Suspended metal wire array as a thermoacoustic sound source

A. O. Niskanen,1 J. Hassel,1,a M. Tikander,2 P. Maijala,1 L. Grönberg,1 and P. Helisto1

1VTT Technical Research Centre of Finland, P.O. BOX 1000, 02044 VTT, Finland
2Helsinki University of Technology, Laboratory of Acoustics and Audio Signal Processing, FIN-02015 TKK, Espoo, Finland

(Received 24 August 2009; accepted 18 September 2009; published online 19 October 2009)

We demonstrate that a suspended metal wire array can be used to produce high-pressure sound waves over a wide spectrum using the thermoacoustic effect. We fabricated air-bridge arrays containing up to $2 \times 10^3$ wires covering an area of a few square centimeters. The supporting silicon wafer was isotropically plasma etched to release the wires thereby avoiding heat contact with the substrate. Sound pressure levels reaching 110 dB at a distance of 8 cm were demonstrated near 40 kHz in free field. The devices are also able to reproduce music and speech. They have potential for applications especially in the ultrasound range. © 2009 American Institute of Physics. [doi:10.1063/1.3249770]

Mechanically suspended microscale and nanoscale metal wires are used for many purposes at the forefront of physics and applications. Suspension is useful in avoiding heat contact with the supporting substrate e.g., in cryogenic devices such as solid-state coolers1 and terahertz bolometers.2 Metallic or metal coated beams are also used as nanomechanical resonators approaching the quantum limit.3–7 In single electron transistors suspended metal islands8,9 may help to reduce noise. Such devices usually require a cryogenic vacuum. Here we demonstrate that a similar on-wafer suspended metal wire array can produce high-pressure sound at room temperature and atmospheric pressure using the thermoacoustic effect.10–12

In the thermoacoustic effect the Joule heating of a conductor results in time-dependent temperature variations proportional to the square of the applied voltage. The temperature variation in the conductor on the other hand leads to temperature variations in air with the device is properly designed. This in turn results in time-dependent pressure variations in the air, i.e., sound waves. Since the effect is proportional to power, frequencies may be mixed or doubled unless a dc bias is used. The magnitude of these waves is frequency dependent in the sense that the thermoacoustic effect is more suitable for producing higher frequency sounds.

An efficient thermoacoustic sound source requires a conductor whose heat capacity per unit area is small, and which conducts heat efficiently to the surrounding fluid, in our case air. The first condition can be satisfied using very thin conductors which may be patterned. The latter can be guaranteed by ensuring that the heat conduction to air dominates compared to other heat conduction mechanisms which do not produce sound. While the concept of a thermoacoustic thermophone is rather old,10 it has found little practical use. Metal films are typically not suitable for thermoacoustic sound production. However thin Al films on porous Si can be used to generate high frequency sound,11 especially ultrasound. It was recently shown that a film of carbon nanotubes can be used to make a surprisingly good loudspeaker12 based on the thermoacoustic effect. In both these experiments the crucial features are the smallness of heat capacity per area and small heat conductance into the substrate. In the present work, the heat capacity per area is similar to these experiments. Especially compared to porous Si, air under the metal bridges is a superior insulator, contributing to the magnitude of the sound pressure. It will turn out that the present devices are comparable with the nanotube loudspeakers while being much easier to fabricate using standard clean room processes. Thus we show that metal films can indeed produce high-pressure sound waves thermoacoustically.

Figure 1 illustrates the device that we have fabricated and experimentally tested. The device consists of 200-μm-long Al wires that are 3 μm wide and 30 nm thick. The wires are clamped at their ends to wider crossbars thereby forming air bridges between the supports. The distance between the suspended Al wires and the substrate beneath is not known exactly due to the method of fabrication but it is estimated to be on the order of microns. Blocks of parallel wires are formed between the electrically floating wider crossbars and there are many such blocks in series.

**FIG. 1.** (Color online) Images of the suspended wire loudspeaker. (a) Scanning electron microscope image taken near the edge of the wire array. The length of the wires is about 200 μm, the width is about 3 μm and the thickness of the Al film is 30 nm. The distance between wires is in this case 30 μm. The image is taken after measurements and handling outside clean room which is responsible for the impurities seen on the supporting Al. (b) Closeup of the wire supporting crossbar and five Al wires. (c) Photograph of the measurement arrangement inside an anechoic chamber. The round 150 mm wafer is seen in the middle attached to the circuit board.
That is, the wires form two-dimensional arrays on the wafer covering macroscopic areas. This paper focuses on three different devices out of altogether six designs. The three kinds of measured loudspeakers, named B, C, and E had 6000, 12000, and 233 200 wires, respectively. The covered areas were $1 \times 0.5$ cm$^2$ for B and C while the area of E was $5 \times 3.5$ cm$^2$. In C the pitch was $15 \, \mu$m while in B and E it was $30 \, \mu$m.

The devices are all included on a single 150 mm silicon wafer coated with 10 nm of SiO2 deposited by plasma-enhanced chemical vapor deposition. The Al was deposited using sputtering and patterned using standard contact mask UV photolithography and plasma etching. Following this the metal beams were released by an isotropic SF6 reactive ion etch. Due to the selectivity of SF6 between Al and Si this can be done without extra lithography steps. The wires are only 3 $\mu$m wide while the supporting crossbars at the ends of the wires are 50 $\mu$m wide. We thus etch just enough to release narrow Al wires while the wider structures remain attached to the substrate. Note that while we are able to fabricate quite huge arrays of suspended wires, the design of the loudspeaker is robust against the possible failure of individual wires. As a whole the process is very simple compared to most microelectronics processes, and could be easily incorporated as part of some more complicated process. The measured resistances of the samples were $R_B = 46 \, \Omega$, $R_C = 40 \, \Omega$, and $R_E = 58 \, \Omega$.

The audio measurements were performed in two different setups. Most of the results presented here were measured inside an anechoic chamber using a 1/2 in. Brüel and Kjær microphone. The distance between the Al-wire sound source and the microphone was approximately 7 cm. This setup had a flat frequency spectrum up to about 20 kHz. To study the frequency dependence further, some additional measurements were later carried out in a different laboratory inside a semianechoic chamber and using a 1/4 in. Brüel and Kjær microphone. This setup had a measured flat response up to about 40 kHz. The results obtained using the two setups were in agreement with each other. All the data shown here are measured using logarithmic frequency sweeps and Fourier analyzed using suitable windowing. For comparison maximum-length-sequence analysis (data not shown) was carried out in the latter case for comparison, and the findings were similar. The stability of the sound pressure against possible drifts during the measurement sequence was checked by applying a single frequency excitation. It was found that the stationary sound pressure level was reached within one period of oscillation and maintained throughout the duration of the excitation. Standard sound pressure scale was used in which 20 $\mu$Pa rms corresponds to 0 dB. The measurement error is estimated to be below 1 dB. When dc voltage was used, the dc and ac parts of the input signal were separated with a simple dc block.

Figure 2 shows an example of the measured frequency response of the largest speaker E. The data are obtained both with and without dc biasing, i.e., in the first and second harmonic modes of operation. It can be seen that the sound pressure level is strongly dependent on frequency. In the 20 kHz bandwidth data the pressure level reaches as high as 104 dB (3.2 Pa rms) at the nominal total power level of 17.4 W which is slightly below 1 W/cm$^2$. In this case both ac and dc are used. The ac-only 9.8 W and 40 kHz bandwidth data have a similar form but reaches 110 dB at 40 kHz. A most microelectronics processes, and could be easily incorporated as part of some more complicated process. The measured resistances of the samples were $R_B = 46 \, \Omega$, $R_C = 40 \, \Omega$, and $R_E = 58 \, \Omega$.

The audio measurements were performed in two different setups. Most of the results presented here were measured inside an anechoic chamber using a 1/2 in. Brüel and Kjær microphone. The distance between the Al-wire sound source and the microphone was approximately 7 cm. This setup had a flat frequency spectrum up to about 20 kHz. To study the frequency dependence further, some additional measurements were later carried out in a different laboratory inside a semianechoic chamber and using a 1/4 in. Brüel and Kjær microphone. This setup had a measured flat response up to about 40 kHz. The results obtained using the two setups were in agreement with each other. All the data shown here are measured using logarithmic frequency sweeps and Fourier analyzed using suitable windowing. For comparison maximum-length-sequence analysis (data not shown) was carried out in the latter case for comparison, and the findings were similar. The stability of the sound pressure against possible drifts during the measurement sequence was checked by applying a single frequency excitation. It was found that the stationary sound pressure level was reached within one period of oscillation and maintained throughout the duration of the excitation. Standard sound pressure scale was used in which 20 $\mu$Pa rms corresponds to 0 dB. The measurement error is estimated to be below 1 dB. When dc voltage was used, the dc and ac parts of the input signal were separated with a simple dc block.

Figure 2 shows an example of the measured frequency response of the largest speaker E. The data are obtained both with and without dc biasing, i.e., in the first and second harmonic modes of operation. It can be seen that the sound pressure level is strongly dependent on frequency. In the 20 kHz bandwidth data the pressure level reaches as high as 104 dB (3.2 Pa rms) at the nominal total power level of 17.4 W which is slightly below 1 W/cm$^2$. In this case both ac and dc are used. The ac-only 9.8 W and 40 kHz bandwidth data have a similar form but reaches 110 dB at 40 kHz.

Let us now look at the performance of the devices in more detail. The interesting questions include how the sound pressure level scales as a function of applied power and frequency. In the case of pure sinusoidal driving at frequency $f$, the response is at $2f$ and we find that our data are phenomenologically well explained by $P_{\text{rms}}(2f) \approx \kappa P_f(2f)^{\alpha}$, where $P_f = V_{\text{ac}}^2/2R$ is the ac electrical power while $\alpha$ and $\kappa$ are fitting parameters. Note that sound intensity therefore scales quadratically with electrical power, increasing efficiency with applied power. This is however intuitively satisfying due to the thermoacoustic origin of the sound. Figure 3 illustrates fits obtained using this model. Note that the obtained values of $\alpha \approx 1.34$ are within the error margins for the two different sound sources. The prefactor $\kappa$ is about twice larger in the sparser array B which is otherwise similar to array C. This may be due to the higher power consumption per wire in the former. Similar values of $\alpha$ are consistently obtained by fitting to our other data as well (not shown), while there is some scatter in the prefactor $\kappa$. We also note that the shape of the frequency response curve was roughly independent of measurement distance.
In order to use thermoacoustic loudspeakers for reproducing conventional audio signals a dc bias can be used. In fact, our loudspeakers can quite well produce e.g., speech and music. However, when a dc bias is superposed with the ac signal, the frequency response is slightly more complicated. In case of a single sine wave superposed with the total power is $P = \frac{(V_{dc} + V_{ac} \cos(2\pi ft))^2}{R}$ and therefore the prefactor of the first harmonic in the power is $P_1 = 2V_{dc}V_{ac}/R$ while the prefactor of the second harmonic is $P_{2\alpha} = 0.38$ as defined above. Then the expression for the first harmonic should read $p_{rms}(f) = \kappa P_{2\alpha}f$. This gives us an estimate for the harmonic ratio $p_{rms}(2f)/p_{rms}(f) = 2^2V_{rms}/(4V_{dc})$ which is roughly consistent with our data, although there is considerable frequency dependence in the amplitude. This is illustrated in Fig. 4.

A theoretical expression for the behavior of the rms pressure $p_{rms}$ is given in Ref. 12 in the context of carbon nanotubes, which modifies an earlier result presented in Ref. 10. While the general features such as the linear power dependence and the fact that sound pressure increases with frequency for given power level are consistent with our findings, those theories are not directly applicable to our experiment due to the patterning and the air bridges. Exact theoretical understanding of our device remains a future challenge. For comparison, in the nanotube experiment the authors find that $\alpha = 0.7 - 0.8$ while for thicker films Ref. 10 predicts $\alpha = 0.5$, which is not valid for thin films as pointed out in Ref. 12.

In conclusion, we have demonstrated that metal wire arrays can produce thermoacoustically high-pressure ultrasound with a sound pressure of 110 dB (6.3 Pa rms) at the distance of 8 cm when the applied power per area is about 0.6 W/cm². The key was the use of suspended wires that are thermally decoupled from the substrate. The same devices can also reproduce music using conventional audio equipment. Our devices may find use in directional ultrasound sources, phased arrays or even in some audible sound applications. Interesting directions to explore in the future include nanoscale suspended metallic wires or even the use of miniaturized thermoelectric coolers for sound production.14,15

We thank A. Oja, A. Luukanen, T. Varpula, J. Pekola, and J. Holmberg for discussions. This work is supported by the Academy of Finland.