A Compact Ultrasonic Transducer using the Active Piezoceramic Material as Electronics Carrier

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Abstract

The integration of sensor and electronics is important to reduce size, cost and power consumption for a measurement system. Sensors based on piezoelectric ceramic materials traditionally have a low degree of sensor and electronics integration. This paper describes the design of a highly integrated ultrasound transmit/receive unit where the piezoceramic sensor is used as the carrier for the driver electronics. An optimized ASIC driver stage in bare die format and two lithium battery cells which give 6 V supply voltage are glued directly to the back side of the sensor. Electrical connections are made from the driver stage to the crystal using wire bond technology.

Measurements have been performed with an air backed crystal and Plexiglas as the medium. The absence of long wiring and parasitic components between the driver stage and the driven crystal give excellent pulse control possibilities. The power consumption of the driver stage/crystal combination is linearly dependant on the repetition rate, with a current consumption of less than 20 μA at 1 kHz repetition rate. The approach taken introduces issues regarding the influence of vibrations in the MHz-range on die attachment and wire bonding connections, which need to be further investigated.

Keywords: Ultrasonic transducer, wire bonding, low power, bare die, driver stage, piezoelectric

1. Introduction

Piezoelectric ceramic materials are widely used in ultrasound measurement systems. In the industry, measurements include properties of suspensions and fluids, density, flow etc. Traditionally these systems have a low degree of sensor and electronics integration. They are built to be powered using a mains outlet, and data are transmitted to and from the system with wires.

Ease of installation is one important factor in the cost picture of a measurement system. Here, data and power supply cabling are cost drivers. If these could be omitted, the system cost would be lowered. The removal of all cabling sets two requirements: battery operation and wireless transmission of data. For a battery operated system, low power consumption is vital as battery lifetime should be maximized. Ideally, a system should be possible to place in an industrial application, and not be touched again for several years [1].

This paper presents the design of a compact ultrasonic transducer as one step to reach the above discussed system goals. The focus in the design of the transducer has been on a high integration level between sensor and electronics, which has made it possible to reach small size and low power consumption. The electronics is mounted directly to the surface of the piezoelectric disc, where they are subject to high frequency, low-amplitude vibrations with very high acceleration.

2. Design

The setup is built as a pulse-echo system, where the piezoelectric disc is glued directly to a 10 mm thick plate of plexiglas (PMMA). The PMMA serves as the ultrasonic transmission media. No backing is used for the transducer. The PZ27 crystal used for the measurements in this paper has a diameter of 16 mm and a thickness of 487 μm, which gives a resonant frequency of about 4 MHz. The crystal is covered with a thin layer of screen-printed silver on both sides. The electrodes are of the wrap around type, which enables both electrodes to be connected from the same side of the disc.

The driver electronics is an optimized CMOS ASIC in bare die format [2]. The driver rapidly discharges and charges the piezoelectric disc, whereafter it automatically goes to high impedance state in preparation to receive an echo. The size of the driver die is 3x3 (mm)^2. It contains several differently sized driver stages, and the active silicon area used for this work is 730x840 (μm)^2. The nominal maximum supply volt-

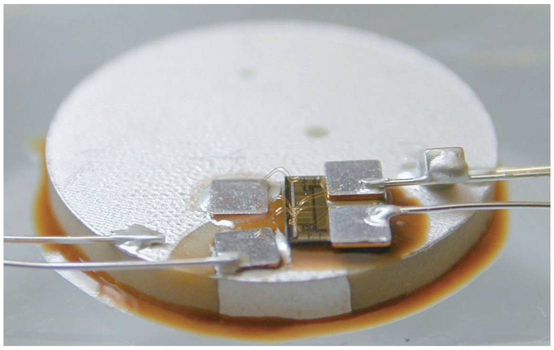

Figure 1: The driver chip mounted on a 16 mm diameter 1 MHz PZ27 disc. The 25 μm gold bond wires are visible in the picture.

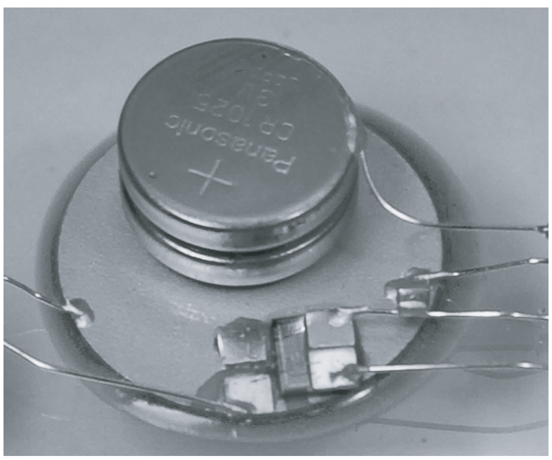

Figure 2: The driver chip mounted on a 16 mm diameter PZ27 disc together with two lithium button cell batteries.

age for the chip is 5.5 V, with an absolute maximum voltage of 7 V.

Several prototypes, with and without attached lithium battery cells have been fabricated. The arrangement is shown in figures 1 and 2. The driver stage is glued directly to the piezoelectric disc with non-conductive heat curing glue, type Epotek H70E. For all glue operations with heat curing glue a curing temperature of 130 ^{o}C for 20 minutes was used. The temperature is low enough not to damage the piezoelectric material, which has a curie temperature of 350 ^{o}C.

Electrical connections from the chip to the piezoelectric disc has been made with 25 μm gold bonding wire [8]. Two possibilities for the bonding from the chip have been investigated. The first takes the bond directly to the silver layer on the piezoelectric crystal. A second alternative was to use an intermediate material glued to the crystal with conductive glue as target for the bond wire. For the first approach, several experiments showed that the silver layer had very bad adhesion to the gold bonding wire, and it was not possible to make consistently good bonds. One possible reason for this behavior is that the screen-printed silver has a few percent adhesive additive to give better adhesion to ceramic surface [9]. The additive might also make the surface harder, and thus make it difficult to produce good bonds. Secondly, the silver on the crystal forms a silver sulphide layer during storage. Although a cleaning process in a plasma-cleaner was used before bonding, this might not have been sufficient to remove all oxide. The manufacturer Ferroperm A/S [10] recommends cleaning with a glass brush before soldering. This procedure will be tested for future prototypes.

For the second approach to bonding, 2x2 (mm)^2 silver clad copper bond pads were used as an intermediate conductor between bond wire and crystal. The bond pads have one side covered with silver, and this side was used for bonding. The other side is bare copper, and this was glued to the silver surface of the crystal with Epotek H20E silver based heat curing conductive epoxy. The bond pads gave good bonds with the gold bond wire. Thus, it was decided to use this method. The bond pads were also used to form an interface between the bond wire and the wire going to an external connector. In this case, the bond pads were glued on top of the non-used chip surface with Epotek H70E nonconductive glue.

Prototypes were also built with batteries attached. Lithium button cells were glued with Epotek H20E directly to the silver surface of the piezoelectric device. As the present version of the driver stage needs an external trigger pulse, connections were provided for this purpose. To create a true stand-alone prototype, one of the fabricated devices was equipped with a small pulse generation electronic block, which was mounted on top of the batteries.

3. Electrical and mechanical properties

Electrical

Measurements were performed with a supply voltage of 6 V, as this is the nominal output voltage of the two series connected lithium cells. As an alternative, one 3.6 V lithium cell could be used to decrease the risk for electrical stress in the electronics. To maximize the echo amplitude a pulse width of close to a half-period of the ultrasonic transducer resonant frequency was used [4]. The excitation and the received echo were measured directly at the transducer with an ac-

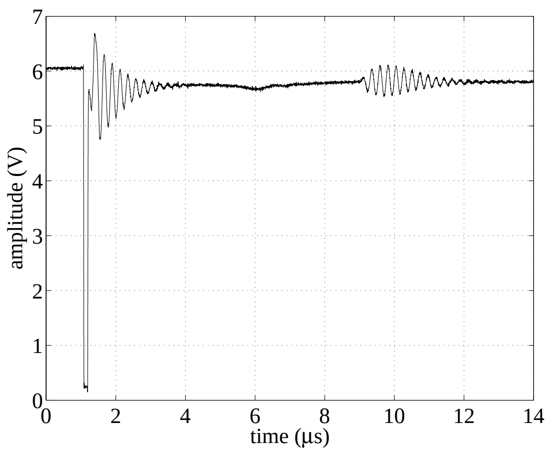

Figure 3: Oscilloscope trace of excitation and received echo.

tive oscilloscope probe providing a load of <2 pF and 1 MΩ. A complete excitation and echo reception sequence is shown in figure 3.

As there is no cabling in the path from the driver stage to the driven device, the amount of parasitic components, e.g. inductance and capacitance from circuit board and cabling, is minimal. This makes it possible to provide the piezoelectric device with a very clean excitation pulse, as shown in figure 4. For comparison, an excitation of a piezoelectric device through a 7 cm coaxial cable is shown in figure 5. It is here seen that the inductance of the short cable creates a resonance circuit together with the capacitance of the transducer, and causes the ringing seen during the excitation pulse. This behavior is further discussed in [3], where the conclusion is drawn that varying cable lengths have large effects on the performance of a pulse echo system. With the driver mounted as presented here, this dependence is completely eliminated.

The power consumption of two prototypes was measured for various repetition frequencies. As shown in table 1 the power consumption is highly dynamic and linearly dependent on the repetition frequency. This is also to be expected, as there should be only minimal leakage in the circuit. The main source of power consumption is assumed to be the energy required to charge the static capacitance C_0 of the piezoelectric disc. For a 16 mm disc the value of C_0 is 5 nF. The energy stored in this capacitance for a given voltage *V* is

$$W = \frac{C_0 V^2}{2}. \tag{1}$$

Thus, the minimum theoretical power consumption to charge and discharge this capacitor with a repetition frequency *f* is

$$P = \frac{f C_0 V^2}{2}. \tag{2}$$

For 6 V supply and a repetition frequency of 1 kHz, this yields 90 μW. Note, however, that in order to reach this value the charging of the capacitor must be lossless, i.e. adiabatic. In the test setup the charging is done from a fixed voltage source, which should generate resistive loss of the same amount as the energy stored in the capacitor. Thus the total power consumption should be in the order of 180 μW. As can be seen from the measurement results, the consumption of the device lies very close to the theoretical lower limit. The conclusion at the writing of this paper is that the low energy consumption is due to the fact that the piezoelectric device does not behave as a pure capacitor at the time of charging. There are most probably interactions between the electronics and the mechanics which give the unexpectedly low result for power consumption. This phenomenon will be further investigated in future work.

Measurements were made both with and without attached batteries. The added mechanical load on the piezoelectric disc with attached batteries serves as a backing, which slightly attenuates the ringing after excitation as well as the received echo.

Table 1: Measured power consumption for two prototypes at various repetition frequencies.

Repetition rate	P1	P2
100 Hz	10 μW	11 μW
500 Hz	51 μW	56 μW
1 kHz	102 μW	112 μW
2 kHz	206 μW	227 μW

Mechanical

Both the driver chip and the bond wires are subject to the ultrasonic vibrations imposed by the piezoelectric disc. To get a very rough approximation of the mechanical properties of these vibrations, the static deformation Δz of the PZ27 for the applied voltage can be written as

$$\Delta z = d_{33} U \tag{3}$$

where d_{33} is the piezoelectric charge coefficient for the material. Assuming a sinusoidal vibration of frequency *f*, the peak speed and acceleration on the surface are

$$v_{max} = 2\pi f \Delta z \tag{4}$$

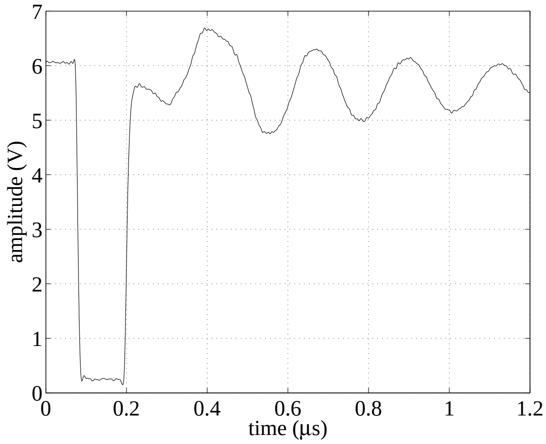

Figure 4: Oscilloscope trace of excitation pulse generated with the driver stage mounted directly at the 16 mm PZ27 disc.

and

$$a_{max} = (2\pi f)^2 \Delta z \tag{5}$$

respectively. For the system at hand we have V = 6 V, d_{33} = 425 $\cdot 10^{-12}$ C/N, and f = $4 \cdot 10^6$ Hz. This gives the mechanical vibration data

$$\begin{aligned} \Delta z &= 2.55\, nm \\ v_{max} &= 64\, mm/s \\ a_{max} &= 1.6 \cdot 10^6\ m/s^2. \end{aligned} \tag{6}$$

The estimate for acceleration is very high, although the amplitude of the oscillation is extremely small. The effects of acceleration and vibration on wire bonds are discussed in [8]. The areas of application discussed therein are however different than the one described in this paper, e.g. high accelerations in military equipment and ultrasonic cleaning in frequency ranges below 50 kHz. Most likely, resonance induced errors and mechanical displacement should not be an issue in this work, as we are dealing with very high frequencies and extremely small amplitudes. On the other hand long term reliability has to be raised as an issue, as the device may be excited with a repetition rate of several kHz for several years. This issue must be dealt with also for the chip and its attachments. Although a different area of research, similar amplitudes and frequencies of vibration are found in Micro-Electro-Mechanical-Systems, [7]. A next step to investigate these questions further will be an accelerated lifetime high temperature test on the unit.

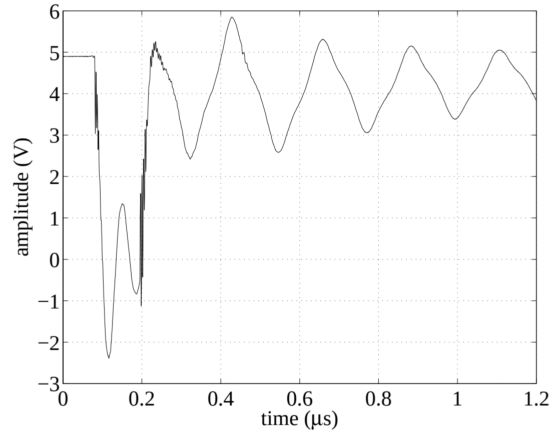

Figure 5: Excitation of a 12 mm diameter PZ27 disc through a 7 cm long coaxial cable.

4. Discussion

Mechanical sensor design

In the design of an ultrasound sensor, mechanical matching and backing layers are used to tailor the shape of the generated ultrasound pulse [11]. We have in this work drawn the conclusion that the load of a pair of button cell batteries does not significantly impair the pulse shape on a non-backed system. For a complete sensor the batteries may however present a problem when a mechanical backing shall be built, as this then does not come in direct contact with the piezoelectric device. To solve this dilemma, an alternate mounting strategy for a sensor is proposed in figure 6. Here, the batteries are moved away from the disc to give room for backing. The driver chip is left in place to provide ease of mounting and to keep the pulse control possibilities discussed above.

Electrical matching issues

Traditional ultrasonic measurement systems often involve a coaxial cable to connect the transducer to the electronics. This cable has a certain characteristic impedance which will require a matching network in the transducer end to achieve optimum power transfer and system performance [5], [6]. These matching networks are most often analyzed in the frequency domain. When all cabling and interconnection networks between the electronics and the transducer is removed as presented in this paper, the voltage control is not dependant on intermediate electrical networks. The issue can then be turned from impedance matching in the frequency domain, to control of time constants and rise and fall times in the time domain. With this setup we

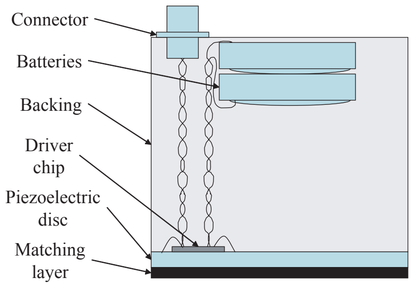

Figure 6: Proposed sensor design with batteries cast into the backing material.

have direct control of the charge injected into the transducer, and the focus will be to achieve a certain voltage level within a given time period. These requirements will then in turn determine the dimensioning of the driver stage transistors. The same reasoning applies if the transducer is driven with a digital-to-analog converter (DAC) instead of a simple on/off stage. The DAC is then presented with a capacitive load which needs to be charged to a target value within a given time period to achieve the desired pulse shape.

5. Acknowledgements

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6. Conclusions and further work

This paper has presented the design of a compact ultrasonic transducer, where the driver electronics are mounted directly at the piezoelectric sensor. Measurements have been performed with an air backed sensor and Plexiglas as the medium. The absence of long wiring and parasitic components between the driver stage and the driven crystal give excellent pulse control possibilities. The power consumption of the driver stage/sensor combination is highly dynamic, with a current consumption of less than 20 μA at 1 kHz repetition rate. The results show the feasibility to achieve high integration for electronics and sensor in an ultrasound transducer.

Future development will involve a complete sensor mounted ultrasound measurement system based on the presented design. The approach taken introduces issues regarding the influence of vibrations in the MHz-range on die attachment and wire bonding connections, which need to be further investigated.

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