THE ERA OF SILICON MEMS MICROPHONE AND LOOK BEYOND

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ABSTRACT

After having been long incubated originally for miniature hearing aid application, silicon condenser microphone found its adoption in mobile phone applications 12 years ago and has since then explosively grown to one of the most pursued products in the MEMS industry. Development of silicon MEMS microphone looks simple but has many intrinsically hidden issues and challenges to overcome and solve. Lessons and experience from both failed and successful developments will be shared. Future outlook of its application roadmap will be envisioned. As being driven by fast paced mobile phones and smart devices, silicon MEMS microphone may soon encounter its technical boundary and restraints. Potential disruptive solutions for sustaining growth will be discussed in this talk.

KEYWORDS

Silicon MEMS microphone, chip structural design, packaging, prospective technologies.

INTRODUCTION

Explosive Growth of MEMS Microphone

Silicon MEMS microphone has started a new era of MEMS technology in acoustic application since year 2003, being ranked as the 5th most successful commercial MEMS product in the history of MEMS following silicon piezo-resistive pressure sensor, thermal actuated microfluidic ink-jet printing head, capacitive accelerometer and gyroscope, and electrostatic micro-mirrors array in digital light projection. Originally, researchers from over the world were motivated to develop silicon condenser microphone for miniaturization to replace electret condenser microphone (ECM) used in hearing aid application. Meanwhile, it was also discovered that silicon microphone can sustain high temperature processing such as solder reflow and thus have potential application for highly automated surface mount assembly at low cost manufacturing [1]. Owing to this comparative advantage over ECM, it was only until year 2003 when silicon MEMS microphone was mature for mass production and consequently was promoted to mobile phone application. Since then, silicon MEMS microphone has been growing rapidly with its adoptions in a very wide range of applications such as telecommunications (mobile phones), computers (PDA, Laptop PC, Tablet PC, wearable computing devices), bluetooth headsets, hearing aids, consumer electronics (earphones, camcorder and digital camera), automotive voice control, etc.

Compared with ECM that is manufactured using precision engineering technology with the best accuracy at tens of micrometers, silicon condenser microphone is fabricated in sub-micron accuracy using silicon micro-machining processing equipment borrowed from CMOS IC fabrication process. For this reason, silicon microphones can have excellent matching in both sensitivity and phase frequency responses. This merit makes an additional strong boost to silicon MEMS microphone in microphone array application for beam forming sound detection as well as noise cancellation, where beam forming methods use the phase information of two or more microphone signals to selectively include a lobe in the desired direction and thereby increase the signal-to-noise ratio (SNR) of speech signal. Nowadays, microphone array with two or more microphones can be widely seen in most of smart phones, tablet PCs as well as headphones.

Bright Prospect of MEMS Microphone

Advances in fast-paced consumer electronics provide an unlimited sky for silicon MEMS microphone applications. One of major drives is voice recognition as a key tool for human-machine interface. For examples, voice input or command is highly desired as user interface for Internet of Things and voice signature could be used to enhance the security of on-line transactions over internet. Furthermore, application of MEMS microphone is being further extended from audible range to ultra-sonic range for gesture recognition and command.

Further research will be needed towards performance improvement, especially in SNR, as is required for voice recognition, voice signature, voice command and noise suppression in microphone array application. In parallel, MEMS microphone will be optimized with trade-off between performance and ultra low power consumption, which is highly demanded in most of wearable computing devices. Accompanying its increasing adoptions, MEMS microphone will further evolve itself towards cost competitive to ECM. For all these reasons, silicon MEMS microphone will still be one of the most pursued MEMS research & development topics in future. The objective of this paper is to provide a review of current technology, challenges as well as bottlenecks and then discuss about future possible directions in order to arouse further research interest.

MEMS MICROPHONE DESIGN REVIEW

Typical Structural Designs

MEMS microphone chip plays a role to convert acoustic pressure to capacitive signal. Despite of its various embodiments in material, configuration and fabrication, it is basically composed of a compliant diaphragm and a rigid perforated backplate that are spaced dielectrically with a certain air gap. In terms of direct impact to performance and reliability, primary design consideration is given to the diaphragm of MEMS microphone chip.

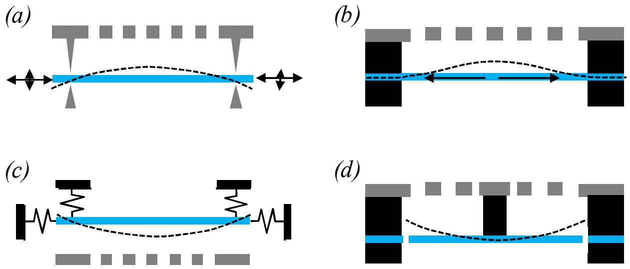

Figure 1: Typical diaphragm designs in MEMS microphone. (a) Free floating plate. (b) Tensile stressed plate. (c) Spring supported plate. (d) Center-supported plate.

Typical diaphragm designs are illustrated in Figure 1. Type (a) and (b) diaphragms can be widely seen in most of commercial viable MEMS microphones in market. In terms of reliability to impact proof, type (a) is the best design because it is free from lateral constraints so as to yield easily and avoid breakage due to excessive stress. In contrast, type (c) is weak in its supporting springs for impact proof. Type (d) is a feasible design concept.

MEMS microphone can be also designed to have diaphragm and perforated backplate combined together as shown in Figure 2. In such a configuration, diaphragm moves together with attached perforated plates, generating capacitive change against conductive substrate [2].

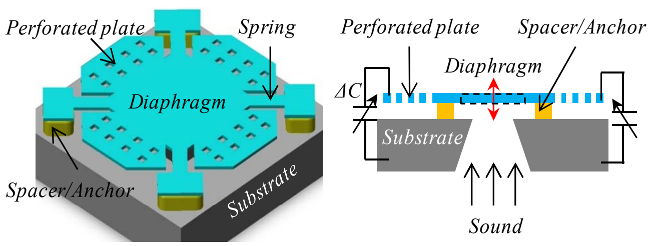

Figure 2: MEMS microphone without dedicated backplate.

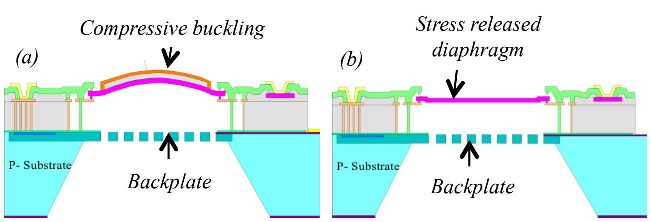

Figure 3: A MEMS microphone with an ultra-large diaphragm. (a) pre-buckled diaphragm counterforces to sticking. (b) diaphragm is released after removal of stress layers.

In a pursuit of ultra-high sensitivity performance, a silicon microphone was designed to have a size of 2000 µm in diameter and a thickness of 3 µm [3]. Such an extremely compliant diaphragm may be easily stuck to its backplate in wet sacrificial release process. To solve this issue, a pre-buckled diaphragm with composite stressed layer was designed to counterforce surface tension and thus induced sticking, as shown in Figure 3(a). After release and drying process, a flat diaphragm was formed by removal of the composite stressed layers, as shown in Figure 3(b).

For improvement of SNR, multiple microphones can be simply put together in parallel connection. As shown in Figure 4, four acoustic sensing elements are combined with parallel connection onto a single chip. In this way, microphone sensitivity remains unchanged but overall acoustic noise drops by 6 dB.

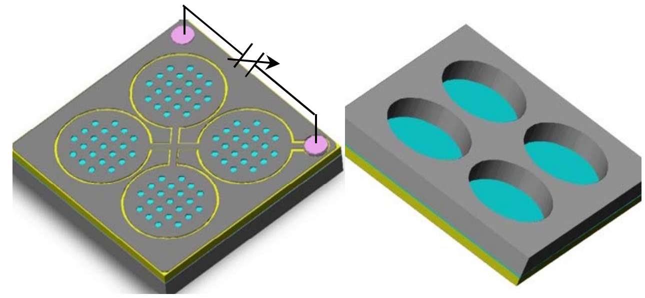

Figure 4: The 4-in-1 combination for SNR improvement .

Another way to improve SNR is to design a differential structure such that microphone have differential output. As shown in Fig. 5 (a), a differential sensing scheme can have double signal output at cost of noise increased to $\sqrt{2}$ times, thus making SNR improved by 3dB. Figure 5(b) shows a double backplate differential structure [4] and Figure 5(c) illustrates a double diaphragm differential configuration [5].

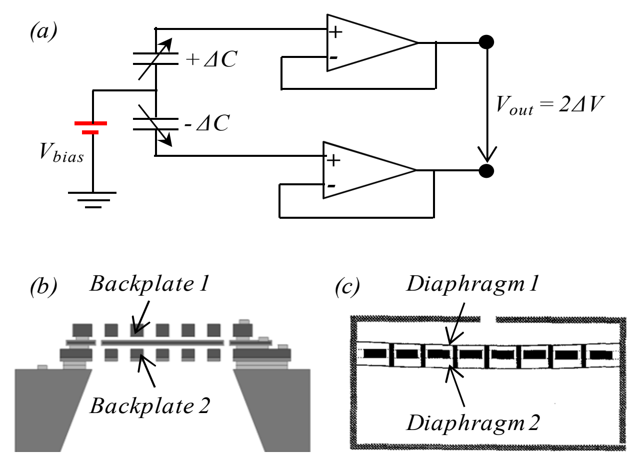

Figure 5: Differential structures for SNR improvement.

In microphone design, parasitic capacitance should be always minimized. Non-movable structural portion such wire bonding pads and anchors form non-contributing parasitic capacitance that decreases microphone sensitivity and SNR. As shown in Figure 6, an effective way for parasitic reduction is to introduce guarding layers biased at the same voltage potential as backplate to shield off the areas of parasitic capacitors.

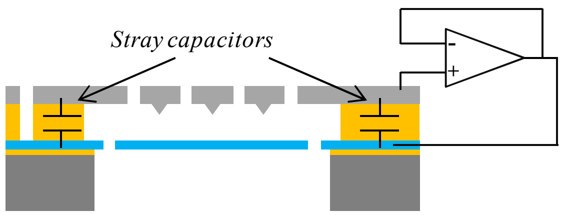

Figure 6: Guarding layer to shield away parasitic.

A good microphone design should tolerate fabrication process variation as much as possible. For example, the backhole formed in silicon substrate by either wet etching methods (KOH or TMAH) or dry etching (ICP) is very inaccurate as compared to other structural features fabricated using sub-micron processing. Figure 7 shows a design to tolerate processing window for backhole.

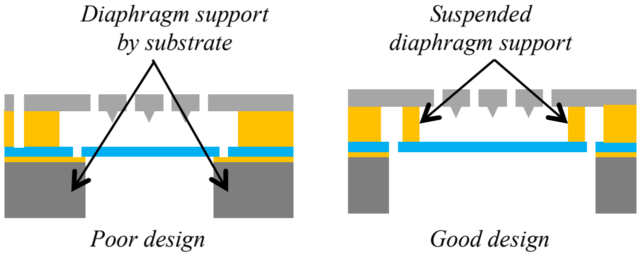

Figure 7: Design to tolerate backhole processing variation

Structural Designs for Challenging Applications

Silicon MEMS microphone is required to meet not only desired electro-acoustic performance but also challenging reliability requirements, which are sometimes considered beyond physical limit for acoustically sensitive device. Typical mechanical robustness related reliability requirements include shock test, drop test and air blow/suction test, where DUT microphone is subject to extremely high impact on its compliant but fragile diaphragm as well as backplate. For those bottom ported microphones where diaphragms are directly facing to inlet sound port, fragile diaphragm or even backplate can hardly survive from sound pressure impact with extremely high level and sharp rise time.

To survive from these harsh requirements, one of design solutions is to introduce a silicon plate between MEMS chip and sound port, which has multiple holes offset away from its center. As shown in Figure 8, any sound pressure impact can be diverged and damped [6].

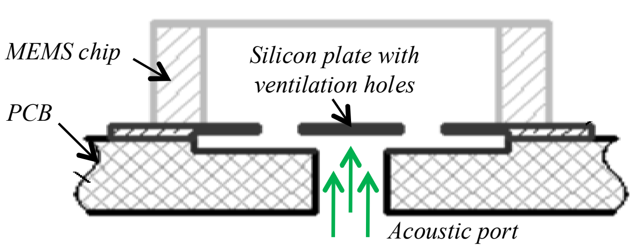

Figure 8: Silicon plate with offset holes to diverge pressure impact.

Figure 9 shows another method to improve the robustness of fragile diaphragm by introducing a stopper structure so that the diaphragm is reinforced and restrained from excessive movement under pressure impact [7].

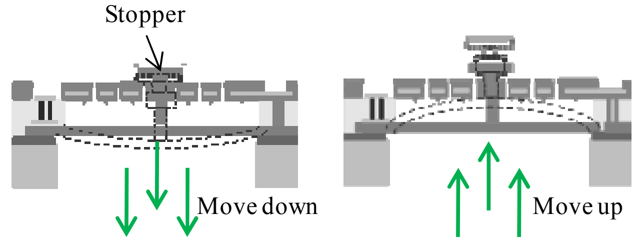

Figure 9: Stopper structure for robustness improvement.

A shutter structure is conceptualized as shown in Figure 10 to serve as a valve that can be closed at beginning of sound/pressure impact, thus protecting fragile diaphragm from experiencing impact at peak level [8].

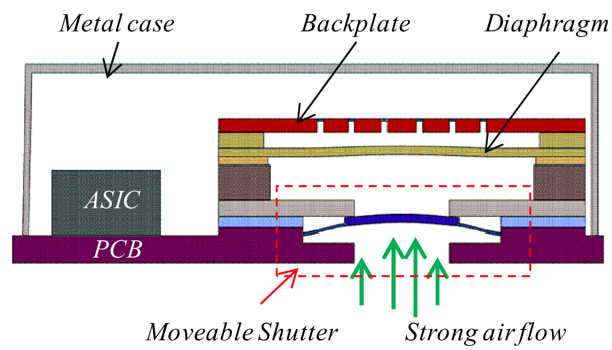

Figure 10: Shutter valve to shield off pressure impact.

In addition to robustness related reliabilities, MEMS microphones are required to survive without significant performance shift for other environmental reliabilities such as damped heat, water proof as well as harsh ESD test, etc. In most of reliability tests, microphones are required to be powered on. These all are presenting major challenges in design of MEMS microphone.

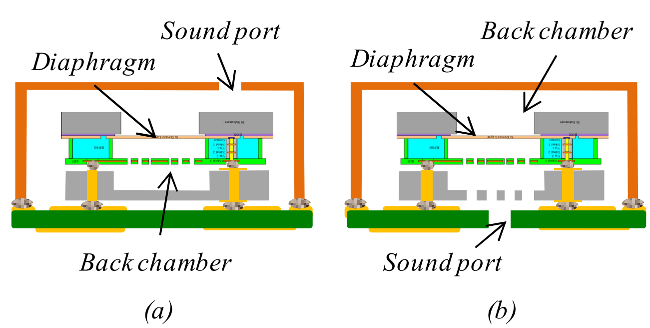

Figure 11: Package shrinkage with wafer-level packaging for (a) top port packaging and (b) bottom port packaging.

Though MEMS microphone brings the merit in small form factor, further size reduction is still a general trend for microphone packaging. In addition to shrinking MEMS and ASIC chips, the space taken by interconnecting wirings between discrete MEMS and ASIC chip as well as between ASIC and PCB needs to be reduced or even eliminated. It is foreseen that flip chip technique will be employed to eliminate the need of wire bonding. Figure 11 shows a concept of using wafer level packaging technique for chip interconnection and a silicon carrier with through-silicon via (TSV) for chip to PCB interconnection [9].

Approaching Bottleneck

For the current MEMS microphone typically composed of diaphragm and perforated backplate, its acoustic noise is mainly decided by design of air gap and perforated holes. Given other performance and reliability requirements as well as fabrication constrains, structural design window becomes very limited, making acoustic noise performance of MEMS microphone is now reaching its bottleneck.

FUTURE MICROPHONE TECHNOLOGIES

Monolithic MEMS Chip Microphone

In current technology, MEMS and ASIC chips are discrete and interconnected using bonding wires. Bonding pads and their electric lead-outs on both MEMS and ASIC chips requires spaces and cause parasitic. Moreover, bonding wires between MEMS and ASIC chips form an antenna susceptible to electro-magnetic interference. To avoid these issues, CMOS compatible MEMS microphone structure that can be integrated with CMOS circuits on a same substrate should be a research topic deserving more attentions.

Other Technologies for Microphone

In current configuration with diaphragm and backplate, acoustic noise is contributed largely by air ventilation resistance through perforated holes on backplate as well as thermal noise in air squeezed film between backplate and diaphragm. Some acoustic transducing methods that eliminate the need of backplates include field effect transistor microphone and magneto-resistive (MR) microphone, the former employs a silicon membrane as vibrating gate that causes drain current change, the later measures resistive change of MR film on a vibrating diaphragm in presence of magnetic field.

Another technology for backplateless microphone is piezoelectric microphone where piezoelectric film deposited on deforming diaphragm converts stress change to charge output signal. With advances in processing equipment and design optimization, it is expected that aluminum nitride based piezoelectric microphone could be promising to make a breakthrough in commercialization.

SUMMARY

Silicon MEMS microphone technology has advanced dramatically since its adoption by mobile phone application 12 years ago. Various improvements have been achieved in MEMS microphone chip, ASIC chip as well as packaging method for both performance and reliability requirements. However, current MEMS microphone technology is also facing some major bottlenecks in view of increasing demands and broadening applications. Through reviewing key aspects in current technology and discussing potential breakthrough technologies, the author of this paper hopes to attract more research interests so that silicon MEMS microphone technology could move further to a new stage.

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