Improved voltage transfer method for lithium battery string management chip

Kai-Kai Wu | Hong-Yi Wang | Chen Chen | Tao Tao | You-You Fan | Hao Zhang | Yu-Xin Liu

School of Microelectronics, Xi’an Jiaotong University, Xi’an City, Shaanxi Province, China
Huatech Semiconductor Co. Ltd., Xi’an City, Shaanxi Province, China
School of Electronics and Information, Northwestern Polytechnical, Xi’an City, Shaanxi Province, China

Correspondence
Hong-Yi Wang, School of Microelectronics, Xi’an Jiaotong University, Xi’an City, Shaanxi Province, China.
Email: wanghongyi@mail.xjtu.edu.cn

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1 | INTRODUCTION

Recently, the lithium-breed batteries gradually replace other types of batteries due to their advantages of higher voltage level, long service life, nontoxic and no pollution, and are widespread exist in a variety of hand-held electronics [1–5]. As discussed in [3,6–15], lithium batteries can be damaged by many conditions, such as excessively high or low voltages, and in some cases the results can be catastrophic. For example, if their voltages become too high, they will ignite, which equates to an over-charged condition. Therefore, the lithium battery management chip plays a very important role in the application of lithium batteries. What’s more, voltage transfer circuit is an indispensable part to prevent the abnormal use of lithium battery in the lithium battery management chip. Consequently, the robustness of the voltage transfer circuit directly determines the security performance of the lithium battery. Besides, cost is also one of the important considerations of management chip [16–21].

Optimum performance of the series battery packs in applications such as electric vehicles requires voltage detection for each of the individual batteries. Hence, as shown in Figure 1, in order to measure BAT;i (i = 1~n), these voltage transfer circuits must transfer each segment voltage to a common reference level, such as the circuit GND. There are several techniques to measure the battery voltages in series packs. Resistive divider measurement is mentioned in study [22–25], the disadvantages for such a system are fairly clear. First, switches must be provided in the battery divider branch to prevent the current from the batteries when not in use. Second, when the voltages near the top of the stack, very accurate divider ratios are required, which also mean high cost. The circuit discussed in [22] has certain ability to achieve battery voltage transfer, but it was built with discrete devices, which not only cost a lot, but also accelerate the imbalance of the battery. The op amp transfer circuit proposed in [23] avoids the matching of discrete transistors, but it uses many discrete...
amplifiers, such as LM224, which leads to high cost. The relay matrix transfer circuit proposed in [15,17,24–26] can’t meet the requirement of all batteries sampling at the same time in many applications. Moreover, they integrate analogue–digital (AD) converting circuits internally and are not suitable to battery management chips without AD converting circuit. In [27], many amplifiers and resistor networks implement the transfer circuit, which may cause area waste and increases manufacturing cost. In the literature mentioned above, all of them have the disadvantage of the leakage current between batteries.

An improved voltage transfer method for lithium battery string management chip is proposed. This method can not only reduce the cost, but also eliminate the leakage current of batteries caused in traditional method, which is well beneficial for battery voltage balance. In Section 2, one of the traditional methods of voltage transfer circuit is analyzed. In Section 3, an improved voltage transfer circuit is presented based on the improved voltage transfer method. Section 4 of this study describes the application circuit diagram and block diagram of a typical battery management chip, which is used to analyze the proposed circuit. Section 5 presents the measurement results, and Section 6 concludes the study.

2 | THE TRADITIONAL CIRCUIT

Voltage transfer circuit is an important circuit in the lithium battery management chip. Figure 2 exhibits a typical traditional voltage transfer circuit, which is published in [23] and composed by many discrete amplifiers, resistors and comparators. Here, this study takes the analysis of three batteries as an example. The pack of three lithium batteries is composed by \( \text{BAT}_1 \) to \( \text{BAT}_3 \) batteries connected in series, and each cell's positive electrode is connected to the voltage transfer circuit. \( I_{\text{BAT}_1}, I_{\text{BAT}_2} \) and \( I_{\text{BAT}_3} \) are the currents flowing through batteries \( \text{BAT}_1 \) to \( \text{BAT}_3 \), respectively. \( I_1 \) and \( I_2 \) are the leakage current of batteries flowing into the voltage transfer circuit from the first battery and the second battery, respectively.

The first battery directly obtains the transfer voltage \( VB_1 \) through the divider resistors \( R_1 \) and \( R_2 \). And the second battery is converted to \( VB_2 \) through the amplifier \( OP_1 \) and the resistor networks \( R_3 \) and \( R_4 \). Since the transfer process of the third battery is similar to the second battery, and \( VB_3 \) can be obtained. This voltage transfer circuit transfers each battery to VSS and thus the transfer voltage of the three batteries can be expressed as:

\[
VB_1 = \frac{V_{\text{BAT}_1} \times R_1}{R_1 + R_2} \tag{1}
\]

\[
VB_2 = \frac{V_{\text{BAT}_2} \times R_3}{R_4} \tag{2}
\]

\[
VB_3 = \frac{V_{\text{BAT}_3} \times R_5}{R_6} \tag{3}
\]

By comparing the voltage \( VB_i (i = 1 \sim 3) \) converted by each battery with \( V_{\text{REF}} \) of over charge or over discharge, we can judge whether the battery voltage is in the normal voltage range. The current flowing through each battery is different, which can be expressed as:

\[
I_{\text{BAT}_2} = I_{\text{BAT}_3} + I_2 = I_{\text{BAT}_3} + \frac{V_{\text{BAT}_2}}{R_4} \tag{4}
\]

\[
I_{\text{BAT}_1} = I_{\text{BAT}_2} + I_1 = I_{\text{BAT}_3} + \frac{V_{\text{BAT}_2}}{R_4} + \frac{V_{\text{BAT}_1}}{R_1 + R_2} \tag{5}
\]

As a result, the currents \( I_{\text{BAT}_1}, I_{\text{BAT}_2} \) and \( I_{\text{BAT}_3} \) flowing the batteries \( \text{BAT}_1 \sim \text{BAT}_3 \) are unbalanced with each other, respectively.

The traditional voltage transfer circuit is not complicated and can be easily extended to multicells lithium battery management systems. However, since this voltage transfer circuit is always operating, there is always a problem of leakage current consumption of each battery. Therefore, in order to make the current consumption of all batteries as close as possible, the value of the transfer resistors \( R_1 \) to \( R_6 \) is larger. The sum of \( R_1 \) and \( R_2 \), \( R_4 \) and \( R_5 \) is often selected as the resistance of 2 MΩ. Therefore, when the battery voltage is around 3.8 V, the
current consumed by each transfer branch is about 1.9 μA. Besides, it uses many discrete amplifiers and resistors, which cause high cost. However, the problem of the leakage current between batteries is still inevitable even when the value of transfer resistors is very large and using expensive amplifiers, which cause the voltage imbalance between cells.

### 3 | AN IMPROVED VOLTAGE TRANSFER METHOD

The primary purpose of the voltage transfer circuit is to transfer each cell voltage to a common reference level, which can detect voltage of the individual batteries. In addition, it is necessary to solve the two problems of the leakage current of batteries and high cost in traditional circuit. In response to the aforementioned requirements, this study proposes an improved voltage transfer method for voltage transfer circuit, and lithium battery string management system is integrated into one chip is adopted to reduce the cost. In this proposed method, a compensation current is added in the transfer branch of the battery except the top battery, which eliminates the battery leakage current and is well beneficial for battery balance.

The proposed method for voltage transfer equivalent circuit is shown in Figure 3. The transfer current can be obtained by transferring the voltage of each battery to the resistance \( R \) through the amplifiers, which flow through the resistor \( R_i \) \((i = 1 \sim n)\) to obtain the transfer voltage \( V_{B_i} \) \((i = 1 \sim n)\), respectively. \( I_C \) \((i = 1 \sim n-1)\) is the compensation current for other batteries except the top battery, the value of which is the current consumed in the branch transfer process. Finally, the compensation current compensates the transfer current, so the currents flowing through the batteries can be balanced with each other, respectively. Next, an improved three cells voltage transfer circuit is presented in Figure 4 based on the improved voltage transfer method.

The transfer circuit of the first battery is realized by resistors \( R_1 \) and \( R_2 \), NMOS \( NM_3 \) and NMOS \( NM_4 \), which are matched with each other, respectively. Then, the transfer voltage of the first battery can be expressed as:

\[
V_{B_1} = \frac{V_{BAT} \times (R_1 + R_{NM_1})}{R_1 + R_2 + R_{NM_1} + R_{NM_2}}
\]

In the conversion process, the current consumption of this branch copies to \( PM_2 \) by \( NM_3 \), \( NM_2 \) and \( R_3 \), which can be expressed as:

\[
I_1 = \frac{V_{BAT}}{R_1 + R_2 + R_{NM_1} + R_{NM_2}}
\]

With the current mirrors of \( PM_1 \) and \( PM_3 \), the value of compensation current is the same as the current consumed by the branch, which is compensated to the first battery from the anode of the top battery. Meanwhile, \( NM_1 \sim NM_4 \) are the same size and type, and the resistor \( R_8 \) meets the following requirement:

\[
R_8 = R_1 + R_2
\]

After the above design, the current of the pin connected to the first battery anode is zero, that is, \( I_1 \) is zero.

The voltage transfer circuit of second cell is similar to the traditional method. The difference is the addition of \( NM_5 \), \( NM_6 \) and \( R_6 \), as well as current mirrors \( PM_3 \) and \( PM_4 \). \( NM_5 \) and \( NM_6 \) are used to copy the transfer branch current to \( PM_4 \), which is the same as the compensation method of the first cell. The amplifiers \( OP_1 \) and \( OP_2 \) were designed with the same normal structure in Figure 4, which will not give necessary details here. In addition, resistors, amplifiers and comparators do not need to be built entirely with discrete devices like traditional method and they are all integrated into a single-chip lithium battery management chip, which reduces the cost of lithium battery management system.

### 4 | THE BATTERY MANAGEMENT CHIP DESIGN

The analysis of typical application circuit of three lithium battery string management chip exhibited in Figure 5, which helps to comprehend the important role of voltage transfer circuit in battery management chip. The whole application battery pack includes three lithium batteries, RC filter, the designed battery management chip, sampling resistor \( R_{IS} \), the charge FET \( NM_3 \) and discharge FET \( NM_2 \), \( R_{LOAD} \) or charger is connected to the battery pack according to usage. The
designed battery management chip is consisted of voltage transfer circuit, oscillator OSC, bandgap, LDO, delay circuit, comparator, driver circuit DRV, etc. After filtered by corresponding RC, \( BAT_1 \) to \( BAT_3 \) are connected to the battery management chip. Sampling resistor \( R_{IS} \), which is connected in series in the discharge path, converts the discharge current to voltage \( V_{IS} \), then it is used to detect discharge overcurrent by the pin IS. The open and close of \( NM_1 \) are controlled by the pin CFET of battery management chip, while \( NM_2 \) is controlled by corresponding pin DFET. The OSC block generates the basic clock signal in the chip, which is provided to the delay generation circuit. When an abnormal situation

**FIGURE 4** Diagram of improved battery voltage transfer circuit

**FIGURE 5** The block diagram and application diagram of the lithium battery string management chip
functions. If overcharge or over discharge can trigger the chip to turn on the protection function at the protection threshold voltage ($V_{THUP}$ or $V_{THOV}$), it indicates that the voltage transfer circuit has been worked successfully.

5 | MEASUREMENT RESULTS

A three lithium battery string management chip was fabricated with 180-nm 45 V Bipolar-CMOS-DMOS (BCD) technology, which also integrates the improved voltage transfer circuit. Figure 7 presents a microphotograph of this chip, which has a silicon area of 1.38 mm$^2$. The improved voltage transfer circuit itself occupies just 0.18165 mm$^2$. The main specifications of the proposed battery management chip is listed in Table 1.

To check the function and performance of the voltage transfer circuit in the battery management chip, the measurements are carried out. The measurement waveforms of overcharge and over discharge protection process from the first battery to the second battery are shown in Figure 8, respectively. It can be seen from the waveform that the voltage transfer circuit designed can effectively convert the battery

| Parameters                          | Specifications |
|------------------------------------|----------------|
| Technology                         | 180 nm 45 V    |
| Operating temperature range (°C)   | -40~85         |
| Overcharge limit (V)               | 4.25           |
| Over discharge limit (V)           | 2.7            |
| Delay time, s                      | 1              |
| BATn leakage current ($n = 1$ to 2) (µA) | <0.1          |
**FIGURE 8** Battery overcharge and over discharge measured waveform

(a) Overcharge protection for BAT₁  
(b) Overcharge protection for BAT₂  
(c) Over discharge protection for BAT₁  
(d) Over discharge protection for BAT₂

**FIGURE 9** The first battery's leakage current

Mean = 20.34nA  
Std.Dev = 20.02  
N = 50
FIGURE 10 The second battery’s leakage current

voltage even after adding the compensation current, thereby preventing the abnormal situation in the application of Li-ion battery. Figures 9 and 10 present the histogram obtained from the measurement of 50 chips, which show the leakage current of the first and the second battery flowing into the chip, respectively. It can be seen from the data that the current flowing into the chip of the first battery and the second battery is at the nanoampere scale, which proves that the proposed voltage transfer method is well beneficial for battery voltage balance.

6 | CONCLUSION

This study presents an improved voltage transfer method for lithium battery string management system, and then designs the corresponding circuit based on the 180-nm 45 V BCD process. Finally, it is taped out and verified on the three lithium battery string management chip. By adding current compensation circuits in the transfer process and integrating it into the lithium battery string management chip, it can suppress the imbalance of battery voltage and reduce the cost effectively. Moreover, the results indicate that the proposed circuit can reliably transfer voltage with the characteristics of lower cost and more competitive. The battery voltage transfer method proposed can be easily applied to other multiple lithium battery string management chips.

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