Acoustics'08 Paris
June 29-July 4, 2008
www.acoustics08-paris.org

A thermoacoustic device for sound reproduction

Fotios Kontomichos[a], Alexandros Koutsioubas[b], John Mourjopoulos[a], Nikolaos Spiliopoulos[b] and Alexandros Vradis[b]

[a]Audio and Acoustic Technology Group, Wire Communications Laboratory, Electrical Engineering & Computer Technology Department, University of Patras, 26500 Patras, Greece
[b]University of Patras Dept. of Physics, Rio, 26500 Patras, Greece
fotkon@wcl.ee.upatras.gr

Thermoacoustic loudspeakers are devices converting A/C current electrical signals to thermal energy, causing a local fluctuation of air pressure which generates acoustic waves. This work discusses former research efforts in the field and examines such novel and alternative audio transduction technologies based on a recently developed prototype. This hybrid solid state device without moving parts is based on the thermoacoustic method of sound reproduction and preliminary response measurements of its performance are presented. The thermoacoustic transduction is viewed as a promising technology for future implementation of small size loudspeakers integrated on chip.

1 Introduction

Current research efforts [7, 8] focus on the study of alternative electroacoustic transduction devices having no moving parts, in order to achieve sufficient audio performance from compact devices. Solid state loudspeakers such as the thermoacoustic devices which generate the acoustic wave without a conventional moving piston or other comparable mechanism, offer such possibility. The potential advantages of the above systems are significant for reducing the manufacturing costs and complexity associated with traditional loudspeakers.

Thermoacoustic transduction was initially studied in 1898 by F. Braun [2] who discovered that via the flux of alternate electric current through conducting materials, acoustic wave is produced in the free air field in front of the device. An article by Weinberg [3], describes experimental processes that study the phenomenon more methodically, using resistances, heated drivers and rheostats. The acoustic generation of these systems was initially explained as vibration due to the contraction and expansion of the conducting materials.

Subsequently, the effect of thermoacoustic transduction was discovered through the study of the operation and the implementation of the thermophone device which took place in 1917 when the work of H. D. Arnold and B. Crandall [1] was published. More specifically, this publication was the first qualitative and quantitative theoretical approach of the novel thermoacoustic device which could transform alternate electric current in sound wave.

Further research, produced more reliable theoretical models in order to describe thermoacoustic devices and to optimize prototype implementations. Newer theoretical approaches attribute the production of acoustic wave in the alteration of pressure in front of the solid state material and not in its oscillation [8]. According to these, when AC current flows through a conducting plate, it results in a periodical fluctuation of heat in this surface, which follows the periodical change of the current amplitude. The temperature of an infinitesimally thick air volume between the driver and the air medium, is proportional to the periodical flow of heat, so that it contracts and expands because of the fluctuation of the speed of molecules, playing the role of an idealised piston which oscillates. This vibrating movement of the molecules of air, results in the generation of an acoustic wave.

A similar principle of operation was also adopted for the photoacoustic transformation phenomenon which was first discovered by Alexander Graham Bell [4] in 1880 who studied the generation of acoustic waves when chopped light falls on solid surfaces. Tyndall [5] and Rontgen [6], realised that the photoacoustic phenomenon, appears even when the chopped light falls on gases and liquids. 50 years later the photoacoustic phenomenon was applied to a reliable gas analysis technique which is named PhotoAcoustic Spectroscopy (PAS) [10]. In this technique the recorded signal emitted by the sample corresponds qualitatively to the spectrum of the optical absorption of the material.

During the late 90s a new appliance which exploits the phenomena of the thermoacoustic and photoacoustic transformation was described in a publication by Shinoda, Nakajima et al [7]. This is a hybrid type of electroacoustic transducer that reproduces ideally ultrasonic frequencies and consists of three layers of different materials. The first layer consists of a conductive material, which in the particular case is aluminium 30 nm thick, the second layer of porous silicon which is extremely insulating, while the back plate of the appliance consists of crystal silicon and behaves like a heat sink. The desirable periodical electric signal to be reproduced, is applied through the use of suitable electrodes adjacent to the conductive layer of aluminium.

This work studies such an alternative transduction method based on thermoacoustic principle. The paper will present the theoretical principles which describe the thermoacoustic mechanism and the operation of such transducers. Furthermore, some measurement results from a novel hybrid transducer based on thermoacoustic transform will be shown, outlining the benefits and drawbacks of this transduction technique, leading to conclusions for future optimization and further research considerations.

2 Theory

The actuator based on the thermoacoustic transformation does not involve any movement of solid components in order to generate an acoustic wave and it is based on a mechanism of a “virtual” piston produced by vibrating air molecules via alternating heat transfer to the medium. Such typical thermophone device is shown in Fig.1. According to the theory of the thermophone, when a single frequency A/C current flaws through a conductor material, an acoustic pressure is produced with frequency equal to the double of the fundamental. Thus, if it is excited with a sinusoidal signal of fundamental angular frequency $2\pi f$ and amplitude A of the form $A \sin(2\pi ft)$, the resulting acoustic wave is proportional with the formula below:

$$(A\sin(2\pi ft))^2 = \frac{A^2}{2}(1-\cos(4\pi ft)) \tag{1}$$

Recent research studies as mentioned in Section 1, have lead to the implementation of a solid state ultrasonic loudspeaker without moving parts, which consists of three layers of materials having different conductivity value [7].

Input sinusoidal current signals, are transformed into acoustic waves which are proportional to the thermal energy density transferred between the transducer and the air. The thermoacoustic loudspeaker consists of three layers: a conductive layer of aluminium, an insulating layer of porous silicon and a heat sink consisting of crystalline silicon. The device is implemented on a silicon wafer as shown in Fig.2.

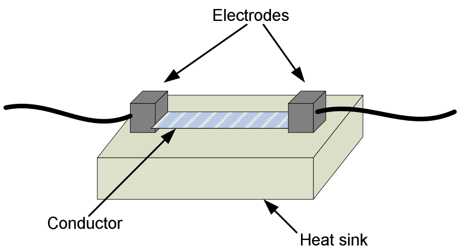

Fig.1 Typical solid state thermophone

The acoustic pressure produced by the thermoacoustic loudspeaker, driven by sinusoidal signals, is proportional to the thermal power density *q(ωt)exp(jωt)* and is described by the following equation:

$$P(x,\omega) = A\frac{\exp(-jkx)}{\sqrt{\alpha C}}q(\omega) \qquad (2)$$

where:

$$A = \sqrt{\frac{\gamma\alpha_\alpha}{C_\alpha}\frac{P_A}{\nu T_A}} \qquad (3)$$

α is the thermal conductivity and C the heat capacity per unit volume of porous silicon P_A is atmospheric pressure, T_A is room temperature, v is the sound velocity, $\gamma=C_p/C_v=1.4$ a constant, k is the wavenumber of free-space sound, a_a the thermal conductivity of the air and C_a the heat capacity of the air.

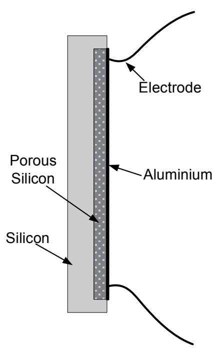

Fig.2 Construction layers of solid state thermoacoustic loudspeaker prototype

3 Thermoacoustic prototype construction

Such a novel hybrid thermoacoustic transducer prototype was developed on silicon at the University of Patras through the cooperation between Audio and Acoustic Technology Group and Solid State Physics Laboratory. Silicon technology could offer a variety of optimization alternatives for thermoacoustic transduction, due to the simplicity in constructing layers of different thermal characteristics. Hence, the proposed implementation introduces great flexibility for adapting the transducer to special requirements.

Following the work of Shinoda, Nakajima et al [7], the thermoacoustic device under study is composed of a patterned, thin aluminium film and a porous silicon layer on p-type silicon wafer. A porous silicon layer is composed of a silicon body permeated by a complex network of pores [9] which is characterized by the porosity factor, the average pore diameter and the porous layer thickness.

The fabrication procedure begins with the formation of a porous layer on a silicon wafer of 1 mm thickness. This porous layer is fabricated by electrochemical anodisation in a hydrofluoric acid (*HF*) electrolyte, using a custom-made anodisation apparatus that ensures high layer uniformity without the need of any back metallization of the silicon wafer. Anodisation was performed under a constant current density of $180 mA\cdot cm^{-2}$ for about 80s.

The gravimetric analysis performed, shows that the porosity of the fabricated porous silicon is equal to 78%. Cross section scanning electron micrographs taken on the porous silicon layer provide an independent measure of the layer thickness, which was found equal to 10.7μm. A picture of the prototype thermoacoustic device is shown in Fig.3.

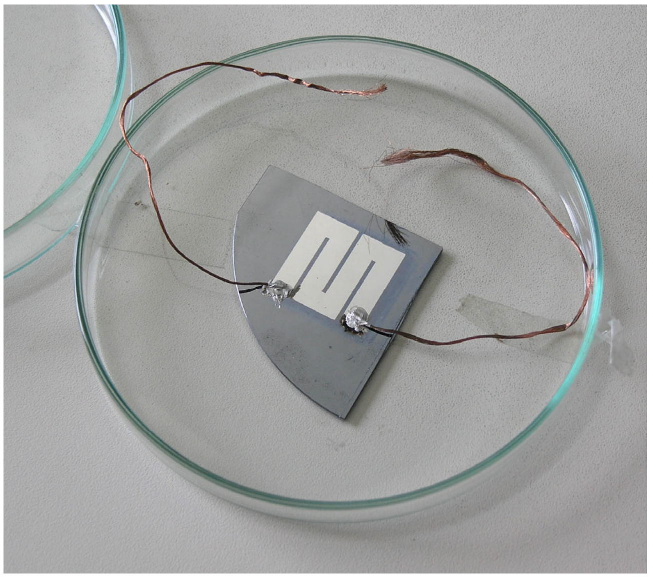

Fig.3 The thermoacoustic prototype device at Patras University

The patterned, thin aluminum film (30nm thickness) on top of the porous silicon layer is deposited by thermal vacuum evaporation of 99.999% pure aluminum wire under a base pressure of about 10^{-6} Torr. The final thickness of the aluminum film is controlled by an oscillating quartz crystal with sub-nanometer precision. The desired lateral pattern of the film is obtained using an appropriate evaporation mask.

4 Measurements and evaluation

The electroacoustic performance of the system was measured via a suitable testing procedure as shown in the measurement setup of Fig.4. The input sinusoidal signals are generated by a PC through an external sound card, they are amplified using an analogue power amplifier and fed to the thermoacoustic transducer. In order to measure the current that flows on the surface of the transducer, a very small resistance (R_o) needs to be connected in series with the loudspeaker. The A/C current, the voltage which drives the device and the acoustic pressure produced by it, are measured simultaneously with another sound card and the data are stored to the PC. The microphone which is used for the sound recording is a condenser cardioid measurement microphone placed very close to the thermoacoustic loudspeaker (at a distance of less than 6 mm) in order to reduce as much as possible contributions due to room noise and reflections.

The fundamental frequency of the input signals was varying from 1 kHz to 16 kHz, increasing at octave steps and all signals were sampled at 44100 Hz.

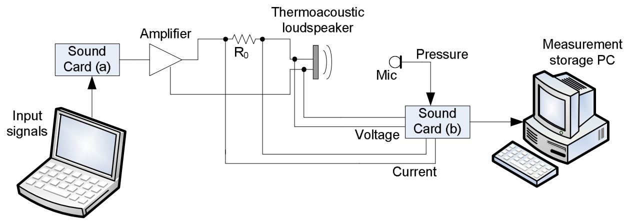

Fig.4 Measurement setup

Typical results for the time response of the system, concerning the fundamental frequency of 8 kHz are shown in Fig.5. The current rms amplitude which depends on the amplitude gain, was calculated by the voltage measurement on the resistance R_o and had a value of 2.7A for the case of the time response shown in Fig.5. Furthermore the rms voltage amplitude measured on the thermoacoustic prototype had a value of 2.15V, hence resulting to an energy consumption by the device of approximately 4.5W.

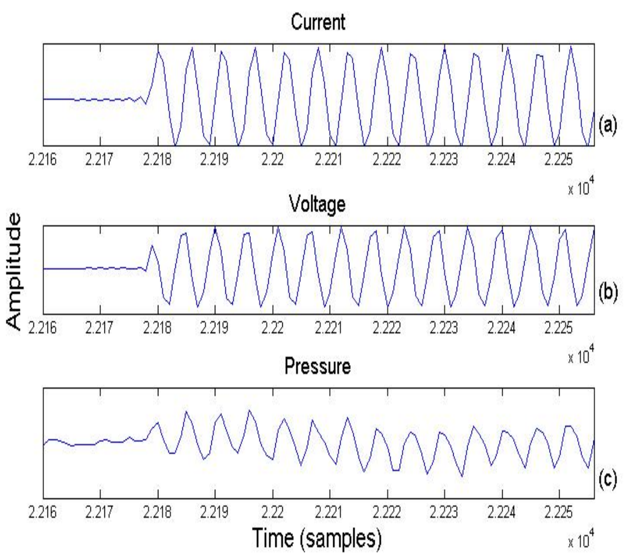

Fig.5 Time response for an 8 KHz input signal, measured at a 44100 kHz sampling rate. (a) Input current, (b) voltage fed to the device and (c) generated acoustic pressure

Similarly, typical frequency domain results for the system are shown in Fig.6. For this example, the spectrum was derived via FFT transformation of the pressure produced by the thermoacoustic transducer for an 8 kHz input signal. It is clear that the device suffers from harmonic distortion mainly at the double frequency of the fundamental (here, 16 kHz). This is a result which confirms a behavior of the prototype as a thermophone, given in the analysis of Section 2, Eq.1.

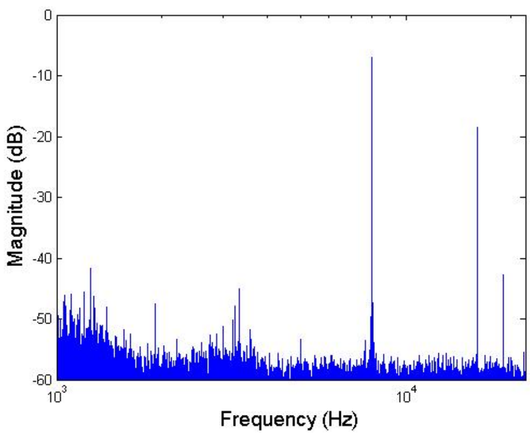

Fig.6 Pressure spectrum for an 8 kHz signal reproduced by the thermoacoustic device

From the time response results due to single frequency excitation the magnitude frequency response of the system was derived, as shown in Fig.7. The resulting response indicates an approximate 6 dB/octave high pass characteristic for the magnitude transfer function of the prototype device, a fact that confirms the theoretical approach of former research which describes similar performance mainly for the ultrasound range [7].

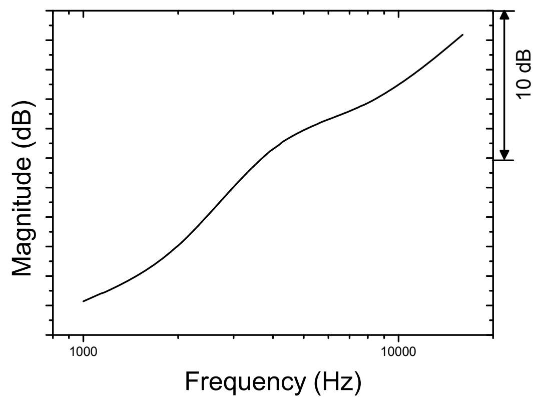

Fig.7 Frequency response of the thermoacoustic device

5 Conclusions

This work describes novel transduction technologies based on the thermoacoustic phenomenon. A prototype device was fabricated and preliminary tests in terms of time and frequency response are calculated and presented here.

The thermoacoustic prototype is a device generating sound without any moving parts. It operates forming a virtual air piston which distributes the sound wave by proper transfer of the heat produced by the alternating current which flows on the aluminum layer.

This implementation technique is ideal for a future development of a loudspeaker on chip which will include the amplification stage and filtering in a single integrated circuit on the silicon wafer. Furthermore, it provides several options for adaptation to special requirements such as frequency response and performance.

It is evident that the current state of this technology suffers from certain limitations which need to be considered. The most important is that such thermoacoustic devices are only capable to generate single frequency acoustic waves which is a result of the fact that the spectrum of pressure produced is affected by a component which is proportional to the energy of the input signal. Hence, this leads to undesirable harmonic distortion which might be avoided with appropriate input signal modulation and/or encoding.

Further optimization is needed in terms of physical constraints having to do with the high pass and nonlinear behavior of the device. Furthermore different materials with more appropriate thermal characteristics may optimize the performance of the loudspeaker. These aspects, together with more extensive analysis of the electroacoustic behavior of the system, will be the topic of future publications by the authors.

References

[1] H. D. Arnold and I. B Crandall, “The thermophone as a precision source of sound”, *Phys. Rev.* 10, 22-38, (1917)

[2] F. Braun, *Ann der Physik* 65, p. 358, (1898)

[3] Weinberg, *Elektrot. Zeit* 28, p. 944, (1907)

[4] A. G. Bell, *Am. J. Sci.* 20, 305, (1880)

[5] J. Tyndall, *Proc. R. Soc.* London 31, 307, (1881)

[6] W. C. Rontgen, *Philos Mag.* 11, 308, (1881)

[7] H. Shinoda, T. Nakajima, K. Ueno, and N. Koshida, “Thermally induced ultrasonic emission from porous silicon”, *Nature* 400, 853 – 855, (1999)

[8] R. R. Boullosa and A. O. Santillan, “A note on the use of novel thermoacoustic radiators for ultrasonic experiments: the importance of phase in a focused field”, *Eur. J. Phys.* 27, 95-102 (2006)

[9] R. L. Smith, D. S. Collins, “Porous silicon formation mechanisms”, *J. Appl. Phys.* 71, R1 (1992)

[10] F. A. McDonald and G. C. Wetsel Jr., “Generalized theory of the photoacoustic effect”, *J. Appl. Phys.* 49(4), 2313-2322, (1978)