FPGA Implementation and Evaluation of Ternary Content Addressable Memory with Individuality

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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 of each LSI. The results of the maskable search by the ITCAM are different for each LSI. The ITCAM was implemented on two FPGA chips and tested in practice. The characteristic evaluation results show that the mask value for each LSI and word is slightly different due to the manufacturing variations. The reproducibility of mask value was confirmed under certain conditions. The reproducibilities were 88%, 73%, and 32% for one FPGA chip (CHIP A) and 94%, 52%, and 47% for another (CHIP B) when the operating time of ITCAM is 8, 64, and 128 system clocks, respectively. Thus, the reported ITCAM is a promising solution for providing a little individuality to each LSI.

1. Introduction

Content Addressable Memory (CAM) has recently become important for use in robotics technology [1] and artificial intelligence [2]. CAM also has faster processing capability than when using software-based CPU and hardware ASICs and is used, for example, in the obstacle avoidance function of a robot. Robots are used for various applications, such as nursing care and conversation partners. However, the robots often give the same responses when communicating with humans. Thus, some software programs are used to implement individual differences in each of them [3].

To meet this challenge, the Ternary Content Addressable Memory with Individuality (ITCAM) was developed as the first step in our study for generating small individual differences in the data retrieval of each LSI due to manufacturing variations [4]. 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. Then, if the ITCAM is implemented in the control circuit, the robot will have a unique individuality like a human. Therefore, it is an efficient method that can provide an individual difference to each LSI.

2. Related Researches

There are studies currently being conducted to reduce manufacturing variations [5, 6]. 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) [7-10]. 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 [11, 12]. The delay variations of the ring oscillators of the ITCAM with the 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. Ternary Content Addressable Memory with Individuality

This section discusses the architecture and describes the block diagram of the ITCAM in detail. The ITCAM was developed on the basis of 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 differ-
ence 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 \(a\)-bit address value.

The memory cell, comparator, and mask memory cell in a one-word block are shown in Fig. 2. Here, Figure 3 shows the word block configuration.

When the variation acquisition signal is 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 1, one of the XNOR logic inputs is fixed at 0, and the XNOR logics are 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 \(n\)-bit 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 circuit of TCAM 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.

4. Implementation and Experimental Results

4.1 ITCAM on FPGA

Table 1 lists the synthesis results of the TCAM and ITCAM. The ITCAM are calculated by using Xilinx ISE 14.7. ITCAM has 6697 (47.7%) more Slice LUTs and 13.251MHz (17.2%) lower maximum frequency than TCAM. The ITCAM was implemented in the FPGA evaluation board (Fig. 4) to verify the mask value for each LSI and word. Two FPGA (Spartan6 xc6slx150) chips were used for checking the manufacturing variations. The floor-plan for fixing the comparators and mask cell LUT in shown in Fig. 5.
The floor-plan is required in order to obtain stable variations by fixing the placement and routing of the ring oscillators. The ITCAM is controlled by CPU through the terminal software to apply to the robot. Reproducibility of ITCAM was verified by checking the mask value three times under the conditions of the same place and route for each FPGA. This experiment was performed to investigate the balance between the reproducibility and variations. Also, these experiments were performed by varying the operating time of ring oscillators of 8, 16, 32, 64, 128, 254, and 512 system clocks.

<table>
<thead>
<tr>
<th>Number of Slice Registers</th>
<th>TCAM</th>
<th>IT CAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Slice LUTs</td>
<td>6,120</td>
<td>12,817</td>
</tr>
<tr>
<td>Maximum Frequency (MHz)</td>
<td>89.985</td>
<td>76.734</td>
</tr>
</tbody>
</table>

### 4.2 Characteristic evaluation

This section discusses the characteristic evaluation of the differences of each address in one FPGA chip and the same address between two FPGA chips. The characteristic evaluation is required in order to impart the individuality to the robot.

Figure 6 confirms the differences of each address in the same FPGA chip. Comparing the measured values and the average, variations were verified for each address in the same FPGA. Figure 6 shows the variations increase when operating time of ring oscillators is extended.

Figure 7 confirms the differences between the two FPGA chips of each address. In Figure 7, ring oscillators were operated for 32 system clocks. Thus, the variations between two chips were verified at the same address.
Figure 8 shows the relationship between the reproducibility and operating time of the ring oscillator. The reproducibility was calculated using the weighting. The weighting coefficient is 2 when three mask values are the same, 1 when two mask values are the same, 0 when no mask values are the same. When the operating time of ring oscillators is 8, 64, 128 system clocks, the reproducibilities were 88%, 73%, and 32% for one FPGA chip (CHIP A) and 94%, 52%, and 47% for another (CHIP B). The reproducibility of ITCAM was decreased by extending the operating time of ring oscillators in Fig. 8.

The decrease in reproducibility of ITCAM means that the variation of mask values increases. For example, the patterns of robot individuality are spread by increasing the variation of mask values. Thus, if a user can freely set the operating time of a ring oscillator, the pattern of reactions in the robot will be able to be changed.

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 characteristic evaluation results show that the mask value for each LSI and word is a little different due to the manufacturing variations and that reproducibility varies depending on operating time of ring oscillators. The ITCAM outputs different search results for each word and LSI by using the delay variations of the comparators as mask values. The interactive application of ITCAM is scheduled in the future.

References