Testing and simulation of a thermoacoustic transducer prototype

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ABSTRACT

Thermoacoustic transduction is the transformation of thermal energy fluctuations into sound. Devices fabricated by appropriate materials utilise such a mechanism in order to achieve acoustic wave generation by direct application of an electrical audio signal and without the use of any moving components. A thermoacoustic transducer causes local vibration of air molecules resulting in a proportional pressure change. The present work studies an implementation of this alternative audio transduction technique for a prototype developed on silicon wafer. Measurements of the performance of this hybrid solid state device are presented and compared to the theoretical principles of its operation which are evaluated via simulations.

1. INTRODUCTION

Current research activity in audio transduction [1, 2, 3, 4] increasingly considers alternative electroacoustic devices having no moving parts, in order to achieve sufficient performance from compact devices. Solid state transducers such as the thermoacoustic devices generate the acoustic wave without a conventional moving piston or other comparable mechanism. 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 [5] who discovered that via the flux of alternate electric current through conducting materials, an acoustic wave is produced in the free air field in front of the device. An article by Weinberg [6], describes experimental processes that study the phenomenon more methodically, using resistances, heated drivers and rheostats. The acoustic output 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 studied and implemented via the thermophone device in 1917 when the work of H. D. Arnold and B. Crandall [7] 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 describing thermoacoustic devices and optimized prototype implementations. Newer theoretical approaches describe the production of acoustic wave due to the alteration of pressure in front of the solid state material and not due to its oscillation [2]. According to these, when AC current flows through a conducting plate, it results in a periodical fluctuation of heat in the device surface, which follows the periodical change of the current amplitude. The temperature of an infinitesimally thin air volume between the driver and the air medium, is proportional to the periodical flow of heat, so that it contracts and expands due to the fluctuation of the molecule velocities, 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.

During the late 90s a new device which exploits the phenomena of the thermoacoustic and photoacoustic transformation was described in a publication by Shinoda et al [1]. This is a hybrid type of electroacoustic transducer that ideally reproduces ultrasonic frequencies and consists of three layers of different materials. The first layer consists of a conductive material, in this particular case 30 nm thick aluminium, the second layer is 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 periodic electric audio signal, is applied through the use of suitable electrodes adjacent to the conductive layer of aluminium. As will be discussed in detail in Section 2, the performance of the device depends mainly on the thermal and physical characteristics of the porous silicon layer.

A more recent research effort [3] demonstrates the behaviour of a thermoacoustic transducer based on carbon nanotube technology. The operation of such a loudspeaker is based on the thermophone principle mentioned above [7]. Its efficiency depends on the combined properties of heat capacity of the conducting material and its thickness and density. The transduction method of the carbon nanotube loudspeaker is similar to the one based on the porous silicon except for the material which actually implements the transduction.

This work studies this alternative transduction method via a porous silicon-based solid state device. The paper will present the theoretical principles which describe the thermoacoustic mechanism and the operation of such transducers. Furthermore, some simulation and measurement results from a novel hybrid transducer based on thermoacoustic transform fabricated on silicon wafer will be shown, outlining the benefits and drawbacks of this transduction technique, leading to conclusions for future optimisation and research.

2. THEORY

As was discussed earlier, the thermoacoustic actuator studied here does not involve any mechanical movement in order to generate an acoustic wave. A "virtual" piston is produced by vibrating air molecules via alternating heat transfer to the medium. The recent research study [1], has lead to the implementation of a solid state ultrasonic loudspeaker, which consists of three layers of materials having different conductivity value. These three layers are: a conductive layer of aluminium, an insulating layer of porous silicon and a heat sink consisting of crystalline silicon all implemented on a silicon wafer as shown in Fig. 1. This type of thermoacoustic device has been also constructed and it is studied here.

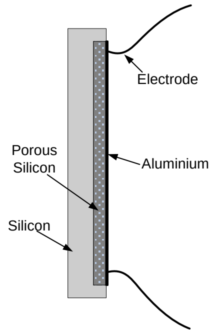

Figure 1 The layers of the solid state thermoacoustic loudspeaker prototype

The acoustic pressure produced by this thermoacoustic transducer, when is driven by sinusoidal signals, is proportional to the thermal power density (in units of ($W \cdot cm^{-2}$)) $q(\omega)exp(j\omega t)$ and is described by the following equation [1]:

$$P(x,\omega) = A\frac{\exp(-jkx)}{\sqrt{k_{ps}C_{vps}}}q(\omega) \qquad (1)$$

where:

$$A = \sqrt{\frac{\gamma k_a}{C_{va}}}\frac{P_A}{vT_A} \qquad (2)$$

where:
k_{ps} is the thermal conductivity of the porous silicon in ($W \cdot m^{-1} \cdot K^{-1}$)
C_{vps} the heat capacity per unit volume of porous silicon in ($J \cdot m^{-3} \cdot K^{-1}$)
P_A is atmospheric pressure in (atm)
T_A is room temperature in (K)
v is the sound velocity in the air in ($m \cdot s^{-1}$)
$\gamma = C_p/C_v = 1.4$ is constant
k is the wavenumber of free-space sound
k_a the thermal conductivity of the air in ($W \cdot m^{-1} \cdot K^{-1}$)
C_{va} the heat capacity per unit volume of the air in ($J \cdot m^{-3} \cdot K^{-1}$)

The minimum frequency that can be reproduced by such device is calculated by the following equation:

$$f_{\min} = \frac{k_{ps}}{\pi C_{vps} d_{ps}^2} \qquad (3)$$

where:
d_{ps} is the thickness of the porous silicon layer in (m)

It is clear that the minimum frequency mainly depends on the porous silicon thickness d_{ps} and its thermal properties. Furthermore [8] introduces a relationship between the porosity of the porous silicon layer and its thermal conductivity:

$$k_{ps} = \frac{1}{3}(1-P)^3 \rho c_p u d_k \qquad (4)$$

where:
P is the per cent porosity factor of the porous silicon layer
ρ = 2330 (kg·m^{-3}) is the bulk silicon density
c_p = 710 (J·Kg^{-1}·K^{-1}) is the specific heat capacity of silicon
u = 6562 (m·s^{-1}) the sound velocity in silicon
d_k the mean crystallite size which in our case is equal to 3 (nm)

Similarly [9] provides an expression which associates the thermal diffusivity, a_{ps} in (m^2·s^{-1}), of the porous silicon layer with its porosity:

$$a_{ps} = \frac{1}{3}(1-P)^2 u d_k \qquad (5)$$

where:

$$a_{ps} = \frac{k_{ps}}{C_{vps}} \qquad (6)$$

3. MEASUREMENTS AND SIMULATIONS

3.1. Prototype construction

A hybrid thermoacoustic transducer prototype based on the above principles, was developed on a silicon wafer at the University of Patras via the cooperation between the Audio and Acoustic Technology Group and the Solid State Physics Laboratory. Silicon technology could offer a variety of optimization alternatives for thermoacoustic transduction, due to the simplicity in constructing layers with different thermal characteristics. Hence, the proposed implementation has great flexibility for adapting the transducer to special requirements as will be discussed later in this work.

Following the work of Shinoda et al [1], the Patras device is composed of a patterned, thin aluminum 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 [10] which is characterized by the porosity factor, the average pore diameter and the porous layer thickness. The specific device studied in this work has a porous silicon layer with porosity equal to 78% and thickness equal to 10.7 (μm).

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. The patterned, thin aluminum film (30 (nm) thickness) on top of the porous silicon layer is deposited by thermal vacuum evaporation. The desired lateral pattern of the film is obtained using an appropriate evaporation mask.

The thermal conductivity of the fabricated porous layer is calculated by eq. (4) and found equal to 0.115 (W·m^{-1}·K^{-1}) and its thermal diffusivity equal to 3.17×10^{-7} (m^2·s^{-1}) according to eq. (5). A picture of the prototype thermoacoustic device is shown in Fig. 2.

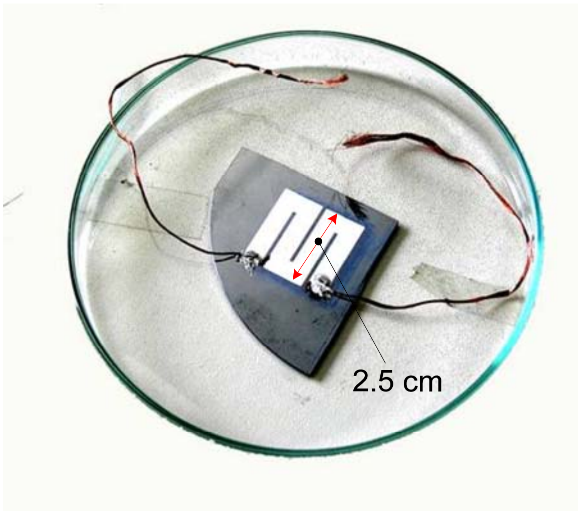

Figure 2 The thermoacoustic prototype device at Patras University

3.2. Simulations

The minimum frequency reproduced by such a thermoacoustic device as a function of the thickness of the porous layer is calculated via eq. (3) and is shown in Fig. 3. The thermal diffusivity here is considered constant and equal to the one calculated by eq. (5) for the specific porosity value of 78% of the constructed device. The marker shows the minimum frequency value for the fabricated thermoacoustic transducer as is the case for all the subsequent simulation figures.

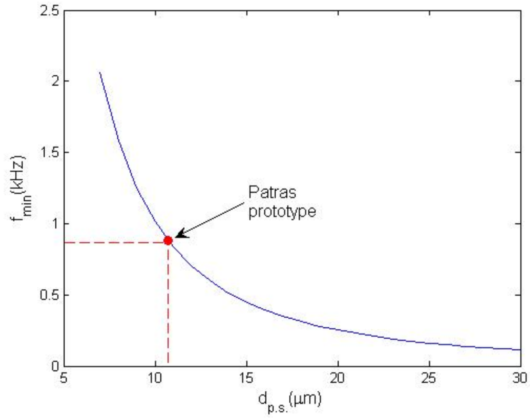

Figure 3 Minimum frequency reproduced by a thermoacoustic loudspeaker as a function of porous silicon layer thickness

Furthermore the minimum frequency as a function of the porosity value is shown in Fig. 4 for the case of porous silicon thickness of 10.7 (μm).

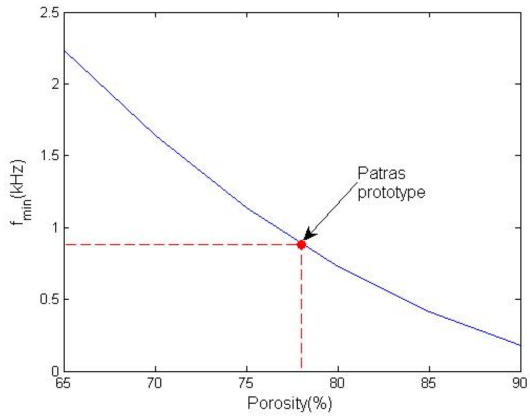

Figure 4 Minimum frequency reproduced as a function of porous silicon layer porosity for a thickness of 10.7 μm

The thermal conductivity of the porous silicon layer is a factor which according to eq. (1) affects the efficiency of the device and depends on the porosity value (eq. (4)) as shown in Fig. 5. Ideally its value should be minimised.

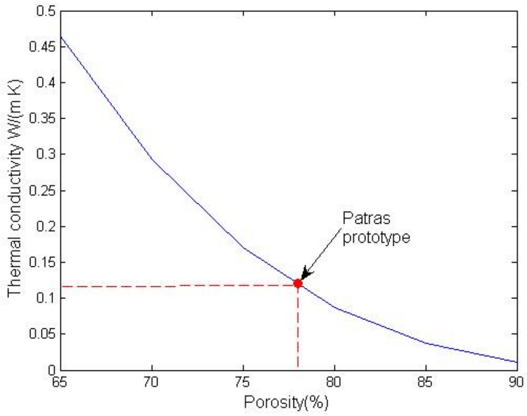

Figure 5 Thermal conductivity of the porous silicon layer versus its porosity

The calculated sound pressure level produced at the distance of 1 (m) by the thermoacoustic loudspeaker (eq. (1)) as a function of the porous silicon layer porosity for the case of an input signal power density of 1 ($W \cdot cm^{-2}$), is shown in Fig. 6, below.

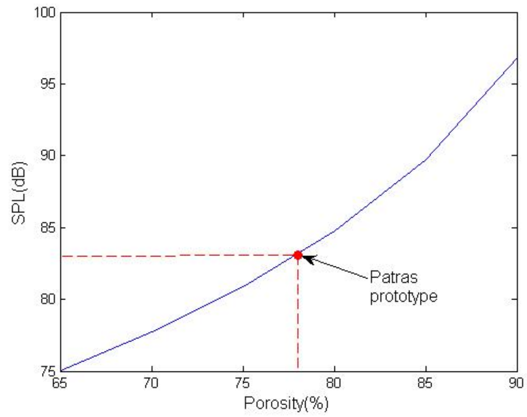

Figure 6 Estimated SPL produced at a distance of 1 m by the thermoacoustic device versus porosity fed with input signal power density of 1 ($W \cdot cm^{-2}$).

It is clear that the efficiency as well as the frequency response of the thermoacoustic loudspeaker is improved with the increase of the porosity factor and the thickness of the porous silicon layer.

3.3. Measurements

The electroacoustic performance of the prototype was measured via the testing procedure shown in the measurement setup of Fig. 7. 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 device. 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 in the PC. The microphone which is used for the sound recording is a condenser 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 interference 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).

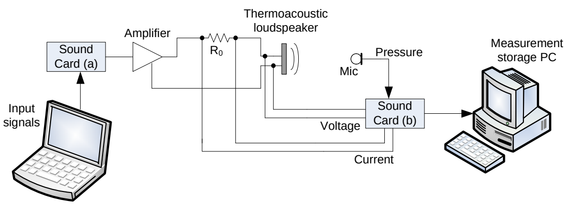

Figure 7 Prototype measurement setup

Typical results for the time response for the fundamental frequency of 8 (kHz), are shown in Fig. 8. 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 2.7 (A) for the case of the response shown in Fig. 8. Furthermore, the rms voltage amplitude measured on the thermoacoustic prototype had a value of 2.15 (V), hence resulting approximately to 4.5 (W) energy consumption by the device. From the electrical measurements becomes clear that the thermoacoustic prototype has largely a resistive behaviour.

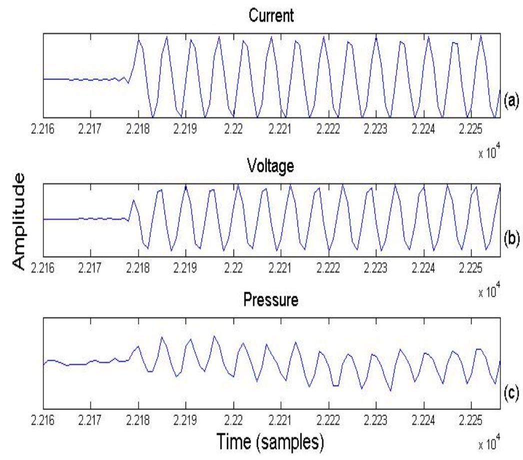

Figure 8 Time response for an 8 (KHz) input signal, measured at a 44100 (Hz) sampling rate. (a) Input current, (b) voltage fed to the device and (c) generated acoustic pressure

Similarly, typical frequency domain results for the system are shown in Fig. 9. For this example, the spectrum was derived via FFT of the pressure produced by the thermoacoustic transducer for the 8 (kHz) input signal. It is clear that the device introduces harmonic distortion mainly at the double frequency of the fundamental (here, at 16 (kHz)).

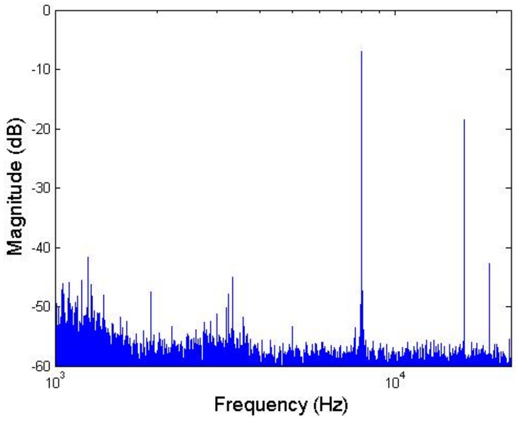

Figure 9 Pressure spectrum for an 8 (kHz) signal reproduced by the thermoacoustic device

From the single frequency excitation results, the magnitude frequency response of the system was derived, shown in Fig. 10. 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.

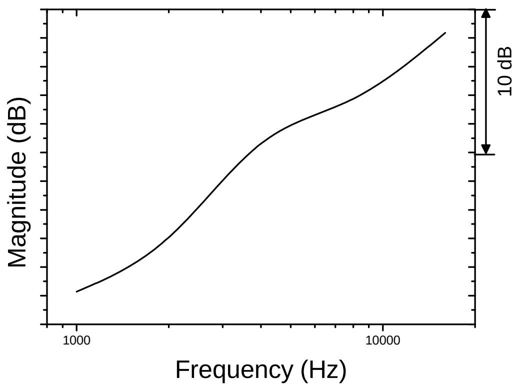

Figure 10 Measured frequency response of the thermoacoustic device

4. CONCLUSIONS

The novel transduction prototype is a device generating sound without any moving parts. It operates forming a virtual air piston which distributes the sound wave by transfer of the heat produced by the alternating current which flows on the aluminum layer. The proposed solid state implementation technique is suitable for a future development of a loudspeaker-on-chip which may integrate the amplification stage and filtering within a single integrated circuit on the silicon wafer.

The work introduces estimates concerning the effect of thermal and physical characteristics of the porous silicon layer on the overall behavior of the device.

It is shown that is possible to optimise the performance of the thermoacoustic transducer with proper design of the thermal and physical characteristics. More specifically, in order to increase the efficiency of the transduction, the product of thermal conductivity and heat capacity per unit volume of the porous silicon layer should be minimised. Furthermore, the minimum frequency reproduced by the device is inversely proportional to the square of the porous silicon layer thickness. Therefore, porous silicon layer thickness has to be increased in order to lower the device minimum operating frequency. Both of the above issues can be addressed via the increase of the porosity factor and the thickness of the porous silicon layer, with the appropriate calibration of the electrochemical fabrication procedure.

As was confirmed by the measurements, the prototype device currently operates at higher frequencies. A deviation between the estimation and measurement of the sound pressure level reproduced by the device is an issue which needs consideration in future work.

It is evident that the current state of this technology suffers from limitations which need to be carefully addressed. The most important is the undesirable harmonic distortion, which might be avoided with appropriate input signal pre-conditioning. Furthermore, the fabricated device needs optimisation with respect to its electrical power consumption via the increase of its efficiency factor.

Furthermore, different materials with more appropriate thermal characteristics may achieve such performance improvements for the device. These aspects, together with more extensive analysis of the electroacoustic behavior of the system, will be the topic of future publications by the authors.

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