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Spintronics Based Non-Volatile MRAM for Intelligent Systems:
Memory for Intelligent Systems Design

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ABSTRACT

In this paper the spintronic-based memory MRAM is presented that showed how it can replace both SRAM and DRAM and provide the high speed with great chip size. Moreover, MRAM is the nonvolatile memory that provides great advancement in the storage process. The different types of MRAM are mentioned with the techniques used for writing purpose and also mention which one is more used and why. The basic working principle and the function performed by the MRAM are discussed. Artificial intelligence (AI) is mentioned with its pros and cons for intelligent systems. Neuromorphic computing is also explained along with its important role in intelligent systems. Some reasons are also discussed as to why neuromorphic computing is so important. This paper also presents how spintronic-based devices especially memory can be used in intelligent systems and neuromorphic computing. Nanoscale spintronic-based MRAM plays a key role in intelligent systems and neuromorphic computing applications.

KEYWORDS

Intelligent Systems, MRAM, Neuromorphic Computing, Spintronic and Non-Volatile

1. INTRODUCTION TO MRAM

MRAM stands for Magneto-resistive Random Access Memory. It is used to store the information with the help of magnetic field and the stored information can be retained or read after many years without any damage due to its non-volatility property. Non-Volatile Memory (NVM) is a sort of processor memory which can preserve the stowed data stably when the power is disconnected, whereas volatile needs continuous power to hold the data. MRAMs (Slaughter et al., 2002) described as a memory which utilize Magneto-resistance effect for the reading theory but not considering the writing principles. There are different type's magneto resistance effect like AMR, GMR and TMR. Popularize MRAM utilizeTMR (Tunnel Magneto-resistance Effect) and Junction which have TMR effect is named as MTJs. (Apalkov et al., 2016) (Bhatti et al., 2017)

The MRAM prime arrangements are based on MTJ (Magnetic Tunnel Junction) (Zhang et al., 2020) is an active device in which the double Ferro-Magnetic films are detached by the insulated

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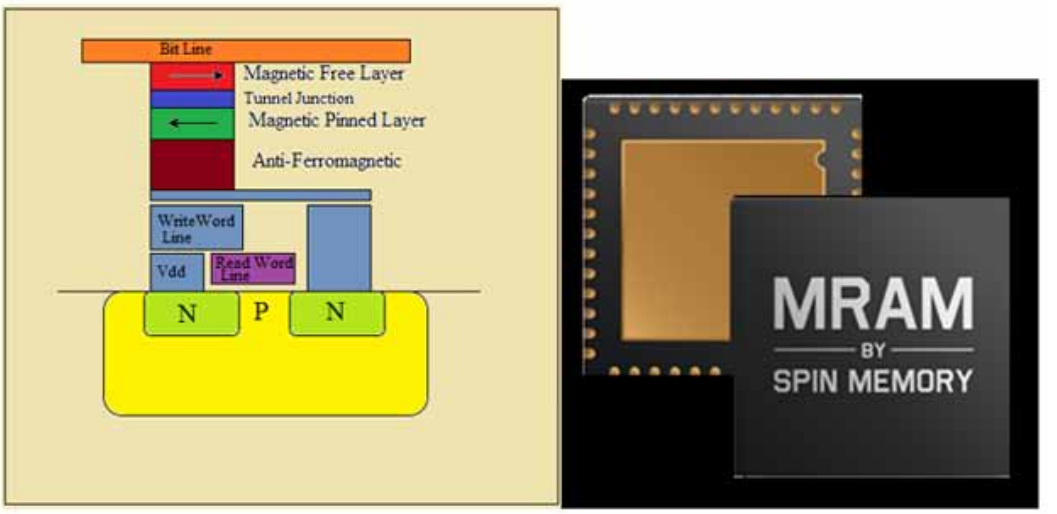
Figure 1. Arrangements of MRAM based on MTJ device



film. This insulating layer is called as Tunnel barrier see figure 1.The AlOx material is use to formed the tunnel barrier because it provides the large tunneling magneto-resistance effect in the MTJ at the ambient temperature and its spin dependent tunneling transfer characteristics brings curiosity on a huge scale ensuring the biggest Magneto-resistance (MR) ratio of 81%at RT and 107% at 4.2 k in AlOx based tunnel junctions. The various types of Al-O barrier based, between the two layer of metal in MTJ's such as spin valve type pinned MTJ, double barrier magnetic tunnel junction (DBMTJ), Half-metal MTJ, perpendicular anisotropic MTJ, diluted magnetic semiconductor composite MTJ, superconductors composite MTJ, granular film composite MTJ and Nano ring shaped MTJ. In MJT, lowresistance (Rp) is experienced when the magnetization in both Ferro-magnetic layer is parallel, the electrons simply cross the tunnel barrier from one layer to another. On the other hand, highresistance (Rap) is experienced when the magnetization in both magnetic layer is anti-parallel and electrons cannot cross the barrier easily from one layer to another. As MTJ is TMR effect based junction play a vital role that is, it measurehow one can distinguish between high and low resistance states. Data can be kept as '1' mean high resistance state and '0' means low resistance state in the junction by controlling the magnetization of the layers and the data can be study by evaluating the resistance of junction. When the exterior electric filed is applied to the junction one can change or control the direction of the magnetization of the layer's. For writing principle, the MRAM utilize the STT (Spin Transfer Torque) writing and termed as STT-MRAM, Spin RAM or, STT-RAM. (Dieny et al., 2017)

It offer non-volatile speedy memory range which can be coupled quickly with processors, otherwise large volume system were used for the data storage. Presently, it has attained a guaranteed position in the industrial market. Many companies like Toshiba, Hitachi, IBM, Samsung and TSMC are vigorously expanding MRAM chip modified machinery. With next production memory technologies, MRAM is supposed to have the major market in the coming year, tracked by FeRAM, PCRAM and Memristors. In the last the uniqueness of the MRAM which make it differ from other memories are (Titu-Marius, 2018):

1. It can maintain its information even when the applied power is switched off.
2. It provide great read and write speed in contrast to other memories like Flash memory or EEPROM.
3. It do not disintegrate with time.
4. It utilize low power level relatively to other memories.

1.1 Historical Perspective

In 1995, core memory is also called the universal memory was the first magnetic memory which was developed by employing the magnetic material. This core memory was prompt and adequately low-cost to utilize as a cache memory with storage at the same time.

The core memory was modified by using the magnetic field produced by the electric current for writing purpose and utilization of electro-magnetic induction for data reading purpose was created in 1820 by H.C.Oersted and in 1831 by Faraday respectively.

Figure 2. Past, current/future of memory hierarchical structure for different devices (Ikegawa et al., 2020)

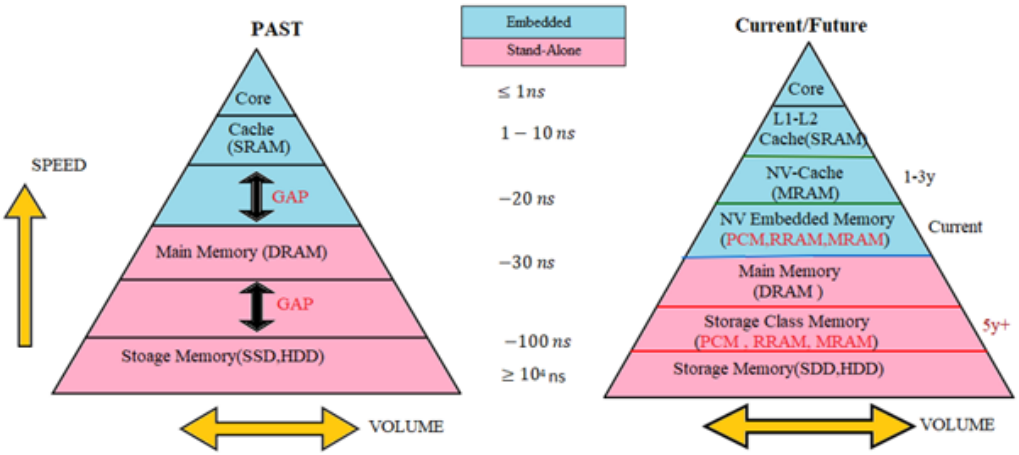
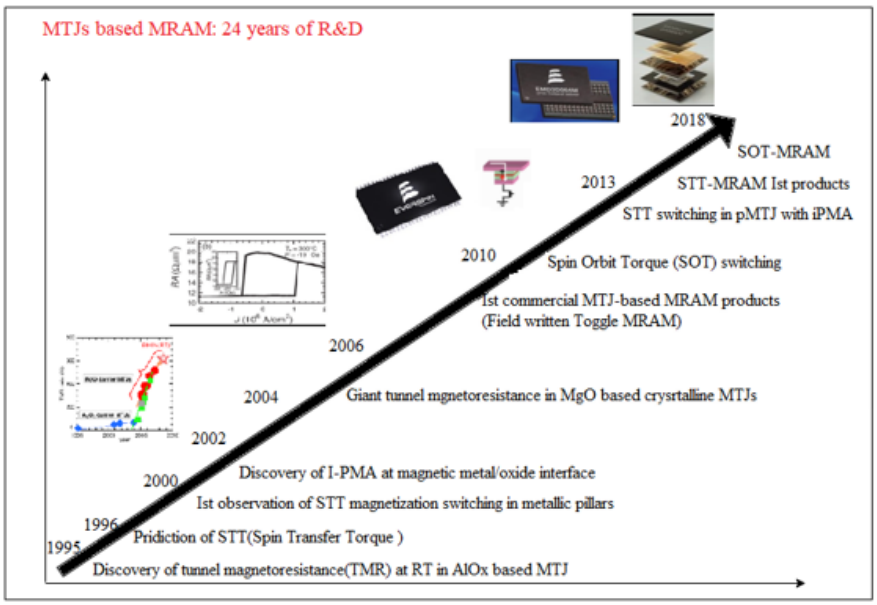


Figure 3. Development in MRAM



After this lots of developments and modification were done by different scientist which is mentioned in Table 1.

1.2 Working Principle of MRAM

MRAM is a spintronic based memory in which the data is stockpile by utilizing the electrons another property that is "SPIN". The memory cells are incorporated on the ICs and in result it provide the high storage speed and high density like SRAM and DRAM (Fujita & Xu, 2016).

A memory device structure is made up of series of numerous MRAM cells. Figure 4 depict the MRAM structure. A classic MRAM cell consist of transistor and a magneto-resistive element, analogous to DRAM which have a transistor and a capacitor (Tetsuo & Honjo, 2018).

In DRAM, the capacitor is used to stockpile the charge which describe its memory state and the resistance of magneto-resistive element verify the state i.e. '0' or'1'. The transistor play important role that it offer the current which is essential for the writing operation and also resolve the variation among the resistance, otherwise the voltage level among the states is not too huge to operate the transistor. The memory device should pursue three basic necessities which are: (1)Non-Volatile i.e. the device is able to stockpile the data for the long period of time without any damage and power.(2) there should be a method to read the stored data.(3)and a method to write data again on the device. To attain the above described necessities the researchers had developed different kinds of model and explored the several types of MRAM in the past as mentioned in the history. In MRAM these tasks are done in the following manner: (1) The reading action is done by sensing the difference of resistance among the two states of the device.(2)The capacity of data depends on the magnetic maintenance properties, emerging from the magnetic anisotropy of the capacity layer.(3)The written activity is executed by varying the direction of the capacity layer polarization which can be accomplished by inciting an attractive field or by utilizing the standards of STT (Hirohata et al., 2020).

1.3 MRAM Technology Generation and Classification

There are some different switching methods used for writing the data in MRAM (see Table 2).

Table 1. History of memory based devices (Yoda, 2015) (Dieny, 2016)

	DISCOVERIES		Growth for memories Applications		
SR. No.	YEARS	Discoveries of Technlogies	YEARS	Improved Memories	Remarks
1	1820	Generation of magnetic field through electric Current(H.C.Oersted)			Utilize as a universal memory
2	1831	EM Induction by Faraday	1955	Core Memory	
3	1856	Magneto-Resistance in Fe by Lord Kelvin	1980s	Field-writing MRAM(AMR)	
4	1988	GMR by A.Fert and P.Grunberg	1990s	Field-writing MRAM(GMR)	
5	1994	Room temperature TMR by T.Miyazaki and J.S.Moodera	1990s	Field-writing MRAM(TMR)	DARPA Project (1996)
6	1996	STT by J.C.Slonczewski and L.Berger			
7	2004	MgO Tunnel barrier in TMR by S.Yuasa and S.Parkin	2000s	STT-Writing MRAM(in-plane)	
8	2006	STT-Writing with perpendicular GMR by			NEDO Project (2006)
9	2007	STT-Writing with perpendicular TMR by	2000s	STT-Writing MRAM(in-perpendicular)	

Figure 4. Memory cell structure

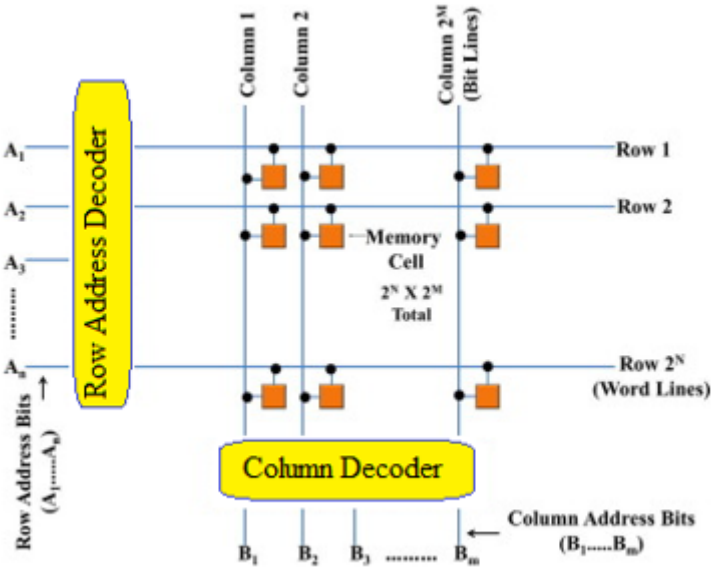


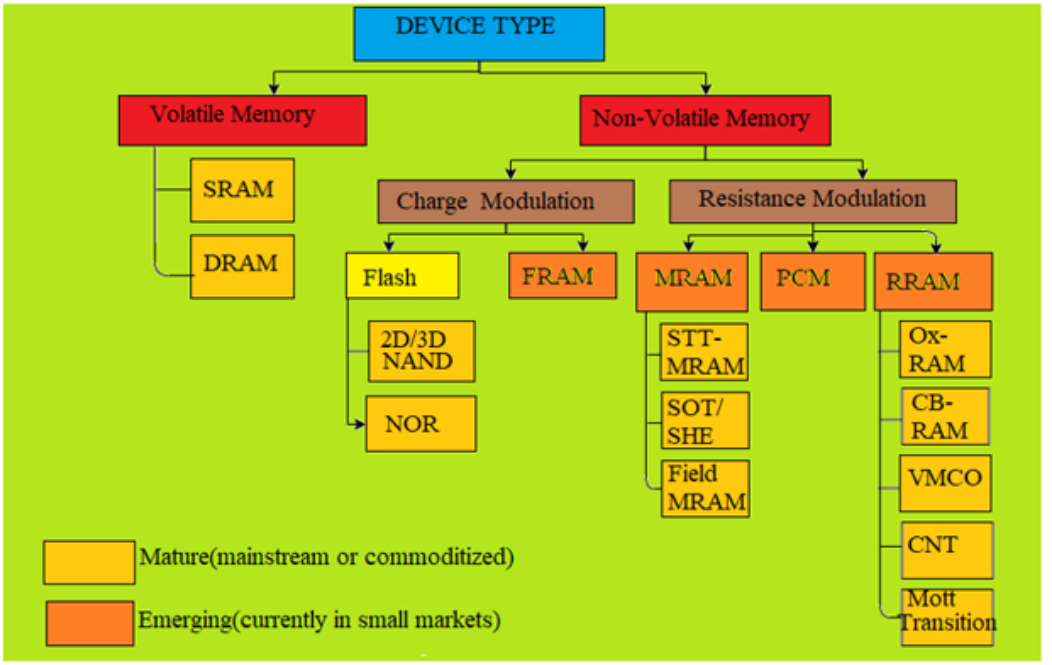
Table 2. Different MRAM generations (Apalkov et al., 2016)

Genration	Devices(Mram)	Techniques
FIRST-GENRATION	TOOGLE-MRAM	Magnetic fields are used to program the Arrays.
SECOND-GENRATION	STT-MRAM	It uses STT (Spin Transfer Torque) technique with perpendicular MTJ devices to program the array.

In first generation the TOOGLE-MRAM provide the large number of advantages. Using of field switching method it provide unlimited writing durability, since there will be no wear out mechanism when the free layer magnetization is reversed with magnetic field. But in this case we face problem while scaling down to smaller cell size because of various factors like involving the magnitude of the prerequisite switching current which make the memory cell design complex. Next in second generation MRAM the Spin Transfer Torque is used to program the array in memory. STT switching can be implemented by utilizing the MTJ devices in-plane or perpendicular-to-plane magnetization (Apalkov et al., 2016). The last or third generation in which various phenomena are examined in MRAM are (Ikegawa et al., 2020):

1. VCA(Voltage Controlled Anisotropy)
2. VCM(Voltage Controlled Magnetization)
3. SHE(Spin Hall Effect)
4. SOT(Spin-Orbit Torque Switching)

Figure 5. Classification of different memories



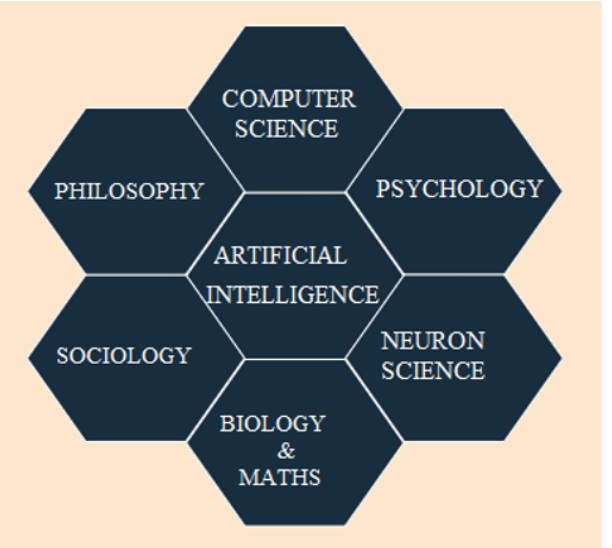
2. ARTIFICIAL INTELLIGENCE

Every day the new technology is emerging and expanding very vastly in the market and captivating the great position in the market. Artificial Technology (AI) is one of the thriving technology of the supercomputer which is prepared to produce a new innovation in the globe by building smart machineries. In day to day life everyone is now surrounded with artificial intelligence. Presently, it is covering wide area from common to certain like Self-driving cars, playing Ludo or chess, web searching, Digital assistants, social media etc. (Rupesh & Chaudaiah, 2019).

Artificial Intelligence is one of the captivating and world-wide area of Information technology which have a plentiful opportunity in future. It grasps an affinity to manufacture a robot or mechanism to function as a human.AI is the combination of two terms that is artificial and intelligence where artificial means “Man-Made”, and intelligence means “intellectual power”, therefore, it means AI is a “man-made intellectual power”. One can define the AIas, “It is the field of the computer science where one can manufacture a smart machinery which can work like a human being, imagine like humans and capable of making smart judgment’s” (Karrar & Sun, 2018).

Basically, AI is a kind of methodology in which the PCs, robots or a machine is developed which can think or behaves just like the human do. AI is the analysis of how human’s brain feel, imagine, resolve and work while put efforts to crack the solution of the difficulties. At the end this analysis output is given to smart software logic. The goals of artificial intelligence are thinking, knowledge demonstration, planning, recognition, capability to move, learnings, natural language processing and objects manipulation. There are enduring objectives in the over-all intelligence area. There are different a methodologies comprises of numerical methods, calculation intelligence and conventional coding AI. Through the AI study associated to exploration and mathematical enhancement, artificial neural network and techniques constructed on statistics, probability and economics, many tools were used. The areas like science, math, psychology, linguistics, philosophy and many more are the areas of computer science which attracts the artificial intelligence.

Figure 6. Artificial Intelligence contribution in different fields (Priya et al., 2016)



The Artificial Intelligence is further divided into two subfields:

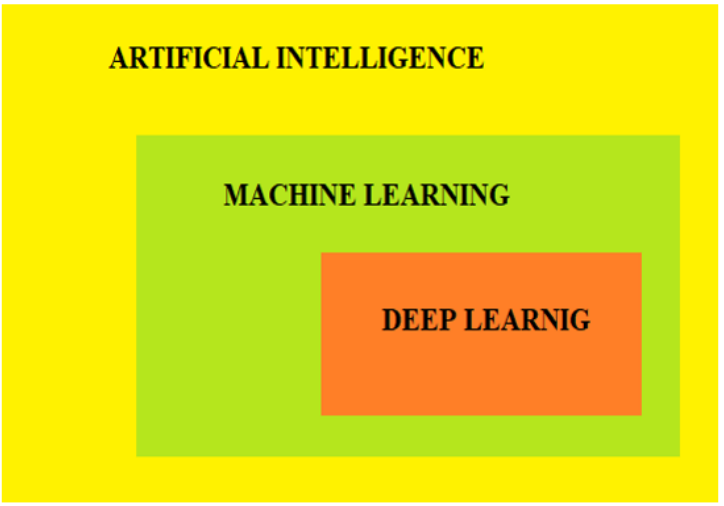
1. **Machine learning:** It is the ability to do the analysis of the algorithm which is realized from the examples and experiences. Basically it is based on the thought that there is already existing some design or pattern in the data which we will utilize for the identification and future estimations. The main dissimilarity between the hard-coding rule and machine learning is that machine learn own its own, find its guidelines.
2. **Deep Learning:** It is the sub-area of the ML but in this case the machine do not learn more in depth intelligence, which means that machine utilize the various layers to learn from the information. The number of the layer in the pattern characterized the complexity of pattern. For example, in Google LENET there are 22 layers for the image recognition. The learning process in the deep learning is done with help of neural network. Neural network is the based on the various layer which are stacked on top of each other (Cioffi et al., 2020).

Now, the AI and ML both are different from each other in such a way that AI is basically a machine or computer which consist of human –like properties in which a machine can think, solve and analysis the problem just like humans can do. We can say that AI is the huge field of science in which the computer or machines behave like a human. Whereas, the machine learning is the sub-area of the artificial intelligence which explain the machine how to learn and ML models depend upon the pattern in information and try to understand that pattern an then perform the future predictions.

2.1 Advantages of AI

1. **Accuracy of Predictions:** The results of any experiment will be more accurate as compared to the result calculated by human. So AI provide zero human error. The machine will predict the result by observing the pervious information or data such as weather forecasting in which they identify from the previous information by applying some algorithms.

Figure 7. Sub-fields of AI



2. **Reduce Human Risk:** The implementation of AI can be done where the humans can't work or participate. For example nuclear plants in which there are some sensitive areas where human can't work directly or detect any problem.
3. **Always Available (Work 24*7):** A normal human can work for 7-8 hour of a day including breaks, then work for the same hours next day and also have weekly off for their personal life. Through the implementation of AI, machines can work continually for 24*7 without taking any break and don't get bored doing the same work like human beings.
4. **Digital Assistance:** Because of the implementation of AI technology, it can provide digital assistant for various services, in fact many online websites used AI and show the products according to the requirement or from previous searching.
5. **Quick Decisions:** The machines with AI technology can take quick decisions which mostly depend upon the data or information provided then human beings because sometime human may think emotionally or practically and then analyses the information, provide the results. Whereas the machine with AI only work on the provided algorithm and data and provide decisions based on the input such as chess, Ludo etc.

2.2 Disadvantages of AI

1. **Expensive Technology:** As the technology is upgraded every day with advancement in human requirement, the machines hardware and software also needs to be upgraded regularly according to the demand which increase the cost factor hence AI is expensive technology and need proper set for up gradation and machines repairment also with time.
2. **Causing Sluggishness in Humans:** As most of the work will be done by the humans so because of that humans completely depend upon the machine, hence became lazy and also effect the body of the human.
3. **Lack of Creativeness:** As machines can work fast then humans but side by side they can't upgrade themselves just like humans. They only worked according to the applied algorithm or program. So the engineer needs to change the program. Hence the machine can't think out of the box.
4. **Reducing the Employment:** As most of the work is done by the machines now, hence reducing the jobs and creating unemployment. A single machine can do a lot of work at a same time better than human.

5. **No Sentiments:** There are various advantages of AI technology but some time engineer's needs to work in team and at that time the connection between then can't be understand by the machines.

2.3 Types of AI

There are different types of artificial intelligence but mainly classified into two main groups and this classification is done on the bases of abilities and the working of the AI. The flow diagram is mention below which explain the types of AI (Rupali & Amit, 2017).

TYPE-I: Type-1 consist of three different types AI fields which are based on the capabilities of machines and which are explained below:

1. **Narrow AI:** The machines based on this artificial intelligence will only perform the dedicated task. The AI do not perform beyond its limit and only performed the specified task. So because of its limitation it is termed as Narrow or weak AI.
2. **General AI:** An artificial intelligence grasps the over-all state when it can achieve any intelligent mission with the equal correctness level as a person would. The research is ongoing to develop such systems.
3. **Strong AI:** In this type of AI a robust AI system which can smash the human in numerous duties or tasks.

TYPE-2: The type-II basically depend upon the functionality of the machine or memory:

1. **Reactive Machines:** This is the simplest and the first type of Artificial intelligence in which the machine perform its function based on the current input. These types of machine do not have any memory so it do not store any data or information. Some examples of reactive machines are IBM's deep blue system and Google Alpha Go.
2. **Limited Memory:** These machines have some memory which is used to improve the system functionality. These memory stores the pervious data for short period of time and used to improve the system and also predict the output. The data stored in these

Figure 8. Classification of AI

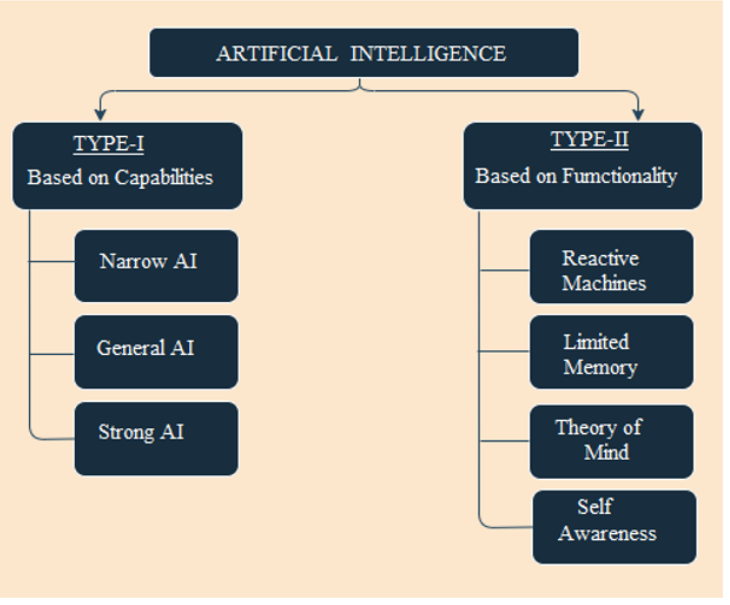


Figure 9. Task performed by type-1 AI

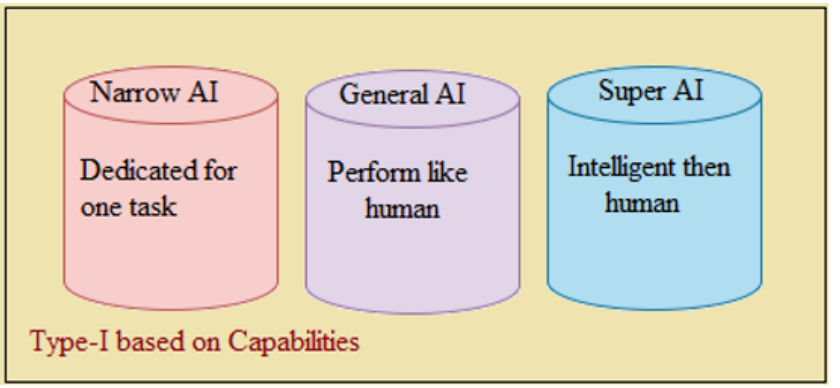
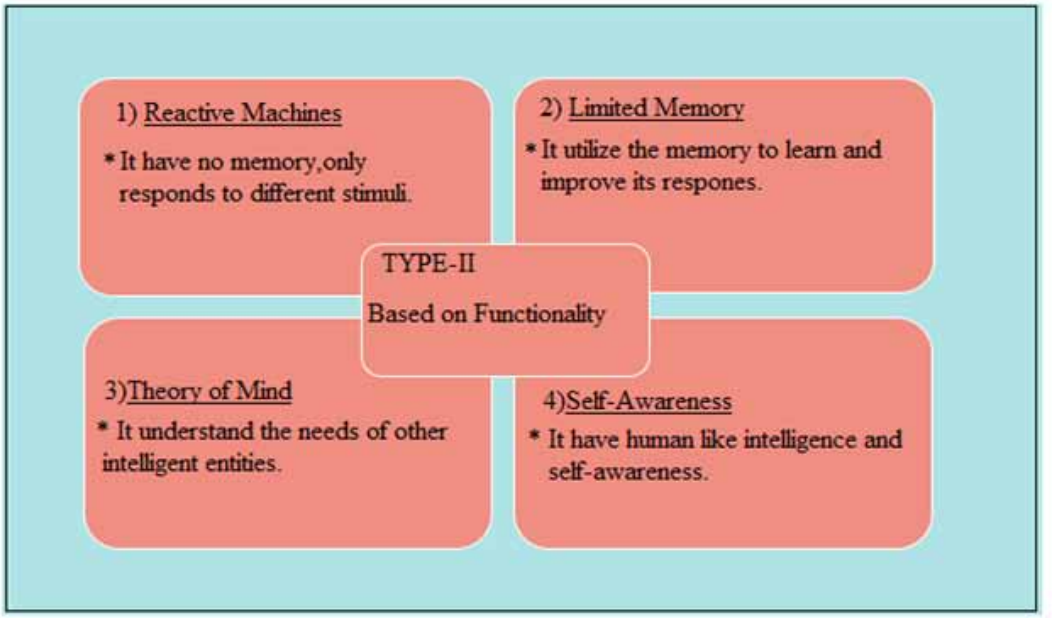


Figure 10. Tasks performed by Types-2 of AI



memory is for short duration or temporary .The best example for this memory system is self-driving car which stored the recent data like speed of car, speed of near driving systems, distance from other etc.

3. **Theory of mind:** This is the most important point to discuss in Artificial intelligence because it provide the difference between the machines or systems we have and the machines or system engineers will built in future. In this engineers discuss the machines with advanced representation of "Theory of Mind". Under this theory the machines will think with emotions and their thoughts. Well the system under this theory are still under research area and engineer's still working on these types of machines.

4. **Self-Awareness:** This will be the future of the artificial intelligence in which the systems or machines will be super intelligent then humans and will have their own emotions, feelings and understanding. But these types of machines still not development hence only present in theoretical way.

2.4 Artificial Intelligence Applications

As we discuss various advantages of AI, from that it is easy to improve some areas for betterment of peoples and AI cover wide area of several fields for example online shopping, Healthcare, banking, money transections, training, and so on Artificial intelligence is making our day by day life more agreeable and quick. Some of the applications are explained below how they will solve the problem or helpful (Borana, 2016):

1. **AI in Astronomy:** It is extremely valuable to crack difficult space challenges and this technology is also supportive to understand the working of universe and its origin etc.
2. **AI in Healthcare:** From fast few year, the AI technology is also implemented in the hospital to increase the health facilities. These machines help to get the accurate and faster result. Especially it diagnoses faster and better than humans. It improves the work flow of the hospitals and hence helps the doctor to understand firstly and patients to get better treatment (Chanchaichujit et al., 2019).
3. **AI in Robotics:** AI play the vital role in the robotics. Without AI in robotics, once the robots are programmed they perform the same work again n again and do not solve the error if occurs, but with AI the robots can work according the experience and can solve the problem itself by understanding the issue.
4. **AI in Gaming:** When we play online games, the hints or help is provided by the AI technology. Moreover the games like chess in which another player is computer and play like a smart chess player is also done with the help of AI technology.
5. **AI in Social Media:** AI play a huge role in the social media and presently most of the things, pages or suggestion we get that all are basically based on the previous data. When we start searching for a particular product like headphones or clothes etc. after that one see all those references or suggestion on the social media. And nowadays the websites are using to attract more and more customer.

2.5 Research Areas of AI

As we mentioned above that artificial intelligence cover wide areas or fields. For easy understanding, engineer divide the area in common fields. Moreover with the division of these common fields some real life examples are also mention in the figure. With this figure user is able to understand that which area cover which real life application (Pannu, 2015).

3. NEUROMORPHIC COMPUTING

Neuromorphic computing is also called as Neuromorphic engineering, theory was established by Carver Mead in 1980s, explaining the usage for systems like VLSI which holds the electronic analog circuits to simulate Neuro-biological architecture existing in neurons model (Schuller & Stevens, 2015).Newly the word Neuromorphic have been utilized to define various systems like Analog, Digital, Mixed-Mode Analog /digital VLSI and Software system which execute prototype of Neural Systems .The utilization of Neuromorphic computing on the hardware level can be achieved by using Memristors, Spintronic based memories, Threshold Switches and Transistors.

A Neuromorphic computer is a kind of machine which consist of various basic processors/ memory structures like Neurons and Synapses and interlinking using easy messages like spikes.

Figure 11. Applications of AI

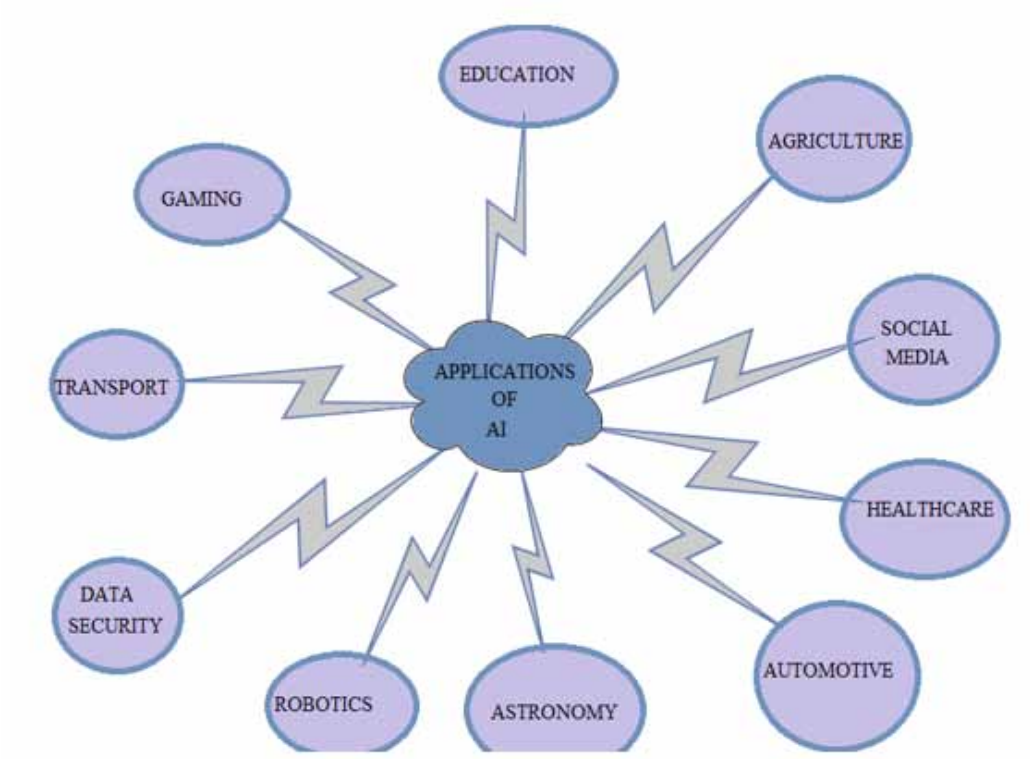


Figure 12. Research areas of artificial intelligence

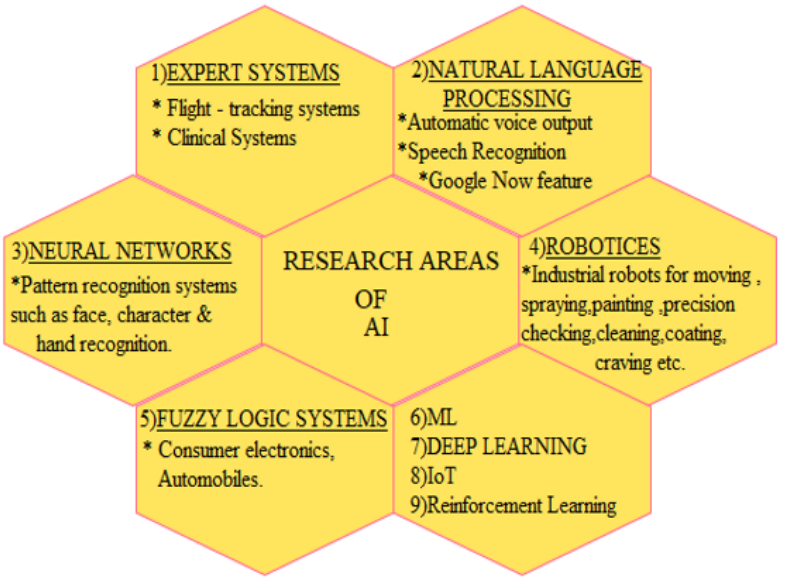
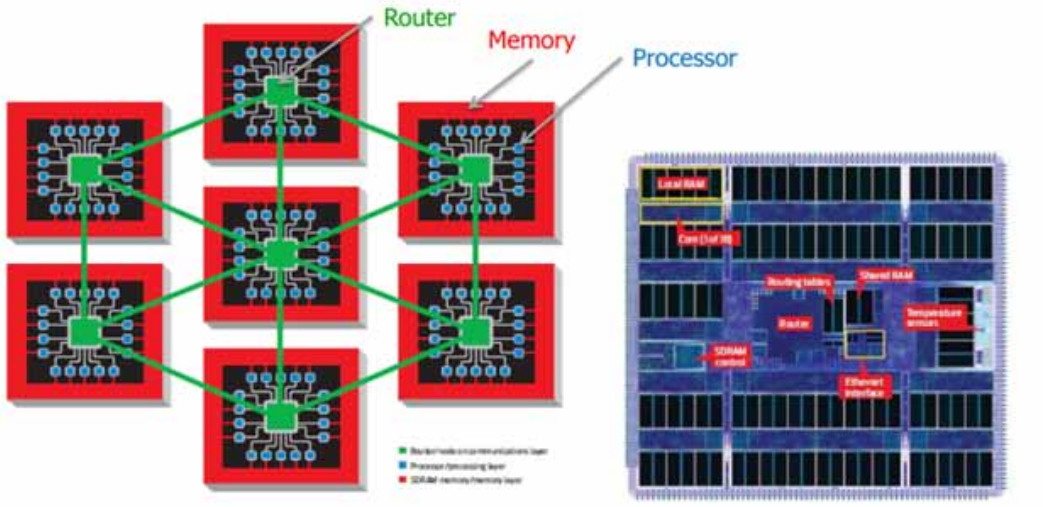


Figure 13. Neuromorphic computing hardware architecture



(Vianello et al., 2019) Neuromorphic procedures highlights the sequential interface between the processor's processing and the memory and every single message have some time characteristics like explicit and implicit. Neuromorphic computing approach is best at calculating difficult gestures or movements by employing a small series of calculating primitives like neurons, synapses, spikes.

Our equipment based PCs and processors can't deal with similar sorts of handling loads as the human mind. The objective of numerous software engineers, equipment producers, and server farms is to change that. The field of Neuromorphic computing is devoted to joining science, electrical designing, software engineering, and arithmetic advances to make counterfeit neural frameworks equipped for detecting and preparing loads comparable in ability to the human cerebrum and sensory system.

"In simple words the Neuromorphic computing is defined as which employ brain inspired theory to construct circuits that execute the calculation tasks with greater power efficiency to traditional PCs." The two main objectives of Neuromorphic Computing also termed as Neuromorphic engineering are: -The very first step is to produce a device which can learn, remember the information and moreover able to take logical decisions just like a human brain can basically a understanding machine.Then second step to attain the new data and feasibly demonstrate the rational theory which means that how a human brain work or solve the problem. (Wunderlich et al., 2019)

3.1 How Neuromorphic Computing and AI are Connected?

1. In First generation of artificial intelligence it explained the rules and monitored classical logics to attain the decisions with specific, closely defined problem domain.
2. In second generation of AI the main focus was on the study of input, sensing and perception by using the deep learning networks.
3. In third generation of AI it move further and worked with human cognition, with abilities like adaption and interpretation.
4. In fourth generation of AI applied the mixture of various ML algorithms and further types of AI algorithms to attain the desired objective or aim.
5. Now, Neuromorphic computing is the fifth generation of AI.

Conventional registering is arriving at its breaking point are getting wasteful to deal with the following flood of AI. With Moore's Law (the quantity of semiconductors duplicates at regular intervals while the cost parts) nearly arriving at its breaking point, there is a quest for new ways to build the computational capacities to take AI to the following level. Generally, all PCs depend on Von Neumann design where memory and processor are detached and information moves between them. This is unique in relation to organic PCs, for example cerebrum where the memory and rationale are firmly associated in neurons and signs are communicated through neurotransmitters (Grollier et al., 2020).

A Neuromorphic chip duplicates this model by executing neurons in silicon with an objective to bestow intellectual capacities to machines (Chen et al., 2018). This thick organization on Neuromorphic chips is called Spiking Neural Network (SNN). This organization encodes data in type of spike trains, i.e., time distinction between two spikes decides network properties. Neuron working is administered by differential condition and uses simple signs trading electric sign blasts at various forces. It has an occasion driven nature of just making neurons in real life dynamic. This is not normal for the current computerized chips which are twofold based and have consistent qualities. Because of this uniqueness, the SNN has an alternate preparing strategy than Artificial Neural Network (ANN). It utilizes Spike Time Dependent Plasticity (STDP) instead of inclination plunge. Associated processor and memory makes Neuromorphic chips more effective at preparing and running neural organizations. They run AI models quicker than identical CPUs and GPUs while devouring less force. This is critical as force utilization is an immense test for AI. The little size and low force utilization likewise make them appropriate for use cases that require running AI calculations at the edge rather than the cloud. Neuromorphic processing can make algorithmic ways to deal with manage dubious and uncertain circumstances (Rajendran & Alibart, 2016).

Example: One of the most currently achievement in Neuromorphic computing has come from IBM research termed as a biologically inspired chip ("TrueNorth") in which one millions of spiking neurons and 256 synapses are implemented on the chip with 5.5billion transistors which gain the power of 70 mill watts.

CONCLUSION

The basic concept of MRAM and its different types along with their reading and writing operations has been presented in this paper. Further artificial intelligence (AI) is explained briefly and as the technology is developing day by day with great features alike low power consumption, compact in size and robust etc. The basic idea behind this paper is to present the stat of the art literature review on how we can use spintronic devices with artificial intelligence and role of Neuromorphic computing. AI is all around us and many developments and research work is going to improve performance of intelligent systems. The main motive of the researchers are to develop the machines or robots which can work, think like human beings.

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