ULTRATHIN LOUDSPEAKERS FROM ALD

Joseph J. Brown*, Nathan C. Moore, Omkar D. Supekar, and Victor M. Bright

Department of Mechanical Engineering, University of Colorado, Boulder, Colorado, USA

ABSTRACT

Arrays of suspended microbridges (Figures 1 and 2) with sizes as small as $17 \mu\text{m} \times 1 \mu\text{m}$ have been fabricated and demonstrated to produce audible sound using the thermoacoustic effect. The microbridges were fabricated by atomic layer deposition (ALD) of 6.5 nm Al_2O_3 and 19.3 nm tungsten on sacrificial polyimide [1], with ALD performed at 130°C and patterned with standard photolithography. Loudspeaker sensitivity of these first-generation devices is $\sim 29 \text{ dB SPL/1 mW}$. These devices demonstrate industrially feasible nanofabrication of thermoacoustic transducers and a sound production mechanism pertinent to submicron-scale device engineering.

INTRODUCTION

The development of nanomaterials and nanoscale engineering has enabled new capabilities in nanoscale thermal engineering. These have, in turn, led to a resurgence of interest in thermoacoustic sound production. In this transduction mechanism, Joule heating creates temperature fluctuations in a solid material, heat conduction generates coupled temperature and pressure fluctuations in the surrounding fluid, and the pressure fluctuations propagate away from the device as sound waves. This transduction mechanism was first explored in the early 20th century [2]. Work on porous Si in 1999 [3] and CNTs in 2008 [4] initiated the wave of recent interest in thermoacoustic transducers. In addition to porous Si and CNTs [4]–[9], thermoacoustic loudspeakers have been demonstrated from nanowire arrays [10]–[13], and graphene [14]–[18]. This prior work has suggested the following principles to maximize nanomaterial sound production:

- (1) Minimize substrate losses by suspending devices [11], [17].
- (2) Minimize the areal heat capacity of the transducer [16], [17].
The devices here have $0.18 \text{ J m}^{-2} \text{ K}^{-1}$ (calculated from Refs. [19], [20]), lower than any sample in Ref. [21].
- (3) Maximize or concentrate heat flux q_0 [J m^{-2}] from the transducer (see Eqs. 1 and 2, below) [5], [12].
- (4) Maximize the heat transfer to the surrounding fluid, such as by maximizing the transducer surface area, and distribute power evenly through a sample [21].

Devices using ultrathin ($< 50 \text{ nm}$) films produced by ALD allow engineering according to these principles. In particular, ALD provides control of heat capacity and thermal conductivity. Furthermore, ALD is readily integrated in manufacturing, having already been integrated into wafer-scale CMOS processing. It may be expanded to continuous roll-to-roll production, adapted for flexible substrates, and used to produce many materials including insulators and metals. Resolution is limited only by lithography.

Thermoacoustic Physics

Thermoacoustic loudspeakers operate at low voltages, providing an advantage over piezoelectric, electrostatic, and other capacitive acoustic transducers. Very good (85–100 dB SPL in air, 200 dB SPL for encapsulated devices in water) sound production has been measured from thermoacoustic devices [9], [21]. For most audio frequencies, the efficiency η (sound power out/electrical power in) is typically $\sim 10^{-6}$ to 10^{-5} at best [5], [10]–[13], [17], [21]. In auditory frequencies these devices typically have a frequency-dependent behavior of sound pressure and

Figure 1: SEM image of suspended microbridges used for thermoacoustic sound generation. Beams are $17 \mu\text{m}$ long, $1 \mu\text{m}$ wide, 25.8 nm thick and suspended $3.5 \mu\text{m}$ above the substrate. Anchor regions provide mechanical connection to the substrate.

Figure 2: Cross-section diagram of the fabricated devices.

efficiency, increasing with frequency f (Eq. 1) until saturating at some maximum level (Eq. 2) [3], [5], [12], [22]. Here, ρ_g is the density of air ($\sim 1.2 \text{ kg/m}^3$), v_g is the isothermal speed of sound in air ($\sim 340 \text{ m/s}$), c_p is the specific heat of air ($\sim 1007 \text{ J kg}^{-1} \text{ K}^{-1}$), T_0 is ambient temperature ($\sim 300 \text{ K}$), and A is the area of a transducer.

$$\eta = \frac{\pi f^2}{4\rho_g v_g c_p^2 T_0^2} q_0 A \quad (1)$$

$$\eta = \frac{q_0 v_g}{2\rho_g c_p^2 T_0^2} \quad (2)$$

Under certain conditions, i.e. plane wave production and $\omega \gg \alpha_s/2L_s^2$ (where $\omega = 2\pi f$, α_s is the thermal diffusivity of the transducer film, and L_s is the distance through which heat propagates to a substrate), the frequency dependence of Eq. 1 may be mitigated, resulting in a relatively flat frequency response [22]. In encapsulated systems, other behavior may emerge such as $f^{-3/2}$ dependence [2] and mechanical resonance [5]. Optimization of these transducers is a balance among efficiency, electrical power consumption, sound output, manufacturability, and packaging.

THERMOACOUSTIC MODEL

The development of practical models for thermoacoustics is an area of ongoing inquiry and optimization [21]. The fundamental physical problem is expressed by coupled temperature

and pressure field equations [12], [23]. Most models take a distributed approach or ignore some of the relevant conduction effects in the transducer materials. With some simplification [5], thermoacoustic sound generation can be interpreted as a source driving a temperature wave, which drives a propagating pressure wave. The thermal wave decays rapidly, with diffusion length μ_i (100 Hz) = $(\alpha/\pi f) = 268 \mu\text{m}$ and μ_i (100 kHz) = $8.46 \mu\text{m}$ [23], where α is thermal diffusivity of air ($2.25 \times 10^{-5} \text{ m}^2/\text{s}$).

Suspended thermoacoustic bridges of finite length have not been thoroughly considered in literature, with the closest models assuming infinite length beams [12]. While this assumption allows assessment of the upper bounds of sound production efficiency (Eqs. 1–3), it ignores effects of thermal conduction within finite beams on the output frequency spectrum. The thermal diffusivity calculated for ALD W beam material is $\alpha_s = 2.25 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ [19], [20]. Combined with typical thermal conduction lengths of suspended microbridges, the criterion $\omega \gg \alpha_s/2L_s^2$ may be satisfied for low frequencies, such as 20 Hz for 600 μm beams. This suggests that models of thermoacoustic emission from nanoscale beams should account for heat flux through the beams in addition to emitted power. This is accomplished below in a new model for heat flow from thermoacoustic transducers that is distinct from previous models in that (1) it accounts for heat conduction and capacitance in microbridges of finite length, and (2) it does so using a lumped element approach.

Lumped Element Model for Microbridge Sound Production

In each transducer beam, energy production from Joule heating is balanced (Eq. 3) by emission of a thermal wave from the top surface of the beam (Eq. 4), heat conduction and storage in the beam (Eq. 5), and, from the bottom surface, both emission of a thermal wave and conduction through the air to the underlying fabrication substrate (Eq. 6). Here each $\dot{Q}$ term is a lumped heat power flow and harmonic analysis is used to find solutions to these equations, which is a common approach in thermoacoustic analysis. Heat flow from the top surface is given by the 1D thermal wave output, Eq. 4, wherein κ is thermal conductivity of air ($0.0263 \text{ W m}^{-1} \text{ K}^{-1}$), T_{AC} is the oscillating component of the beam temperature, L_B is the beam length, w_B is the beam width, and k_1 is the thermal wavenumber, given by $k_1 = (j\omega/\alpha)^{1/2}$. Heat loss in the beam is described by Eq. 5, where the thermal resistance $R_{beam} = (L_B/4) / (\kappa_f \delta w_B)$ and thermal capacitance $C_{beam} = \rho_f c_f w_B L_B/2$. Film thickness is δ , film density is ρ_f , specific heat of the film is c_f , and thermal conductivity of the film is κ_f . Input power supplied to the transducer beam is modeled as $P_{AC} = P_0 e^{j\omega t}$. In reality AC Joule heating power can have several frequency components. The power flowing from the bottom of the beam, Eq. 6, is a combination of a thermal wave and heat conduction to the substrate, with R_{gap} approximated as $R_{gap} = g / (\kappa_f L_B w_B)$, where g is the gap distance between the beam and substrate.

$$\dot{Q}_{in} = \dot{Q}_{top} + \dot{Q}_{bottom} + \dot{Q}_{beam} \quad (3)$$

$$\dot{Q}_{top} = -j\kappa k_1 T_{AC} L_B w_B \quad (4)$$

$$\dot{Q}_{beam} = T_{AC} R_{beam}^{-1} - j\omega C_{beam} T_{AC} e^{-j\omega t} \quad (5)$$

$$\dot{Q}_{bottom} = -j\kappa k_1 T_{AC} L_B w_B + T_{AC} R_{gap}^{-1} \quad (6)$$

Rewriting Eq. 3 using Eqs. 4–6 yields the system model Eq. 7. If P_{AC} is given, this allows calculation of T_{AC} , “piston velocity” u , rms sound pressure p_{rms} , and sound production efficiency η , Eqs.

9–12. Calculation of u uses the continuity and ideal gas equations [5], and assumes sound generated from each beam is distributed across the width d_n that is allocated to each beam in an array (d_n = beam width + beam separation).

$$T_{AC} = P_{AC} \left[-2j\kappa k_1 L_B w_B + R_{beam}^{-1} - j\omega C_{beam} + R_{gap}^{-1} \right]^{-1} \quad (7)$$

$$u = 2 \left(\frac{\omega}{k_1} \right) \left(\frac{T_{AC}}{T_0} \right) \left(\frac{w_B}{d_n} \right) \quad (8)$$

$$p_{rms} = \rho_g v_g \frac{|u|}{\sqrt{2}} \quad (9)$$

$$\eta = \frac{(p_{rms}^2 / \rho_g v_g)}{(\dot{Q}_0 / L_B d_n)} = \frac{p_{rms}^2 L_B d_n}{P_{AC} \rho_g v_g} \quad (10)$$

Although the P_{AC} appears in the denominator in Eq. 10, when Eq. 7 is carried through Eqs. 8–10, the result is that P_{AC} is in the numerator and $\eta \propto P_{AC}$, similar to Eqs. 1 and 2. If the losses of Eqs. 5 and 6 are omitted, Eq. 2 can be recovered from Eqs. 7–10. The sound pressure level (SPL) from one device is related to η using p_{rms}^2 , given $\text{SPL} = 10 \log_{10} (p_{rms}^2 / p_0^2)$, with reference pressure $p_0 = 2 \times 10^{-5} \text{ Pa}$. Figure 3 examines η and SPL under several conditions. When there are no losses through the beam or conduction through air, the sound output is near the maximum of Eq. 2. Losses in the beam maintain a relatively flat output. Conduction through the air to the substrate significantly decreases the low frequency output. In Eqs. 7–10, the only mechanisms to improve η are to increase P_{AC} , increase R_{beam} and R_{gap} , decrease C_{beam} , and to select beam size and spacing to maximize u and T_{AC} .

Figure 3: Near-field model result for applied power of 1 W/cm^2 (device total 0.195 W) from one of the $17\text{-}\mu\text{m}$ microbridge transducers described below. This figure compares the effect on sound production efficiency η of the different loss terms on the right-hand side of Eq. 7.

EXPERIMENT

Device Design and Fabrication

Microbridge arrays were designed such that series and parallel electrical connections among the microbridges would allow a total array electrical resistance of $10 - 20 \Omega$. A 500 nm Al layer was deposited on the W film in order to distribute electrical power throughout the array. One design used 12,000 microbridges $600 \mu\text{m} \times 2 \mu\text{m}$ in size. A second variation used 576,000 microbridges $17 \mu\text{m} \times 1 \mu\text{m}$ in size. Devices were fabricated on $15 \text{ mm} \times 15 \text{ mm}$ Si chips as described in Figure 4.

Figure 4: Fabrication process. (i) Provide a silicon wafer substrate. (ii) Spin-coat a $3.5 \mu\text{m}$ polyimide layer. (iii) Perform ALD of alumina (6.5 nm) and tungsten (19.3 nm) at 130°C . (iv) Pattern the ALD layers using O_2/CF_4 RIE. (v) Deposit and pattern 500 nm of aluminum. (vi) Release the microbridge structures using an isotropic O_2 plasma etch.

Acoustic Characterization

An anechoic chamber with $18'' \times 18''$ base and $15''$ height was built using with $\geq 6''$ of open cell foam surrounding all sides, of which $3''$ were pyramid-shaped. Current delivered to each transducer array was determined by monitoring the voltage across a $1\text{-}\Omega$ resistor in series with the device. Sound waves were recorded (Figure 5) by a calibrated microphone (Dayton Audio EMM-6). Data were collected by an NI USB-6259 with 100 kHz sampling rate, and processed with LabVIEW and MATLAB. Acoustic performance was measured from device arrays with 0 – 10 V supplied by an Agilent 33250A function generator, or unbiased voltage from an audio amplifier (Dayton APA150).

Figure 5: Near-field experimental setup in anechoic chamber.

RESULTS AND DISCUSSION

Under a linear chirp (frequency varies linearly with time), over 50 dB SPL was generated at frequencies above 10 kHz (Figure 6). Measured device arrays with 0.0838 W input power displayed 48.5 dB sound pressure level at 1 cm distance (Figure 7). This is much less than the ~ 92 dB SPL that the model predicts for this power input. Spherical wave propagation, losses in electrical connections, and other device impedances resulting from the experimental setup account for a portion of this discrepancy and may be accommodated with further optimization. For instance, device resistance was higher than designed, on the order of 40 – 100 Ω , largely due to solder connections. Efficiency of these first-generation devices ($\eta = \sim 10^{-10}$, Figure 7) is comparable to other thermoacoustic nanomaterial devices but much less than commercial headphones (~ 100 dB per 1 mW, or $\sim 10^{-3}$ for a device with 1 cm^2 area). Even with no beam and substrate losses, maximum T_{AC} at 1 W/ cm^2 input is 92 K. Clearly the transducers

can be driven with much higher power. The microbridge arrays displayed good fidelity, with relatively flat spectral response across the audible range, Figure 8. This may be expected because electrical impedance is due primarily to resistivity, providing an advantage over conventional electromagnetic voice-coil loudspeakers, which have resonance peaks due to inductance and mechanical dynamics.

Figure 6: Spectrogram of time-varying sound output. Electrical input: 50 Hz – 30 kHz unbiased linear chirp. Chip output: 100 Hz – 60 kHz due to frequency doubling from Joule heating. Measured at 5 cm microphone distance (add 14 dB for 1 cm equivalent).

Figure 7: Single tone frequency response measured at 1 cm microphone distance, 0 – 10 V, 5 kHz input.

Figure 8: Spectral output for thermoacoustic devices, compared with a conventional electromagnetic loudspeaker 37 mm in diameter. Sound output spectra in response to white noise electrical input. The conventional speaker displays resonant peaks in the 5 – 25 kHz range. The white noise was supplied to the thermoacoustic device ($R=83.8 \Omega$) as an electrical current of $0.103 A_{\text{rms}}$, with 0.88 W total. The thermoacoustic device shows relatively broad frequency response, peaking around 25 kHz.

CONCLUSIONS

Planar microbridge array loudspeakers formed using ALD and microfabrication were produced and demonstrated to operate in the audible range, with frequency response clearly distinct from an electromagnetic loudspeaker. Transducers consisted of suspended 25.8 nm thick microbridges subject to Joule heating, producing sound by means of the thermoacoustic effect. This transduction mechanism provides a compact means of generating pressure fluctuations in a fluid, and can integrate readily with other microdevices. The operation of arrays of devices provides resilience against failure of individual microbridges, and demonstrates a macroscale effect from large-scale parallelization of microdevices. Analysis of the thermoacoustic transducers indicates that geometry and materials selection play critical roles in optimization of the efficiency and frequency response.

Although the efficiency of these devices in the audible range is below that of electromagnetic transducers, the frequency spectrum can achieve relatively flat response. The devices are scalable to both large area and nanoscale operation. Modeling predicts near-field sound pressure levels of > 90 dB from thermoacoustic microbridges. Further nanoengineering may allow the devices to reach their ultimate limits, through reduction of heat capacity, and improvement of substrate reflectance. Far field sound levels will improve with use of larger arrays. Device encapsulation may provide an additional mechanism to improve efficiency of audible sound production.

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CONTACT

*J.J. Brown, tel: +1-303-735-8054; joseph.j.brown@colorado.edu