CMOS COMPATIBLE MEMRISTOR ARRAYS: MATERIALS, INTEGRATION AND APPLICATIONS

A Dissertation Presented

by

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DEDICATION

To my family

ACKNOWLEDGMENTS

Thanks to all those fine shepherds. Not to mention all the great border collies and suchlike fine animals.

ABSTRACT

CMOS COMPATIBLE MEMRISTOR ARRAYS: MATERIALS, INTEGRATION AND APPLICATIONS

SEPTEMBER 2018

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In the past decades, the computing capability has shown an exponential growth trend, which is observed as Moores law. However, this growth speed is slowing down in recent years mostly because the down-scaled size of transistors is approaching their physical limit. On the other hand, recent advances in software, especially in big data analysis and artificial intelligence, call for a break-through in computing hardware. Memristor, or resistive switching device, is believed to be a potential building block of the future generation of integrated circuits. The underlying mechanism of this device is different from that of complementary metal-oxide-semiconductor (CMOS) transistors, which provides better scaling potential than that of CMOS transistors to make the Moores law last longer. More importantly, the resistance of the of the two-terminal device, depends on the history of the applied voltages, and therefore the

computing based on this device takes place in the exact location where information is stored. As the result, a revolutionary computing machine based on this device circumvent the need of data transfer between computing unit and memory unit in a conventional von-Neumann machine.

There are still challenges to build memristor based machine to solve real-world applications. As an emerging device, despite promising properties demonstrated in single device level, it is still not mature enough to make integrated circuit chip with decent array performance, mostly due to large spatial and temporal variation. The problems may be solved in the future by continuous device and material engineering, they can also be remedied with the help of the mature CMOS technology, while maintaining most advantages that memristor provides. In this dissertation, we present our experimental work to integrate memristors with CMOS circuitry and demonstrate real-world applications. Firstly, we explore the possibility to use CMOS foundry compatible material (e.g. silicon oxide and hafnium oxide) to make working memristors. After that we study the advanced memristor fabrication technology including three-dimensional stacking and foundry compatible integration with transistors. The maturity of the integrated memristor chip is then demonstrated by real-world applications, which includes an ex-situ method to precisely calculate matrix multiplication for signal and image processing and an in-situ method to compensate defects and variability for training of neural networks. The calculation based on this system suggests that, with integrated peripherals which will be available in the near future, the memristor based system gains significant advantages over the conventional digital CMOS approaches in both speed and energy efficiency.

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CHAPTER 1

AN INTRODUCTION TO SHEEP

Is there life after sheep? [1] Yes, I say there is.

1.1 Pulling the wool over your eyes

Sheep are fabulous creatures. The noises they make are truly stupendous [2]. We also want to refer to figure 1.1 here. Here's some verbatim text to screw us up:

```
xxx := y;
xy := x;
```

1.1.1 All about sheep noises

Lots of text here just to fill up some space so we can be sure that we really are double-spacing and doing all the other things that might be necessary in formatting a dissertation to U.Mass. guidelines. We're also going to have another figure here, figure 1.2, just for fun, and to make sure that the list of figures is formatted correctly. Now it's time for table 1.1. We really are going to need a third figure, figure 1.3, two more tables, table 1.2 and table 1.3 and a fourth figure, figure 1.4, just to really make sure.

Table 1.1. Some numbers.

Type of Animal	Minimum Observed	Average Observed	Maximum Observed
Cats	12	20	24
Dogs	20	20	20

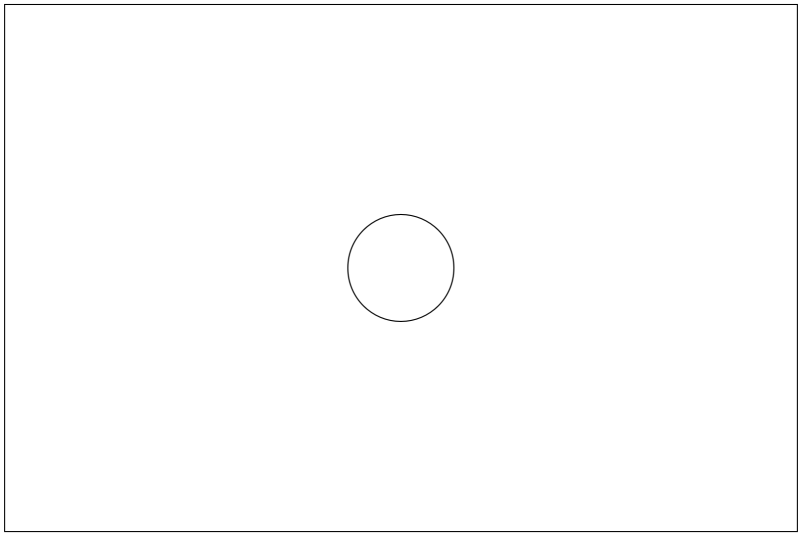

Figure 1.1. A circle in a square.

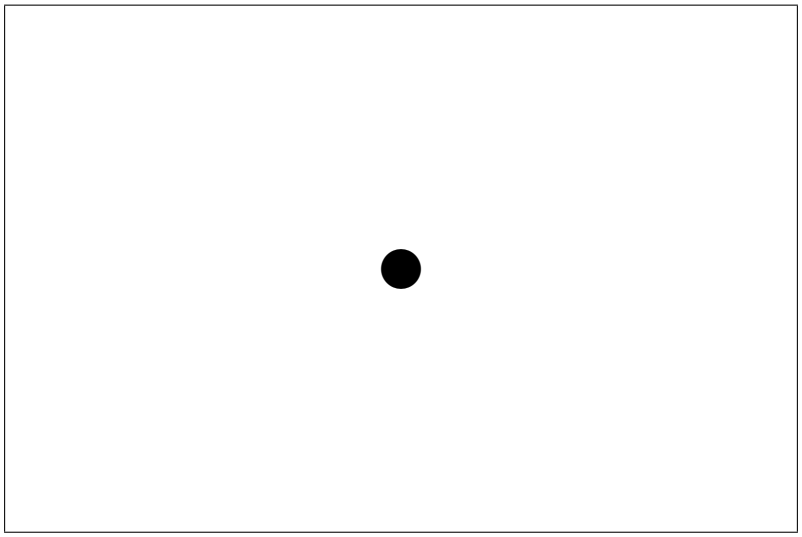

Figure 1.2. A disc in a square.

Table 1.2. More numbers.

Type of Animal	Arms	Legs	Ears
Person	2	2	2
Dog	0	4	2

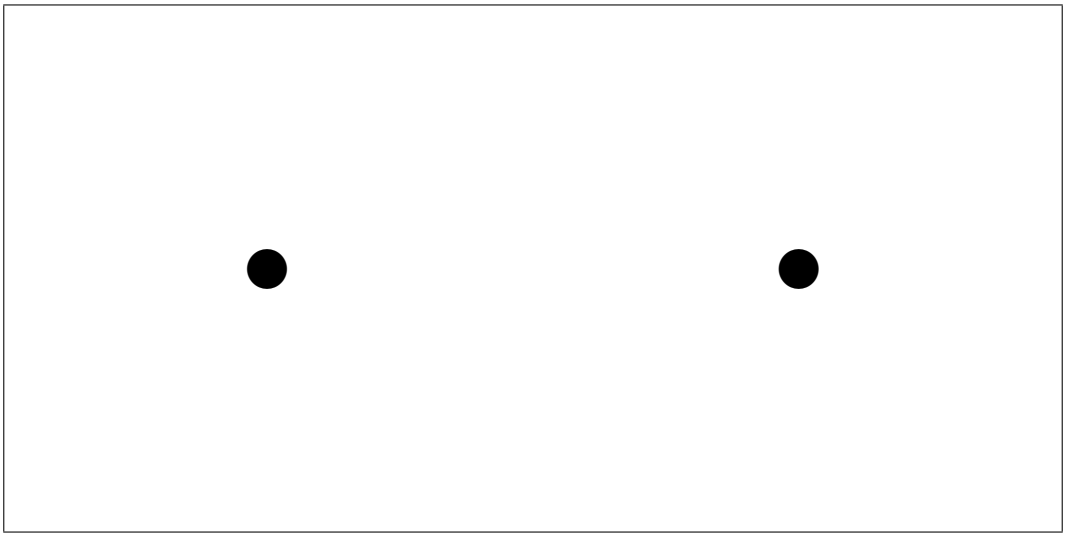

Figure 1.3. Two discs in a rectangle.

Table 1.3. Even more numbers; together with a caption long enough to ensure that multi-line caption formatting works correctly. If you want a shorter caption to appear in the Table of Figures you're going to have to put the shorter caption in the `[]` as shown in this example.

x	1	1	1
y	2	2	2
z	3	3	3

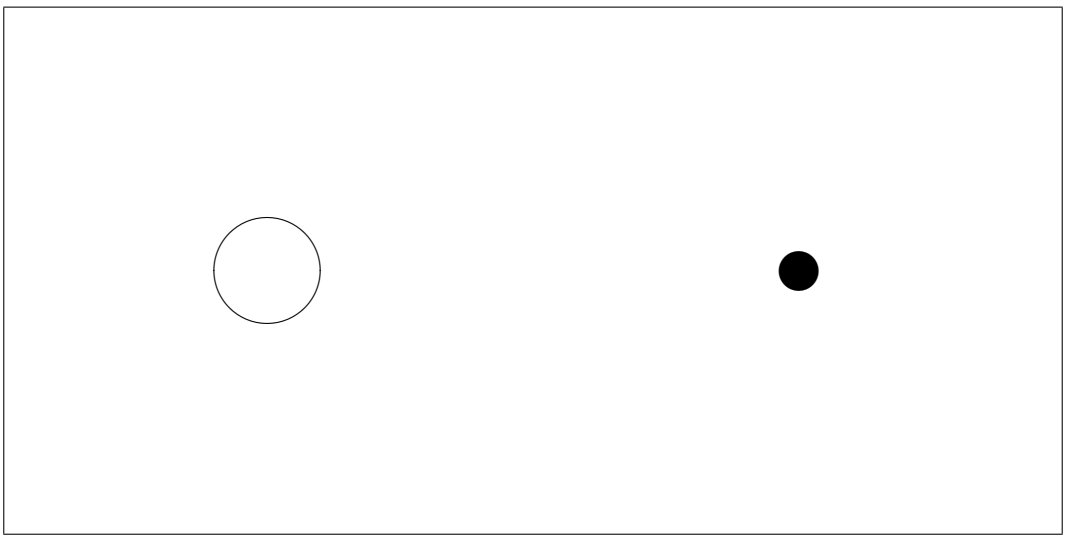

Figure 1.4. A circle and a disc in a square. We want this caption to be very long to ensure that the formatting of very long captions is handled correctly. The case of short captions has already been dealt with.

1.1.1.1 Baahs

1.1.2 Even more about sheep noises

1.1.3 And yet more about sheep noises

1.2 What about wolves?

What about wolves?[1]

1.3 What about shepherds?

What about shepherds? I don't really know, but I want some text here to fill things in so that I can verify that everything is OK.[2]

---

[1] To be fair, some wolves are probably nice...

[2] Some shepherds are good, some are bad. The reader is referred to Mary and The Boy Who Cried Wolf for further insight into this much-debated issue. (This needs to be a very long footnote so we can test the spacing between lines on a footnote.)

1.3.1 A subsection

This is a subsection of the subsection about shepherds.

1.3.2 Another subsection

This is another subsection of that section.

1.3.2.1 A subsubsection

This is a subsubsection of that subsection that will in turn havae a paragraph with a pair of subparagraphs. I am aware that I shouldn't have only one subsubsection in the subsection...

1.3.2.1.1 A Paragraph This is the text associated with this paragraph. I really want enough text to make it look like a paragraph. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah.

1.3.2.1.1.1 A Subparagraph This is the text associated with this subparagraph. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah.

1.3.2.1.1.2 Another Subparagraph Better not have subparagraphs without text in them. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah.

1.3.2.1.2 Another Paragraph Baah, baah, baah.

Baah, baah, baah. Baah, baah, baah.

1.3.2.2 Another Subsubsection

With some text. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah. Baah, baah, baah.

...

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[2] Scrooge, Ebenezer, and Shepherd, Alan. On the growth of green in space. *Journal of Astrophysical Economics 3*, 4 (August 1992), 47–89.