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Research and Analysis on Artificial Intelligence in Integrated Circuits

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Abstract. In the contemporary digital era, artificial intelligence (AI) emerges as a pivotal industry, playing a critical role across various sectors. Concurrently, the integrated circuit (IC) industry represents a highly specialized field characterized by swift technological advancements and innovation. Anchored on this premise, this paper embarks on a comprehensive exploration of the IC domain, delineating its evolutionary trajectory and current dynamics. Subsequently, this paper extends to a detailed examination of the practical deployment of AI within the IC industry, highlighting specific application scenarios where AI's transformative potential is harnessed to enhance efficiency, design, and operational processes. This paper culminates in a forward-looking analysis, contemplating the prospective trends, opportunities, and challenges that define the intersection of AI and IC technologies. This paper inquiry not only sheds light on the symbiotic relationship between AI and the IC industry but also underscores the imperative for adaptive strategies in navigating the complexities of their integration.

Keywords: Artificial intelligence; Integrated Circuit; Applications.

1. Introduction

The development of integrated circuits has accelerated over years and continue to develop in the direction of intelligence and miniaturization. Integrated circuits present its potential and several benefits, such as being tiny, light, long-lasting, and inexpensive [1]. At the same time, due to the highlighting of these advantages, electronic devices are becoming more and more portable for users. Computers have evolved from occupying the space of several rooms to being carried in hands [18]. Its development potential is evident. Meanwhile, the development of AI is also one of the hot topics in today's society. Algorithms are the foundation of artificial intelligence applications. They are used to achieve training and summary of actual problems, and eventually the solution to the problem will be found by matching real circumstances. The complex advancement of science and technology has led to an increase in the complexity of algorithm research.

With the continuous upgrading of algorithms, a series of algorithms such as machine learning, deep learning, and artificial neural networks have emerged, which has made great strides in the process of artificial intelligence. As integrated circuits continue to develop to the micro-nano level, the difficulty of circuit fault diagnosis, circuit optimization and other problems are increasing. Therefore, if artificial intelligence can be applied to integrated circuits, it will greatly reduce the workload and improve the operation of the circuit correct rate.

This article introduces the current development status of artificial intelligence and integrated circuits. Meanwhile, summarizing the application of artificial intelligence in integrated circuits. At the same time, the future development and application trends will also be introduced in this article.

2. Theoretical basis

2.1. The development of integrated circuit

Integrated circuits combine resistors, capacitors, inductors, the transistors and the connections between them are integrated and packaged on a silicon chip to achieve a specific function. The development direction of integrated circuits is high performance, small size, low power consumption and intelligent features as mentioned in the introduction.

The development of integrated circuits began with electron tubes in the early 20th century. It was one of the earliest electrical signal amplification devices and was used in electronic products such as televisions and radios. In 1906, the invention of the triode can be regarded as the origin of transistors. It also can be regarded as the beginning of the modern electronics industry. Bipolar junction transistors were created in 1948 after the first transistor, also known as a solid-state active device, was developed in 1947 as a point contact bipolar transistor employing germanium. In 1958, bipolar transistors were implemented to create the first integrated circuit [2]. In the 1950s, Bell Labs successfully demonstrated the first point-contact transistor which had the amplification function based on germanium semiconductor. It can be marked as the birth of the modern semiconductor industry which promoted the birth of the first electronic computer ENIAC. In 1965, Gordon Moore proposed the famous Moore's Law, which is an empirical law that reveals the development speed of integrated circuits to a certain extent. At present, the development of integrated circuits still follows this law. The main content of this law is: the number of transistors on an integrated circuit will double every 18-24 months. Integrated circuits first developed from small scale to very large-scale integrated circuits currently and still follow Moore's Law.

Silicon large-scale integrated circuits, enable us to do an enormous number of tasks at high speeds and frequencies while maintaining low costs, low power consumption, compact physical dimensions, light weight, and outstanding dependability. Over the past thirty years, MOSFETs have seen a 140-fold decrease in gate length, DRAM density rose by 256,000 times, and The MPU's clock frequency increased 2670 times [2].

2.2. Current situation of integrated circuit

FET and BJT are widely known transistors in the semiconductor industry. Now CMOS applications are gradually becoming dominant in this industry. CMOS, called Complementary metal oxide semiconductor, is an integrated circuit device that can produce PMOS and NMOS components on silicon wafers. Since PMOS and NMOS are complementary in characteristics, then they are called CMOS.

The development history of CMOS technology has a long history. At the International Solid-State Circuits Conference in 1963, Frank Wanlass of Fairchild Semiconductor made the initial proposal and Wanlass and Chih-Tang Sah gave the demonstration. Later, Wanlass applied for a U.S. patent for CMOS circuits and was granted it in 1967. The RCA Corporation popularized the technology under the trademark "COS-MOS" in the late 1960s which forced other manufacturers to find other names. As a result, "CMOS" was adopted as the technology's general name. The main MOSFET manufacturing technique for VLSI devices was switched from NMOS to CMOS in the 1980s, meanwhile transistor-transistor logic (TTL) technology was superseded. The industry standard for producing MOSFET semiconductor devices in VLSI chips is still CMOS. As of 2011, CMOS technology is used in the production of 99 percent of integrated circuit chips, which includes the vast majority of digital, analog, and mixed-signal integrated circuits.

2.3. Analysis of the current situation of artificial intelligence

2023 is considered as a watershed year for artificial intelligence. Before this year, artificial intelligence only developed chatbots and artificial neural networks. The so-called artificial neural network simulates the form of the human brain, abstracts information processing and builds a simple model to work. The more famous one during this period is Alpha Go, which was the first artificial intelligence machine to defeat a human professional Go player.

The iteration of artificial intelligence is actually updating different algorithms. Here the author lists several artificial intelligence algorithms that are currently widely used.

2.3.1. Artificial Neural Network (ANNs)

An artificial neural network (ANN) is a machine or mathematical model that mimics the architecture and operation of biological neural networks, such as the brain and the central nervous systems of animals. It is used to estimate or approximate functions. Artificial neural network is an adaptive system which indicates that the system has the ability to learn.

Artificial neurons provide the foundation of an artificial neural network, and the basic principle of its operation can be expressed as follows. Each neuron takes in information from several other neurons, multiplies it by the weights that are distributed to it, adds together, and then sends the total to one or more other neurons which is shown in Figure1.

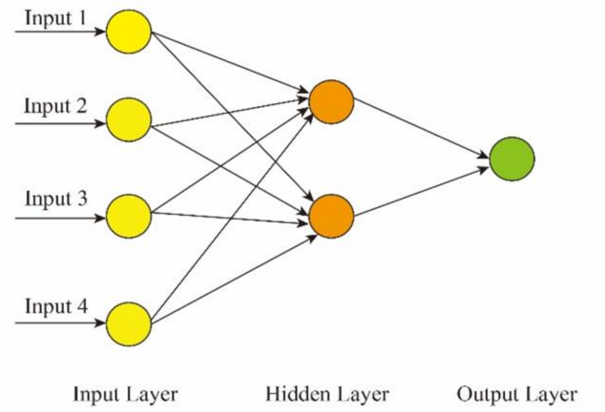

Figure 1. Artificial Neural Network [3]

A typical ANN model mainly consists of three parts: structure, activation function and learning rules. Structure is used to determine the variables in the network and their topological relationships. Excitation function is used for describing how neurons alter their own excitation values in response to other neurons' activity. The majority of neural network models use a short time scale dynamic rule. The network's learning rules dictate how the weights change over time.

ANNs can also be used to characterize or identify linear relationships, however the outcome is frequently less beneficial than that of employing a different, more straightforward conventional statistical technique. As we usually don't know at the start of an experiment whether the responses are related to the inputs in a nonlinear or linear way, it's an excellent choice to always use some standard statistical technique for analyzing the data in addition to using ANNs [3].

Applying the ANN model can be divided into two steps. The problem type should be determined first whether it is a regulatory or non-regulatory question. Once you have identified the type of problems, you have the direction to search for the best strategies and approaches to deal with the challenges.

2.3.2. Machine learning

Machine learning is a method of data analysis that automates analytical model building. It allows computers to automatically learn and improve from experience without being explicitly programmed [4]. In short, Machine learning is an approach to train machines how to make more efficient calculations. What’s more, there’re limitations to manual reading which indicates that sometimes manual ability to extract more information is not as efficient as artificial intelligence. In that case, we apply machine learning [5]. Thus, the ability to learn from numerous data automatically has become one of the advantages of machine learning.

There are many forms of machine learning, which can be divided into supervised learning, unsupervised learning, etc. based on different learning styles. From a formal or functional perspective, it can be divided into categories such as decision trees, deep learning and so on. Supervised learning methods are mostly used among all the machine learning methods. The basic principle of supervised learning is to construct a predictive model by learning the relationship between input variables and output variables. The generated prediction model can process new input data. For example, assuming that the input value is x, the corresponding f(x) is obtained through mapping, and then prediction is made based on the obtained value, thereby generating a model to predict and estimate the subsequent input value [6]. Computer science and numerous other sectors that deal with data-intensive obstacles, such as consumer services, the diagnosis of complicated system challenges, and logistics chain control, were also significantly affected by machine learning.

When compared to human learning, this technique acquires knowledge quicker and makes learning outcomes more widely disseminated. Therefore, any advancement in machine learning by humans will boost computer abilities, which will have an impact on human society [7]. Nowadays, more and more industries have embraced machine learning techniques. The usage of machine learning has increased a lot especially in decision making and methods proposing [6].

2.3.3. Deep Learning

Deep learning is a branch of machine learning using ANN as its structure and it is to learn the inherent patterns and representation levels of samples, which includes multiple hidden layers which is shown in Figure 2.

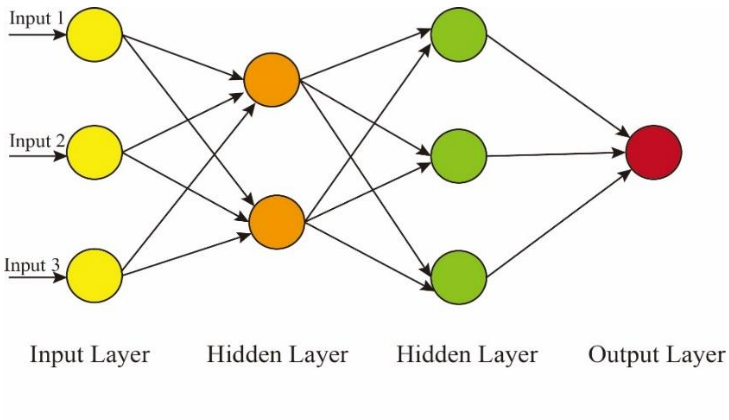

Figure 2. Deep Learning [8]

Typical models of deep learning can be divided into three categories in form or function: convolutional neural networks, deep trust networks and stacked autoencoding network models. It also can be classified into four types based on learning style: unsupervised, partially supervised (semi-supervised), supervised, deep reinforcement learning [8].

For supervised, there are several learning techniques, such as recurrent neural networks (RNNs), convolutional neural networks (CNNs) and so on. This technique's primary benefit is its ability to gather data or produce data output based on previous data. For semi-supervised technique, the learning process is based on semi-labeled datasets. Another technique is unsupervised. When labeled data is not available, this strategy allows the learning process to be implemented. The last one is deep reinforcement learning (DRL). Reinforcement Learning operates on interacting with the environment, while supervised learning operates on provided sample data [8].

The most commonly used and frequently applied method in the field of deep learning is the CNN (Convolutional Neural Network) algorithm. The key benefits this algorithm has over its predecessors is that it can automatically identify significant details without the need for human monitoring. Because of this advantage, CNN has become one of the most popular algorithms in DL area. CNNs were constructed using neurons present in the brains of humans and other animals, much like a conventional neural network. More precisely, the CNN simulates the intricate cell sequence.

2.3.4. Generative Artificial Intelligence

Generative AI models have the ability to generate original and new content. This technique is based on neural networks to recognize patterns and structures. There is a breakthrough needed to be mentioned in Gen AI is that this technique has the ability to take advantage of different learning methods in different circumstances including unsupervised or semi-supervised learning for training.

As a result, companies can employ vast volumes of unlabeled data to build underlying models more quickly and easily. For example, GPT-4 and Copilot constructed by Gen AI are widely used around the world, which are rapidly changing the way we work and interact with others [9].

A Gen AI model is also a branch of machine learning that depends on the patterns and relationships found in the training data to generate new data instances using AI algorithms. Although crucially important, its model is not yet complete because systems and applications need to be used to further fine-tune it to certain needs [9].

Generative artificial intelligence will be used more widely in the future and become more and more relevant to life. For example, people can use this artificial intelligence to reserve seats or help to make choices. On the other hand, the utilization of this technology in professional fields will be more powerful and reliable, such as giving reasonable legal advice, inspecting engineering issues or proposing feasible solutions, etc. The potential of generative artificial intelligence is rapidly being exploited.

3. Analysis of Application Scenarios of Artificial Intelligence in Integrated Circuits

3.1. Artificial Intelligence in Integrated Circuits

3.1.1. Artificial intelligence chips (AI Chips)

Artificial intelligence (AI) chips, sometimes referred to as computing cards or AI accelerators, are modules made to manage a lot of processing in AI applications. These chips are specially designed to improve performance when performing intelligent processing tasks, often several times higher than ordinary chips while consuming less energy. MAC (multiplier and accumulation) acceleration array is the core of AI chips and it is used for boosting the convolution operation in CNN. Due to its powerful function, it is used for handling a great number of computing assignments [10].

Currently, in the field of AI chips, GPU and CPU still dominate. With the continuous development in recent years, the proportion of FPGA and ASIC is also rising [11]. The characteristics of the four types of chips are described below.

(1) CPU

Central Processing Unit (CPU), also known as the central processing unit or main processor, is the most important processor in the computer. It is the core component of a computer and is responsible for interpreting computer instructions and processing data in computer software. There’s at least one processor in CPU which is the chip that’s responsible for calculations. For several years, there’s only one processor in CPU. However, after a few years of improvement and evolution, a single CPU contains at least two or more processor cores now which indicates the calculation speed has been increased. For example, a dual-core CPU is a CPU that has two processing cores; a quad-core CPU is a device that has four cores.

(2) GPU

Graphics Processing Unit (GPU) is a graphics processor that is widely used in personal computers, workstations in order to present graphics beautifully and accurately. GPU can not only process complex three-dimensional graphics, but can also be used as a co-processor in general computing. A microprocessor that performs image and graphics related operations.

There are differences between GPU and CPU in architecture. When handling numerous data in parallel, GPU contains more ALU known as Arithmetic Logic Unit, while CPU area mostly is controller and register [11].

(3) ASIC

Application Specific Integrated Circuit (ASIC) is a proprietary application chip designed and manufactured for specific user requirements and specific electronic systems. Its efficiency of processing and computing power can be adjusted to suit the requirements of different algorithms. ASIC chips are mainly divided into fully customized ASIC chips, semi-customized ASIC chips and programmable ASIC chips. It has small size, minimal power use, outstanding performance, and low cost that can all be enhanced at the hardware level. In recent years, ASIC has gradually presented its own advantages due to the improvement of AI algorithms and this chip has been widely used in different scenarios [11].

(4) FPGA

FPGA is a pre-designed and silicon-chip-implemented integrated circuit with programmable capabilities. It can be used to analyze individual data streams as well as numerous instructions.

Compared with ASIC, FPGA has the following advantages. First, it is editable and more flexible than customized chips. Second, FPGA products have a short time to market, which has great advantages in terms of time and cost. The benefits include high performance, low power consumption, and programmability. It offers clear advantages in terms of performance and energy usage over CPU and GPU. FPGA, however, has strict user requirements. By burning the FPGA configuration file, the user can specify how the gate and memory are connected.

AI chips can bring simpler and more efficient computing. At the same time, AI chips require less power and consume less energy when operating. However, this technology still in the beginning of AI chips which indicates that there is wide space for innovation in whether in industrial or scientific applications [11].

3.1.2. Artificial neural network modelling for Cryo-CMOS devices

Nowadays, more and more devices based on quantum mechanics are beginning to appear, such as quantum computers, quantum sensors, etc. These devices, based on quantum mechanics, often require low-temperature electrical interfaces. The implementation cryogenic electrical interfaces require CMOS integrated circuits and needs to be implemented at low temperatures. However, there are differences in the working performance of CMOS integrated circuits at room temperature and low temperature.

In order to solve this problem, Artificial Neural Network (ANN) is introduced which can generate the cryo-CMOS device models automatically and the model will be directly derived from the experimental data. All that is needed for ANNs is a discrete set of experimental data. The automatically generated ANNs from these data are suitable for precise analog-circuit simulations because they produce endlessly differentiable functions that describe the device's nonlinear current/voltage and charge/voltage relations [12].

3.1.3. Optimization in circuit design

Traditional circuit simulation optimization often involves too many parameters to perform manual calculations. Therefore, machine learning can be a good assistant in sampling the parameters before optimization. What’s more the target parameters will be gained through circuit simulation. Besides, the relationship between the design parameters and the target parameters will be shown clearly. Then each optimization will be created by the model. Taking circuit synthesis as an example, it is defined as an automated procedure to ascertain the device’s dimensions in order to satisfy the given nodes’ target specification. On the other hand, ML-based methods are used for improving the efficiency which have already become more and more popular [13].

3.2. Troubleshooting in integrated circuits

Integrated circuits are developing towards smaller sizes and can now reach the nanometer level. Therefore, it is essential to guarantee the quality and dependability of ICs which are used as vital parts in numerous systems and products [14]. Some errors will inevitably occur during circuit design and operation. However, the circuit structure is complex and cumbersome and also human detection efficiency is low. Therefore, AI detection is introduced. Using artificial neural networks (ANNs) as an example, this technique can keep data independently and concentrates on the information's capacity for self-organization and self-learning [9]. It is capable of handling complex fault diagnostic scenarios that cannot be expressed by explicit formulas and resolve issues with non-linearity, tolerance, and feedback cycles that are difficult to address in traditional models.

Another example is that Three-phase rectifier circuit is a common type in integrated circuit systems. In the process of troubleshooting, the fault coding and type can be compared with those in the neural network. A specific function is used for matching, using the sampled values of the three-phase rectifier circuit as the neural network. The input of the network, through the calculation and encapsulation of the neural network, the neural network output obtained when the error code is consistent with the fault code, the problem can be accurately diagnosed [15].

3.3. Control and protection in integrated circuits

In terms of circuit protection and verifying, artificial intelligence deep learning model can be used to perform this work. Deep learning is a branch of machine learning that makes utilization of deep neural networks (DNNs), which are multi-layered neural networks. For example, Artificial Intelligence (AI)/Deep Learning (DL)-based image analysis framework [16]. Digital integrated circuit hardware assurance can be achieved using this model. DL-based methods contain several advantages which includes the ability to automate processes that were previously primarily done by hand and being quick, accurate, and noise-resistant. This can be accomplished by introducing innovative applications for DL models as well as novel architectures for DL models. DL-based techniques outperform the conventional alternatives in three primary manners. First, because of their intrinsic advantage over parallel processing technology, they are quick at completing some positions; second, applying an organized neural network, for instance, they can learn global and abstract extraction rules as opposed to local and concrete rules used by many conventional strategies (keep in mind that representative training data is necessary for DL-based methods to generalize well); third, the method of end-to-end training and inference are used in many DL-based methods means that with proper model design, multiple tasks that were previously challenging to complete because of the many processes involved are now possible from beginning to completion [16].

Artificial intelligence has the advantage of employing deep learning framework algorithms to reason about integrated circuit status independently and protect the circuit in the case of an abnormal state.

4. Future trends and challenges

4.1. Future trends

4.1.1. Gen Ai in Integrated Circuit

For a period of time, the semiconductor industry has been employing artificial intelligence (AI) tools to assist in chip design, but that was just the beginning. Gen AI can support the implementation of best practices and enhance operations throughout the semiconductor industry value chain: 72% of respondents to Deloitte's upcoming Gen AI in Semiconductors Study (2024) think that gen AI will have a "high to transformative" influence on their industry [17].

Both established and growing gen AI chipmakers are anticipated to bring out new chips. In addition, companies that were formerly renowned for purchasing chips but have now chosen to begin manufacturing their own are likely to be the origin of future chips. At this point, nobody knows how any of items will turn out.

Because there exists so many distinct generation AI models and methodologies available, it is unlikely that one particular chip design will be most effective in all circumstances. It is anticipated that billions of dollars will be spent creating these "flavors" of next-generation artificial intelligence chips, which will likely include data center chips, edge chips, training chips, and inferencing chips [17].

4.1.2. AI in Manufacturing in IC

The primary cause of expenses in the semiconductor industry is manufacturing. The cases that utilize AI/ML will take up 40 percent of all value. Additionally, here are several options to apply ML or AI in manufacturing. First, it can be used for adjustment of tool parameters. To get higher precision, semiconductor manufacturers can integrate metrology measurements, tool-sensor readings from earlier process stages, and real-time tool-sensor data [18].

Second, it can be used for visual wafer inspection. Due to advances in deep learning for computer vision, wafer-inspection systems of today are capable of autonomously recognizing and classifying imperfections on wafers with precision that matches or exceeds that of human inspectors. Tensor processing units and other specialized hardware, along with cloud services, enable computer-vision algorithms to be automatically taught [18].

4.1.3. Artificial Intelligence and Machine Learning in Chip Design

During the research and chip-design process, semiconductor companies can enhance their efficiency and optimize their portfolios by utilizing AI/ML use cases. Companies can reduce the amount of money required to maintain yield, prevent time-consuming iterations, and speed up the yield ramp-up by eliminating of faults and out-of-tolerance process stages. They may additionally automate the laborious procedures related to the design of the physical layout and the verification process. Integrated circuit design using automated yield learning and manufacturing feedback, semiconductor businesses must go through several costly and intricate iterations if errors are made during integrated circuit (IC) design. Semiconductor manufacturers may avoid this problem by using ML algorithms to identify patterns in component failures, forecast potential failures in new designs, and suggest optimal layouts for increasing yield. With the aid of AI-based analytics, IC designs are dissected into individual components throughout the process [18].

4.2. Challenges

The size of a single molecule still places limitations on the 2D material, despite its unique potential for further downscaling. Beyond that, "more Moore" approach will be investigated and offer a path toward an even more "powerful" integrated circuit.

Currently, as the size of electronic devices continues to shrink, the physical size of the device has reached its limit. The smaller the device, the more problems and difficulties need to be overcome. 3D ICs offer a solution to the limitations of 2D chip technology. However, challenges in 3D ICs include low yield, reliability issues, and high production costs. Except these, the choice of materials significantly impacts the success of 3D ICs.

5. Conclusion

Artificial intelligence and integrated circuits have become two of the hottest development industries currently and the two complement each other and rely on each other. The article introduces the use of AI in integrated circuits and then elaborates on the inseparable relationship between the two. Applying artificial intelligence to circuit design, optimization, fault diagnosis, etc. will greatly improve the efficiency of the integrated circuit industry.

In the future, as the utilization of artificial intelligence in IC continues to deepen, the development of integrated circuits will be more intelligent, and problems existing in the circuits will be solved more effectively. The continuous development of integrated circuits will also make human life more convenient. The combined application of artificial intelligence and integrated circuits will continue to improve science and technology and make more contributions in the future.

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