Memristive Phase Change Memory

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Abstract: The paper presents study on and simulation of resistive nonvolatile phase change memory (PCM) cell in NG Spice programming environment. The chalcogenide alloy based PCM cell model demonstrates switching between amorphous and crystalline phases. The crystalline factor, responsible for the phase change process, is programmed by applied variable electrical pulse. Parameters phase change, range of operating temperature, the crystalline factor are mapped and presented.

Keywords: Memristor, Nonvolatile memory, Thermal properties, Phase transformation, Electrical properties, Simulation and modeling.

I. INTRODUCTION

The performance of the electronic devices is based on computing capacity. This capacity is essentially based on memory access time and power consumption in memory subsystem [1]. Conventional memory technology is under stress because of implementation of embedded DRAM in memory subsystem, scalability of SRAM, and Flash memory as replacement of Hard Disk Drives (HDD) [2]. This emphasizes on potential of high-density embedded technology. Recent research has indicated high density non-volatile memory technology as potential competitor to present memory technologies, prominent being Phase Change Memory (PCM) [3, 4]. These new memory devices have retention/endurance/read/write capacity, cyclability, and addressability up to individual element. The features like generous improvements in speed and power consumption allows leverage to think about design of memory subsystems from new perspective. Fundamental change in memory technology will bring new devices with features like enhanced computing capacity at less power [5, 6]. The paper emphasizes on one of the new emerging memory technology, study on concept of PCM, memory effect and characteristics of PCM material, switching mechanism of PCM material, PCM cell structure, its working, I-V characteristics, NGSpice PCM cell model, transient analysis, discussion and future scope of study.

II. PHASE CHANGE MEMORY

Dr. Leon Chua proposed memristor as fourth fundamental passive device by establishing relationship between charge and flux [7-9]. The equations and memristor characteristics are depicted in Table 1. Memristor remembers magnitude and direction of the current which passes through, it in form of a resistive value which is termed the memory effect. The wide application areas induced interest in memristive systems with major emphasis on ultra-high density, high-speed and low-energy consuming non-volatile memories for use in RAM and processor caches.

Market of memory is growing exponentially. For non-volatile memory technologies like Flash to scale beyond a certain limit requires new architectures. Also, the market driving force is based on delivering more gigabytes in same package size at same cost with more functionality, thereby generating more applications, leading to high investment in R&D with the aim of enhanced satisfied customers – the basis of Moore’s law [10]. This necessitates the need to investigate new non-volatile memory with smaller dimensions. The non-volatile candidate technologies are FeRAM (Ferro-electric RAM), MRAM (Magnetic RAM), ORAM (Organic RAM), PCM, ReRAM (Resistive RAM) and solid-electrolyte memory.

Table 1: Equation and characteristics of memristor

| $\phi$ | $Q$ | $I$ | $V$ |
|-------|------|-----|-----|
| $\phi = \frac{1}{2} M d\phi$ | $Q = L \frac{d\phi}{dt}$ | $I = C \frac{d\phi}{dt}$ | $V = R \frac{d\phi}{dt}$ |

Switching Mechanism in PCM Material

Fig. 1 (a) shows threshold switching $I-V$ characteristics of PCM cell, in which the decrease in resistance increases the current, when applied voltage reaches threshold voltage $V_{th}$. The phenomenon is termed voltage snapback and is responsible for switching. Joule heating of material takes place because of flow of large current causing change of phase of material from crystalline to amorphous. Material reaches crystalline phase at low temperatures. This change of phase of materials gives memory effects [11]. After switching, maintaining the state is important. Switching may take place with different degrees of crystallization permitting multistate operation. Chalcogenides materials satisfy the properties required for PCM [12]. Phenomenon is valency of elements and bending and non-bending flexibilities of lone-pair electrons. These are disordered materials and the mechanism is based on local atomic order. The change in phase is produced by light irradiation or application of a voltage. There materials which caters to phase change memory are Ge-Te, GeSbTe$_2$, GeSbSbTe$_2$, AgSbSe$_2$, $Sb-Te$, Ag-In-Sb-Te owing to properties like very low power requirements, down-scaling, high-speed and high-density, and CMOS compatibility.
Switching mechanism is based on heating and cooling process of the material.

During cooling process of the melt, the viscosity becomes large and a point is reached where the structure is not able to follow change in temperature. This property when combined with the speed of cooling, result in either crystalline (Set - low-resistance) or amorphous (Reset - a high-resistance) phases. For slow cooling, material reaches equilibrium crystalline phase and if cooling process is fast by quenching process, the disordered phase is frozen to glass and material reaches to amorphous phase generating large resistance contrast of order of 3-4 between the phases which is utilized by PCM as shown in Fig 1(b).

The material can be annealed between melting and glass transition temperatures to obtain phase transfer between crystalline and amorphous. Annealing is done by applying a pulse of current or short intense laser. The duration and intensity of the pulse determines the phase that the material will reach. To obtain crystalline phase a low intensity pulse for longer duration is applied.

### III. THE PCM CELL

PCM cell structure is depicted in Fig. 2(a). Current controlled heater heats the GST alloy sandwiched between the bottom and top electrodes. A reset state of cell is reached to by applying a short duration large magnitude electric current pulse which melts the material. By abruptly removing the pulse the molten material quenches to high resistance amorphous region within the cell. This amorphous region in series with the crystalline region determines net effective resistance [13]. To obtain low resistance crystalline phase, a large portion of cell is heated above the crystalization temperature by applying long duration low-intensity current pulse. To read either of the state a small value of current is passed through cell [14] so that status of amorphous or crystalline state of the cell is maintained as shown in Fig. 2(b).

### IV. NGSPICE PCM CELL MODEL

The challenge the industry in general face is risky divergence to some less known technology from a well-known one. This transition calls for large investment in lesser known domain which may prove to be a costly affair in long run. Also, development of first product requires a lot of research and development work but may be prone to early failure when subjected to mass production. This mar the possibility of progression to higher generations products which may have been thought upon earlier and fallout being early exit and reaching to start of the learning procedure altogether. This calls for studies to identify and produce the solution to roadblocks, keeping in mind the far future of the device roadmap. Essential factors for this are full and proper understanding of underlying physics and identification of set of critical device characteristics. At this juncture, the role of inexpensive simulation technology becomes profoundly important because it helps in predicting near future developments of the product that may be built over next few years, and the reason for its profuse use in the industry.
It can be virtually used infinite times to verify the results. Simulation provides opportunity to design and analyze complex circuit, investigate diverse areas and to reach to the desired application/s. However, reliable and proper methodology for accurate modelling is the necessity.

Simulation Program with Integrated Circuit Emphasis – SPICE is one such software simulation approach that is being used extensively in the industry, for over half a decade now. It provides many features like reliability, flexibility, precision and strong predictions; the basis for future product market. The memelement models are built keeping in mind the accuracy of the analysis and any divergence or convergence issues is identified by violation of the characteristic fingerprint of the memelement. It is modified using rules of behavioral modelling, proper setting of program options and parameters. The modelling is based on the differential equations of the memelements which are responsible for internal state variables and control the port parameters effectively to memristance, memcapacitance and meminductance resulting in element ports of memristive, memcapacitive and meminductive nature respectively. This leads to division of memelement model to two sub-models. The SPICE environment uses mix of conventional and behavioral modelling to produce the desired resultant. The SPICE state equations are modelled to the circuit containing a grounded integrator of 1F capacitor with a parallel controlled current source. DC path to ground is provided by a shunt very large value resistor connected to the ground so that the current source equals the quantity being integrated. Shunt capacitor produces the computed integral in volts. Memelements namely; memristor, memcapacitor and meminductor may be considered as the electronic devices – the resistor, capacitor and inductor with memory. Their inherent property is to remember information in the absence of a power supply. The mathematical description of a memelement [16] is as follows

\[ y(t) = h(x, u, t) \quad u(t) \]  
\[ \dot{x} = f(x, u, t) \]

Here u(t) and y(t) represents circuits variables (voltage, current, charge and flux) and denotes input and output of the system respectively, h is the generalized response, x represents the n-dimensional vector of internal state variables and f is a n-dimensional vector function which is continuous in nature [16].

Phase-Change memory is created using a Germanium Antimony Tellurium (GST) alloy, which has the benefit of fast heat-controlled changes in the material's physical properties between amorphous and crystalline forms. High resistance as logic 0 (in amorphous state) and low resistance as logic 1 (in solid state) (in crystalline state) electrically separate the states that resemble logic ‘0’ and ‘1’ in PCM. Because PCM reads and writes logic at low voltage, it has various advantages over flash and other embedded memory systems. This behaviour is depicted in Fig.3 in which the phase transition [15] is accounting from crystalline to amorphous and vice versa. The generic equation for temperature effects on the resistance is given by

\[ R_t = R_f [1 + \alpha (\Delta T)] \]  
\[ R_t = R_f [1 + \alpha (T - T_f)] \]

Where \( R_t \) = Resistance of material, \( R_f \) = Resistance of material at reference temperature \( \alpha \) = Coefficient of temperature \( T \) = Temperature of conducting material in degree Celsius \( T_f \) = Temperature of conducting material at which \( \alpha \) coefficient exists.

The Fig. 4(a) shows the diagram of PCM cell with zero resistance. Fig. 4(b) shows device model with infinite resistance.

![Fig. 4 (a) Device model with zero resistance](image)

![Fig. 4 (b) Device model with infinite resistance](image)

The value of memresistance depends on the current

\[ V = I \cdot R \]  
\[ \text{Where} \ I = \frac{\Delta q}{\Delta t} \]  
\[ R_t = R_a (x) + R_c (1 - x) \]  
\[ R_c (1 - x) = \alpha \cdot R_f \cdot (T - T_f) \]

Where

\[ Z_a /R_a = \text{Impedance/Resistance in amorphous state} \]
\[ Z_c /R_c = \text{Impedance/Resistance in crystalline state} \]
\[ Z_t /R_t = \text{Total Impedance/Resistance} \]
\[ Z_pa /R_pa = \text{Impedance/Resistance projected in amorphous state} \]
\[ Z_pc /R_pc = \text{Impedance/Resistance projected in crystalline state} \]
V. RESULT & DISCUSSION

Transient analysis of PCM cell is depicted in waveform 1. PCM concept is based on reversible phase transition of the material. Transient analysis is observed for the duration of 660 ns. It can be seen that the passage to crystallization phase occurs when temperature reaches to 340°C and is caused by application of 4.5 V with the time of 330 ns voltage pulse. During same time, crystalline factor changes from ‘0’ to ‘1’. The study is verified based on the work that has been reported already [20].

Waveform 1. Transient analysis of PCM cell

VI. CONCLUSIONS

PCM memory cell working has been simulated and demonstrated. It has many advantages compared to conventional memory but simultaneously opens door to fresh new challenges as well. Future scope of study indicates evaluation of computing capacity from memory access and power consumption view point, calculation of duration of retention of memory state, improvement in speed, reduction in power consumption, designing and performance evaluation of PCM memory as a product, exploration of new material with better characterstics and performance, and development of entirely new EDA tools for this new technology. However, there are many contending technologies in the non-volatile memory domain so PCM has the challenge to prove its independent existence.

The material melts and transits to amorphous phase upon application of 7V for the duration of 110 ns pulse. For this, the temperature reaches to maximum 780°C and crystalline factor reverses to ‘0’. The process is reversible and controlled by applied voltage, which in turn controls the current in cell responsible for Joule heating. The process can be controlled to vary the resistance to different resistance values indicating multibit storage capacity for an individual PCM memory cell. The domain of memory storage is resistive in nature compared to conventional memories based on the principle of holding the charge, which requires periodic refresh circuitry. PCM suggests simple circuit for read and write operation. Memristive effect is inherently prevalent at nanoscale indicating high-density high-speed applications.

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