

Application of Integrated Circuits in Cardiac Pacemakers

Zihan Li

School of Microelectronics, Xi'an Jiaotong University, Xi'an, China

lizihannb@stu.xjtu.edu.cn

Abstract. This article briefly describes the application of integrated circuits in the medical field, such as wearable and implantable medical devices. The article introduces the development process of integrated circuits used in cardiac pacemakers, explaining how it evolved from bipolar junction transistors integrated circuits in the past to today's complementary metal oxide semiconductor integrated circuits. The basic components of the pacemaker are described from a system level, including the signal amplifier, pulse generator, battery management system, and analog-to-digital converter. This allows for a clear presentation of the working process of the pacemaker. Furthermore, the article explains how analog integrated circuits and digital integrated circuits can be used together to achieve the goal of low power consumption of cardiac pacemakers at a circuit level, with reference to some cutting-edge scientific and technological achievements. The necessity and advantages of integrated circuits in medical applications are demonstrated, and the future development of integrated circuits in related aspects is forecasted based on the current development situation.

Keywords: Cardiac pacemaker, CMOS, low-power, implantable pacemaker.

1. Introduction

With the rapid development of microelectronics technology, the scale of integrated circuits is gradually expanding, and the integration of chips is getting higher and higher. The number of logic gates has reached a considerable number, and the circuit can realize more complex functions. Therefore, people also have more precise control over the circuit. Integrated circuits have occupied a large proportion in medical care. Some wearable medical devices, such as smart watches that can monitor heart rate and blood oxygen, use integrated circuits designed with photoelectric sensors and photodiodes, which can receive red and green light reflected from the skin. The optical signal is amplified by the signal processing circuit, and the clock circuit in the chip can be used to monitor the heart rate. This article will specifically discuss the implantable medical device cardiac pacemaker, which also has a lot of integrated circuit applications, which will be discussed in more detail in a later article. In addition, in terms of medical ultrasound systems, the most important and ubiquitous modules in a medical ultrasound system are addressed. The development of integrated circuits has achieved transducer driving circuit, low-noise amplifier, beamforming circuit and analog-to-digital converter (ADC) [1]. All in all, the development of integrated circuits is of great benefit to the development of medicine.

This paper is organized as follows. Section 2 introduces the circuits in cardiac pacemakers. Section 3 looks forward to the future development of integrated circuits in pacemakers, and Section 4 concludes.

2. Circuits in Cardiac Pacemakers

2.1. The Principle of Cardiac Pacing

There are two types of cardiomyocytes, one is the working myocardium that does not exhibit pacing function under physiological conditions, and the other is the special conduction system of the heart that has pacing function. The sinoatrial node and the atrioventricular node, which have poor conduction function and strong pacing function, belong to the latter [2].

The sinoatrial node and the atrioventricular node act as pacemakers, controlling the contraction and relaxation of the heart. The sinoatrial node periodically sends out electrical signals that direct the

heart to contract. The atrioventricular node can conduct electrical signals from the sinoatrial node to the ventricles, guiding the ventricles to contract. In many patients, the heart is unable to generate or conduct electrical signals. At this time, a pacemaker is needed to generate or conduct electrical signals according to the normal heart beat rate, and to send pulses according to the normal rhythm of the heartbeat to guide the heartbeat.

2.2. Past Integrated Circuit Pacemakers

In simple terms, a pacemaker has two parts: a generator and electrodes. A generator is a small, battery-operated device that sends out electrical signals to control your heart's rhythm. Electrodes are connected to the generator through wires that transmit electrical signals to the heart.

Around 2000, a built-in cardiac pacemaker became popular on the market. This electronic device implanted in the body emits a series of pulses with a width of about 2ms and an adjustable range of 1 to 7V at an interval of about 1s. Pulse voltage to stimulate the heart to beat accordingly. Moreover, the frequency and amplitude of the output pacing pulse can be modified by program control in an external wireless mode, and the external programming function is realized. The pacemaker also has the function of wireless charging outside the body, so that the built-in battery can work for a long time [3].

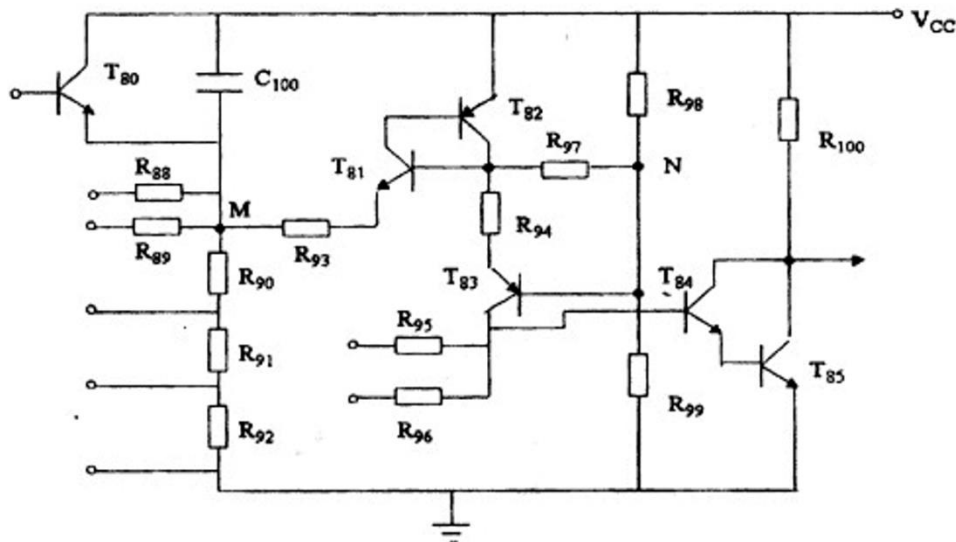


Figure 1. Signal generator unit circuit [3]

It can be seen from Fig. 1 that the past integrated circuits were mainly bipolar junction transistors (BJT). The function of T81 and T82 is to form a positive feedback complementary circuit to regulate the charging and discharging process of C100. The charging circuit of C100 can be composed of multiple Resistors (such as R88 ~ R92) form. In this circuit, the potential VN at point N remains basically unchanged, while the potential VM at point M will gradually decrease below VCC with the charging of C100. When VN-VM=0.5V, the complementary switch will conduct a short circuit quickly, force C100 to discharge and make VM rise rapidly. Since the saturation period of switches T81 and T82 is only about 2 milliseconds, they then go into the off state, so that T83 gets a short pulse. This pulse has an adjustable frequency of approximately 1 Hz and a duty cycle of approximately 500. Composite tubes T84 and T85 then isolate the pulse and send it to a bidirectional pulse forming circuit, which ultimately generates the pacing pulse [3].

But this circuit composed of bipolar junction transistor (BJT) has many disadvantages compared with metal-oxide-semiconductor field-effect transistor (MOSFET):

- (1) High energy consumption
- (2) Poor thermal stability
- (3) Larger design area is required
- (4) The noise is large

2.3. Overview of CMOS pacemaker development

2.3.1 Implantable pacemaker system outline

The following article will introduce a low-power analog-digital hybrid cardiac pacemaker system mainly based on complementary metal oxide semiconductor (CMOS) devices. CMOS has many advantages such as low power consumption, high integration and high reliability.

For a qualified cardiac pacemaker integrated circuit, the sensing amplifier, gain amplifier, and filters detect and enhance the cardiac signal, which is then converted into digital form by an ADC. Switched capacitor amplifiers and filters are widely used to produce precise frequency response and reduce power consumption (in the region of nanowatts). Fig. 2 shows the specific process. It's clear that this device can be categorized into several key functional components:

- (1) A sensor system with amplifiers, filters, and an ADC is built onto the input side.
- (2) To create therapeutic electrical pulses, a high voltage multiplier and a pulse generator are used on the output side.
- (3) The housekeeping side is responsible for managing the device's battery, generating reference signals and bias, and ensuring proper device operation.
- (4) The device's logic includes algorithms for controlling therapy parameters and oscillation [4].

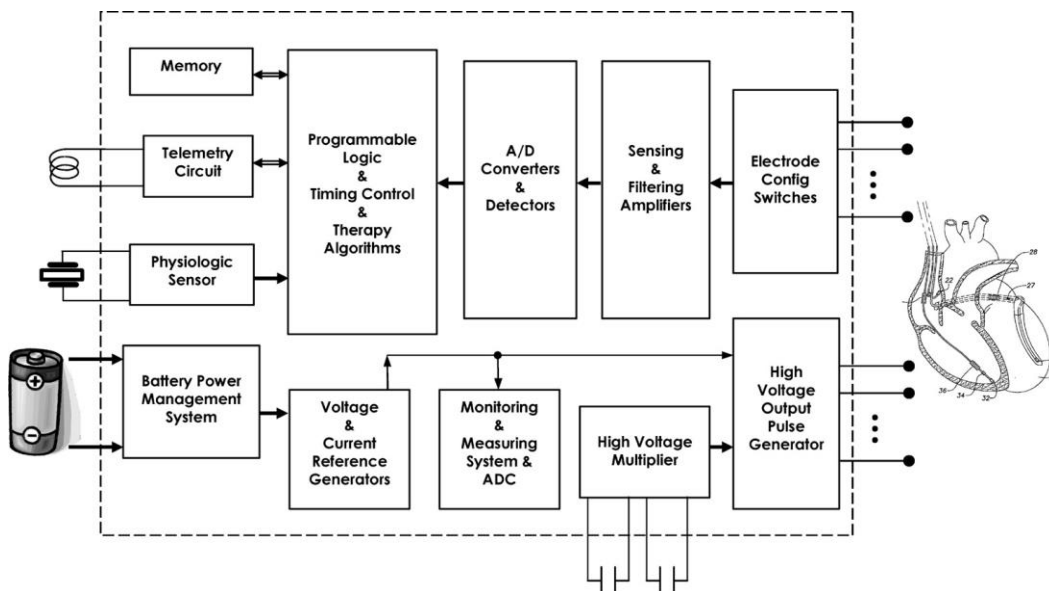


Figure 2. Implantable pacemaker system outline [4]

2.3.2 Low Power Bio-Potential Measurement System

Conventional biopotential measurement devices operate on the power-hungry output of an ADC to change the type of signal for modulation. This article describes a circuit that converts a voltage signal into a frequency signal. In this case, the power is greatly reduced, and it is more precise and simpler [5].

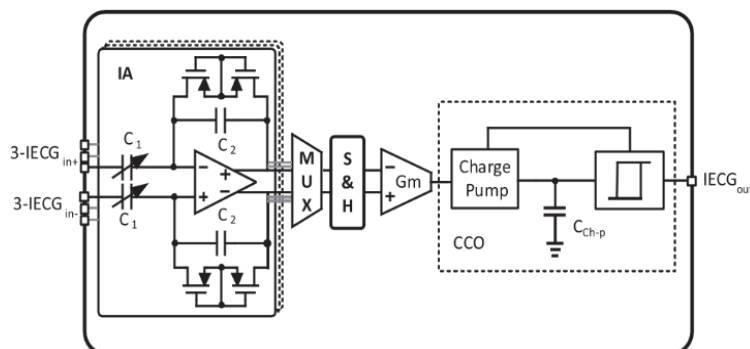


Figure 3. Bio-potential measurement system [6]

The system for measuring bio-potentials is depicted in Fig. 3 to eliminate input offset and increase the input dynamic range. It uses an instrumentation amplifier with configurable gain settings (based on $C1/C2$ ratio) and capacitive coupling. The instrumentation amplifier offers three gain settings and increases the intrinsic heart voltage. The V_{in} is held in a sample and hold block before being processed by a transconductance amplifier. The output voltage of the instrumentation amplifier is converted into a current through transconductance amplifier. The output current of the transconductance amplifier supplies power to the charge pump, which injects current into the capacitor through two adjustment switches to generate a waveform. The saw-tooth waveform is then compared to high and low voltage references by a Schmitt trigger, which in combination with the charge pump, functions as a current controlled oscillator. The output of the Schmitt trigger produces both the switching signal for the charge pump and the output of the bio-potential system [6].

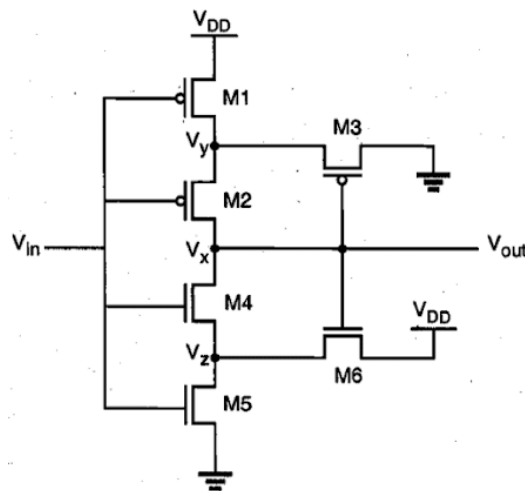


Figure 4. Basic Schmitt trigger [7]

Next, a brief explanation will be given to the Schmitt trigger mentioned above. Fig. 4 is a basic Schmitt trigger. Qualitative analysis of this circuit: When V_{in} changes from 0 to V_{DD} , since V_{out} starts to be high level, M_6 is turned on, making V_z level higher, and M_4 is turned off. When V_{in} is high enough, the on-resistance of M_5 decreases, which reduces V_z , makes M_4 conduction, and the output begins to decline. Once V_{out} becomes low, M_6 is cut off, M_4 is turned on more, and V_{out} drops faster, forming positive feedback. When V_{in} changes from V_{DD} to 0, since V_{out} starts to be low level, M_3 is turned on, V_y is low level, and M_2 is turned off. When V_{in} is low enough, M_1 conducts more, so that V_y rises high enough, M_2 conducts, and the output starts to turn high.

2.3.3 Bipolar Pacing Mode

As the cardiac pacemaker is an implanted medical device, the capacity of the battery and the voltage consumption during operation are very important. If the battery dies easily, the patient will need surgery to replace the battery. This is not good for the patient's economic status and physical health [8].

When it comes to wire design, early cardiac pacemakers used to have a unipolar configuration where only a cathode was present on the electrode wire for heart stimulation. The current flow would then return to the pacemaker's anode, located on its surface, through the human tissue. Another approach to wire design is the bipolar configuration, which involves two wires that are insulated and bundled together. The cathode is located at the head end of the bundle for stimulation, while the anode is placed on the outer layer of the wire, not far from the head end, allowing the current to circulate through the wire harness and back to the pacemaker [9].

3. Future development

3.1. Wireless Charging for Cardiac Pacemaker

As mentioned above, the battery management system of a cardiac pacemaker is very complex, and power consumption of many components needs to be considered. If wireless charging can be realized, it will not only solve the problem of difficult power supply for implanted medical devices, but also reduce the chance of re-injury caused by multiple operations of patients.

Technologies for wireless power transfer are continuously being developed. A series-parallel configuration is employed for pacemaker applications because it offers a steady output voltage over a reasonable transmission distance, making the design appropriate for wireless biomedical implant charging. Because of the Spider Web Coil's enormous surface area and low parasitic capacitance, the system is designed to have a high inductance [10].

3.2. Leadless Cardiac Pacemaker

Due to its capacity to get around the main drawbacks connected to lead issues; the leadless pacemaker system is anticipated to displace traditional cardiac pacemakers in the near future. The creation of an energy-efficient communication framework with low-power capabilities is required to provide better follow rate and communication capability across the many nodes of this technology [11].

Unlike conventional pacemakers, which are implanted with leads that are threaded through blood vessels to connect to the heart, leadless pacemakers are entirely self-contained and are placed directly in the heart through a minimally invasive procedure. They are battery-powered and use small prongs to attach to the heart muscle, delivering electrical pulses that regulate the heartbeat. Leadless pacemakers have the potential to eliminate the need for leads, which can be a source of complications in some patients, and may offer a more streamlined and convenient option for pacing the heart.

4. Conclusion

This article mainly starts with the integrated circuit in the cardiac pacemaker. The integrated circuit composed of BJT decades ago is very simple compared with today, and has the disadvantages of high power consumption, high noise, and large occupied area, but it is a big step forward in the development of integrated circuits. Afterwards, the article introduces the components of the cardiac pacemaker composed of CMOS integrated circuits. The process of cardiac pacing from signal reception to signal processing and response is discussed systematically. Then the article introduces some cutting-edge research results, such as the design required by people to achieve low power consumption, and some basic circuits. Finally, the future development of cardiac pacemaker integrated circuits is prospected. The realization of wireless charging and wireless technology will make great contributions to implantable medical devices.

References

- [1] Zhang Y, Demosthenous A. Integrated Circuits for Medical Ultrasound Applications: Imaging and Beyond. *IEEE Transactions on Biomedical Circuits and Systems, Biomedical Circuits and Systems, IEEE Transactions on, IEEE Trans Biomed Circuits Syst.* 2021; 15(5): 838-858.
- [2] Xu Youqiu. Cardiac Pacing Principles and Regulation, *Chinese Heart Journal.* 2001; 13(4): 322-325.
- [3] Geng Shijun, Wang Baoguang, Li Gengli, et al. The Developing of Embed Automatic Pacemaker. *Journal Of Hebei University of Technology.* 1999; 28(4): 48-51.
- [4] Hossain, Shahadat. A Very Low-Power CMOS Mixed-Signal IC for Implantable Pacemaker Applications. *IEEE Journal of Solid-State Circuits,* 2004.

- [5] Gerosa A, Novo A, Mengalli A, Neviani A. A micro-power low noise log-domain amplifier for the sensing chain of a cardiac pacemaker. 2001 IEEE International Symposium on, Circuits and systems. 2001; 1: 296.
- [6] Rezaeiyan Y, Zamani M, Shoaie O, Serdijn WA. Mixed-Signal IC With Pulse Width Modulation Wireless Telemetry for Implantable Cardiac Pacemakers in 0.18- μm CMOS. IEEE Transactions on Biomedical Circuits and Systems, 2018; 12(3): 589-600.
- [7] Sung-Mo Kang, Yusuf Leblebici, Chulwoo Kim. CMOS Digital Integrated Circuits: Analysis and Design, Fourth Edition. 2015.
- [8] Thijssen K M J, Vlemminx M W C, Westerhuis M E M H, et al. Uterine monitoring techniques from patients' and users' perspectives. AJP Rep, 2018, 8(3): e184-e191.
- [9] Ding Ding, Lin Kaibin, Huang Dong, Guo Xinwei, et al. Impedance study of implantable cardiac pacemaker in unipolar/bipolar pacing mode and in vitro experimental plan. Chinese Journal of Medical Instrumentation. 2022; (3): 237.
- [10] Mahmood AI, Eldosoky MA, Soliman AM, Gharghan SK. Wireless charging for cardiac pacemakers based on class-D power amplifier and a series-parallel spider-web coil. International Journal of Circuit Theory and Applications. 2023; 51(1): 1-17-17.
- [11] Bose P, Khaleghi A, Mahmood S, Albatat M, Bergsland J, Balasingham I. Evaluation of Data Telemetry for Future Leadless Cardiac Pacemaker. IEEE Access, Access, IEEE. 2019; 7: 157933-157945.