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An air-breathing single cell small proton exchange membrane fuel cell system with AB5-type metal hydride and an ultra-low voltage input boost converter☆

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ABSTRACT

A new strategy for increasing the power density of an air-breathing small proton exchange membrane fuel cell (PEMFC) system for the main energy source of portable consumer electronics is presented. The small PEMFC system is composed of a single cell. Utilizing the output voltage of the single cell, we introduce a newly designed ultra-low voltage input boost converter. The boost converter can generate 4.1 V output from input sources with low voltage ranges, such as under 1.0 V. The cathode plate is made from a thin SUS 316L stainless steel plate and has ribs that prevent the cathode from bending. The hydrogen is supplied by a metal hydride (MH) tank cartridge. The MH tank contains highly packed AB5-type MH. The MH tank cartridge has a volume of 13.2 cm^3 and can absorb 6.7 L of hydrogen.

The maximum power of the small PEMFC is 4.42 W at room temperature. Using 6.7 L of hydrogen, the small PEMFC can generate 11 Wh of electricity. The power density of the small PEMFC reaches 0.51 Wh cm^{-3}. And the power density of the whole small PEMFC system, which contains the boost converter, a small Li-ion battery for a load absorber, and a case for the system, reaches 0.14 Wh cm^{-3}. This value matches that of external Li-ion battery chargers for cell phones. We installed the small PEMFC system in a cell phone and confirmed the operations of calling, receiving, videophone, connecting to the Internet, and watching digital TV. And also confirmed that the small PEMFC system provides approximately 8.25 h of talk time, which is about three times as long as that for the original Li-ion battery.

1. Introduction

Recently, the energy consumption of portable consumer electronics, such as cell phones, PDAs, and laptop computers, has continued to increase [1]. Such devices are mainly powered by Li-ion batteries. The energy density of the Li-ion batteries is approaching its limit, so further large increase in the energy density are not expected in the future [2]. In the meantime, overheating and ignition of Li-ion batteries have been reported in all parts of the world. As a result, attention has shifted from improving their energy density to improving their safety. This has in turn led to increasing interest in fuel cells, which are expected to be safer and offer higher energy density than Li-ion batteries.

Fuel cells can be classified into several types according to electrolyte used. Proton exchange membrane fuel cells (PEMFCs) and direct methanol fuel cells (DMFCs) are candidates for energy sources of portable consumer electronics. Because the operating temperature is around room temperature and the structures are comparatively simple, it is possible to miniaturize these fuel cells. Considering that methanol exists as a liquid at room temperature, its energy density is higher than that of gaseous hydrogen and is easy to handle. Therefore DMFCs are promising power sources for portable consumer electronics. And DMFC has advanced all over the world [3]. However, the generated voltage or power of the DMFC is lower than that of the PEMFC due to its low electrochemical activity. As a result, it is difficult to reduce the size of the cell. We therefore choose the PEMFC as a power source for portable consumer electronics despite the difficulty in handling gaseous hydrogen.

Processes for storing or making hydrogen, such as reforming of hydrocarbon [4], hydrolysis of $NaBH_4$, and mechanochemical reactions of Al particles with water [5] have been reported. Differed from these methods, we chose BCC-type metal hydride (MH) for hydrogen storage and made a small PEMFC [6]. The MH is easy to obtain and can store a large volume of hydrogen safely. The original system has three distinguishing characteristics. First, it is a single cell system, which makes the fuel cell system simple. Second, the hydrogen flow field is directly equipped on the MH tank. With this structure, generated heat from the fuel cell can be conducted to the

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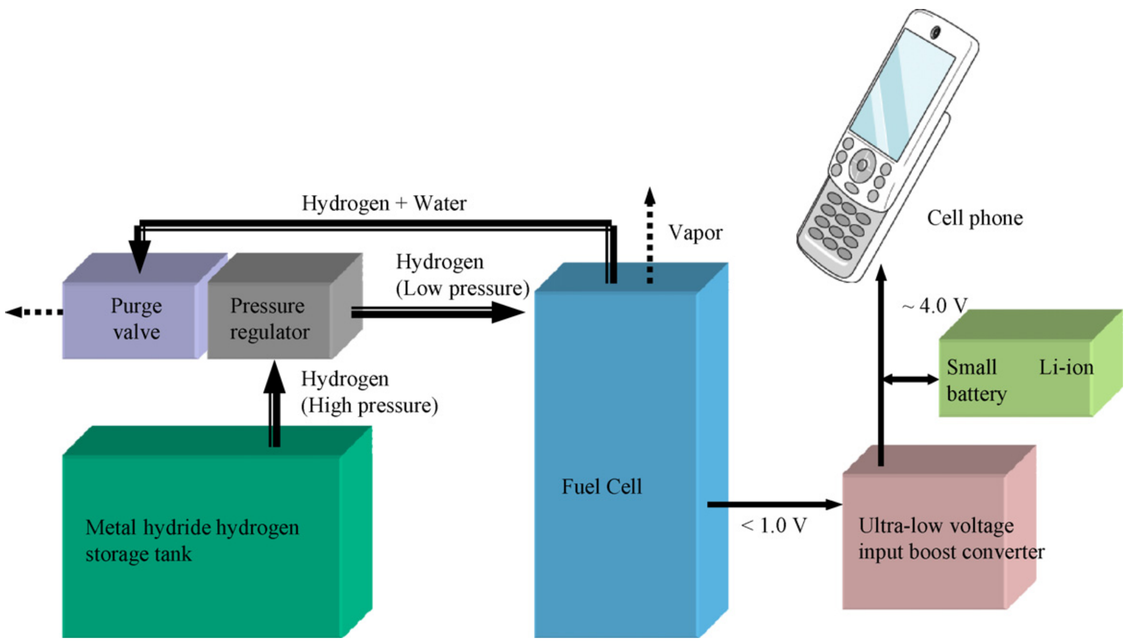

Fig. 1. System configuration.

MH tank and the MH. The heat from the fuel cell is used as heat for the reaction required to discharge hydrogen from the MH. This also prevents temperature rises and keeps the fuel cell from drying up. Third, the MH tank is used as the electrode. This can reduce voltage drops caused by interconnections of components.

In this paper, we describe a new small PEMFC. We made some substantial improvements to the original PEMFC. To miniaturize the original small PEMFC, we removed the end plate and reinforced the cathode plate with ribs. We use a small pressure regulator, which has 1/4 of the volume of that in the original small PEMFC, and tightly packed AB5-type MH. Compared to the original small PEMFC, the hydrogen content per unit volume of the MH tank is increased. Further, a cartridge MH tank system is adopted so that empty MH cartridges can be replaced easily. And the cartridge MH tank system is adopted, we do not use the MH tank as the electrode. Utilizing the output voltage of the single cell, we introduce a newly designed ultra-low voltage input boost converter. The boost converter can generate 4.1 V output from input sources with low voltage ranges, such as under 1.0 V.

We also describe the system configurations of the new small PEMFC for a cell phone and present the power generation characteristics of the small PEMFC.

2. Experimental

2.1. System configurations

The system configuration of the new small PEMFC is illustrated in Fig. 1. Hydrogen is supplied from the MH hydrogen storage tank. The regulator decompresses the hydrogen and the hydrogen is supplied to the single cell. To improve hydrogen availability and safety, we choose a dead-end hydrogen flow system. The

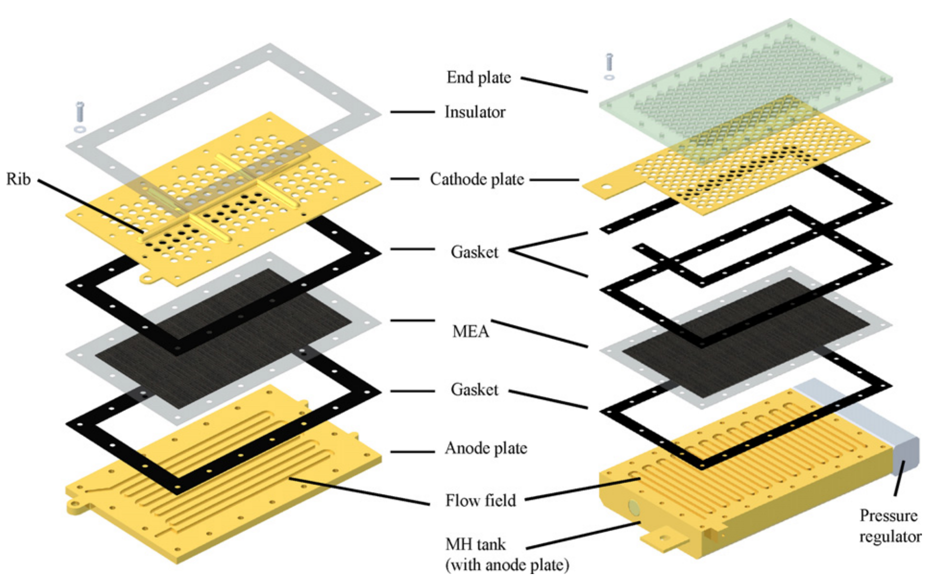

Fig. 2. Fuel cell configuration. Left: new small PEMFC. Right: original small PEMFC.

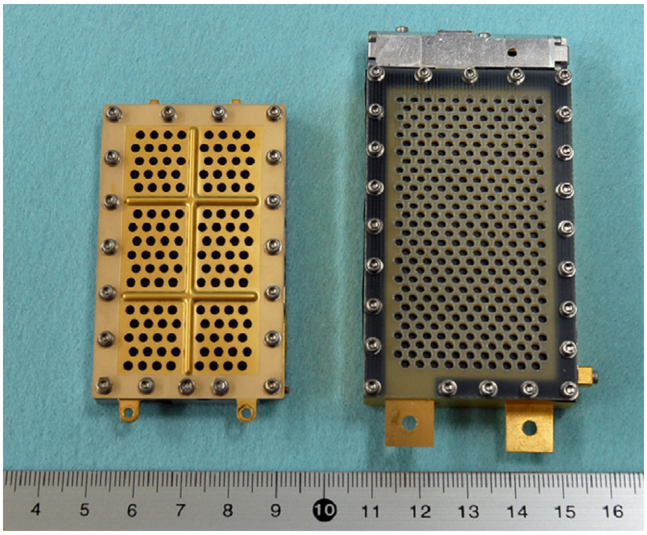

Fig. 3. Front views of the new small PEMFC (left), and the original small PEMFC (right).

supplied hydrogen is controlled only by pressure; the flow rate is not controlled. With a long-term generation of electricity, anode flow field flooding will occur because of the back diffusion of water from the cathode. So the water must be removed from the anode flow field. To eject the water, the small PEMFC system is equipped with a purge valve. The purge valve is normally closed. By pushing the valve, the water is removed by the pressure of the hydrogen.

The generated voltage of the single cell, which is less than 1.0 V, is boosted to 4.1 V by using the ultra-low voltage input boost converter. The small PEMFC cannot follow a sharp change of electrical load. So the small PEMFC system uses a small Li-ion battery as a load absorber. The small Li-ion battery is connected to the output of the boost converter in parallel.

2.2. Configuration of the small PEMFC

The configuration of the new small PEMFC and that of the original small PEMFC are shown in Fig. 2. Front views of the two small PEMFCs are shown in Fig. 3 and an oblique view of the new small PEMFC is shown in Fig. 4. The specifications are listed in Table 1.

The new small PEMFC comprises the anode plate, gaskets, the single cell or membrane electrode assembly (MEA), the cathode plate, and insulation sheet. Screws secure each part. Compared to the original small PEMFC, the new one can reduce the number of gasket and end plate. Moreover, it can be realized in a low profile. We choose PRIMEA® for the MEA and CARBEL®-CL for the gas-diffusion layer. The anode and cathode plate are made of stainless steel (SUS316L) with 0.1 μm thick gold plating. The anode plate has a 0.75 mm-wide and 0.75 mm-deep flow field. A cutting process is used to these grooves. The cathode plate has 2 mm-Ø air holes and 2 mm-wide and 1 mm-high ribs that prevent the cathode plate from bending due to differences between the ambient pressure and decompressed hydrogen pressure which is supplied from the MH tank. The ribs are made by pressing to reduce cost.

2.3. MH hydrogen storage tank cartridge

A photograph of the MH hydrogen storage tank cartridge is shown in Fig. 5. The specifications of the MH tank of the new small PEMFC and that of the original one are shown in Table 2. In the original small PEMFC, we used BCC-type MH with the intention of increasing hydrogen storage capacity. The new one uses AB5-type MH, former has a large capacity of hydrogen storage per unit weight, its equilibrium pressure is higher than that of the AB5-type

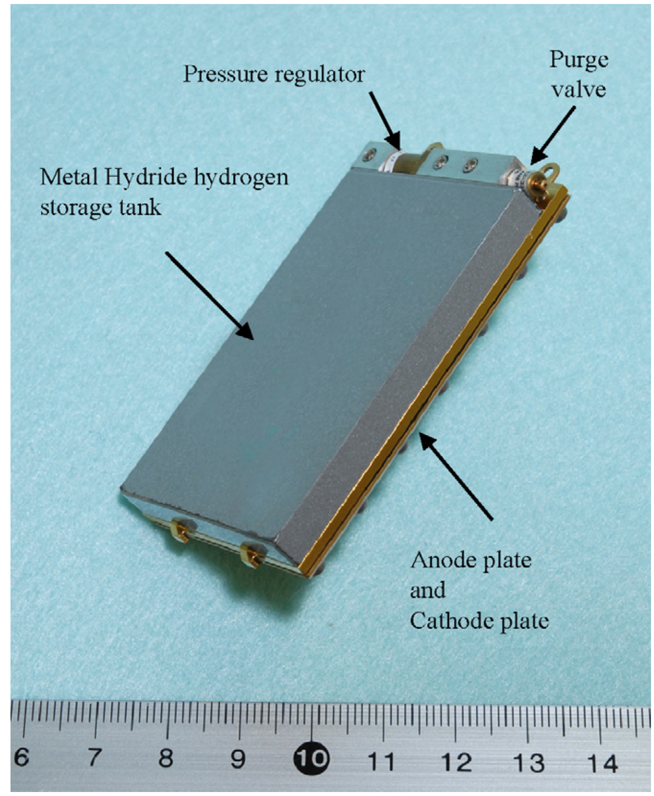

Fig. 4. Oblique view of the new small PEMFC.

Table 1
Specifications of the small PEMFC.

	New small PEMFC	Original small PEMFC
MEA		
Membrane and electrode	PRIMEA®	PRIMEA®
Size of membrane	40 mm × 65 mm × 30 μm	44 mm × 72 mm × 30 μm
Size of electrode	28 mm × 53 mm	34 mm × 62 mm
Gas diffusion layer (GDL)	CARBEL®-CL	CARBEL®-CL
Size of GDL	29 mm × 54 mm × 400 μm	35 mm × 63 mm × 400 μm
Anode plate		
Material	SUS 316 L	A2024
Size	40 mm × 65 mm × 1.6 mm	
Coating	Gold 0.1 μm	Gold 0.1 μm
Flow path	0.75 mm width, 0.75 mm depth	1.0 mm width, 1.0 mm depth
Cathode plate		
Material	SUS 316 L	SUS 316 L
Size	40 mm × 65 mm × 0.5 mm	35 mm × 63 mm × 0.3 mm
Coating	Gold 0.1 μm	Gold 0.1 μm
Gasket		
Material	Silicon rubber	Silicon rubber
Insulator		
Material	Polyethylene naphthalate (PEN)	
End plate		
Material		Epoxy glass
Size		44 mm × 72 mm × 1.6 mm

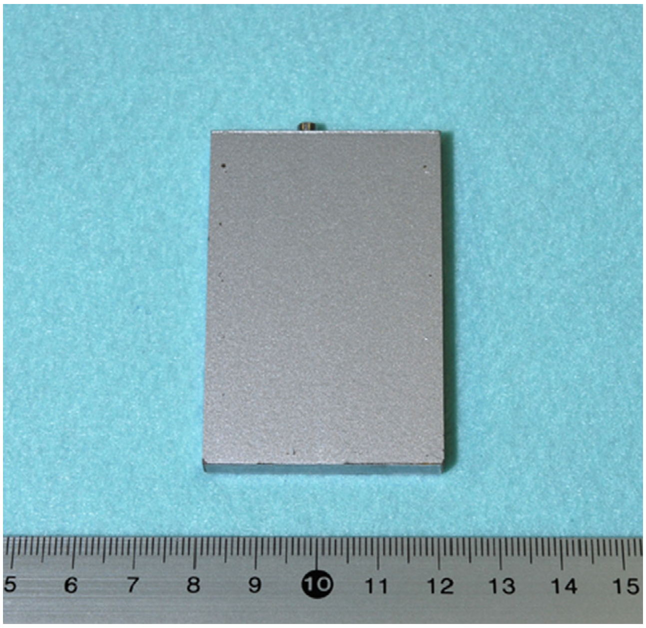

Fig. 5. The MH hydrogen storage tank cartridge.

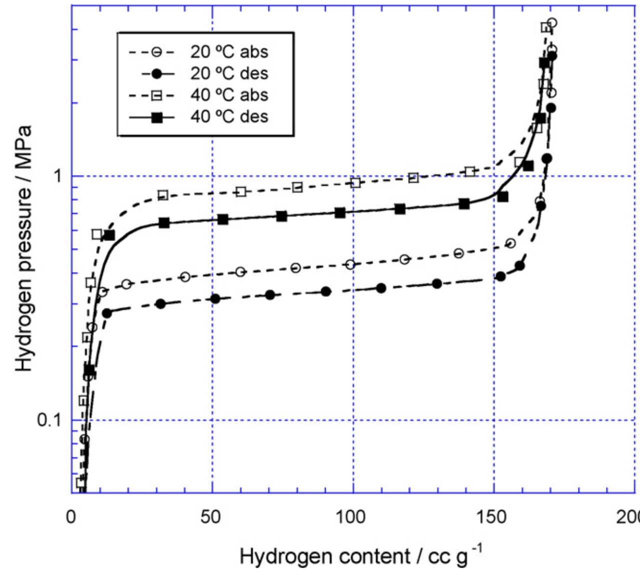

Fig. 6. Pressure composition isotherm of MH.

MH [7]. Therefore, the tank for the BCC-type MH requires a higher pressure capacity. For this reason, we chose aluminum alloy A2024 (duralumin) as the material of the MH tank. The MH tank was fabricated by cutting, and it provided 23 MPa of burst pressure and 287 NL L^{-1} of hydrogen absorbing capacity.

The new small PEMFC increases hydrogen absorbing capacity owing to the high-density packing of the AB5-type MH. With this technology, 508 NL L^{-1} of hydrogen absorbing capacity for the MH tank is attained. Further, the equilibrium pressure is reduced, so that we can design the pressure capacity to be lower than that of the BCC-type MH. As a result, we can use general structural rolled steel (SS400). The MH tank was made by deep drawing process with the aim of lowering a cost of the small PEMFC.

A pressure composition isotherm (PTC) curve of the AB5-type MH is shown in Fig. 6. As shown in Fig. 6, hydrogen pressure rises exponentially as the MH temperature rises. For example, in summer, the temperature of a dashboard will exceed 70 °C and the hydrogen pressure will be 5 MPa or higher, depending on the hydrogen content in the MH tank. We therefore designed the burst pressure to be 8.7 MPa so that the MH tank should not explode in such a condition.

The desorption and absorption speed of MH is shown in Figs. 7 and 8. Throughout the measurement, the MH tank was immersed in the water of 20 °C. The hydrogen was charged up to 0.99 MPa then discharged to atmospheric pressure. The volume of the hydrogen was measured by a mass flow meter. The charging time of 6.7 L hydrogen is about 8 min, and that of 5 L hydrogen, which is 75% of capacity, is only 3 min. The hydrogen can be charged in only 1/25 of the charging time of a normal Li-ion battery [8].

Table 2
Specifications of MH hydrogen storage tank.

	New small PEMFC	Original small PEMFC
Size	40 mm × 60 mm × 5.5 mm	44 mm × 72 mm × 11 mm
Weight	74 g (including MH)	137 g (including MH)
Material of the tank	SS400 Steel	A2024 (duralumin)
MH type	AB5	BCC
Design pressure	2.0 MPa	6.9 MPa
Burst pressure	8.7 MPa	23 MPa
Hydrogen content	6.7 NL	10 NL
Hydrogen content	508 NL L^{-1}	287 NL L^{-1}

2.4. Pressure regulator and purge valve

Photograph of the pressure regulator and purge valve is shown in Fig. 9. The specifications of the pressure regulator and purge valve are shown in Table 3. The volume and weight is reduced to 1/4 that of the original without loosing performance. The pressure regulator and the purge valve are made of a brass because high processing accuracy is necessary. The connector is made of aluminum for weight saving. The maximum hydrogen pressure of the MH tank is 1 MPa at 20 °C and the hydrogen is decompressed to 0.06 MPa by the pressure regulator. Then it is supplied to the single-cell.

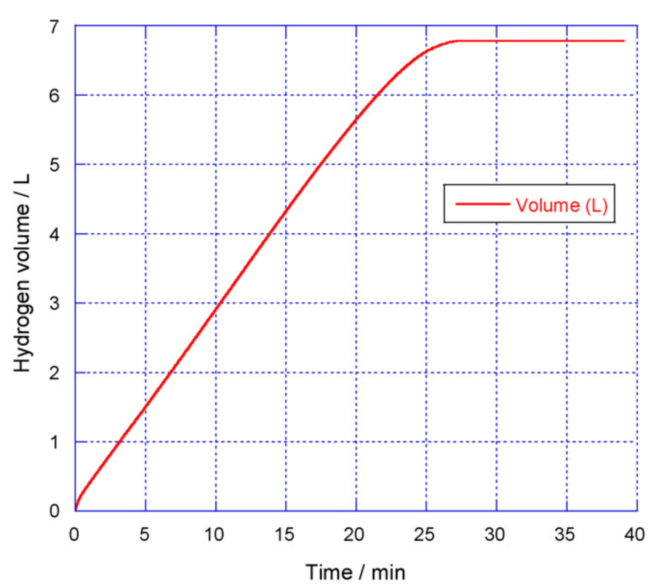

Fig. 7. Desorption speed of MH hydrogen storage tank at T = 20 °C.

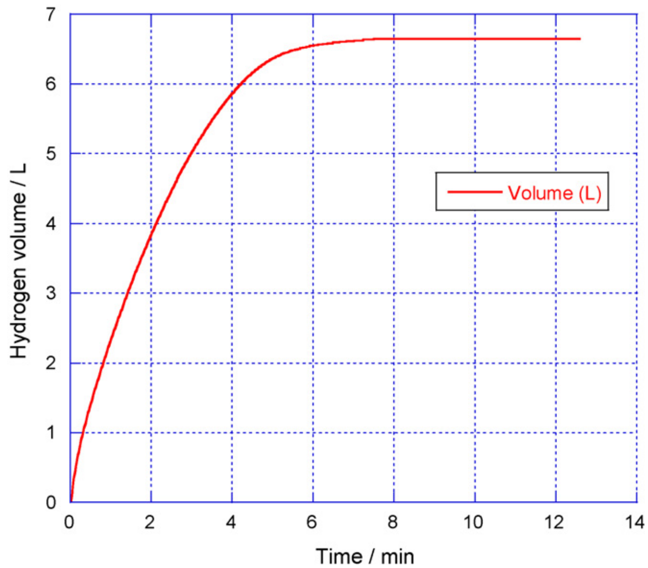

Fig. 8. Absorption speed of MH hydrogen storage tank at $T = 20\,^{\circ}\mathrm{C}$.

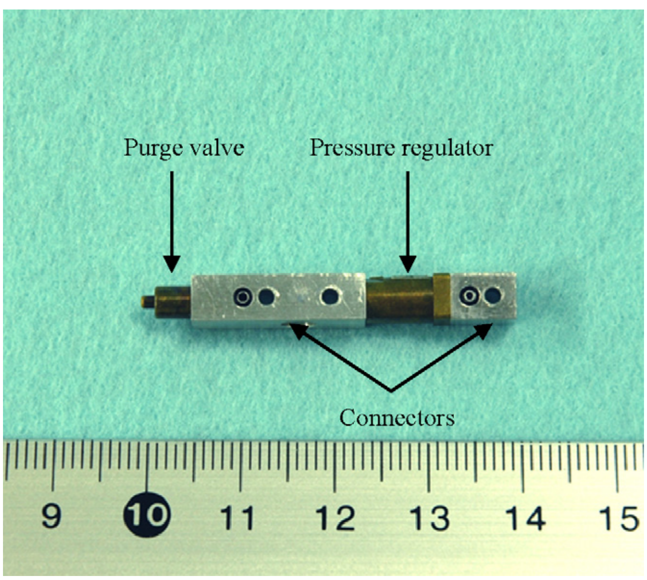

Fig. 9. The pressure regulator and the purge valve.

The hydrogen flow rate (χ) to generate 1 Ah at 0.1 MPa and $0\,^{\circ}\mathrm{C}$ is calculated by Faraday's law as

$$\frac{(\chi/22.4) \times 2 \times 96,485}{3600} = 1 \qquad (1)$$

Table 3
Specifications of the pressure regulator and the purge valve.

	New regulator	Original regulator
Weight (including a connectors)	3.3 g	12.1 g (not including purge valve)
Decompression ability	Primary: 1.0–0.1 MPaG Secondary: 0.1–0.04 MPaG	Primary: 7.0–0.1 MPaG Secondary: 0.8–0.04 MPaG
Material	Regulator, purge valve: brass connectors: aluminum	Regulator: brass connectors: aluminum

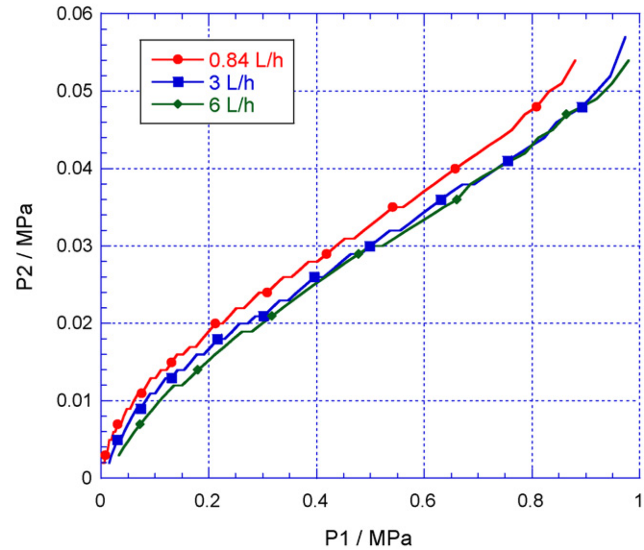

Fig. 10. Relationships between primary pressure (P1) and secondary pressure (P2) of the pressure regulator.

We find from Eq. (1) that $\chi = 0.42\,\mathrm{L\,h^{-1}}$. Fig. 10 shows the relationship between the primary pressure (P1), which is the internal pressure of the MH tank, and the secondary pressure (P2), which is a supplied pressure to the cell. The correlation between P1 and P2 does not depend on the hydrogen flow rate.

2.5. Ultra-low voltage input boost converter

Photograph of the ultra-low voltage input boost converter is shown in Fig. 11, and the specifications are shown in Table 4. The generated voltage of the single cell is less than 1 V. As generated current increases, generated voltage decreases because of polarization. Some commercially available boost converters can boost the voltage to about 4 V, which is equivalent to Li-ion battery voltage. However, the output current is not sufficient and conversion efficiency is low [9]. The new converter [10] can operate from input

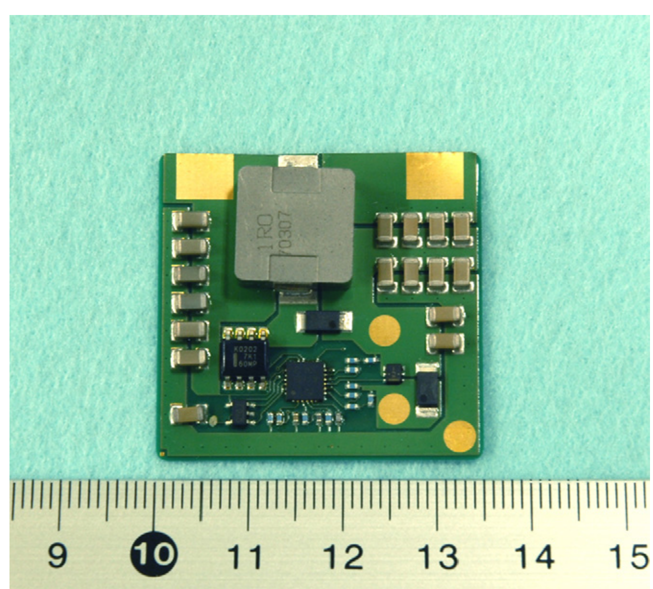

Fig. 11. Ultra-low voltage input converter.

Table 4
Specifications of the Ultra-low voltage input boost converter.

Weight	7.9 g
Size	35 mm × 35 mm × 5.3 mm
Output voltage (no load)	4.1 V (output is adjustable with external resistors)
Input voltage	>0.4 V

voltage down to 0.4 V and has a high efficiency of up to 75% at up to 2 W output.

2.6. Operating conditions

The current–voltage (*I*–*V*), power, and impedance characteristics were measured by four-terminal method with an impedance meter (SPEC 40026 KIKUSUI ELECTRONICS CORP.) controlled by PC. Air was not supplied by force (air-breathing). The temperature of the small PEMFC was not controlled and was exposed to ambient condition. The hydrogen was charged up to 0.85 MPa for 30 min. The MH tank was immersed in 20 °C water during the hydrogen charging.

3. Results and discussion

3.1. I–V and power characteristics

The *I*–*V* and power characteristics are shown in Fig. 12. The new small PEMFC achieves 4.42 W of maximum power and 298 mW cm^{-2} of power density at 0.52 V. On the other hand, the maximum power density of the original small PEMFC is 203 mW cm^{-2}. So the improvement of 1.5 times maximum power density is achieved. It would appear that the cathode plate with ribs prevents contact resistance and ensures high output voltage.

Meanwhile, a maximum electric power consumption of a cell phone (NTT DoCoMo FOMA®) is about 2 W. Therefore, the small PEMFC has enough power to operate the cell phone.

3.2. Long-term voltage and impedance characteristics

The long-term voltage and impedance characteristics are shown in Fig. 13. The generation current was set to 2 A, which means 1.5 W of output power. Considering the conversion efficiency of the boost converter, 1.5 W of output power is equal to the power consumption of the cell phone when talking.

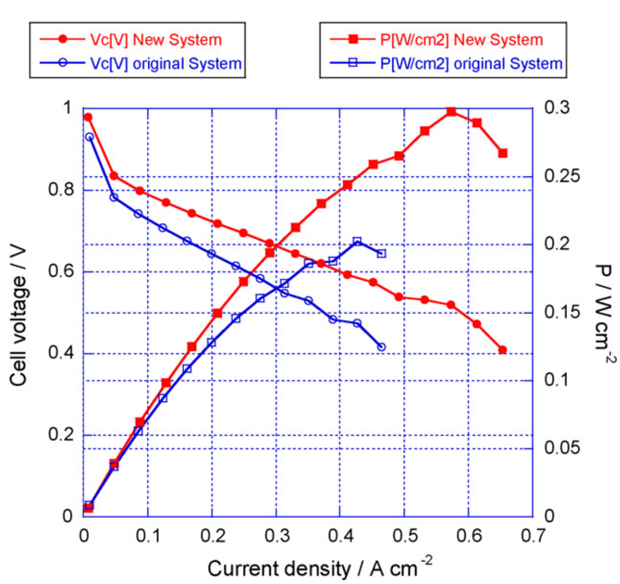

Fig. 12. *I*–*V* and power characteristics.

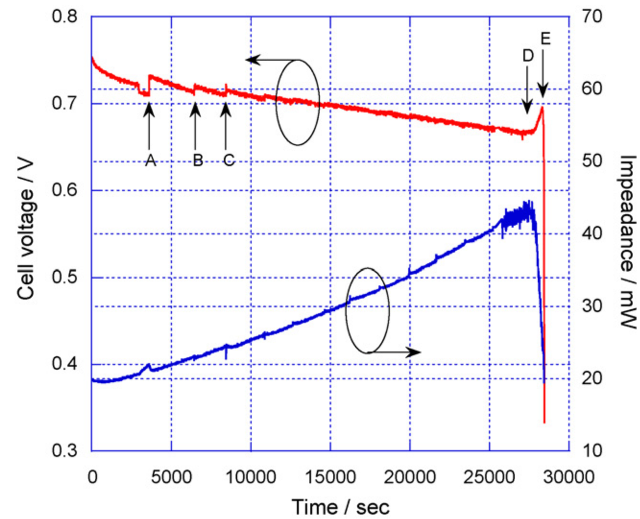

Fig. 13. Long-term voltage and impedance characteristics. Generation current is 2 A.

The generated voltage reduces slowly with time. So the cell is purged with hydrogen gas at points A, B, and C in Fig. 12. At this time, water is ejected with the hydrogen gas. As a result, the cell voltage rises sharply. The cell voltage decrease is mainly caused by anode flooding. Liquid water in the anode channels results from condensation of water on cooler and more hydrophilic channel walls and that water available for condensation in the anode comes from the cathode through membrane transport [11]. After point C, the hydrogen gas is purged every 30 min. Even though water is ejected from the purge valve, the rise of the generated voltage cannot be confirmed. It would therefore appear that the voltage decrease is mainly caused by the flooding of the anode flow field from the power generation beginning before 10,000 s. On the other hand, from the power generation beginning after 10,000 s, the voltage decrease is mainly caused by the flooding of the carbon cloth used as a gas diffusion layer. This is because the water purge is not effective for recovering the voltage. The impedance increases monotonically until point D. This is also attributed to the gradual accumulation of water in the carbon cloth and it caused increase of diffusion overvoltage of the hydrogen.

At point D, the cell voltage rises and the impedance drops. This is because the hydrogen pressure (P1) decreases as the residual quantity in the MH tank decreases. This causes a decrease of output pressure of the regulator (P2). With decreasing P2, the pressure difference between P2 and the atmospheric pressure decreases. Consequently, cathode plate bending due to the atmosphere reduces and contact resistance also reduces, leading to reduced impedance and increased cell voltage. The drop of the cell voltage at point E means that the hydrogen in the MH tank is exhausted.

Total generation time is 28,290 s. The average generated voltage is 0.7 V and the generated current is 2.0 A. From these results, the generation capacity is 11.0 Wh.

3.3. Conversion efficiency of the ultra-low voltage input boost converter

The relationship between the output power and conversion efficiency of the ultra-low voltage input boost converter is shown in Fig. 14. A stabilized power supply that has *I*–*V* characteristics similar to Fig. 12 was used. The output voltage of the converter was set

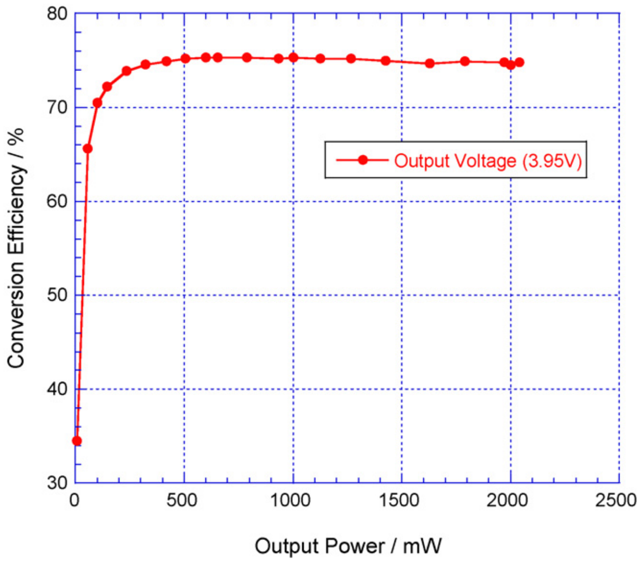

Fig. 14. Relationships between output power and conversion efficiency.

to 3.95 V. When output is over 500 mW, the conversion efficiency is nearly constant at 75%. But when it is less than 100 mW, the conversion efficiency is very low. This converter is designed to have high conversion efficiency at low input voltage. Fig. 12 shows that the cell voltage has a negative correlation to output power. Therefore, when the output power or input power of the converter is low, the input voltage of the converter becomes high. So it would appear that the conversion efficiency becomes low.

3.4. Small PEMFC system

We made a case for the new small PEMFC, the ultra-low voltage input boost converter, and small Li-ion battery. Photographs of the small PEMFC system are shown in Figs. 15–17, and the specifications are shown in Table 5. We installed the small PEMFC system in a cell phone and confirmed the operations of calling, receiving, connecting to the Internet, and watching digital TV. In this case, the original Li-ion battery was removed from the cell phone. The boost converter and small Li-ion battery were designed to be the same size of the original Li-ion battery. Utilizing the space for the original Li-ion battery, the small PEMFC system can

Fig. 15. Small PEMFC system (right) and the cell phone (left) is operated by the small PEMFC.

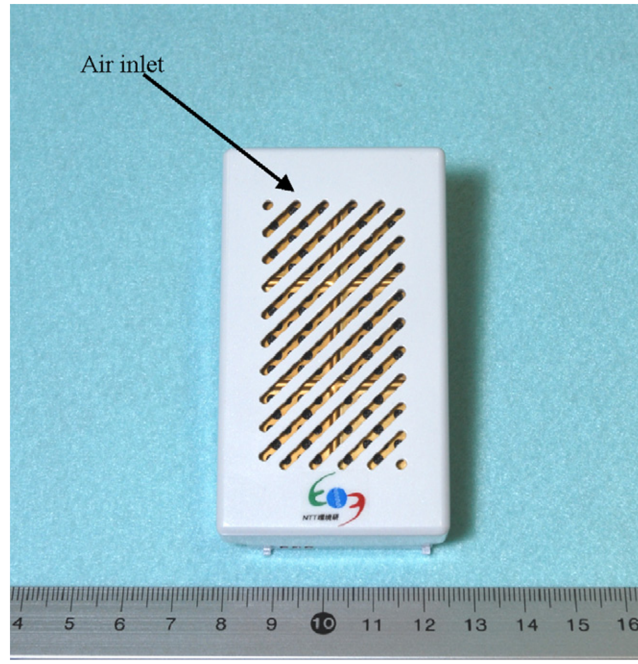

Fig. 16. Small PEMFC system (front view).

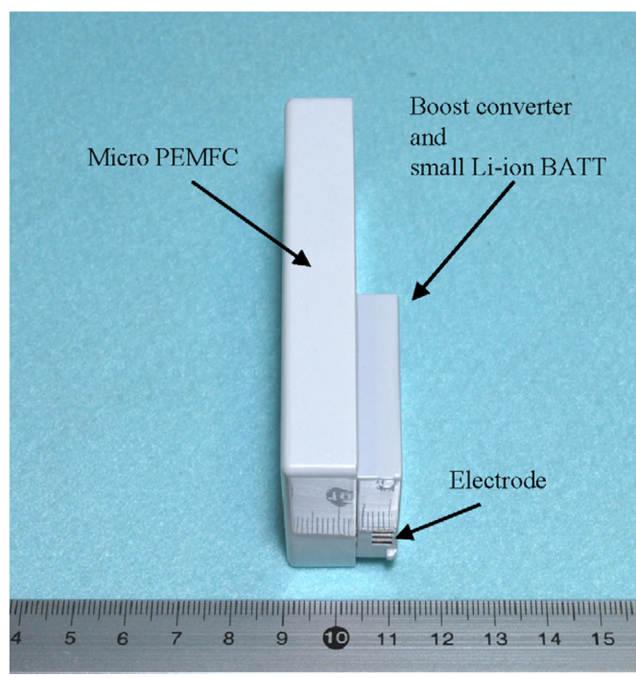

Fig. 17. Small PEMFC system (side view).

Table 5
Specifications of the small PEMFC system.

Weight	144 g
Volume	57 cm^3
Output voltage	4.1 V
Power density	298 mW cm^{-2}
Energy density	0.14 Wh g^{-3}, 0.058 Wh cm^{-3} (including the boost converter and case)

be easily fitted to the cell phone. By changing the shape of the space, the small PEMFC system can be fitted to many portable consumer electronics. The volumetric and gravimetric energy are 0.14 Wh cm^{-3} and 0.058 Wh g^{-1} when generation capacity is 11 Wh, and the conversion efficiency of the boost converter is 75%. These values match those of external cell phone Li-ion battery chargers [12], which have a Li-ion battery with 1800 mAh capacity (0.13 Wh cm^{-3}, 0.095 Wh g^{-1}). As mentioned in Section 3.2, the small PEMFC has capacity of 11.0 Wh. Taking into account the conversion efficiency, which is 75%, and the power dissipation of a cell phone when talking, which is about 1 W, the small PEMFC system provides 8.25 Wh of capacity and 8.25 h of talking time.

4. Conclusions

We developed an air-breathing single-cell small PEMFC system for the main energy source of portable consumer electronics. The maximum power of the small PEMFC is 4.42 W at room temperature. Using 6.7 L of hydrogen, the small PEMFC can generate 11 Wh of electricity. The power density of the small PEMFC reaches 0.51 Wh cm^{-3}, and the power density of the whole small PEMFC system, which contains an ultra-low voltage input boost converter, small Li-ion battery, and a case for the system, reaches 0.14 Wh cm^{-3}. This value matches that of external Li-ion battery chargers for cell phones.

We installed the small PEMFC system in a cell phone and confirmed the operations of calling, receiving, connecting to the Internet, and watching digital TV. We also confirmed that the small PEMFC system provides approximately 8.25 h of talk time, which is about three times that for the original Li-ion battery.

Acknowledgement

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