Solar Battery Charger in CMOS 0.25 um Technology

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Abstract: A solar cell powered Li-ion battery charger in CMOS 0.25um is proposed. The solar battery charger consists of a DC/DC boost converter and a battery charger. The voltage generated by a solar cell is up converted from 0.65V to 1.8V, which is used as the VDD of the battery charger. In this way, the solar battery charger automatically converts solar energy to electricity and stores it directly to a Li-ion rechargeable battery. In this system, a super capacitor is needed as a charge buffer between the boost converter and the charger.

Keywords: solar energy; battery charger; super-capacitor

Introduction

Concerns for peak oil and climate change have focused global attention on renewable energy resources. Solar energy is widely seen as an promising future solution because of its high energy intensity, which reach 15mW/cm^2 [1, 2]. However, this energy density is dependent on stable and fair weather conditions. In real world conditions, solar energy extraction can be quite unstable and can only be generated during daylight hours. Thus, maximizing solar energy potential requires methods for efficient transduction and storage.

Power consumption of CMOS integrated circuits has been reduced to milliwatts, thus CMOS ICs can be powered by button-sized Li-ion rechargeable batteries. Therefore, a battery charger able to convert energy from a solar cell to a Li-ion battery would be very useful [3]. Figure 1 illustrates the architecture of the proposed charger. A solar battery charger stores energy directly to the battery without an external control system. The energy is first stored in a super capacitor, which is used as an electricity buffer. When the super capacitor has stored enough energy, the charger starts to function and begins energy conversion.

To topology of a small-size solar battery charger is quite different from that of a conventional battery charger which uses a complex control circuitry to meet the accuracy requirements of the battery charging procedure. The disadvantages of this complexity are accentuated as the size of solar cell shrinks because the expense in power and area becomes non-negligible in a low power system, thus reducing the charger's efficiency. As a result, a simpler topology is preferable for a small-size solar-energy powered charger.

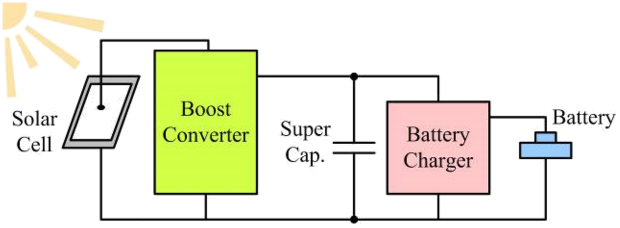

Figure 1. Architecture of the proposed solar battery charger.

Another issue raised by small battery chargers lies in the limited power available from the solar cell. For a solar cell with a large light receiving area, the power available from the cell is high enough to continuously supply the battery charger. However, when the size of solar cell shrinks to a size suitable for use in a portable device, the amount of power the solar cell can acquire is too limited to maintain continuous charging and battery charging will be easily interrupted. The battery charger switching on and off frequently resulting in increased dynamic power consumption. The following section discusses adding a capacitor between the solar cell and battery charger help to reduce this interruption effect.

Solar Battery Charger Design

DC/DC Boost Converter

Figure 2 shows the schematic of the DC/DC boost converter in the proposed system. A diode-connected mosfet M_1 is connected to inductor L_D , R_L, C_L and switch M_2 [4]. Switch M_2 is controlled to a clock. When M_2 shorts, the current passes from the solar cell to the ground through M_2. At this time, energy is stored in the inductor as current. When M_2 suddenly opens, the conducting current in L_D cannot respond in time, so the current is forced to flow into the diode-connected mosfet M_1. As a result, the charge is stored in C_{load}. In steady state, the output voltage of this converter is constant as shown in Figure 3. By adjusting the clock frequency and capacitance value C_L , one can control the final voltage of this stage.

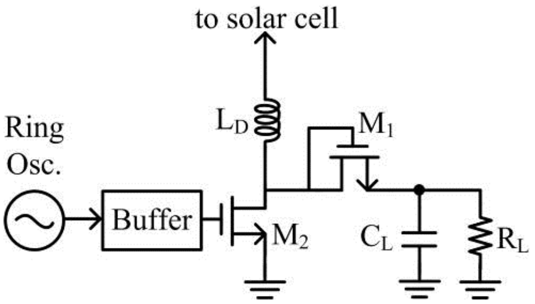

Figure 2. Schematic of DC/DC Boost Converter.

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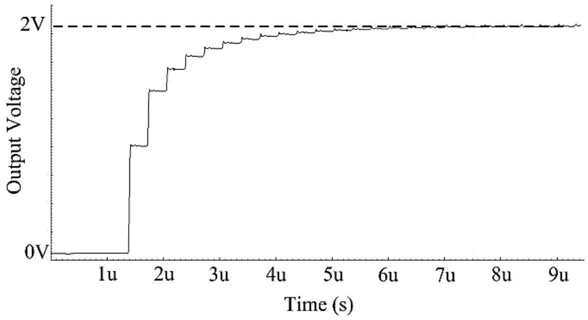

Figure 3. Time response of a DC/DC boost converter.

The switching signal of the DC/DC boost converter is generated from an inverter-based ring oscillator followed by an inverter-chain buffer. Note that the DC/DC boost converter is supplied by the solar cell, providing a voltage as low as 0.65V. The loading of M_2 can be too large for the clock generator, thus a buffer is needed between the clock generator and the boosting stage.

Battery Charger

Li-ion battery offer high electricity capacity but this advantage is based on the assumption that the charging procedure is precisely controlled. An ideal Li-ion battery charging procedure is shown in Figure 4. The process entails three charging modes: trickle charging mode (TC), constant current mode (CC), and constant voltage mode (CV).

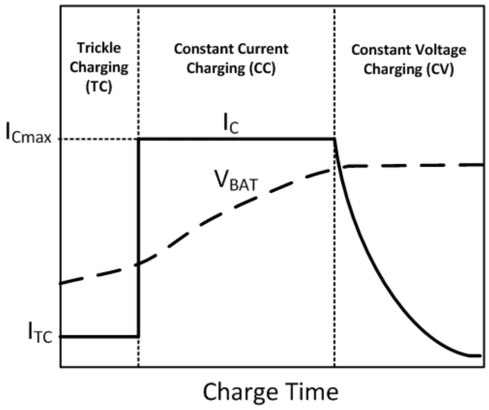

Figure 4. Ideal charging procedure of a Li-ion battery.

When battery voltage (V_{BAT} in Figure 4) is low, the inner resistance of battery is large. During this period, a large charging current (I_C in Figure 4) will cause thermal damage to the electrodes and shorten the battery lifetime. Therefore, a mode with a small charging current, namely trickle charging mode, is required as illustrated in Figure 4. Once the battery voltage reaches a certain value, the inner resistance is reduced, thus the charge current can maximized to shorten the charging time. The charging mode with the maximum charging current is defined as the constant current mode (CC mode). As shown in Figure 4, the battery voltage rises rapidly due to the high charging current in CC mode. Finally, when the battery voltage approaches a nominal voltage set by a reference voltage V_{ref}, the charger starts to enter the constant voltage CV mode. In CV mode, the charging current drops dramatically, and V_{BAT} will eventually be locked with V_{ref}.

A conventional charger uses a microprocessor as a control unit to manage the three charging modes. However, our proposed system uses analog circuits instead [5]. The block diagram of battery charger is shown in Figure 5. It comprises a low voltage battery V_{BAT} detector, a current driver, an amplifier and a reference voltage (V-Ref). The low V_{BAT} detector is adopted to sense the battery voltage V_{BAT} for TC to CC mode switching, while the CC to CV mode switching is accomplished by the nonlinearity of the amplifier (Amp in Figure 5). Figures 6(a)-(d) show schematics of the circuit blocks in this solar charger.

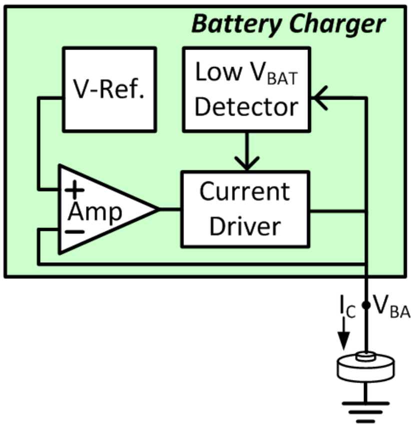

Figure 5. Block diagram of battery charger.

In the early charging procedure, when V_{BAT} is low in the trickle charging mode, the low V_{BAT} detector senses this low V_{BAT} value and outputs a high EN_{TC} voltage as shown in Figure 6(c). Receiving the high EN_{TC} signal, the current driver is switched to the trickle charging mode (Figure 6(b)). V_{BAT} increases gradually. Once V_{BAT} meets a specific voltage determined by the transistor size ratio in the low V_{BAT} detector), EN_{TC} voltage is shifted to a low voltage, which changes the charging current to a higher value for CC mode.

Note that this analog circuit makes use of the saturation and linear regions of an amplifier as shown in Figure 7. In the beginning of the CC mode, the amplifier operates in the saturation region, in which the output current of this amplifier is constant, leading to a constant charging current as needed by CC mode. As V_{BAT} approaches V_{ref}, the amplifier enters the linear region and its gain rises, forming a negative feedback loop that locks V_{BAT} with V_{ref}. Through this step the charger moves from CC mode to CV mode.

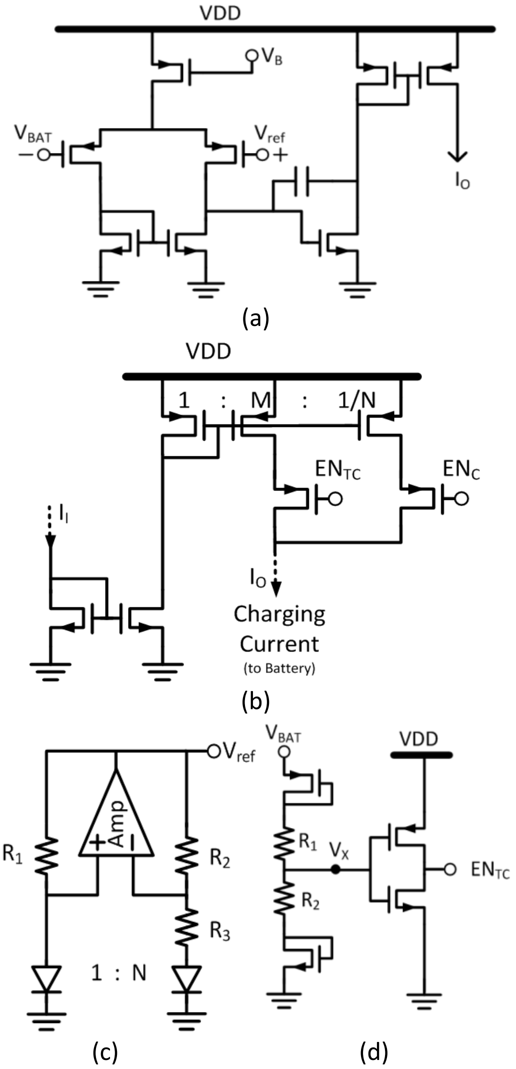

Figure 6. Circuit blocks schematics in the solar battery charger: (a) amplifier (b) current driver (c) low voltage detector (d) voltage reference.

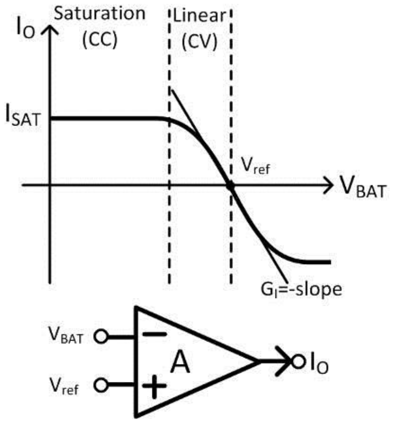

Figure7. Mapping the modes of the amplifier to charging modes.

To maximize power efficiency, it is better to bias the transistors in sub-threshold region. The transconductance over bias current (g_m/I_D) versus V_{GS} is shown in Figure 8. It is obvious that one can have a higher g_m in sub-threshold region with power constraints. In the battery charger design, the battery is simply modeled by a capacitor. The simulated time response is shown in Figure 9. Three modes are found to exist in this transient response. However, different curves of the CC mode between Figures 4 and 9 can be observed because the battery model is simplified by a small capacitor for faster simulation results, whereas an enormous capacitor would be needed to accurately model the battery, but this would result in unacceptably long simulation times.

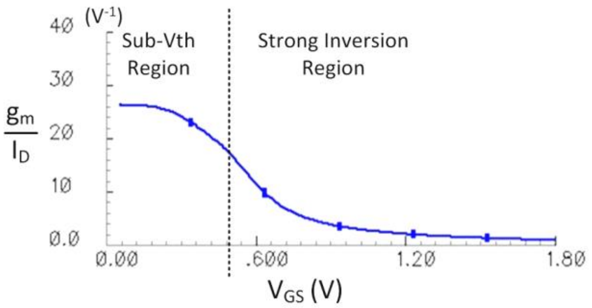

Figure 8. Comparison of gm efficiency in sub-threshold region and strong inversion region.

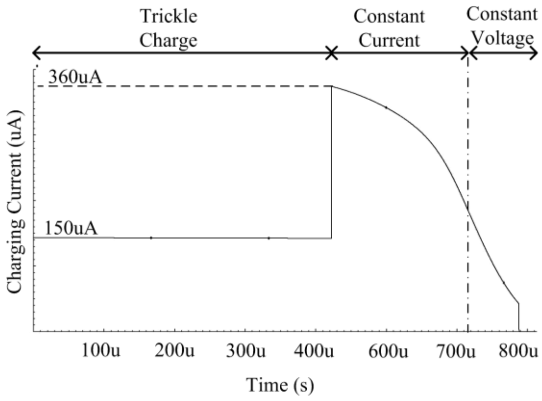

Figure 9. Time response of the battery charger.

System Simulation and Preliminary Measurement

The DC/DC boost converter is connected to battery charger for system simulation as shown in Figure 10.

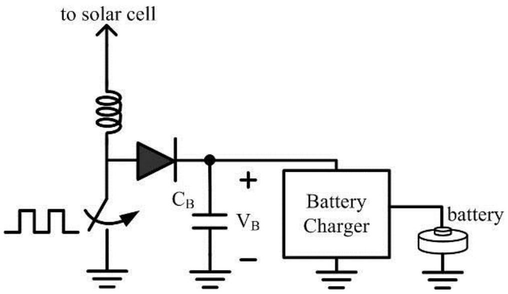

Figure 10. Schematic of system simulation.

In this system, the capacitance (C_B) between the boost converter and battery charger is essential since it is used to save sufficient charge to keep the battery charger functional. It is well known that if C_B is small (e.g. 0.4pF), the output voltage can be easily boosted to a high voltage. However, the charge stored in C_B will be insufficient to sustain the battery charger, because the charge stored in C_B is quickly drained. As illustrated in Figure 11, the battery charger is periodically turned on/off because of a lack of charge. To solve this problem, we use a super-capacitor to store enough charge before turning the charger on. Figure 12 shows the time response when a 40 mF super capacitor is used. With a large capacitor, the battery charger keeps charging without interruption. The drawback is that it requires more time to first charge the super-capacitor.

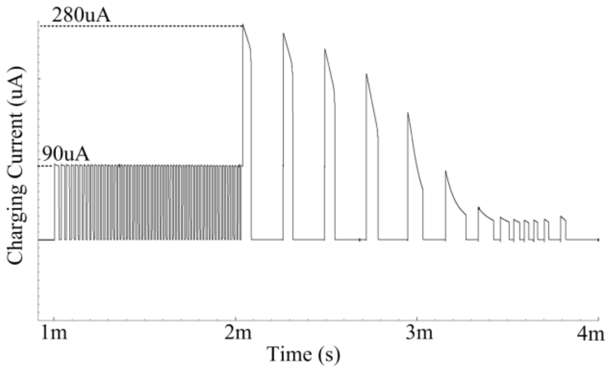

Figure 11. Time response of solar battery charger with CB of 0.4 pF.

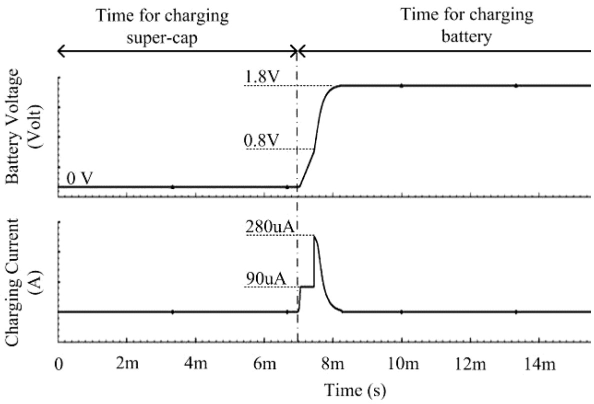

Figure 12. Time response of solar battery charger with CB of 40 mF.

The stand-alone DC/DC boost converter and battery charger have been taped out in CMOS 0.25um technology, with the layout shown in Figure 13. Integration of both circuits are also to be taped out to CMOS 0.18 um technology as shown in Figure 14.

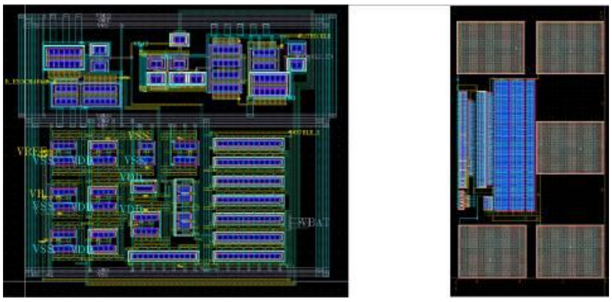

Figure 13. Layout of the battery charger and the DC/DC boost converter in CMOS 0.25um technology.

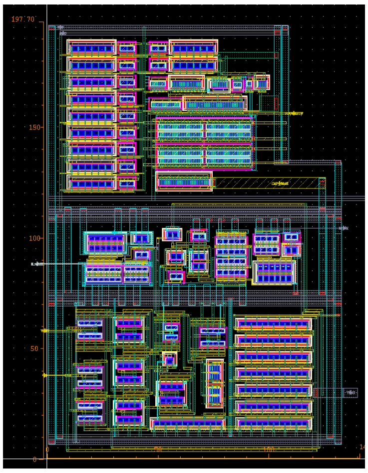

Figure 14. Layout of the DC/DC boost converter and battery charger integration.

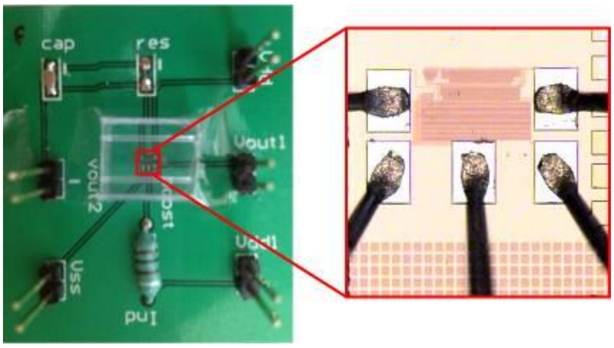

Figure 15. DC/DC boost converter test bench.

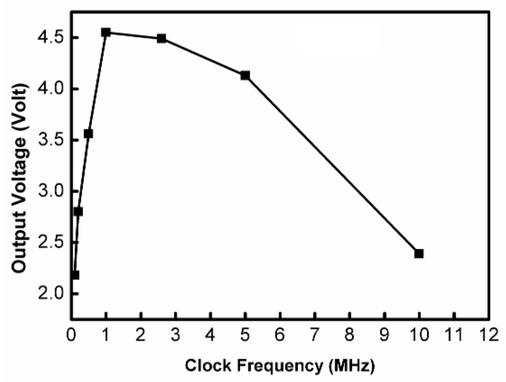

Figure 16. Output voltage versus clock frequency of DC/DC converter.

Measurement results of the DC/DC boost converter in 0.25um technology is done by loading the output with a resistor with 1MΩ as shown in Figure 15 . The relationship between the output voltage and clock frequency is measured and shown in Figure 16, where the input DC is 0.65V. A clock frequency needed to obtain the maximum output DC voltage can be observed. When the switching frequency is low, charge pumping time will be reduced, leading to a lower averaged dc voltage output. On the other hand, if the clock frequency is too high, the MOS switch cannot catch up to the clock speed, thus reducing dc voltage output.

Conclusion

A solar battery charger consisting of a DC/DC boost converter and an analog battery charger is proposed for an SOC powered by a rechargeable battery. The proposed system is able to charge a 1.8V Li-ion battery from a 0.65V solar cell. This system requires a super capacitor, and future work will focus on refining the integration.

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