SiSonic™ – THE FIRST COMMERCIALIZED MEMS MICROPHONE

Peter V. Loeppert and Sung B. Lee
Knowles Electronics, LLC
Itasca, Illinois USA

ABSTRACT

The Knowles SiSonic™ MEMS microphone has been successfully commercialized for use in cell phones, cameras, PDA's, and other high volume consumer electronics. One advantage that MEMS microphones have over traditional Electret Condenser Microphones (ECMs) is the ability to be reflow soldered. Cost is a significant driver in the design of a MEMS microphone. SiSonic™ uses a non-integrated approach to MEMS and CMOS while minimizing both die sizes. Key to the small MEMS die size is the use of a simply supported freeplate diaphragm. The CMOS die has been optimized to work with very low input capacitance. A low cost package has been developed utilizing laminated FR4 PCB material. The microphones are 100% tested on a high speed automated acoustic test station.

INTRODUCTION

The Knowles SiSonic™ MEMS microphone is targeted towards high volume consumer electronic products where price is a key factor. In 2005, about 2 billion microphones of all types were produced including about 1 billion for cell phones, cameras, computers, etc. These later products use Electret Condenser Microphones (ECM's) produced by a number of low cost Asian suppliers. For a MEMS microphone to compete effectively in this market, it must at a minimum, meet the performance, reliability, and price expectations set by the ECM suppliers. However MEMS microphones have one distinct advantage over current ECM's; that is the ability to withstand lead-free solder reflow cycles. This ability permits the MEMS microphone to be pick and placed like any other component and thus leads to significantly lower manufacturing costs for the integrator. SiSonic™ is the first MEMS microphone to meet all of these requirements and gain significant market share.

MICROPHONE OVERVIEW

SiSonic™ is a condenser microphone comprising a MEMS die and a CMOS die combined in an acoustic housing. The condenser or variable capacitor consists of a highly compliant diaphragm in close proximity to a perforated, rigid backplate. The perforations permit the air between the diaphragm and backplate to escape. Together, the diaphragm and backplate pair is referred to as the motor. As shown in Figure 1, the motor capacitance couples a voltage source to a high impedance amplifier.

Figure 1. Condenser microphone schematic diagram.

The capacitance of the motor in conjunction with the amplifier input resistance forms a high pass filter with a -3dB point well below the audio band. Thus within the audio band the motor is operating in constant charge mode and the sensitivity of the microphone can be represented as follows:

$$S = \frac{\Delta V_{out}}{\Delta P} = \frac{V_{bias}}{C_{motor}} \cdot \frac{\Delta C_{motor}}{\Delta P} \quad (1)$$

where ΔP is sound pressure

If the distance (gap) between the diaphragm and the backplate is d and the sound pressure causes a change in the gap, Δd , the sensitivity can be approximated as:

$$S = \frac{V_{bias}}{d} \cdot \frac{\Delta d}{\Delta P} \quad (2)$$

The first term is the electric field in the gap while the second term is the mechanical compliance of the diaphragm. In an ECM, the bias voltage is typically several hundred volts and comes from a permanently charged electret layer. The gap is usually tens of microns so the resulting electric field is on the order of 10-15 V/ μ m. The bias voltage in a MEMS microphone is typically derived from the power supply and the gap is much smaller so the resulting electric field is on the order of 2-4V/ μ m. This means that to achieve a similar sensitivity the diaphragm compliance of the MEMS microphone must be several times larger than that of the ECM diaphragm.

MEMS DESIGN

Since cost is the key factor for SiSonic™, the MEMS die size and hence the diaphragm area must be minimized. At the same time the motor capacitance must be adequate to drive a CMOS amplifier. Achieving consistently high diaphragm compliance has been the major roadblock to developing a successful MEMS microphone. Sessler [1] reviewed a number of important development programs throughout the 1980's and early '90s. All used diaphragms with fully clamped edges and most were tensioned by the intrinsic stress in the film from which the diaphragm was formed. It was recognized during this period that controlling the tension was a critical factor and is all the more critical for very small diaphragms [2].

To achieve a consistently high compliance with a small diameter, a diaphragm with a simply supported boundary condition was chosen for SiSonic™. This diaphragm depends on plate bending forces [3] rather than tension as the restoring force and is referred to as a free plate diaphragm. Thickness control is essential in this type of diaphragm and fortunately this is routine in thin film deposition. The SiSonic™ freeplate diaphragm has a half millimeter effective diameter and is made of 1 micron thick poly silicon. It is suspended above a through hole in the wafer and separated from the backplate, which is 4 microns above it, by a

series of support posts. Figure 2 shows this schematically. The freeplate design releases all intrinsic stress in the poly silicon. For this diameter a tension as small as 1MPa would reduce the diaphragm compliance by 3dB.

Figure 2. MEMS microphone cross section.

Equation 2 indicates a tradeoff between electric field and compliance for a given sensitivity. The limiting factors are dynamic range and electrostatic stability. SiSonic™ operates with an 11V bias across the 4 micron gap. There is no limit to the transient pressure to which a microphone can be exposed. In light of this, the small gap, and the limited non-linear stiffening of a freeplate with deflection, there is a real possibility of electrostatic collapse. SiSonic™ has over pressure stops built into the 1.5 micron thick silicon nitride backplate. These stops make the motor unconditionally stable at the operating bias by limiting the diaphragm travel towards the backplate. Poly silicon on the underside of the backplate serves as the stationary electrode of the capacitor. The perforations in the backplate serve to damp the diaphragm motion. The SiSonic™ MEMS process is a custom 10 mask, dual poly process produced for Knowles primarily by Sony Semiconductor in Japan. Figure 3 shows a plan view of the MEMS die while Figure 4 shows details of the various features. Table 1 summarizes the MEMS design parameters.

MEMS die size	1.651 x 1.651	mm
Diaphragm thickness	1	μm
Effective diaphragm diameter	560	μm
Gap	4	μm
Backplate thickness	1.5	μm
Over pressure stop height	1	μm
Damping hole size	4	μm
Damping hole fraction	22.8	%

Table 1. MEMS design parameters

Figure 3. MEMS motor

Figure 4. MEMS motor details

CMOS DESIGN

The SiSonic™ motor capacitance is only 0.5pF. The CMOS amplifier must be able to accept the millivolt level signal from the MEMS die with minimal loading and buffer the signal to drive the next chip in the audio path. As shown in Figure 5, the SiSonic™ CMOS chip does this in two stages. The first stage is a unity gain buffer with an input capacitance of 0.25pF and an output impedance of several thousand ohms. The second stage is a typical opamp connected in a non-inverting configuration. This stage can be externally configured for 0-20dB of gain. The output of the first stage is fed back to the MEMS die to guard out the approximately 0.2pF of parasitic capacitance associated with the bond pad. Without the guarding, sensitivity drops by 2-3dB.

The CMOS die also must supply the 11V bias supply. Since the microphone presents a purely capacitive load, the charge pump used to generate the bias voltage is quite small. However this does mean that the CMOS process must contain a high voltage option. The SiSonic™ CMOS die is currently being made in both a 0.8 micron and a 0.35 micron process at Austria Micro Systems.

Integration vs. non-integration of MEMS and CMOS is a constant theme in the community. If the cost of a silicon chip in general is related to the product of its complexity, in number of masks, times the chip area, the decision will almost always be not to integrate. This is the case for SiSonic™. The performance improvement attainable through integration is negligible since the

parasitic capacitance is guarded out. The cost of bonding two die instead of one is also small compared to the higher yield achieved individually and the much shorter design cycles possible as separate die.

Figure 5. CMOS block diagram

PACKAGING

The SiSonic™ package must be extremely low cost, provide open access for the MEMS die to the environment, yet protect the MEMS and CMOS die both physically and from electromagnetic radiation. This has been accomplished, as illustrated in Figure 6. The package consists of a base, a wall, and a lid all made from FR4 PCB material and laminated together. The inside surfaces are plated to provide a Faraday shield against EMI interference.

The two die are adhesively bonded to the base. Gold wire is thermo-sonically bonded between the two die and between the CMOS die and the base. The MEMS die has gold pads so corrosion is no issue however the CMOS die has standard aluminum pads. An opaque silicone encapsulant is used to cover the CMOS die to prevent moisture from entering and causing corrosion on the CMOS pads. The encapsulant also blocks light from reaching certain sensitive nodes in the CMOS circuit. Figure 7 shows a photo of the package with the lid removed.

Figure 6. Microphone package cross section

The MEMS die is actually a differential pressure sensor and needs a reference pressure against which the tiny acoustic signal can be measured. The back volume under the MEMS die serves this purpose. Pressure equalization is accomplished at sub-audio frequencies by the flow of air around the diaphragm and into the back volume.

The acoustic port is offset from the MEMS die to prevent dirt accumulation or physical damage to the die. The acoustic port in conjunction with the front volume around the two die form an acoustic resonator with a peak frequency around 14KHz. With the lid removed, the frequency response is virtually flat throughout the

audio band. Figure 8 shows the frequency response of a microphone with and without its lid.

Figure 7. Photo of microphone package with lid removed

Figure 8. Frequency response effect of front cavity

Packaging is performed on 4" by 4" panels containing hundreds of microphones. The panel size is limited by the stage travel limits of typical wire bonders. Only standard semiconductor packaging equipment is used in the assembly of the microphones. When a panel is complete, it is mounted on a dicing frame and the microphones are singulated with a diamond dicing saw. Figure 9 shows a completed panel ready for testing.

Figure 9. Panel of microphones ready for testing

TESTING

The SiSonic™ microphones are 100% tested using a custom test system to determine sensitivity as a function of frequency and self noise level. The system, shown in Figures 10 & 11, tests 12 parts at a time.

Figure 10. Test system

Figure 11. Close-up of test head with microphones in place

Each microphone to be tested is placed within a pressure cavity containing a microspeaker and a 1/4" B&K reference microphone. The first step of the test is the application of a pseudo random noise signal to the microspeaker and the calculation of an FFT to determine the response of each microphone's output relative to the reference microphone. The second step of the test requires muting the microspeaker and the measurement of the self noise of each microphone. The 12 parts are then removed from the test head and sorted into 3 grades plus a reject bin based on the measured sensitivity and noise. Rejects are categorized to provide feedback to the assembly line. For instance, a high, low frequency roll-off point indicates an acoustic leak at the MEMS die bond site. This is most likely caused by inadequate die bond adhesive. The tester averages one part per second for a capacity of nearly 2.5 million parts per month.

CONCLUSIONS

A MEMS microphone has been successfully developed for high volume consumer applications. Cost has been optimized at every step including minimizing die sizes, making maximum use of automated, batch assembly of the microphone packages, and

utilizing standard equipment wherever possible. With careful attention to detail, MEMS technology is once again displacing older, entrenched technology.

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