Ultrasonics 57 (2015) 84–89

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

Ultrasound radiation from a three-layer thermoacoustic transformation device

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ARTICLE INFO

Article history:
Received 23 June 2014
Received in revised form 23 October 2014
Accepted 24 October 2014
Available online 10 November 2014

Keywords:
Broadband
Thermoacoustic transformation
Thermophone
Three-layer structure
Ultrasound emission

ABSTRACT

A thermophone is a thermoacoustic transducer, which generates sound via time-varying Joule heating of an electrically conductive layer, which leads to expansion and contraction of a small pocket of air near the surface of the film. In this work, a 10-μm-thick Ag–Pd conductive film was coupled with heat-insulating and heat-releasing layers to fabricate a three-layer thermophone for generating ultrasound. The heat-insulating layer was 47 μm thick, and was made of glass. The heat-releasing layer was 594 μm thick, and was made of 94% alumina. Because of the simple sound-generation mechanism, which does not require mechanical moving parts, the Ag–Pd conductive film on the glass substrate can produce ultrasound radiation with broadband frequency characteristics, where exiting commercial electrode materials were used. We also demonstrate that the measured directivity patterns are in good agreement with theoretical predictions, assuming a rectangular diaphragm with the same size as the metallic film.

1. Introduction

The first thermophones were introduced in the early 20th century as electric-sound transduction devices [1–3]. The prototype thermophone was a single-layer structure consisting of a metallic thin film, and the sound was emitted from both the front and back surfaces [4]. In 2008, Xiao et al. reported carbon nanotube (CNT) loudspeakers in air [4] and water [5], and demonstrated capacity for generating sounds with a high pressure level (SPL), i.e., the SPL at 10 kHz was approximately 90 dB SPL at a 5 cm from the loudspeaker. Other researchers have since demonstrated that using graphene and graphite as an electrically conductive layer, thermophones can be produced in a flexible format based on the thermoacoustic effect [6–10]. Then Niskanen et al. [11] and Vesterinen et al. [12] demonstrated a suspended metal wire array which could produce an SPL of 110 dB at 8 cm and at 40 kHz [11]. In their device, the air surrounding the wire acted as a heat-insulating layer. More recently, Daschewski et al. [13] demonstrated that the theoretical predictions of the SPL were in good agreement with the measurements generated by a thermophone using a laser vibrometer at frequencies up to 1 MHz.

A thermophone generates sound waves based on the surface heat of an electrically conductive layer. When an alternating electric current is applied to a metallic thin film with a given resistance, the temperature of the film surface varies due to time-varying Joule heating. This reads to expansion , and contraction of a small pocket of air near the metal film, which generates sound waves [1]. Because the sound generation mechanism of a thermophone is based on heat, and does not include resonance phenomena, nor mechanical moving parts, it can provide broadband frequency characteristics. Conventionally, narrow-band piezoelectric devices with resonance characteristics have been used as transducers for object detection in air. However, high time resolution and broadband frequency information are required for ranging and detecting object shapes with high precision, suggesting that the broadband characteristics of thermophones have potential application in ultrasound radiation devices. One problem for practical application of thermophones, however, is that the energy conversion efficiency is lower than that of commercial piezoelectric

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http://dx.doi.org/10.1016/j.ultras.2014.10.019
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devices. To address this problem, Shinoda et al. developed a thermophone with a three-layer structure in 1999 [14]. They used a nanocrystalline porous silicon as substrate because the conversion efficiency depends on thermal effusivity of the second layer of the thermophone [15–17].

In this study, we fabricated a new type of three-layer thermophone composed of an insulating layer (glass) and a heat-releasing layer (alumina) on the back of a metal thin film. This work is a collaboration with the electric component manufacturer *Murata Manufacturing Co., Ltd.*, and we investigated a new thermophone device for applications in ultrasonic sensing which requires a high resolution in a close range. Existing technologies for practical and inexpensive fabricating process were used, and the thermophone device can produce ultrasound using a material system that is already established. We described the relationship between the generated SPL and the working frequency, and also report the directivity pattern and frequency characteristics.

We manipulated the materials composition to achieve ultrasound generation with a three-layer structure, within the range tolerated by existing fabricating process used for mass production. Therefore, we examined the internal structure of each layer using scanning electron microscopy (SEM) to investigate the thickness of the three layers, and characterized the physical properties of each layer: the data can be subsequently used for theoretical investigations.

2. Sound radiation mechanisms of the thermophone

Fig. 1 shows pictures of the thermophone developed as part of this work. For the acoustic measurements, the thermophone was placed in the center of the polymer backing material (Duracon). Fig. 2(a) shows the detailed structure of the thermophone with the metallic thin film (2×3 mm^2) placed on the base material (4×5 mm^2). This design is smaller than has previously been reported for thermoacoustic transducers [1–8,11–21]. Fig. 2(b) shows a cross-sectional view of the thermophone showing the heat-insulating and heat-releasing layers on the back surface of the metallic thin film. The heat-insulating layer insulates the alternating current (AC) component of the Joule heating generated on the metallic thin film, while allowing the direct current (DC) component to propagate. The DC component of the Joule heating is then released into the heat-releasing layer at the back of the thermophone [14]. The electrical current input to the electrode induces surface temperature changes via Joule heating, ultimately giving rise to an acoustic wave. In other words, input electric power is converted into the sound.

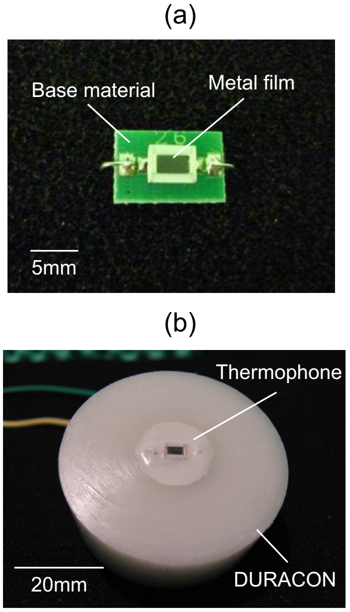

Fig. 1. (a) The size of the thermophone is 4×5 mm^2 and the radiated ultrasound space (metallic thin film) is 2×3 mm^2. Both sides of the electrode are used to send current. (b) The thermophone is embedded in Duracon backing with a diameter of 52 mm. This is used for directive measurement.

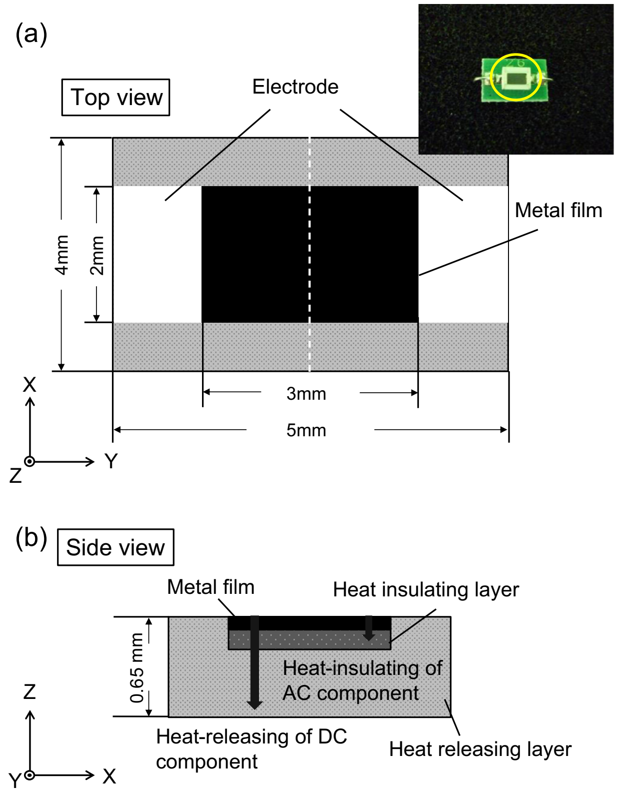

Fig. 2. (a) Top view of the thermophone: the dotted red line (*xz*-plane) is the break line. (b) Cross-sectional view (*xz*-plane) of the thermophone, showing the role of each layer. The heat-insulating layer insulates the AC component of the Joule heat generated on the metallic thin film, while the releasing layer releases the DC component of the Joule heat. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

When an AC current, $i = I_m \sin 2\pi f_0 t$, is supplied to the metallic thin film, Arnold [1] expressed the temperature (T) of a small pocket of air near the surface of the film as follows:

$$0.24(I_m \sin 2\pi f_0 t)^2 R = 2a\beta T + a\gamma \frac{dT}{dt} \tag{1}$$

where R is the resistance of the metallic think film, a is the area of the film, γ is the product of the thickness of the film and the specific heat capacity per unit area, and β is the rate of heat loss per unit area, and f_0 is the frequency.

According to Eq. (1), the temperature change (ΔT) can be expressed as follows:

$$\Delta T = \frac{0.12 I_m^2 R}{2a\sqrt{\beta^2 + \gamma^2\omega^2}} \cos\left(2 \times 2\pi f_0 t + \tan^{-1}\frac{\gamma\omega}{2\beta}\right) \tag{2}$$

where $f_0 = \omega/2\pi$.

The sound pressure at a distance r is given by:

$$P(t) = \frac{R I_m{}^2 \rho_0 \sqrt{2 \times 6.0 \times 10^{-11} \times 2f_0}}{r\gamma} \cos(2 \times 2\pi f_0 t - \theta) \tag{3}$$