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Miniature pin-type lithium batteries for medical applications

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Abstract

Miniature pin-type batteries featuring lithium-ion rechargeable chemistry and lithium/CF_x chemistry have been developed for implantable medical applications. The characteristics of these batteries include hermeticity, small volume, and high power. Optimizing the jellyroll configuration and battery electrode design allows small volumes and high power.

Keywords: Miniature pin-type lithium battery; Lithium-ion battery; Lithium/CF_x battery; Implantable battery; Medical device

1. Introduction

The number of implantable medical devices has increased rapidly in recent years [1]. Medical implantable devices require power sources that impose stringent specifications on physical size and performance. Previous batteries designed for medical implantable applications are large and short life. With the advent of the miniature, implantable devices for application, such as drug delivery, glucose sensing, and neurostimulation, high power is required in a significantly small volume to operate these tiny devices. In addition to miniature size, an implantable power source is subject to very demanding requirements, including long useful life, low self-discharge rate, hermeticity, high reliability over a long time period, and compatibility with the patient's internal body chemistry.

Recently, we successfully developed miniature pin-type batteries capable of high power for implantable medical devices. These power sources include lithium-ion rechargeable and lithium/CF_x primary batteries. In this study, we report the battery design and performance characteristics of miniature pin-type lithium batteries, QL0003I, a 3 mAh lithium-ion rechargeable battery, and QC0025B, a 25 mAh lithium/CF_x primary battery.

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2. Battery mechanical design

One drawback for conventional miniature batteries is low power output. In order to overcome this disadvantage, a spiral wound battery design has been developed [2]. Fig. 1 shows the schematic view of positive electrode subassembly with feedthru pin and a spiral wound electrode assembly. A feedthru pin was directly welded to the inner end of a positive electrode substrate and was used as a winding arbor to form a spiral wound jellyroll. This spiral wound design allows adequate surface area to deliver high power output demanded by the application.

Table 1 summarizes the specification of QL0003I (lithium-ion rechargeable battery) and QC0025B (lithium/CF_x primary battery). Fig. 2 shows the photographs of QL0003I and QC0025B. The QL0003I batteries were built with a $LiNiCoAlO_2$/graphite and an electrolyte of 1.2 M $LiPF_6$ in a mixture of EC and DEC in a titanium–6Al–4V case. The negative electrode used a titanium substrate instead of the conventional copper substrate [2]. The QC0025B batteries were built with a lithium/CF_x and an electrolyte of 1.2 M $LiPF_6$ in a mixture of PC and DMC in a stainless steel case. The positive electrode was fabricated by coating of CF_x, PTFE, and CMC on aluminum foil.

An area of great concern for implantable medical devices is electrolyte leakage, which can affect safety and shorten the battery life. Following insertion of the electrode assembly

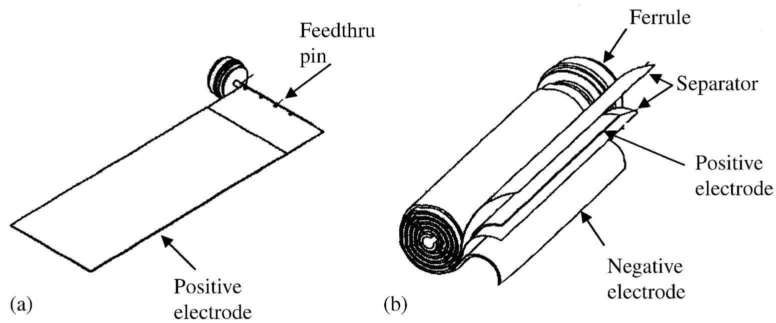

Fig. 1. (a) Schematic view showing the inner end of the positive electrode substrate welded to the feedthru pin and (b) the layers of a spirally would electrode assembly.

Table 1
Specification of QL0003I and QC0025B

	Product code	
	QL0003I	QC0025B
Volume	0.080 cm^3	0.155 cm^3
Chemistry	Li-ion	Li/CF_x
Nominal capacity	3 mAh	25 mAh
Voltage range	2.7–4.0 V	2.0–3.5 V
Discharge current	Maximum 15 mA	Maximum 10 mA (pulse condition)
Hermeticity	Maximum helium leak: 5×10^{-8} atm cm^3 s^{-1}	Maximum helium leak: 5×10^{-8} atm cm^3 s^{-1}

into the case, the battery was hermetically sealed using laser welding and a glass to metal feedthru. All components were 100% helium leak tested per MIL-STD-202 F [3,4].

3. Lithium-ion rechargeable battery: QL0003I

3.1. Rate capability

Some implantable medical applications require fast charging. Fig. 3 shows the charge characteristics of QL0003I battery. A constant current charge at 1.5 mA (=0.5 C) or 3 mA (=1 C) was followed by a constant voltage charge at 4.0 V, with a cutoff current of 0.15 mA. At 0.5 C rate charge, it takes less than 2.5 h to achieve full charge. A 1 C rate charge enables the batteries to get to the full charge state within 1.5 h.

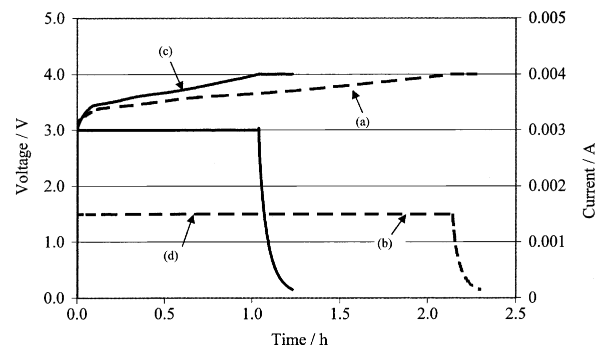

Fig. 3. Charge characteristics of QL0003I with different rates at 37 °C: (a) voltage and (b) current profile at 1.5 mA (=0.5 C), and (c) voltage and (d) current profile at 3.0 mA (=1 C).

The rate capabilities of QL0003I were also evaluated. The batteries were tested at 37 °C, charging to 4.0 V at 1.5 mA followed by a 0.15 mA cutoff, and discharging at 0.6, 1.5, 3.0, 6.0, 9.0, and 15 mA down to 2.7 V shown in Fig. 4. The QL0003I battery demonstrated the good rate capabilities. At 15 mA (=5 C) discharge, the battery retained greater than 80% of the capacity obtained from the battery discharged at 0.6 mA (=0.2 C).

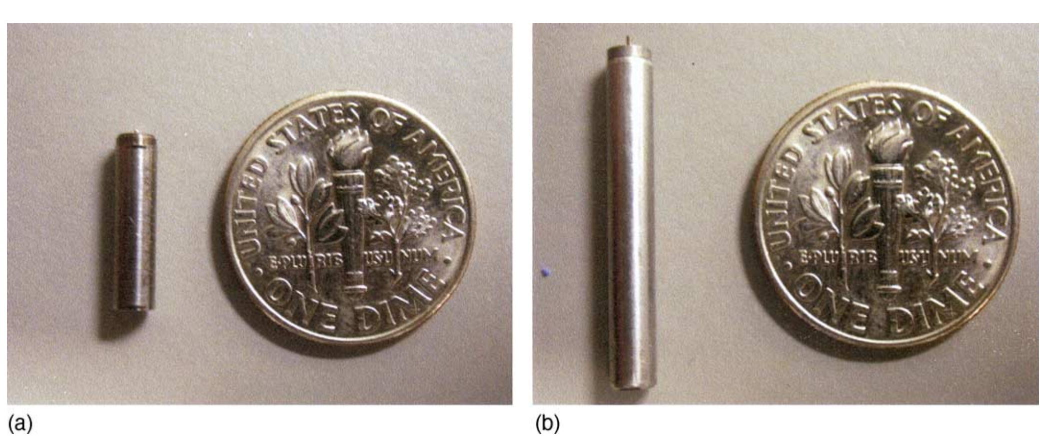

Fig. 2. Photographs of (a) the lithium-ion rechargeable battery: QL0003I and (b) the lithium/CF_x primary battery: QC0025B.

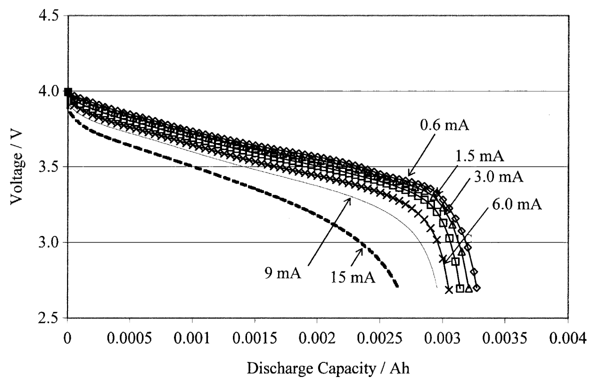

Fig. 4. Discharge curves of QL0003I in the voltage range of 2.7–4.0 V at 37 °C. Battery was discharged at 0.6 mA (=0.2 C), 1.5 mA (=0.5 C), 3.0 mA (=1 C), 6.0 mA (=2 C), 9.0 mA (=3 C), and 15 mA (=5 C).

3.2. Cycle life and calendar life

Implantable medical batteries require long cycle life. The QL0003I batteries were cycled between 3.0 and 4.0 V at 37 °C. A constant current charge at 1.5 mA was followed by a constant voltage charge at 4.0 V, with a cutoff current of 0.15 mA. The discharge was at 1.5 mA down to 3.0 V. Fig. 5 shows the cycle life of QL0003I battery. The QL0003I battery retained over 80% of its initial capacity after 500 cycles.

Calendar life is also critical for implantable medical batteries. To examine the calendar life, the batteries were stored at 37 °C at 100% stage of charge. Fig. 6 shows the calendar life of QL0003I battery at 37 °C. Capacity check was performed periodically in the voltage range of 3.2–4.0 V at 1.5 mA (=0.5 C) at room temperature. The QL0003I battery retained over 80% of its initial capacity after one year of testing.

3.3. Deep discharge capability

In applications such as implantable medical devices, it is likely that batteries would be kept for prolonged periods of

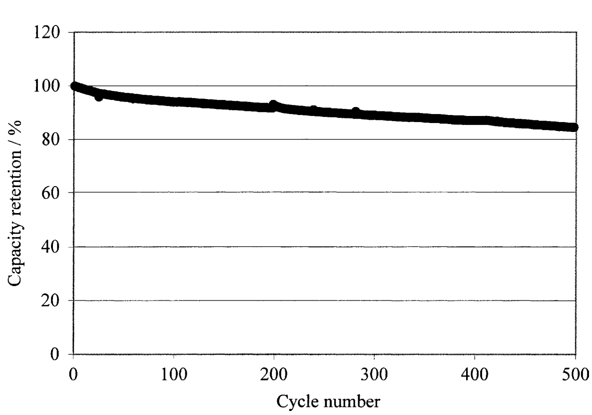

Fig. 5. Cycle life of QL0003I cycling in the voltage range of 3.0–4.0 V at 37 °C.

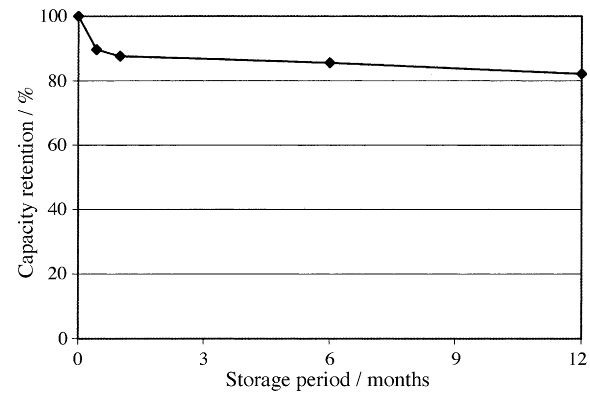

Fig. 6. Calendar life of QL0003I stored at 37 °C at SOC 100%.

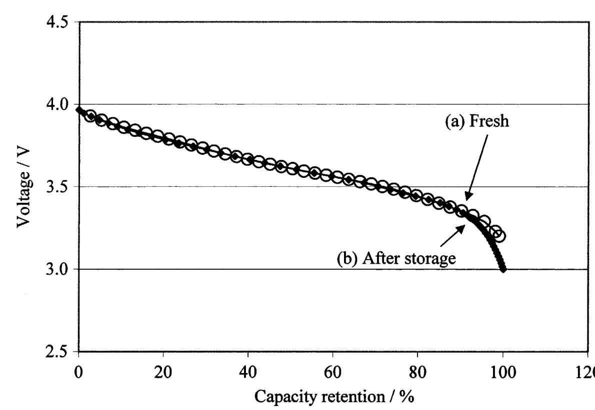

Fig. 7. Discharge curves of QL0003I in the voltage range of 3.0–4.0 V at 37 °C. Battery was stored with a 3 kΩ load in a deep discharge state for 120 days at 37 °C.

time in a deep discharge state. Conventional lithium-ion batteries cannot survive in a deep discharge state. The QL0003I battery has improved deep discharge capability [5,6]. Fig. 7 shows the discharge curves before and after storage in a deep discharge state at 37 °C. The batteries were cycled to determine the pre-storage capacity, then discharged to 2.7 V and connected to a 3 kΩ load to further discharge the battery down to 0 V. After the batteries with a resistive load were stored at 37 °C for 120 days, the cells were cycled to check the full capacity. Discharge curves before and after storage are almost identical and the QL0003I battery suffers little capacity loss after 120 days of storage in a deep discharge state.

4. Lithium primary battery: QC0025B

4.1. Rate capability

Conventional lithium/CF_x batteries generally have high energy density and a flat discharge profile [7]. However, conventional lithium/CF_x batteries are suitable for applications requiring low- to moderate-power output.

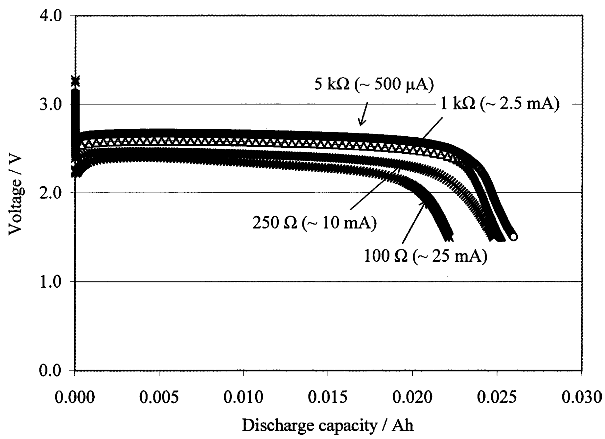

Fig. 8. Discharge curves of QC0025B in the voltage range of 1.5–3.5 V at 37 °C. Battery was discharged at 5 kΩ (∼500 μA), 1 kΩ (∼2.5 mA), 250 Ω (∼10 mA), and 100 Ω (∼25 mA).

The QC0025B batteries were tested at 37 °C for rate capabilities, discharging at different resistive loads of 5, 1 kΩ, 250, and 100 Ω shown in Fig. 8. A continuous discharge down to 100 Ω (∼25 mA) was possible and the capacity was maintained greater than 20 mAh.

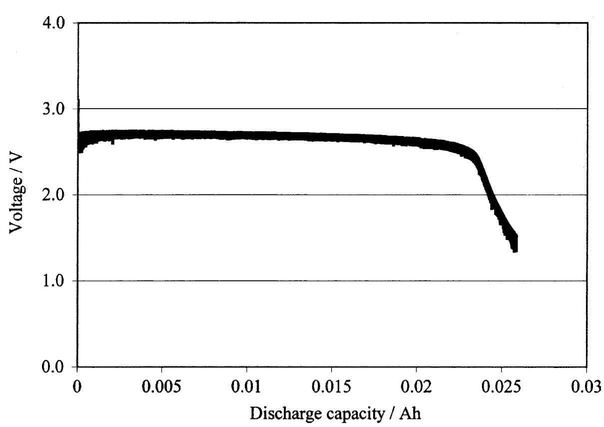

Fig. 9. Discharge curve of QC0025B at 37 °C. Battery was discharged using 20 ms, 10 mA pulses every 5 min with 100 μA quiescent draw down to 1.5 V at 37 °C.

4.2. Pulse capability

A high current pulse test was performed on the QC0025B battery. Fig. 9 shows the voltage profile during the high pulse discharge. The pulses were 20 ms long at 10 mA with 100 μA quiescent draw for 5 min between pulses at 37 °C. The voltage drop during pulse discharge was very small throughout high rate pulsing and the battery retained over 90% of its nominal capacity.

5. Conclusion

We developed miniature pin-type batteries including lithium rechargeable batteries and lithium/CF_x primary batteries capable of high power for implantable medical devices. A unique spiral wound jellyroll design allows small size and high power. The miniature pin lithium batteries are particularly suited for the miniature, and implantable medical devices for applications, such as drug delivery, glucose sensing, and neurostimulation.

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