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Effects of Thermal Effusivity in Nanocrystalline Porous Silicon on Long-Term Operation of Thermally Induced Ultrasonic Emission

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1. Introduction

Due to complete carrier depletion in strongly confined nanocrystalline porous silicon (nc-PS), its thermal conductivity α and heat capacity per unit volume C are extremely lowered in comparison to those of single-crystalline silicon (c-Si). Utilizing this high contrast in the thermal constants between nc-PS and c-Si, ultrasonic wave can be generated at the nc-PS surface via thermo-acoustic effect with no mechanical vibrations [1]. To confirm the theoretical expectation that the acoustic output of this device is inversely proportional to the thermal effusivity $(\alpha C)^{1/2}$ in the nc-PS layer, the correlation between the acoustic output and the $(\alpha C)^{1/2}$ value is reported here in terms of practical long-term operation.

2. Experimental

The experimental device is composed of an nc-PS layer, a thin film heater electrode, and a c-Si substrate. The nc-PS layer was prepared by anodization of p-type (100) c-Si substrate (80-120 Ωcm) in an ethanoic solution of 50 wt% HF at a current density of 100 mA/cm^2. After anodization, a thin metal film heater (50 nm thick) and aluminum pads were deposited onto the nc-PS layer surface by RF sputtering. The heater electrode size corresponding to the ultrasonic emission area is 5×5 mm^2.

The acoustic output amplitude was measured under a sinusoidal half-wave electrical input (a pulse width: 16 μs; peak amplitude: 90 V) by a microphone located at a distance of 30 cm from the device surface. As previously reported [2], this device operates well for pulse drive. To accelerate the aging effect, the nc-PS device was kept in a high temperature and wet air ambience (85 °C and 85 %) for 0-100 h. The $(\alpha C)^{1/2}$ values in the nc-PS layer were determined in various stages of operation by the thermo-reflectance method based on the photo-thermal modulation technique [3] as shown in **Fig. 1**. As related information, the evolution in the porosity and pore-size distribution of the nc-PS layer were measured separately by the gas adsorption technique, including the surface chemical analysis by Auger electron spectroscopy (AES).

3. Results and discussion

In **Fig. 2** the acoustic amplitude measured before aging is plotted by the dashed line as a function of the input peak power. The result is consistent with the theoretical implication [1], in which the acoustic output P is represented by $P=Aq/(\alpha C)^{1/2}$, where A and q are the thermal constant of emitting medium (air in this case) and the input power, respectively. In this figure, the theoretical output estimated from the measured $(\alpha C)^{1/2}$ value (640 Jm^{-2}s$^{-1/2}$K^{-1}) is also shown by the solid line. It coincides well with the experimental result.

The observed acoustic pressure amplitude at an input peak power of 1.4 kW is shown in **Fig. 3** by the dashed curve as a function of the aging time. The sound pressure decreases to 80 % of the initial value at about 100 h. The behavior of $(\alpha C)^{1/2}$ is also shown in this figure by the solid curve. Obviously the deterioration in the acoustic output properly corresponds to the increase in $(\alpha C)^{1/2}$ as expected from theoretical analysis.

To investigate the origin of the increase in $(\alpha C)^{1/2}$, the change in both the porosity and the relative surface chemical contents of the nc-PS layer are shown in **Fig. 4**. It looks that the porosity decreases upon aging process in high temperature and wet air due to a volume expansion of nanocrystalline silicon associated with surface oxidation. This is also supported by observation of the structural change. As indicated **Fig. 5**, the nanoporous structure tends to disappear with increasing the aging time. The effective space of nanopore region is significantly decreased with time. At 100 h, the relative volume becomes 50 % of the original value. Both the decrease in the effective nanopore space and the formation of nanosilicon-oxide composite causes an increase in α and C. The consequent increase in $(\alpha C)^{1/2}$ influences the efficiency of thermo-acoustic conversion at the nc-PS surface.

4. Conclusion

It has been shown by nanocharacterization studies that the thermal effusivity of the nc-PS layer is the most important determining factor for the long term stability of ultrasonic emission. Appropriate combination of nanostructural control and anti-oxidation treatment prior to operation would make it possible to develop the device with a practical life.

References

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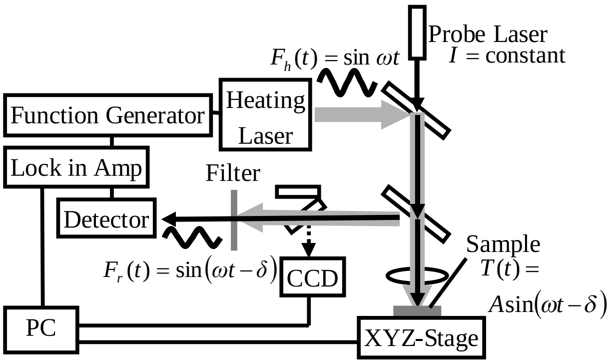

Fig. 1. Schematic diagram of the thermal effusivity measurement system on a basis of thermoreflectance technique.

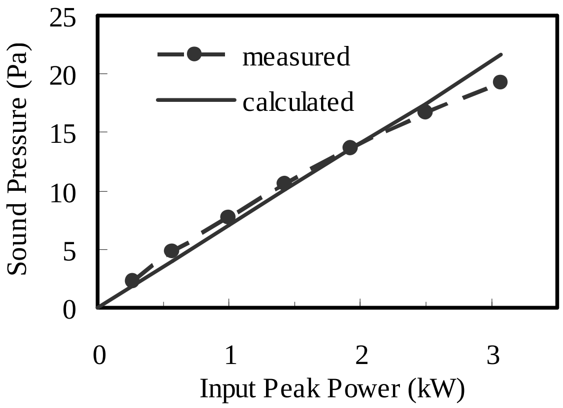

Fig. 2. Experimental and theoretical relationships between the output sound pressure and the input peak power (note that the input mean power is the order of 100 mW). The theoretical sound pressure is calculated using the thermal effusivity value of nc-PS layer measured at the initial stage.

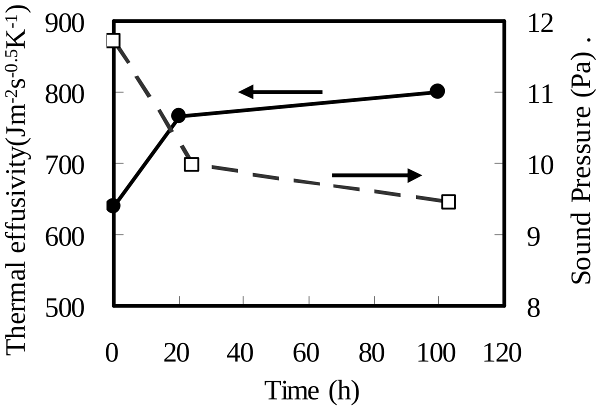

Fig. 3. Change in the thermal effusivity and the acoustic output with time of aging in air ambience at a humidity of 85% and a temperature of 85°C.

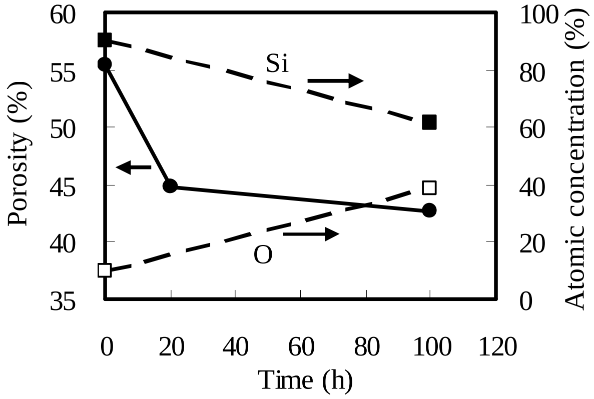

Fig. 4. Time evolution of the porosity and the surface chemical composition of the nc-PS layer. The relative atomic content was estimated from AES analysis.

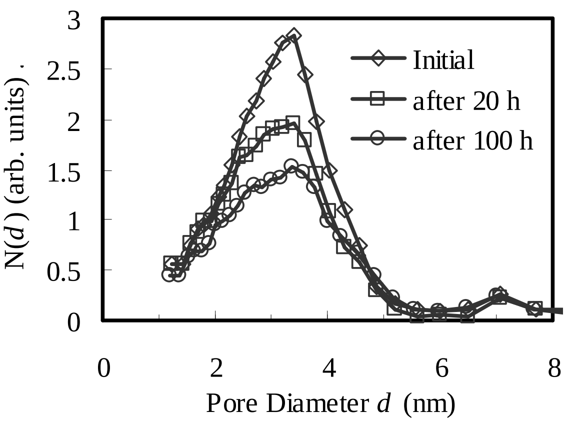

Fig. 5. Change in the pore-size distribution of nc-PS layer with time upon aging in air ambience under the same condition as Figs.3 and 4.