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Investigation on the factors to determine the efficiency of energy harvesting method with multilayered dielectric capacitors in temperature fluctuating environment

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Abstract

An energy harvesting method with dielectric film capacitors in temperature fluctuating environment and the ways to improve the efficiency were investigated. It was experimentally demonstrated that the enhancement of both capacitance and temperature dependence of flat-band voltage can increase the variation of charge stored on capacitors induced by temperature change. The efficiency would be improved by utilizing both of the temperature-induced change of interface dipole layer strength and that of the amount of trapped charges in dielectrics. The guideline to design the suitable dielectric stack for the proposed energy harvesting method is discussed.

1. Introduction

The energy harvesting method with dielectric film capacitors in temperature fluctuating environment uses the variation of charges stored on capacitors caused by both the temperature-induced variation of interface dipole strength and trapped charges in dielectric films and at their interfaces (Fig. 1). The energy harvesting efficiency would be improved by the design of dielectric materials. We have reported that interface dipole strength for high-k/SiO_2 and high-k/high-k interfaces changes with temperature [1][2]. This phenomenon, as well as the change of trapped charge density, can be interpreted as polarization strength change in dielectric film capacitors with temperature change which is quite a similar with the pyroelectric effect [3]. In this study, the relationship between the measured variation of charge stored on capacitors induced by temperature change and the one expected from the observed temperature dependence of flat-band voltage (V_{FB}) was investigated to see the validity of this energy harvesting method.

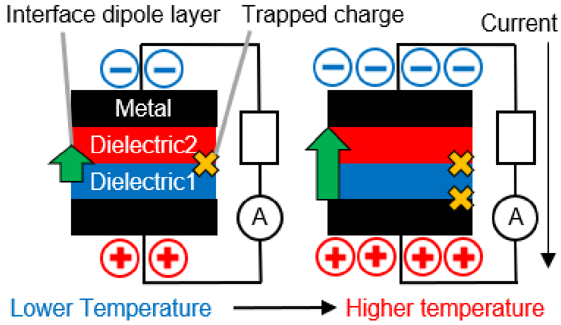

Fig.1. Schematics of the variation of charge stored on capacitors induced by the temperature change, due to the temperature-dependence of the interface dipole layer strength and that of the amount of trapped charges in the stack.

2. Experimental methods

The MOS capacitors with two kinds of dielectric stacks were fabricated as shown in Fig. 2(a): (i)SiO_2 and (ii)Al_2O_3/SiO_2. These layers were deposited on p-Si substrates, by thermal oxidation for bottom-SiO_2 while rf-sputtering for Al_2O_3 layer. Post-deposition annealing in 0.1% O_2 ambient was done at 800°C after Al_2O_3 deposition. Finally, Al was deposited as the gate electrode. The 1MHz C-V characteristics at several temperatures from 24°C to 54°C were measured to determine the temperature dependence of V_{FB}. QSCV characteristics at room temperature were employed to determine the capacitance in short circuit condition (C_{0V}).

Fig. 2(b) shows the schematic diagram of the system to measure the displacement current of MOS capacitor under temperature fluctuation. The gate electrode was connected to a femtometer while with the bottom electrode grounded. Temperature was monitored by thermocouples set nearby the capacitor, which was intentionally fluctuated by heating the metal box surrounding the capacitor with a hair dryer.

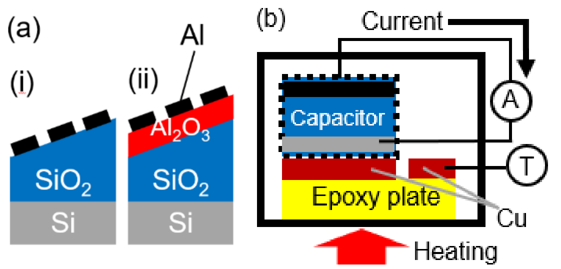

Fig.2. (a) Sample structures employed in the demonstration of the observation of displacement current. (b) Schematic of the system to measure the displacement current and temperature of MOS capacitors.

3. Results and Discussions

When the temperature of a short-circuited MOS capacitor changes, the charges stored on the capacitor flow to the external circuit to cancel out the variation of V_{FB} induced by temperature change. For example, the area density of charges flowing from a capacitor during its temperature rising from 24°C to 54°C is expected to be $C_{0V}\times\Delta V_{FB}^{T}$, where ΔV_{FB}^{T} is the subtraction of the V_{FB} at room temperature from the one at 54°C. On the other hand, the measured area density of charges flowing from a capacitor induced by temperature change (ΔQ) is given by the integral of the displacement current density with respect to time. Changes over time of displacement current density flowing from the capacitor (i) and its temperature are shown in Fig. 3, as an example. ΔQ during the temperature of this capacitor rising from 24°C to 54°C is equal to the area within the broken line in Fig. 3. The relationship between ΔQ and $C_{0V}\times\Delta V_{FB}^{T}$ for several samples (i) and (ii) is shown in Fig. 4. The coincidence in the order of magnitude between the measured variation of charge stored on capacitors induced by temperature change and the one expected from the observed temperature dependence of V_{FB} indicates the validity of the proposed energy harvesting method.

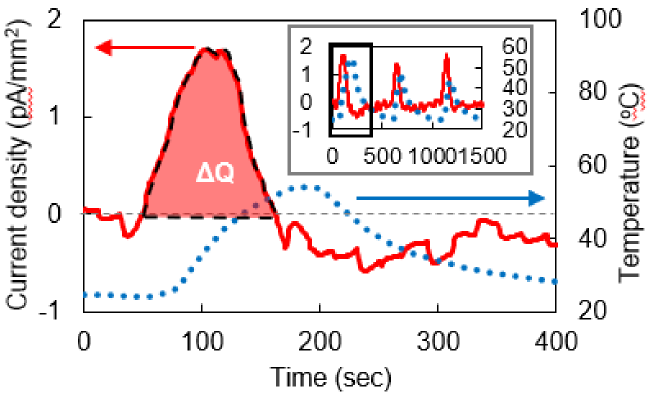

Fig.3. Time-dependent change of the displacement current density (solid line) flowed from capacitor (i) Al/SiO2(58nm)/Si, and the temperature (dotted line) measured by the thermocouple. The current density is represented after eliminating the background noise level current.

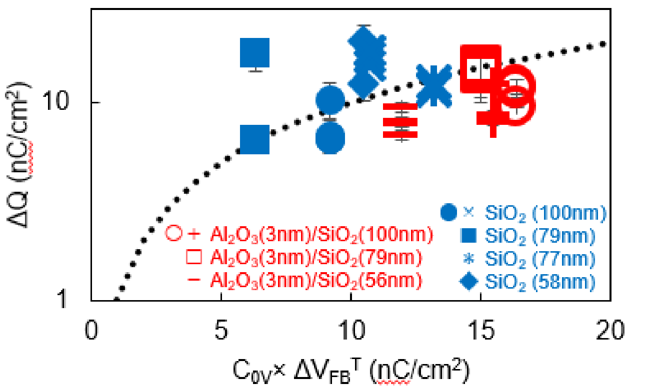

Fig.4. The variation of charge (ΔQ) observed during temperature increasing from 24°C to 54°C for the capacitors (i) Al/SiO2(58~100nm)/Si and (ii) Al/Al2O3(3nm)/SiO2(56~100nm)/Si. The dotted line shows the ideal ΔQ determined as $C_{0V}\times\Delta V_{FB}^{T}$.

Based on the considerations so far, the enhancement of temperature dependence of V_{FB} is the crucial factor to improve the energy efficiency of energy harvesting proposed in this study, as well as the capacitance of the stack (C_{0V}). For the capacitors with multilayer dielectrics, it is expected that ΔV_{FB}^{T} would be enhanced by increasing the number of stacked dielectric layers, thanks to the increase of number of interfaces forming both the interface dipole layers and the trapped charges. The change of interface dipole layer strength by temperature has been already experimentally demonstrated [2], and it is also naturally expected that the amount of trapped charges at the interface gradually changes by temperature. However, a critical difference is expected in the impact on ΔQ ~ $C_{0V}\times\Delta V_{FB}^{T}$ between the variation of interface dipole layer strength and that of interface trapped charge density. For the case of bilayer dielectrics for example, the expected ΔQ by the former would be enhanced by decreasing the capacitance equivalent thickness (CET) as schematically shown in Fig. 5 (a), while ΔQ by the later would not be influenced by CET. On the other hand, when the number of interfaces increase without changing each layer thickness as another example, ΔQ by the variation of trapped charge density should be proportional to the number of dielectric interfaces assuming the trapped charges exist just at the interfaces as shown in Fig. 5 (b), while ΔQ by the variation of interface dipole layer strength is not affected by the number of interfaces. These considerations give a guideline to design the dielectric stacks suitable for the proposed energy harvesting method.

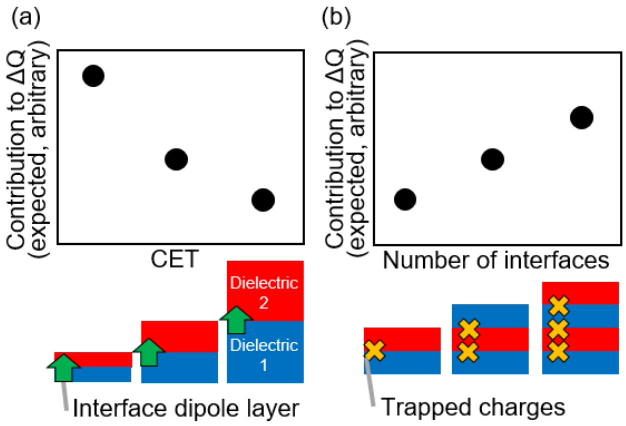

Fig. 5. (a) Expected relationship between contribution to ΔQ of the variation of interface dipole layer strength and CET of the bilayer dielectrics. (b) Expected relationship between contribution to ΔQ of the variation of interface trapped charge density and the number of interfaces without changing each layer thickness as another example.

4. Conclusions

Energy harvesting method with capacitors in temperature fluctuating environment and the methods to improve the efficiency were proposed. The coincidence in the order of magnitude between the measured variation of charge stored on capacitors induced by temperature change and the one expected from the observed temperature dependence of V_{FB} indicates the validity of the proposed energy harvesting method. The efficiency would be improved by utilizing a multilayer dielectrics with the multiple interfaces, which is expected to show the temperature-induced change of interface dipole layer strength and that of the amount of trapped charges.

Acknowledgements

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References

[1] T. Hamaguchi, S. Nittayakasetwat and K. Kita, 2018 International Conference on Solid State Devices and Materials (SSDM), Tokyo, September 9-13, 2018.

[2] S. Nittayakasetwat and K. Kita, J. Appl. Phys. **125**, 084105(2019)

[3] C. R. Bowen et al., Mat. Lett. **138** (2015) 243-246.