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Integrated Circuits for High Performance Electret Microphones

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ABSTRACT

Electret condenser microphones (ECM) are used in almost every consumer and communication audio application with total yearly volume of well over one billion units. Over the years, ECM innovation has concentrated mainly on lower production cost and smaller sizes, but improvements of sensitivity, signal-to-noise ratio (SNR), linearity and supply current have not been addressed.

In this article, we introduce significant innovations to ECMs through new amplifier IC and package designs. First, we describe current ECMs using junction field effect transistors (JFETs), focusing on advantages and drawbacks. After that, we discuss two analog amplifiers replacing the JFET in an ECM, showing the performance improvements achieved. Finally further innovation through complete Analog to Digital conversion inside the ECM is presented.

1. INTRODUCTION

Electret Condenser Microphones (ECM) are used in almost every consumer and communication audio application. The total yearly volume of all ECM's is well over one billion units. Over the years, innovation in ECM's has concentrated mainly on lower cost production and smaller sizes.

In this paper we introduce significant innovations to ECM's through new amplifier IC and package designs. First, a description of current ECM's using Junction Field Effect Transistors (JFET) is given, showing its functionality inside the ECM. Then, the challenges of integrating an amplifier IC inside an ECM are discussed. Next, further innovation through complete Analog-to-digital conversion inside the ECM is presented. Finally, some measurement results of the created products are shown.

2. Current Electret Condenser Microphones

The most commonly used ECM's consist of a JFET inside an electret microphone canister, which acts as a buffer between the capacitive sensor and the output. JFET's are small, three-terminal devices that have been improved toward very small, low cost plastic packages. This enabled the main innovation of ECM: their increasingly smaller sizes. Currently, ECM's as small as 2mm in height are common. With a stack of condenser microphone plates and spacers, this requires packaged JFET's as small as 0.5mm in thickness. A cross sectional view of a typical ECM is shown in Figure 1.

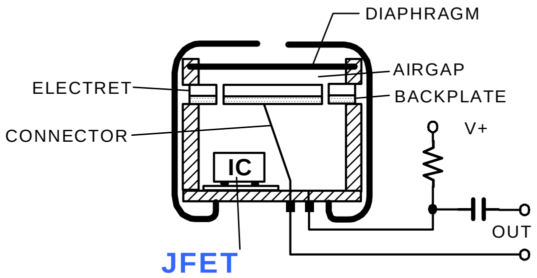

Figure 1. Typical cross section of an ECM with JFET buffer and Phantom Biasing

2.1. Biasing And Interfacing The ECM

An Electret microphone consists of a *pre-charged, non-conductive* membrane between 2 plates that form a capacitor. One of the plates is fixed and the other plate moves with sound pressure. Movement of the plate results in a capacitance change, which in turn produces a change in output voltage due to the charge on the membrane. An electrical representation of such an acoustic sensor consists of a signal voltage source in series with a source capacitor. The most common method of interfacing this sensor has been a high impedance buffer/amplifier. A single JFET with its gate connected to the sensor plate and biased as shown in Figure 1 provides the following properties:

2.1.1. *Signal Buffering*

The high input impedance of a JFET gate provides a good interface to the capacitive sensor, and the relatively low resistance connected to the drain provides sufficient output drive toward a signal-conditioning block such as an ADC.

2.1.2. *High Pass Filtering*

Audio microphones need high pass filtering with a cut-off frequency around 100Hz to attenuate large low frequency signals. The input impedance of a typical JFET is around a few 100 MΩ, which, with a typical source capacitance of an electret microphone, results in a high pass frequency of a few 100 Hz.

2.1.3. *Self-Biasing Of Active Component*

The gate of a JFET is a reverse biased diode, which has some small leakage. This leakage current makes the DC gate voltage settle around 0V, which is the preferred bias condition for this device. Large overdriving signals are either clipped by the reverse leakage or the forward conduction of the gate diode.

2.1.4. *External Phantom Biasing*

The method of biasing and interfacing the ECM, called "phantom biasing" through a load resistor of a few kΩ, and a series capacitor enables a very efficient ECM design with only 2 connections: GND and signal/bias (see also Fig 1.). This enables very low cost ECM's for high volume applications.

The main benefits of this type of ECM are its small size, low cost and relatively low noise. However, the combination of a single JFET and low load resistor results in a low gain (typically -3 dB) and therefore low sensitivity of the ECM. Also JFET's are inherently non-linear (THD of 1-10% typical) and have a large spread on their supply current, due to process spread in threshold voltage.

Having a low sensitivity of the ECM results in small output voltages of the sensor (on the order of 0.1-10mV average, 100mV peak). To make such a microphone work in a system (such as a mobile phone) requires careful board design, along with additional filtering components, to keep a reasonable signal-to-interference ratio. In systems such as wireless communication devices, significant interference is present due to RF transmission and high speed digital processing. Also, to supply a proper signal to an Analog-to-Digital (ADC) converter, pre-amplification is necessary.

Harmonic distortion makes it difficult to design complex audio systems, such as echo cancellation, or achieve Hi-Fi audio specifications.

A large and varying supply current affects battery life in handheld systems, resulting in lower audio performance or talk time in the case of mobile phones.

3. Analog Pre-Amplified Microphone

The above-described disadvantages of ECM's using a single JFET can be addressed through more complex amplifier circuitry. Over the past decades, low cost amplifiers have been improved significantly. Innovation in circuit techniques, such as overall feedback around a block with large open loop gain have improved THD and gain accuracy. Furthermore, semiconductor devices have become much smaller and faster, resulting in increased signal bandwidth at much reduced supply current. It has been feasible to create a pre-amplifier with large gain, low THD and sufficient bandwidth at very low supply currents. There have been many examples of these circuits, both in research and in products, for application in hearing aids [1,2], and as integrated pre-amplifiers for Analog-to-Digital converters in (mobile) communication systems [3]. A few stand-alone Hi-Fi microphones have also employed extensive amplifier circuits for improved sensitivity, lower THD and rejection of environmental variations [4,5].

As discussed earlier, the enormous rise in popularity of the ECM, as a microphone device in various applications, was driven mainly by the very cost effective manufacturing capability as well as a constant evolution toward smaller sizes, fitting very well with the explosive growth of handheld and portable devices. In the meantime, despite the increasing packing density of electronic circuits on a chip, a fully packaged product such as a high input impedance amplifier does not fit inside the microphone canister. Furthermore the by now well established standard 2-wire interface to a ECM (see Figure 1) is not well suited for general purpose amplifiers, using separate supply, ground, output and input pins. The smallest amplifiers than can be produced at very low cost currently use a 5 lead plastic package with a maximum thickness of about 1.1mm [6]. To enable the integration of high performance amplifiers into the mainstream microphone canisters, the packaged thickness of a device must be below 0.5mm, with a possibility to reduce this further along with the ECM development. Secondly amplifier circuits need to be developed that can provide the expected improvements, while maintaining the interface to the electret and the phantom biased 2-wire connection.

4. Thin packaging

A cost effective way to manufacture complex IC's for placement inside an ECM has been developed through *chip scale packaging.* The advantage of this approach is the lack of a leadframe, bondwires and plastic encapsulation of the IC. The micro-SMD package [7] is essentially no larger than the IC thickness plus a back-coating. By back-grinding the IC before applying solder bumps and back-coating, final product thickness of less than 0.5mm can be achieved. The common way of packaging of IC through plastic encapsulation, results in a stack of leadframe, IC, bondwire and plastic encapsulation, which makes achieving this thickness more difficult.

5. Amplifier circuit design

For the discussion of the design considerations of amplifier circuit than can directly replace a JFET inside an ECM the application of a microphone commonly used in mobile and cordless telephones is kept in mind. From this application constraints of supply voltage, signal bandwidth, maximum SPL value and interface are derived in Table 1.

Property	Unit	Value	Comment
Supply voltage	V	1.5 – 3	2V typical
Supply current	μA	200 – 300	Set by Phantom biasing Resistor
Interface Resistor	kΩ	2	
Maximum Sound Pressure (SPL)	dB	108	For THD < 0.5%
ECM sensitivity	dBV	-44	Without JFET gain
Signal to Noise (SNR)	dB	55	With typical JFET

Table 1. Typical ECM properties in Mobile Telephones

In an advanced BiCMOS technology, creating high input impedance, low input leakage is relatively easy, as CMOS devices have near ideal high input impedances at low frequencies. Also creating a low input capacitance to minimize signal loss from the electret capacitor is possible. However this high impedance node should be biased such that the complete circuit is a linear operating mode, as well as have fast recovery from overdrive signals. A JFET has a natural small leakage because of the reverse biased diode acting as the gate. This diode also acts as a clamp for overdrive signals. Finally, a properly designed JFET has an equivalent input resistance of a few hundred MΩ, which, together with the electret capacitance, forms a very desired high pass filter with cut-off frequency of about 100Hz. Especially close-talking microphones receive unwanted large low frequency signals due to wind or the breath of a person speaking into it. For this application, even higher order filters around 100Hz are desirable. These properties combined into a single JFET are not easily realized in a modern-day BiCMOS technology. The reported solutions either have a large resistor of several 100 MΩ, which is difficult to integrate [5], or use some active resistor to achieve this [1]. Using a

BJT instead of a MOS device is difficult because the need for a base current while the input impedance is greater than 150MΩ. In reference [8], finding the optimal value of this resistor in an ECM consisting of a single FET buffer is discussed.

One way to overcome this problem and have more freedom to create a high pass filter with a separate resistor and capacitor is to first buffer the electret capacitor with a MOS follower, followed by a filter stage and a gain stage. A set of small back-to-back diodes form a low capacitance biasing and fast recovery circuit for the input MOS follower.

Because in a phantom biased configuration the power supply node and output node are connected together, a conventional amplifier cannot be applied. Having the supply line also carry the output signal requires a large PSRR to avoid signal dependent feedback, which deteriorates the THD. Also the output signal should be DC biased to a point preferably exactly between the minimum and maximum output voltage. This maximizes the possible output swing. In a phantom biased configuration, the maximum output voltage is simply the available supply voltage. The minimum output voltage is determined by the minimum operating voltage of the amplifier.

All these requirements lead to a low voltage amplifier design with high PSRR, and built-in offset. The available swing for a given target supply voltage sets an upper limit to the gain of the amplifier. Given a maximum SPL of the application and a typical sensitivity, a voltage gain of around 20dB is achievable. Other applications, resulting in lower signal levels on the electret capacitor can enable higher voltage gains. For the feedback amplifier, the upper limit is only a function of gain accuracy and AC loop gain. Figure 2 shows a block diagram of the designed amplifier.

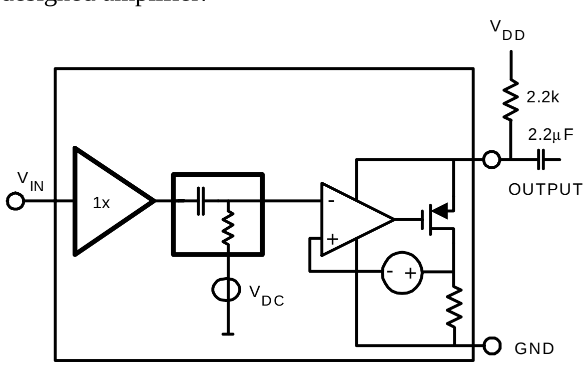

Figure 2. Block diagram of a phantom powered Amplifier

It shows the input buffer, followed by a filter stage, consisting of a large capacitance and resistance. Large low-frequency signals are attenuated before they reach the amplifier. This way, the amplifier cannot easily be saturated through large low-frequency signals. At the output a transconductance stage creates an output current which flows through the load resistance. The transconductance is set such that the overall voltage gain is around 20dB. A low THD is achieved through feedback around the gain stage, where the output signal is large, while the input buffer only has small signals, keeping a linear transfer.

One final challenge of a phantom bias configuration is the sensitivity to RF interference. Since the output node is also the supply rail, RF signals coupling into the output pin are easily coupled into the circuit. Careful design and decoupling needs to be applied to maintain sufficient RF immunity.

6. Digital pre-amplifier microphone

Almost every audio application will convert the input Audio signal into a digital representation to further process the information. With the right packaging and IC technology it is therefore a natural progression to perform this ADC function also inside the ECM, yielding a very robust and flexible sensor component. Some of the system considerations and overall ECM performance are discussed below.

6.1. System Partitioning

Most common (integrated) systems will pre-amplify the audio signal, and use an *over sampled Sigma-Delta converter* followed by digital filtering to process the analog audio input. The pre-amplification and Sigma-Delta conversion is usually fixed in gain and sample frequency, while the digital filtering is adaptable to enable software customization and real time adaptation.

From this viewpoint it is important to have the correct level of functionality inside the ECM. While an increased signal processing inside the ECM and a simple, digital interface is desired, user customization should be possible. Moreover it is clear that Digital Signal processing benefits from different IC technologies (e.g. deep sub-micron CMOS) than Analog to digital conversion.

For these reasons a product was developed which integrates an analog preamplifier, and an over sampled Sigma-Delta modulator into a single IC, which fits inside the ECM canister. The interface consists of an Analog supply and ground, an input clock signal and output data signal. The DSP module should provide the clock signal and the data signal forms the input to the DSP module's digital filter and further processing of audio signals. This is illustrated in Figure 3.

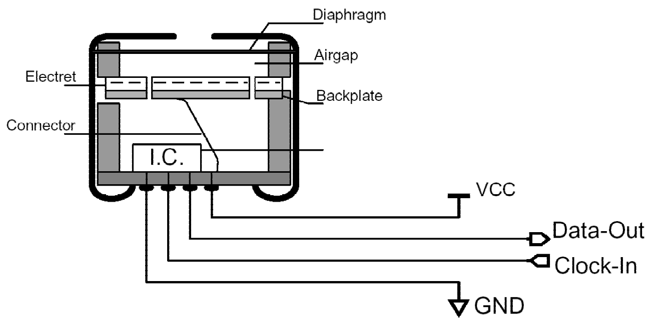

Figure 3. Cross section of digital ECM

7. Product results

Three ICs were designed, produced and subsequently built inside a commercial available ECM.

7.1. Two-Wire, Direct Replacement for JFET ECM

For the two-wire ECM application, the Amplifier design goal is to be 100% compatible with JFET ECM's: simply replacing the JFET for a pre-amp that works with a phantom biased interface can bring improvements in sensitivity, gain and THD. The resulting product, LMV1012 [9] has about an 18dB gain increase over the same ECM with a JFET inside [10]. Output swing levels at the maximum Sound Pressure Levels (SPL) set this gain. For a close-talking microphone and a 2V supply voltage, higher gains (although easily implemented) will result in clipping of the audio signal. The THD is below 0.5% over the complete output range and the supply current is around 300µA. The block diagram of LMV1012 is shown in Figure 2. A typical frequency response of an ECM with LMV1012 is shown in Figure 4. The significantly increased sensitivity is clearly seen.

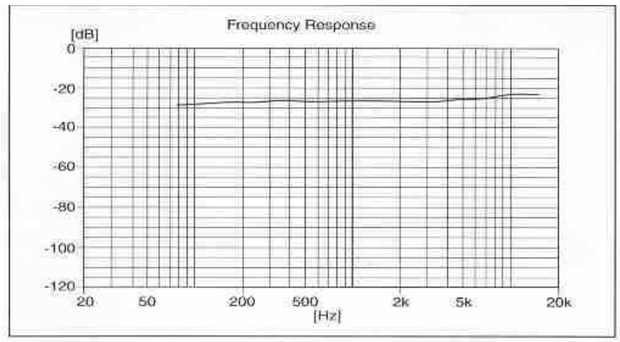

Figure 4. Frequency response of BSE OBBG-0615S/622S ECM with LMV1012

Some additional microphone specifications are shown in Table 2.

	Condition	OBBG-0615S	OBBG-0622S
Sensitivity	f = 1KHz, S.P.L. = 1Pa 0dB = 1V/Pa	-27±3dB	
Impedance	f = 1KHz	2.2KΩ Max.	
VDD		2.0V	
IDD	VDD = 2.0V, RL = 2.2KΩ	170~250µA	
SNR	S: f = 1KHz, S.P.L. = 1Pa N: A-weighted curve	〉70dB	

Table 2. Specifications of a commercially available ECM with LMV1012.

7.2. Three-Wire, High Performance ECM

If an ECM design with a separate supply signal is available, significant improvements to the PSRR, output impedance and supply current can be made.
Achieving a high PSRR with phantom biasing is limited because of the direct connection between Vdd and the output. Disconnecting this results in a more general amplifier configuration (see Figure 5). Now the PSRR can be designed high without affecting the gain or output swing.
In this configuration it is also possible to create low output impedance, making the output signal less susceptible to interference signals.
Finally, because the supply current does not flow through the load resistor, a much lower supply current can be achieved for the same noise level.

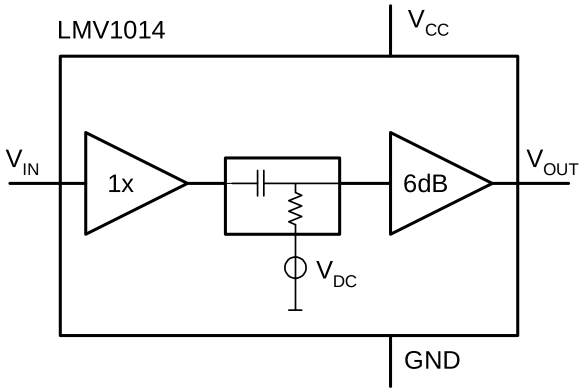

Figure 5. Block diagram of LMV1014

The LMV1014 [11] has been designed for this application and has a low total supply current of 30µA while keeping an overall ECM SNR of >55dB [12]. Furthermore, it has a very low output impedance of 200Ω and high PSRR of >60dB. The minimum supply voltage is 1.7V. This makes an ECM with LMV1014 very suitable for low power applications. This IC has been evaluated inside a Unidirectional Microphone to better suit it’s intended application, but is equally applicable to an Omnidirectional microphone. Figure 6 and Table 3 show the measurement data.

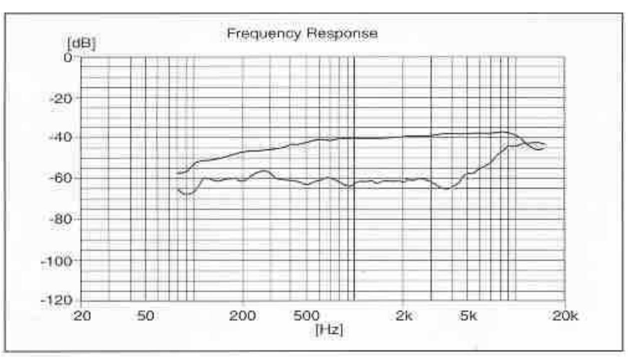

Figure 6. . Frequency response of BSE UBCG-0618L/622L/636L ECM with LMV1012

Electro-Acoustic Properties

		Condition	UBCG-0618L	UBCG-0622L	UBCG-0636L
Sensitivity	0°	f=1KHz, S.P.L.=1Pa 0dB=1V/Pa	-50±3dB	-45±3dB	-40±3dB
	180°		-70±3dB	-67±3dB	-64±3dB
VDD			2.0V		
IDD		VDD=2.0V, RL=2.2KΩ	35~40µA		
SNR		S:f=1KHz, S.P.L.=1Pa N:A-weighted curve	〉60dB	〉60dB	〉70dB

Table 3. Specifications of a commercially available ECM with LMV1014.

7.3. Digital Microphone Performance

A commercial, 4 wire ECM with LMV1021 digital mic amplifier was also build. The performance of this ECM was evaluated with a basic decimation filter. An overall SNR of 60dB was measured, while the supply current draw was around 600µA. The RF immunity and PSRR were both very high, resulting from the robust digital interface. Figure 7 shows measurement results.

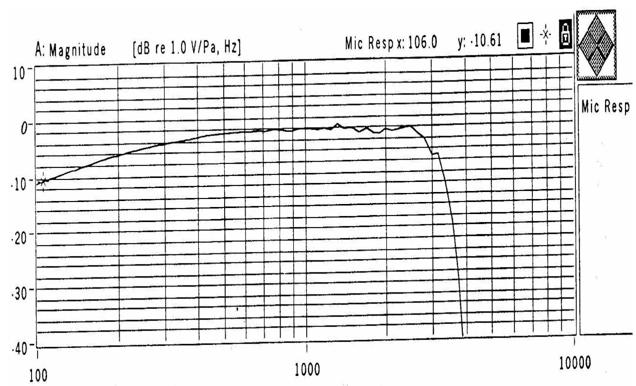

Figure 7. Normalised frequency response of an ECM with LMV1021. The output of the digital microphone is fed into a decimation filter, and output to a A/D converter resulting in an analog voltage.

8. Conclusion

Combining new Amplifier technologies and advanced miniaturized packaging has created new microphones with significant performance improvements. These ECM’s have new active components inside the ECM canister, making them transparent to the microphone user.

Starting from direct replacement of conventional JFET’s in common two-wire microphones, higher sensitivity and lower THD is achieved. In high performance three-wire microphones, very low supply current and excellent PSRR and output impedance results. Finally further integration of the key audio signal conditioning resulted in a fully integrated digital microphone using a robust and simple 2-wire interface to a DSP module.

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9 National Semiconductor, LMV1012 Product Datasheet, http://www.national.com/pf/LM/LMV1012.html

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11 National Semiconductor, LMV1014 Product Datasheet, http://www.national.com/pf/LM/LMV1014.html

12 Best Sound Electronics (BSE), Buildt-in-Gain (BIG) ECM product datasheet UBCG-0618L, UBCG-0622L and UBCG-0636L