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A review of the development of transistor technology and its application in electronic devices

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Abstract. Less than a century has passed since the invention of the transistor, but it has become one of the most critical components of modern electronic devices after several stages of development. Its advantages of high-speed switching, high reliability and small size as well as low power consumption have made it widely used in communication, computing and even medical fields, which has greatly contributed to the development of science and technology, with revolutionized many industries and improved people's quality of life. This paper reviews the development of transistor and its applications in different electronic devices by analyzing a large number of cases in the literature to give a basic understanding of transistors. This paper finds that transistors were invented due to the discovery of the field effect, its development was facilitated by the emergence of integrated circuits and Metal-Oxide Semiconductor Field Effect Transistor (MOSFET), and with the advancement of nanotechnology, transistors are widely used in amplifiers, digital logic circuits, integrated circuits and sensors in electronic devices.

Keywords: Transistor, Amplifier, Digital Logic, Integrated Circuit, Sensor.

1. Introduction

Transistor refers to a group of semiconductor electronic components, which has many types such as bipolar junction transistor (BJT) and Metal-Oxide Semiconductor Field Effect Transistor (MOSFET). Despite their differences in structure and operation, all transistors are capable of performing signal amplification, switching, and a variety of digital logic operations. In just a few decades, a significant number of research on power amplifiers has emerged due to the amplification; secondly, research on smaller-sized transistors has continued, with advancements in semiconductor fabrication technology allowing for smaller transistors and greater chip integration, leading to the later known of Moore's Law; and now even more advanced research is on their materials with the hope of using them in biosensors for diagnosing disease. The study of transistors is crucial to modern technology since they have a wide range of uses and are irreplaceable as unique electronic components. This paper is a review of the transistor, and after an extensive literature review, the historical process of the invention and development of the transistor is described in the second part; and then based on case study, its applications in four important electronic devices: amplifiers, digital logic, integrated circuits and sensors, are summarized in the third part. The significance of this paper is to provide relevant industry professionals with a wider understanding of transistor technology and promote ongoing research in transistor technology.

2. Development of transistors

2.1. Early electronic tubes to transistors

The electron tube was an early signal amplifier in the 20th century and made an important contribution to long-distance communications, but it had many drawbacks. The world's first computer, ENIAC (Electronic Numerical Integrator and Computer), contained 18,000 tubes but weighed 30 tons and consumed up to 150 kW of power. Its main purpose was only to solve ballistic total differential equations in the military, and ENIAC had to replace some of its broken tubes nearly daily [1]. This was an enormous gap compared to the billions of calculations per second and reliability of modern processor chips, and the invention of the transistor was the beginning of all this change. In 1926, the American physicist Lilienfeld proposed a structure using copper sulfide semiconductor material, i.e., he invented the concept of the Field Effect Transistor (FET), and although it did not materialize into a physical object, he still stated in his patent that "This invention is particularly suited for the amplification of oscillating currents such as radio communications " [2, 3]. It wasn't until the end of 1947 that William Shockley, Walter Brattain, and John Bardeen of Bell Labs, together invented the world's first transistor, which shocked the entire scientific community, and then the transistor literally found its way into applications such as television signal receivers, radios, and other communication devices.

2.2. Key stages of transistors' development

A little over a month after the birth of the transistor, Shockley invented the junction transistor by improving on the point-contact alone, proposing the NPN semiconductor structure, which is now the working principle of all Bipolar Junction Transistors (BJTs); In 1958, Kilby, working for Texas Instruments, used germanium wafers to make oscillator circuits, which opened up the era of integrated circuits and pushed the transistor in smaller size and high integration direction; two years later, Atalla perfected the technology of silicon dioxide, and invented the first working MOSFETT together with Kahng, followed by the emergence of Complementary Metal Oxide Semiconductor (CMOS) to further promote the development of integrated circuits [4]. In the 21st century, technological advances have brought transistors down to the nanoscale, and newer technologies have led to the production of today's processors and various types of chips, From the previous Pentium processor to Intel's new generation i9 10 nm process processor, the number of transistors has increased from several million to more than ten billion, the performance has very large differences but none of them can do without Field Effect Transistors (FETs).

3. Applications of transistors in electronic devices

3.1. Applications in power amplifier

One of the essential characteristics of the transistor is amplification, which is what led to the transistor's replacement of vacuum tubes. Therefore, many types of transistors are present in power amplifiers (PAs) in electronic devices such as mobile phones, radars, etc., both in the commercial and military fields. The most typical is CMOS, which consists of a P-type and an N-type MOSFET. It has the advantage of low power consumption and durability. Modern 5 GHz RF transceiver ICs are capable of using it, but it is challenging to efficiently combine the transistors and control the chip current to achieve the desired high output power. Jeng-Han Tsai proposed a power splitting/combining architecture that contains a differential drive amplifier (DA), three identical differential PA units, and designed output matching networks and radial power combination networks based on three transformers, respectively. A gain effect of more than 30 dB was achieved by adding the drive amplifier before the power stage; finally, the power performance is improved by a better layout, which reduces the parasitic resistances in the DC bias network, and a more uniformly distributed DC current mitigates the current density problem [5]. A fully integrated CMOS PA that produces 30.7 dBm/30.1 dBm saturated output power and complies with the 5.2 GHz standard and 5.6% Wireless Local Area Network (WLAN) specification was created by Tsai after testing and parametric simulations. Additionally, he discovered that by using this architecture, it was possible to take advantage of the CMOS process environment to achieve more compact circuit sizes, more efficient power combinations and smaller chip areas [5]. It can be said that since the invention of MOSFET, the function of amplification has always attracted scientists to explore it, and it has always great potential for application value.

3.2. Applications in digital logic

Another role of transistors is to perform switching functions and in Wanlass' 1963 patent, it is stated that CMOS can perform inverter and switching functions without any passive components like load resistors [6]. In digital circuits, logic gates such as logical "AND" and "OR" can be physically implemented by more transistors based on CMOS. More sophisticated and advanced Reconfigurable nanowire transistors (RFETs) were created and fabricated by Trommer's team in 2015; according to their study, these RFETs display symmetry and can mix P-type and N-type MOSFETs to produce timing features that are not possible with traditional CMOS techniques [7]. Furthermore, they explored deeper into the devices' structure and theoretical properties using circuit scaling models, while also analyzing their operational efficiency. Ultimately, an improved RFET-based logic library was constructed that not only implements the original logic representation but also demonstrates the benefits of lower latency and reduced transistor count in a specific full adder illustration. This implies its potential utility in forthcoming digital circuit enhancement and breaks through some of the limitations of CMOS [7]. In addition, Dragoman's team proposed a three-gate field-effect transistor in 2022, which has a single-layer graphene channel, fabricated through a ferroelectric structure HfO_2/Ge-HfO_2/HfO_2 at wafer level. It is capable of remembering the previous state and the current in the transistor can be controlled by one or more gates; After instrumental measurements, they found that the device's non-volatility was from the fact that the ferroelectric HfGeO layer acts as a floating gate, where the polarization dipole controls the concentration of charge carriers in the graphene channel and does not change the current until a new gate voltage is applied [8]. Regarding digital logic aspects, the strategy for realizing logic gates like “XOR” can be implemented using the same approach by considering the magnitude of the drain current when the top gate voltage (VTG) is 0 as a reference value, with a logic high corresponds to current magnitude higher than this reference, while a logic low operates accordingly [8]. For important general purpose logic gates, NAND, can also be implemented by way of data selection, and this technique can be adapted to achieve more functional logic gates. Finally, they conducted a performance analysis in contrast to MoS2 channel transistors, revealing that graphene as the channel’s material could have superior parameter performance and process control throughout the fabrication process. Unsurprisingly, the implementation of logic circuits is closely linked with transistors, and researchers are improving the overall performance of the circuits through the use of new materials.

3.3. Applications in integrated circuit

Transistors, as was previously mentioned, can regulate the flow of electric current, making it possible for functions such as switching, signal amplification, and logical operations. Integrated circuits, on the other hand, are a significant technological achievement that fabricates a large number of transistors on a single substrate (such as a silicon wafer). This design is not a completely new discovery because it fundamentally relies on the basic functionality of transistors. However, what's important is that it represents an entirely new way of implementing ultra-large-scale circuits, and significantly shrinking the size of electrical devices. Alongside cost reduction, this approach enhances product performance, thus significant impact on the development of electronics industry. The processor integrates multiple functional units and is the main application of integrated circuit, which has powerful capabilities for high-speed calculations. In 2008, Intel introduced an Itanium processor manufactured using a 65 nm process. It contains four dual-threaded 64-bit cores, each with three levels of cache. Additionally, two memory controllers were integrated on the chip, enabling a peak bandwidth communication of 96 GB/s between the cores, agents, and I/O channels through a 12-port crossbar router [9]. In terms of circuit design, this processor incorporates more logic circuits compared to the previous generation. It utilizes pulse latches as the primary elements to maintain static states. Clock pulses are generated through two

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circuits, with clock gaters driving numerous latches and determining pulse width through transfer gates. The local pulse generator is designed for a backup drive. To reduce yield loss to below 1%, the length, width, and other parameters of the transistors were designed and subjected to simulation testing [9]. The cache design of the processor minimized the influences of soft errors and area losses. By employing the downsizing of conventional FETs and utilizing 85% low leakage FETs, the overall power consumption of the chip decreased by one-fifth [9]. The processor finally achieved the integration of 205 million transistors and improved performance. Later, carbon nanotube field-effect transistors (CNT FETs) emerged. In 2017, a team from Peking University demonstrated that even CNT-based CMOS transistors with less than 5 nm channel lengths exhibit significantly improvement in critical parameters compared to traditional silicon-based transistors [10]. This shows a promising potential for their application in integrated circuits. Nowadays, a more mainstream innovation is the Fin Field-Effect Transistor (FinFET), invented by Chenming Calvin Hu in 1999. This transistor designed a fin-like 3D structure to enhance gate control over the channel in smaller-sized transistor fabrication technique, which overcame the limitations of planar structure of MOS transistors and achieves superior control capabilities. Starting with Intel's Core processors in 2011, TSMC and Samsung also adopted FinFET technology in later products. This highlights the indispensable role that transistors play in the development of integrated circuits, continuously pushing the boundaries and advancing towards smaller, higher-performing solutions.

3.4. Applications in sensor

A sensor is a device that converts perceived information into forms like electrical signals for output. Ranging from tiny optical sensors in mouse to speed sensors and gyroscopes on airplanes, its utilization has brought tremendous convenience to humanity. For instance, CMOS technology not only plays a role in electronic circuits but also extends to the field of digital and photography, became the image sensors that handle pixels. Byoung-Soo Choi and colleagues proposed a camera implementation approach for both 2D and 3D imaging. Specifically, they used in-pixel aperture technology and CMOS image sensors. In contrast to the conventional combination of camera lenses and apertures, this approach directly integrates a 2x2 aperture array onto the metal layer of the sensor chip. Array includes blue, red, and white apertures along with integrated PA pixels. Moreover, they have considered the impact of incident light angles and the obstruction effect of internal apertures. The main focus lies in deriving depth position information by comparing the clarity of the PA and W arrays. Through testing, this sensor effectively mitigates external light interference, capturing high-resolution depth images while consuming lower power than Time of Flight (TOF) cameras [11]. This technology might have broader applications in fields involving motion detection. Intriguingly, bio-sensors in the medical field have demonstrated as a hot area of research interest for many. In tumor detection, miRNA expression profiles have proven to be an ideal early biomarker for precisely gather alike tumor types, enabling early-stage tumor diagnosis. However, the challenge faces the fact that conventional methods of miRNA detection can be susceptible to interference from other fragments, leading to a decrease in sensitivity. Therefore, Li and his team chose carbon nanotube field-effect transistors (CNT FETs), which is sensitive to changes in the external environment. A layer of CNTs on silicon dioxide connects the source and drain electrodes. DNA probes were linked to the deposited gold nanoparticle (AuNP). When they encounter the target miRNA, negative charges were introduced, leading to a change in the drain current (I_{DS}). By measuring this change, the before and after concentration relationship of miRNA can be quantified [12]. According to the tests, there was a well-established linear relationship between the current variation and the concentration, ultimately achieving an error rate of less than 3.7%. Moreover, based on electron microscope observations and clinical analysis, this biosensor not only shows high sensitivity and specificity but also allows for a certain number of repeated uses, achieving rapid and accurate tumor detection on a single chip [12]. It was proven that transistors, once their properties were better understood, have been applied to a broader range of fields.

4. Conclusion

The development of modern electronic devices is inseparable from the invention and advancement of transistors. This article briefly outlines the history of transistors and their applications in four categories of electronic devices, which was invented by Shockley and others, and continues to improve the structures like BJT and MOSFET. Plus, more materials like carbon and graphene were added to transistors, which led to the realization of power amplifiers, digital logic circuits, and large-scale integrated circuits, with significant potential value also in sensor applications. Many researchers have made remarkable contributions to the development and exploration of transistor applications. This article only touches upon key aspects, leaving out many specific details and expansion directions. Currently, transistor fabrication processes and integrated chip power consumption face significant challenges. Exploring breakthroughs through new structural designs and the use of novel materials requires further research. Transistors will undoubtedly continue to play a crucial role in bringing better electronic devices in the future.

References

[1] A. W. Burks, "Electronic Computing Circuits of the ENIAC," in Proceedings of the IRE, vol. 35, no. 8, pp. 756-767, Aug. 1947, doi: 10.1109/JRPROC.1947.234265.
[2] W. F. Brinkman, D. E. Haggan and W. W. Troutman, "A history of the invention of the transistor and where it will lead us," in IEEE Journal of Solid-State Circuits, vol. 32, no. 12, pp. 1858-1865, Dec. 1997, doi: 10.1109/4.643644.
[3] J. E. Lilienfeld, “Method and apparatus for controlling electric currents,” U.S. Patent 1745175. Application filed Oct. 8, 1926, granted Jan. 28, 1930.
[4] Sah Chih-Tang, "Evolution of the MOS transistor-from conception to VLSI," in Proceedings of the IEEE, vol. 76, no. 10, pp. 1280-1326, Oct. 1988, doi: 10.1109/5.16328.
[5] J. -H. Tsai, "Design of a 5.2-GHz CMOS Power Amplifier Using TF-Based 2-Stage Dual-Radial Power Splitting/Combining Architecture," in IEEE Transactions on Circuits and Systems I: Regular Papers, vol. 66, no. 10, pp. 3690-3699, Oct. 2019, doi: 10.1109/TCSI.2019.2915616.
[6] F. M. Wanlass, “Low Stand-by Power Complementary Field Effect Circuitry,” U.S. Patent 3356858. Application filed June. 18, 1963, granted Dec. 5, 1967.
[7] J. Trommer, A. Heinzig, T. Baldauf, S. Slesazeck, T. Mikolajick and W. M. Weber, "Functionality-Enhanced Logic Gate Design Enabled by Symmetrical Reconfigurable Silicon Nanowire Transistors," in IEEE Transactions on Nanotechnology, vol. 14, no. 4, pp. 689-698, July 2015, doi: 10.1109/TNANO.2015.2429893.
[8] Dragoman, M.; Dinescu, A.; Dragoman, D.; Palade, C.; Teodorescu, V.Ş.; Ciurea, M.L. Graphene/Ferroelectric (Ge-Doped HfO2) Adaptable Transistors Acting as Reconfigurable Logic Gates. Nanomaterials 2022, 12, 279. https://doi.org/10.3390/nano12020279.
[9] B. Stackhouse et al., "A 65 nm 2-Billion Transistor Quad-Core Itanium Processor," in IEEE Journal of Solid-State Circuits, vol. 44, no. 1, pp. 18-31, Jan. 2009, doi: 10.1109/JSSC.2008.2007150.
[10] Qiu, C., Zhang, Z., Xiao, M., Yang, Y., Zhong, D., & Peng, L.-M. (2017). Scaling carbon nanotube complementary transistors to 5-nm gate lengths. Science (American Association for the Advancement of Science), 355(6322), 271–276. https://doi.org/10.1126/science.aaj1628
[11] B. -S. Choi et al., "In-Pixel Aperture CMOS Image Sensor for 2-D and 3-D Imaging," in IEEE Sensors Journal, vol. 18, no. 22, pp. 9163-9168, 15 Nov.15, 2018, doi: 10.1109/JSEN.2018.2869383.
[12] Li T., Liang Y., Li J., Yu Y., Xiao M.-M., Ni W., Zhang Z., Zhang G.-J. Carbon Nanotube Field-Effect Transistor Biosensor for Ultrasensitive and Label-Free Detection of Breast Cancer Exosomal MiRNA21. Anal. Chem. 2021; 93: 15501-15507. 10.1021/acs.analchem.1c03573. 34747596