Floating-gate Based CMUT Sensing Circuit Using Capacitive Feedback Charge Amplifier

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Abstract—This paper describes the use of a floating-gate based capacitive feedback charge amplifier as a receive circuit for CMUT and investigates the charging effects. Detailed analysis of the capacitive sensing charge amplifier along with a floating-node charge adaptation circuit is presented. Compared with conventional approaches, using a charge amplifier, instead of a transimpedance amplifier, to detect capacitance variation avoids the dilemma of sensitivity-bandwidth trade-off. A version of the capacitive sensing charge amplifier is fabricated in a 0.5 \( \mu m \) CMOS process. The chip contains a 8-to-1 multiplexer and is interfaced with a CMUT annular-ring array, which is designed for forward-looking intravascular ultrasound imaging applications. Pulse-echo experiment is performed in an oil bath using a planar target 3mm away from the array and the measurement result shows the signal-to-noise ratio of 16.65dB with 122 \( \mu W \) power consumption around 3MHz. In another implementation, channel hot electron (CHE) injection and Fowler-Nordheim tunneling currents are used to adjust the charge on the floating node and stabilize the output voltage. By using open-loop configuration, the leakage current of a CMUT device is characterized.

I. INTRODUCTION

As capacitive micromachined ultrasonic transducers (CMUTs) have advantages of wide bandwidth, ease of fabricating large arrays of practically any size and shape, and potential for integration with electronics, they have emerged as an alternative to piezoelectric transducers for ultrasound imaging. Particularly in intravascular ultrasound (IVUS) applications, the piezoelectric transducer technology has prevented effective implementation of systems with diameters below 1mm. On the other hand, the latest advancements in CMUT technology enable the construction of forward-looking (FL) annular-ring transducer arrays that can be placed in front of the catheter [1].

Due to the small size of each CMUT element in FL-IVUS array, which is in the order of 100 \( \mu m \) and is much smaller than that in non-invasive 1-D CMUT array, the parasitic capacitances introduced by the electrical interconnects can easily overwhelm the device capacitance and impair the achievable signal-to-noise ratio (SNR). Either integrating the CMUT array with electronics on the die level or building the CMUT array directly on CMOS electronics, as illustrated in Fig. 1(a), can avoid the performance degradation caused by the cable losses. Since the probe is located inside the patient’s body, the power dissipation is also a major concern. Also, because IVUS imaging requires a high resolution and because the imaging depth for vessels is relatively shallow, the transducers usually operate at a high frequency. In brief, sensing a minute capacitance variation in the presence of large parasitic capacitances, and providing high bandwidth and large dynamic range with low power dissipation poses significant challenges to the CMUT sensing circuit design.

In this paper, we present a new approach to capacitive sensing. Instead of the usual resistive feedback transimpedance amplifier (TIA) scheme, we use a capacitive feedback charge amplifier to detect the CMUT output and to investigate the charging effects. Compared with more conventional approaches, the charge amplifier approach can avoid the dilemma of the sensitivity and bandwidth trade-off, and provides better performance. Further, amplifying signals in the first stage results in relatively low power consumption. To deal with the charge at the floating node, a floating-gate based charge adaptation circuit is used to adjust charges on one of the CMUT terminals, as illustrated in Fig. 1(b). A version of the charge amplifier is fabricated in a 0.5 \( \mu m \) CMOS process and the chip is interfaced with a IVUS CMUT element. In this paper, we also present results of the pulse-echo experiment, which is performed in an oil bath.
II. CAPACITIVE SENSING CHARGE AMPLIFIER ANALYSIS

A detailed analysis of an ideal charge amplifier for capacitive sensing has been proposed in [2]. In this section, we briefly review the results and provide the analysis of the charge amplifier with charge adaptation circuit, based on which the comparisons with conventional approaches will be given in the next section.

A. Ideal Charge Amplifier

Figure 2(a) shows the small signal model of an ideal capacitive sensing charge amplifier. The amplifier is modeled as a first order system which can be a simple cascode common-source amplifier, as illustrated in Fig. 2(b). The simple common-source configuration is suited for high frequency operation and the cascode topology can increase the amplifier gain as well as reduce the parasitic feedback capacitance which affects the sensitivity of the charge amplifier. The parasitic capacitance introduced by the interconnect and the static capacitance of the CMUT are included in $C_m$. The output DC voltage depends on the CMUT capacitance and its bias voltage, as well as on the charge on the floating node. Assuming the amplifier gain is large enough, the output voltage can be given as:

$$V_{out} = -\frac{V_{bias}C_{CMUT} + Q}{C_f}. \quad (1)$$

By controlling the floating-gate charge $Q$, the output DC voltage can be adjusted at the mid rail and the circuit can have a large dynamic range. The transfer function from the CMUT capacitance to the output voltage can be expressed as:

$$\frac{V_{out}(s)}{C_{CMUT}(s)} = \frac{V_{bias}}{C_f} \frac{sC_f/G_m - 1}{s\tau + 1}, \quad (2)$$

where $\tau$ is the time constant of the circuit and is given as:

$$\tau = \frac{1}{\omega_{3dB}} = \frac{\text{C}_{\text{eff}}}{G_m}, \quad (3)$$

where $C_{\text{eff}} = (C_oC_T - C_f^2)/C_T$, $C_T = C_{CMUT} + C_m + C_f$, and $C_o = C_L + C_f$. Typically, both $C_T$ and $C_o$ are larger than $C_f$ and hence the zero, due to the capacitive feedthrough, is at much higher frequency than the amplifier bandwidth. High sensitivity and large bandwidth can be achieved by choosing a small value of $C_f$ and a large value of $G_m$, respectively. The circuit also provides signals with high linearity and high SNR as detailed in [2].

B. Charge Amplifier with Charge Adaptation Feedback

The charge adaptation circuit shown in Fig. 1(b) can be modeled by a small feedback conductance, $g_f$, as shown in Fig. 3(a). The transfer function of the sensing circuit becomes:

$$\frac{V_{out}(s)}{C_{CMUT}(s)} = \frac{V_{bias}}{g_f} \cdot \frac{s(sC_f - 1)}{s^2C_fC_m - C_f^2} + \frac{s(sC_f - 1)}{s^2C_fC_m + C_f^2 + C_f - 2C_f^2}, \quad (4)$$

where $A$ is the amplifier gain. As shown in Fig. 3(b), the adaptation scheme creates an extra zero at the origin and an extra low-frequency pole around $g_f/C_f$, assuming $A$ is large enough. If the transistors are in subthreshold region, we can approximate the output referred noise as:

$$\frac{\hat{V}_{out,\text{total}}^2}{2\kappa} = \frac{nqU_T}{2\kappa} \cdot \frac{C_f}{C_fC_m}, \quad (5)$$

where $\kappa$ is the subthreshold slope coefficient of transistors, $n$ is the effective number of noisy transistors, $q$ is the charge of an electron, and $U_T$ is the thermal voltage. From (5), the minimum detectable capacitance can be derived as:

$$\Delta C_{\text{min,CA}} = \frac{1}{V_{bias}} \cdot \sqrt{\frac{nqU_T}{2\kappa}} \frac{C_fC_T}{2}\frac{C_m}{C_f}. \quad (6)$$

III. COMPARISONS AND DISCUSSIONS

Conventionally, CMUT signals are converted from capacitive currents into voltages [3] by using either resistive terminations followed by amplifiers, common-gate amplifiers, or resistive feedback TIAs. The first approach, as shown in Fig. 4(a), suffers from the direct trade-off between bandwidth...
and input-referred current noise because they both are proportional to \(1/R_{\text{in}}\). In the common-gate topology shown in Fig. 4(b), although the noise can be minimized by maximizing the load resistance and the overdrive voltage of \(M_2\) without affecting the bandwidth, this incurs a reduction in the output voltage headroom. In Fig. 4(c), because the feedback resistance does not limit the voltage headroom and because the input capacitance can be reduced by the amplifier gain, the “shunt-shunt” feedback TIA topology is most widely used in capacitive sensing applications. However, when the operating frequency is high, the bandwidth can be limited by the parasitic feedback capacitance.

It is interesting to note that Fig. 3(a) can also be viewed as a small signal model of a TIA with a parasitic feedback capacitance. The expression of (4) can be rearranged to describe the transfer function of the TIA as:

\[
\frac{V_{\text{out}}(s)}{I_{\text{CMUT}}(s)} = \frac{V_{\text{out}}(s)}{sV_{\text{bias}}C_{\text{CMUT}}(s)} = \frac{1}{s} \cdot \frac{C_{\text{out}} - C_{\text{in}}}{s^2 C_{\text{out}} C_{\text{in}} + s C_{\text{out}} + C_{\text{in}}} + 1.
\]

(7)

We can derive the minimum detectable capacitance of the TIA as:

\[
\Delta C_{\text{min, TIA}} = \frac{g_t}{\omega_0 V_{\text{bias}}} \sqrt{\frac{n q U T C_T}{2 e C_I C_D}}.
\]

(8)

where \(\omega_0\) is the operating frequency.

Although the topologies of a TIA and a charge amplifier are the same, their design philosophies are different. In a typical TIA design, the operating frequency should be lower than the first pole, which corresponds to the ascendent region in Fig. 3(b). The sensitivity-bandwidth trade-off of a TIA is obvious from (7) and (8). Increasing the bandwidth by increasing \(g_t\) results in a decreased sensitivity. On the other hand, using a charge amplifier to sense the CMUT signals can avoid all the dilemmas mentioned before. The sensitivity can be improved by choosing large values of \(V_{\text{bias}}\) and \(C_L\) and a small value of \(C_I\). The bandwidth, corresponding to the second pole, can be extended by using a larger value of \(G_m\).

IV. PULSE-ECHO EXPERIMENT AND RESULTS

A version of the charge amplifier, using a \(p\)MOS transistor as the charge adaptation feedback, is fabricated. As shown in Fig. 5(a), the chip with electronics is wire-bonded to an annular-ring IVUS CMUT array [4]. The size of each element is \(70\ \mu\text{m} \times 70\ \mu\text{m}\) giving rise to a measured capacitance of \(2\ p\text{F}\), including the parasitic capacitance. A Petri dish with an opening at the bottom is glued on top of the package by epoxy. During measurement, transducers and the circuit are immersed in a vegetable oil bath, as shown in Fig. 5(b).

By applying different bias voltage to the feedback transistor, the same circuit can be configured as a TIA or as a charge amplifier. Because the charge effect due to the capacitance change is equivalent to that due to the voltage change, the frequency response of the circuit can be performed by applying an ac signal at one of the CMUT terminals. The results are shown in Fig. 6. As can be seen, as long as the operating frequency is less than the second pole, a charge amplifier can obtain a larger output magnitude than a TIA.

The pulse-echo experiment is performed by using one CMUT device as a transmitter and the other element bonded to the circuit as a receiver. The transmitter element is stimulated by a 20V-peak pulse. The receiver device is biased by a 50V DC voltage and the feedback capacitance is extracted as \(200\ \text{fF}\). The distance between these two devices is about 6\text{mm} corresponding to a pulse-echo distance from a planar target \(3\text{mm}\) away. The recorded waveform, shown in Fig. 7, indicates a center frequency of 3MHz, which is mainly limited by the amplifier bandwidth. The measured output noise floor is 2.5mVrms and the measured SNR from the first received
acoustic signal is 16.65dB. The extracted feedback capacitance is about 200 fF and the power consumption of the charge amplifier is only 122 µW.

V. Measurement Results of Using Tunneling and Injection Mechanisms

We also use channel hot electron (CHE) injection and Fowler-Nordheim tunneling mechanisms to control the charge on the floating node. Fowler-Nordheim tunneling removes electrons from the floating node and the CHE injection puts electrons onto the floating node. The injection current can be controlled by the drain voltage of the injection transistor. Fowler-Nordheim tunneling and CHE injection have already been used in precisely programming floating-gate transistors as well as been used in an auto-zeroing amplifier [5].

A version of the sensing circuit with integrated tunneling junction and injection transistor is fabricated in 0.5 µm CMOS process. The circuit is interfaced with a CMUT element and the setup is shown in Fig. 8(a). According to the output voltage, a low gain comparator applies an appropriate voltage to the drain of the injection transistor. By applying steps at the CMUT bias voltage to perturb the charge on the floating node, the injection current can compensate for the perturbation and can balance out the CMUT leakage current. The output voltage returns to the mid rail with a time constant of seconds as shown in Fig. 8(b). In [6], we have shown that the tunneling-injection adaptation does not degrade the noise performance.

With the open loop configuration, we can characterize the relation between CMUT leakage current and its bias voltage. Before measurement, the drain voltage of the injection transistor is pulled to ground so that the injection current overwhelms the CMUT leakage current and the output voltage is $V_{DD}$. When the measurement starts, the drain terminal is set to $V_{DD}$ to shut down the injection current. CMUT leakage current is integrated over time by the charge amplifier and can be extracted from the output voltage decreasing rate. The measured and extracted results are consistent with results obtained by other measurement methods.

VI. Conclusion

By using a floating-gate based capacitive feedback charge amplifier to detect CMUT signals, unlike the conventional transimpedance amplifier, the dilemma of the sensitivity and bandwidth trade-off is avoided. The pulse-echo experiment performed in an oil bath shows more than 16dB SNR when the circuit is interfaced with an element in an IVUS CMUT array. A charge adaptation scheme using Fowler-Nordheim tunneling and channel hot electron injection is used to characterize the leakage currents of a CMUT device. We also demonstrated that the charge adaptation scheme can stabilize the output DC voltage.

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REFERENCES


