# Evaluation on the Thin-Film Phase Change Material-Based Technologies

by

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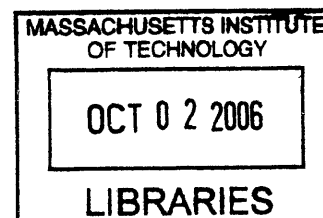MASTER OF ENGINEERING IN MATERIALS SCIENCE AND ENGINEERING
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## ABSTRACT

Two potential applications of thin film phase-change materials are considered, non-volatile electronic memories and MEMS (Micro-Electro-Mechanical Systems) actuators. The markets for those two applications are fast growing and rapidly changing, so new materials technologies with superior performance are of great interest. Devices made with thin film phase change materials are shown to offer significant performance improvements for memory applications and new triggering mechanisms for MEMS actuation. IP (Intellectual Property) analyses for both markets indicate significant new IP space in each of them. Rough estimations for cost and revenue are provided.

Thesis Supervisor: Carl Thompson
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# 1. Introduction

In this report, the so-called "phase change material" (chalcogenide alloys, e.g. Ge-Te-Sb system) thin film based technologies would be reviewed. The unique feature of this alloy system is that, there is great reflectivity (~0.2-0.4 [2]) and resistance contrast (up to three orders [5]) between its amorphous state and crystalline state, which could be easily identified by optical or electrical means. Therefore, the two distinct states could store digital data and the material could be used as the storage medium in a memory cell.

Another potential application of thin film phase change materials is in MEMS (Micro-Electro-Mechanical Systems). It is reported that the reversible phase transformation between amorphous state and crystalline state is accompanied by significant volume (density) change (5%-10%) [1][2][3][4]. Consequently, such material could be used as mechanical switches or actuators, as long as we could control the phase change in a desired way.

A general technical background of phase change materials would be provided first. I would examine the concepts of crystalline and amorphous states, and the transformations between the two. Then, the experimental methods for making phase change material thin films would be discussed. After that, I would analyze the application of thin film phase change materials on the non-volatile memory field. An IP (Intellectual Property) analysis is followed, and we would see that there is great IP space in this area. In addition, I would provide a possible business model for new start-up companies based on the technological, IP, and market analysis discussed before.

Finally, I would talk about the potential application of phase change materials as MEMS actuators and switches. We could see that this application is a purely untouched research field, which has a lot of IP space, as well as a promising market prospect. A business model would be provided as well, followed by a rough market estimate.

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## 2. Technological Background

The so-called "phase change materials" take advantage of the reversible phase transformation between amorphous state and crystalline state of chalcogenide alloys. In this section, I will first review the concepts of crystalline and amorphous states, followed by discussions on the transformation between the two. Then, I will give a brief introduction to thin film phase change materials, and talk about the experimental techniques to make and characterize them.

### 2.1 Crystalline and Amorphous Materials

A **crystal** is a solid in which the constituent atoms, molecules, or ions are packed in a regularly ordered, repeating pattern extending in all three spatial dimensions with translational symmetry [6]. In other words, we can say that crystalline materials have "long range order". While, amorphous materials do not have long range order but have highly short range order and can be relatively dense. They have liquid-like order, but solid like viscosity, and may have different densities, depending on how they are made [7]. Figure 1 gives the microscopic structures for crystalline and amorphous $SiO_2$, respectively, and we could easily see their difference in order, i.e. long range order for crystalline $SiO_2$ and short range order for amorphous $SiO_2$, respectively.

Continuous random network of
$SiO_2$: no 'dangling' bonds.

(a)

(b)
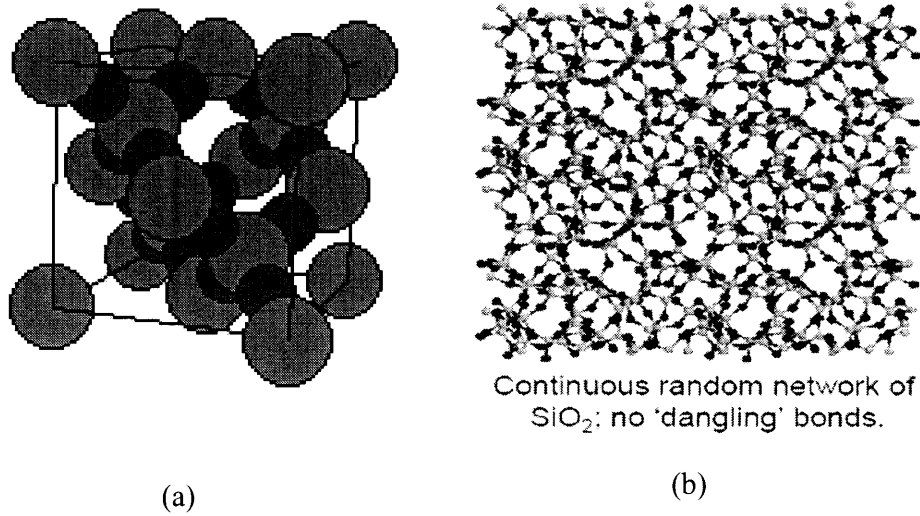
Figure 1 (a) Lattice for crystalline $SiO_2$. The lattice is duplicated periodically throughout
the space [8].

(b) Microscopic structure for amorphous $SiO_2$ [7].

Crystalline state is the thermal-dynamically-stabled phase, i.e. the crystalline state of a particular material has the lowest Gibbs free energy of all possible atomic configurations. On the contrary, amorphous state is metastable and thus strongly dependent on kinetic processes. To be specific, when a liquid is cooled down below its melting temperature, $T_m$, either crystallization or undercooling may occur. During the latter process, homogeneous nucleation of crystalline phases is suppressed for an extended period of time (Some researchers call it "incubation time" for nucleation). If the cooling rate is sufficiently high (too fast to allow nucleation to occur, or, in other words, the cooling time is sufficiently shorter than the "incubation time"), homogeneous nucleation of crystalline phases can be completely avoided. Then, with decreasing temperature, the undercooled liquid becomes more and more viscous and finally, as the temperature falls below the so-called "glass transition temperature", $T_g$, the liquid falls out of equilibrium into the structurally arrested glassy state [9]. The process can be showed on Figure 2 [7].
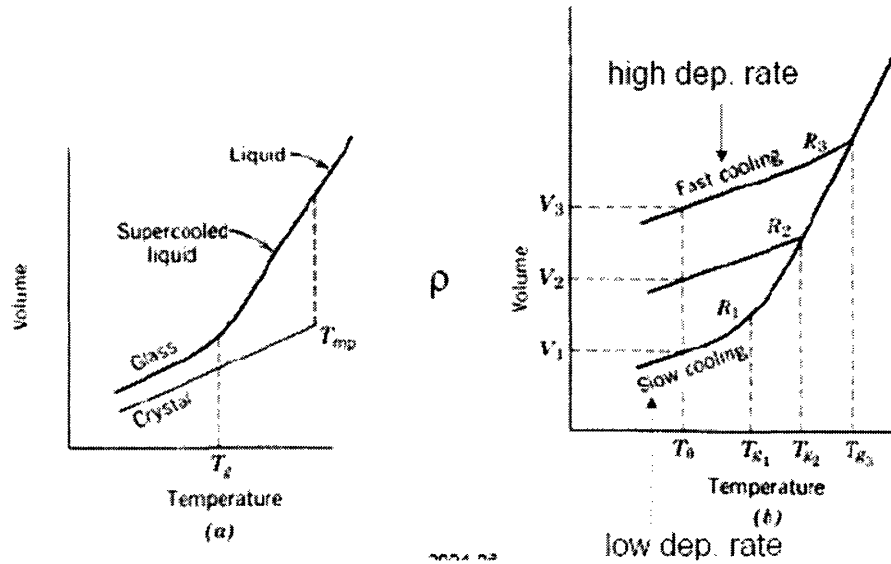
Figure 2 (a) Comparison between crystallization curve and amorphization curve. $T_{mp}$ is
the melting point and $T_g$ is the glass transition temperature [7].

(b) Comparison among amorphization curves of different cooling rate. $R_1$,
$R_2$, $R_3$ are three different cooling rates, and $T_{g1}$, $T_{g2}$, and $T_{g3}$ are their
corresponding glass transition temperatures [7].

From Figure 2a, we can see that, there is an abrupt drop in volume upon crystallization, i.e.
$\Delta V/\Delta T \rightarrow \infty$ at $T_m$. Nevertheless, for sufficiently high cooling rate (equal to or larger than the
"critical cooling rate"), the liquid would be undercooled below the melting temperature and the
volume drops continuously until reaching $T_g$ where the liquid is "frozen" into the amorphous
state.

From Figure 2b, we could also observe that the volume and glass transition temperatures of an
amorphous material depend on the cooling rate from the liquid state, i.e. those parameters are
sensitive to the details of kinetic processes. In addition, it can also be shown here that the volume
and glass transition temperature similarly depend on the deposition rate and substrate
temperature [7].

## 2.2 Amorphization and Root of Critical Cooling Rate

Here we firstly examine the transformation from crystalline to amorphous state. Suppose we start from crystalline state. We heat the material above its melting temperature and then cool it down. As mentioned in last section, only if the cooling rate is equal to or higher than a critical value ("critical cooling rate"), can we obtain the amorphous state. The reason is that, crystallization is a nucleation and growth process, which involves atomic diffusion, and thus is time-consuming. The homogeneous nucleation needs certain time for the statistical fluctuation in the undercooled liquid to generate nuclei of critical size. Therefore, if the cooling rate is so high that there is not enough time (incubation time) for nucleation, crystallization is suppressed and the liquid would be quenched into the amorphous state.

A TTT (Temperature-Time-Transformation) diagram would make the points clearer. Figure 3 [10] is a typical plot of this kind.
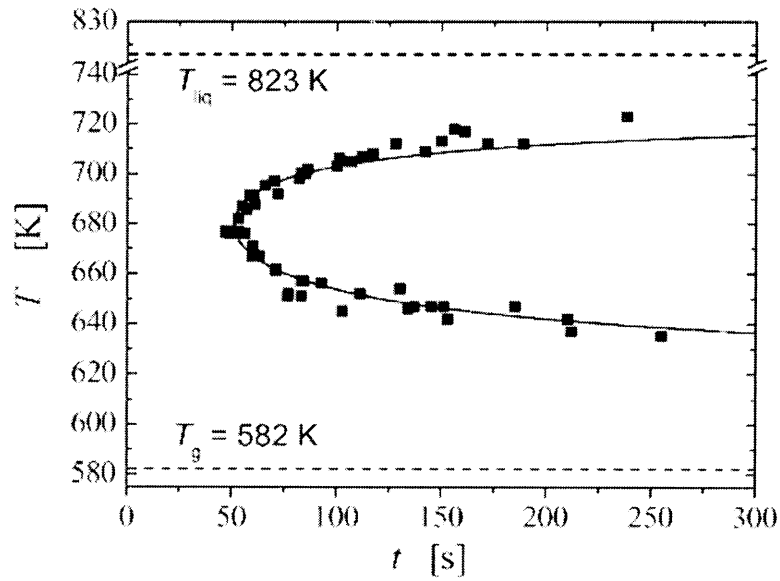


Fig. 2. Time-temperature transformation (TTT) diagram of Pd$_{40}$Cu$_{30}$Ni$_{10}$P$_{20}$. The solid line is a fit using the inverse function of $t$ (T), given in Eq. (5).

Figure 3 A typical TTT diagram [10]

The curve means that, to achieve a certain percentage of phase transformation, what combination of temperature and time should be. Notice that the transformation curve has a "nose" on the left, which is the result of the competition between the driving force of crystallization (increases with the undercooling) and atomic mobility (decreases with the undercooling). From the plot, we could easily come to a conclusion that, in order to suppress crystallization, we must avoid the "nose" of the curve, i.e. the cooling rate should be at least equal to the slope of the tangent at the "nose". Therefore, we could define the slope of that tangent as the "critical cooling rate" in order to get an amorphous material.

## 2.3 Re-Crystallization

Suppose we start from the amorphous state. When we heat the material above its glass transition temperature but below its melting point, the atoms would gain sufficient energy to rearrange themselves, return to the lattice sites, and finally, if we wait for long enough time the material would transform to the energetically more favourable crystalline state.

From a kinetic point of view, re-crystallization is a nucleation and growth process, and is initiated by crystal nucleation. The crystalline nuclei lower the free energy of the system (driving force of re-crystallization), however, nucleation involves the creation of an energetically unfavourable amorphous-crystalline interface [11] [12] [13]. Therefore, the total energy for crystal cluster formation in the amorphous material is a sum of the negative free energy term, which is proportional to the cluster volume, and the positive interface term, which is proportional to the cluster surface. The schematic energy plot is shown in Figure 4 [14].

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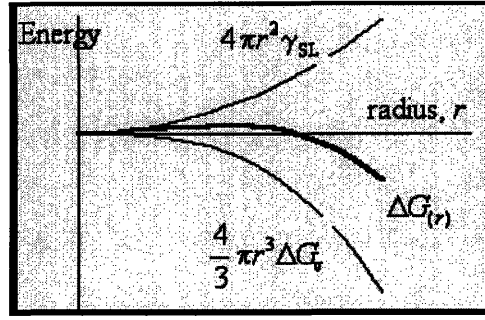
Figure 4 Energy-radius relationship for nucleation [14]

$\Delta G_v$ is the free energy difference between amorphous state and crystalline state, $\gamma_{sl}$ is the interface energy between amorphous material and crystalline nuclei, and $\Delta G_{(r)}$ is the total energy with respect to the radius of the nuclei.

From Figure 4, we know that a critical nuclei size $R_c$ exists, that above $R_c$, the nucleation and growth would proceed, and the crystalline clusters would grow to macroscopic size. While, if the size of nuclei is smaller than $R_c$, the nuclei would dissolve back to supercooled liquid. Consequently, the number of clusters of critical size per unit volume determines the crystal nucleation rate I. And, as we discussed in sections 2.1 and 2.2, formation of crystal clusters of critical size involves atomic fluctuations in the amorphous phase (or undercooled liquid), thus a certain minimum time (incubation time) is needed for the nuclei of critical size to form. In this way, it becomes obvious that the re-crystallization process is more time-consuming than amorphization and thus is the time-limiting step in the reversible phase transformations.

## 2.4 Material Preparing and Characterization

The so called "phase change materials" were discovered in 1968 by Stanford Ovshinsky [15], and they are basically chalcogenide alloys (e.g. Ge-Sb-Te system, Figure 5 [16]). The unique feature of this class of alloys is that, **there is great reflectivity and resistance contrast between its amorphous states and crystalline states, which could easily be identified by optical or electrical means.** Therefore, the two distinct states could store digital data and the material could

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be used as a memory cell. The reversible phase transformation could be triggered either by laser or current pulses. In fact, such characteristic has already been used in optical data storage regime. From Figure 5 [16], we know that the $Ge_2Sb_2Te_5$ (GST 225) composition is the material used for DVD-RAM, and the doped SbTe material is used for DVD+RW.
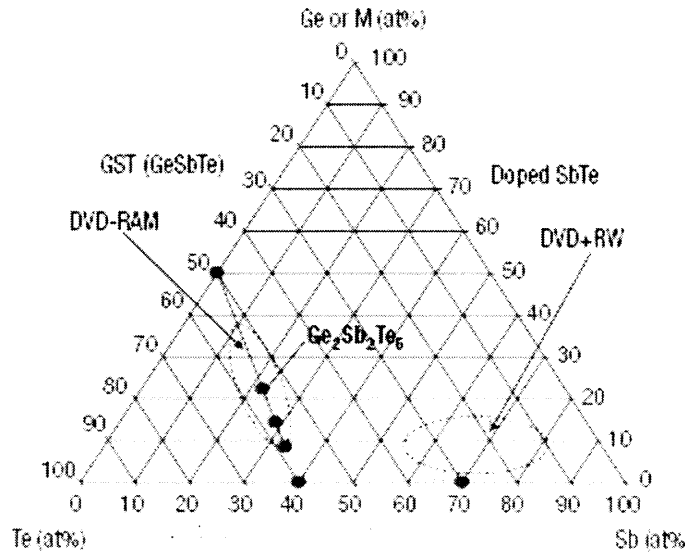


Figure 5 Ge-Sb-Te Ternary System [16]

Thin film phase change materials are often made by sputter deposition on silicon or glass substrates, and the as-deposited films are usually amorphous. A typical set of parameters may be as follows [19]: Thin $Ge_2Sb_2Te_5$ films with a thickness between 5 and 85 nm could be deposited by DC-magnetron sputtering using a stoichiometric target with a diameter of 10cm. The target is bonded to a wafer cooled copper plate. The base pressure in the deposition chamber is typically $2\times10^{-5}$Pa. Sputtering is performed using Ar ions at a pressure of 0.49 Pa. And the film is deposited on glass substrate.

After that, several methods could be adopted to study the kinetic processes of amorphization and re-crystallization on various time scales [2] [17] [18] [19], includes:

(1) Isothermal crystallization measurement on minute time scale using atomic force microscopy (AFM), shown in Figure 6 [17].
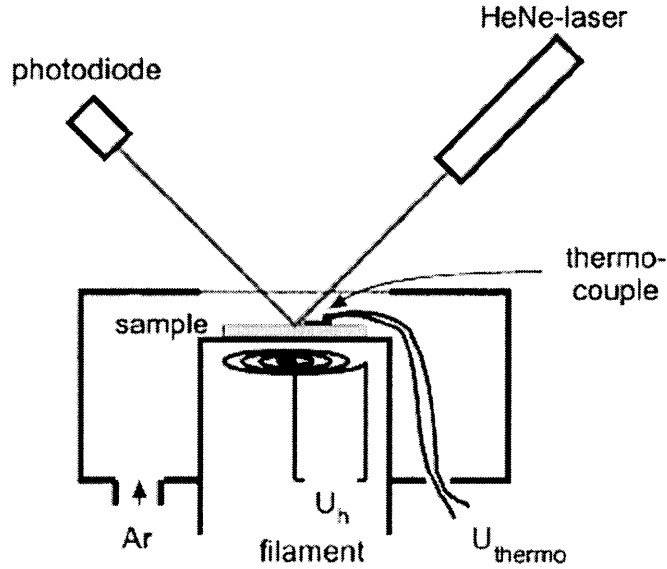


Figure 6 Schematic setup for the isothermal measurements of the sample
reflectance to characterize the crystallization of as deposited
amorphous $Ge_2Sb_2Te_5$ films on minute time scale [17]

Here, thin amorphous films were isothermally crystallized in a furnace under a protective Ar atmosphere. The sample is uniformly heated by a filament distinctly larger than the sample. The temperature was measured by a thermocouple on the sample surface, and was controlled by the heating voltage $U_h$. The desired temperature was reached within one minute. The rise of reflectance with time $R_{(t)}$ is used to evaluate the crystalline fraction, and it is measured by a collimated, low power HeNe laser to avoid increasing the temperature in the illuminated sample region [17]. The AFM setup is to measure the change in thickness during the phase transformations, i.e. during crystallization, the thickness of the film would significantly decrease, and during amorphization, the thickness would greatly increase.

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From such kind of measurement, the activation energy for re-crystallization can be obtained. And the measurement also reveals a temperature dependent incubation time for the formation of nuclei at critical size.

(2) Crystallization of as-deposited amorphous films on nano-second time scale [17] [18]. Here the phase change material thin films are locally crystallized with a focused laser. Then by using AFM, the minimum time, i.e. the incubation time, of the re-crystallization process could be measured. Also, in those experiments, we can measure the change of thickness before/after the transformation, and thus can indirectly find the related density (volume) change upon re-crystallization and amorphization.

(3) Morphology and structure characterization using transmission electron microscopy (TEM) [18]. Using this method, the structural evolution of phase change material thin films can be characterized. Average grain size, as well as grain size distribution could be observed directly. However, the drawback of this method is that, the preparation of TEM samples might be very difficult.

(4) In-situ stress measurement using AFM [2]. As mentioned before, there is significant volume change upon phase transformations, which would lead to big stress in the films. If we use the phase change material thin films as data storage media or mechanical switches/actuators, after finite number of cycles, such stress might result in fatigue of the material (if the stress is not totally elastically-accommodated) and finally, the failure of the device.

Researchers in RWTH, Aachen, Germany have succeeded in incorporating AFM into the experimental facilities for phase transformation studies, which could monitor the stress evolution during phase change processes. A typical output of such measurement is shown in Figure 7 [2]. In this cited stress-temperature relationship for $Ge_4Sb_1Te_5$ thin films, it is clearly shown that at about 190°C, re-crystallization takes place, and the reflectivity increases significantly.

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Using this type of in-situ stress measurement, we could measure the stress as a function of laser annealing parameters and laser quench rate (suppose that the phase transformations are triggered by laser pulses), so that we could find the best experimental parameters to get minimum/maximum stresses as we desire [20].
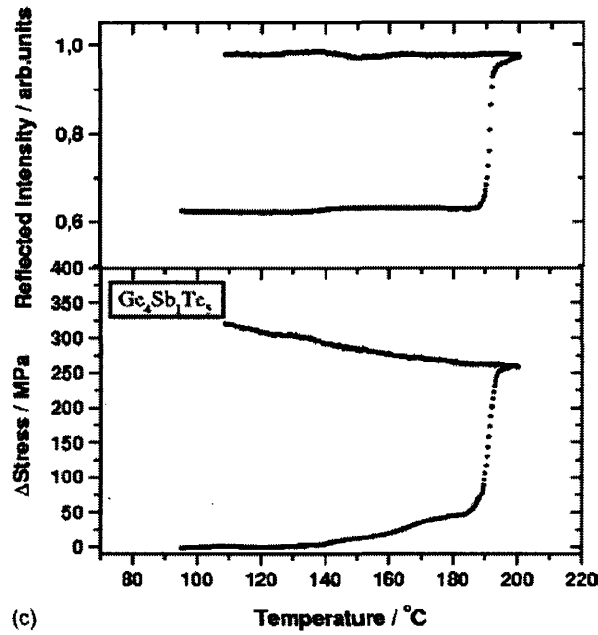


Figure 7 Reflectivity/stress-temperature relationships during the re-crystallization process of $Ge_4Sb_1Te_5$ thin films [2].

In the discussions above, I briefly reviewed the technological background of thin film phase change material and its related topics. In the next sections, I will concentrate on the greatest two fields on which those materials can be applied, i.e. non-volatile memory and micro-mechanical switches/actuators.

## 3. Evaluation I: Thin Film Phase Change Material Based Memory Technology

### 3.1 Introduction

The memory technology has been developing dramatically through years at the speed predicted by Moore's Law. However, there is a consensus that the conventional DRAM and Flash technologies might meet their scaling down extremes in near future. Therefore, technological replacements to DRAM and Flash are badly needed. Among all the potential alternatives, thin film phase change material based memory technology stands out because of its superior performances and good scaling down abilities. In this section, we will first review the dilemma met by current technologies, then introduce the phase change material based memory from a scientific point of view and compare it with several competitive technologies. After that, we will discuss the non-volatile memory market and analyze the opportunities for new business on this field. An IP analysis is followed, and we would see that there is great IP space for thin film phase-change material related issues. Finally, a business model for new enterprises working on phase change material based non-volatile memory is brought forward.

### 3.2 Technological Background

### 3.2.1 Difficulties Met by Conventional Memory Technologies

DRAM (Dynamic Random Access Memory) and Flash are the two current mainstream memory technologies. DRAM is the most widely used memory in computers because it is relatively fast and inexpensive. It is used as the medium to store information when the power of the computer is on. Flash is used in almost all the portable consumer electronic devices, such as MP3 player and digital camera, because it could provide relatively high density of storage at low cost. However, after years of development at the speed predicted by Moore's Law, the two technologies are thought to be close to their scaling down extremes and thus meet a great technological barrier for further development.

The main problem with DRAM is that, it is volatile. "Volatile" means that the system needs to constantly supply energy to the memory cells in order to maintain data. DRAM works on basis of the charge storage in the cells. If no energy is supplied, the charge would leak out of the cell. Therefore, computer power sources have to "refresh" the memory cells at a certain rate to prevent the data from being lost. One big issue is that, when we shrink the size of DRAM cells (increase the density of the cells), we need to refresh them at a higher rate, which leads to great increase in power consumption. It is estimated that as the density of DRAM moves from currently 512Mbit to 1Gbit, the refresh rate might become 1-10ms/Mbit, making the refresh power the dominant component in the power dissipation budget of the chip during standby operation [21].

Flash is a non-volatile memory technology, which basically is a metal oxide semiconductor (MOS) transistor with two gates. It is well-established that, along with the scaling down of the size of the transistors, the thickness of the gate oxide would become thinner and thinner, and the electric field in the oxide layer would be stronger, making it a big reliability issue to the performance of the memory [22]. When the electric field in the oxide exceeds some certain point, there would be electron tunneling effect and consequent breakdown of the dielectrics, thus the operation of the memory would be destroyed. Also, scaling process is accompanied by the decrease in operational voltage. However, for the proper operation of Flash, the gate voltage should be around 10V, and the drain-source voltage should be around 4V, which are significantly higher than the typical voltage range for current computer systems (<1V). I think that is part of the reason why that there is no integration of Flash into computer system, because such high voltage contrast would result in great complexity in driving circuits of the system. Other drawbacks of Flash include low speed (programming time>10μs) and weak endurance (<$10^6$cycles) [23]. Under such context, "It is expected that the planar transistor-based Flash memory cells can scale through 2010 using techniques that are available today or projected to be available in near future" [24]. This statement shows the great necessity to find an alternative non-volatile technology to replace Flash.

To generalize, a new "ideal" memory is badly needed. This technology should have the non-volatility and high storage density as Flash, and have high speed and low cost as DRAM. Further,

it should be compatible with today's mainstream CMOS technology in order to be integrated to the computers, and be able to scale down for future generations. Here I will introduce a technology named "thin film phase change material based memory", which has already showed great potential to meet those requirements.

## 3.2.2 Operation Mechanism and Performances

As we have discussed in section 2.4, the unique feature of phase change materials is that, there is great reflectivity and resistance contrast between its amorphous state and crystalline state, which could be easily identified by optical or electrical means. The two distinct states could then store digital data and the material could be used as a memory cell. The reversible phase transformation could be triggered by laser or current pulses. From Figure 5, we know that such characteristic has already been used in optical data storage regime (DVD-RAM and DVD+RW). Originally, the electronic applications are largely ignored, but it attracts much more research interest in recent years due to the scaling down problem of traditional memory technologies mentioned in the last section (One proof for that is, in the 2006 MRS Spring Meeting in San Francisco, there was an individual symposium named *"Chalcogenide-Based Phase-Change Materials for Reconfigurable Electronics"*, which showed the vibrant research on this field).

The basic operation mechanism of thin film phase change materials in electronic memory application is schematically showed in Figure 8 [23].

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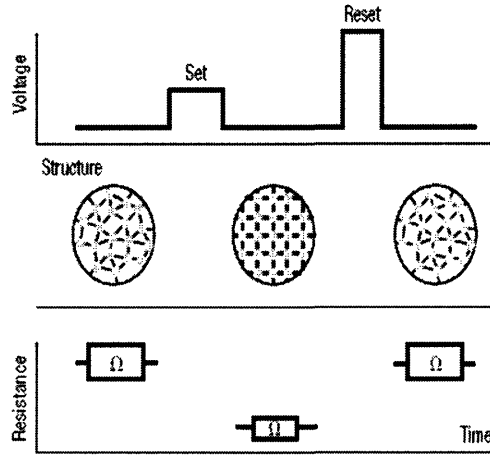
Figure 8 Operation principle of a memory based on phase change materials [23]

Suppose we start from the amorphous state on the left. If we apply a well-designed voltage pulse of particular amplitude and duration (longer than the "incubation time" for nucleation), the material would transform to the crystalline state ("write"). Then if we apply another voltage pulse of higher amplitude and shorter duration (satisfies the "critical cooling rate" criterion), the crystal would be "frozen" back into the vitric amorphous state ("erase"). The resistance contrast between the two states might be as high as three orders [23], and the states could be identified ("read") by a pulse of moderate amplitude and duration.

Figure 9 [23] is a Temperature-Time plot for the operation process. We could see that the "erase" operation (amorphous state→ crystalline state) needs much longer time than the "write" process. There is no surprise. From the discussion in section 2, we know that the re-crystallization process involves nucleation, growth, coalescence, and coarsening, which are accompanied by atomic diffusion. On the contrary, to "erase" the data, we need to heat the material above its melting temperature and cool down quickly enough ($\sim 10^{11}$ K/s [25]) to get an amorphous material. Therefore, the pulse should be short enough to achieve the "critical cooling rate" for the crystalline material to vitrify.
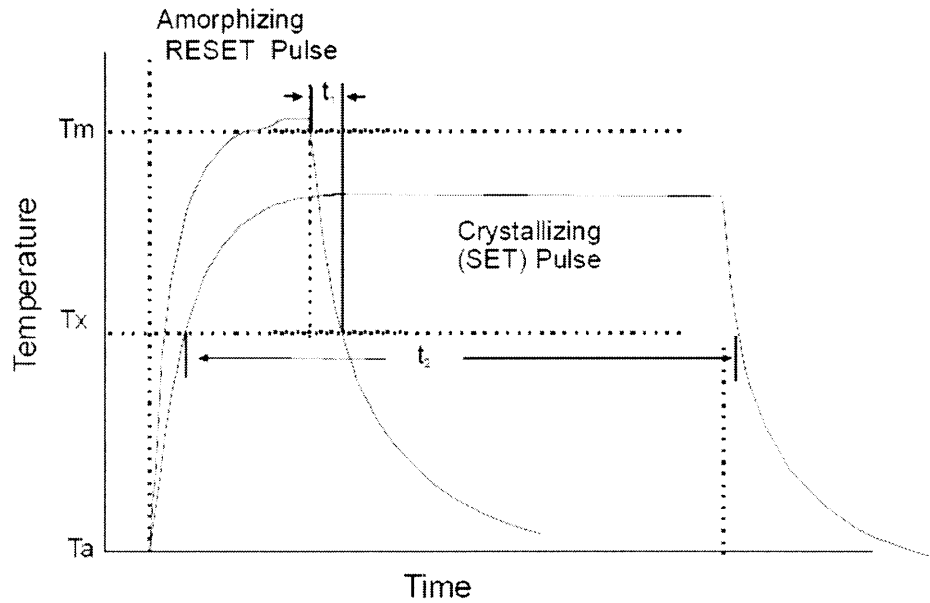
Figure 9 Schematic temperature-time relationship during programming in a phase change rewriteable memory device [23]

Currently, prototype thin film phase change material-based memory devices have already been fabricated and are at the beginning of their commercialization. OUM ("Ovonic Unified Memory") from Ovonyx. Inc. is by far the only one player in this market. Figure 10 is the schematic plot of the structure Ovonyx used to investigate basic device physics of the memory cell [26], and Figure 11 is a prototyped OUM device being integrated to CMOS platform [23].
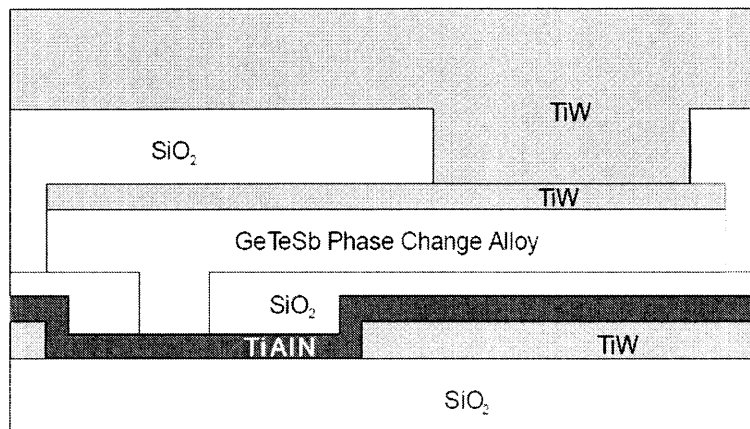
Figure 10 Simple planar offset structures used to investigate basic device physics for OUM
memory cells [26]
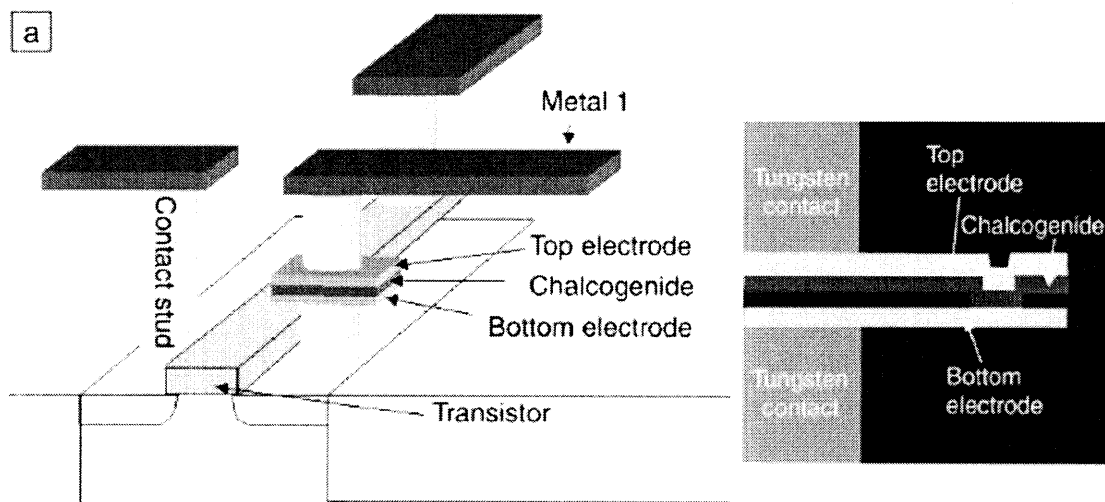


Figure 11   Prototyped memory cell fabricated, STMicroelectronics, in collaboration with
Ovonyx [23]

According to the technical report Ovonyx has published [26], the key features of such prototyped devices are claimed to be:

- Use $Ge_2Sb_2Te_5$ (GST225) composition (directly taken from the material composition used for DVD-RAM)

- Non-volatile (compared to the volatile DRAM)

- High speed: 20ns of read/write cycle (compared to Flash ~10μs)

- Much better endurance:$10^{13}$ cycles (compared to Flash ~$10^6$)

- Better reliability: 10 years at 130°C

- Low voltage required:~0.8V (compared to Flash~10V)

- Compatible to mainstream CMOS process (several prototyped devices have been developed by Ovonyx Inc. and its licensees with standard CMOS processing), only adding two to four mask steps to conventional CMOS logic process with low topography.

- It is claimed by Ovonyx, that OUM memory cells have better scaling-down ability, i.e. no physical limit to OUM memory cell scaling for the next 3-4 lithography generations has been identified. However, in my opinion, as all current prototypes depend on Si based MOSFETs, the phase change memory cells would probably have the same scaling issues as existing technologies.

By identifying the above superior performances and being aware that such memory cell is only prototyped device and just at the beginning of its development, we could say that the thin film phase change material based memory is very promising. It has the potential to replace Flash because of its higher speed, longer endurance and better scaling down ability, and has the

potential to replace DRAM because of its non-volatility.

### 3.2.3 Technological Challenges

Thin film phase change material based non-volatile memory is promising to replace conventional DRAM and Flash, however, some characteristics of those materials need to be further improved in order to make satisfactory memory devices. The issues may include:

- A better cyclability is required. The reversible phase transformation between amorphous state and crystalline state is accompanied by big volume change [1] [2] [3] [4], because crystalline state has significantly higher packing density than amorphous state. Therefore, big mechanical stress is developed during phase transformation, and some part of the stresses is plastically accommodated, which would lead to irreversible deformation. After finite number of cycles, this plastic deformation might result in material fatigue and finally, failure of the device.

  However, I should point out that, few academic publications have been found on this cyclability/fatigue issue, which, I think, is largely due to the fact that this is mainly a manufacturing problem and researchers at academic institutions do not pay enough attention to it. Nevertheless, as most of the stress during phase transformation is plastically accommodated, it is reasonable to think that it is potentially a big issue for the development of the phase change memory technology.

- The speed of the phase change material based memory should be further improved. As being mentioned before, the rate limiting step during operation is the recrystallization process, which involves atomic diffusion, which is time consuming. Therefore, researchers need to find a way to accelerate that process to get higher speed of the device.

- Heat dissipation. To transform the material from crystalline state to amorphous state, a critical cooling rate ($\sim 10^{11}$ K/s [25]) must be satisfied. To achieve that high cooling rate,

the contact material must have very high thermal conductivity and a well-designed structure is needed to help the conduction of heat. However, on the other side, crystallization requires certain time to take place and the heat involved should not be dissipated too fast. Thus, there is a trade-off between the heat transfers for the transformations. This brings challenge to both material selection and device design.

### 3.2.4 Competitive Technologies

Section 3.2.1 discussed the difficulties met by current DRAM and Flash memories. Under such context, several new technologies are being developed, and thin film phase change material based memory is only one of them. Other promising technologies include MRAM (Magnetoresistive Random Access Memory), FeRAM (Ferroelectric Random Access Memory), ORAM (Organic Random Access Memory), and CBRAM (Conductive-Bridge Random Access Memory).

### 3.2.4.1 MRAM

The operation of MRAM is based on the polarization direction of ferromagnetic materials [27]. The key problem with MRAM is: there is fundamental difficulty for MRAM to scale down to high densities i.e. the thermal stability and reliability of data would deteriorate when the size of the cell becomes smaller. "The thermal stability of a memory bit is determined by the height of the energy barrier that prevents switching relative to $kT$, where $k$ is Boltzmann's constant and $T$ is absolute temperature. As the volume of storage material in the cell decreases, the height of this barrier shrinks in proportion. As the energy stored in an MRAM cell approaches about 55 $kT$, the failure rate of the cell is barely acceptable for random access memory applications." [28] In other words, for sufficiently small MRAM cells, if the environmental temperature becomes higher, the data stored in the cell might be lost. That is the basic difficulty faced by MRAM and to find a proper solution seems to be very hard.

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### 3.2.4.2 FeRAM

The operation of FeRAM is based on the polarization direction of ferroelectric materials like PZT (lead-zirconium-titanate). The development of FeRAM is limited by several factors generalized below:

- The materials (like PZT) used to make FeRAMs are not commonly used in integrated circuit manufacturing. Both the PZT ferroelectric layer and the noble metals used for electrodes raise process compatibility and contamination issues [29].

- The retention of data is a big issue, because of leakage current and depolarization field [30].

- The "Read" operation is destructive to the material, which limits the endurance of the device.

Because of those weak points, *Wikipedia* comes to a conclusion that "FeRAM array storage capacities currently lag behind those of Flash memory by more than three orders of magnitude. Consequently, FeRAM has so far tended to be used only in niche applications, such as smart cards and electronic metering. " [29]

### 3.2.4.3 ORAM and CBRAM [31]

ORAM and CBRAM are based on two alternative novel non-volatile memory concepts. Development of both devices is in the initial stages, and only single-cell memory units have been made so far. Thus, currently, they do not form direct competition to phase change memories, but have the potential to take some market share in the future.

In ORAM, the data is stored in an organic storage material thin film which exhibits reversible resistive switching. One problem with ORAM is that organic materials are generally not used in

standard microelectronics processes (as is also the case for ferroelectric materials) and thus have the potential to contaminate the existing manufacturing environment. Also, it is reported that making organic thin films in large areas with high thickness uniformity is an issue, which may limit the mass production of this memory cell. Another limitation is that, the operational voltage for ORAMs is fixed, i.e. independent of the size of the cell (the same as Flash). Therefore, scalability is not good for this technology.

CBRAM is another idea for non-volatile memory proposed during the past two or three years. It works on basis of a polarity-dependent, resistive switching in chalcogenide glasses. The ON state (low resistance) of a CBRAM cell is achieved after a redox reaction driving metal ions into the chalcogenide glass forming metal-rich clusters that lead to a conductive bridge between the electrodes. The OFF state (high resistance) can be obtained by applying a reverse bias voltage. Because it is a pretty new idea and far from maturity, only the phenomenon of resistive switching is showed and no actual devices have been fabricated. Thus, in this evaluation we will not further consider this approach.

### 3.2.5 Conclusion on the Technological Aspect

Table 1 is a comparison between different non-volatile memory technologies [31]. "PCRAM" (Phase Change Random Access Memory) in the table represents the thin film phase change material based memory which we are talking about.

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| | Flash | CBRAM | FeRAM | MRAM | ORAM | PCRAM |
|---|---|---|---|---|---|---|
| Maturity | High Volume Product | Single Cells | Niche Products | Product Samples | Single Cells | Product Demonstrators |
| Density | 4Gb | - | 32Mb | 16Mb | - | 64Mb |
| Cell Size [um$^2$] | 0.025 | - | 0.6 | 1.4 | - | 0.5 |
| Embeddability | Yes | Yes | Yes | Yes | Yes | Yes |
| Nonvolatile | Yes | Yes | Yes | Yes | Yes | Yes |
| Random Read Access | 80ns/10µs | <200ns | 50ns | 30ns | <200ns | 50ns |
| Random Write Access | ~10µs (erase 100ms) | <200ns | 75ns | 30ns | <100ns | 50ns |
| Destructive READ | No | No | Yes | No | No | No |
| Write Endurance | $10^6$ | $>10^5$ | $>10^{12}$ | $10^{15}$ | $10^5$ | $>10^{12}$ |
| Write Voltage | Vdd+~10V | Vdd | Vdd | Vdd | Vdd+~2V | Vdd |
| Companies (Criteria: IEDM, ISSCC, VLSI publication during last 3 years) | Actrans Systems, eMemory Tech., Fujitsu, HaloLSI, Infineon, Intel, Macronix, Motorola, Powerchip, Renesas / Hitachi, Samsung, Sandisk, Sony, SST, ST, Toshiba | | Agilent, Fujitsu, Hynix, Infineon Matsushita, Oki Ramtron Samsung Sanyo Toshiba TI | IBM Infineon Motorola NEC Renesas Samsung Sony | Infineon | Hitachi Intel Macronix Ovonyx Samsung ST |

Table 1 Comparison of different non-volatile memory technologies [31]

From the table, we could easily see that, for the most important indices, i.e. density, cell size, random read access time, write endurance, the PCRAM showed the best or second best performances among all the available technologies (For example, for the index of cell size, the size of PCRAM cell is smaller than that of MRAM and FeRAM and only larger than Flash. For the index of "random write access time", PCRAM is only slower than MRAM and significantly faster than Flash and FeRAM). As for the "write voltage", we can see that Flash and ORAM require constant high voltage (10V and 2V respectively), but PCRAM could be well scaled down to smaller operational voltage.

In a word, among all the alternatives, from a purely scientific perspective, thin film phase change material based memory seems to be the most promising one to become the dominant technology in near future. In the next few sections, I will review and analyze the market and related

intellectual properties (IP), and then put forward a business model that might be suitable for new businesses on phase change material based memory field.

### 3.3 Market Analysis

#### 3.3.1 Non-Volatile Memory (NVM) Market Analysis

The non-volatile memory (NVM) market is fast growing (Figure 12 and Table 2 [32]). According to the report compiled by Business Communication Company (BCC) Inc., the NVM market occupied about the one third of the total memory market, and is growing at a rate of 31.8% per year. What is more, non-volatile memory would occupy more and more percentage in the total memory market, from 2002's 32.0% to 2010's 45.0%. It is also expected in the report that the total market per year for non-volatile memories may achieve $69.1 Billion in year 2010.
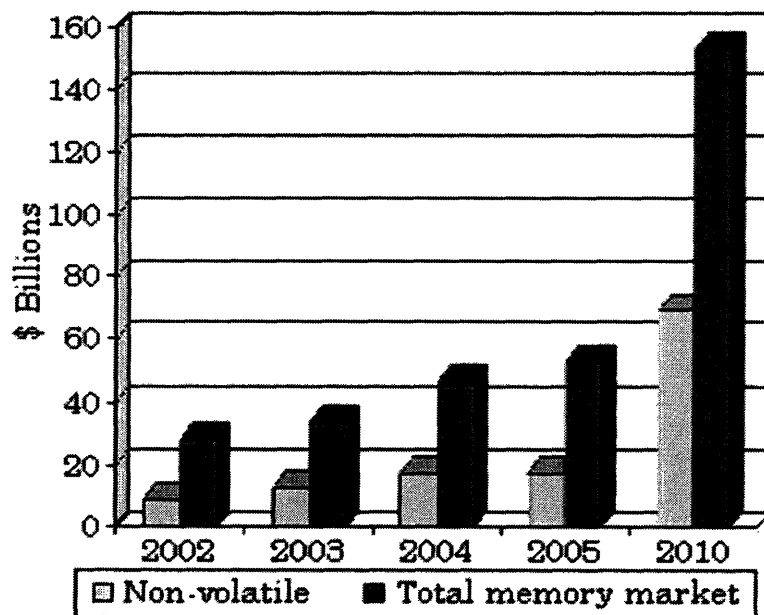
Figure 12 Worldwide non-volatile and total memory market, 2002-2005 and 2010 [32]

|  | 2002 | 2003 | 2004 | 2005 | 2010 | Annual Increase |
|---|---|---|---|---|---|---|
| NVM Market | 9.1 | 12.9 | 17.3 | 17.4 | 69.1 | 31.8% |
| Total memory market | 28.4 | 33.7 | 46.0 | 52.6 | 153.6 | 23.9% |
| NVM percentage | 32.0 | 38.3 | 37.6 | 33.1 | 45.0 | |

Table 2 Worldwide Non-volatile and Total Memory Market per year, through 2010

($ Billions) [32]

One impressive statement in the report is that, among all the existing non-volatile memory technologies, Flash comprises almost 90% of the market. From my point of view, it is largely due to the spread of low-cost, high-quality portable consumer electronic devices such as MP3 players and digital camera/video cameras. However, as mentioned again and again in section 3.2, in 2010, Flash might meet its scaling down extreme and could no longer sustain further development. If this situation becomes real, one or several alternative technology/technologies need to take the place of Flash, which could be regarded as a driving force for the research and development of the new technologies like phase change memory technology. If phase change memory could occupy appreciable share out of the tens of billion dollars non-volatile memory market, there is no doubt that the companies doing this business would earn a lot of money.

### 3.3.2 Business Opportunity for New Enterprises on Phase Change Memory Field

As I mentioned at the very beginning of section 3, OUM (Ovonic Unified Memory) of Ovonyx Inc. is by now the only one player in the development and commercialization of phase change material based non-volatile memory. To be objective, it has done a very good job. Started in

1999, Ovonyx Inc. has already licensed its OUM technology to major semiconductor manufacturers like STMicroelectronics (2000), Intel (2000) and Samsung (2005), and got big investment on R & D from Lockheed Martin (1999) and Intel (2000) [33]. Together with those semiconductor companies, Ovonyx did intensive research on prototype devices, reliability, manufacturing, testing, and etc., and has already filed various patents on those aspects (Please refer to the IP Analysis section for details). It is undoubted that Ovonyx is at the forefront of this phase change material based memory technology and has the best chance to win the competition. In fact, when people talk about "phase change memory", they would be most likely referring to OUM from Ovonyx, i.e. OUM has become the representative for the phase change material based memory technology. One simple proof is that, at *Wikipedia* (www.wikipedia.org, the biggest free online encyclopedia), when you type in "phase change memory", you would be re-directed to the page of OUM.

So far, OUM seems great. However, does that mean that, there is no business opportunity for new companies in this area? Taking this question with me, I visited a senior research engineer Dr. Hu Xiang, of Data Storage Institute (DSI), Singapore [34]. Dr. Hu has been doing basic research on phase change materials for several years and has enough professional experiences on such field. What he thinks about the OUM technology is that, the context set by Ovonyx' OUM is too focused, especially from material scientist's point of view. He let me first look at the Figure 5 of the Ge-Sb-Te ternary phase diagram. He pointed out the fact that Ovonyx did not do much research on materials science and just took GST225 composition from DVD-RAM applications for granted. Yes, GST225 might be the best choice for DVD-RAM, however, is it also the best choice for non-volatile memory applications? Does GST 225 give the best trade-off between volume change, re-crystallization speed and heat transfer (Those issues are major challenges for phase change material based memory as I mentioned in section 3.2.3)? Ovonyx neglects such issues. What it is trying to do is to market the existing OUM cells and commercialize them as soon as possible.

Consequently, this situation leaves great space for materials science-based new business in the phase change memory market. In the following IP analysis section, I will confirm this idea by

investigation and statistics on related US patents, and then, I will propose a business model for new companies entering this market.

## 3.4 IP Analysis

### 3.4.1 US Patent Overview [35]

According to my personal statistics, there are about 174 US patents directly related to phase change material based non-volatile memory technology. Among those patents, over 80% are filed within last 3-4 years.

There is no surprise. The filing of patents is well consistent with the commercialization of OUM cells by Ovonyx Inc. As we already know, Ovonyx licensed its OUM technology to Intel, STMicroelectronics, and Samsung after the year 2000. Then, Ovonyx works cooperately with those semiconductor manufacturers to develop prototype devices and structures, manufacturing methods, testing methods, algorithm, and driving circuits, whose patents comprised most of (~80%) the total patents in this area within the past few years.

## 3.4.2 Detailed Analysis of the Patents

### 3.4.2.1 Statistics on Patent Holders

| | |
|---|---|
| Ovonyx | 99 |
| Intel | 35 |
| HP | 5 |
| Infineon | 2 |
| Matsushita | 6 |
| IBM | 3 |
| Samsung | 6 |
| STMicroelectronics(with Ovonyx) | 7 |
| Others | 17 |

Table 3 Statistics on patents' holders

From Table 3, we could easily see that Ovonyx holds most of the phase change memory related patents (99 out of total 174), and the licensees of Ovonyx, i.e. Intel, Samsung, STMicroelectronics hold most of the remaining patents. Such situation is accordant with the fact that most of the patents are accountable for the commercialization and manufacturing of OUM cells.

### 3.4.2.2 Statistics on Patent Types

Table 4 is a statistics on patent types.

| Structure/Device | 126 |
|---|---|
| Driving circuit/ data access/ algorithm/operation | 27 |
| Fabrication/Manufacture/Packaging | 18 |
| Testing | 1 |
| Material | 2 |

Table 4 Statistics on patent types

From this table, we could find that the structure/device related patents are major part of the whole patents pool (126 out of 174 ~ 72%), and other patents are mostly on circuits, operation, testing, and packaging, which are directly pertinent to manufacturing. That is not coincidence either. Because, after the licensing of the technology, the main task for Ovonyx and its licensees becomes finding a way to manufacture the phase change memory cells in a reproducible and repeatable way as soon as possible. Device, driving circuits, algorithm, packaging, and testing are all practical issues, which are critical to the quality of the final memory products.

One distinct feature in this statistics is that, only two patents are on materials' aspect. The first patent US #6770531 is about "adhesive material", and the other, US #5825046, filed by Ovonyx, is truly about the phase change material itself (In this patent, Ovonyx tried to combine GST225 with some dielectrics to improve the overall performance of memory cells). Therefore, as a matter of fact, only one intellectual property in the US patents pool is about the selection of data storage materials for the phase change memory application. Recall that in section 3.3.2, the expert in DSI, Singapore said that there is great IP space for materials scientists on this field. He is correct, and his idea is confirmed here.

The filing date of that US #5825046 patent by Ovonyx is also worth paying attention to. The patent was filed in 1998, right before the licensing of OUM to those semiconductor companies.

Therefore, before the licensing of OUM technology, Ovonyx seemed to do some research on the phase change materials, as showed by this #5825046 patent. However, after the commercialization, Ovonyx seems to put all its resources to the manufacturing and marketing aspects, and thus the basic material issues are totally neglected.

### 3.4.3   IP Opportunities for New Business in Phase Change Memory Market

So far, we have analyzed the current US IP status of the phase change memory development. We could see that there is a big space for materials scientists who could discover new phase change materials that have better performance than GST225 for non-volatile memory applications. However, there is a trade-off between time and performance. Doing basic scientific research on the materials aspect might take a long time but might improve the performances fundamentally. That is the first way of optimizing the technology. The other way is that, like what Ovonyx is doing now, researchers just adopt the materials from experience or former applications (e.g. OUM adopts GST225 composition from DVD-RAM), and then try to improve the quality through engineering the structures, devices, packaging, and etc. This latter way may take shorter time than the former does, and the companies involved may bring the prototype devices to real market quickly. Nevertheless, as the phase change material is the key component of the phase change memory concept, improvement on this side would no doubt improve the technology dramatically.

### 3.4.4   IP Comparison of Phase Change Memory with Other Memory Technologies

As being discussed in former sections, MRAM and FeRAM are main technological competitors of thin film phase change material based non-volatile memory technology. We have reviewed their drawbacks from a scientific perspective. Here, we are going to look at the technology competition from IP's point of view.

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According to my rough statistics, there are about 1800 filed US patents for MRAM, and approximately 800-900 patents for FeRAM, both are much more than the 174 patents for phase change memory. Therefore, there seems to be little IP space for new business of MRAM and FeRAM. Consequently, new companies doing phase change memory with their own IP(s) might probably have more chance of surviving than the companies on MRAM and FeRAM fields.

## 3.5  Business Model

### 3.5.1  Review of the Business Models Adopted by Current Players

Ovonyx seems to be the "monopoly" in the thin film phase change material based non-volatile memory market currently. It obviously adopts an IP business model (or, in semiconductor industry, people may call such companies as "fabless company"). The basic feature of such kind of model is that, the company (Ovonyx) owns its own IPs on a particular field (phase change memory), and it licenses its IPs to the manufacturers and earns money by collecting the so-called "royalty fee", which is about several percent of the total revenue of the manufacturers from selling the product.  For Ovonyx particularly, it licensed its OUM technology to several major semiconductor manufacturers, and the semiconductor manufacturers also invest money into Ovonyx to do joint research and development of the product. They file patents together, just as we saw in last section of this report, but the semiconductor manufacturers would take charge in the marketing and selling of the final product. Such  IP model is good for start-up high-tech companies in the sense that it would not cost a lot of money, and as long as the small companies owns good intellectual properties, it would easily draw attention from the manufacturers of the industrial supply chain.

Recently, there are several new players coming into this phase change memory field, such as HP and Hitachi. Hitachi announced its prototype device in December, 2005 [36]. And HP's prototyped memory takes advantage of the phase change of a polymeric material, which is expected to be commercialized in 2006 [37]. The common feature of Hitachi and HP is that, they have their own R & D teams, hold their own IPs, have "fabs" (semiconductor manufacturing

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factory) themselves, and then manufacture and sell the products themselves. Evidently, such "IP+ manufacture+product" model is only suitable for the giants in the semiconductor industry like Hitachi and HP, for they can spend big money into the development of new technology, and they have a whole supply chain themselves. For small start-up companies, this seems not to be a practical way.

### 3.5.2 Business Model Proposed for New Companies in the Market

### 3.5.2.1 Product/Manufacture Model

As mentioned in last section, this costly model seems to be bad for small companies just coming into the business of phase change memory market. The greatest entry barrier is the big initial investment of fabs. Figure 13 [38] is a plot of the cost of a 300mm fab with respect to the revenues of major semiconductor companies. We could see from the plot that, even for the top companies in the industry, a bit ironically, it is very difficult to afford a fab.
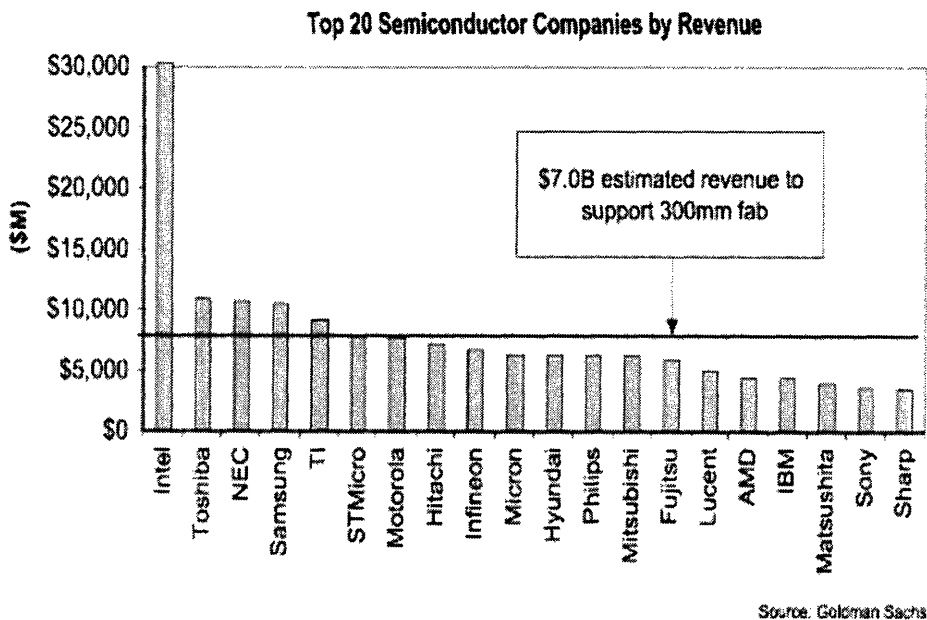
Figure 13 Revenues of top semiconductor companies versus the cost of supporting a fab [38]

An illustration would make my point clearer. Recently, IBM is going to **expand** its fab in USA [39]. The whole construction is expected to cost $2.5 Billion and made up of "200 miles of pipe and tubing, 600 miles of cable and wiring, two million pounds of ductwork, 50,000 gallons of paint, server room holds over 1,700 1GHz-plus processors, 1.5 terabytes of memory and 110 terabytes of storage".

Obviously, for small companies, such scenario is impractical. Actually, if the company holds its own IP on phase change materials, it is not necessary for it to construct a fab and build its own network of business. The reason is that, after tens of years of development, the semiconductor industry has been well divided into very professional segments (Figure 14 [40]), which in all comprise a huge and effective supply chain in the market. Instead of building a whole new supply chain itself, a new company in the business only need to first identify its position in the supply chain of the industry, and then try to educate the suppliers below to understand how to supply and what is in it for them. At the same time, it should also educate the customers above about the advantages of the new technology and persuade them to by the products [40].
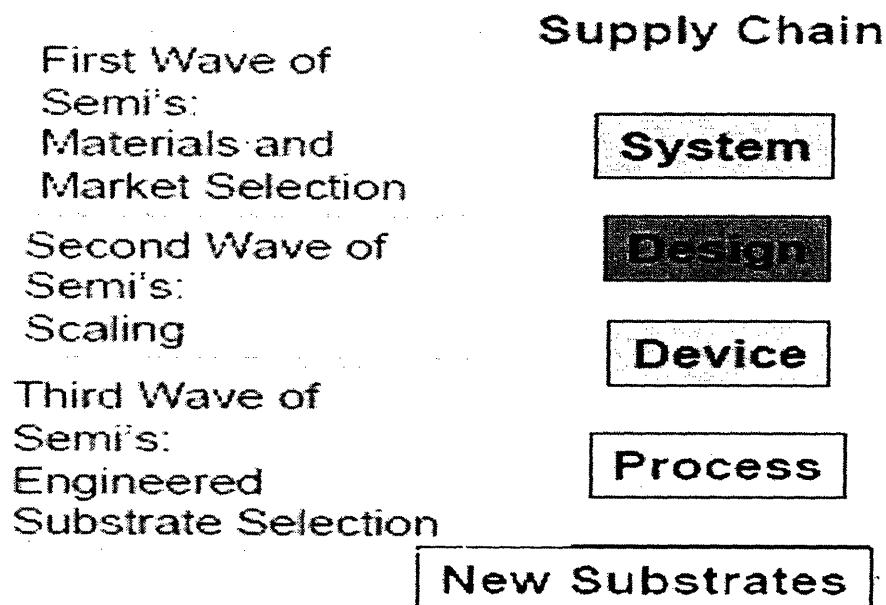


Figure 14 Supply chain of semiconductor industry [40]

### 3.5.2.2 IP Model

By now, we could see that an IP model might be the best choice for new companies which hold their own IPs and just enter this phase change memory market. The first consideration is that, as discussed in section 3.4, there is big IP space for new discoveries in phase change materials. If a materials science-based company has IPs of a phase change material with much better performances than that of GST225, it is probable that the company may attract initial investment from major semiconductor manufacturers on developing prototyped structures and devices, because almost all the semiconductor manufacturers are making memories, and thus are eager to find replacements for Flash and DRAM (as we discussed in the very beginning of section 3) for future applications. And the potential licensees may include: Intel, STMicroelectronics, Samsung, Motorola, and etc.

Let us do a simple calculation. Suppose the royalty fee for licensing is 2% of the total revenue of the licensee. According to Figure 12 and Table 2, the total revenue of non-volatile market might achieve $69.1 Billion per year. Assume a market occupancy of 5%, we could get the total royalty income is approximately $69.1 Million per year, which in my opinion, is already a great number for a small IP company.

### 3.6 Conclusions on the Thin Film Phase Change Memory Technology Section

This section first reviewed the crisis met by current mainstream DRAM and Flash technologies, and introduced several potential technological replacements for them. The key point is that, among all the alternatives, phase change material based non-volatile memory might be the most promising one to become the dominant technology in near future. Market and IP analyses are followed, indicating that there is big IP space and market opportunity for new businesses on this field. Finally, an IP model is proposed as the best choice for small start-up companies in the phase change memory market.

## 4. Evaluation II: Thin Film Phase Change Materials as MEMS Actuators

Actuator is one of the key components in MEMS. In this section, general concepts of actuators in MEMS are provided first, and examples will be given. After that, I will explain the reason why thin film phase change materials are very promising for MEMS actuation applications. Because such field is almost virgin soil for research and development and no actual product, or even prototyped device, has been made, there is huge business opportunity, and the market prospect is optimistic. Then, IP analysis and market evaluation are followed. Finally, a simple business model would be put forward for new businesses on this field.

## 4.1 Reviews on Actuators in MEMS

An **actuator** is the mechanism by which an agent acts upon an environment [41]. It is a controllable work-producing machine, and serves as the interface between an engineering system and the physical world [42] [43]. Just as its name implies, MEMS (Micro-Electro-Mechanical Systems) actuators are actuators in micro meter scale. In the following discussions, we would see that, in this length scale some useful effects exist and people have already made some astonishing structures and devices containing MEMS actuators.

The applications of mechanical actuators are broad in both macro scale and MEMS scale, which can be summarized in Table 5 [42].In each case, a mechanical action is activated in response to a control signal.

| aerospace | automotive | industrial equipment |
|---|---|---|
| flight control surfaces<br>landing gear movement | braking<br>tappets | automation equipment<br>numerically controlled<br>machines |
| nose wheel steering<br>air brakes<br>powered doors/hatches | active suspension<br>active engine mounts<br>airbag deployment | presses<br>lifting equipment |
| electrical goods | developing technologies | instrumentation |
| automatic switches/thermostats<br>video/compact disc reading head<br>camera auto-focus | active control of structures<br>vibration suppression<br>active materials<br>surgical equipment<br>robotics<br>space structure deployment | atomic force microscope |

Table 5 Typical applications of actuators [42]

Also, MEMS actuators take advantage of various actuation mechanisms, including electrostatic actuators, piezoelectric actuators, and etc. Table 6 [43] is a classification of all the actuation mechanisms.

| Electrostatic | Piezoelectric | Thermal | Magnetic |
|---|---|---|---|
| Comb drive [38]<br>Scratch drive [42]<br>Parallel plate [46]<br>Inchworm [49]<br>Impact [52]<br>Distributed [53]<br>Repulsive force [55]<br>Curved electrode [57]<br>S-shaped [58]<br>Electrostatic relay [59] | Bimorph [39]<br>Expansion [43] | Bimorph [40]<br>Solid expansion [44]<br>Topology optimized [47]<br>Shape memory alloy [50]<br>Fluid expansion [19]<br>State change [54]<br>Thermal relay [56] | Electromagnetic [41]<br>Magnetostrictive [45]<br>External field [48]<br>Magnetic relay [51] |

Table 6 Families and classes of work mechanical MEMS actuators with force and axial
displacement output [42]

In order to let the readers get a tangible understanding, and a feeling of the strength of MEMS actuators, an illustration is given below. The example is the thin film piezoelectric actuator as flexible anchor support of micro mirror arrays (Figure 15 [45]) commercialized by Daewoo, Korea. Piezoelectric materials can develop a strain under electric field, and vise versa (Figure 16 [45]). In Figure 15, the MOS (Metal-Oxide-Semiconductor) circuit on bottom of the structure gives out electronic controlling signal and the thin film piezoelectric actuator (two beams) acts in response to the stimuli and develops strain, and thus, bends the top mirror in a desirable way. Figure 17 and 18 [45] are schematic plots of cross section view for the micro mirrors.

The micro mirror array is used for optical displays, which can provide ultra high quality images. Figure 19 [45] is a comparison between a traditional VGA display and an XGA display driven by micro mirror arrays. Obviously, the latter one provides much better images than the former. Thanks to piezoelectric actuators, such technology may bring revolutionary progress to the display industry.
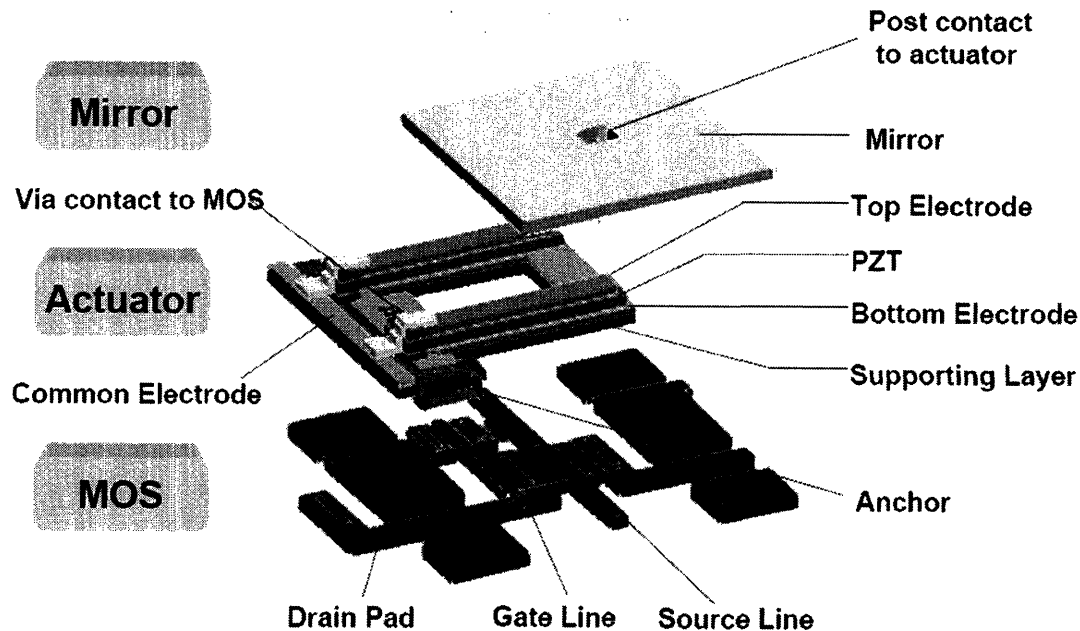


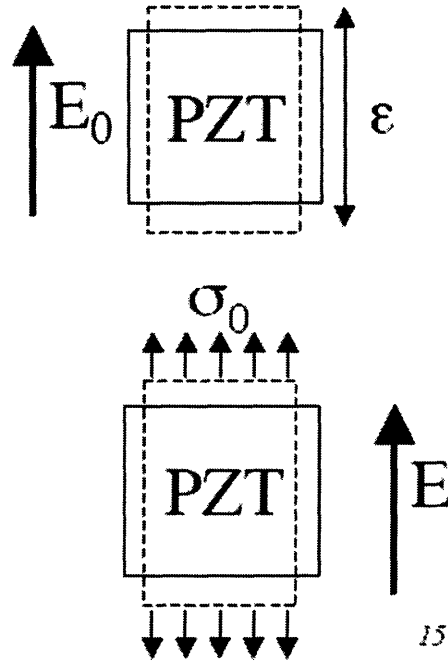Figure 15 Pixel architecture of Daewoo's thin film micro mirror array [45]

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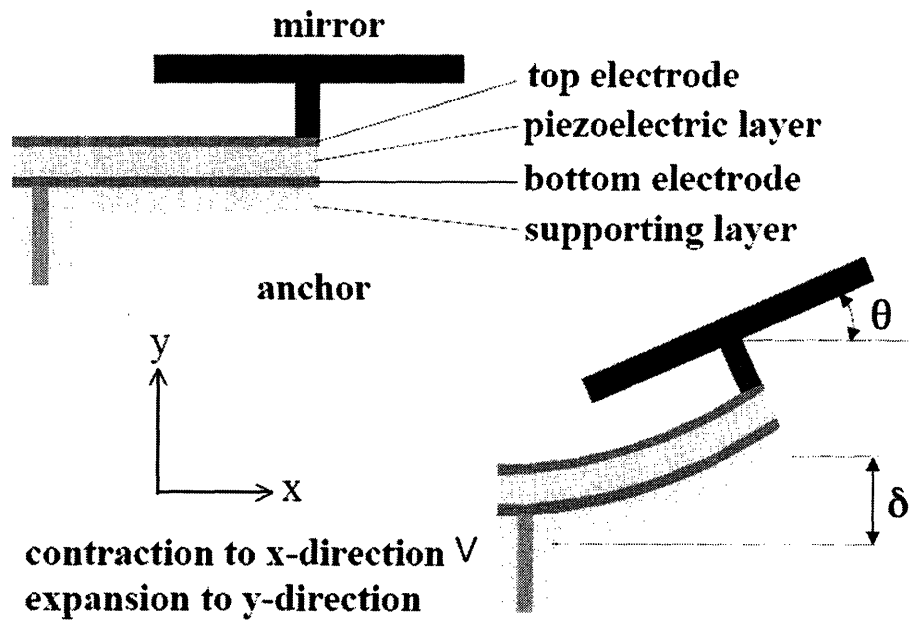Figure 16 Schematic illustration of piezoelectric effect [45]



Figure 17 Schematic cross section view of the micro mirrors [45]
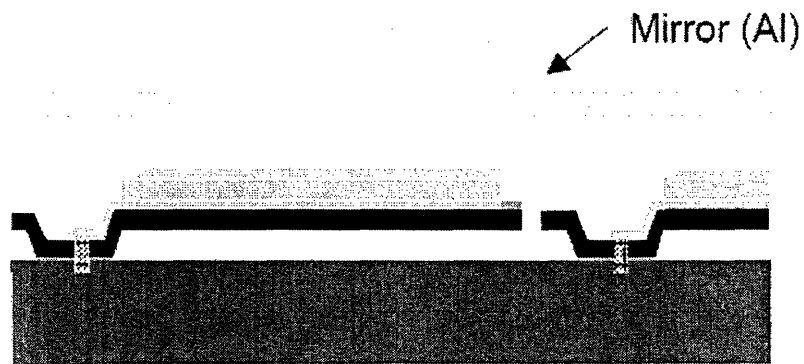
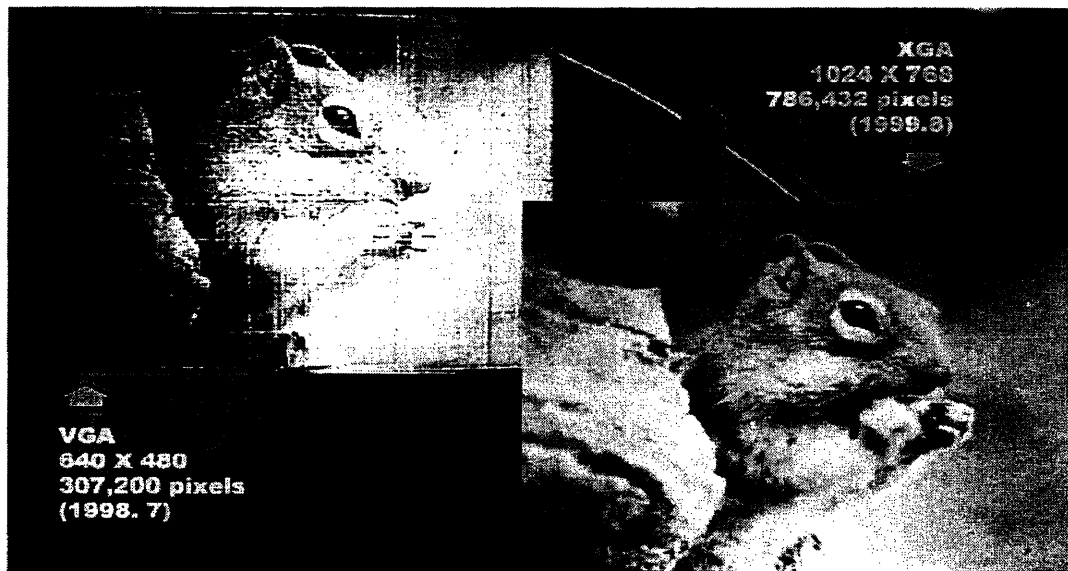Figure 18 Cross section view of actual device [45]



Figure 19   Comparison between traditional VGA and novel XGA displays [45]

To conclude this section, I would say that actuators are crucial building blocks in MEMS. In the next section, I will explain the reason why, thin film phase change materials have the potential to make high quality MEMS actuators.


## 4.2 Advantages of Potential Thin Film Phase Change Material MEMS Actuators

Performance characteristics of MEMS actuators include a lot of different parameters, which may be generalized in Table 7 [42]. Feasible combination of those parameters will generate the so-called "performance indices", which could serve as the guidelines when selecting the most appropriate class of actuator for a given mechanical task, especially in the early stages when designing an active system [42]. In this section, I will examine each of those indices in turn for thin film phase change materials, compare them with existing actuation mechanisms, present some examples, and finally come to a conclusion that, by using thin film phase change material based MEMS actuators, the various performances may improve significantly. When doing these evaluations, I will adopt the experimentally-measured data reported in published papers, and will use the property charts complied by MF. Ashby and co-workers [42]. One point should be mentioned that, rigorously, these charts are for macro scaled actuators, and actuators at MEMS scale may behave differently. Therefore, corrections and adjustments for MEMS actuators would later be given according to more specific work done by Mark Spearing and his collaborators [43].

| performance characteristic | definition |
| --- | --- |
| actuation stress ($\sigma$) | The applied force per unit cross-sectional area of an actuator. |
| maximum actuation stress ($\sigma_{max}$) | The maximum value of actuation stress in a single stroke which produces maximum work output. |
| actuation strain ($\epsilon$) | The nominal strain produced by an actuator; an actuator of initial length $L$ extends to a total length of $(1 + \epsilon)L$. |
| maximum actuation strain ($\epsilon_{max}$) | The maximum value of actuation strain in a single stroke which produces maximum work output. |
| actuator density ($\rho$) | The ratio of mass to initial volume of an actuator. (We neglect the contribution to mass from power supplies, external fixtures and peripheral devices. For example, in the mass of a hydraulic cylinder, we include the working fluid and the cylinder, but neglect the compressor, servo-valve, cooling system and mounting fixtures.) |
| actuator modulus ($E$) | The ratio of a small increment in $\sigma$ to the corresponding small increment in $\epsilon$ when the control signal to an actuator is held constant. (In general this differs from the measured modulus $d\sigma/d\epsilon$ which depends upon the control signal.) |
| volumetric power ($p$) | The mechanical power output per unit initial volume in sustainable cyclic operation. |
| efficiency ($\eta$) | The ratio of mechanical work output to energy input during a complete cycle in cyclic operation. |
| strain resolution ($\epsilon_{min}$) | The smallest step increment of $\epsilon$ (order of magnitude approximations are given). |

Table 7 Definitions of the parameters when evaluating the performances of an actuator [42]

## 4.2.1 Actuation Stress σ vs. Actuation Strain ε

Actuation stress σ and actuation strain ε are two basic parameters for evaluating the performance of an actuator. Mechanical actuators are work-producing devices and from basic mechanics, we know that work done per unit volume by a device equals to ½(εσ), therefore, this index directly represents the ability of an actuator to do work. The performance chart is shown in Figure 20 [42], and typical σ and ε values for currently known actuators are provided in Table 8 [42].
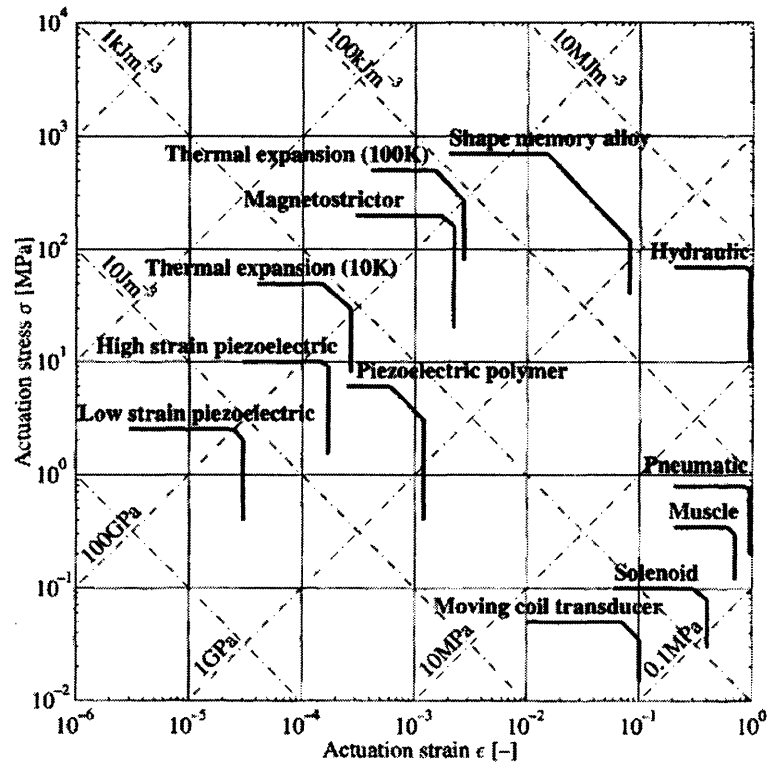
45

Figure 20 Actuation stress versus actuation strain for various actuators. Heavy lines
bound the upper limits of performance [42]

| actuator type | maximum actuation strain $\epsilon_{max}$ [−] | maximum actuation stress $\sigma_{max}$ (MPa) | modulus $E$ (GPa) |
|---|---|---|---|
| low strain piezoelectric | $5 \times 10^{-6}$–$3 \times 10^{-5}$ | 1–3 | 90–300 |
| high strain piezoelectric | $5 \times 10^{-5}$–$2 \times 10^{-4}$ | 4–9 | 50–80 |
| piezoelectric polymer | $2 \times 10^{-4}$–$1 \times 10^{-3}$ | 0.5–5 | 2–10 |
| thermal expansion (10 K) | $9 \times 10^{-5}$–$3 \times 10^{-4}$ | 20–50 | 70–300 |
| thermal expansion (100 K) | $9 \times 10^{-4}$–$3 \times 10^{-3}$ | 200–500 | 70–300 |
| magnetostrictor | $6 \times 10^{-4}$–$2 \times 10^{-3}$ | 90–200 | 40–200 |
| shape memory alloy | $7 \times 10^{-3}$–$7 \times 10^{-2}$ | 100–700 | 30–90 |
| moving coil transducer | $1 \times 10^{-2}$–$1 \times 10^{-1}$ | $4 \times 10^{-3}$–$5 \times 10^{-2}$ | $4 \times 10^{-5}$–$5 \times 10^{-3}$ |
| solenoid | $1 \times 10^{-1}$–$4 \times 10^{-1}$ | $4 \times 10^{-2}$–$1 \times 10^{-1}$ | $3 \times 10^{-4}$–$1 \times 10^{-3}$ |
| muscle | $3 \times 10^{-1}$–$7 \times 10^{-1}$ | 0.1–0.4 | $5 \times 10^{-3}$–$2 \times 10^{-2}$ |
| pneumatic | $1 \times 10^{-1}$–$1 \times 10^{0}$ | 0.5–0.9 | $5 \times 10^{-4}$–$9 \times 10^{-4}$ |
| hydraulic | $1 \times 10^{-1}$–$1 \times 10^{0}$ | 20–70 | 2–3 |

Table 8 Maximum actuation strain and actuation stress for various actuators [42]

As for the ability to do mechanical work, it is obvious that the preferred actuator had better be in the upper right corner on the performance chart of Figure 20. For example, among all the existing actuation technologies, shape memory alloys and hydraulics seem to be the best choice for maximum output work criterion.

For potential thin film phase change material based actuators, a similar evaluation may apply. One adjustment is that, in this case, biaxial modulus replaces the Young's modulus, due to the assumptions for the thin film structure. According to the research done in RWTH, Germany, the experimentally measured stress/strain values for different phase change material thin films are shown in Table 9 [2].

| | $\alpha(10^{-5}/K)$ | $M_f$ (GPa) | $\varepsilon_{zz\ total}$ (%) | $\Delta\sigma_{elast}$ (GPa) | $\Delta\sigma_{exp}$ (GPa) |
|---|---|---|---|---|---|
| AgInSbTe | $1.50\pm0.04$ | $53\pm1$ | $-(5.5\pm0.2)$ | 1.5 | 0.105 |
| $Ge_2Sb_2Te_5$ | $1.81\pm0.06$ | $50\pm2$ | $-(6.5\pm0.2)$ | 1.7 | 0.165 |
| $Ge_4Sb_1Te_5$ | $1.99\pm0.18$ | $47\pm4$ | $-(9.0\pm0.3)$ | 2.3 | 0.215 |

Table 9 Coefficient of thermal expansion $\alpha$ and biaxial modulus $M_f$ obtained from stress measurements for phase change films on different substrates.$\varepsilon_{zz\ total}$ describes the total change in film thickness upon crystallization, while $\sigma_{elast}$ is the expected stress change upon crystallization assuming elastic behavior. The observed stress change is denoted as $\sigma_{exp}$ [2]

From Table 9, two conclusions can be reached. Firstly, not all the mechanical stress is elastically accommodated. From the data, only around 7-9% $(\sigma_{exp}/\sigma_{elast})$ of the total deformation is elastic, and thus the remaining 91-93% of the total strain is plastically accommodated. Secondly, let us compare the phase change thin film actuator with other kinds of actuators. The actuation stress ranges from 0.105 to 0.215GPa (105-215MPa), and the actuation strain ranges from 0.00198-0.00457 (approximated by $\sigma_{exp}/M_f$). Put such stress-strain values on to Figure 20 and compare them with other actuators listed in Table 8, we can see that, although thin film phase change material based actuators can not compete with shape memory alloys or hydraulics, they can do a lot of work and are better than all the other actuation mechanisms according to this work output criterion. Therefore, purely from a work output point of view, thin film phase change materials have the potential to make pretty good actuators.

### 4.2.2 Specific Actuation Stress σ/ρ v.s. Actuation Strain ε

Figure 21 [42] is the specific actuation stress verses actuation strain plot for various kinds of macro scaled actuators.
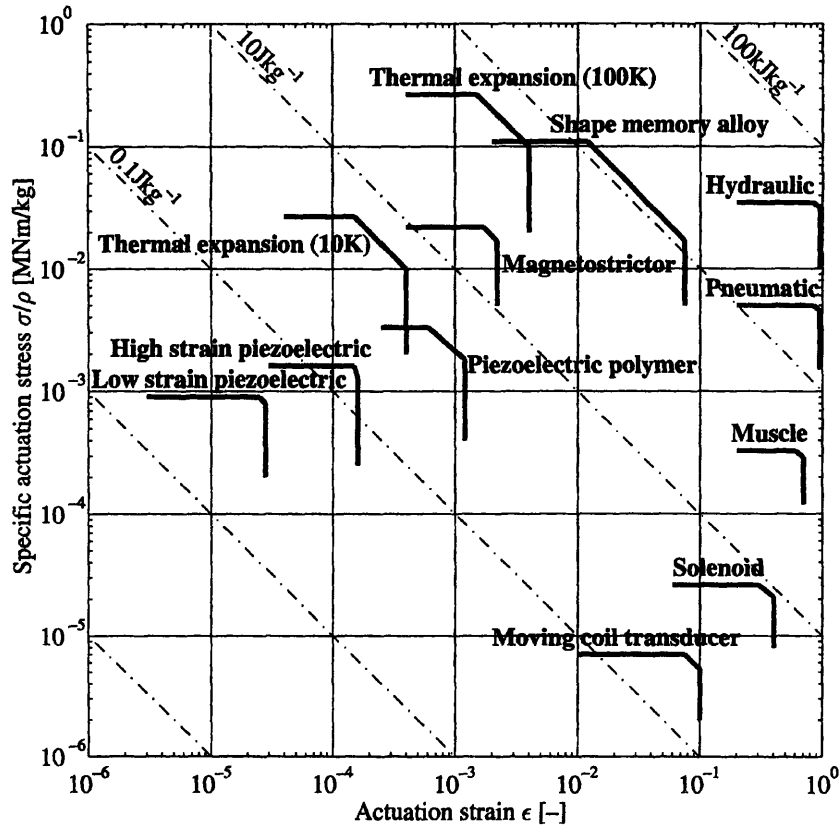
Figure 21 Specific actuation stresses versus actuation strain for various actuators. Heavy lines bound the upper limits of performance [42]

However, as here we only consider thin film phase change materials with a thickness of several tens of nanometers, the density of the film is not that important. Actually, the decisive factor in determining the mass of the actuator is the mass of the substrate. Also, as the reversible phase transformation is accompanied by significant density change itself, the concept of "specific" actuation stress might not be feasible to apply here. Therefore, at least for the case we are discussing, we can neglect the specific actuation stress verses actuation strain criterion.

## 4.2.3 Power Output vs. Frequency

The greatest attraction of phase change materials as actuators comes from the power-frequency response. Figure 22 [42] shows the frequency response for all the currently used actuators.
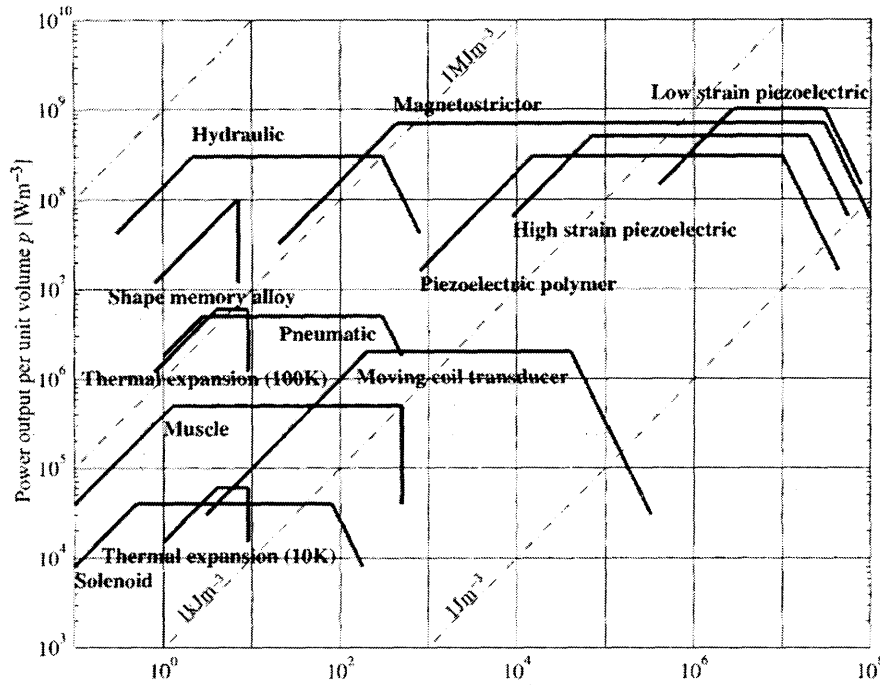


Figure 22 Volumetric power, p, versus frequency, f, for various actuators [42]

We firstly concentrate on the frequency term. According to Figure 22, piezoelectric actuators provide the best frequency response. How about phase change materials? When we look up the technical report presented by Ovonyx [26], the $Ge_2Sb_2Te_5$ thin film they are using in the OUM phase change memory cells have a programming time of 20ns (Please refer to section 3.2.2). If we take this data, we can get a working frequency of about $10^8$ Hz, well competing with piezoelectric actuators. If we want to be more conservative, we can look at the incubation time for re-crystallization (as we discussed, re-crystallization is the rate limiting step in the operation of phase change materials and the incubation time determines the lower limit of the time needed for re-crystallization to take place) reported in the academic publications. According to Ref. [17],

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the incubation time measured for as-deposited amorphous $Ge_2Sb_2Te_5$ film to re-crystallize is about 100ns ($10^7$ Hz), and the incubation time for amorphous bits is around 10ns ($10^8$ Hz). Therefore, even at research level, the frequency response of phase change materials still compete with the best known materials used for MEMS actuation.

Secondly, let us look at the "Power output per unit volume" axis. Conservatively, we assume that there are $10^7$ cycles per second (i.e. working frequency equals to $10^7$ Hz) for thin film phase change actuators, and adopt the actuation stress/strain data from section 4.2.1, i.e. actuation stress $\sigma$=0.215GPa, actuation strain $\varepsilon$=0.00457. Then the power output per unit volume of the actuator equals to $\frac{1}{2}(\varepsilon\sigma) \cdot 10^7 \sim 10^{12}$ Wm$^{-3}$, far exceeding the power output of all the existing actuation technologies.

Therefore, the curve for thin film phase change material based MEMS actuators locates in the top right corner of Figure 22, meaning that such technology undoubtedly is the best choice for this power-frequency performance criterion.

### 4.2.4 Resolution $\varepsilon_{min}$ versus Actuation Strain $\varepsilon$

The same graphical presentation of the characteristics of actuators can also be used to assess performance in terms of resolution. The number of distinct positions through which an actuator must be able to step varies from application to application, e.g. an actuator for opening or closing a lock needs only two stable positions, whereas an actuator for controlling the position of a cutting tool or the micro mirror array discussed in section 4.1 may need several thousands [42]. The selection chart is plotted in Figure 23 [42].
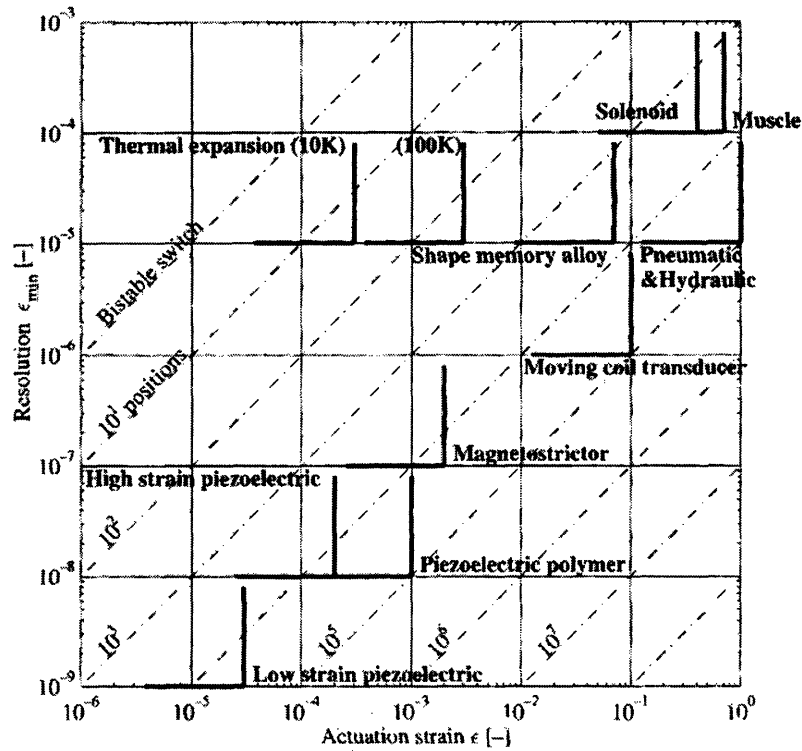
Figure 23 Strain resolutions versus actuation strain for various actuators. Heavy iines
bound the limits of performance [42]

Thin film phase change materials may not do well in this aspect. Phase transformation between
amorphous and crystalline states leads to abrupt change in volume/density (and thus stress level)
with a temperature window of smaller than 10K, as shown in Figure 7 of section 2.4. Hence, it is
almost impossible to control the stress level during the phase change. Consequently, instead of
being controlled linearly with respect to temperature, phase change material based thin films are
better to make switches, which only need two stable states.

## 4.2.5 Adjustments at MEMS Scale

Rigorously, the discussions in section 4.2.1 to 4.2.4 are strictly valid only for macroscopic
actuators. The actuators may behave slightly different in MEMS scale, particularly, small
mechanical structures are intrinsically working at high frequencies and are stiffer (due to surface

effects) than big ones [45]. And in general, MEMS actuators offer better resolution than macro scaled devices [43]. Figure 24 and 25 [43] are plots comparing various macro actuators and MEMS actuators. We could easily see that for the same actuation mechanism, the curve of MEMS scale devices have significant deviation from that of macro scaled ones. But above all, the charts for macro-actuators can still provide insightful guidelines for the initial design of an active system.
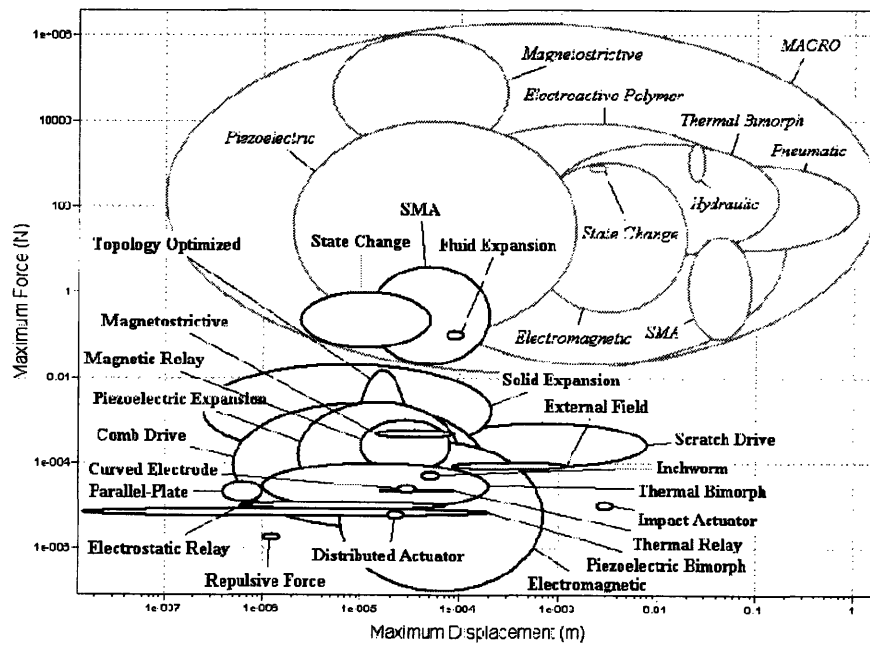


Figure 24 Maximum force versus maximum displacement for actuators in MEMS scale and macro scale. The MEMS devices are labeled in bold, and macro devices are labeled in italics [43]

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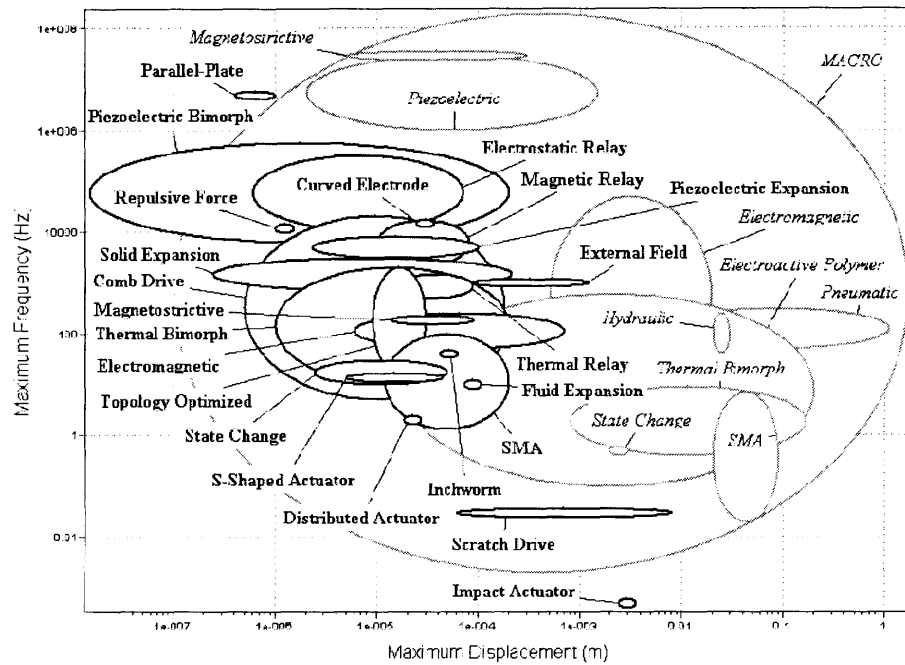
Figure 25 Maximum frequency versus maximum displacement for MEMS and macro actuators. The MEMS devices are labeled in bold, and macro devices are labeled in italics [43]

## 4.2.6 Generalization of the Performances

From the last five sub-sections, we can come to the conclusions below:

- For the largest work output criterion, phase change material actuators can make pretty good MEMS actuators.

- For the power-frequency response criterion, phase change material actuators behave the best in all the MEMS actuators.

- Phase change materials have only two stable stress states, and thus are particularly feasible to make micro switches.

\- In MEMS scale, the frequency response and stiffness of the material may greatly improve.

Therefore, we can see that **phase change materials are second to none in doing work and working at high frequencies at the same time**. None of the current actuation technologies has such feature. For example, shape memory alloys can compete with phase change materials based on the maximum work output criterion; however, their highest working frequency is only around 10Hz (Figure 22). Similarly, piezoelectric actuators are the best choice for high frequency applications; however, it makes much less work than phase change materials (Figure 20).

In the next two sections, I will analyze the IP and market for MEMS actuators, and then develop a business model for companies with IPs on the thin film phased change material field. It is very promising that by adopting phase change materials, the MEMS actuator market may be changed significantly.

## 4.3 Intellectual Property (IP) Analysis

Making MEMS actuators by phase change materials is a novel idea. Although there are vibrant research activities on stress evolution and density change for phase change materials, no actual research has been specifically done for actuation applications. Therefore, **in principle**, the IP space is almost empty (no US patent is directly based on phase change material actuation applications, according to my investigation). Various patents could be filed on the fields of structure and device, fabrication, packaging, testing, and etc.

However, things are not that simple. One big issue we should concern is that, when trying to file a phase change material actuator based intellectual property, we need to examine the existing relevant IPs to see if their claims are broad enough so that the new discovery/invention might fall into the scope of the previous IPs and thus infringe them. If that happens, there would be trouble because although we make new inventions, they would not be "new" enough in a legal sense so that we can't have IPs based on them.

One illustration would make my points clear. US patent # 6947201 "Transverse electrodisplacive actuator array" has claims as the following:

*<1>A transverse electrodisplacive actuator array for controlling the optical phasing of a reflective surface comprising: a support structure; a plurality of **ferroic** electrodisplacive actuator elements extending from a proximate end at said support structure to a distal end; each actuator element including at least one addressable electrode and one common electrode spaced from said addressable electrode and extending along the direction of said proximate and distal ends along a transverse strain axis; a reflective member having a reflective surface and a mounting surface mounted on said actuator elements; and a plurality of addressable contacts and at least one common contact for applying voltage to said addressable and common electrodes to induce a transverse strain in addressed actuator elements to effect an optical phase change in the reflective surface at the addressed actuator elements.*

*<2> The transverse electrodisplacive actuator array of claim 1 in which said support structure and said actuator elements are integral.*

*<3> The transverse electrodisplacive actuator array of claim 1 in which said actuator elements are **electrostrictive**.*

*<4> The transverse electrodisplacive actuator array of claim 1 in which said actuator elements are **magnetostrictive**.*

*<5> The transverse electrodisplacive actuator array of claim 1 in which said actuator elements are **piezoelectric**.*

*<6> The transverse electrodisplacive actuator array of claim 1 in which said actuator elements are **lead magnesium niobate**.*

......

Claim <1> describes the structure and working mechanism for the **ferroic** actuators, and the following claims set the concrete boundaries of the patent, saying that the actuators can also be made by **electrostrictive, magnetostrictive, piezoelectric, and lead-magnesium-niobate** materials. In this way, the inventor of this # 6947201 patent successfully excludes others who make the actuators from materials rather than ferroics for this specific application.

Come back to our case. Although there are no IPs directly based on MEMS phase change material actuators, it is well possible that, the claims of other MEMS actuator IPs, (e.g. shape memory alloys IPs, because shape memory alloys also work on basis of a phase change mechanism), can be so extensive that careless design of the device or literal formulation might lead to the infringement of them and thus the failure in filing a patent.

Under the guidelines above, I searched the database of US patent office. The key words in my search were "phase change" and "actuator". For obvious reasons, I only look for those two words in the **claims** category of all the patents. Most of the patents found are irrelevant to our investigation here, however, there are two of them which could be limitations in filing new patents on phase change material MEMS actuators:

<1> US patent # 6119984: *Low shock anti-friction release device*

The first claim of this patent is as follows:

*"A tension release device for retaining a pin subject to a tension force and for selectively releasing the pin, the tension release device comprising: an actuator that develops a force at a selected time, based on a **phase change** of a **metal alloy** contained in said actuator, and an anti-friction release mechanism that retains the pin until the selected time, whereupon the anti-friction release mechanism releases the pin in response to the force developed by said actuator."*

So, we can see that, in this patent, the material making the actuators is not specified, instead, the inventors only mentioned "a phase change of a metal alloy", which is so broad a category. The

material could be shape memory alloys, phase change materials (e.g. GST225), or even piezoelectrics. In this way, the inventors of US patent #6119984 implicitly exclude others from making the actuators from those materials. Consequently, when people want to find some alternative ways to make such tension release devices, they must be aware of this, or otherwise, they might infringe the existing patent unintentionally.

<2> US patent #5903099: *Fabrication system, method and apparatus for microelectromechanical devices*

Similar to the patent #6119984, this patent also has an ambiguous language on the material making the actuators in the MEMS device. The first claim of this patent is as follows:

*"A flat panel display apparatus comprising a substrate having a surface formed with a plurality of light emitters, a plurality of spacers positioned in an array over the substrate surface, each spacer having a distal end together with a proximal end which is mounted on the substrate surface for tilting movement from a nested position to a deployed position, an actuator carried on the substrate surface, the actuator being formed of* **a metal alloy material** *which is characterized in undergoing deformation when heated through a* **phase-change transition temperature**, *the actuator* **contracting responsive to said change in volume**, *the actuator being connected with the spacer to move the spacer toward the deployed position responsive to said contraction of the actuator, and a translucent panel having a surface which is mounted on the distal ends of the spacers in their deployed positions with the spacers supporting the substrate and panel in spaced-apart relationship. "*

The analysis of the literal formulation is the same with that of <1>. I should point out that, compared with patent #6119984; this patent might be more relevant with our discussion here, for the patent set some boundaries on the fabrication of actuators in MEMS scale, which is the subject of this section.

To generalize, there are some limitations set by existing intellectual properties. When people are doing research on developing novel MEMS actuators, they must be aware of those limitations. However, as I would discuss in section 4.4, the most promising field on which phase change material based MEMS actuators may play a big role is likely to be in the optical switch applications. While, the two existing patents I mentioned above are macroscopic friction release device and MEMS device for display applications, respectively. Therefore, in my opinion, there would not be much trouble in the IP aspect for researchers on phase change material MEMS actuators.

## 4.4 Market Analysis

The global market for solid-state sensors and actuators remains relatively small when compared to other major semiconductor product categories. However, the sensor/actuator (sensors have the reverse function with respect to that of actuators, i.e. the external stimuli cause mechanical deformations, which can be transformed into electrical/optical signals recognized by the system. Their relationship is just like that of photo detectors and photo emitters, e.g. LED and lasers. And as we often use the same material for both photo detectors and emitters, we can use the same material for both MEMS sensors and actuators, such as piezoelectrics) market is forecasted to grow at double the rate of integrated circuit (IC) sales, according to IC Insights' *2006 Optoelectronics, Sensor/Actuator, and Discrete (O-S-D) Report.* In fact, the sensor/actuator market is poised to become the fastest growing semiconductor segment in this decade, and is expected to increase at a cumulative average annual growth rate (CAGR) of 21% between now and 2010 [46].

Figure 26 [46] is a forecast for the actuator/sensor market in 2006. We could see that actuators occupies most of the market (58%), and its corresponding revenue would be $5.7 Billion × 58%=$ 3.3 Billion.

**2006 Sensor/Actuator Marketshare Forecast ($5.7 Billion)**



Temperature sensors
1%

Pressure sensors
10%

Acceleration & yaw
sensors
13%

Actuators
58%

Magnetic field
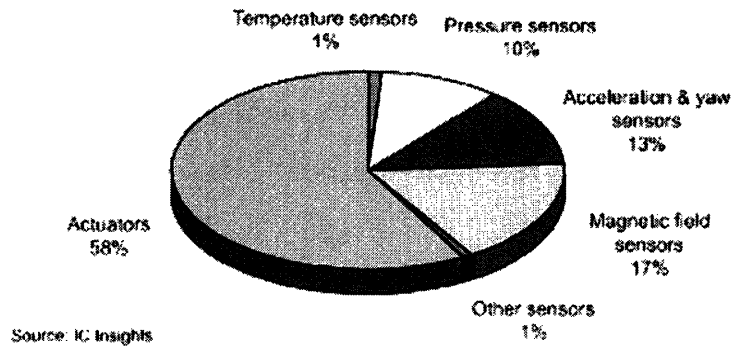sensors
17%

Other sensors
1%

Source: IC Insights

Figure 26 [46]

Therefore, the total market for MEMS actuators is huge. As we have discussed in last section, thin film phase change material based actuators have the best power-frequency response and can do a lot of work at the same time, compared with the already existing technologies. What is more, phase change materials are of low cost. The actuator would only use conventional substrates (silicon or glass) and the thin film materials would be sputter deposited, patterned and finally packaged with high throughput.

To be more concrete, let us discuss the most promising sub-market where phase change materials may play a big role. As being mentioned in last section, phase change materials are especially suitable to make micro mechanical switches. According to my investigations, the **optical switch** market stands out. An illustration of optical switch is shown on Figure 27 [47].
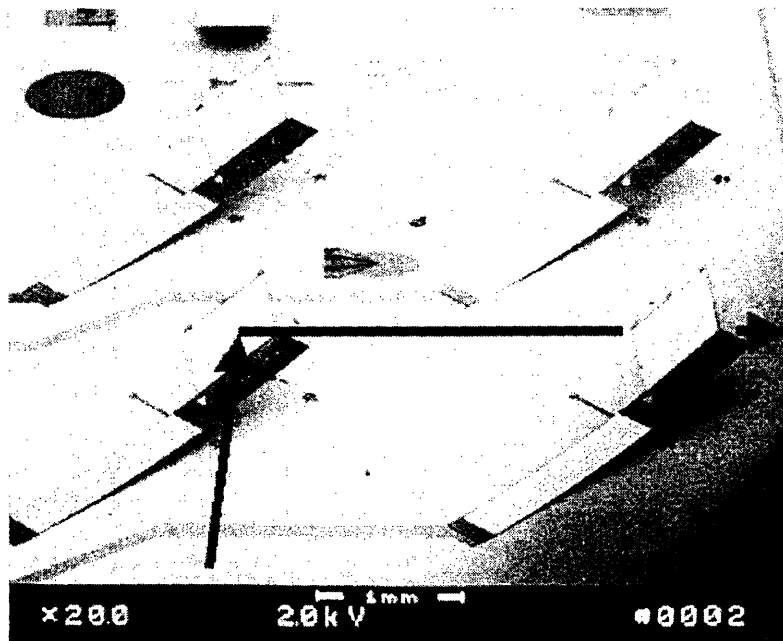
Figure 27    A 2×2 optical switch using RSC (Residual Stress Cantilever) actuators and
fold-up mirrors. When actuated, the mirror is pulled down to the substrate,
reflecting the optical beam as shown [47].

Optical switch is the device that can modulate light in a controllable way. The reason why optical switches are critical is that, "the explosive growth of data traffic, such as the Internet, has produced a pressing need for large-capacity optical networks. Optical switches are now in high demand in the telecommunications industry for their ability to reconfigure an optical network for traffic management or circuit protection without having to resort to low-bandwidth, protocol-dependant, opto-electronic conversions" [47]. As a matter of fact, there are already a lot of MEMS driven optical switches in the market, which can be integrated into the whole data network.

Also, in recent years, the so-called "microphotonics" has become a hot research topic [48]. The meaning of "microphotonics" is that, all the digital signal processing could be done using photons instead of electrons. Then, the electronic integrated circuits would be replaced by integrated optical networks, comprised of photon emitters (LED or laser), optic fibres, couplers, modulators, photo-detectors and etc. The advantage of this idea lies in the fact that electronic

circuits can not get rid of RC delay and there are complex interactions between electrons, and such effects would become more and more evident when people scale down the device. On the contrary, there is no interaction between photons and the speed photons transmit through a medium only depends on the refractive index of that medium, thus the delay caused by interconnects would be greatly alleviated and become much less complicated (however, the so called "dispersion" effect comes in, while people already have good ways to deal with that). It has become a general consensus that if microphotonics turns out to be successful, it may move our "information era" to a totally new stage.

In microphotonics, optical switches are indispensable. As shown in Figure 27, we need to use micro-switches to modulate light and guide it in the desired way. This is where thin film phase change materials based MEMS actuators can play a great role. We could deposit materials of high reflectivity on to beams with phase change materials on them, and then the deformation of the beams would cause the light to bend, i.e. modulate light. What is more, the optical processing operates at high frequencies (GHz regime), and section 4.2.3 shows that the existing phase change material based device already can work in such frequency regime. An extra is that phase change material actuators can do pretty large amount of work (Piezoelectrics can work in the same frequency range, but can not produce as much work. While, shape memory alloys and hydraulics can do as much work but can only work at up to 10Hz). Consequently, there is no doubt that phase change material based actuator is the best choice for optical switches.

Although microphotonics and optical integration are only at their research stage and no real market or market forecast exists, undoubtedly, if successful, such technology would become a great breakthrough and has the potential to replace today's electronic integrated circuits industry, which is a hundreds of billion dollar's business. Therefore, as a critical component of microphotonics, thin film phase change material optical switches would have a limitless market scenario.

## 4.5 Business Model

In this section, IP model and product model would be examined. I neglect other kind of business models, because here I would like to analyze the problem from a scientific point of view. I suppose we are materials scientists, who have important IP(s) on this field and would like to put it into real market.

## 4.5.1 IP Model

Undoubtedly, IP model is the easiest model people can imagine, especially for those who are researchers or engineers inventing new technologies themselves. Because this field (thin phase change material-based actuators) is almost virgin soil, thus, various patents could be filed on the fields of structure and device, fabrication, packaging, testing, and etc.

One distinct difference of actuation application from non-volatile memory application is that, the phase transformation is usually not triggered by electronic circuits, but by laser beams, and MEMS actuators are not necessarily a part of integrated circuits, so the integration issue no longer exists and the complexity of the device decreases significantly. The actuators/switches can be made into an independent modular device e.g. optical modulators, or polychromators [49], which serves as either an individual product, or a critical component/sub-system in an optical integrated system.

The "Polychromix" polychromator is a good example [49]. It was invented by MIT professor Prof. Senturia and his PhD students. It is a modular optical subsystem based on an innovative core technology platform that enables dynamically re-configurable optical networks. Its main function is to detect and analyze the composition of the sample with high accuracy. The key component in the device is a series of electrostatic actuators. Prof. Senturia and his students developed the structure of the device and its process flow, then filed core IPs for such device. After that, they started the "Polychromix" company and got venture capital investment from Siemens Venture Capital [50]. What they do is that, they give the design to relevant

manufacturers to make the products, which labeled the trademark "Polychromix". Therefore, "Polychromix" has a different IP model with Ovonyx in the non-volatile memory market. "Polychromix" makes money not by receiving royalty fees, but directly by designing and selling their product.

In my opinion, IP model would still be the choice for new companies in the phase change actuator/switch market, because it needs less money in the initial stage, and the financial risk would be low.

## 4.5.2 Product Model

Unlike non-volatile memory cells, the actuators/switches can make independent devices, therefore, the cost for new companies to build a production line for actuators/switches would be much lower than that of building an integrated circuits manufacturing factory. Further, the structure of actuators/switches is much simpler, and thus lowers the fabrication cost.

After consulting some professionals [51], cost estimation for building a factory manufacturing actuators/switches is given as below:

- Price of main machines (sputter machine, facilities for lithography, etching, and etc.) : approximately $1,000,000USD
- The cost of building a clean room is about $1,500USD per square meter, and at least 1,000 square meter's space is needed, supposing that we want to establish a small actuator/switch manufacturing factory in Boston area.

Therefore, the initial investment should be at least $3,500,000USD. It is not a small number. What is more, to maintain such a factory, only one product (phase change material based actuators) seems not to be enough. The facilities, e.g. sputtering machine and lithography equipment, can be used for manufacturing other products as well, such as thin film shape memory alloys (TiNi alloy) or thin film thermal expansion actuators/sensors. But producing

other stuffs might well beyond the expertise of the company founders (suppose them as materials scientists specialized in phase change materials), and thus make the company not competitive enough compared with the professional manufacturing companies.

## 5. Summary

In this thesis, thin film phase change material based technologies are examined, basically from a materials scientist's point of view. Two potential markets, non-volatile memory market and MEMS actuator market, are discussed. Both of them are fast growing and rapidly changing, where new technologies are badly desired. It turns out that, devices made of phase change materials can give superior performances on both fields and thus are very promising to become the dominant technologies. IP models are preferred for both markets because there is great IP space in each of them. Rough estimation for cost and revenue is given, in which the bright future and nice business opportunity for phase change material-based enterprises are shown.

## Acknowledgement

I owe my greatest thanks to my thesis supervisors, Prof. Carl Thompson of MIT and Prof. Li Yi of NUS. They are both highly accomplished scientists, and I learnt a lot from their erudition, and broad academic perspectives during the past year. But what impressed me more are their working spirits. Last December, in the Mexican food restaurant on MIT campus, Prof. Thompson told me that he seldom drives to school, but instead, takes "T" to work every day. The reason is that, on the train, he is able to read papers and books but if when driving a car, he would be not. Prof. Li works six and half days a week and almost always goes back home after having supper at school. The diligence of those two professors constantly encourages and empowers me to devote myself to scientific study, and frankly, whenever I meet difficulties in my work, I would think of them and then regain courage.

Secondly, I would thank Singapore-MIT Alliance (SMA) faculties Prof. Choi Wee Kiong and Prof. Chua Soo Jin. On March 14th, 2005, I attended the interview for prospective incoming SMA graduate students in Hilton Hotel of Beijing, and these two professors were the interviewers. During the interview, their scholastic and modest manners left me great impression on the SMA program and faculties, and finally helped me make the decision of coming to Singapore. I will appreciate them all my life.

I must thank my family. My father, a scholar of Greek history, endows me the calibers of critical thinking and helps me form a sensible character. My mother, a high school teacher of music and a woman of kindness and strong will, is the root of my strength and power of my moving ahead.

My best friends in SMA, Xiaodong Wang and Miao Wang, accompany me from US to Singapore. We walked along Freedom Trail together, visited Boston Museum of Fine Art together, cooked Thanksgiving dinner together, work together, share the happiness and bitterness together. Without them, my life could not be so colorful and meaningful.

I will continue to do my SMA PhD after this MIT M.Eng. study. I really know the academic journey I have undertaken. The way ahead is long and brambly, but I believe, with the help and encouragement from my professors, parents, and friends, I could do something different and enjoy great pleasure from scientific work.

July 2, 2006

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