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MEMS (Microelectromechanical Systems) Audio Devices- Dreams and Realities

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ABSTRACT

MEMS (microelectromechanical systems) technology is more than a scientific curiosity. Commercial MEMS products are being produced using semiconductor manufacturing techniques. What kind of audio devices can be made using this technology? Surveillance, hearing aids, and directional microphones spring to mind. Less obvious are ultrasonics, in-ear translators and surround-sound wallpaper.

The small size of MEMS devices brings up issues of physical limits and appropriate size scales for acoustic applications. MEMS microphone/speaker design involves many of the same issues as conventional microphones/speakers, but the scale difference changes their relative importance. Over the past four years, the MEMS lab at Carnegie Mellon University has developed both microphones and speakers using CMOS-MEMS micromachining, and the technology is being commercialized by Pittsburgh startup Akustica.

1. INTRODUCTION

At the end of 1959 Richard Feynman, in his famous lecture “There’s Plenty of Room at the Bottom”, put forth the challenge to write the Encyclopedia Britannica on the head of a pin [1]. As we well know from “Moore’s Law” [2], there’s been plenty of progress toward shrinking electronics. It is not as well known (to the average person) what has been happening in the last two decades in shrinking mechanical devices. More than a scientific curiosity or a “neat” technology to make tiny gears and motors [3], MEMS (microelectromechanical systems), or as it is known in Europe, “microsystems” is being used to make things for our everyday world.

Micromachined accelerometers, essentially tiny masses on tiny springs, are in almost every car built today, to sense collisions and fire the air bag [4]. Gyroscopes are also being developed along the same lines [5]. Video projectors are now being made using arrays of tiny mirrors, "digital multimirror devices" (DMD) that switch a light beam toward and away from the lens [6]. Chemical sensors detect poisonous gases by measuring the change in resonance frequency of tiny beams with coatings that bond to target chemicals [7]. One important theme (aside from being small) that ties all of these devices together is the use of techniques from semiconductor manufacturing to produce large numbers of devices with uniform quality. CMOS-MEMS, in particular, piggybacks on existing infrastructure for producing CMOS (complementary metal-oxide-semiconductor) chips, and thus gets a free ride as capabilities increase according to Moore's Law.

1. WHY MEMS AUDIO?

The small size of MEMS devices leads the audio-inclined to think about the possibilities for sound recording and reproduction. Some of these have a sci-fi feel to them: tiny microphones for spying; giant arrays of tiny speakers on flexible substrates to make surround-sound wallpaper; microphones and speakers integrated onto a single integrated circuit to form not just a hearing aid, but an in-ear MP3 player and - for a few more dollars- an in-ear translator.

Even if the above sounds far-fetched, there are demonstrable advantages of MEMS audio that are available at present. There is the economics of mass production using the existing semiconductor infrastructure, and the lack of assembly costs (e.g. no diaphragm tensioning). For example, the cost of producing a CMOS chip at the wafer scale is on the order of \$0.05/mm^2; packaging may add another \$0.02/pin-out [8]. For a microphone 5 mm on a side (which is quite large by MEMS standards) with 20 connections, this would be about \$1.65 per device. While this price may still seem high compared to something like an electret microphone, keep in mind there are performance benefits- the tightly controlled environment of semiconductor manufacturing produces reliability and uniformity between devices; because of the small size, microphones are easily designed to have small gaps and high resonance frequencies; circuitry integrated into the devices means less parasitic capacitance and EMI pickup.

New abilities that would be unheard of in a conventional transducer will also become possible for this same price, simply because of the large number of diaphragms that could be built on the same chip (diaphragms on MEMS microphones are usually on the order of about 0.1-1.0 mm across). "Brute multiplicity" can be employed to increase reliability by producing redundant elements, or to perform more creative tasks, such as directional sensing with multiple elements. The diaphragms, as a result of the uniformity of the semiconductor manufacturing process, will also be very uniform in their mechanical properties, which will facilitate making matching elements, for example for matched stereo pairs.

2. SIZE MATTERS

The small size of MEMS devices is attractive, yet brings up issues of physical limits and appropriate size scales for acoustic applications. Which scenarios are realistic? What physical limitations apply? Is smaller always appropriate and/or better? MEMS microphone/speaker design involves many of the same issues as conventional microphones/speakers, but the scale difference changes their relative importance. What is interesting is that while a small microphone element may have worse performance than a conventional-size element, for a given total area and rolloff frequency, it can be shown that an array of very small membranes can outperform a single large diaphragm in terms of noise floor, absolute sensitivity, and vibration rejection.

An important spec for microphones is equivalent input noise, usually given in terms of dB(A) SPL. For conventional microphones, larger diaphragms correlate with lower noise floors. This is due partly to the reduced thermomechanical equivalent input noise (essentially the diaphragm interacting with the Brownian motion of individual air molecules), but also to a large extent on the increased electrical capacitance facilitating the job of the preamp electronics. In the case of the micromechanical microphone, thermomechanical noise may become greater than electronic noise if the designer is not careful about the noise of the acoustic circuit as well. Attention must be paid to the acoustic resistances such as vents, and pressure equilibration holes. In analogy to electrical circuits, a "Johnson noise" is generated by the acoustic resistances. However, some interesting insights into the noise problem may be gained by considering the interaction of the compliance of the diaphragm and the acoustic resistances (the problem may be simplified even further by just looking at the mechanical response of the diaphragm alone). The equipartition theorem from thermodynamics allows us to estimate the noise energy in one degree of freedom of a mechanical system (e.g. the displacement of the diaphragm) as

1/2 $k_B T$ where k_B is Boltzmann's constant and T is the temperature. This noise energy will be distributed according to the frequency response of the diaphragm [9]. If we have a square diaphragm (α=0.0138) [10] with thickness t, Young's modulus E, and side length a, then we can compute that the total equivalent input noise p_{noise} is:

$$p_{noise}^2 = \frac{k_B T E t^3}{\alpha a^6}$$

This shows clearly that larger areas are better, which seems at first to be bad news for MEMS microphones. However, we can instead consider an array of diaphragms which fill an area $L*L$, and choose the size of the individual diaphragms to achieve a given cutoff frequency ω_0. When the signals from the individual diaphragms are averaged together, the noise power drops by a factor $N=(L/a)^2$. Then

$$p_{array}^2 = \frac{p_{diaphragm}^2}{N} = k_B T \frac{E t^3}{\alpha a^6} \frac{a^2}{L^2}$$

$$= k_B T \omega_0^2 (0.61) \frac{t\rho}{L^2}.$$

Now we see that for a given L and ω_0 the thermomechnical noise performance is determined by the areal density of the diaphragm, $t\rho$, that is the mass per unit area.

A similar analysis can be performed that shows the sensitivity, i.e. the change in capacitance with sound pressure is

$$\frac{dC}{p} = \frac{0.61 L^2 \varepsilon_0 \alpha}{g^2 \omega_0^2 t\rho}$$

where g is the capacitor gap and ε_0 is the permittivity of the space in the gap.

The vibration rejection, which compares the diaphragm displacement due to sound pressure compared to displacement due to inertial effects (e.g. shaking the microphone) also improves by using diaphragms of small areal density: The following relation expresses the ratio of diaphragm displacement due to sound pressure p over the displacement due to an acceleration x-double dot:

$$\frac{x_p}{x_{accel}} = \frac{p}{\ddot{x}} \frac{1}{t\rho}.$$

Because the sizes of MEMS microphone diaphragms (usually 2 mm or less) are much smaller than any audio wavelength of interest (17 mm), the shape of the diaphragm is not an issue; however, just like conventional microphones, diffraction effects from packaging may still be the dominating effect on frequency response. This effect was ignored in the above analyses.

MEMS speakers face greater challenges than microphones because of their small size. While the smaller diaphragms are advantageous for frequency response (unlike traditional speakers, the MEMS devices are operated below resonance frequency), they are inefficient at radiating acoustic energy. This is because the radiation impedance, the ratio of pressure to diaphragm displacement, becomes very small when the size of the diaphragm is much smaller than a wavelength. The resistive part of the force the diaphragm exerts on the surrounding medium, i.e. the part that determines the total radiated energy, is [11]

$$F = \frac{\rho_{air} \pi a^4 \omega^2}{2 c_{air}} v$$

where ρ_{air} and c_{air} are the density and sound speed of air, and a is the side of the diaphragm. v is the velocity of the diaphragm. Note the strong dependence on frequency, and even stronger dependence on size. This can be compensated somewhat by building large arrays of MEMS speakers, but it is always necessary to move a certain volume of air, regradless of the method. Therefore, MEMS speakers may be useful mainly for in-ear applications such as hearing aids and portable music devices.

3. OVERVIEW OF EXISTING DEVICES

There has been some work in recent years to produce MEMS speakers. Most have involved the use of piezoelectric materials and/or polymers deposited on a silicon substrate [12,13,14]. Geometries have included diaphragm structures, cantilever beams [13], and thermally actuated domes [12]. These devices work best at higher frequencies, and are aimed mainly at ultrasonic applications. In fact, the cantilever beam designs contain significant gaps around the vibrating structure which severely limit the response over much of the audio range. Work at Carnegie Mellon University [15] has focused on building sealed diaphragms in CMOS devices, which has the advantages of integrated electronics and a much simpler process flow than the others. The diaphragm skeleton is built out of the metal and glass layers of the CMOS chip, greatly reducing the layering ad patterning required, compared to other MEMS designs. The result is a compliant structure capable of large (on the MEMS scale) displacements on the order of tens of microns. Recently a large digital array of microspeakers has been demonstrated, which is audible at a distance of several feet [16]. Here again "brute multiplicity" is useful to circumvent the poor linearity of the individual elements; the number of elements determines the distortion of the total sound produced, not the quality of the transducer. Other than this development, it is not clear that MEMS is well suited for sound generation because large volumes of air need to be moved to produce appreciable sound. For speakers, frequency response aside, physics says that bigger is better.

Much more promising is the application of MEMS as sensors (microphones). A number of MEMS microphones have been built and tested using custom fabrication processes, usually using silicon or silicon nitride to form the diaphragm [17,18,19]. At least one design uses an electret material deposited on the diaphragm [20]. A very different approach is taken with the "microflown" (www.microflown.com), which uses no diaphragm, but instead directly measures the particle velocity of the air moving between two heating elements [21]. An even more radical design (but not completely MEMS) involves a micromachined mirror attached to a diaphragm. Modulations in the strength of laser light reflected through a fiber optic cable are translated into an electrical signal [22]. Recently another optics-based design was introduced, using vibrating polymer beams, which mechanically filter the incoming sound, and the beams act similar to fiber optics, modulating the light intensity as the tip of the beam moves back and forth relative to another beam connected to a photosensor [23]. A different approach is taken at Carnegie Mellon (and commercialized at Akustica, www.akustica.com), where a metal and oxide skeleton is covered with polymer to form the airtight diaphragm [16]. Micromachining CMOS chips has the advantages of integrated sensing circuitry and uniform quality.

4. HISTORY OF CMU ACOUSTIC MEMS

The history of acoustic CMOS-MEMS at Carnegie Mellon starts with the development of the CMOS-MEMS process around 1995 [24]. It involves the use of plasma etching of silicon and silicon dioxide, using the CMOS metal layers as masks to define the mechanical structures. This has some advantages over other types of MEMS fabrication. First, there is no need to develop a custom fabrication process, as the difficult job of depositing and patterning layers of material is handled by any standard CMOS fabrication house. This has positive implications for economics, performance and reliability. Second, because the mechanical structures are built directly out of the CMOS layers, integration happens naturally. Each beam in the structure can have multiple electrical conductors, which can be connected in a variety of 3-dimensional topologies, often to form capacitive sensors and actuators across gaps in the mechanical structures. Sensing circuitry can be placed close by (around 30-50 microns) to eliminate long wires which could contribute electromagnetic interference (EMI) or parasitic capacitance which would reduce sensitivity.

In 1999, the author devised a method to create large structures without the stress and buckling problems that plagued earlier CMOS-MEMS designs. The key to this was a serpentine mesh design which relieves both lateral (in-plane) and torsional stress [microspeaker paper]. An additional polymer deposition step added to the CMU CMOS micromachining recipe sealed the mesh skeleton to form an airtight diaphragm. This allowed membranes to be formed on CMOS chips that could be used for tactile actuators (for electronic Braille tablets), microfluidic valves, and of course microphones and speakers. A prototype earphone was demonstrated in late 2000 [15], which achieved an in-ear sound pressure level of about 80 dB. In late 2001 a microphone with frequency-modulated output was demonstrated [25] and a spin-off company, Akustica, Inc. (www.akustica.com) was soon incorporated to commercialize the technology. This prototype used the variation in the capacitance between the diaphragm and silicon substrate (about 0.5 pF) to modulate the frequency of a radio-frequency (100 MHz) oscillator. Measurements were made with an FM radio receiver. The commerciallized version of the technology uses a method similar to a traditional condenser microphone to measure the diaphragm capacitance.

5. FUTURE DEVELOPMENTS

In the immediate future, Akustica plans to develop microphones for cell phones and hearing aids. Other plans include noise-cancellation devices and multichannel directional microphones.

6. ACKNOWLEDGMENTS

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