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FEA of CMUTs Suitable for Wide Gas Pressure Range Applications

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Abstract

The ability of ultrasound transducers to operate over a wide and varying pressure range is essential in applications such as ultrasonic flow metering (UFM) of flare gas. We propose a new operational mode for capacitive micromachined ultrasonic transducers (CMUTs), in which the plate is in permanent contact with the bottom of the cavity, even at zero DC bias and 1 atm pressure. Finite element analysis (FEA) software was used to investigate the performance of these CMUTs within the pressure range of 1 to 20 atm. First, we performed a static analysis to determine the plate deflection and, thus, the gap height. Further, from the static analysis, we obtained the static and free capacitances for calculating the coupling efficiency, and a modal analysis identified possible design geometries for frequencies lower than ~ 300 kHz. Our calculations show that conventionally operated CMUTs have huge changes in static operational point at different pressures, while our proposed mode exhibits an acceptable frequency range (73 – 340 kHz) over 1 – 20 atm pressure and an improved coupling efficiency at lower dc bias voltages. A donut shape partial electrode further allows us to tune the coupling efficiency, which translates into a better performance, especially at the higher pressure range. FEA shows that our proposed operation mode is a promising solution for flare gas metering applications.

Index Terms

FEA; CMUT; high pressure; ultrasonic flow meter

I. Introduction

For environmental protection and emerging regulations, it is important for oil production facilities to measure the flare gas emission and to detect possible gas leaks. Disastrous examples, such as the recent British Petroleum Gulf oil spill, clarify the need for strict regulations in this area. Detecting gas leaks on off-shore oil rigs is essential to avoid such explosions with its consequences.

The challenge of flare gas metering in general is the wide pressure range. Our research focuses on providing an ultrasonic transducer technology that can operate efficiently over such a wide pressure range.

In ultrasonic transit time gas flow meters, at least one pair of transducers is used to transmit and receive ultrasound up-stream and down-stream. From the difference in transit times, one can calculate the velocity of the flow. Various UFM schemes have been explored to improve the flow meter performance in terms of rangeability. Mylvaganam [1] demonstrated that adjusting the transducer inclination angles can be used to compensate for the sound drift effect. Kupnik et al. [2] demonstrated that shifting the receiving transducers alone in flow direction can be used to increase the rangeability.

Ultrasonic flow meters are generally designed for specific environmental conditions, such as a certain pressure range. In our target application, however, the pressure ranges from 1 to 20 atm. In terms of flow velocity we face 80 dB dynamic range (0.01 – 100 m/s). Further, we aim for frequencies in the range of 300 kHz and temperatures up to 300°C.

The main focus in this work is the varying pressure range, which can be considered challenging for piezoelectric transducers due to acoustic impedance mismatch, especially at the lower pressure range. CMUTs are known to be efficient in gases, but the static dc operation point of a conventionally operated CMUT plate varies significantly with pressure, as illustrated in Fig. 1(a). The details of the shown wafer-bonded CMUT based on a thick buried oxide layer is described in [3] in detail. The pressure indicated in Fig. 1(a) is for illustration purposes only. The plate can be brought in contact with the bottom of the evacuated cavity at low pressure, which results in a dramatic change in device behavior [(0,1)-mode frequency approximately doubles, the total device capacitance increases, as well as the coupling efficiency]. All of these can happen even without a change of the dc bias voltage, i.e. just due to the change in ambient pressure. On the other hand, if we design the gap to be large enough so that the plate never gets into contact with the bottom of the cavity even at a higher pressure, the device performance is severely degraded, in particular in the lower pressure range.

To address this challenge, we propose to operate the CMUTs with the plate in permanent contact with the bottom of the cavity already at 1 atm ambient pressure and zero dc bias [Fig. 1(b)]. From previous work [4] we know that the fabrication of similar CMUTs, which have the plate touching the bottom of the cavity, is feasible. However, the devices from [4] were designed to work at pressures far lower than 1 atm (Mars atmosphere), i.e. during device operation there was no contact between the plate and the bottom of the cavity. To avoid stiction between plate and bottom of the cavity, small oxide bumps were used in the cavities.

As illustrated in Fig. 1(b), in our proposed mode, with increasing pressure the contact area between the CMUT plate and the bottom of the cavity increases, which results in a more gradual change in static operational point. Note that this is different from the pull-in mode (collapse mode [5]), where a dc bias is required to bring the plate into contact with the bottom of the cavity (biasing beyond pull-in point). It is also different from approaches describes in recent patents [6, 7] on the pre-collapsed CMUTs with mechanical collapse retention (by casting polymer lens over the pre-collapsed plate, or by depositing new material over the plate with a pre-etched hole): First, in [6, 7] a dc bias voltage larger than the pull-in voltage is required to achieve contact between plate and bottom of the cavity. Second, the devices are based on sacrificial release method, which does not support the fabrication of large enough cells to meet the frequency requirements of our target application, ultrasonic gas flow metering. Third, the devices do not benefit from the wafer bonding technique, which allows us to use single-crystal-silicon plates without residual stress and with excellent predictability in terms of static plate deflection.

II. Details about FEA

A 2-D axial symmetric model was set up in the FEA software ANSYS (Fig. 2). The waveguide approach, as described in [8], was used, and, thus, this model assumes a single cell surrounded by an infinite number of neighboring cells. A uniform surface load ranging from 1 to 20 atm was applied as parameter for all calculations. Because some of the designs simulated have a large deflection-to-thickness ratio, geometric nonlinearities (stress stiffening effect) must be included in the model [9].

First, we started with a static analysis at 1 atm and 0 V bias voltage to calculate the plate deflection profile for various geometries (diameters, plate thicknesses). Then the gap height for the next run was set slightly smaller than the previously calculated deflection at the center of the plate. This ensures contact between plate and the bottom of the cavity already at 1 atm and 0 V.

With the gap height determined, we used a modal analysis over ambient pressures ranging from 1 – 20 atm, and dc bias voltages ranging from 0 – 800 V to calculate the (0,1)-frequency over the entire geometry design space (cell diameters sizes, plate thicknesses). The output of this calculation are suitable designs that operate in the desired operation frequency range for our application (~ 300 kHz or below).

In addition, with another static analysis calculation the static and free capacitances were determined, based on the plate deflection profiles over 1 – 20 atm and 0 – 800 V. The equations used for static and free capacitances and the coupling efficiency kT^2 are taken from [10], and are rewritten in this work in their discretized form (i refers to each transducer element in the FEA model, which corresponds to a ring in the axial symmetric model):

$$C^S(static)=C(V)|_{V_{DC}} = \sum_{element_ring_i} (C_{gap_i}^{-1} + C_{ox_i}^{-1})^{-1} = \sum_i \frac{\epsilon_0 A_i}{(d_0 - deflection_i) + t_{ox} / \epsilon_{ox}} \quad (1)$$

$$C^T(free)=\frac{dQ(V)}{dV}|_{V_{DC}} = \frac{d}{dV}(VC^S)|_{V_{DC}} = C^S + V \frac{dC^S}{dV}|_{V_{DC}} = C^S + V_{DC} \frac{C_i^S - C_{i-1}^S}{V_{bias_i} - V_{bias_{i-1}}} \quad (2)$$

$$k_T^2 = 1 - C^S / C^T \quad (3)$$

Finally, another static analysis was carried out to determine the pull-in voltage of CMUTs operated in the conventional mode.

III. Results and Discussion

The pull-in voltage as a function of pressure is plotted in Fig. 3 for CMUT cells operated in conventional mode. The device dimensions chosen for illustration purposes are a 40- μm thick plate, a 36- μm gap height, and three cell radii (1000, 1300, and 2000 μm). For all three designs the pull-in voltage changes from almost 3000 V down to zero within a few atm change in pressure. As expected, this demonstrates the large change in terms of static operational point of these CMUTs with varying pressure.

In Fig. 4 we show the coupling efficiency kT^2 of the design with cell radius of 2000 μm . The 1-atm curve in Fig. 4(a) shows the coupling efficiency as a function of dc voltage for a conventional CMUT, with a pull-in voltage of 1016 V and a pull-out voltage of ~550 V. Typical for a device that experiences pull-in is the hysteresis, which does not exist in our devices. As discussed in [5], a higher coupling efficiency can be achieved in the collapse mode, but this requires the CMUT to be first biased at a voltage higher than the pull-in voltage and then at a voltage larger than the pull-out voltage. In most designs, biasing the device above the pull-in voltage results in a high electric field strength in the insulation layer (risk of electrical breakdown) during the time of first contact between plate and the bottom of the cavity and the time until the bias voltage is reduced to a value slightly larger than the pull-out voltage.

As the pressure increases, the plate is brought into contact with the bottom of the cavity, starting at 2 atm and higher. As shown in Fig. 4(b), the coupling efficiency change from 2 to 20 atm is monotonic rising. Furthermore, if we compare the 1 atm and 2 atm curves in Fig. 4(a), we can see that for the in-contact case (2 atm) the high efficiency can be achieved at a much smaller dc bias voltage.

By reducing the gap height based on our first static analysis (e.g. $\sim 27 \mu\text{m}$ gap for a device with a $40\text{-}\mu\text{m}$ thick plate and $2000 \mu\text{m}$ radius), we achieved designs in which the plates are in permanent contact with the bottom of the cavity, even at 1 atm and zero bias. The (0,1)-mode frequency of this CMUT design, obtained from the modal analysis, is presented in Fig. 5. Note that since the gap height is chosen so that at 1 atm pressure and zero bias voltage the plate is only in slight contact with the bottom of the cavity, different plate thickness cases in Fig. 5 correspond to different gap heights.

For each curve with a fixed pressure (Fig. 5), the frequency increase at low plate thickness comes from plate with a reduced vibrating portion (because a thinner plate is softer, which results in a larger contact area), while the frequency increase at high plate thickness comes from the effect of increasing stiffness on resonance frequency. Therefore, there is an optimal plate thickness that would give the smallest frequency value or range desired, which is around $27 \mu\text{m}$ for the $2000 \mu\text{m}$ cell radius design (gap height is $44 \mu\text{m}$). This particular CMUT cell design exhibits frequencies that range from 73 to 340 kHz, as the pressure goes from 1 to 20 atm.

IV. Idea of Only Partially-Connected Electrode

The choice of the CMUT fabrication process as introduced in [3], allows us to connect only a part of the bottom electrode to the dc bias voltage source (Fig. 6). The objective of this idea is a reduction of the parasitic capacitance at the location of the contact area, which results in improved coupling efficiency. Further, this reduces the high electric field strength in the insulation layer at the contact area and, thus, improves device reliability and reduces parasitic charging effects.

Fig. 7 shows the coupling efficiency kT^2 for different partial electrode sizes for a cell with a $40\text{-}\mu\text{m}$ -thick plate, a $26.9 \mu\text{m}$ gap, and a $2000 \mu\text{m}$ cell radius. As the electrode gets smaller, the coupling efficiency first increases due to the reduction of parasitic capacitance near the contact area, and later decreases since the electrode becomes too small to cover the active vibrating part of the plate. Therefore, we can tune the partial electrode size (diameter) to achieve higher coupling efficiency for the pressure range we want to optimize for.

V. Conclusion

FEA results show that our proposed mode for operating CMUTs with the plate in permanent contact with the bottom of the cavity does have a more stable behavior over varying pressure in terms of frequency and coupling efficiency. The results have not been validated by measurements yet, but the same FEA model has been used in other work and proved its validity. We are confident the proposed CMUT operational mode is a promising solution for wide pressure range applications, and with the fabrication of the devices in progress, we will be able to do the characterization and validation of our FEA results in the near future.

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Fig. 1. shows the schematic (cross section) view of a single CMUT cell. (a) A cell operated in conventional mode suffers from a drastic static operational point change due to varying pressure. (b) The proposed mode with the plate in contact with the bottom of the cavity at 1 atm has a more stable static operational point as the pressure increases.

Fig. 2.
A 2-D axial symmetric model was built in ANSYS with the waveguide approach [8].

Fig. 3.

shows the pull-in voltage as a function of pressure for CMUT cells operated in the conventional mode with a 40- μm thick plate, 36 μm gap, 3.3- μm thick insulation layer, and three plate radii (1000, 1300, 2000 μm).

Fig. 4. shows the coupling efficiency of a CMUT cell with 40- μ m thick plate, 36 μ m gap, 3.3 μ m insulation layer, and 2000 μ m radius. (a) The 1 atm curve shows a cell in conventional mode, while the 2 atm one is in contact mode; (b) From pressure 2 to 20 atm the plate is in contact with the bottom of cavity.

Fig. 5. shows the (0,1)-frequency at zero dc bias for CMUT designs with plate in contact with the cavity bottom. The cell radius for all designs is 2000 μm. The gap height is chosen so that at 1 atm, zero bias the plate slightly touches the cavity bottom, which is different for each plate thickness.

Fig. 6. illustrates a CMUT cell structure with partial electrode. The central part of the bottom electrode is kept floating, while only the outside donut-shaped part is connected to the dc bias.

Fig. 7. shows coupling efficiency as a function of dc bias for different partial electrode sizes for a cell design with 40 μm plate thickness, 26.9 μm gap, and 2000 μm cell radius.