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# Memristive Phase Change Memory

**Manish Bilgaye, Adesh Kumar, Anurag Srivastava, Piyush Dua**

***Abstract:** The paper presents study on and simulation of resistive nonvolatile phase change memory (PCM) cell in NGSpice 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 PCM, 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.

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* Correspondence Author
**Manish Bilgaye***, Research Scholar Electrical & Electronics Engineering, School of Engineering, University of Petroleum and Energy Studies (UPES), Dehradun India, E-mail: manishbilgaye@gmail.com
**Adesh Kumar**, Department of Electrical & Electronics Engineering, School of Engineering, University of Petroleum and Energy Studies (UPES), Dehradun India E-mail: adeshmanav@gmail.com
**Anurag Srivastava**, Professor at ABV-Indian Institute of Information Technology and Management, Gwalior, India
**Piyush Dua,** Department of Physics, University of Petroleum and Energy Studies (UPES), Dehradun India

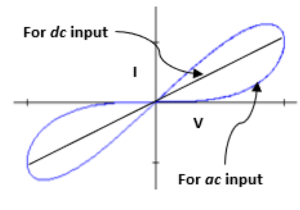


## II. PHASE CHANGE MEMORY

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**

| | $\phi$ | $Q$ | $I$ | $V$ |
|---|---|---|---|---|
| $\Phi$ | | $d\phi = M\,dq$ | $d\phi = L\,di$ | $d\phi = v\,dt$ |
| $Q$ | | | $dq = i\,dt$ | $dq = C\,dv$ |
| $I$ | | | | $dv = R\,di$ |
| $V$ | | | | |




### 1. 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].





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Phenomenon is divalency 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, $GeSeTe_2$, $Ge_2Sb_2Te_5$, $AgSbSe_2$, Sb-Se, 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).

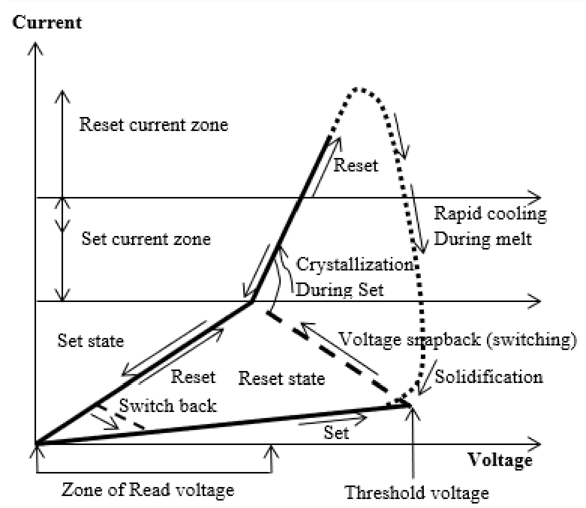



**Fig. 1(a) I-V characteristics of threshold switching**

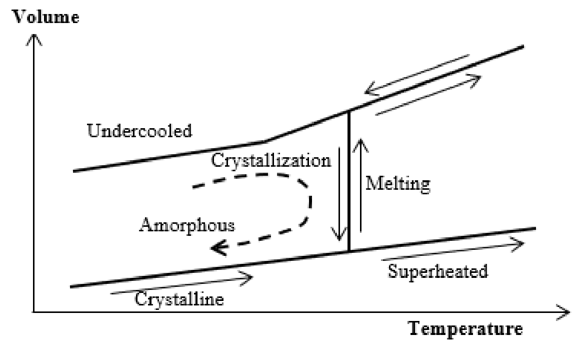



**Fig. 1(b) Formation of crystalline and amorphous phase**

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 crystallization 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).

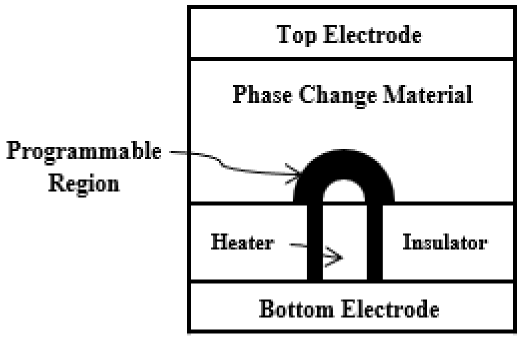



**Fig. 2 (a) PCM cell structure**

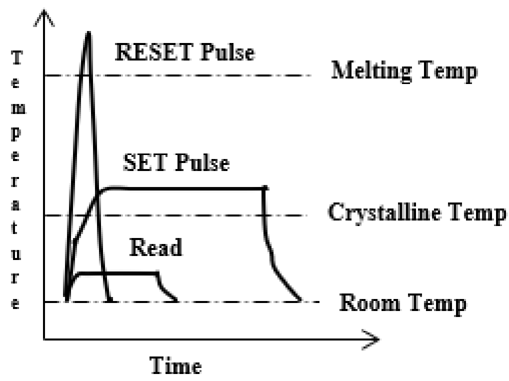



**Fig. 2 (b) Read operation of PCM cell**

## 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 is as follows:

$$y(t) = g(x, u, t)\ u(t) \qquad (1)$$

$$\dot{x} = f(x, u, t) \qquad (2)$$

Here u(t) and y(t) represents circuits variables (voltage, current, charge and flux) and denotes input and output of the system respectively, g 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. NGSpice model of PCM cell is shown in Fig. 3. Bases of the model are the equations (3–6) which describe phase change and thermal processes, wherein the crystalline fraction '$C_x$' and temperature 'T' are internal state variables. Crystallization and amorphization of the PCM cell take place for the condition when ($T > T_m$) and ($T_m > T > T_x$) respectively. Model representing phase change memory comprises of three sub-models, namely; a resistive port and two sub-models as integrators to compute the crystalline factor $C_x$ and temperature T [15].

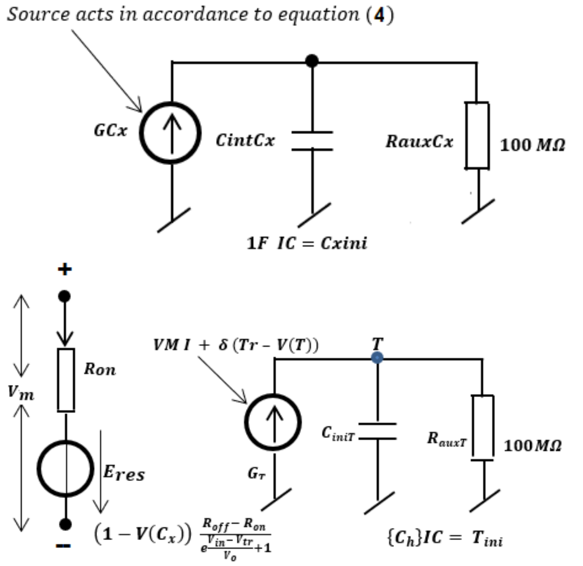



**Fig. 3. NGSpice memristive phase change model**

$$I = R^{-1}(C_x, V_M)V_M \qquad (3)$$

$$\frac{dT}{dt} = \frac{V_M^2}{C_h R(C_x, V_M)} + \frac{\delta}{C_h}(T_r - T) \qquad (4)$$

$$\frac{dC_x}{dt} = \alpha(1 - C_x)\theta(T - T_x)\theta(T_m - T) - \beta C_x \theta(T - T_m) \quad (5)$$

Where,

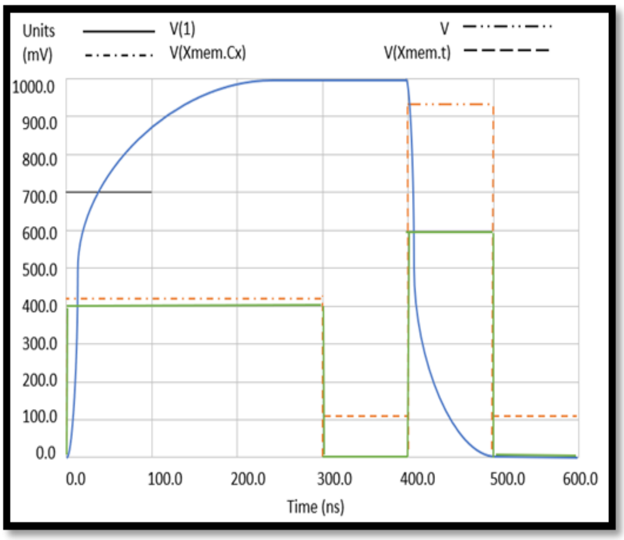
$$R(C_x, V) = R_{on} + (1 - C_x)\frac{R_{off} - R_{on}}{e^{\frac{V - Vt}{Vo}} + 1} \qquad (6)$$

Here,

$C_h$ = heat capacitance,
$\delta$ = dissipation constant,
$T_r$ = ambient temperature,
$\theta[.]$ = step function,
$T_m$ = melting temperature,
$T_x$ = glass transition point,
$\alpha$ and $\beta$ = constant describing crystallization and amorphization rates respectively,
$Vt$ = threshold voltage,
$R_{off} \wedge R_{on}$ = limiting value of memristance,
$Vo$ = parameter determining shape of *I-V* curve

## 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 for duration of 600ns. It can be seen that the passage to crystallization phase occurs when temperature reaches to 335°C and is caused by application of 4V/300ns voltage pulse. During same time crystalline factor changes from 0 to 1.




**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 characteristics 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 6V/100ns pulse. For this the temperature reaches to 735°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.

## REFERENCES


1. Kavehei, O., Iqbal, A., Kim, Y. S., Eshraghian, K., Al-Sarawi, S. F., & Abbott, D. (2010). The fourth element: characteristics, modelling and electromagnetic theory of memristor. Proceedings of Royal Society A: Mathematical, Physical and Engineering Sciences, 2175-2202.
2. Qureshi, M. K., Srinivasan, V., & Rivers, J. A. (2009). Scalable high-performance main memory system using phase-change memory technology. In ACM SIGARCH Computer Architecture News (Vol. 37, 3, 24-33).
3. Burr, G. W., Brightsky, M. J., Sebastian, A., Cheng, H. Y., Wu, J. Y., Kim, S., & Eleftheriou, E. (2016). Recent progress in phase-change memory technology. IEEE Journal on Emerging and Selected Topics in Circuits and Systems, 6(2), 146-162.
4. Chen, Y. (2019). Reshaping Future Computing Systems with Emerging Nonvolatile Memory Technologies. IEEE Micro, 39(1), 54-57.
5. Zhou, P., Zhao, B., Yang, J., & Zhang, Y. (2009). A durable and energy efficient main memory using phase change memory technology. In ACM SIGARCH computer architecture news (Vol. 37, 3, 14-23).
6. Wong, H. S. P., Raoux, S., Kim, S., Liang, J., Reifenberg, J. P., Rajendran, B., & Goodson, K. E. (2010). Phase change memory. Proceedings of the IEEE, 98(12), 2201-2227.
7. Chua, L. (1971). Memristor-the missing circuit element. IEEE Transactions on circuit theory, 18(5), 507-519.
8. Chua, L. O., & Kang, S. M. (1976). Memristive devices and systems. Proceedings of the IEEE, 64(2), 209-223.
9. Strukov, D. B., Snider, G. S., Stewart, D. R., & Williams, R. S. (2008). The missing memristor found. nature, 453(7191), 80.
10. Thompson, S. E., & Parthasarathy, S. (2006). Moore's law: the future of Si microelectronics. Materials today, 9(6), 20-25.
11. Terao, M., Morikawa, T., & Ohta, T. (2009). Electrical phase-change memory: fundamentals and state of the art. Japanese Journal of Applied Physics, 48(8R), 080001.
12. Kolobov, A. V., Fons, P., Saito, Y., & Tominaga, J. (2017). Atomic Reconfiguration of vander Waals Gaps as the Key to Switching in GeTe/Sb2Te3 Superlattices. ACS Omega, 2(9), 6223-6232.
13. Raoux, S., Burr, G. W., Breitwisch, M. J., Rettner, C. T., Chen, Y. C., Shelby, R. M., & Lam, C. H. (2008). Phase-change random access memory: A scalable technology. IBM Journal of Research and Development, 52(4.5), 465-479.
14. Yu, D., Brittman, S., Lee, J. S., Falk, A. L., & Park, H. (2008). Minimum voltage for threshold switching in nanoscale phase-change memory. Nano letters, 8(10), 3429-3433.
15. Dao-Lin, C. A. I., Zhi-Tang, S., Xi, L., Hou-Peng, Chen, & Xiao-Gang, Chen. (2011). A compact SPICE model with Verilog-A.


## AUTHORS PROFILE

**Manish Bilgaye** is currently associated as Research Scholar with the department of Electrical & Electronics Engineering, University of Petroleum and Energy Studies (UPES), Dehradun India. He is B.Tech in Electronic Design Technology from Nagpur University India. M.Tech in Computer Technology, from Pt. Ravishankar Shukla University, Raipur. He has worked with different engineering universities in a span of 21 years in the department of Electronics and Communication Engineering. His areas of interest are Ultra High-density nonvolatile memory, neuromorphic architectures and computing, Embedded Systems Design, Network on Chip.

**Dr. Adesh Kumar** is currently working as Assistant Professor (Selection Grade) with the department of Electrical & Electronics Engineering, University of Petroleum and Energy Studies (UPES), Dehradun India. He is B.Tech in Electronics & Communication Engineering from Uttar Pradesh Technical University (UPTU), Lucknow India in 2006. M.Tech (Hons) in Embedded Systems Technology, from SRM University, Chennai in 2008. Ph.D (Electronics Engineering) form University of Petroleum and Energy Studies (UPES), Dehradun India in 2014. He has employed in TATA ELXSI LIMITED Bangalore as Senior Engineer and faculty member in ICFAI University, Dehradun. His areas of interest are VLSI Design, Embedded Systems Design, Network on Chip, Digital Image Analysis. He has published more than 50 research papers in international peer reviewed journals and conferences. He has contributed as Conference secretary in ICICCD-2016, ICICCD-2107 and editor in ICICCD 2018. He is the reviewer of many SCI and SCIE journals such as Wireless Personal Communications, Microsystem, Technologies, 3D research, Springer, Journal of Visual Languages and Computing, Elsevier, etc are few of them.

**Dr. Anurag Srivastava** is Professor at ABV-Indian Institute of Information Technology and Management, Gwalior, India. He has demonstrated history of working in the education management industry. Having strong education and professional skills in Materials Science, Nanotechnology, Software Development, Innovation, Incubation and Startups.

**Dr. Piyush Dua** is working with Department of Physics, University of Petroleum and Energy Studies, Dehradun. He is B.Sc. (Physics), Ch. Charan Singh University, Meerut, M.Sc. (Physics.), Ch. Charan Singh University, Meerut, Ph.D. (Physics) (Computational Condensed Matter Physics), Indian Institute of Technology, Roorkee. Post Doc. Pohang University of Science and Technology, South Korea. His area of specialization is computational condensed matter physics, magnetic nanowires, PEC water splitting and material science.