Extended Abstracts of the 2005 International Conference on Solid State Devices and Materials, Kobe, 2005, pp.790-791

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Dynamic Analyses of Thermally Induced Ultrasonic Emission from Nanocrystalline Silicon

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1. Introduction

As previously reported [1-3], efficient ultrasonic emission can be obtained from nanocrystalline porous silicon (nc-PS) layers without any mechanical surface vibrations. This is based on an extremely high contrast in the thermal properties between nc-PS and single crystalline silicon (c-Si). Due to a complete thermal insulating property of nc-PS, temperature fluctuations induced by an electrical ac input at the surface is quickly transferred into air as a sound pressure.

To understand the mechanism of this thermo-acoustic effect in more detail, dynamic thermal analyses have been conducted taking the heat capacity of the surface heater electrode into account. The experimental data of the transient thermal behavior at the device surface are presented here including theoretical considerations.

2. Experiment

The schematic illustration of the cross-sectional view and the top-view of the fabricated device are shown in **Fig. 1**. The device is composed of an nc-PS layer, a thin film heater electrode, electrical pads, 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 tungsten film heater (50 nm thick) and aluminum pads were deposited onto the nc-PS layer by RF sputtering. The heater size corresponding to the ultrasonic emission area is 5×5 mm^2.

The electrical signal of a sinusoidal half-wave with a pulse width of 16 μs was introduced into the heater electrode. A transient temperature change at the heater induced by Joule heating was measured with a high-speed radiation thermometer at a sampling time of 0.8 μs. The emissivity of the tungsten heater electrode used here was 0.092. The emitted sound pressure amplitude was measured by a microphone located at a distance of 30 cm from the device surface.

3. Results and discussion

A typical result of the detected temperature change at the central part of the heater electrode is shown in **Fig. 2** together with an electrical input signal. We can see that the temperature quickly changes fairly in response to the electrical input. The observed delay is due to the overall heat capacity of this device. Associated with this temperature change, a significant acoustic pulse was also detected with no reverberations.

In the actual device operation as ultrasonic emission, it is important whether or not the induced temperature change is uniform. **Fig. 3** shows the distribution of peak temperature measured along the central line of the heater electrode. Obviously the heater temperature changes uniformly over the whole range of the emission area. This high spatial uniformity reflects a sufficiently small thermal diffusion length in the nc-PS layer. This result allows us to discuss the thermo-acoustic transfer process at the device surface under the condition of a uniform temperature change as follows.

Taking the heat capacity of the heater electrode into account, the relation between the surface temperature fluctuations and the sound pressure amplitude is given by

$$\Delta T = \frac{P}{A\left(\sqrt{\frac{2\pi}{t}} + \frac{2\pi}{t}\frac{C_h L}{\sqrt{\alpha C}}\right)} \quad (1)$$

$$A = \sqrt{\frac{\gamma \alpha_A}{C_A}}\frac{P_A}{vT_A} \quad (2)$$

where ΔT, P, α, C, t ,C_h and L are the transient surface temperature change, the induced sound pressure amplitude, the thermal conductivity of nc-PS, its heat capacity per unit volume, the input pulse width, the heat capacity per unit volume of the heater, and its thickness, respectively. The constants v, α_A, C_A, P_A and T_A are the sound velocity, the thermal conductivity and the heat capacity per unit volume of air, the atmospheric pressure and the room temperature, respectively. The γ value is the specific heat ratio c_P/c_V=1.4.

The measured and calculated ΔT values are shown in **Fig. 4** as a function of P. The experimental data exhibit a linear behavior as expected from Eq. (1). Also, as shown by the solid and dashed lines, the introduction of the heat capacity leads to a realistic interpretation of the

device characteristics, in comparison to the case of conventional calculation.

4. Conclusion

It has been shown that in the nc-PS thermo-acoustic emitter, the heat transfer uniformly occurs at the device surface, and that the transient acoustic output behavior coincides well with that expected from theoretical calculation. The present results are very useful for development of efficient and functional emitter.

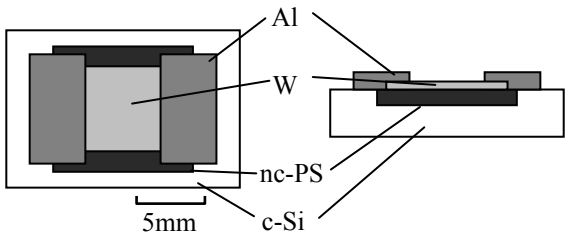

Fig. 1. Schematic illustration of fabricated nc-PS device (left : top view, right : cross-sectional view).

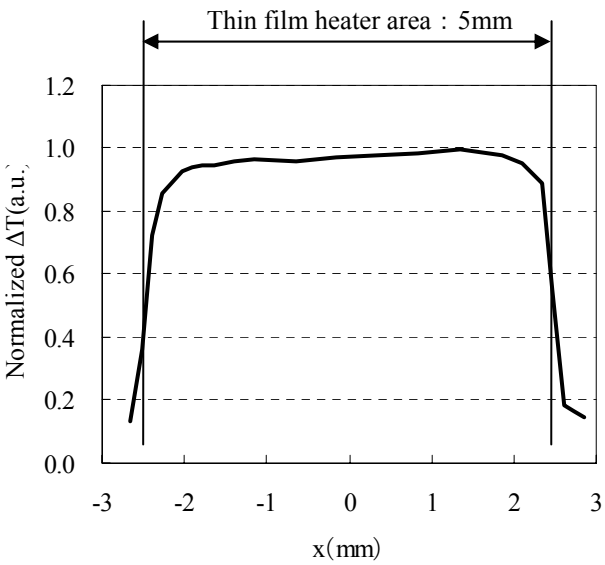

Fig. 3. Normalized spatial distribution of the temperature change of thin film heater electrode along the central line of the device shown in Fig. 1..

References

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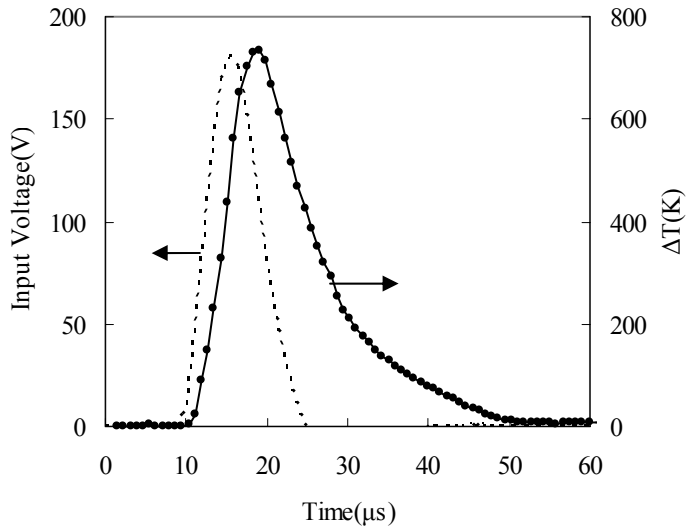

Fig. 2. Measured dynamic response of heater temperature change for a pulsed input voltage represented by dashed curve.

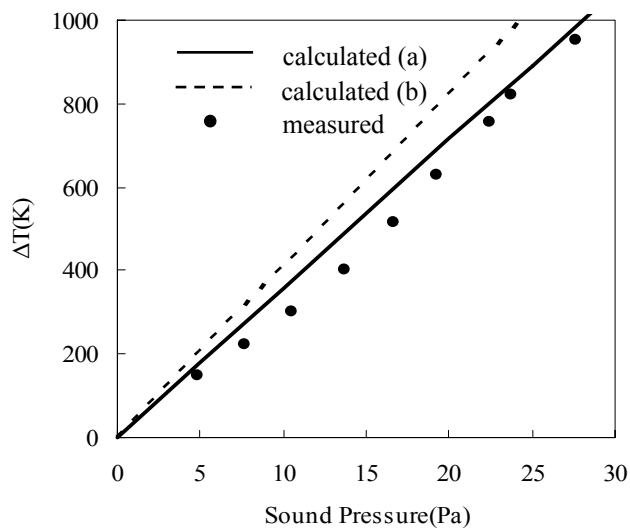

Fig. 4. Experimental and theoretical relationship between the heater temperature change and the output sound pressure. The heat capacity of the heater electrode is involved (solid line: a) and excluded (b) in the calculation.