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DC current distribution mapping system of the solar panels using a HTS-SQUID gradiometer

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Abstract. Solar panels are expected to play a major role as a source of sustainable energy. In order to evaluate solar panels, non-destructive tests, such as defect inspections and response property evaluations, are necessary. We developed a DC current distribution mapping system of the solar panels using a High Critical Temperature Superconductor Superconducting Quantum Interference Device (HTS-SQUID) gradiometer with ramp edge type Josephson junctions. Two independent components of the magnetic fields perpendicular to the panel surface ($\partial Bz/\partial x$, $\partial Bz/\partial y$) were detected. The direct current of the solar panel is visualized by calculating the composition of the two signal components, the phase angle, and mapping the DC current vector. The developed system can evaluate the uniformity of DC current distributions precisely and may be applicable for defect detection of solar panels.

1. Introduction

Effective means of using sustainable energy such as solar panels are required due to the depletion of fossil fuels, global warming and energy problems. Non-destructive evaluation of solar panels is important to develop solar panels with high efficiency and high durability. For example, the photoexcitation method using laser and microwave technologies has been developed to assess the concentration, lifetime, and mobility of carriers in semiconductors. The thermography method [1], laser Superconducting Quantum Interference Device (laser–SQUID) method [2] and electro luminescence method [3] have been used to evaluate these technologies. The above evaluation methods are useful techniques in evaluating the solar panels because they are capable of measuring the excitation current and detecting micro-cracks.

We developed a system of evaluating solar panels using a SQUID, which is an ultra-high sensitivity magnetic sensor. Although the sensitivity of LTS (Low Critical Temperature)-SQUIDs made of a low-temperature superconductor is higher compared to HTS- (High Critical Temperature) SQUIDs, there is the problem that LTS-SQUIDs require a large operating system due to coolant recovery apparatus and the high running costs of liquid helium. Therefore, we developed a system using a HTS-SQUID made of a high temperature superconductor. The HTS-SQUID is inferior to LTS-SQUID in sensitivity; however, it has reasonable running costs and requires a smaller system, because it works at liquid nitrogen temperature. The developed system allows to us visualize the electrical characteristics of the solar panels using HTS-SQUID and an external normal conducting pickup coil [4]. In addition, this system was able to evaluate the solar panels depending on the differential conductance characteristics in the solar panels. Furthermore, the solar panels could be separated from the HTS-SQUID using the pick-up coil to reduce interference. However, the intensity of the current mapping flowing through the solar panel was difficult to detect because the modulation voltage should be applied to the solar panels. Therefore, in this study, we developed a direct detection system for detecting the magnetic field from the sample using the HTS-SQUID gradiometer. We report the current distribution measurement of the solar panels by using this system.

2. Experimental

2.1. *HTS-SQUID gradiometer*

Cross-sectional view of the HTS-SQUID and the HTS-SQUID chip are shown in Fig. 1. The HTS-SQUID has ramp-edge type Josephson junctions[5].The base and counter superconducting electrodes were $La_{0.1}Er_{0.95}Ba_{1.95}Cu_3O_y$ and $SmBa_2Cu_3O_y$, respectively. $SrSnO_3$ (SSO) was used in the insulating layer. The size of the SQUID chip was 15 mm × 7.5 mm with an on-chip 3 turns feedback coil provided in each SQUID, and four SQUID elements were fabricated on the same substrate in the chip. Also, a gradiometer connected to these SQUIDs was fabricated on the same substrate and the baseline is about 7.5 mm.

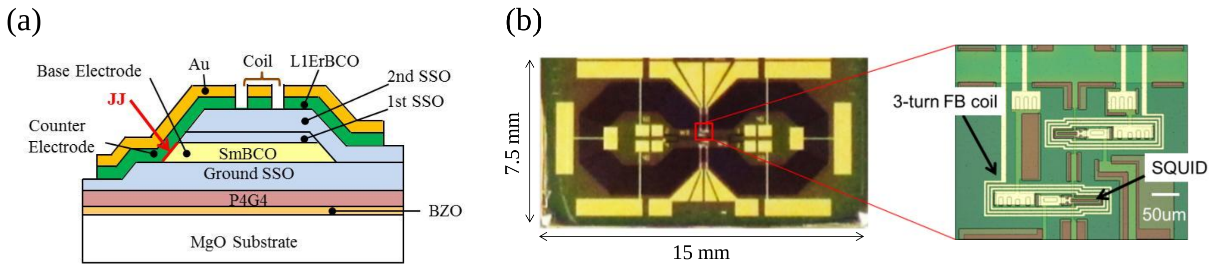


Figure 1. (a) Cross-sectional view of a SQUID, (b) HTS-SQUID gradiometer.

2.2. *System configuration*

The measurement system developed in this study is shown in Fig 2. Two independent components of the magnetic fields perpendicular to the panel surface (∂Bz/∂x, ∂Bz/∂y) of the magnetic field were detected by the HTS-SQUID gradiometer. The HTS-SQUID was placed on a sapphire rod and cooled by liquid nitrogen through heat conduction. The measurement sample and the HTS-SQUID were placed in a two-layer permalloy magnetic shield. The size of the magnetic shield is 912 mm × 700 mm × 942 mm. The SQUID is operated by a Flux Locked Loop (FLL) circuit (SEL-1, MAGNICON). The obtained signals detected by the HTS-SQUID gradiometer were recorded through an analog-to-digital converter (NI USB-DAQ, National Instruments). Furthermore, in order to enable highly reproducible, high spatial resolution and automatic measurement, a measurement sample was placed on a PC-controlled XY stage. The magnetic flux noise level of the developed system did not show significant changes at the time of excitation and operation of the XY stage.

2.3. *Examined sample and procedure*

A commercially available amorphous silicon solar cell was measured as the test sample. The effective area of the panel is 141.9 mm × 107.0 mm, the thickness was 2.3 mm. First, the characteristics of the magnetic field to the applied voltage were measured. This measurement was carried out in 2 places while being swept by 0.1 V intervals from 0 to 10 V of DC voltage. Then, to evaluate the DC current distribution of this sample, 9 V of the DC voltage was applied to the test sample. In this case, the scanning area was 80 mm × 60 mm, the scanning interval was 2 mm, and measurements were performed at 1200 points on the solar panel.

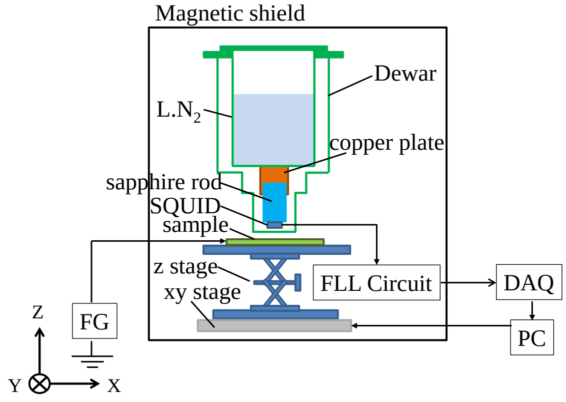


Figure 2. Schematic diagram of the developed system.

3. Results and discussion

The magnetic field characteristic with respect to the voltage of the solar panel is shown in Fig. 3 (left) and (right). The output of the SQUID changed with the increase in voltage. With the use of a gradiometer in this system, when the current is uniformly distributed, the output of the SQUID does not change. Therefore, the results show that the current flowing through the solar panel was not uniform. The value of $\partial B_z/\partial x$ showed that the current flowing was not uniform between the positive and negative electrodes, and the direction of the current flowing perpendicular to the electrodes was also different in the two measurement points. The variations in the initial value of the signal were due to the DC offset of the SQUID by the FLL circuit. In addition, the change of $\partial B_z/\partial y$ component was similar because current flow horizontally between the electrodes was in the same direction.

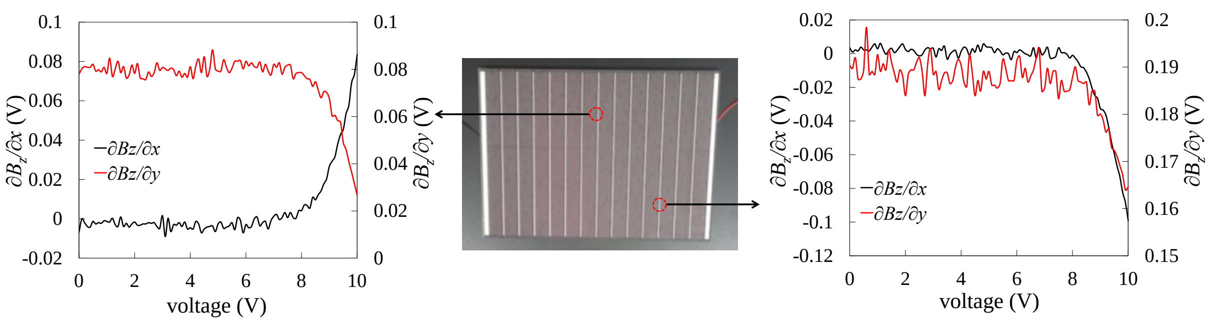


Figure 3 (left) and (right). Voltage-Magnetic field characteristic of solar panel.

The signals obtained in this system were two independent components of the magnetic fields perpendicular to the panel surface below the HTS-SQUID. As the gradiometer was used in this system, the two signals of the magnetic field gradient generated by the sample were obtained. Therefore, it was possible to calculate the intensity of the current and phase angle of the current flowing in the samples by using two components of the obtained signals. The intensity of the current ($I_x=\partial B_z/\partial x$, $I_y=-\partial B_z/\partial y$) is expressed by the following equation (1).

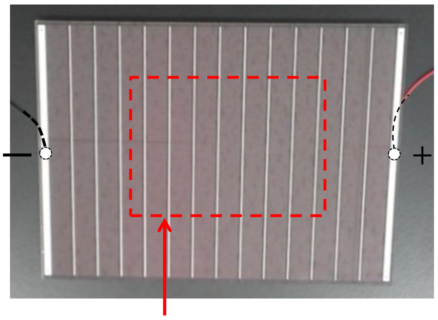
$$I = \left(I_x^{\,2} + I_y^{\,2}\right)^{1/2} = \left\{(\partial Bz/\partial x)^2 + (-\partial Bz/\partial y)^2\right\}^{1/2} \tag{1}$$

The current phase angle θ of the current is expressed by the following equation (2).

$$\theta = a\,tan\left(\frac{Ix}{Iy}\right) - \frac{\pi}{2} = a\,tan\left(\frac{-\partial Bz/\partial y}{\partial Bz/\partial x}\right) - \frac{\pi}{2} \tag{2}$$

The vector using arrows displays the current phase obtained by the calculation described above, depicting the current arrow map that shows the contour lines of the current intensity.

The result of DC current distribution measurement of the solar panel is shown in Fig.4 left. The measurement was performed from the rear surface of the solar panel without a light source. Around the external positive electrode, it is found from Fig. 4 that the direct current that flows in a direction perpendicular to the inter-electrode is not flowing uniformly. Thus, we succeeded in identifying non-uniform current distribution points by using the developed system.



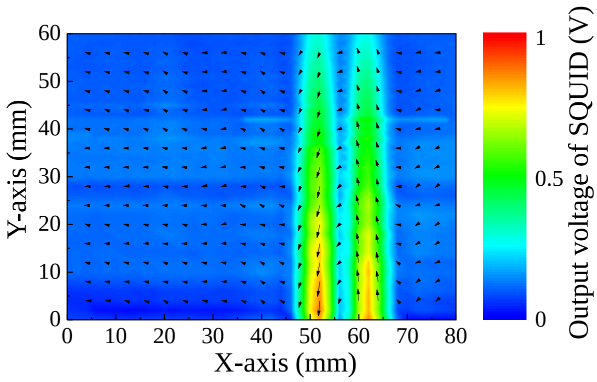


Figure 4 (right). DC current distribution of a solar panel.

4. Conclusion

We developed a system for visualizing the DC current distribution of a solar panel using an HTS-SQUID gradiometer. The current vector was detected by using a gradiometer. Therefore, it is possible to visualize the current distribution by the composition of two independent components of the magnetic fields perpendicular to the solar panel. The developed system was able to visualize a non-uniform current phase and the place of the DC current distribution in an amorphous silicon solar cell. Therefore, the developed system is useful as a non-destructive testing method in the process of solar cell development. The developed system can be applicable to the evaluation of a defective portion and the uniformity of the current in various types of solar panel.

Acknowledgments

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