the transition has been saturated. A read-out switch 25 which is open during the writing-in interposed between storage unit 10 and the load 26 is inserted to insure that none of the write-in power reaches the load.

The operation of the system 20 typically is as follows. At a time t_1 the master control has available a piece of information which is to be stored in a particular storage cell corresponding to a particular frequency band f_1 . The master control accordingly develops a voltage of magnitude such that when applied to the backward wave oscillator, the latter generates an output frequency f_1 . The

master control also provides a control pulse to the traveling wave tube serving as the switch 23 for closing the switch when frequency f_1 is available at the output of the backward wave oscillator. Accordingly, energy of frequency f_1 is supplied to the microwave circuit of the storage unit 10 for saturating the corresponding storage cell.

At a later time t_2 , the master control has available a different piece of information which is to be stored in a different storage cell corresponding to a frequency band f_2 . The master control accordingly develops a voltage of magnitude such that when applied to the backward wave oscillator frequency f_2 is developed at its output. The master control also arranges to have energy of frequency f_2 supplied to the circuit of the storage unit for saturating the appropriate storage cell.

The process is continued at times t_3 , t_4 , etc., for storing succeeding pieces of information in different cells of the storage unit.

An important advantage of the described arrangement is that the various cells may be stored in a random manner.

Reading out is accomplished in an analogous fashion. The master control can read out the piece of information in a particular cell simply by developing the appropriate voltage for generating in the backward wave oscillator the frequency which corresponds to the resonant frequency of the particular cell. Energy of this frequency when applied to the microwave circuit of the storage unit will be absorbed if the storage cell is not in a charged or saturated state but will pass it little attenuated to the load if the storage cell is in a charged state. The two read-out switches 24 and 25 are closed at appropriate times in the reading-out stage under the control of the master control unit.

It can be appreciated that the system is characterized by random access of the stored information. Simply by supplying the appropriate voltage to the backward wave oscillator a particular cell can be sampled. Alternatively, by supplying a particular wave form to the backward wave oscillator the cells may be sampled in a desired sequence. In the reading process too, the master control is used to develop appropriate gating pulses for closing the read-out switch at appropriate times.

Various other modes of operation can be devised particularly if it is satisfactory to employ a regular sequence for storing and reading out. In such instance, the backward wave oscillator can be supplied simply with a voltage of sawtooth wave form for developing sequentially the resonant frequencies of the different cells in the storage unit. The signal input information can be applied simply to the write-in switch for closing it whenever there is a piece of information to be stored. In this way the input information can be stored in a first sweep of the sawtooth wave. The stored information is read out in a succeeding sweep of the sawtooth wave simply by closing the read-out switch regularly as the output frequency of the backward wave oscillator passes through successive resonant frequencies of the storage system.

It is evident that various modifications can be introduced without departing from the spirit of the invention.

In particular, it will be obvious that a plurality of pieces of information can be stored simultaneously and/or read out simultaneously by applying to the storage unit energy including simultaneously appropriate frequency components. In particular, by applying a pulse having all the resonant frequencies of the storage unit all the cells can be sampled simultaneously and the output will contain only energy of those resonant frequencies which had previously been stored. It is obvious that this adapts the system to various logic functions important to computers. In such applications, the multifrequency source may be provided by a plurality of backward wave tubes each supplying a common or separate microwave circuit surrounding the storage medium.

What is claimed is:

1. A data storage system comprising a storage medium having a plurality of paramagnetic ions characterized by at least two discrete electron energy levels, means for supplying to said storage medium, under the control of information to be stored, read-in energy of frequencies corresponding to the separations between a pair of said energy levels, said read-in energy being effective to transfer a substantial proportion of the electron population in the lower of said pair levels to the upper level of said pair, means for supplying to said storage medium, under the control of read-out intelligence, read-out energy of frequencies corresponding to the separations between said pair of energy levels, and means for simultaneously detecting absorption of said read-out energy.

2. A data storage system as in claim 1 and further comprising means forming an inhomogeneous magnetic field, said storage medium being positioned in said field, said field being effective to establish in said medium a plurality of storage cells each having a different characteristic separation between pairs of energy levels.

3. A storage system in accordance with claim 1 in which the storage medium comprises a powder of randomly oriented crystallites.

4. A data storage system comprising a paramagnetic electron-resonant storage medium characterized by an electron-resonance frequency band, means for supplying to said medium, under the control of information to be stored, read-in energy of frequencies within said resonance band for saturating corresponding storage cells, means for supplying to said medium, within the electron spin-lattice relaxation time of the storage cells and under the control of read-out intelligence, energy of frequencies within said resonance band for sampling corresponding storage cells, and means for simultaneously detecting absorption of said read-out energy.

5. A data storage system as in claim 4 and further comprising means forming an inhomogeneous magnetic field, said storage medium being positioned in said field, said field being effective to establish in said medium a plurality of storage cells each having a different resonant frequency band.

6. A data storage system as in claim 4 wherein said storage medium comprises a powder of randomly oriented crystallites.

7. A storage system comprising means forming a magnetic field, a storage medium characterized by a plurality of paramagnetic ions each of which has at least a pair of

discrete electron energy levels said medium being positioned in an inhomogeneous portion of said magnetic field, said field being effective to establish in the storage medium a plurality of storage cells each having a different characteristic resonant frequency, a microwave circuit coupled to the storage medium, a backward wave oscillator capable of generating the resonant frequencies of the medium, means under the control of input information for supplying to the backward wave oscillator voltages adapted for providing at the output of the backward wave oscillator energy of selected resonant frequencies of the medium for application to the microwave circuit for saturating corresponding storage cells of the medium, means under the control of read-out intelligence for supplying voltages to the backward wave oscillator adapted for providing at the output of the backward wave oscillator energy of selected resonant frequencies of the medium for application to the microwave circuit for sampling corresponding storage cells of the medium, and means for simultaneously detecting absorption of said selected frequencies.

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