

# Emulation of spike-timing dependent plasticity in phase-change memory cells for neuromorphic applications

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## ABSTRACT

We emulate the spike-timing dependent plasticity (STDP) behavior of biological synapse in two phase change memory (2-PCM) cells with 3x nm technology, which has been considered as a formulated Hebbian learning rule of our cognition, learning and memory abilities. Various STDP behaviors are successfully realized in 2-PCM synapse by varying the interval of set pulses on two cells and their pulse shape as well, which helps to design diverse synaptic connection abilities. In addition, its small form factor and low energy per synaptic event compared to conventional silicon neuron networks (SiNs) make very promising candidate for electronic synapse in the large-scale neuromorphic system applications.

**Key words:** phase change memory, synapse, neuron, spike-timing dependent plasticity

## 1. INTRODUCTION

The cognition and learning capabilities of human being are attributed to signal receiving, transmission and storing abilities of numerous neurons in the neocortex. Figure 1 shows the schematic of two pyramidal neurons which occupies 80% among tens of billions neurons in our neocortex and in-between synapses, where it is known that the signal receiving and transmission are achieved by the generation of action potential in soma and its propagation along axon of the neuron, respectively (integrate-and-fire) while the signal storing is determined by the connection strength of synapse between neurons (learning and memory). Recently, it has been also known that so-called spike-timing dependent plasticity (STDP) is a timing algorithm accounting for a Hebbian learning rule which attributes our cognitive, learning, and memory abilities to the strength of synapse connectivity [1]. However, most SiNs are quite inappropriate to practical use in neuromorphic applications since they do not only occupy large area but they consume large power due to their complicated circuits [2, 3]. Recently, single electronic devices with multi resistance levels of transition metal oxide [4], Te-based phase change material [5, 6], or AgSi [7] are paid attention to since they have emulated STDP behaviors with nano fabrication technologies in semiconductor industry. In particular, the phase change memory based on the phase transition between amorphous and crystalline Ge-Sb-Te material is most promising because it has very similar functionalities to biological synapses [8] and it is matured in the mass production level in non volatile memory of phase change random access memory and optical recording media of CD-RW and DVD-RAM during last decades [9].

As shown in Fig. 2(a), the strength of synapse ( $\xi$ ) is positive (the synaptic connectivity is potentiated) and becomes higher at short  $\Delta t$  when the action potential in pre-synaptic neuron precedes one in post-synaptic neuron ( $\Delta t > 0$ ), which is called as long-term potentiation (LTP). On the other hand,  $\xi$  is negative (the synaptic connectivity is depressed) and becomes negatively higher at short  $\Delta t$  when  $\Delta t < 0$ , which is long-term depression (LTD). Figure 2(c) shows a typical STDP consisting of LTP and LTD in biological neuron. And Fig. 2(d) gives a CMOS logic circuit for STDP which requires too large area from many transistors to be used for practical applications. In this study, we show various STDP behaviors by varying the interval of set pulses on two cells and their pulse shapes as well in two phase change memory cells with 3x nm technology.

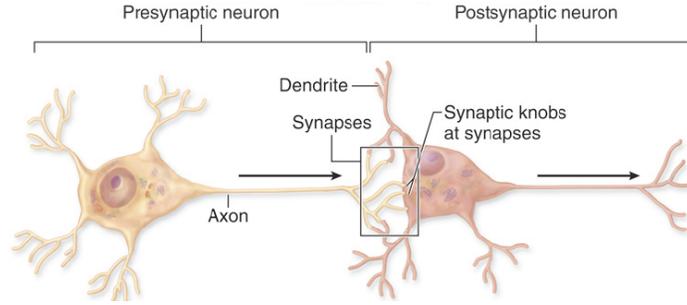


Figure 1 Typical pyramidal neurons and synapses in our neocortex.

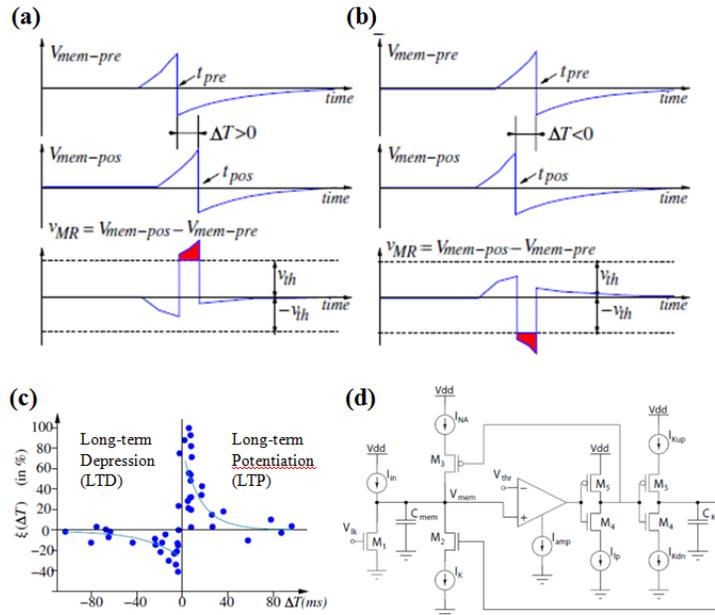


Figure 2 Membrane voltage waveforms [1] in (a) LTP (long-term potentiation), (b) LTD (long-term depression) (c) typical STDP in biological neuron [1] and (d) A CMOS circuit for STDP emulation [2].

## 2. EXPERIMENTS

Phase-change memory cells with the stacking structure of top electrode/GeSbTe/bottom electrode/pn diode are considered as shown in Fig. 3, where each cell at the crossing point of one wordline and one bitline can be independently programmed to have many resistance levels by applying various voltage pulses to the corresponding bitlines. For emulating an STDP of one synapse, we take into account two phase change memory cells (2-PCM) which are connected to pre-synaptic and post-synaptic neurons via their respective bitlines (is designated as BL1 and BL2). After reset initialization by a 5V reset pulse with the width of 10ns-rising, 80ns-duration, and 10ns-falling for two cells to be high-resistive, we have applied independent set pulses, as shown in Fig. 4. Here, it is noted that the set voltage to BL1 is fixed for the cell at BL1 to be always low-resistive whereas the set voltage to BL2 is modulated to have various resistance levels so that two cells have the different resistance values with respect to the time interval between set pulses to BL1 (pre-synaptic) and BL2 (post-synaptic). It is also noted that the cells are always reset with a reset pulse of 5.0 V with 10ns/80 ns/10ns widths before each set pulse process so as to have similar resistances of  $2M\Omega$ – $4M\Omega$ . An example of interval time-

dependent set voltage modulation of BL2 is described as Fig. 4(c), where it is noted that the set voltage at BL2 is inversely proportional to  $\Delta t$  as seen in right inset figure.

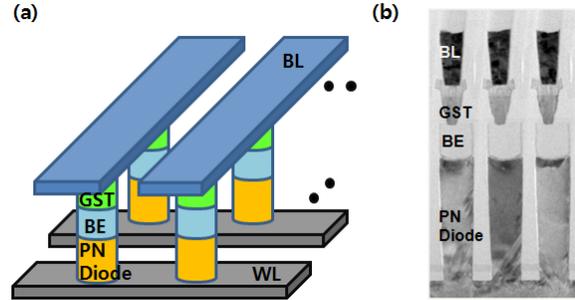


Figure 3 (a) Schematic diagram of phase change memory cell array and (b) its vertical image

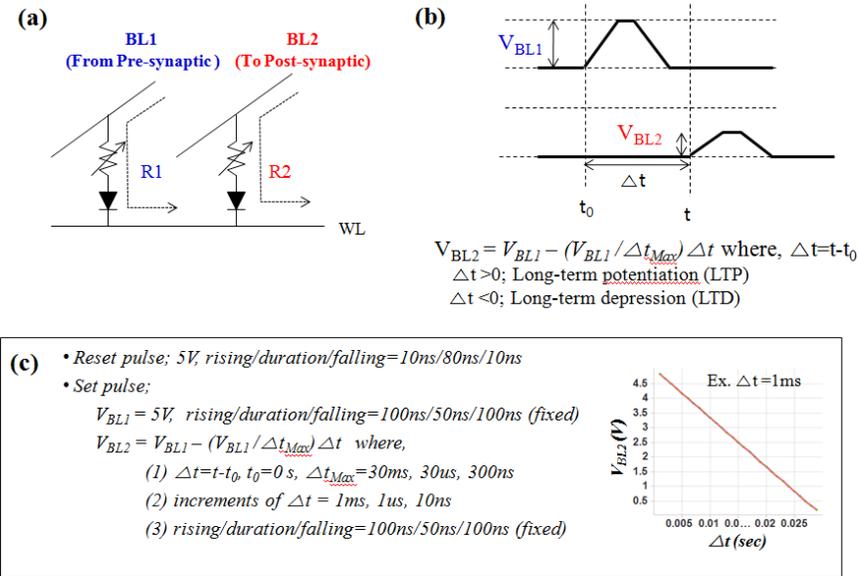


Figure 4 (a) A schematic of 2-PCM synapse in phase change memory cell array (b) Pulse shape with time interval of  $\Delta t$  and (c) Pulse voltage conditions in 2-PCM synapse for emulating STDP behaviors.

### 3. RESULTS & DISCUSSION

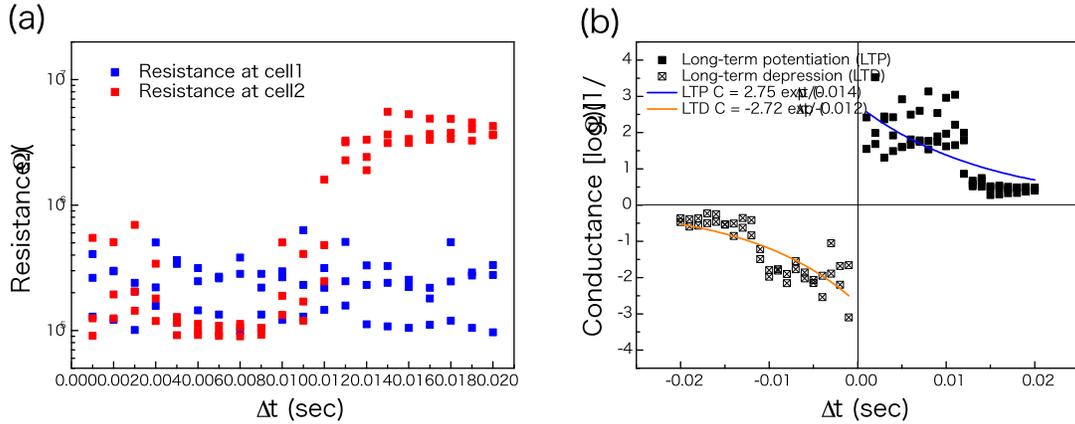
Under the pulse conditions as listed in Fig. 4(c), a cell at BL1 has always a low resistance since the fixed set pulse through BL1 can make the cell to be fully crystallized. However, a cell at BL2 can have low resistance values at small  $\Delta t$  due to high  $V_{BL2}$  whereas its resistance remains high resistive at large  $\Delta t$  due to too low  $V_{BL2}$  to crystallize, as shown in Fig. 5(a). Since  $1/(R_{BL1} - R_{BL2})$  is regarded as the conductance in 2-PCM synapse ( $C_{2-PCM}$ ), we can achieve high conductance at small  $\Delta t$  whereas low conductance at high  $\Delta t$ . Accordingly, we can obtain an STDP behavior when the  $C_{2-PCM}$  is regarded as

$$C_{2-PCM} = \frac{\Delta t}{|\Delta t|} \log \frac{10^7}{|R_{BL1} - R_{BL2}|}, \text{ as shown in Fig. 5(b). Similar to biological one [1], we can fit such}$$

conductance changes in 2-PCM with respect to  $\Delta t$  as exponential decays as Eqn. 1 where  $\tau^+$  or  $\tau^-$  is a characteristic time parameter and  $a^+$  or  $a^-$  is a scaling factor, respectively.

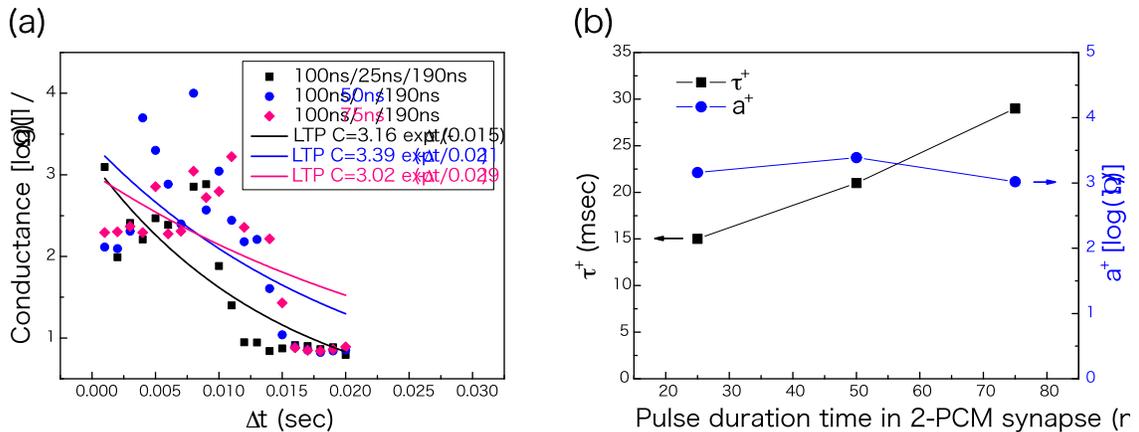
$$C_{2-PCM}(\Delta T) = \begin{cases} a^+ e^{-\Delta T/\tau^+} & \text{if } \Delta T > 0 \\ -a^- e^{\Delta T/\tau^-} & \text{if } \Delta T < 0 \end{cases} \quad (1)$$

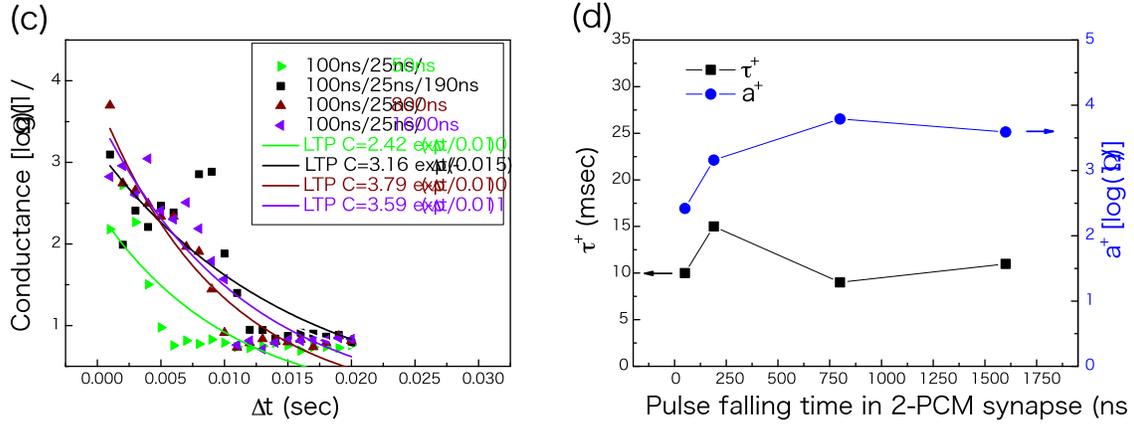
In case of Fig. 5(b),  $\tau^+$  is 14msec and  $\tau^-$  is -12msec, respectively. It is known that biological synapses have  $\tau$  values with tens of msec [5].



**Figure 5 (a) Resistance changes of cells in BL1 and BL2 under the pulse condition as shown in Fig. 4(c), where  $\Delta t_{Max}$  is 30msec. (b) Conductance as a form of  $\log[1/(R_{BL1}-R_{BL2})]$  with respect to  $\Delta t$  which is quite analogous to STDP in biological neuron as already shown in Fig. 2(c).**

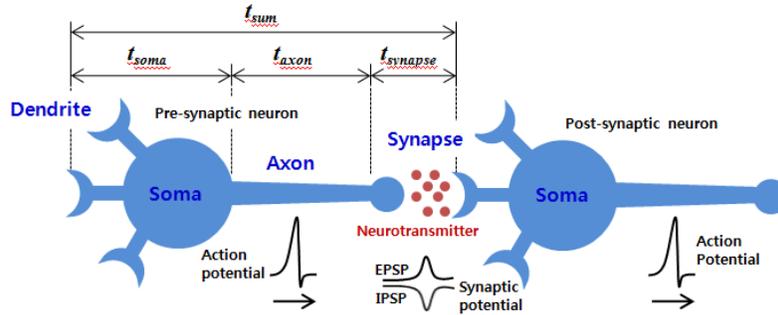
We examine how the pulse shape affects the STDP behaviors in 2-PCM synapse. The set pulses which induce the crystallization of initially reset (amorphous) cells at BL1 and BL2 have slow-quenched set pulse forms with tunable rising/duration/falling widths. Firstly, when the duration width is varied from 75ns to 25ns [Fig. 6(a)], the corresponding  $\tau^+$  decreases while  $a^+$  is rarely changed as the duration is decreased [Fig. 6(b)]. It is well known that slow-quenched type set pulse is not enough to crystallize especially when its duration width is smaller since the amorphous region is not melted and/or total set pulse width is effectively shorter than required. Thus, at lower duration width such as 25ns, a cell at BL2 is partially crystallized at small  $\Delta t$  so that its resistance is higher than a cell at BL1 to make the conductance lower. Next, the decrease in falling time does not largely affect  $\tau^+$  value but makes  $a^+$  value smaller, as shown in Fig. 6(d). Accordingly, the duration time in set pulse shape is effective to change  $\tau^+$  value whereas the falling time is to  $a^+$  value in 2-PCM synapse in this study.





**Figure 6 (a) LTP behaviors and (b) the corresponding  $\tau$  changes with respect to the pulse duration time in 2-PCM synapse. (c) LTP behaviors and (d) the corresponding  $\tau$  changes with respect to the pulse falling time in 2-PCM synapse.**

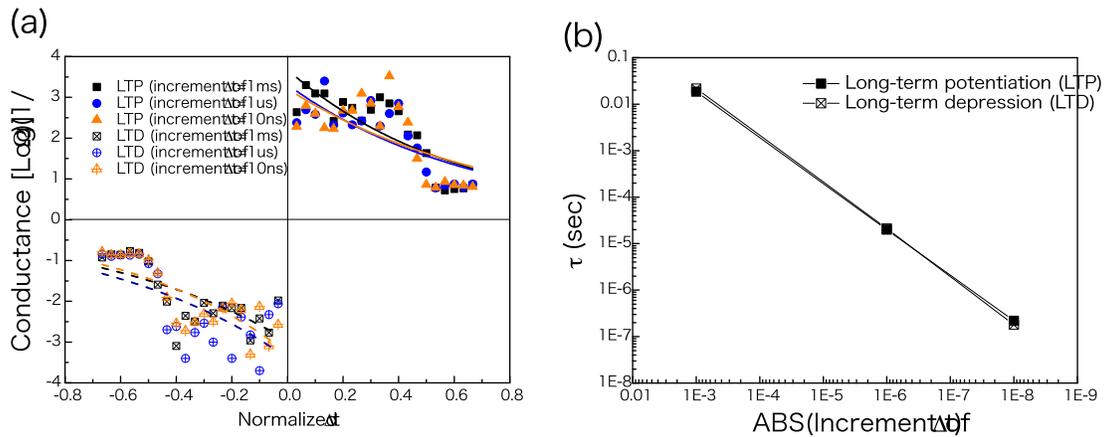
On the other hand, it is believed that the signal transfer time per one spiking-and-synaptic transfer event ( $t_{sum}$ ) is a basis to determine the overall signal processing speed in biological neuron network and it can be composed of three sequential processes; (1) the integration-and-fire time of synaptic potentials in cell body or soma ( $t_{soma}$ ), (2) the electro-chemical transfer time at synapse ( $t_{synapse}$ ), and (3) the propagation time of generated action potential along axon ( $t_{axon}$ ), as depicted in Fig. 7.



**Figure 7 Schematic of two neighboring neurons and an in-between synapse for showing a spiking-and-synaptic transfer event.**

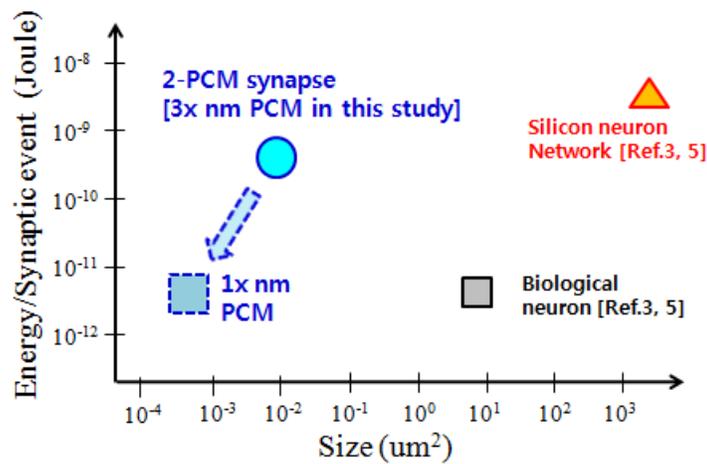
That is,  $t_{sum} = t_{soma} + t_{synapse} + t_{axon}$  (2)

where  $t_{axon}$  is as short as nsec or  $\mu$ sec at most because the propagation speed of action potential is as fast as  $\sim 150$ m/sec along axon with the length from  $\mu$ m to mm whereas it is known that  $t_{soma}$  and  $t_{synapse}$  have time scales of a few and tens of msec [2]. Thus  $t_{sum}$  is mainly determined by  $t_{soma}$  and  $t_{synapse}$ . Here, we only consider  $t_{synapse}$  which can be also represented by  $\tau$  value in Eqn. 1 since  $\tau$  indicates how fast the synaptic transfer (synaptic connectivity) is achieved. Accordingly, it is worthy to evaluate how small  $\tau$  can be smaller. Figure 8 shows that we can achieve good LTP curves to get  $\tau$  values as small as tens of a few  $\mu$ sec and hundreds of nsec when the incremental step in  $\Delta t$  is decreased to  $\mu$ sec and nsec ranges. This means that the 2-PCM synapse has faster synaptic transfer time ( $t_{synapse}$ ) by several orders of magnitude compared with biological neurons or SiNs.



**Figure 8 (a) LTP and LTD behaviors when the increment of  $\Delta t$  is changed from msec to  $\mu$ sec and nsec (b) the corresponding  $\tau$  values.**

The 2-PCM synapse in this study occupies the area of  $\sim 0.01 \mu\text{m}^2$  at most by adapting 3x nm technology for fabricating phase change memory cells, which is much smaller by several orders of magnitude than those of biological and conventional SiNs synapses, as shown in Fig. 9. As for the energy per one synaptic event, it consumes the energy per synaptic event of  $\sim 100\text{pJ}$  which is lower than SiNs but still higher than that of biological neuron. Since the power and speed of phase change memory cell can be achieved below tens of  $\mu\text{A}$  and tens of nsec, respectively [10], it is estimated that the energy consumption per synaptic event can be comparable to that of biological neuron when adapting the phase change memory cells at sub 10nm technology.



**Figure 9 Comparison of synapse area and energy per synaptic event among the biological, SiNs synapses [3, 5] and 2-PCM synapse in this study.**

#### 4. CONCLUSION

Low power consumption, small form factor, and high reliability are prerequisites to emulate a spike-timing dependent plasticity (STDP) in biological synapse for large-scale neuromorphic systems. In this study, we successfully emulate various STDP behaviors in 2-PCM synapse with 3x nm phase change memory cells by changing the set pulse shapes such as duration and falling times. In addition, it is demonstrated that the synaptic transfer time can be reduced as short as hundreds of nsec which is much faster than those of biological or conventional SiNs synapses. Thus, the 2-PCS synapse in this study is very likely to be more advantageous for high-speed and high-capacity neuromorphic applications, which enables mass-production-level PRAM to be a strong candidate for neuromorphic applications.

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## Biographies

Dr. Dae-Hwan Kang was born in 1968. He received a B.E in Materials Science and Engineering from Pohang University of Science and Technology, Korea. And he received an M.E and Ph.D. degree in Materials Science and Engineering from Seoul National University, Seoul, Korea, respectively. He was a senior researcher at KIST (Korea Institute of Science and Technology) working on the material design for developing low-power and high-speed phase change memory and in-situ electrical evaluation of the threshold switching and crystallization processes of amorphous chalcogenide semiconductors. Then he joined phase-change random access memory (PRAM) development team at Samsung Electronics in 2005 and he has been a principal engineer working on mass production of world-first 512Mb PRAM with 82nm technology and on the development of low-power and high-speed cell technologies for next-generation phase change memory device.