博士論文（要約）

A Robust On-Chip-Integrated High-Voltage Photovoltaic Cell Array and Application to High-Speed Remote Optical Operation of MEMS Actuators

（オンチップ集積高電圧太陽電池の
高安定化と遠隔光駆動型 MEMS の
高速動作応用に関する研究）

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A microdevice working in a remote place has been widely investigated for various applications such as sensor nodes, devices in a vacuum chamber, endoscopes, and biomedical implants. For such applications, the device is required to be as small as possible. In microdevices, microelectromechanical systems (MEMS) are typically used. There are many kinds of MEMS devices such as electrostatic sensors and actuators, piezoresistive sensors, piezoelectric actuators, and thermal actuators, but, in order to use MEMS devices, electrical circuits and a power supply are required. Although there are several methods for power supply to microdevices, light is preferable because they can transmit not only power but signals simultaneously for a long distance, which saves the area for signal transmission circuits.

One of the issues of employing light as a medium of power transmission is that a single photovoltaic (PV) cell is limited to 0.7 V (crystalline silicon) due to the physical property. One of the solutions to this issue is series connection of PV cells; however, the conventional methods are not compatible with a standard CMOS process. Modification in a standard CMOS process reduces the number of foundries which can accept fabrication; moreover, even if they accept, the cost is considerable.

To solve this issue, we have previously proposed an on-chip high-voltage silicon PV cell array. This array consists of mesa-isolated PV cells connected in series. It is fabricated by post-processing a silicon-on-insulator (SOI) wafer which is processed with a standard CMOS process. First, p-n junctions and metal wiring are formed on an SOI wafer by a foundry service. Then, each cell is mesa-isolated with an anisotropic plasma etching process followed by an isotropic plasma etching process. These processes forms mesa-isolated PV cells which are connected each other with suspended bridge structures. Because this technology is based on standard CMOS technologies, it ensures high reliability and quality of the cells. In addition, it does not require modifications of a standard CMOS process.

Our PV cell array has been demonstrated in the previous works. However, there still remains some issues when the PV cell array is applied to remote microdevices. Hence, this dissertation focuses on these issues and proposes solutions to them.

This dissertaion firstly addresses the design of the PV cell array. To employ the PV cell array in actual devices, it must be possible to design the array which has desired voltage and current. Presumably the output voltage is proportional to the number of series-connected cells, and the current is also confirmed to be proportional to the area of a p-n junction of a cell. However, it has not been confirmed that these laws hold in our PV array, and, even if they hold, the constants of the proportionality has not been measured. This dissertation demonstrates that the laws hold in the PV array, and shows that the constants of proportionality of output voltage and current are found to be 0.494 V/cell and 8.35 mA/cm^2 respectively under AM-1.5G illumination. In this dissertation, the required area of a PV cell array with certain voltage and current is discussed based on the extracted parameters, and it is found that, as a PV module with the higher voltage is designed, the larger area is required. The operation point for the particular types of devices and the method of increasing the efficiency of the PV cell array are also discussed.

Next, this dissertation addresses a design study of bypass diodes for this PV cell array. Series-connected PV cell array has the feature that the amount of its current is limited to that of the least-illuminated cell, thus a serious degradation of PV output power is caused even by a small dust on only one PV cell. To avoid this degradation, bypass diodes are commonly used for a large-scale PV cell module. However, unlike a large-scale PV cell module, the PV cell array concerned in this paper is based on standard CMOS technologies, meaning that PV cells and bypass diodes are on the same plane. Thus bypass diodes reduce the area of PV cells. In this dissertation, a trade-off between the areas of a PV cell and a bypass diode are discussed. To examine whether bypass diodes work in a microscale PV cell module and to experimentally extract the parameters of a bypass diode, bypass diode test structures are proposed. The experiments using the test structures proved a successful operation of bypass diodes even in a microscale PV module. It also revealed that the gap between cells and bypass diodes should be taken into consideration when the optimum area of a bypass diode in a microscale PV module is calculated. In the discussion, bypass diodes are compared with parallel PV arrays, and the suitability of bypass diodes to the particular types of devices is also discussed.

Then, this dissertation also demonstrates that our PV cell array has the ability to drive a MEMS actuator remotely. In this demonstration, 125-cell PV cell array and a MEMS comb drive actuator was employed. A laser beam which was emitted from the distance of 1.5 m successfully actuated the MEMS actuator, and it is proved that the PV cell array has the ability of driving a MEMS comb drive actuator. However, this experiment also showed that the PV cell array can only charge the actuator and cannot discharge it. Discharging is necessary for fast driving of MEMS comb drive actuator.

To resolve this discharge issue, this dissertation reports a PV cell array with discharging phototransistors. This PV cell array can drive an electrostatic MEMS actuator fast with wavelength-modulated light. In the circuit, a PV cell array and phototransistors are both connected to an electrostatic MEMS actuator in parallel. On the PV cell array and the phototransistors are green and red filters respectively. By changing the color of light, it can charge and discharge the MEMS actuator. Because the phototransistors are used instead of photodiodes, this discharge circuit has an advantage in compactness. In this dissertation, the experiments of demonstrating the system were conducted, and it is found that the proposed system can charge and discharge the actuator. The optimum area of the system and the maximum discharge frequency are also discussed.

This technology of wavelength-modulation light is found to be also useful for a high-voltage CMOS switch. In this dissertation, a high-voltage CMOS switch which can be used in a standard CMOS process was also proposed. The experiments demonstrated the switching successfully. Discussion on what kind of devices this high-voltage switch is suitable is done in the dissertation.

As a conclusion, this dissertation reports a robust on-chip-integrated high-voltage photovoltaic cell array and application to high-speed remote optical operation of MEMS actuators.