A system for determining the logic state of a resistive memory cell element, for example an MRAM resistive cell element. The system includes a controlled voltage supply, an electronic charge reservoir, a current source, and a pulse counter. The controlled voltage supply is connected to the resistive memory cell element to maintain a constant voltage across the resistive element. The charge reservoir is connected to the voltage supply to provide a current through the resistive element. The current source is connected to the charge reservoir to repeatedly supply a pulse of current to recharge the reservoir upon depletion of electronic charge from the reservoir, and the pulse counter provides a count of the number of pulses supplied by the current source over a predetermined time. The count represents a logic state of the memory cell element.
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<td>7/2005</td>
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**FIG. 5**

Sensing Circuit Output (1-bit)

Vout

**FIG. 6**

Voltage Across the Cap

Vout
FIG. 7

CPU 1220

DIGITAL MEMORY 1210

USER INTERFACE 1260

DISK STORAGE 1250

I/O 1230

1200

1240
RESISTIVE MEMORY ELEMENT SENSING

US 8,441,834 B2

1. Field of the Invention
The present invention relates to the field of resistor-based memory circuits. More particularly, it relates to a method for precisely sensing the resistance value of a resistor-based memory cell, for example, an MRAM magnetic memory cell.

2. Description of the Related Art
A magnetic random access memory (MRAM) is one approach to implementing a resistor based memory. In an MRAM, each resistive memory cell includes a magnetizable film. The resistance of the cell varies, depending on the magnetization state of the film. Logical data can be stored by magnetizing the film of particular cells so as to represent the logic states of the data. The stored data can be read by measuring the resistance of the cells, and interpreting the resistance values as logic states. Making the required resistance measurements, however, is problematic.

In a resistance memory, one resistance value, e.g., a higher value, may be used to signify a logic "HIGH" while another resistance value, e.g., a lower value, may be used to signify a logic "LOW." The stored logic state can be detected by measuring the memory cell resistance using Ohm's law. For example, resistance is determined by holding voltage constant across a resistor and measuring, directly or indirectly, the current that flows through the resistor. Note that, for MRAM sensing purposes, the absolute magnitude of resistance need not be known; only whether the resistance is above or below a value that is intermediate to the high and low values.

Sensing the logic state of an MRAM memory element is difficult because the technology of the MRAM device imposes multiple constraints. In a typical MRAM device an element in a high resistance state has a resistance of about 1 MΩ. An element in a low resistance state has a resistance of about 950 KΩ. The differential resistance between a logic one and a logic zero is thus about 50 KΩ, or 5% of scale.

Accordingly, there is a need for a simplified resistance measuring circuit able to repeatedly and rapidly distinguish resistance values varying by less than 5% on a one MΩ scale.

BRIEF SUMMARY OF THE INVENTION
The invention provides a method and apparatus for measuring the resistance of a resistive memory element. The resistance is measured by charging a capacitor, allowing the capacitor to discharge through a selected resistive memory element while maintaining a substantially constant voltage across the resistive memory element, sensing the charge remaining on the capacitor, repeatedly recharging the capacitor with a pulse of definite charge each time the capacitor voltage drops to a predetermined value, and determining a time average current into the capacitor based on a duty cycle of the recharging pulses. Knowledge of the time average current into the capacitor, yields the current flowing into the resistor since the current flowing into the capacitor must equal the current flowing out of the capacitor and into the resistor. One can measure or set the voltage across the resistive memory element and determine the resistance of the element from the current through the element and the voltage across it.

In various aspects of the invention, the actual resistance of the memory element is not calculated. Instead, the number of capacitor charging pulses is counted, and the numerical count thus acquired is compared to a reference count value. The reference value is chosen to lie between count values representing logical one and logical zero. Therefore a count value greater than the reference indicates one logical state, and a count value less than the reference value indicates another. In a further aspect of the invention, more than one reference value is established, and a memory element capable of exhibiting more than two resistance values is used. Consequently the memory element may store more than two logical values. The logical values are determined based on the relationship between the count value counted and the standard values used to establish thresholds between logical values.

In a further aspect, the apparatus and method of the invention may be used to measure the resistance or impedance of any resistive or impedance device.

These and other aspects and features of the invention will be more clearly understood from the following detailed description which is provided in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS
FIG. 1 shows a conventional magnetic random access memory array in schematic form; FIG. 2 shows a magnetic random access memory device according to one aspect of the present invention in schematic form, including resistance sensing circuits; FIG. 3 shows a portion of a magnetic random access memory device according to one aspect of the invention including a sensing circuit and sneak resistance; FIG. 4 shows a circuit for sensing resistance using averaging according to one aspect of the present invention; FIG. 5 shows a graphical representation of sensing circuit digital output over time according to one aspect of the present invention; FIG. 6 shows a graphical representation of voltage across a capacitor over time according to one aspect of the present invention; FIG. 7 shows a computer system incorporating a digital memory according to one aspect of the present invention.

DETAILED DESCRIPTION OF THE INVENTION
FIG. 2 shows a portion of a resistive memory device according to the invention. The device includes an array 200 of Magnetic Random Access Memory (MRAM) elements, a plurality of electrically conductive row lines 210, and a plurality of electrically conductive column lines 220. Each row line is connected to each of the plurality of column lines by a respective MRAM resistive element 230. A plurality of
switches 240, typically implemented as transistors, are each switchingly connected between one of the row lines and a first source of constant potential (ground) 250. A plurality of sensing circuits 260, are respectively connected to the plurality of column lines 220. Each sensing circuit 260 includes a source of constant electrical potential (V{sub A}) which is applied to the respective column line. A plurality of pull-up voltage sources 215, supplying voltage V{sub A}, are respectively connected to each of the plurality of row lines 210.

In operation, an exemplary switch 240, such as switch 270 associated with a particular row line 280, is closed so as to bring that row line to ground potential and a particular column line, e.g., 320 is sensed to read the resistance value of a particular resistor 310.

FIG. 3, shows the resulting electrical circuit for the relevant portion 300 of the memory array when row 280 is grounded. As shown, memory element 310 to be sensed is connected between a grounded row line 280 and a particular column line 320. Also connected to the column line 320 are a plurality of other resistive memory elements (e.g. elements 330, 340, 350, 360, 370) each of which is connected at its opposite end to a pull-up voltage source V{sub A} through a respective row line 210. In addition, a respective sensing circuit 400 is connected to the column line 320. The sensing circuit 400 includes a voltage supply that maintains the column line 320 at electrical potential V{sub A}.

The other resistive memory elements (those tied to ungrounded row lines) 330, 340, 350, 360, 370, form an equivalent resistance referred to as sneak resistance. The effective resistance of the sneak resistance is small. A typical value for sneak resistance might be 1 kΩ. Nevertheless, because both ends of each ungrounded resistor are ideally maintained at the same potential (here V{sub A}) as the column line 320, net current flow through the sneak resistance is desirably nearly zero.

In contrast, a measurable current flows through the grounded resistor memory element 310. This measurable current allows evaluation of the resistance of the memory element 310 by the sensing circuit 400.

One proposal for sensing the resistance value of a memory cell is to charge a capacitor to a predetermined first voltage and then discharge the capacitor through the memory cell resistance until it holds a second lower predetermined voltage. The time taken for the capacitor to discharge from the first to the second voltage is a measure of cell resistance. A problem with this approach is that since the resistance values representing the different logic states of a cell are very close in value (only 5% difference) it is difficult to obtain an accurate and reliable resistance measurement, even if digital counting techniques are employed to measure the discharge time of the capacitor.

Thus, even when using digital counting techniques, the discharge time of the capacitor must be counted quite precisely to sense the different resistance values and distinguish logic states. To achieve this precision, either the counting clock must be operated at a high frequency or the capacitor must be discharged relatively slowly. Neither of these options is desirable, since slow capacitor discharge means slow reading of stored memory values, and a high clock frequency requires high frequency components. In either case, a counter having a large number of stages is also required.

The present invention provides a resistive measuring circuit and operating method which rapidly ascertains a resistive value without storing large data counts, and without requiring highly precisioned components.

FIG. 4 illustrates an exemplary embodiment of a resistance sensing circuit 500 constructed in accordance with the invention. Sensing circuit 500 relies on the cyclical discharge of a capacitor 510 to determine the value of a memory cell resistance 520. The duty cycle of a recharging signal for the capacitor 510 represents a value of resistance 520.

The resistance measuring circuit 500 outputs a bit stream from an output 900 of a comparator 910. The ratio of logic one bits to a total number of bits (or, in other aspect of the invention, the ratio of logic one bits to logic zero bits) in the bit stream yields a numerical value. This numerical value corresponds to the current that flows through the resistance 520 in response to a known applied voltage. For example, assume that a current source can deliver current at two discrete current levels, corresponding to two different states of a logical input signal. When the signal is in a logic one state, the source delivers, for example, 2 μA. When the signal is in a logic zero state, the source delivers, for example, 0 μA. The logical input signal is monitored over a finite time span corresponding to a number of bit-length time periods. Over that time span, the number of logic one and logic zero bits are recorded. By straightforward algebra, the average current delivered by the current source over the corresponding time span may be calculated as follows:

\[
I_{AVG} = \frac{\text{number of logic 1 bits} \times 2 \text{ μA} + \text{number of logic 0 bits} \times 0 \text{ μA}}{\text{total number of bits in the signal}}
\]

As an example, if, over a time span corresponding to 4 cycles, there is one logic one bit and three logic zero bits then the average current over the four cycles is 0.5 μA.

The operation of the FIG. 4 sensing circuit is now described in greater detail. An MRAM resistive memory element 520 to be sensed has a first end 530 connected to a column line 540 and a second end 550 connected to ground 250 through a row line 560 and switch 565. Also connected to the column line 540 is a first end 570 of a sneak resistance 580. The sneak resistance has a second end 590 connected to a source of constant potential V{sub A} 215. The sneak resistance 580 represents a plurality of MRAM resistive elements associated with the particular column line 540 and with a respective plurality of unselected row lines, as described above with reference to FIG. 3.

A first operational amplifier (op-amp) integrator 600 is provided which has a non-inverting (positive) input 610, an inverting (negative) input 620, a calibrate offset input 630, and an output 640. The output 640 of the first op-amp 600 is connected to a control input (gate) 700 of a first transistor 710, which in this exemplary embodiment is an N-channel transistor.

The first transistor 710 includes a drain 720 connected to both the selected column line 540 and the inverting input 620 of the first op-amp 600. The first transistor also includes a source 730 operatively connected to a first terminal 740 of a capacitor 510. The capacitor 510 includes a second terminal 750 operatively connected to ground potential 250. The source 730 of the first transistor 710 is also connected to a drain 760 of a second transistor 770. In this exemplary embodiment, this second transistor 770 is a PMOS transistor. The second transistor 770 includes a source 780 and a gate
As charge is depleted from capacitor 510 the voltage on the capacitor drops until it falls below the voltage (1 volt) applied to the non-inverting input 920 of the second op-amp 910. This causes the second transistor 770 to be placed in a conductive state, permitting capacitor 510 to begin charging. When the voltage on capacitor 510 equals that applied to the non-inverting input 920 of the second op-amp 910 (here 1 volt), the output 900 of the second op-amp changes state to a positive value at the next transition of the clock 950. This turns off the second transistor 770. The charge stored on capacitor 510 is discharged through the first transistor 710 and cell resistance 520 under the control of the first op-amp 600. The first op-amp 600 tries to maintain a constant voltage VA on the selected column line 540.

As charge is depleted from capacitor 510 the voltage on the capacitor drops until it falls below the voltage (1 volt) applied to the reference input 920 of the clocked comparator 910. After this threshold is passed, the next positive clock transition applied to the clock input 940 causes the output of comparator 910 to go low again turning on the second transistor 770 and causing current to begin flowing through the second transistor 770 to recharge capacitor 510.

In one embodiment, the capacitor 510 is recharged during one clock cycle of clock source 950, so the comparator output 900 switches to high and the second transistor 770 is shut off again at the next positive clock transition. Transistor 770 is sized to allow a substantially constant current (e.g., 2.5 μA) to flow to capacitor 510 when transistor 770 is in a conductive state.

The described charging and discharging of capacitor 510 under the control of the first 710 and second 770 transistors occurs repeatedly during one sense cycle. Each time the output of the comparator 910 goes low, a current pulse is allowed to pass through the second transistor 770 and the first counter 1000 incremented. Each time the clock signal 950 transitions positive, the second counter 1010 is incremented. When the second counter 1010 reaches a preset value, it triggers the latch 1050, which latches that number of pulses counted by the first counter 1000 during the sensing period. The number of pulses counted is latched onto the data output 1070 (and data input 1090). The comparator 1100 then evaluates the values presented at the first and second data inputs 1090, 1110, and ascertains whether the value at the first data input 1090 is larger or smaller than the reference value at the second data input 1110. The reference value at input 1110 is set between two count values which correspond to “hi” and “lo” resistance states for resistor 520. Thus if the value of the first data input 1090 is larger than the reference value, then a first logical value (e.g. logic one) is output on an output 1140 of the digital comparator 1100. If the value of the first data input 1090 is smaller than the reference value, then a second logical value (e.g. logic zero) is output on the output 1140 of the digital comparator 1100. This comparator is capable of comparing the digital value applied at the data input 1090 to a plurality of reference values 1110 can distinguish a value stored in a single resistive memory element as between multiple resistance values. In a further variation, the capacitor 510 is pre-charged prior to a measuring cycle. By pre-charging the capacitor 510, the number of cycles of the clock signal 950 required to measure the state of the memory element is reduced. In another variation the capacitor is not pre-charged, in which case sensing the resistance of the memory element takes longer, but the circuitry and/or process is simplified.

FIGS. 5 and 6 show an exemplary relationship between the output signal produced at output 900 of the clocked comparator 910 and the voltage on capacitor 510 over time. FIG. 5 shows the output signal produced by the clocked comparator when a 100 MHz clock signal is applied to the clock input 940. At a clock frequency of 100 MHz, clock pulses are spaced at an interval of 10 ns. In the example shown, the output of the clocked comparator is high 1160 for one clock pulse (10 ns) and low 1170 for three clock pulses (30 ns). This corresponds to the voltage waveform shown in FIG. 6. In FIG. 6, the voltage of the capacitor 510 is shown to begin rising when the output 900 of the clocked comparator goes low (time A), thereby turning on the PMOS transistor 770. The voltage rises for 30 ns, or three clock pulses until time B. At time B, the output of the clocked comparator goes high again, turning off the PMOS transistor. The voltage on the capacitor 510 then begins to drop again while the PMOS device remains off for one clock pulse, or 10 ns (until time C). Accordingly, in the example shown, the duty cycle of the signal output by the clocked comparator 910 is 75% (three on-pulses for every off-pulse).

FIG. 9 shows a computer system 1200 including a digital memory 1210 having a resistance measuring memory cell sensor according to the invention. The computer 1200, as shown includes a central processing unit (CPU) 1220, for example, a microprocessor, that communicates with one or more input/output (I/O) devices 1230 over a bus 1240. The computer system also includes peripheral devices such as disk storage 1250 and a user interface 1260. It may be desirable to integrate the processor and memory on a single IC chip.

While preferred embodiments of the invention have been described and illustrated above, it should be understood that these are exemplary of the invention and are not to be considered as limiting. Additions, deletions, substitutions, and other modifications can be made without departing from the spirit or scope of the present invention. Accordingly, the
invention is not to be considered as limited by the foregoing
description but is only limited by the scope of the appended
claims.

The invention claimed is:

1. A memory storage device, comprising:
a memory cell array arranged along row and column lines;
a switch operably connected between a ground potential
and at least one row line, the at least one row line also
being connected to a voltage source; and
a sensing circuit connected to at least one column line to
determine a resistance of at least one memory cell
arranged along the at least one column line, wherein said
sensing circuit is configured to:
maintain a substantially constant voltage across the at
least one memory cell;
repeatedly charge and discharge a capacitance through
the at least one memory cell;
determine a value of a time-average current into the
capacitance in response to repeatedly charging and
discharging the capacitance; and
determine the resistance in the at least one memory cell
based on the value of the time-average current.

2. The memory storage device of claim 1, wherein the
switch is a transistor.

3. The memory storage device of claim 1, wherein the
voltage source provides a constant voltage to the at least one
row line.

4. The memory storage device of claim 1, wherein the
sensing circuit comprises a constant voltage source which is
applied to the at least one column line.

5. The memory storage device of claim 1, wherein the
sensing circuit comprises:
first and second operational amplifiers, the second opera­
tional amplifier being connected to a clock signal;
a first access transistor, a control input of the first access
transistor being connected to an output of the first opera­
tional amplifier, the first access transistor being con­
ected to the at least one column line and to an inverting
input of the first operational amplifier;
a first capacitance between the first access transistor and
the ground potential;
a second access transistor, a control input of the second
access transistor being connected to an output of the
second operational amplifier, the second access transis­
tor being operably connected to a supply voltage and to
the first access transistor;
first and second counters, the first counter for counting
rising transitions at the output of the second operational
amplifier during a measuring cycle, the second counter
for counting the number of clock transitions from the
clock signal during the measuring cycle;
a latching buffer having a data input connected to an output
of the first counter, a latch input connected to an output
of the second counter, and a data output;
a comparator connected to the data output of the latching
buffer, the comparator being adapted to compare the
number of rising transitions counted by the first counter
to a reference value to determine the resistance of the at
least one memory cell arranged along the at least one
column line.

6. The memory storage device of claim 5, wherein the
supply voltage of the sensing circuit is approximately 2.5
volts.

7. The memory storage device of claim 5, wherein the
second access transistors of the sensing circuit is a PMOS
transistor.

8. The memory storage device of claim 5, wherein the
first access transistor of the sensing circuit is an N-channel tran­
sistor.

9. The memory storage device of claim 5, wherein the
comparator of the sensing circuit is adapted to compare the
number of rising transitions counted by the first counter to a
plurality of reference values and determine a logical state of
the at least one memory cell.

10. The memory storage device of claim 9, wherein the
plurality of reference values include a first reference value
representing a high resistance state of the at least one memory
cell and a second reference value representing a low resis­
tance state of the at least one memory cell.

11. The memory storage device of claim 10, wherein the
comparator is adapted to determine the logical state of the at
least one memory cell by comparing the number of rising
transitions counted by the first counter to a value between the
first and second reference values.

12. The memory storage device of claim 1, wherein the
memory cell array comprises a plurality of memory cells,
each of said memory cells including a resistance connected
between one of said row lines and one of said column lines.

13. The memory storage device of claim 1, wherein said
sensing circuit is configured to determine the resistance of a
single memory cell arranged along the at least one column
line.

14. The memory storage device of claim 1, wherein said
sensing circuit is configured to determine the resistance of a
plurality of memory cells arranged along the at least one
column line.

15. The memory storage device of claim 1, wherein said
sensing circuit is further configured to sense the charge
remaining on the capacitance while discharging the capaci­
tance.

16. The memory storage device of claim 15, wherein said
sensing circuit is further configured to recharge the capaci­
tance with a recharging pulse of definite charge each time a
voltage of the capacitance is less than or equal to a predeter­
mined value.

17. The memory storage device of claim 16, wherein said
sensing circuit is configured to determine the value of the
time-average current by determining a duty cycle of the
recharging pulse.