MOSFET Characteristics and Related Biological Devices Analysis

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Abstract. With the development of modern electronic information technology, portable, fast, and high-performance electronic information products have brought great changes to people's life and health. People pay more and more attention to electronic information products. Not only in the civil aspect, high-end precision electronics industry, such as artificial intelligence, the new generation of electronic communication technology, medical devices, aerospace, and defense fields are based on various chips, to establish a complete national industrial system. This article describes MOSFET basic introduction, working principle and structure, etc., which plays an important role in the modern electronic information industry, including its application in implantable medical devices-current stimulator. The conclusion of this article is that with more and more capital and talent investment, the future of the chip industry with MOSEF as the basic component is very optimistic. The significance of this paper is to introduce the existing MOSFET technology and put forward views for future development.

Keywords: MOSFET, Integrated circuit, current stimulator.

1. Introduction

The semiconductor integrated circuit (IC) has had such a significant influence on modern living that it is now frequently taken for granted. Customers have become accustomed to expecting ever-more advanced electronics at cheaper prices. At the same time, customers favor purchasing lighter, more intelligent electronic devices, including wearable electronic devices, which have recently gained popularity. To some extent, the increasing consumer demand has brought greater challenges to the semiconductor integrated circuit industry. On a macroeconomic scale, electronics have become a huge industry that has increased growth and productivity in practically every sector of the economy [1]. Moore's Law, as it is known, was proposed by Intel founder Gordon Moore in his famous papers published in 1965 and 1975, which contains insights that have widely guided the development of semiconductor electronics for more than 50 years [2]. This theory proposes: With the invention of the integrated circuit (IC) in 1959, the number of components on an IC had increased by a factor of two on average per year. He expected that this trend, which was motivated by economic cost and yield concerns, would last for at least ten years, though later on the speed of integration slowed to doubling roughly every 18 months [3]. As Moore's Law has successfully anticipated past development in IC complexity, it is seen as a reliable tool to predict current trends as well, dictating the pace of innovation and defining the rules and very nature of competition. [4]. The number of atoms in a transistor has decreased over time due to the constant introduction of new process nodes, and a variety of physical limitations prevent further advancement. For instance, quantum tunneling takes place when the gate length is sufficiently short, increasing the leakage current. How far Moore's Law has to go before it ends is a matter of debate. It is obvious, however, that as integrated circuit sizes continue to decrease and semiconductor manufacturing technology advances (photolithography techniques are expected to reach atomic scale by the middle of the 2020s), Moore's Law will eventually run its course. If Moore's Law is indeed coming to an end, then a research program is required to evaluate the viability of new semiconductor technologies and solve the issues they raise.

In this paper, the basic information and application scenarios of MOSFET which are widely used in modern large-scale integrated circuit industry are presented. The second part of this paper: principle of MOSFET. The detailed name of MOSFET is introduced, and the circuit symbol, structure diagram, working principle and three main working states of NMOS and PMOS which are common in MOSFET category are introduced respectively (including trigger conditions of three working states, related formulas of drain current, etc.): cut-off region, triode region and saturation region. At the same time, the simulation circuit and output results are given. An introduction to CMOS is also given in this section. In section 3, the current stimulator will be introduced, which has a wide range of applications in implantable biomedical devices. Biphasic voltages have also been demonstrated to play a role in changing neuronal activity. Therefore, a designed Biphasic voltages current stimulator will be introduced in the fourth part. The fourth part creates a simple Biphasic voltages current stimulator by applying NMOS and PMOS. By adjusting the parameters, the Biphasic voltages current stimulator satisfying the required parameters is obtained, and the simulation results are also given.

2. Principle of MOSFET

2.1. Basic theory analysis

Metal Oxide Semiconductor (MOS) and Field Effect Transistor (FET) are combined to form Metal-Oxide Semiconductor Field Effect Transistor (MOSFET). Oxide layer separates the metal layer's (M) gate (O). The impact of the electric field regulates the semiconductor (S) field effect transistor. The MOSFET is a common semiconductor device that amplifies and switches electrical signals and is widely used in electronic devices. MOSFETs can be classified into the following types: (1) N-channel MOSFET (NMOS): Its electrical conductivity is mainly provided by N-channel. During the operation of NMOS, electrons in the channel will be affected by the electric field on the control gate, so as to adjust their conduction ability. (2) P-channel MOSFET (PMOS): Unlike NMOS, PMOS mainly provide electrical conductivity by P-channel, which works in the opposite principle to NMOS.

The MOSFET gate used to be made of metal in the early days. However, many gate of MOSFET used the metal rather than metal because polysilicon was more resistant to high temperature in the manufacturing process. With the continuous reduction of the characteristic size of semiconductors, metal as a gate material has received the attention of researchers again recently. As technology has advanced, many MOSFET architectures have been documented in industry studies at channel lengths of 0.1 /spl mu/m and below [5]. When MOSFETs are scaled down to the nanoscale scale, they experience performance degradation as well as challenges throughout the fabrication process [6].

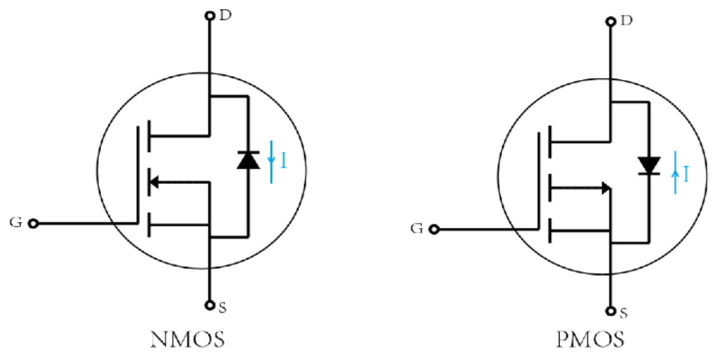

Figure 1. Circuit symbol of PMOS and NMOS.

Figure 1 displays the circuit symbols for PMOS and NMOS, as shown in the figures above. The arrow direction extending from the channel to the right in the MOSFET circuit symbol can be used to identify whether the device is an n or p MOSFET. Since the direction of the arrow is always from P to N, the arrow of a P-type MOSFET, or PMOS (representing the channel of this device is P-type), points from the channel to the base; on the other hand, this indicates that this device is an N-type MOSFET, or NMOS, since the base is P-type and the channel is N-type. In addition to the source (S), drain (D), grid (G), there is a base. In the circuit symbol, the base and source are connected in the most of time.

The gate electrode of the MOSFET has a very high resistance to the oxide between the channels, which gives the MOSFET a very high input impedance. This high input impedance makes the MOSFETs very sensitive to input signals and can effectively amplify low-amplitude signals. At the same time, MOSFET s' gate electrode drive circuits require very small input currents, which means they can be used to make very low-power circuits suitable for many battery-powered devices. Because the channel of a MOSFET is formed by changing the gate voltage, very fast switching speeds can be achieved by changing the gate voltage very quickly. This makes MOSFET s ideal switches for many applications. Compared to traditional transistors and diodes, MOSFET s are very compact, so they can be made very small devices, which makes MOSFET s widely used in integrated circuits. Because the manufacturing process of MOSFET s is very mature, they have very high stability and reliability, and are suitable for applications requiring high reliability. To sum up, MOSFET s have the advantages of high input impedance, low input current, fast switching speed, small size and high stability, which make them widely used in electronic engineering.

2.2. Structure of NMOS and PMOS

As the figure 2 shown, the core of the MOSFET's construction is a semiconductor capacitor with a metal-oxide layer on top of it (the current gold-oxygen half-effect tube mostly uses polysilicon instead of metal as its gate material).

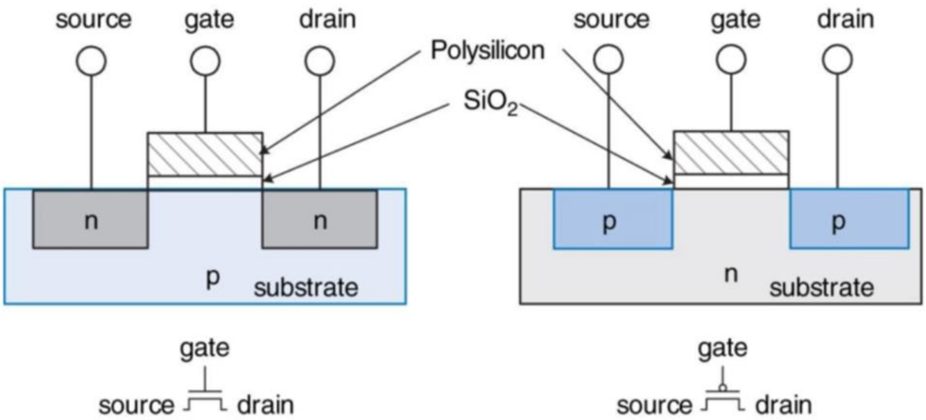

Figure 2. Structure of NMOS and PMOS.

The main component of the oxide layer is silicon dioxide, below which is silicon substrate, above which is polysilicon gate. Such a structure is a perfect match for a capacitor, with the oxide layer serving as the intermediate charge and the capacitance value being defined by the oxide layer's thickness and silica's dielectric constant. The two ends of the MOS capacitor are made of the gate polysilicon and base silicon. Consider that when a positive voltage is supplied to the gate, negatively charged electrons are drawn to the surface and create a channel that allows the majority of carriers to pass from the source to the drain of the n-type semiconductor. This is how NMOS functions. In other words, the voltage applied to the gate may control how the channel switches. The channel cannot form and the majority carrier cannot flow between the source and drain if this voltage is removed or a negative voltage is introduced. If PMOS is used to replace the working object, the source and drain poles will be p-type while the common bulk will be n-type. In a PMOS, holes in the semiconductor are drawn to the surface to form channels when a negative voltage is applied to the gate. This allows the semiconductor's majority carrier to flow from the source to the drain. The channel and carrier flow between the source and drain cannot form if this negative voltage is reduced or if a positive voltage is added.

2.3. Operating modes

The mode of operation of MOSFETs is described in the following sections. According to the gate of the MOSFET, the bias applied by the gate, source and the drain, the MOSFET will have the following three operating modes.

2.3.1. Cut-off region

When the gate voltage V_{GS} of the MOSFET falls below the threshold voltage (Vth), the MOSFET enters the cutoff region. In this case, not enough electrons form in the MOSFET's channel, so it can be considered a circuit breaker. In the cut-off zone, the leakage current (I_D) of the MOSFETs is very small, and the current in the circuit will not flow through the MOSFETs.

2.3.2. Triode region

When the V_{GS} > the threshold voltage (Vth), the MOSFET enters the linear region when the gate voltage of the MOSFET is higher than the threshold voltage but not sufficient to make the channel fully open. In this case, there are enough electrons in the channel of the MOSFET to form a conductive channel, but the resistance of the channel is very high, so the voltage drops considerably as the current flows through the MOSFET. In the linear region, the leakage current of the MOSFETs increases as the gate voltage increases, which following the equation 1 below

$$i_D = [\mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{th})] V_{DS} \quad (1)$$

Where μ_n is the carrier mobility, W is the gate width of the gold-oxygen half effector, L is the gate length of the gold-oxygen half effector, and Cox is the unit capacitance of the grid oxide layer.

According to the equation 1, if V_{GS} >V_{th} and remain constant, the current I_d through MOSFET is linearly related toV_{DS}. Therefore the region is also called the linear region. As V_{DS} is increased, the channel becomes more tapered and its resistance increases correspondingly. For$V_{DS} \leq (V_{GS} - V_{th})$, following the equation 2 below

$$i_D = \mu_n C_{ox} \frac{W}{L} [(V_{GS} - V_{th}) V_{DS} - \frac{1}{2} {V_{DS}}^2] \quad (2)$$

2.3.3. Saturation region

As V_{DS} is increased, when V_{DS}>$(V_{GS} - V_{th})$. Since the MOSFET is conductive, it creates a channel through which the current can flow. But, as the drain voltage rises, going over the gate voltage results in the reversed layer's charge going to zero close to the drain, which results in the channel being erased at this location. Pinch-off is the name given to this ailment. Currently, only the gate voltage and not the voltage V_{DS} between the drain and source electrodes affect the current flowing through the MOSFET.

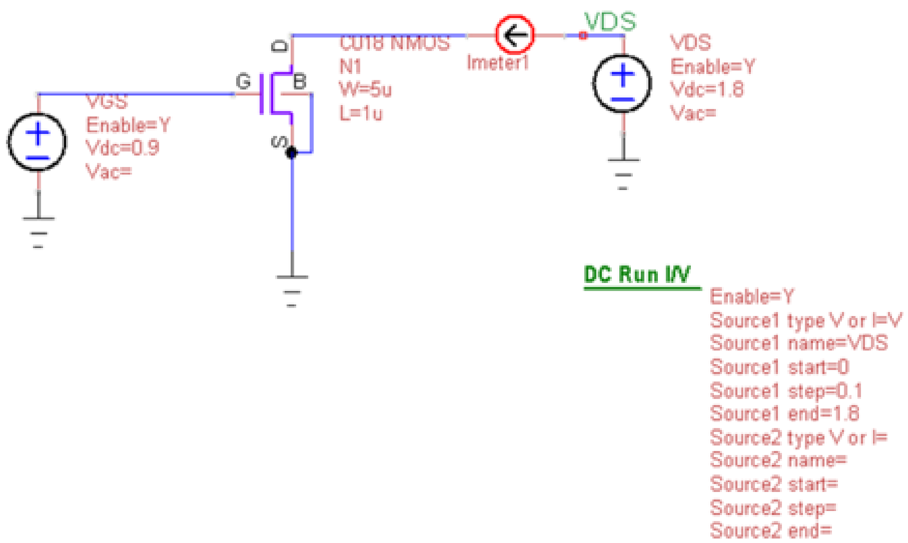

Figure 3. Simulation circuit of NMOS.

As shown in figure 3, the gate of NMOS is connected to a 0.9V power, the source of NMOS connected to the ground. Therefore the V_{GS}=0.9V, which is larger thanV_{th}. By increasing the drain voltage, from 0V to 1.8V, plot the diagram of I_D versus V_{DS} using circuit simulation software as shown in figure 4 below.

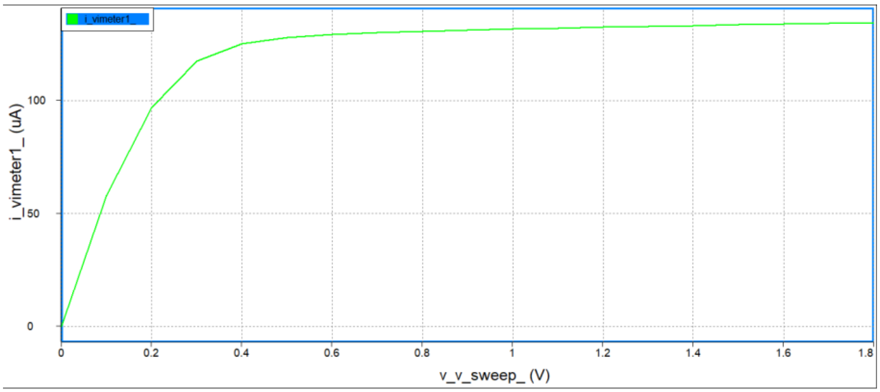

Figure 4. I_D VersusV_{DS}.

Complementary Metal-Oxide-Semiconductor (CMOS) is so named because it combines complementary physical properties of NMOS and PMOS. The benefit of CMOS is that it only uses energy when the transistor needs to turn on and off, which results in significant power savings and less heat production. CMOS is also the most fundamental and widely used semiconductor device method. The structure of CMOS is shown as figure 5 below.

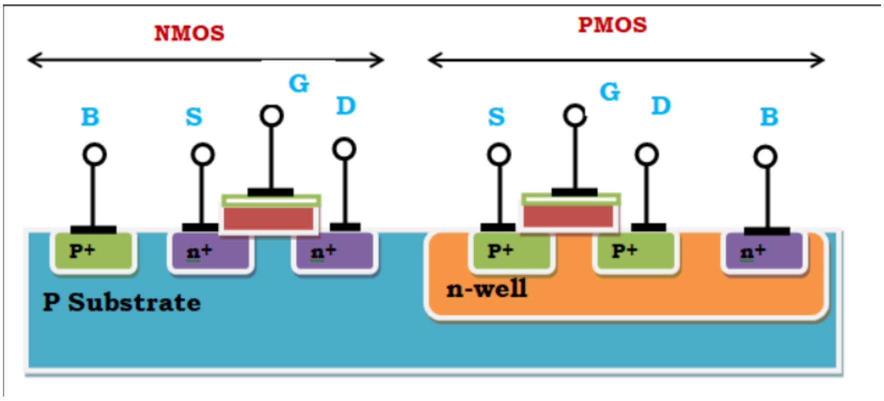

Figure 5. The structure of CMOS

Among the essential parts for the majority of power electronic applications are the MOSFET drivers, or metal oxide semiconductor field effect transistors. Expectations for MOSFET current, power, and efficiency are rising as switching frequency rises from kHz to MHz levels. So, it must come up with fresh ideas for creating quick drivers. Silicon carbide MOSFET uses are currently some of the results and new applications [7].

3. Basic theory of Stimulator

MOSFET has a wide range of applications in implantable biomedical devices. Implantable biomedical devices (IMDs), such as functional electrical stimulation, implanted pacemakers, retinal prostheses, and left ventricular assist devices [8]. Additionally, it has been demonstrated that individuals with severe motor abnormalities can regain capability using closed-loop brain-computer interfaces (BCIs) made up of neural stimulation and recording signal processing blocks [9]. Electrical stimulation of nerve tissue and monitoring of nerve electrical activity are important for the development of new prosthetics and treatments for neurological diseases. By studying the electrical stimulation and electrical activity of nervous tissue, we can understand the electrical signal conduction mechanism of nervous system in normal and abnormal state, thus providing important theoretical and practical basis. Understanding and guiding the behavior of brain stimulation and the electrochemical principles of recording electrodes are particularly important in the development of long-term implanted devices. Especially for devices that involve a large number of microelectrodes, the stability of the electrode and nerve tissue needs to be considered to ensure the long-term effectiveness and reliability of the device. The workflow of BCIs is shown in figure 6.

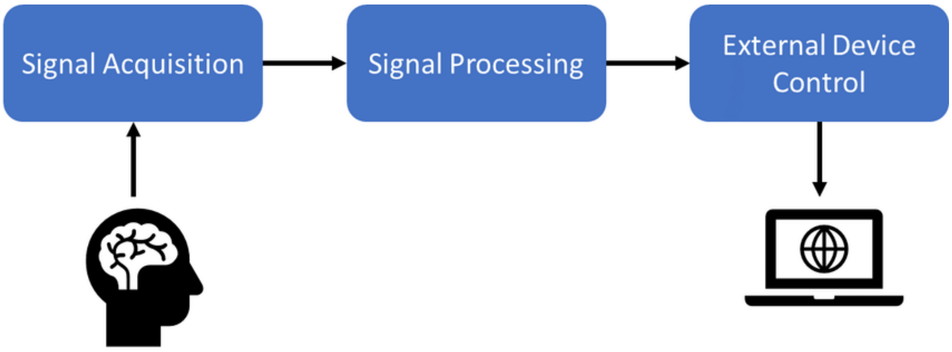

Figure 6. Workflow of BCIs

According to the research, the stimulator IC uses a 0.18-m standard CMOS architecture and only needs a 0.11 mm^2 area to provide up to 1 mA of stimulation current [10]. Powerful and comprehensive functions may be accomplished in a very small space by utilizing the distinctive qualities of CMOS electronic components, which is also an essential aim and development direction of the development of CMOS and its related electronic components. Moreover, biphasic stimulation is frequently employed in many IMDs to electrically stimulate tissues in order to maintain charge balance and avoid tissue or cell damage. Since accumulated residual charges might cause damage to the tissue and cell, two pulses anodic and cathodic should be used from positive and negative sources. Figure 7 depicts an example current waveform for the biphasic stimulation pattern (100 A current amplitude, 200 s phase width, 50 s interphase gap, and 1 ms interstimulus delays). It has also been shown that biphasic voltages influence how neural activity changes.

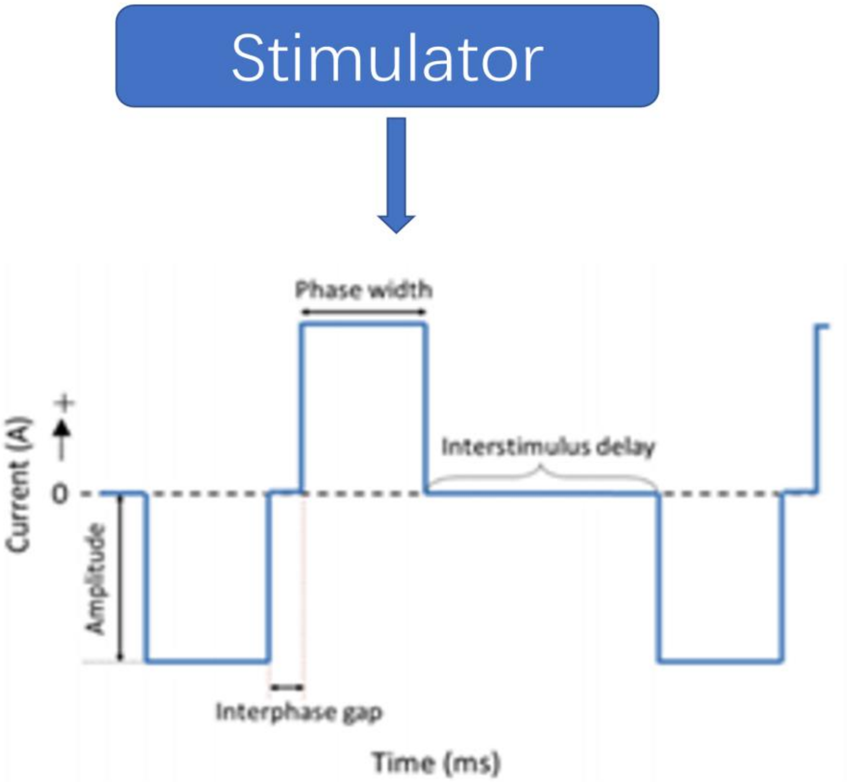

Figure 7. An example current waveform

4. Simulation and analysis

The example current waveform shown above is produced using MOSFET technology and voltage pulse source. The circuit of project to generate the example current waveform was shown in figure 8 below.

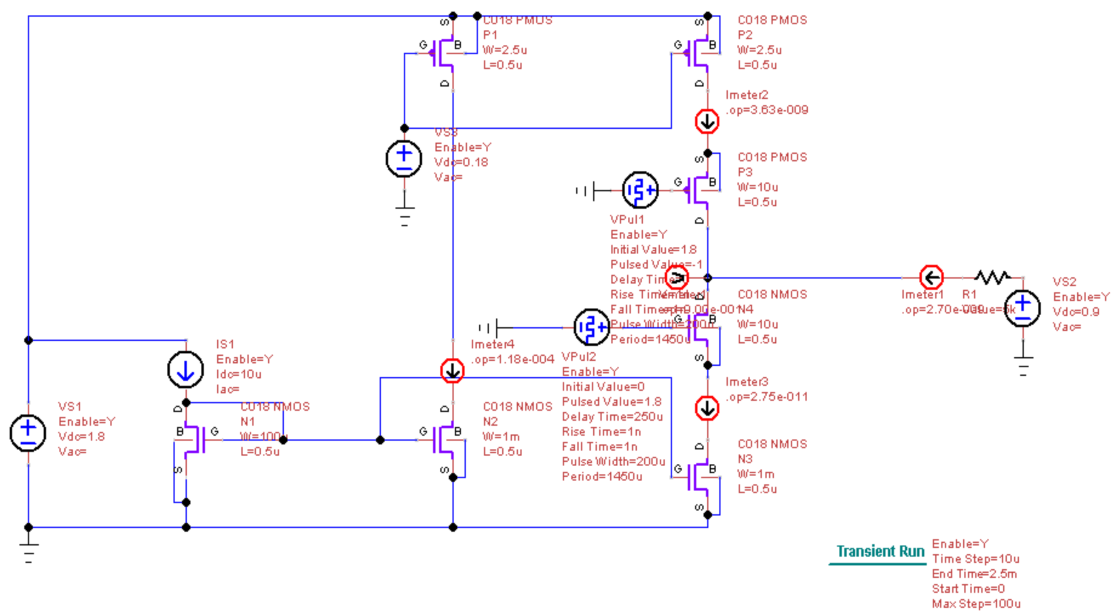

Figure 8. The circuit of project

A current mirror was used in circuit, following the $\frac{I_{dN1}}{I_{dN2}} = \frac{(\frac{W}{L})_1}{(\frac{W}{L})_2}$. Both NMOS and PMOS were used here. According to the formula

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_n)^2 \tag{3}$$

By adjusting the gate voltage of PMOS to about 0.18V to ensure the current in PMOS side achieving 100uA when simulating. Meanwhile, adjusting the parameters (value, delay time) of voltage pulse sources, generate the suitable voltage difference across the resister. The simulation result was shown in figure 9 below.

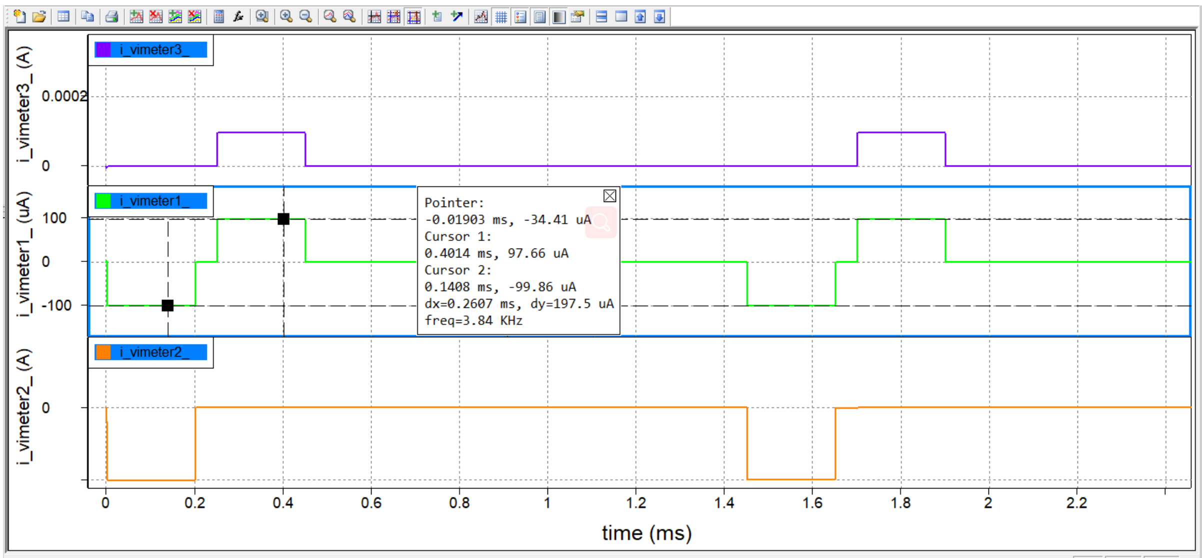

Figure 9. The simulation result.

The purple line shown the current simulation of current meter 3, which measure the current value of NMOS side. The yellow line shown the current simulation of current meter 2, which measure the current value of PMOS side. The current meter 1 measure the current though the resister, required output waveform is obtained by superimposing the above two waveform. The output current waveform's value measured as figure 4 was 97.66uA and -99.86uA. Although there is an error to the required waveform value of 100uA, it is within the acceptable range.

5. Conclusion

In conclusion, the paper elaborates the Modern integrated circuit development of an important component MOSFET. The paper also introduces the famous Moore's Law, which has guided the development of integrated circuits in the past decades. The current stimulator, which has numerous applications in implantable biomedical devices. The fourth portion will introduce a constructed Biphasic current stimulator. The fourth section applies NMOS and PMOS to produce a biphasic current stimulator, which fulfilling the necessary specifications are obtained by modifying the parameters. The simulation results are provided finally. As integrated circuits are ubiquitous in modern human society and will play an increasingly important role in the future. The chip industry based on integrated circuit is not only a small manufacturing technology, but also a representative of high-tech innovation, which is the foundation and core of electronic information technology. The chip industry plays a decisive enabling role in the new generation of information technology. Secure information technology facilities, the fifth generation of mobile communication (5G), VR/AR, autonomous driving, artificial intelligence and even future space exploration and other industries depend on the continuous innovation of chip technology to some extent. As the chip industry based on IC attracts more and more attention, more and more funds and talents will be invested in this industry, the future of IC industry is regarded as optimistic.

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