A Li-ion Battery Charging Design for Biomedical Implants

Chi-Chun Huang, *Student Member, IEEE* Shou-Fu Yen, and Chua-Chin Wang, *Senior Member, IEEE*

Department of Electrical Engineering
National Sun Yat-Sen University
Kaohsiung, Taiwan 80424
email : ccwang@ee.nsysu.edu.tw

***Abstract*— A Li-ion battery charging design for wireless medical implants is presented. Not only the power density is limited in the medical implants, but also the inherent lack of efficiency in a wireless powered system restricts the stability of power supply for medical implants. Therefore, a simple and power saving circuit is proposed to charge the Li-ion battery with 0.1 C. In order to resist the ripple of the voltage supplied of the carrier wave from the inducing coil, a special bias circuit to generate a bias voltage which varies with supply voltage has been designed. Moreover, the proposed design with a protection circuit can limit over-charge voltage of the Li-ion battery to prevent any damage.**

***Keywords*— Li-ion battery, charging circuit, wireless, medical implants**

I. INTRODUCTION

The rapid development of semiconductor technology and wireless communication has thrown a significant impact on the daily human activities as well as the medicare treatment. Traditionally, physicians might reply on in vitro signal acquisition instruments and spectral analysis to detect electrophysiological signals in living tissues, e.g., skin-surfaced electrodes and pads, amplifiers, filters, etc, . Then, physicians can evaluate the health condition of the patients by the readings of heart and lung sounds, arterial blood pressure, and variation of temperatures. Besides sensing the signal, functional electrical stimulation (FES) is also developed as a practical treatment. Such medical treatments have been drastically improved by the advance of modern sciences and technologies lately, particularly the evolution toward the nano-scale semiconductor process.

The treatment and diagnosis lack of accuracy by trans-skin methods, and suffer from the infection by inserting the electrode inside life tissues. Therefore, the medical implants are adopted to deal with the mentioned problem. For example, the implantable microelectrical stimulator has become an astonishing therapeutic tool. The implantable microelectrical stimulators are widely used in the treatment of the bladder leakage control [1], interrupt of pains, muscle nerve stimulation [2], and cochlear implants [3].

Without the wire through the skin, the supply power becomes the most important issue for the medical implants. There are two basic methods to supply the power inside the life body. First, the batteries are adopted in some medical implants. However, the battery has its life time. The implant using battery has to be replaced by another surgery after the battery is dead. Another surgery brings another cost of time and money besides the risk of infection. Second, the power could be supply wirelessly via a pair of induction coils. The supply power of these implants depends on the efficiency of the coil induction. In other words, the devices may be short of supply power in poor environment conditions and out of function. Therefore, a new resolution combining the above mentioned methods is proposed which adopts a rechangeable battery with wireless supply power from the induction coils. The rechangeable battery can provide stable and clean supply voltage independently, and the life time of the implants will be extended very much.

On the other hand, there are different types of rechargeable batteries could be adopted in the implants. The Ni-Cd battery can provide the highest transient current, while the Ni-MH battery has a advantage of fast recharging speed [4]. However, the large current, either charging or discharging, is not necessary and not allowed in the medical implants because of the power density issue. The Li-ion battery has the best energy density, which means there is a largest energy capacity in the limited battery volume. It is particularly suitable for implants. Besides, Li-ion batteries do not suffer from the memory effect, but they still have an ultra low self-discharge rate. The only disadvantage of Li-ion batteries for implants is the safety concern about over-charging. The details will be described in the following text.

Therefore, we propose a Li-ion battery charging design for wireless medical implants. The protection circuit can prevent Li-ion from over-charging even under a variant supply voltage. Moreover, the supply power induced from a coil always suffers from the noise generated by the carrier wave. The proposed charging design can provide a stable current independent of the ripple on the supply voltage. Besides, the charging experiment result shows that the Li-ion battery could be charged with the limited wirelessly induced power. The battery used in the proposed charging design is a Li-ion battery whose full charged voltage and energy are 4.2 V and 400 mAh,

978-1-4244-2342-2/08/$25.00

respectively.

II. LI-ION BATTERY CHARGING DESIGN

The biggest challenge for Li-ion battery charging design employed in a system with wireless induced power is the limited power transfer efficiency. Besides, it is not allowed in a medical implant to strengthen the transmitting power too much. Thus, the proposed battery charging design give up any technique with a complex circuit to save the power consumption for battery. The charging design shown in Fig. 1 is composed of a power transistor (M1), a switch (M2), a Bias Circuit, and a Voltage Detector. M1, whose size is large enough to generate a 40 mA current, works as a power transistor to supply the charging current. It is biased by V_bias from Bias Circuit to keep its V_{GS} constant in order to provide a constant charging current. The Voltage Detector senses the voltage of battery to limit the charge time for the safety concern. When the voltage of the battery is reaching its limit, the Voltage Detector will pull down the Close node to turn the M2 on. Then, the V_bias will be pulled up to the VDD to cut the charging current off.

A. *charging strategy of Li-ion battery*

The Li-ion battery has many advantages, especially when it is adopted in medical implants. However, the major drawback of the Li-ion battery is the safety of charging. There are usually limitations about current and voltage of charging the Li-ion battery. If the Li-ion battery is charging with the voltage or current over the limit, the battery temperature will rise severely to cause fatal problems. Notably, the typical limit of the charging current is 1C, which is the current can completely charge a battery in one hour. For example, the 1C current is 400 mA for the battery with a energy capacity of 400 mAh.

Many charging techniques have been proposed [5]. The constant voltage (CV) mode is the basic method to charge a battery. However, there is a huge charging current at the start of charging which could shorten the lift time of the battery. The CV mode has the longest charging time because the charging current is very small at the end of charging. The constant current (CC) mode has a lethal drawback which is that a very high voltage will be induced between the two poles of the battery when the energy capacity of the battery is almost full [6]. This high voltage will cause the damage of the battery and other circuits nearby. Therefore, a joint CC/CV mode has been developed to cancel the disadvantage of each other. However, the CC/CV mode costs a lot of hardware as well as the power consumption besides relying on the supply power. Therefore, we choose CC mode with 0.1C charging current to avoid the huge voltage difference at the end of charging.

B. *bias circuit*

The bias circuit is designed to provide a stable reference voltage drop, V_diff=VDD-V_bias, which should be independent of variant of supply voltage. The beta-multiplier composed of M3 to M6 in Fig. 2 is adopted as a bias circuit due to the capability of resisting the variation of VDD, [7]. The current is almost not affected by the VDD which makes the V_{GS} of M4 be constant. Besides, the feed-back loop composed of M9 to M11 enhances the dynamic response. When VDD suddenly increases, the V_diff will increase as well. Then, a higher I_D of M9 and M10 forces the V_{GS} of M10 to increase. The increase of V_{GS} of M10 causes more current drawn by M11 to decrease the V_FB. Finally, a lower V_FB reduces the I_D of M4 and M6 such that V_diff is reduced. Therefore, the reference voltage, V_diff, is independent of the variation and the ripple of the supply voltage. In addition, in order to keep the beta-multiplier from being stuck at the static state, M7 and M8 are connected as a start-up circuit.

C. *Voltage detector*

In order to keep away the danger of over-charging to the Li-ion battery, the voltage detector is needed to limit the charging voltage. The proposed voltage detector shown in Fig 3 is composed of the voltage divider, M12 to M15, and the current-source inverter, M16 and M17. The voltage divider divides the V_bat to generate the Va. The Va increases with the V_bat when the battery is being charged. If the V_bat is approaching the voltage limit of the Li-ion battery, the Va will be larger than the threshold voltage of M17. Then, the Close node is pulled down to cut the charging current off.

However, the current-source inverter is biased by V_bias. In other words, the threshold voltage decreases with the V_{GS} of M16. The V_diff is independent of the supply voltage variation, but suffered from the drifting of the temperature and process. Thus, the voltage divider is designed to compensate the variant of the threshold voltage. For instance, when the temperature increases, the threshold voltage of the current-source inverter decreases with the V_{GS} of M16. The Va also decreases such that the charging current will not be cut off ahead of time. The compensation works in the similar way to resist the process drift.

III. SIMULATION AND MEASUREMENT

TSMC (Taiwan Semiconductor Manufacturing Company) 0.35μm 2P4M CMOS process is adopted to carry out the proposed Li-ion battery charging design. Referring to the layout shown in Fig. 4, the chip area is 221 μm × 224 μm without pads. Fig. 5 shows that the V_diff is not affected by the variant VDD or the ripple on VDD. The charging simulation of the proposed design is shown in Fig. 6. The charging current, I_charge, is about 39 mA (0.1 C), while the V_bat increases linearly. Thus, we have proceeded an experiment to charge the Li-ion battery with a 0.1 C current. Fig. 7 shows that the voltage of the battery, V_battery, which increases linearly as well. The Fig. 8 shows that the V_bat is limited to protect the battery. Although the voltage limitations are different at every PVT corner, they are still kept in range of 4.0 ∼ 4.2 V. Fig. 9 shows the time of discharging a battery from 4.0 V to 3.5 V which is about 85 % compared to the discharging time from 4.2 V to 3.5 V. It means the energy capacity of a 4.0 V Li-ion battery is about 85 % of a fully charged battery. The specification of the proposed battery charging design is tabulated in the Table I.

IV. CONCLUSION

We have proposed a Li-ion battery charging design for wireless medical implants. The simple and robust structure of the proposed design costs tiny power consumption and charges the Li-ion bettery with 0.1 C under the consideration of the medical safety issue and the limitation of wirelessly supplied power. The charging current is stable and independent of supply voltage and its ripple noise. The experiment of charging a Li-ion battery with a 0.1 C current has been proceeded to make sure the practicability of the proposed design. The proposed design has a protect circuit to limit the charging voltage of the Li-ion battery to keep it from any non-reversible damage.

ACKNOWLEDGMENT

This research was partially supported by National Science Council under grant NSC 96-2628-E-110-019, NSC 96-2923-E-110-001 and NHRI-EX95-9319EI. The authors would like to thank CIC of National Science Council (NSC), Taiwan, for their thoughtful help in the chip fabrication of the proposed work. The authors also like to thank “Aim for Top University Plan” project of NSYSU and Ministry of Education (grant no. 96C031001), Taiwan, for partially supporting the research.

REFERENCES

[1] J. S. Walter, J. S. Wheeler, W. Cai, W. W. King, and R. D. Wurster, “Evaluation of a suture electrode for direct bladder stimulation in a lower motor neuron lesioned animal mode, ” *IEEE Trans. on Rehabilation Engineering,* vol. 7, no. 2, pp. 159-166, June 1999.

[2] G. E. Loeb, F. J. R. Richmond, D. Olney, T. Cameron, A. C. Dupont, K. Kood, R. A. Peck, P. R. Troyk, and H. Schulman, “BION. bionic neurons for functional and therapeutic electrical stimulation,” *in Proc. 20th Annu. Int. Conf. IEEE Engineering in Medicine and Biology Soc.,* vol. 5, pp. 2305-2309, Nov. 1998.

[3] R. E. Isaacs, D. J. Weber, and A. B. Schwartz, “Work toward real-time control of a cortical neural prosthesis,” *IEEE Trans. Rehabil. Eng.,* vol. 8, no. 2, pp. 196-198, Jun. 2000.

[4] F. Lima, J. N. Ramalho, D. Tavares, J. Duarte, C. Albuquerque, T. Marques, A. Geraldes, A. P. Casimiro, G. Renkema, J. Been, and W. Groeneveld, “A novel universal battery charger for NiCd, NiMH, Li-ion and Li-polymer,” *in Proc. IEEE 29th Eur. Solid-State Circuits Conf.,* pp. 209-212, Sep. 2003.

[5] C.-C. Tsai, C.-Y. Lin, Y.-S. Hwang, W.-T. Lee, and T.-Y. Lee, “A multi-mode LDO-based Li-ion battery charger in 0.35-mm CMOS technology,” *in Proc. IEEE Asia-Pacific Conf. Circuits Syst., 2004,* pp. 49-52, Dec. 2004.

[6] Y.-S. Hwang, S.-C. Wang, F.-C. Yang and J.-J Chen, “New Compact CMOS Li-Ion Battery Charger Using Charge-Pump Technique for Portable Applications,”*in Proc. IEEE Int. Symp. on Circuits and Systems-I,* vol. 54, pp. 705-712, Apr. 2007

[7] S. S. Prasad and Pradip Mandal, “A CMOS Beta Multiplier Voltage Reference with Improved Temperature Performance and Silicon Tunability,” *Proceedings of VLSI Design 2004,* pp. 551-556, Jan. 2004.

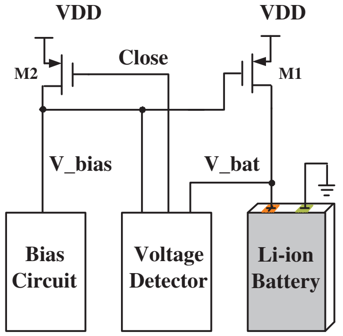

Fig. 1. Architecture of the Li-ion battery charging design.

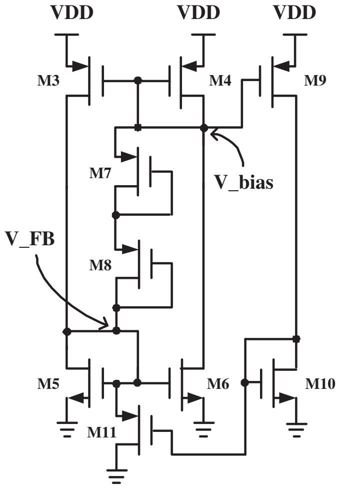

Fig. 2. Schematic of the bias circuit.

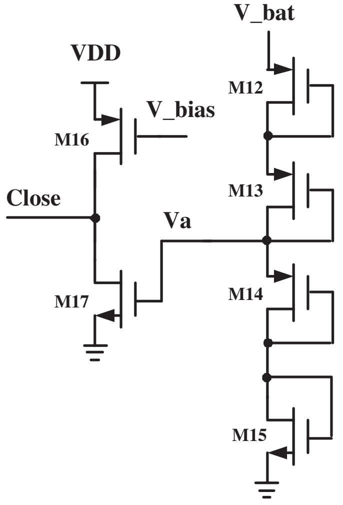

Fig. 3. Schematic of the voltage detector.

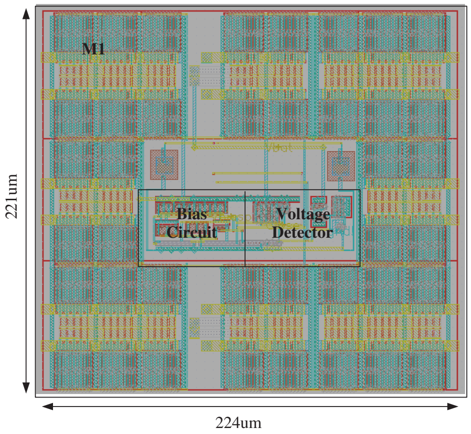

Fig. 4. The layout of the proposed charging design.

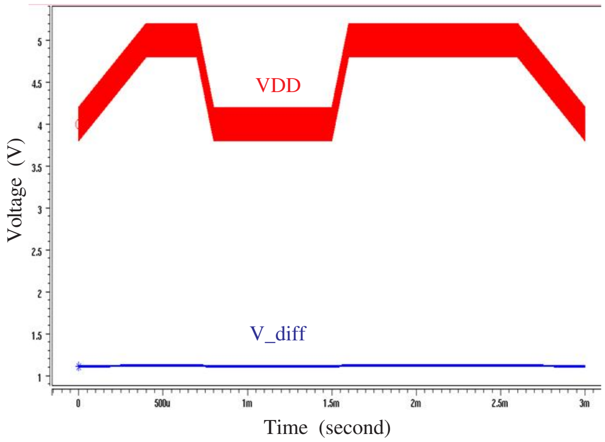

Fig. 5. Simulation results of V_bias vs. the VDD variation.

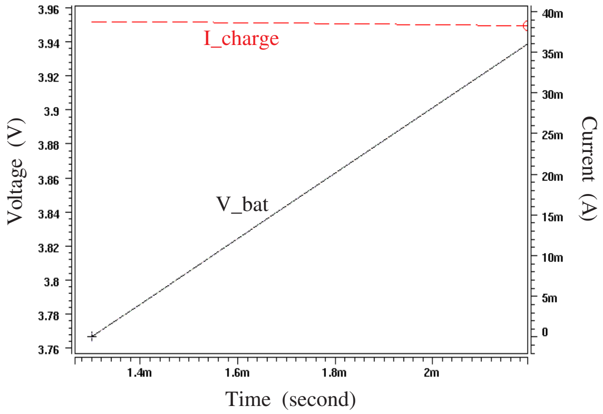

Fig. 6. Simulation results of charge current vs. voltage of battery.

Input voltage range Ripple resist BW. Charging current Voltage limit of battery power consumption	4.2 ∼ 5.2 V 40 MHz 40 mA 4.0 ∼ 4.2 V 0.825 mW

TABLE I

CHARACTERISTICS OF THE PROPOSED DESIGN.

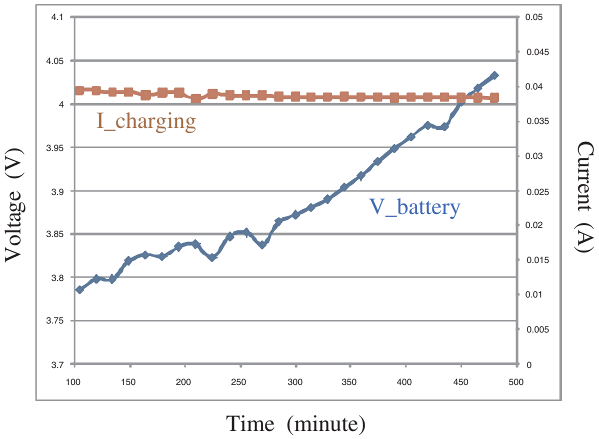

Fig. 7. Experiment results of charge current vs. voltage of battery.

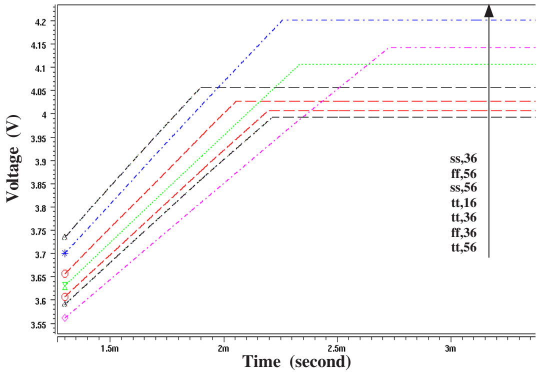

Fig. 8. Simulation result of V_bat at different PVT corners.

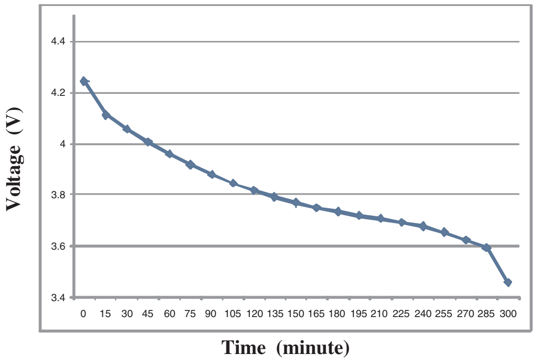

Fig. 9. Experiment results of battery voltage vs. discharge time.