A Very Low-Power CMOS Mixed-Signal IC for Implantable Pacemaker Applications

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***Abstract*—Low power consumption is crucial for medical implant devices. A single-chip, very-low-power interface IC used in implantable pacemaker systems is presented. It contains amplifiers, filters, ADCs, battery management system, voltage multipliers, high voltage pulse generators, programmable logic and timing control. A few circuit techniques are proposed to achieve nanopower circuit operations within submicron CMOS process. Subthreshold transistor designs and switched-capacitor circuits are widely used. The 200 k transistor IC occupies 49 mm^2, is fabricated in a 0.5-μm two-poly three-metal multi-V_t process, and consumes 8 μW.**

***Index Terms*—Analog–digital conversion, biomedical equipment, digital–analog conversion, high voltage, implantable biomedical devices, leakage cancellation, low power, subthreshold, switched-capacitor circuits, switched-capacitor filters.**

I. Introduction

PACEMAKERS were first introduced in the 1950s, with only a few transistors used in the device. Technology has advanced greatly and there are over tens of millions of transistors in today's implantable pacemaker system. A cardiac pacemaker is used to treat bradyarrhythmia (a heart rate that is too slow). This device monitors the heart's rate (how fast it beats) and rhythm (the pattern in which it beats), and provides electrical stimulation when the heart does not beat or beats too slowly. The pacemaker system, as shown in Fig. 1, consists of two components: pacing lead and pacemaker device. The pacing lead connects between the heart and the pacemaker device. It is a flexible insulated wire with an electrode tip. This tip, inserted through a vein into the heart, carries impulses from the pacemaker device to the heart, stimulating the heart to beat. It also carries information from the heart back to the device, which is used to access the status of the patient's heart. The pacemaker device is the "brains" of the system. It is typically small in size, often less than an ounce in weight, and less than two inches wide. Once implanted in the upper chest, the pacemaker's presence is nearly invisible to the eye. Within the pacemaker device, there are two main components: 1) the integrated circuit, which contains all the components necessary to operate a sophisticated device, monitors the heart's rate and provides stimulation when necessary, and 2) a battery, which for pacemaker use is designed to be small and flat in order to fit into the pacemaker case. The battery is typically made of lithium iodine, which gives a life span of up to 10 to 12 years.

The primary goal for pacemaker ICs has been centered around low-power analog/digital design techniques [1], [2]. In this paper, instead of using several analog ICs to sense the heart rate and deliver electrical stimulation, a highly integrated mixed-signal interface single-chip-solution IC [3] is presented. Utilizing many very-low-power design techniques, an large amount of analog and digital circuitries have been integrated to provide new features and functions for future generation pacemakers. Low power consumption is by far the most important design requirement to meet the 10–12 years of single battery operation. Every nanoampere of current consumption has been carefully considered in this design.

II. Pacemaker Block Diagram

A simplified block diagram of the pacemaker system is outlined in Fig. 2. It can be briefly divided into a few major functional blocks:

1) Input side: a sensing system which consists of amplifiers, filters and ADC.
2) Output side: consists of high voltage multiplier and high voltage output pulse generator.
3) Housekeeping side: battery management system, bias and reference generators
4) Logic: algorithms for therapy controls and oscillators.

III. Leakage Cancellation Switched-Capacitor Circuits

Pacemakers need to sense cardiac signals. The pacemaker sensing system block diagram is shown in Fig. 3. The cardiac signal is sensed and amplified by a low-noise amplifier, gain amplifier, and bandpass filters, and digitized by an analog-to-digital converter (ADC). Switched-capacitor (SC) amplifiers and filters are often used for accurate frequency response and low power consumption (in the order of nanowatts). The cardiac or respiration signals may have very low-frequency content, often a corner frequency as low as ~0.05 Hz is expected. Their SC sampling rate is in the tenths of hertz—transistor leakage may become a serious issue in submicron process. To illustrate the issue, consider the sample-and-hold (S/H) amplifier (SHA) in Fig. 4(a): with $C_{\text{hold}} = 1$ pF and a S/H period of 100 ms, 1 pA of leakage will drift 0.1 V during the hold period. This is unacceptable when millivolts or microvolts of resolutions is required. A typical solution to overcome this problem is to use a much larger capacitor. However, a larger capacitor requires a much stronger driver or amplifier at the previous stage, thus

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