A Floating-gate Based Low-Power Capacitive Sensing Interface Circuit


*School of Electrical and Computer Engineering
Georgia Institute of Technology, Atlanta, Georgia 30332
Email: sypeng@ece.gatech.edu shakeel@ece.gatech.edu arindamb@ece.gatech.edu
phasler@ece.gatech.edu levent.degertekin@me.gatech.edu

Abstract—This paper describes a high signal-to-noise ratio capacitive sensing circuit topology based on a capacitive feedback charge amplifier with high power and area efficiency. When the circuit is used in an audio MEMS sensor, 78.6dB SNR in audio band is measured with less than 0.5 µW power consumption. With a MOS-BJT pseudo-resistor feedback scheme, this topology has also been applied to a capacitive micromachined ultrasonic transducer (CMUT) operating around 1MHz. An adaptation scheme using Fowler-Nordheim tunneling and channel hot electron injection mechanisms is also employed to stabilize the output DC voltage in an audio MEMS microphone sensor. The measured noise spectrums show that this slow-time scale adaptation does not degrade the performance of the circuit. Therefore, this simple topology can be employed in many capacitive sensing applications and can achieve high performance with high efficiency.

Capacitive transduction is one of the most important and widely used techniques in microsystems. The main challenge of the interface circuit is to sense very small capacitance variance with huge parasitic capacitance. In general, the sensor’s overall performance is often limited by the interface circuit.

The simplest circuit topology for capacitive sensing is using a transimpedance amplifier in which a feedback resistor sets the gain but also limits the bandwidth and the SNR [1]. Lock-in sensing techniques can detect minute capacitance changes with high sensitivity. Issues like clock generation, clock feed-through, charge sharing, and offset-cancelation [2] have to be taken care of, which usually complicates the design and consume lots of power. The power consumption is in the milli-watt range.

The capacitive feedback charge amplifier has a very simple topology and has been used for decades. However, when it is used in capacitive sensing applications, a large resistor or switches are inserted to provide the DC path for the floating node. These additional components deteriorate the performance of the charge amplifier. Thanks to the recent advancements in programming [3] and adapting floating-gate circuits [4], we present our auto-zeroing capacitive sensing interface circuit without using feedback resistors or switches. This technique provides high signal-to-noise ratio (SNR) with very low power consumption. The analysis of the signal-to-noise ratio of the capacitive feedback amplifier has been detailed in our recent work [5].

In Section I, we show the circuit structure for our capacitive amplifier, and we describe the source of its improved linearity, SNR, and decreased power consumption. In Section II, we show measured results from an audio MEMS sensor interfaced with a version of the capacitive feedback amplifier fabricated in 0.5µm CMOS process. In Section III we demonstrate that this topology can be applied to capacitive micromachined ultrasonic transducer (CMUT) with a pseudo-resistor feedback scheme. Another adaptation scheme using tunneling and injection mechanisms to balance the floating node of the amplifier is presented in Section IV. The noise spectrum shows that this adaptation scheme does not affect the performance of the capacitive feedback amplifier. Finally, we draw conclusions in the final section.

I. CAPACITIVE FEEDBACK CHARGE AMPLIFIER

Figure 1(a) shows the topology of the capacitive sensing interface circuit. An off-chip MEMS microphone sensor biased by a DC voltage is connected to the inverting terminal of a capacitive feedback charge amplifier. The amplifier with constant transconductance is modeled as a first order system. Huge parasitic capacitance at the connection between the MEMS sensor and the inverting terminal of the amplifier is included in $C_w$.

The schematics of the amplifier is shown in Fig. 1(c). If the gain of the amplifier is large enough, given a variance of $C_{sensor}$, the corresponding output voltage change can be...
expressed as:

$$\Delta V_{\text{out}} = \frac{V_{\text{bias}}}{C_f} \cdot \Delta C_{\text{sensor}}. \quad (1)$$

By choosing a large $V_{\text{bias}}$ and a small $C_f$, this topology provides very high sensitivity for capacitive sensing. We design $C_f$ to set the transducer gain. In practice, we often allow for a bank of capacitors that can be switched into the circuit to alter $C_f$, as well as the dynamic range and noise of these signals.

The maximum output linear range is defined as the region where the input voltage to the amplifier is small enough such that the output current of the amplifier is linear with its input voltage. The maximum linear output voltage $\Delta V_{\text{out,max}}$ can be expressed as:

$$\Delta V_{\text{out,max}} = \frac{2U_T}{\kappa} \cdot \frac{C_{\text{sensor}} + C_w}{C_f}. \quad (2)$$

A simplified small signal model for noise analysis shown in Fig. 1(b) is used to calculate the output-referred noise power in terms of the output-referred current noise of the amplifier, $\tilde{i}_v$. In subthreshold region, the thermal noise component can be modeled as

$$\tilde{V}_n^2 = \frac{2}{\kappa} nq U_T g_m,$$

where $\kappa$ is the subthreshold slope coefficient of transistors, $n$ is the effective number of noisy transistors, $q$ is the charge of an electron, $U_T$ is the thermal voltage, and $g_m$ is the transconductance of transistors. The total output voltage noise power can be expressed as:

$$\tilde{V}_{\text{out,total}}^2 = \frac{nq U_T}{2\kappa} \cdot \frac{C_{\text{sensor}} + C_w}{C_f C_L}. \quad (3)$$

By dividing the square of (2) by (3), we obtain the expression for the SNR, as:

$$\text{SNR} = \frac{8U_T}{\kappa n q} \cdot \frac{(C_{\text{sensor}} + C_w) C_L}{C_f} \cdot \frac{1}{\Delta f} \quad (4)$$

Unlikely other amplifier circuits, we can increase the linear range of the capacitive sensing amplifier by increasing $C_w$, and improve the dynamic range by increasing $C_w$ or $C_L$. Because the product term in (4) makes a large effective capacitor, we can achieve high SNR while keeping the relative values (and area) of drawn capacitors smaller than traditional methods.

II. MEASUREMENT FOR AUDIO APPLICATIONS

A version of the capacitive sensing interface circuit is fabricated in a 0.5 $\mu$m CMOS process and its micrograph is shown in Fig. 2(a). The amplifier is a single stage cascode differential amplifier, as shown in Fig. 1(c), operating in the deep subthreshold region. The floating node is pinned out by using a bare pad to avoid large leakage current through the ESD circuitry. Circuit parameters and the measurement results are listed in Table 1.

A MEMS microphone sensor fabricated using Sandia National Laboratory’s silicon based SwIFT-Lite process [6] is used to test the circuit. The typical range of the capacitance is in pico-Farad range. The applied biasing voltage is 5V. The MEMS sensor is soldered to the pad connecting to the capacitive feedback amplifier. The leakage current can be measured directly from this circuit because the circuit integrates the charge over time. The measured leakage current with a bonded

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**TABLE I**

<table>
<thead>
<tr>
<th>MEASUREMENT RESULTS</th>
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<tbody>
<tr>
<td>Measured Leakage Current</td>
</tr>
<tr>
<td>Total Noise Power (Audio Band)</td>
</tr>
<tr>
<td>Signal to Noise Ratio $SNR$</td>
</tr>
<tr>
<td>Minimum Detectable Capacitance (Audio Band)</td>
</tr>
<tr>
<td>Capacitance Sensitivity @1kHz</td>
</tr>
<tr>
<td>Minimum Detectable Displacement @1kHz</td>
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</tbody>
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**CIRCUIT PARAMETERS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>$390 \times 200 \mu$m²</td>
</tr>
<tr>
<td>Power Supply</td>
<td>3.3V</td>
</tr>
<tr>
<td>Amplifier Power Consumption</td>
<td>0.5 $\mu$W</td>
</tr>
<tr>
<td>Open-Loop Gain</td>
<td>80dB</td>
</tr>
<tr>
<td>Bandwidth $f_{BW}$ ($C_f = 0.4$ pF)</td>
<td>25kHz</td>
</tr>
<tr>
<td>Feedback Capacitance $C_f$</td>
<td>20 fF</td>
</tr>
</tbody>
</table>

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sensor is about 5fA. A speaker with an operating range of 150Hz to 100kHz is used as the acoustic signal source.

Without compensating for the leakage current, the inverting voltage will settle to an equilibrium value. By adjusting the non-inverting voltage to keep the output at the mid of the rail, we can measure the frequency response of the system.

In Fig. 2(b) we show the music waveforms recorded from our capacitive feedback amplifier. The spectrum of a 1kHz 1Vrms output waveform with -37dB total harmonic distortion is shown in Fig. 2(c) together with the noise spectrum of the capacitive sensing circuit alone (i.e. without the MEMS sensor). The calculated total noise power of the circuit in the audio band (i.e. 10Hz to 20kHz with uniform weighting) is 117.5μVrms. Because the speaker and the microphone sensor deteriorate the linearity of the transducer, the SNR of our circuit is higher than 78.6dB. The minimum detectable sensor deteriorate the linearity of the transducer, the SNR of the audio band (i.e. 10Hz to 20kHz with uniform weighting) is 117.5μVrms. Because the speaker and the microphone sensor deteriorate the linearity of the transducer, the SNR of our circuit is higher than 78.6dB. The minimum detectable capacitance variance in the audio band is 2.8zF/√Hz and the minimum detectable displacement is 10⁻⁵Å/√Hz.

Without the auto-zeroing mechanism to stabilize the leaky floating node voltage, the equilibrium value is very sensitive to the changes in the test environment. Switches are avoided so that the readable charge at the inverting terminal can be reduced to the level lower than the charge perturbation due to charge sharing and clock feed-through. We can use MOS-Bipolar pseudo-resistor elements to provide DC path from output to the floating node. This feedback scheme has been used with an ultrasonic sensor.

### III. Measurement for Ultrasonic Applications

Capacitive micromachined ultrasonic transducers (CMUT) have been recently developed for ultrasonic imaging [7], [8]. We have used the capacitive feedback amplifier as a detector for CMUT and we show the test setup in Figure 3(a). A piezo transducer is used to generate plane waves at 1MHz using 16V peak 5 cycle tone bursts at its input. The CMUT receiver is biased to 90V DC at one of its terminals and the other terminal is connected to the sensing amplifier input. The CMUT and the piezo device are submerged in oil during the measurement. The capacitance of the CMUT sensor is about 22 pF and the maximum variance is about 1%. One version of our capacitive sensing amplifier with MOS-Bipolar pseudo-resistors feedback is used for recording the received and echo signals from the CMUT devices.

A MOS-Bipolar pseudo-resistor is a pMOS transistor with connections from the gate to the drain and from the well to the source. It can be used to provide DC path and exhibits very large resistance (exceeding 10¹²Ω) when the cross voltage is close to zero. This pseudo-resistor element has been used in neural recording applications [9] and Quasi-floating gate transistors [10]. To extend the output linearity, we use two pseudo-resistors in series to provide DC path from the output to the floating node.

The resulting waveforms are also shown in Fig. 3(b). The initial, highly distorted signal is due to electromagnetic feedthrough. After about 1.5 microseconds the first acoustic signal arrives from the piezo transducer to the CMUT, which corresponds to a distance of about 2.2cm in oil, as expected. By changing this distance and the relative alignment of the piezo and CMUT, the received signal and multiple echoes change drastically, again as expected from an ultrasound transmission experiment. Some important parameters for CMUT measurement are listed in TABLE II.

### IV. Adaptation Using Floating-Gate Programming Currents

Besides using pseudo-resistors, which causes extra distortion, we can autozero the output voltage using Fowler-Nordheim tunneling and channel hot electron injection mechanisms as in [4]. When there exits a high channel-to-source field across a MOSFET transistor with enough current through it, channel hot electrons are injected into the floating node. By applying high voltage across the tunneling junction, tunneling current brings the electrons away from the floating gate. The dynamics of these two mechanisms are detailed in [11].

The schematics of this auto-zeroing capacitive sensing amplifier is shown in Fig. 4(a). A tunneling junction and an indirect injection pMOS transistor are integrated with the amplifier. As in the [11], [12], we provide appropriate supply voltages and use a comparator providing the drain voltage to adjust injection current according to the output voltage. The output adapts to the changes on the floating node so that it can return to the mid of the rail in slow time scale as shown in Fig. 4(b). In Fig. 5, we compare the noise spectrums with the sensor and show that this adaptation scheme does not degrade the noise performance. Because of the addition

![Fig. 3. (a) The measurement setup for measurement using CMUT sensor. (b) The measured waveform from a capacitive feedback amplifier using MOS-BJT pseudo-resistor feedback scheme. The first acoustic signal arrives 1.5 microseconds after the piezo transducer is activated.](image-url)
of the floating-gate programming currents, the low frequency corner of the spectrum using adaptation is higher than that without adaptation. Because the adaptation rate is slow and the injection transistor operates in subthreshold region, the additional power consumption from the comparator and the injection transistor is within \( \mu W \) range. This scheme reserves the high power efficiency benefit.

Besides of the previous two schemes for autozeroing, we can also use a switch to reset the charge before the capacitive sensing amplifier is effective in sensing. The sensing signals are read after the output is settled from the perturbation of charge sharing and clock feedthrough. This method can be used in CMUT sensor array where the capacitive amplifiers are multiplexed.

V. CONCLUSION

By using a floating node in the capacitive feedback amplifier structure, the signal-to-noise ratio is improved by the product of the load and the sum of input and parasitic capacitors. Because large size capacitors are avoided, ultra-low power operation can be achieved by making use of the subthreshold region. Several methods including pseudo-resistor feedback, tunneling-injection adaptation, switch reset scheme can be used to set the charge on the floating node without affecting the circuit performance with very low power consumption. We have demonstrated this technique for MEMS microphone and CMUT device. The same technique can also be used in general capacitive sensing applications and have a significant impact on MEMS applications.

REFERENCES