Extended Abstracts of the 2007 International Conference on Solid State Devices and Materials, Tsukuba, 2007, pp. 1140-1141

I-10-5

Acoustic Wave Manipulation by Phased Operation of Two-Dimensionally Arrayed Nanocrystalline Silicon Ultrasonic Emitters

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1. Introduction

The excellent thermal conductivity of single-crystalline silicon (c-Si) is one of the most important factors for actual device applications. In strongly confined silicon nanomaterials such as porous silicon (PS) and nanosilicon dot, both the thermal conductivity and the heat capacity per unit volume are extremely lowered in comparison to those of c-Si due to complete carrier depletion. As reported previously [1], an extremely big contrast in the thermal constants between PS and c-Si is utilized to generate ultrasonic wave based on thermal exchange from the PS surface into air with no mechanical vibrations.

To make the best use of the advantageous property of this silicon-based PS emitter that the acoustic output shows little distortion in a wide frequency region [2-4], phased operation scheme has been applied to two-dimensionally arrayed PS emitters. The fundamental characteristics are reported here in terms of the controllability of the emission direction.

2. Experimental

The experimental 3×3 emitter arrays were fabricated on a p-type (100) silicon wafer (the resistivity: 3～5 Ω cm) by using a masking technique. The devices are arranged with a spacing of 6.8 mm as shown in **Fig. 1**. The device unit (2×2 mm^2 in the ultrasonic emission area) is composed of a PS layer, a thin film heater electrode, and a c-Si substrate. The PS layer was prepared by electrochemical anodization of a substrate in an ethanoic solution of 50 wt% HF at a constant current density of 20 mA/cm^2 for 20 min. After anodization, a thin tungsten film heater (50 nm thick) was deposited by RF sputtering onto the nc-PS layer surface followed by the deposition of Al pads.

The experimental configuration is illustrated in **Fig. 2**. The angular dependence of the acoustic output of a frequency 25 or 50 kHz was measured by a microphone located at a distance of 4 cm from the central device surface under a cw sinusoidal electrical input. At first, the emission directivity of the single device was measured for the central emitter. The arrayed nine devices were driven by synchronous or phase-shifted input signals. The observed acoustic output and its directivity were compared to the theoretical estimation.

3. Results and discussion

In **Figs. 3 (a)** and **(b)**, the spatial contour mapping of the measured acoustic output amplitude at 25 kHz are shown for a single device and arrayed device, respectively. In this case, the synchronous input mode was employed for driving. It can be seen that the overall acoustic output in the arrayed device is significantly enhanced owing to the superimposed effect.

The operation mechanism of this device is based on the thermal exchange at the heater electrode surface, where the temperature fluctuates uniformly over the whole range of the emission area. This high spatial uniformity reflects a complete thermal isolation property of the PS layer. So the emission directivity can be estimated from a piston resonator model [5]. In fact, the enhancement factor of 17 dB observed in Fig. 3 coincides well with the expected value.

The emission directivity for a 3×3 emitter array device measured under the synchronous input mode is shown in **Fig. 4** by open plots. The output frequency is 25 kHz in this case. As a result of superimposed effect, the directivity is amplified compared with that in the single device. The behavior of the directional emission is explained well by the estimation as shown by the solid curve. The theoretical expectation that the directivity becomes more unidirectional with increasing the output frequency has also been confirmed by the experimental analyses.

When the arrayed device is driven under the phased input mode, the acoustic output direction can be tuned three dimensionally. As a typical example, the measured emission directivity is shown by open plots in **Fig. 5**, in which the phases of input signals are shifted such that the unidirectional emission is generated with an oblique angle of 45° with respect to the x-axis in Fig. 2. In comparison with the estimation curve, we can see that the acoustic wave is manipulated as designed. The directional dispersion could be further decreased with increasing the spatial density of arrays.

4. Conclusion

By the use of the phase-shift drive for the PS ultrasonic emitter arrays, the acoustic output is significantly enhanced, and the emission directivity can be controlled with a sufficient resolution. The arrayed devices are useful as functional ultrasonic emitter.

This work was partially supported by a Grant-in-Aid for Scientific Research on Priority Area (No.18063007) from the Ministry of Education, Culture, Sports, Science, and Technology in Japan and for Scientific Research A (No. 18206039) from Japan Society for the Promotion of Science.

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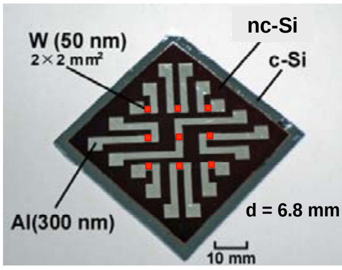

Fig. 1. Photograph of a fabricated 3×3 PS ultrasonic emitter array.

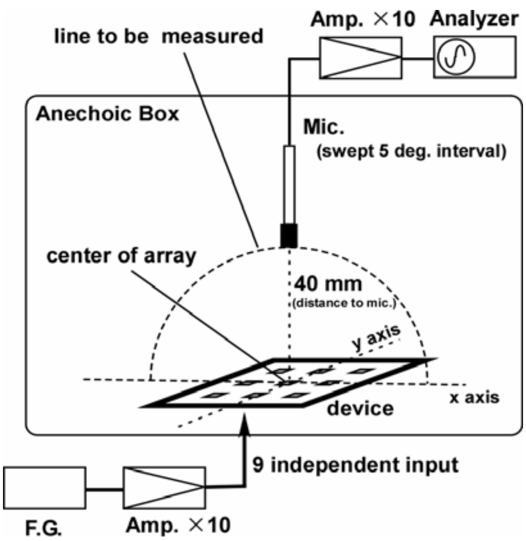

Fig. 2. Experimental configuration of 3×3 arrayed ultrasonic emitters and system for measurement of emission directivity.

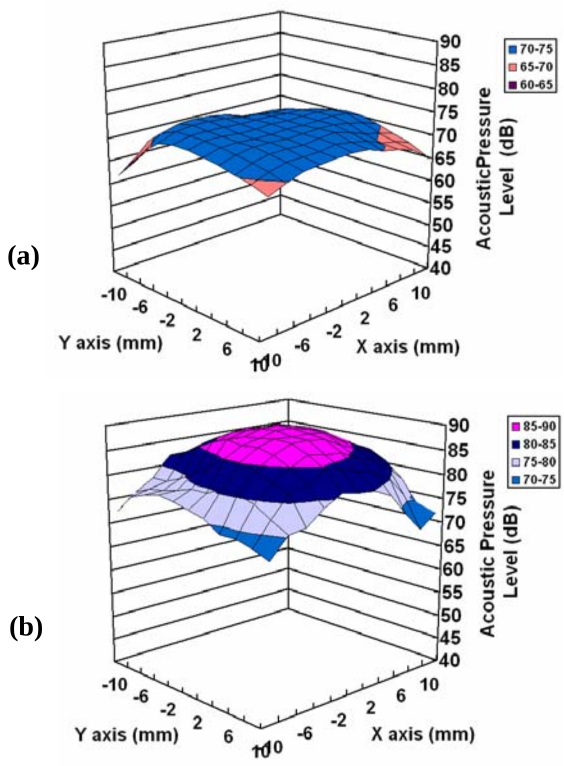

Fig. 3. The contour mapping of the acoustic output at 25 kHz for a single device (a) and arrayed one (b) operated under a synchronous input drive.

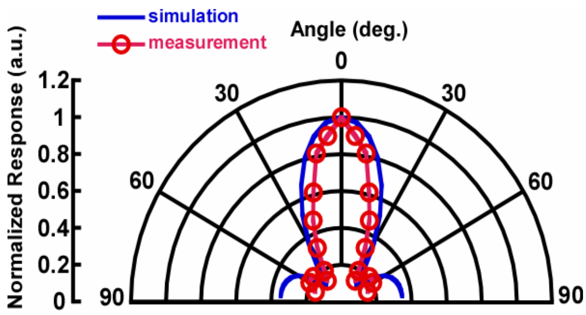

Fig. 4. The emission directivity of the acoustic output at 25 kHz for a 3×3 emitter array device driven under a synchronous input mode.

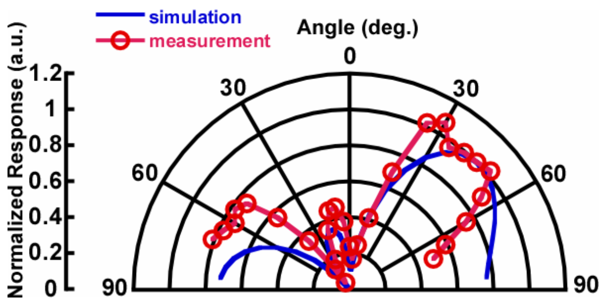

Fig. 5. The emission directivity of the acoustic output at 25 kHz for a 3×3 emitter array device driven under a phase-shift input mode.