Extended Abstracts of the 2008 International Conference on Solid State Devices and Materials, Tsukuba, 2008, pp. 1104-1105

H-10-3

Sound Emission from Nanocrystalline Silicon Device under Operation of Electroluminescence

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1. Introduction

Crystalline silicon (c-Si) is the preferred semiconductor in many applications due to its low cost, VLSI compatibility and the fact that it is neither toxic nor pollutant. This desirable feature is further amplified by introducing quantum confinement effect into c-Si. A typical effect induced in the strongly confined system is a significant bandgap widening. It leads to stable and efficient visible luminescence as observed in nanocrystalline porous Si (PSi)[1,2) Efficient electroluminescence (EL) has also been demonstrated[3)]. Its stability has been recently much improved.[4)]

In addition to light emission, the quantum confinement in PSi enables other new useful functions for Si. For instance, 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. These very low thermal constants have been taken advantage of in order to generate ultrasonic (US) wave based on thermal exchange from the PSi surface into air with no mechanical vibrations.[5)]

In this paper, it is reported that the acoustic and optical device operation can be combined in a single device, and that the fabricated device is capable of generating both EL and US waves, either individually or simultaneously.

2. Experimental

PSi layers were formed from n^+-type Si (100) by anodization in HF electrolyte. A 400 nm thick compact PSi layer is formed first to enhance the contact between the top contact and the underneath light-emissive PSi layer formed later on. The total thickness of the nc-Si layer is about 8 μm. Electrochemical oxidation of the PSi layer is then carried out in a way that was previously reported. [3)]

Figure 1(a) shows the configuration of the top contact and operation of the device. First, a thin semitransparent gold layer is deposited onto PSi by sputtering. EL is obtained by applying a voltage between the thin gold film and the back contact. Furthermore, two tungsten pads are evaporated as shown in Fig. 1(a). US wave generation is achieved by applying an ac signal to the gold layer via these two tungsten pads. Here, the thin gold film plays the role of a heater electrode.

US output was measured using a microphone, as shown in Fig. 1(a). EL was detected using a photomultiplier tube. In order to acquire simultaneously EL and US waves, the configuration shown in **Fig.1(b)** was used.

3. Results and Discussion

The device can be operated as an EL emitter only by applying a voltage to a top contact with respect to the c-Si substrate. The diode generates efficient EL mostly under reverse bias as previously reported.[3)] A voltage V_{EL} of -10 V is enough to get EL visible by naked eye in room lighting.

When operated as an US emitter alone, an ac signal was applied to the gold film and US waves were recorded by a microphone. A significant US signal with no distortion was observed for an ac electrical input at ultrasonic frequencies as reported previously.[5)]

In order to assess the ability of the device to operate simultaneously as an EL and US emitter, the same ac input was applied to the gold film and a voltage V_{EL} of -10 V was applied between the gold film and the substrate. The resulting US output signal at 50 kHz is shows in **Fig. 2(a)**. It has been confirmed that the US output in a whole range of frequency under study is not affected by the additional EL operation as shown in **Fig. 2(b)**.

Figure 3 shows the EL spectra obtained at V_{EL}=-10 V, with or without simultaneous US operation. The EL intensity is somewhat diminished by the US operation due to its thermal effect, but the spectrum shape remains identical and the peak wavelength does not change. This result shows that the EL is not fundamentally changed by the additional US operation.

Both EL and US emission can be excited by pulse driving. Due to the flat response of the US emission versus excitation frequency, digital processing is available for the US component from about 1 GHz down to about 10 kHz. The EL response is mostly limited by the radiative lifetime in Si nanocrystals. The current state of the art of the EL emission put the upper limit at about 100 kHz[6,7)]. The US operation is compatible with the EL emission mode in both the analog and digital drive.

4. Conclusions

We have shown that the two functions of PSi, EL and US wave generation, can be obtained either individually or simultaneously from a single device with no significant affect on the respective performances. This result represents an important step towards monolithic functional integration. Optical and acoustic digital processing is potentially available in this device.

Acknowledgements

This work has been partially supported by a Grant-in-Aid for Scientific Research from JSPS and MEXT, and by SORST Program from JST.

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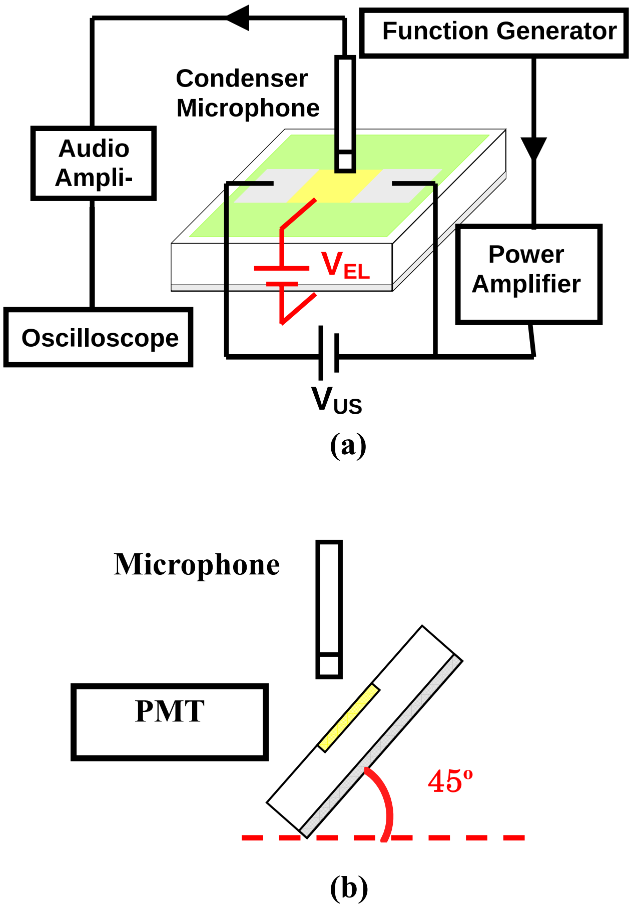

Fig. 1. (a): Configuration of the device structure and the operation as an EL emitter and/or as an US emitter. This arrangement is used to measure the US emission alone. (b): Configuration of the device, microphone and photomultiplier tube (PMT) for simultaneous measurement of EL and US emission.

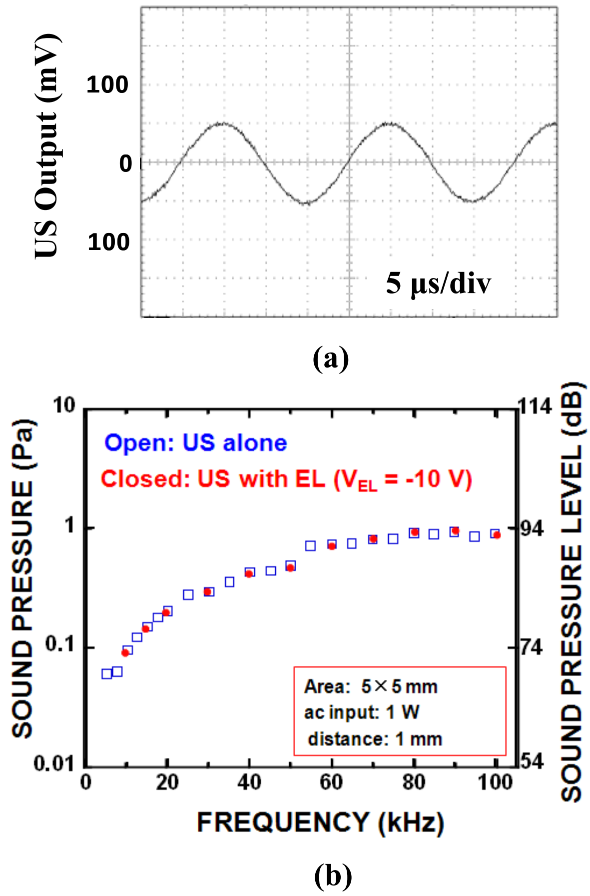

Fig. 2. (a): US output for a sinusoidal input at a power of 1 W under the EL operation at V_{EL}=-10 V. Both the output amplitude and frequency are not affected by the EL emission. (b): Frequency characteristics of the acoustic output emitted from the device with (closed plots) and without (open plots) EL operation.

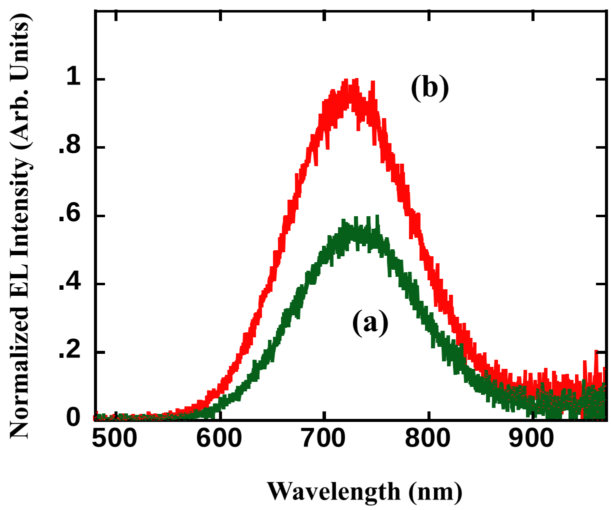

Fig. 3 Normalized EL spectra obtained under V_{EL}=-10 V with (a) or without (b) simultaneous US operation.