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論　文

水素により制御可能な開閉器の実験的検証

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Experimental study of a hydrogen-controllable switch of electric circuits

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Abstract

In this paper, the hydrogen-controllable switch of electric circuits was proposed. The concept of the switch is based upon hydrogen gas pressure controlling the switch condition, either opened or closed, without any electrical supports. The switch has been designed so that it is closed in an atmosphere that does sot contain hydrogen. To study its switching behaviors, the switch was placed in the argon gas flow. When flowing gas was changed to a gas mixture containing 9% H_2 – 91%Ar, the switch was open after 201 s. However, when the mixture was replaced by argon gas, the switch was closed again. In addition, we determined that the threshold for hydrogen concentration while turning the switch on could be adjusted by an arranging a magnet in the switch.

1. Introduction

Safe handling of hydrogen (H_2) gas is a critical issue in the supply network of large amounts of H_2 gas. The H_2 gas is flammable in air at concentration levels of 4-75%, which is a wider range compared to methane and gasoline [1]. Therefore H_2 concentration levels must be monitored at all times in order to maintain safety levels while handling the H_2 gas. In general, if the H_2 concentration in the atmosphere reaches above 1%, all ignition sources must be removed as soon as possible. One of the main ignition sources are electric circuits. As the ignition energy for a mixture of air and hydrogen is relatively low, a small electric spark can ignite the mixture [1]. Thus all electrical equipment in the work space must be turned off when a H_2 leak is detected.

Almost all safety devices operating in the hydrogen-containing air atmosphere require electrical supply, and the safety device can also ignite the mixture. Therefore safety devices without an electrical supply are favorable to maintain safety while H_2 handling. A unique switching device, namely, a magnetic switch controlled by hydrogen gas, is described in this paper. A typical magnetic switch is operated by the change in the external magnetic field. The magnetic field is generated from either an electrical current or a permanent magnet. The switch described in this paper can be controlled by not magnetic field but by H_2 gas within a certain pressure. The switch does not require electrical supply to control it; only H_2 gas can control the switch. Consequently, this switch provides a safe mechanism for using in hydrogenous environment.

In this paper, we explain the basic mechanisms of the hydrogen-controllable switch of electric circuits, how the test switch was constructed, and the methods in which the characteristics of the switch relative to H_2 gas were verified.

2. Experimental

2.1. Principle of operation of the hydrogen-controllable switch

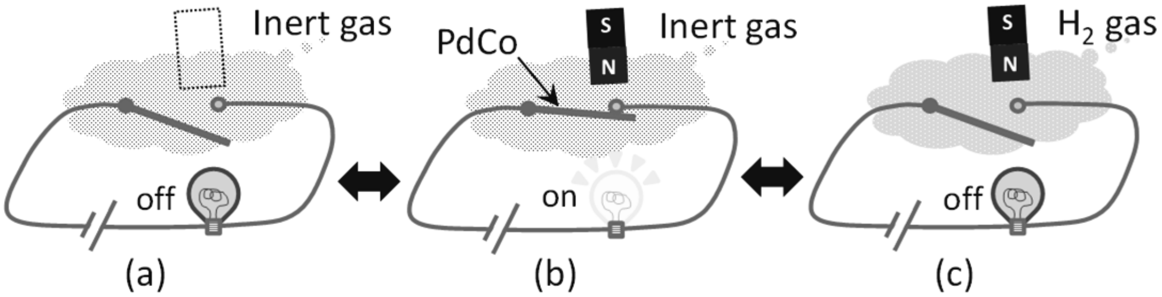

Fig. 1. Basic mechanisms of the hydrogen-controllable switch.

The basic mechanisms of the hydrogen-controllable switch are depicted in Fig. 1. The plate in the switch contains ferromagnetic hydrogen absorbing alloy PdCo. The plate is movable, and the permanent magnet can control both opening and closing of the electrical circuit. Initially, without the permanent magnet the plate is set to open the switch (Fig. 1a). The permanent magnet is placed near the PdCo-containing plate, and the plate contacts a terminal, turning thus the switch on (Fig. 1b).

When hydrogen appears in the surrounding atmosphere, PdCo absorbs hydrogen and the magnetization of PdCo is reduced [2]. As the results, attractive force between the magnet and the PdCo-containing plate is reduced, and the plate leaves from the terminal turning thus the switch off (Fig. 1c).

If hydrogen gas leaves the surrounding atmosphere, PdCo desorbs hydrogen, and the PdCo-containing plate contacts the terminal again. This switch can be used repeatedly, and thus works as the hydrogen-controllable switch.

2.2. Experimental test of operation of the hydrogen-controllable switch

The schematic view of the experimental system is illustrated in Fig. 2. The switch was assembled from two Cu rods, a 0.01 mm thick Cu plate with the $Pd_{0.9}Co_{0.1}$ alloy powder deposited on the back side, an NdFeB magnet, and a glass cell. The opposite sections of each copper rod were machined in such a way that they were flat surface facing each other across a small gap. The Cu plate (with $Pd_{0.9}Co_{0.1}$ alloy on the back side) was put on one flat surface and was bound with Cu wire. A terminal of the plate was bent into a triangular shape, perpendicular to the upper Cu rod. The apparatus described above was covered by the glass cell, and the NdFeB magnet was placed outside of the cell. The position of the NdFeB magnet was adjusted so that the Cu plate touched the upper Cu rod.

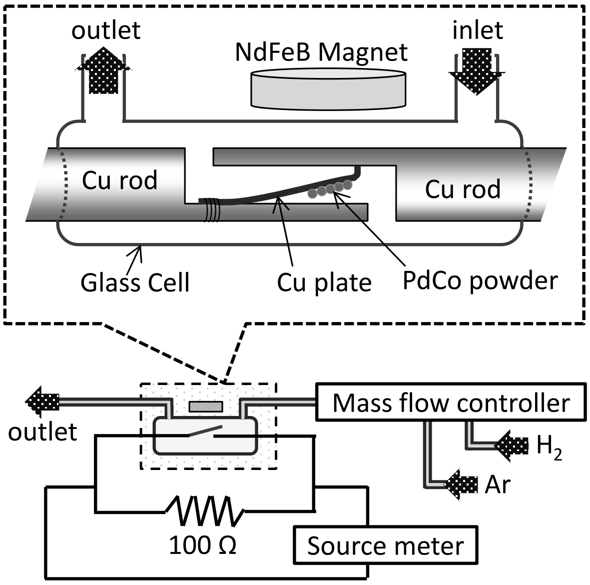

Fig. 2. Schematic view of the basic components to show switching behaviors.

The switch was connected to the low voltage SourceMeter instrument, Keithley 2401. A 100 Ω resistor was set parallel to the switch. The direct electrical current of 100 mA, supported by the SourceMeter instruments, flowed constantly through an electrical circuit, and the changes in the voltage were continuously monitored as measurements were performed. H_2 and Ar gases were supplied to each mass flow controller, making a mixture with a certain H_2 concentration. The mixture flowed into the cell with flow rate of 100 ml/min.

3. Results and discussion

Figure 3 illustrates the typical experimental result for the hydrogen-controllable switch. The distance between the cell and the magnet $d_{\text{sw-mag}}$ was 0.7 cm. The voltage E_{all} showed almost 0 V under Ar gas flow at time t less than 0 second, indicating that the switch was

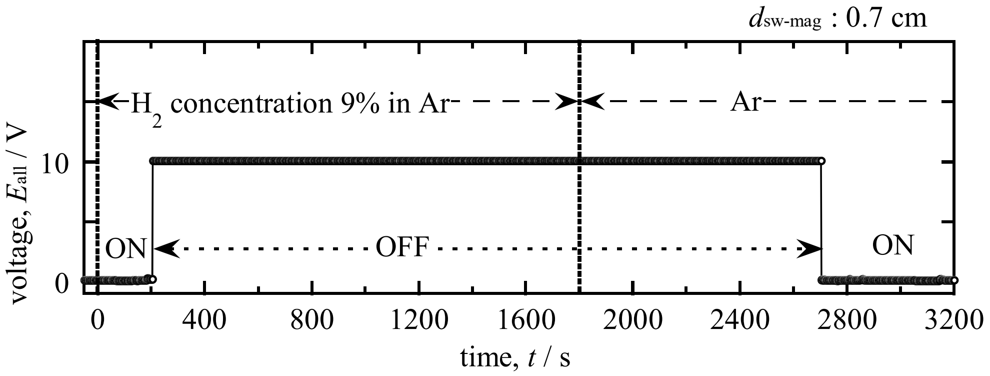

Fig. 3. Typical switching behavior of the hydrogen-controllable switch. H_2 was added to Ar at $t = 0$ s, and H_2 addition to Ar was stopped at 1800 seconds. The H_2 concentration in the H_2-Ar mixture and the distance between the cell and the magnet were fixed at 9% and 0.7 cm, correspondingly.

closed, namely, the Cu plate maintained contact with the upper Cu rod. The gas that flowed into the cell was changed at $t = 0$ s to the mixture of H_2 and Ar with H_2 concentration of 9%. At $t = 206$ s, the E_{all} quickly changed to 10 V, indicating that the switch was turned off, namely, the Cu plate was no longer in contact with the upper Cu rod. The switch was held open during the H_2-Ar mixture flow. The flowing gas in the cell was changed to Ar at $t = 1800$ s. After 904 seconds from the change of the flowing gas (corresponding to $t = 2704$ s), the E_{all} became almost 0 V again. Changing the E_{all} to 0 V implied that the switch was turned on, namely, the Cu plate made contact with the upper Cu rod. These results indicate that the switch, constructed in this study, is controlled by using a mixture of 9% H_2 in Ar.

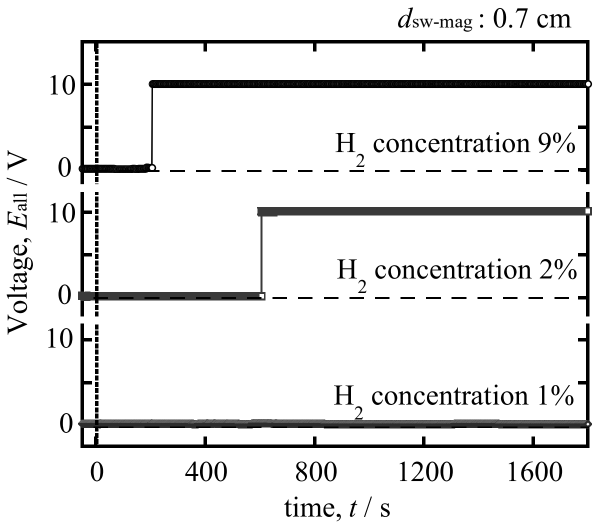

Fig. 4. Switching behavior for various H_2 concentration in the H_2-Ar gas mixture. The distance between the cell and the magnet was 0.7 cm.

Figure 4 illustrates the switching

behavior with different H_2 concentrations in the H_2-Ar gas mixture. The experimental conditions, except H_2 concentration, were the same as in Fig. 3. With H_2 concentrations of 9% and 2%, the switch was turned off at t = 206 s and 606 s, respectively. However, the switch remained closed at the H_2 concentration of 1% in the H_2-Ar gas mixture. It appeared that there was the threshold of H_2 concentration to turn the switch off. In addition, the time to turn the switch off at the H_2 concentration of 2% was three times longer than at the H_2 concentration of 9%. These facts can be explained by the following reasons. The switch was turned off when the attractive force between the magnet and the PdCo alloy was smaller than the gravity and/or the elastic force of the Cu plate. The attractive force is generally governed by a magnetization of the PdCo alloy and the distance between the switch and the magnet. Note that the magnetization of PdCo becomes smaller as higher H_2 partial pressure [2], and the magnetization is proportional to the square root of H_2 partial pressure [3]. In this experimental condition, the magnetization of the PdCo alloy under the H_2 concentration of 1% was larger than threshold magnetization M_{th}. This is the value required to keep equilibrium between the magnetization-induced attractive force on the one hand, and teh gravity and the elastic force of the Cu plate on the other hand. The rate of hydrogen absorption is higher at higher H_2 partial pressure, so the magnetization of the PdCo alloy reaches M_{th} faster under higher H_2 partial pressure.

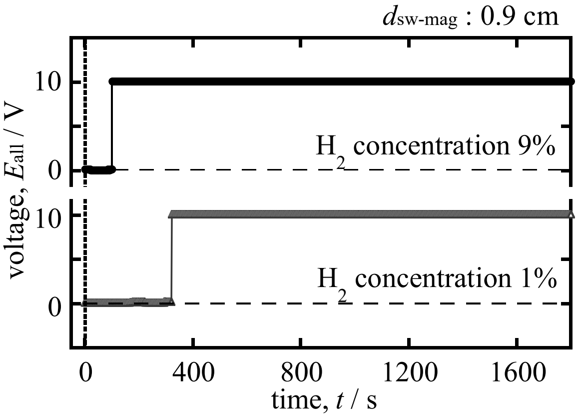

Fig. 5. Switching behavior after changing the distance between the cell and the magnet to 0.9 cm.

Figure 5 shows the switching behavior with a slightly longer distance between the cell and the magnet, $d_{sw\text{-}mag}$, which was set to 0.9 cm. The switch was turned off with the

H_2 concentration of 9% at $t = 101$ s. This time was shorter than for $d_{\text{sw-mag}} = 0.7$ cm. At the H_2 concentration of 1%, the switch was turned off at $t = 322$ s. These results demonstrate qualitatively that the attractive force between the magnet and the PdCo alloy becomes weaker with longer distance $d_{\text{sw-mag}}$. Consequently, it indicated that the threshold of the H_2 concentration to turn the switch off could be adjusted by the distance between the magnet and the PdCo alloy.

A significant problem emerged from this experiment is an instability of the electric contact between the Cu plate and the upper Cu rod. We observed that E_{all} did not change to almost 0 V whereas the Cu plate seemed to be attached to the upper plate. There are two reasons for this instability. The first reason is a weakness of the attractive force without H_2 gas, and the other reason was the surface condition at the contact point. The former reason can be solved by the development of a high performance ferromagnetic hydrogen absorbing alloy, which is favorable in demonstrating a large change of magnetization by hydrogen absorption. The solution for the latter reason is coating the plate with less oxidation materials such as Pt, it is possible to improve the contact. In future we will try to improve the switch.

4. Conclusions

The hydrogen-controllable switch was demonstrated through an experiment. The switch was similar to a conventional reed switch but was characterized using ferromagnetic hydrogen absorbing alloy PdCo with one side of contact. The switch was generally closed by using the permanent magnet taking advantage of the attractive force between the magnet and the PdCo alloy. The switch spontaneously opened in the presence of hydrogen gas due to a decrease in magnetization of the PdCo alloy occurring in the presence of hydrogen gas. While the basic behaviors mentioned above have been confirmed, some improvements are necessary in order to obtain a stable hydrogen-controllable switch.

Acknowledgement

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References

[1] H. Fayaz, R. Saidur, N. Razali, F. S. Anuar, A. R. Saleman, M. R. Islam, *Renewable and Sustainable Energy Reviews* **16** (2012) 5511-5528.

[2] S. Akamaru, T. Matsumoto, M. Hara, K. Nishimura, N. Nunomura, M. Matsuyama, *Journal of Alloys and Compounds* **580** (2013) S102-S104.

[3] N. Nunomura, M. Hara, S. Akamaru, *Proceedings in PRICM8: Pacific Rim International Congress on Advanced Materials and Processing* (2013) 1837-1841.