Ternary Content Addressable Memory with Individuality on FPGA

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Abstract—This paper presents a Ternary Content Addressable Memory with Individuality (ITCAM), which has individuality for data retrieval that is caused by the manufacturing variations of each LSI. The results of the maskable search by the ITCAM are different for each LSI. The ITCAM was implemented on three FPGA evaluation boards and tested in practice. The evaluation results showed that the data retrieval for each LSI is a little different due to the manufacturing variations and there were 179 (13%) more occupied slices, when comparing the ITCAM and conventional TCAM. Thus, the reported ITCAM is a promising solution for providing a little individual difference to each LSI.

1. Introduction

Content Addressable Memory (CAM) has recently become important for use in robotics technology [1] and artificial intelligence [2]. The processing capability of CAM is also faster than when using software-based CPU and hardware ASICs and is used in such as the obstacle avoidance function of a robot. Robots are used for various applications, such as nursing care, and there are also robots that can talk and express feelings [3].

The Ternary Content Addressable Memory with Individuality (ITCAM) was developed as the first step in our study for generating a little individual difference to the data retrieval of each LSI due to manufacturing variations. There are several kinds of manufacturing variations, and we decided to use delay variations in this study. The ITCAM uses delay variations for effective maskable search processing. The delay variations exist in the comparators that are included in the ITCAM. The many ring oscillators were configured by using the comparators of ITCAM and the difference in their frequencies was used as the individual difference. Therefore, it is an efficient method that can provide an individual difference to each LSI.

2. Related researches

There are researches currently being conducted to reduce manufacturing variations [4], [5]. Several researchers have tried to suppress the manufacturing variations because they reduce the hardware reliability. On the other hand, several researchers have used manufacturing variations to develop unique LSIs like the Physical Unclonable Function (PUF) [6-9]. PUF technology generates unique identifiers due to their manufacturing variations. PUF has attracted attention recently as a technique for preventing the replication of LSIs, and PUFs that use the delay variations of the ring oscillators have been previously used. In addition, a CAM and ring oscillator combination has been studied to improve the performance of the CAM [10], [11]. The delay variations of the ring oscillators of the ITCAM with exception of the PUF are considered in this study. The developed ITCAM conducts slightly different data retrievals for each LSI by taking advantage of the delay variations of the ring oscillators.

3. Individuality Ternary Content Addressable Memory

This section discusses the architecture and describes the block diagram of the ITCAM in detail. The ITCAM was developed based on the TCAM so that the delay variations of the comparators can be used as the individual differences of each LSI.

The TCAM is obtained by adding mask memory cells to each word block of the Binary Content Addressable Memory (BCAM) and a 'don't care' can be used by setting a mask in each bit. The ITCAM uses the comparators as a ring oscillator and uses the mask memory as a counter. The ITCAM can store the delay variations in the mask memory, so the difference in each word and LSI will appear in the search results. Figure 1 shows a conceptual diagram of the ITCAM of word number 2^a with a word length of n bits. The ITCAM has the input data of n bits, the search data of n bits, the mask data of n bits, and the delay variations acquisition signal of 1 bit. On the other hand, the outputs are a 1 bit match signal and an a bits address value.

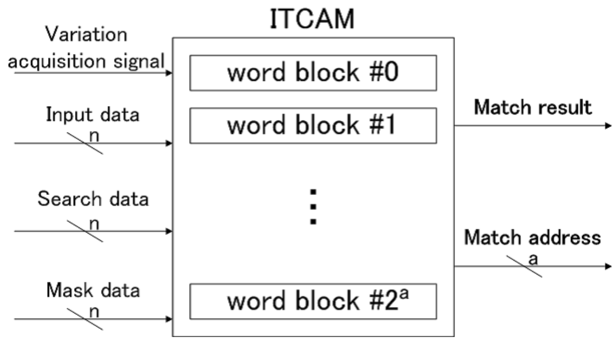

Figure 1: Block diagram of ITCAM.

The memory cell, comparator, and mask memory cell in a one word block are shown in Fig. 2. Here, Figs. 3 and 4 show the word block configuration.

When the variation acquisition signal is a 0, each word performs a search using the input, search, and mask data. The ITCAM performs the same operation as the TCAM.

When the variation acquisition signal is a 1, one of the XNOR logic inputs is fixed at 0, and the XNOR logics is used as inverters. The XNOR logics of n bits are used as a comparator to form a ring oscillator by connecting to the ring form. The output of the ring oscillator is input to the n bits counter using a register of the mask memory cell. Since the frequencies are different due to the delay variations, the value of the counter is different for each word and LSI. When performing a comparison operation, the value of the counter is used as the mask value. A bit where a 1 is stored in the mask memory cell is treated as a 'don't care' when performing comparisons. If the variation acquisition signal passes a predetermined time, it automatically returns to 0, and the ITCAM is transitioned to the state shown Fig. 3 for performing the comparison operation. The value stored in the mask memory cell is the difference due to the delay variations, so the search results for each word and LSI are different.

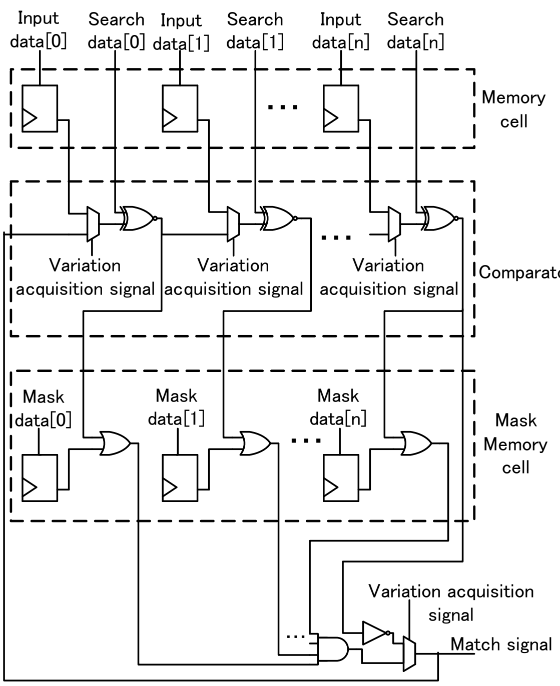

Figure 2: Block diagram of Word block.

4. Implementation and Experimental Results

The ITCAM was implemented in the FPGA evaluation board to verify the difference in the search results for each LSI. Figure 5 shows the experimental environment. Three FPGA evaluation boards equipped with VIRTEX4 VC4VLX25 were used for checking the manufacturing variations. The images of the waveform in Fig. 5 represent the outputs of the ring oscillators of the ITCAM that were downloaded to the board and their difference in frequencies causes the ITCAM to output different results. The frequency of the ring oscillator of board1 is 15.7 MHz, board2 is 15.8 MHz, and board3 is 15.6 MHz. The ITCAM used in this experiment proposed 16 words that were all 32 bits long. Furthermore, its floor-plan for fixing the comparators is shown in Fig. 6. The floor-plan is required in order to obtain stable variations by fixing the placement and routing of the ring oscillators. Table 1 lists the imple-

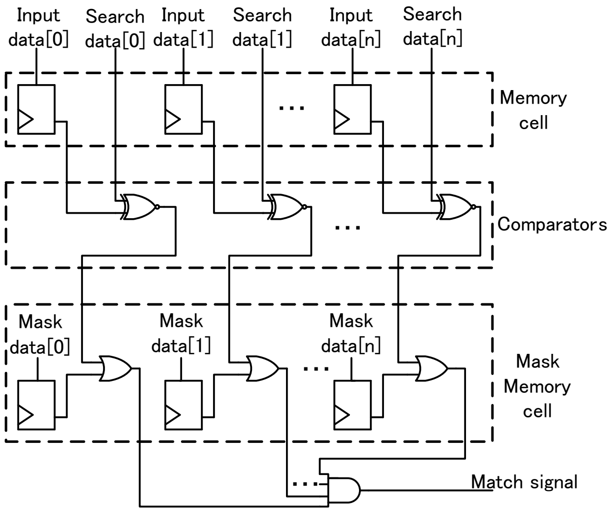

Figure 3: Block diagram of Word block when variation acquisition signal = 0. The ITCAM performs the same operation as the TCAM.

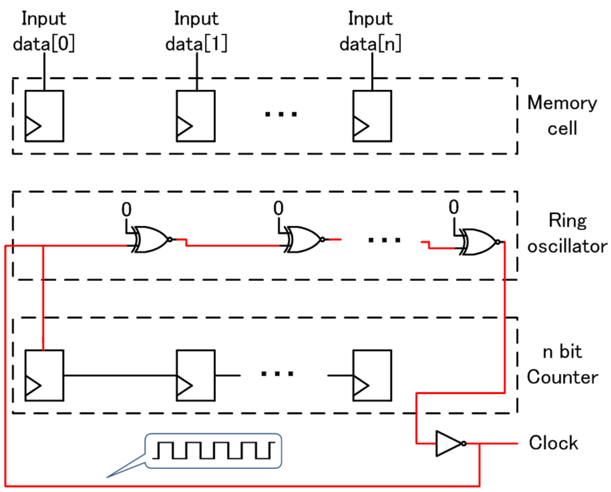

Figure 4: Block diagram of Word block when variation acquisition signal = 1. The ITCAM performs the operation for storing the delay variation of the ring oscillators.

mentation results of the TCAM and ITCAM. The ITCAM are calculated by using Xilinx ISE 14.6. Only about 1,490 of the slices in the ITCAM are occupied and this was an increase of 179 (13%) slices when comparing it with the TCAM.

Figures 7 and 8 confirm the variation values stored in the mask memory cells. In Fig. 7, the variation values in the addresses # 0, # 1, and # 2 on the same board are different. Thus we can see that different word blocks have different variation values. Figure 8 confirms the variation values for the same address word block of three boards are different. Thus, different boards also have different variation values. Figure 9 shows the search results obtained by using the ITCAM. The search data was set to all zeros, and the Hamming distance between the data in the memory cell was set to 2 for all the word blocks. The Hamming distance between the data and search data considering the mask data is shown in Fig. 9, and it was confirmed that the Hamming distance was reduced. In addition, the hatchings show the differences in the search results of each board in Fig. 9. It was confirmed from these results that each board outputs different search results.

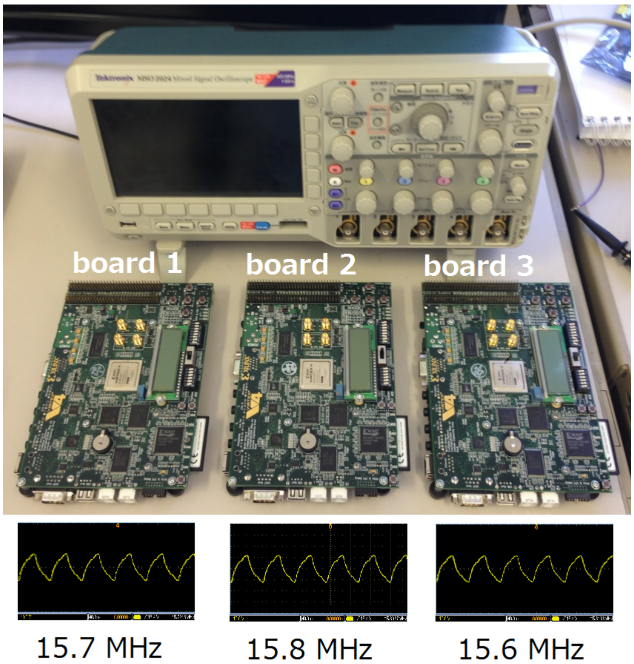

Figure 5: Experimental environment and difference in frequency of ring oscillators of each board.

Table 1: TCAM and ITCAM implementation results.

	TCAM	ITCAM
No. of Slice Flip Flops	1,164	1,135
No. of 4-input LUTs	1,364	2,301
No. of occupied Slices	1,311	1,490

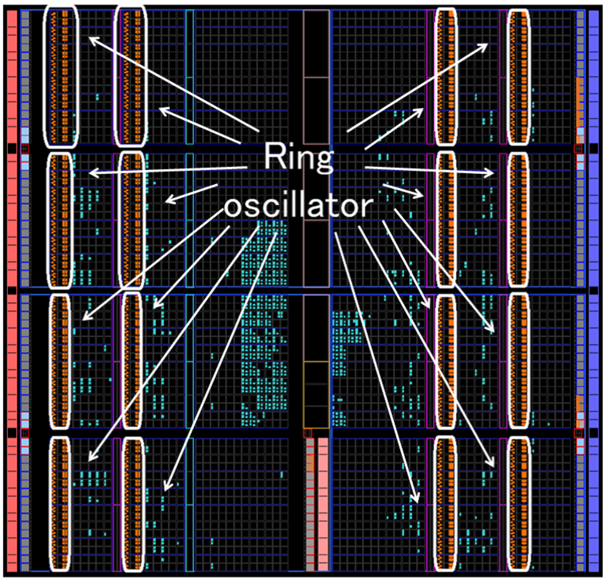

Figure 6: ITCAM floor-plan for obtaining stable variations by fixing placement and routing of ring oscillators.

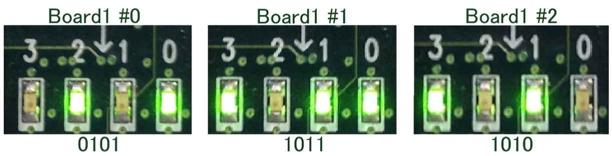

Figure 7: Differences in variations of each word block. Word for address 0 in Board1, word for address 0 in Board2, and word for address 0 in Board3.

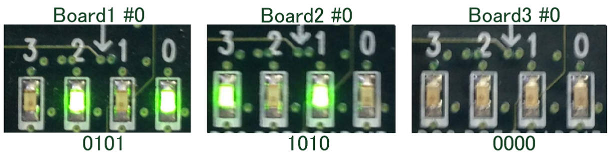

Figure 8: Differences in variations of each board. Word for address 0 in Board1, word for address 1 in Board1, and word for address 2 in Board1.

5. Conclusion

Ternary Content Addressable Memory with Individuality (ITCAM) was proposed as the first technological step for providing a little individual difference to the data retrieval of each LSI caused by delay variations. The ITCAM outputs different search results for each word and LSI by using the delay variations of the comparators as mask values. The confirmation of reproducibility of the variation values and application of ITCAM is scheduled in the future.

Search data 32'h00000000

	Board1	Hamming distance	Match signal	Board2	Hamming distance	Match signal	Board3	Hamming distance	Match signal
#0 Memory cell #0 Mask Memory cell	00000003 BDE6F0FB	0	1	00000003 BAA43DF7	0	1	00000003 C4048782	1	**0**
#1 Memory cell #1 Mask Memory cell	0000000C 75E39A8B	1	0	0000000C 6EAACEC6	1	0	0000000C 73C981F2	2	0
#2 Memory cell #2 Mask Memory cell	00000030 C8C84A6A	1	0	00000030 BD87074E	2	0	00000030 C44C8720	1	0
#3 Memory cell #3 Mask Memory cell	000000C0 47EAE821	2	0	000000C0 463EA206	2	0	000000C0 4D425DFB	0	**1**
#4 Memory cell #4 Mask Memory cell	00000300 01F75461	2	0	00000300 FB803D6E	1	0	00000300 05D74319	0	**1**
#5 Memory cell #5 Mask Memory cell	00000C00 4F1FA264	2	0	00000C00 48A20014	2	0	00000C00 5112BB64	1	0
#6 Memory cell #6 Mask Memory cell	00003000 C6296EF5	1	0	00003000 BE887176	0	**1**	00003000 C5166BE8	1	0
#7 Memory cell #7 Mask Memory cell	0000C000 FDBA7F5C	1	0	0000C000 F8B5504B	1	0	0000C000 FB7BBB0E	1	0
#8 Memory cell #8 Mask Memory cell	00030000 F9B7B77D	0	**1**	00030000 7D611BB4	1	0	00030000 FA60DF0C	2	0
#9 Memory cell #9 Mask Memory cell	000C0000 1B297BAF2	1	0	000C0000 DA32A09E	2	0	000C0000 DECDCC43	0	**1**

Hatchings are differences in search results of each board.

Figure 9: Differences in search results of each board. The same ITCAM is mounted on each board and each ITCAM was stored in the same dataset. Only the mask memory cell data is different.

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