Phase Change Memory: Rewritable Optical Disks and Electronic non-volatile memories

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Abstract

Phase change memory of atomic order (Crystalline)-disorder(Amorphous) phase change phenomena was found by S. R. Ovshinsky(Energy Conversion Devices, Inc.) called "Ovonic Memory. GeSbTe and AgInSbTe material systems are used in commercial optical disks, and GeSbTe is commonly used in semiconductor memories. Million overwrite phase change technology enabled rewritable DVD (Digital versatile disk) phase change optical disks, among others. BAE(British Air Engineering) Systems announced they would introduce non-volatile phase change electronic memory products in 2004. Phase change optical and electronic memory devices show differences of cycle life and sensitivity. The cycle life of the electronic devices is more than 10^{13} cycles, compared to 10^{6} for optical disks. Intel-Ovonyx and Samsung have developed test devices of 4Mbit and 64Mbit respectively by 180nm design rule. Phase change electronic memory (OUM) requires far less energy per bit for recording than the optical devices (3.0pJ vs. 0.8nJ). It suggests a different mechanism of phase change in the electronic switching process. Recently, S. R. Ovshinsky described a unique, new cognitive operation mode of phase change electronic devices, which provides function analogous to neurosynaptic processes in the brain.

1. Introduction

It was big impact that Ovshinsky announced the new switching and memory effect on amorphous thin film materials which includes order and disorder phase change phenomena in 1968$^{1, 2, 3)}$. Accordingly, Professor Helmut Fritzsche of Chicago University(member of co-researcher with Ovshinsky, ECD) visited Japan and had a lecture on amorphous semiconductor and new switching effect at Japan Applied Physics Spring Conference at Chiba University(1971)$^{4)}$. It was my start point that I proposed optical memory project in Matsushita. S. R Ovshinsky says human society is composed with Energy and Information, it is like a coin, one side is energy and another side is information which is encoded energy of human activity. New function of amorphous material can contribute to both Energy and Information area. Amorphous Si solar cell plant of ECD(Uni Solar JV) produces 30MW/ year per line now. Information area, T. Ohta contributed to develop million overwrite cycle phase change optical disk technology and to ship the first phase change rewritable optical disk products from Matsushita in 1990$^{5, 6)}$. Then the phase change optical memory technology realized rewritable CD and also rewritable DVD (the market, >6M units in 2004). The other hands, Electronic memory such as Flash memory card market is growing now rapidly by the digital still camera market and MP3 audio player market and mobile device market which are increasing (>50M units, in 2004). Electronic Phase change memory is the candidate of the next new product in this huge market. This paper reviews phase change memory, optical disks and electronic non-volatile memory devices and discusses their features respectively.

2. Comparison of Phase Change Memories[1, 7, 8)]

2.1 Memory principle

Figure 1 shows the model of phase-change memory. The enthalpy of the material when in the amorphous phase is higher than when the material is in the crystalline phase. When the structure changes from amorphous to crystalline, the optical absorption edge of the material shifts to a longer wavelength. This is accompanied by a change in the complex refractive index N=n+ik (n is the refractive index and k is extinction coefficient) and electronic resistance.

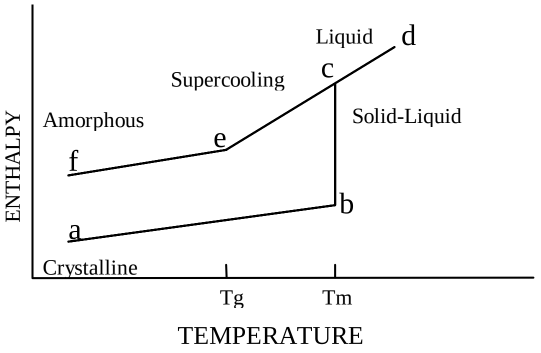

Fig.1. Model of the phase-change memory
Tg: glass temperature, Tm: melting temperature

There are two kinds of Ovonic switching effects. One is the Ovonic Threshold Switch (OTS) and the other is the Ovonic Memory Switch (OMS). Figure 2 shows a schematic figure of the current-voltage (I-V) characteristics of these two types of switches. The arrow labeled OTS shows the Ovonic Threshold Switch process, and the arrow labeled OMS shows the Ovonic Memory Switch process. When threshold voltage Vth is supplied, the voltage decreases to a holding level (Vh), when the current drops below the holding current (Ih), the device returns to its high resistive state (OTS). and After OTS, when the current increases, the device remains in that state(OMS). OTS is special phenomena of Electronic switching process without crystalline structure change as Optical memory phenomena.

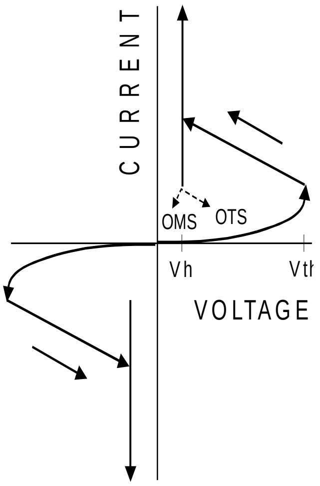

Fig. 2 Reversible electrical switching I-V(current-voltage) model.
OTS (Ovonic threshold switch): at Vh switch again to high resistance state.
OMS (Ovonic memory switch): after current flow, memory switch to low resistance state.

2.2 Phase change operation method

Figure 3 shows the optical overwrite operation method.

By write power level(10mW) and erase power level (5mW)combination, amorphous formation and crystallization erasing is performed by one optical head simultaneously on the track as Fig. 3 (b). This causes the reflectivity of the film to change as Fig. 3(c), which is the basis of the optical storage and retrieval means of phase change optical memory. When the cooling rate is above the critical cooling rate (3.4K/ns)[9)], at the portion of the film where write power irradiated, changes to the amorphous phase and forms amorphous marks. When erase power irradiated on the amorphous marks, the portion crystallizes and the amorphous marks are erased.

In optical disk system, the laser irradiation pulse width is the same for both writing and erasing processes because the effective irradiation pulse width is represented as the pulse width (t) = Rotation linear velocity/ laser spot size and the spot size is the same for writing and erasing. The recording minimum energy is calculated as Pw x t/ mark. For example, in the case of the recording condition of Pw=10mW, V=10m/s and the spot size D=0.8um, the minimum recording energy E becomes E=0.8nJ/ mark.

For the phase change Electronic memory device, Voltage pulse supply is the operation method. S. Lai and T. Lowrey announced 4Mbit of memory test device by 180nm design rule [10, 11]. Figure 4 shows the temperature simulation of the device at the two types of voltage supply, short and high RESET(10—20nsec) pulse and long SET(20 ---80nsec) pulse respectively [10].

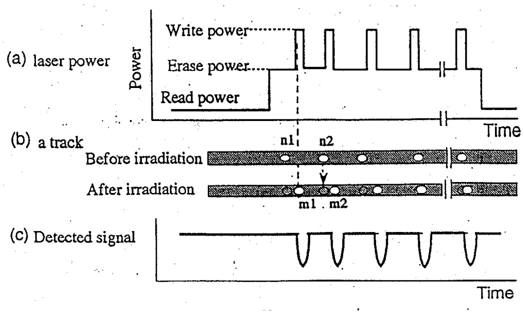

Fig 3. Direct overwriting method by optical mean only

The operation method difference between Optical memory and Electronic memory is that optical disk is dynamic mode such as the disk rotating and the laser scan. They form the amorphous mark and crystallize the mark and erasing by the same pulse width irradiation by the same size of the laser spot in dynamic motion. Otherwise, Electronic device is static mode, the electrode is fixed and we can supply different pulse width voltage pulse for RESET(amorphous) and SET(crystalline).

Figure 5 shows multiple oscilloscope traces of the Electronic cycling operation characteristics of the Phase Change-RAM(OUM) memory cell element. Each trace is a series of 4 sequential operations, write /read /erase /read, cycling at 5MHz. An 8ns RESET pulse is applied with a ~5ns falling edge [11].

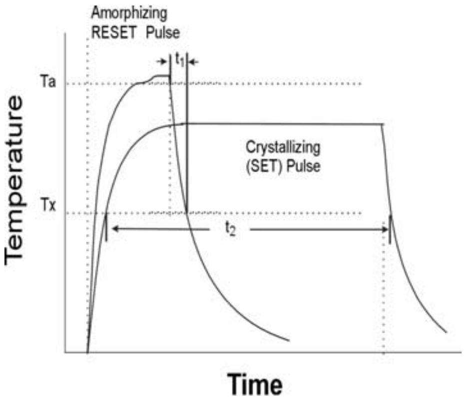

Fig. 4 Electronic programing depiction of the time (pulse width) - temperature relationship of the phase change process.

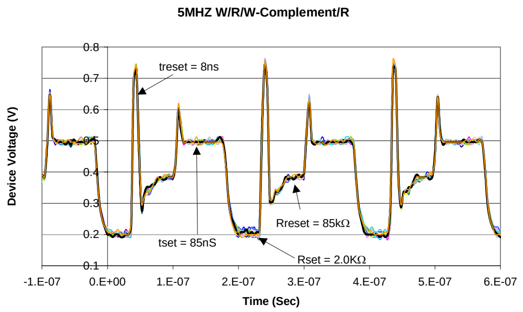

Fig. 5 Electronic programming oscilloscope traces of voltage drop across OUM cell during repetitive write/read/write-complement/read cycling.

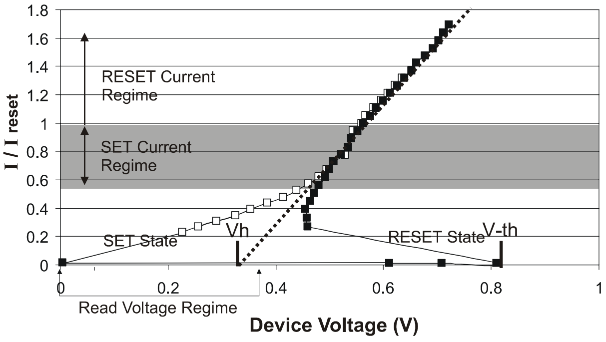

Fig. 6 Current – voltage characteristics for OUM cell element in both the RESET and SET state showing key device parameters: Read/SET/RESET regimes, SET and RESET states, Vh (holding voltage), and Vth (switching threshold voltage).

The subsequent read shows a programmed resistance of 85Kohms. Next application of a SET pulse of 85ns results in a resistance of 2Kohms. The beginning of the SET pulse shows the device threshold voltage, Vth to be approximately 0.6V. The Electronic recording energy is calculated by the SET and or RESET pulse voltage (V), current (I) and the applied pulse width t. The current data is obtained from the (V-I) curves of Fig. 6, in the SET state, V – I curve shows linear relation and RESET amorphous state shows non-linear relation. The RESET current becomes 500uA at the RESET voltage is 0.6V and the RESET pulse with t is 85ns. The recording energy of the cell in this case the RESET energy is calculated as 2.5pJ/ cell. The cell dimension of this 180nm design rule is almost the same dimension of the mark of Phase Change optical disk of 0.8nJ and the recording energy of Electronic memory cell is remarkably smaller than optical memory. One of the reason of this small energy is related the programmable volume in Fig. 8.

3. Device structure and the Phase Change materials

3.1 Device structure and the process

Figure 7 shows the basic 4-layer structure of the phase change optical disk. They are polycarbonate pre-grooved substrate, bottom dielectric protection layer of ZnS-SiO$_2$ mixture, phase change active layer of GeSbTe system, upper dielectric layer of ZnS-SiO$_2$ mixture and reflection layer of Al-alloy. The substrate is formed by injection mold and the 4-layers are formed by sputtering process. The layer number is increasing from 4 to 7 for DVD. The tact time of Phase change Optical disk in this process is around 3 sec by DVD Sprinter (Unaxis).

Figure 8 shows a schematic illustration of the cross section of an OUM memory cell element This device is test 4Mbit VLSI by 180nm design rule $^{11)}$. Because of the very small size cell(50nm x 180nm) of the OUM, the thermal time constant of the device is short -- on the order of a nanosecond. The process of Phase Change Electronic device of Phase Change –RAM(OUM) is CMOS semiconductor process. It is Si substrate, metal oxide semiconductor(MOS) structure with chalcogenide layer process. Electrode materials are Ti, Ni, W, C, N element compounds.

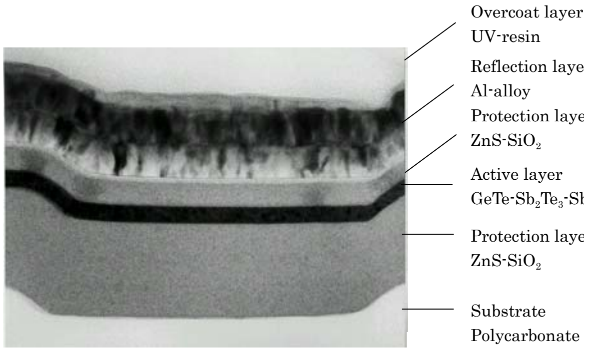

Fig. 7. Cross-sectional TEM observation of the basic 4-layer Phase-change optical disk.

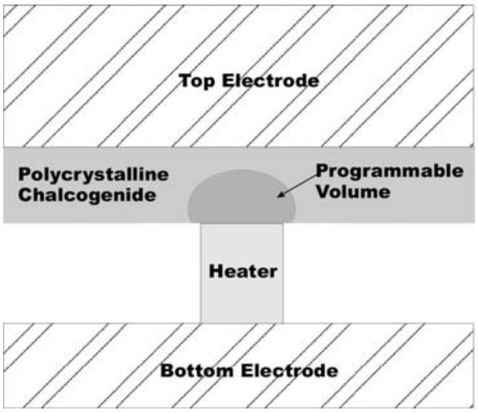

Fig. 8 Cross sectional view of the basic structure of Intel-Ovonyx 4Mbit test device (180nm cell element)

3.2 Phase Change Materials

Chalcogenide materials are used for both phase change Optical disk and Electronic memory device. There are two types of phase change materials, one is Nucleation dominant material (NDM) such as Ge-Sb-Te system [5, 12] and the other is growth dominant material of fast growth material (FGM) based on $Sb_{70}Te_{30}$ [13]. The data rate of phase change optical disk is increasing for document file and audio recording use from 1.2Mbps to video and high definition TV for cinema speed recording to 36Mbps. Figure 9 is GeSbTe system of NDM and Fig. 10 is FGM based on $Sb_{70}Te_{30}$ composition [14]. Both GeSbTe (NDM) system and FGM system such as AgInSbTe system[15] are applied to Phase Change Optical disks of DVD-RAM and CD-RW. Phase Change-RAM(OUM) today's test device applies GeSbTe NDM materials. Both materials have their own features for Phase Change electronic devices.

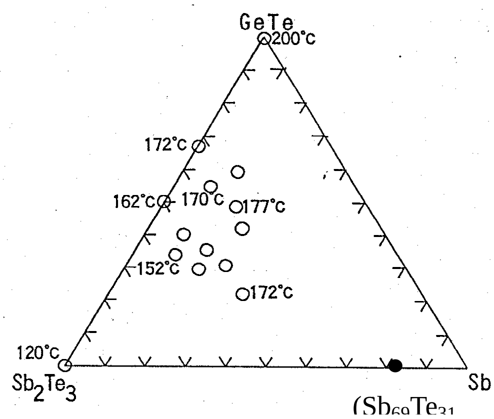

Fig. 9 Crystallization temperature of Nucleation dominant material of GeTe-Sb_2Te_3-Sb quasi ternary alloy system (Heating: 100 C/min)

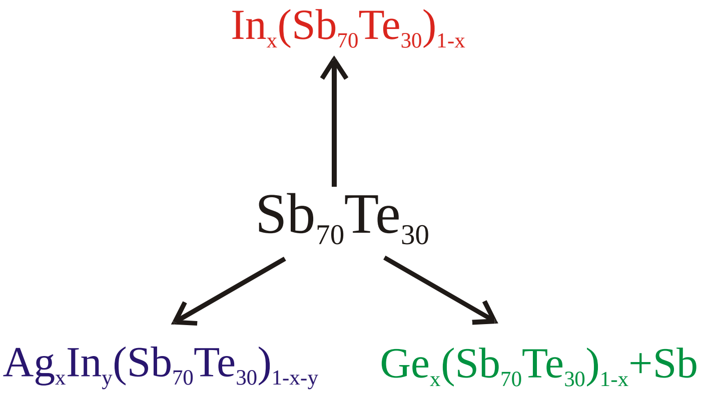

Fig. 10 Eutectic like composition of Sb70Te30 based fast growth materials(FGM).

4. Cycle characteristic of Optical disk and Electronic devices

In early stage of phase change optical disk development in 1980', the cycle characteristic has been the biggest issue. The data showed very poor such as several 1000 cycles compared MO technology of more than 10E+6 cycle. We found the origin of the cycle degradation relates space deformation of the disc layers on a sub-nanometer level, which works as a motive force for sub-nanometer displacement of the active layer components [5]. The deformation is driven by thermal expansion of the layers during the dynamic recording process. The deformation is generally asymmetrical

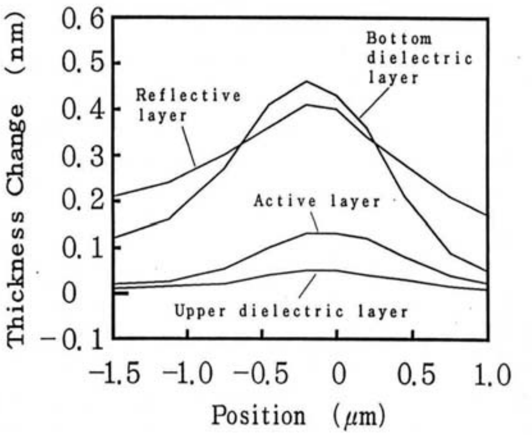

Fig. 11. Distribution of the thickness changes of the disk layers by thermal expansion[35]. (at 30ns exposure)

Horizontal axis : laser passing direction

Zero position : center of the laser spot along the laser scanning direction, greater toward the forward edge and less toward the backward edge. This is dynamic cycle degradation phenomena and it means static device of Phase Change-RAM(OUM) has more tough cycle characteristics. K. Inoue et al calculated the thermal deformation of the phase change optical disc layers16) during the dynamic recording process. Figure 11 shows the thickness change of the layers caused by thermal expansion. The thickness change of upper dielectric layer is less than 0.1nm but upper dielectric layer shows 0.5nm change. The space deformation becomes the motive force of the sub-nanometer displacement of the fluid phase active layer components. This phenomena can be reduced by adding a layer that has small thermal expansion coefficient between the phase change layer and the upper dielectric layer. The thermal expansion coefficient of SiO_2 ($5.5x10^{-7}$) and of ZnS-SiO_2 ($6.1x10^{-6}$) serves this purpose very well. Use of an added SiO_2 layer increases dynamic overwrite cycle characteristics to over $2x10^6$ cycles5, 16).

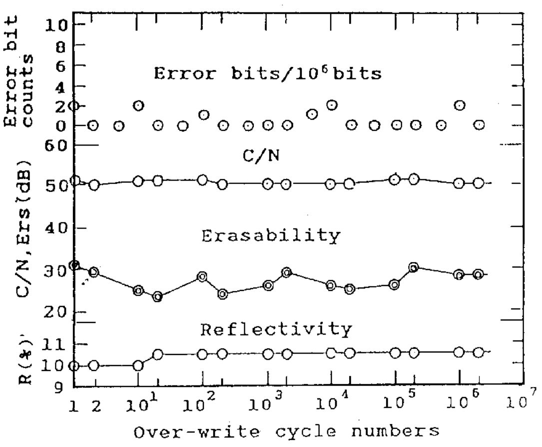

Fig. 11 Two million overwrite cycle test results of phase-change optical disk with additional SiO_2 protection layer8).

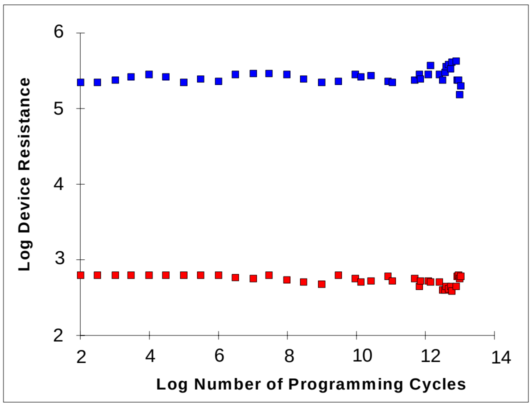

Fig. 12 Set(ON) and Reset(OFF) >10E+13 Cycle measurement of Ovonic unified memory.
Operation condition: f=5.7MHz, RESET Pulse 30ns, SET Pulse 50ns

As we expected, rather static mode cycle operation of Phase Change electronic memory device has much larger cycle characteristics. Figure 12 shows the cycle characteristics of Phase Change-RAM(OUM), high resistance state is amorphous and low resistance state is crystalline and it has extremely large cycle numbers of 10E+13.

5. Future directions of phase-change technology

5.1 High density recording technologies and Ultra fast response phenomena

There are several approaches for High density recording, K. Kishima et al developed a near-field optical head using a super-hemispherical solid immersion lens (Super-SIL) to increase recording density of phase-change optical disc17). A recording density of $50.4Gbit/in^2$ is achieved using an extremely small 160nm track pitch and an 80nm minimum bit length. J. Tominaga proposed Super-RENS phenomena and proposes more than 4 times higher density recording capability 18). The other approach to increased storage density is multi-level recording on phase-change optical disks, M.P. O'Neil showed 8-level phase-change recording technology and announced a CD-RW system having a capacity of 2GB14, 19).

T. Ohta et. al showed Femto laser response of 120fs amorphous mark recording 20). J. Seagel and L. P. Shi found very fast transient phenomena by Pico and Femto laser exposure 21, 22). Femot sec recording mark does not show the crystalline band zone around the amorphous marks. This first experiment shows the amorphous mark recording data rate of phase-change optical disk is expected to be more than a Tbit/s.

Femto-second laser pulses provide an opportunity to develop materials and devices for ultra high speed phase change optical data storage.

5. 2 Phase Change and Magnetic technology Racing again

Next generation nonvolatile memory technology race starts in these years such as MRAM, FeRAM, RRAM(resistiveRAM) so on. They all has the advantage of today's Flash memory technology but has some limitation of process complexity or destructive read or high voltage operation other than compact process Phase Change-RAM(OUM). Table 1 shows the technology comparison of Phase Change Optical disk and Magneto-optical disk and the comparison of Phase Change non-volatile memory v.s. MRAM.

The key factors of non-volatile memory are the power consumption and the cell size. Phase Change-RAM shows advantages of these characteristics.

Table 1 Optical Disk Phase Change (PC) v.s. MO and Non-volatile memory PCRAM v.s. MRAM

Term	(PC) Phase change Optical	(MO) Magneto-Optical	PCRAM (Phase Change RAM)(OUM)	MRAM (Magnetic RAM)
Memory Density	D: >50Gbit/in2	D: 100Gbit/in2	5F2---8F2	8F2---15F2
Capacity	P: 25GB	P:1GB	D: 64Mbit	D: 1Mbit
Recording Energy	0.8nJ/ mark (10mW)	0.3nJ (10mW)	2.5pJ/ cell <1mA	>10mA
Data Rate	>36Mbps	>36Mbps	>5MHz (20-90ns)	10—50ns
Temperature Life	>50Y, 32C	>10Y, 32C	>10Y, 120C	>10Y, 150C
Cycle	P: >10E+5	P: >10E+8	D: >10E+13	D: >10E+15
Recording	Overwrite	2-Head O-write	(Overwrite)	(Overwrite)
Memory Material	GeSbTe system AgInSbTe system	TbFeCo	GeSbTe system (AgInSbTe	NiFe, CoFe, Fe-Mn/ AlOx

S. R. Ovshinsky announced at MRS2003 Fall in Boston the quite new innovation technology of the cognitive function of the phase change material. It will realize the neurosynaptic device for computers by conventional DVD and OUM phase change materials23).

6. Summary

Phase Change Optical memory promoted new industry of rewritable CD, DVD. Phase Change Electronic memory can provide new non-volatile memory products in growing mobile device market. Electronic memory device shows more than 10E+13 cycle characteristics and around 100 times higher sensitivity than optical disk memory which means special phase change process in electronic device. New cognitive function will promote new computer devices by order-disorder function.

Acknowledgement

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