Integrated Micromachined Electrostatic True RMS-to-DC Converter

B. P. van Drieënhuizen and R. F. Wolffenbuttel

Abstract— **An integrated electrostatic true rms converter has been developed. It uses a compatible surface micromachining post-process, which combines the mechanical structure with standard electronic readout circuitry, thereby creating an integrated measurement system. The converter uses two identical bridge structures, which are capacitively driven. The system generates an rms voltage V_{rms}, which forces the second bridge structure to give the same deflection as the one driven by the ac-input voltage. When a feedback loop is used, the converter can achieve a high accuracy. The converter features a high bandwidth compared to existing fully electronic converters and a very high input impedance compared to existing thermal converters.**

I. Introduction

ONE of the important parameters in the measurement of electrical signals is the root mean square value of a signal, which gives the average energy content. This energy content is important in noise measurements, power measurements, and measurements of output signals of sensors, which measure shocks or other nonperiodic effects. The rms value can be used to describe a variety of signals, such as a dc signal, and also a heavily fluctuating nonperiodic signal. Although for periodic signals the rms value can be calculated from the average value, a true rms converter should be suitable for signals of arbitrary shape. From existing converters, like electronic, thermal, electrodynamic, and electrostatic types, only electronic and thermal converters have been monolithically fabricated to date. Using new techniques like surface micromachining, an electrostatic rms converter can also be fabricated. Because the surface micromachining can be carried out as a post-processing technique, standard electronic circuitry can be combined with the micromechanical structure, thereby creating a fully integrated accurate electrostatic true rms converter.

II. Integrated True RMS Converters

The definition of the root-mean-square value of a signal $V(t)$ with period T_p is given by

$$V_{RMS} = \sqrt{\frac{1}{T_p}\int_{-\frac{T_p}{2}}^{\frac{T_p}{2}} V(t)^2\,dt}. \tag{1}$$

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This is equivalent to the amplitude of a dc voltage that transfers the same energy as the ac signal in a period of time T_p.

To realize this calculation, two types of integrated converters are widely used [1]. The first type is a full electronic converter, where the input signal is squared and integrated, and the root taken by electronic circuits. Two types of electronic converters are used, direct and indirect converters. In the direct converter the three operations are directly cascaded to produce the rms value. The drawback of this method is the increase in the dynamic range of the input signal after the first multiplication. The indirect converter uses the feedback output signal to limit the dynamic range required and to circumvent the necessity of taking the root.

The advantages of the electronic converters are the very high input impedance, fast response time, and ease of integration. The disadvantage is the already mentioned limited dynamic range, which can be handled. The bandwidth of these converters is also restricted. To achieve a 1% accuracy bandwidth, the usually specified -3 dB bandwidth, which corresponds to an accuracy of 70%, must be seven times higher. This means that the 1% bandwidth of most electronic converters is less than 1 MHz.

Another widely used rms converter is based on a thermal principle. The squaring of the input signal is realized by measuring the temperature of a resistor, which is heated by the Joule heat of the electrical current. The dissipated energy is proportional to the square of the input signal. Integration can be achieved by using the thermal time constant of the circuit or by an extra electronic integration circuit. Most thermal converters use a feedback system, which compares the temperature of a dc-driven resistor with the temperature of the resistor driven by the input signal. The temperature can be measured using a bipolar transistor [2] or a thermopile [3], which can be realized by using extra bulk micromachining steps.

The advantage of this converter type is the high 1% bandwidth, which is limited by the parasitic capacitances of the input resistor to about 100 MHz. The electronic measuring and control circuit uses only relatively low-frequency signals and therefore does not impose a bandwidth limit to the converter. The disadvantage of the thermal converter is the low input resistance, which loads the signal to be measured. An input amplifier can be used to increase this impedance, but this drastically decreases the maximum achievable 1% bandwidth. Special fabrication techniques are required to achieve thermal isolation between the drive and the feedback resistor. The sensitivity is limited by the heat exchange with the ambient air.

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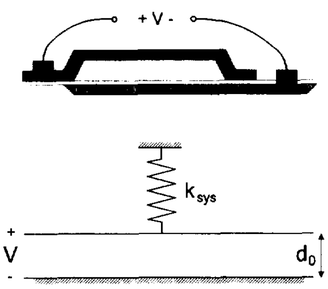

Fig. 1. Simplified model of an electrostatic rms converter.

With the development of surface micromachining techniques, it is possible to fabricate mechanical structures on top of the chirp surface. The structures are used to measure nonelectrical quantities like acceleration and pressure. However, it is possible to drive these structures using electrostatic forces, thereby measuring electrical parameters. This behavior can be used to fabricate an integrated electrostatic rms converter, which overcomes the disadvantages of the converters mentioned above.

III. Operating Principle of the Electrostatic rms Converter

By depositing a structural layer such as polysilicon over a patterned sacrificial layer, such as silicon oxide or PSG, and then patterning the structural layer and etching the structural layer, a simple micromachined bridge structure can be fabricated. A simple electromechanical model of the behavior of this bridge is given in Fig. 1.

The bending of the structural layer can be modeled in first order by a spring constant given by [4]

$$k_{\text{sys}} = \frac{48Ewt^3}{12l^3}. \tag{2}$$

This equation is valid for a single beam with clamped ends [5], with width w, thickness t, and length l. The Young's modulus of the material is given by E. This first-order approximation is valid for relatively small deflections compared with the beam length. Because in IC technology the lateral dimensions are much larger than the layer thicknesses, this approximation can be used. For the same reason, the electrical behavior of the structure can be modeled by a plane plate.

When a voltage is applied between the two electrodes, the upper electrode is attracted electrostatically to the lower electrode. When the displacement is small compared to the initial distance between the electrodes, the displacement is given by

$$F_{el} = F_k \Rightarrow \frac{\epsilon A}{2(d_0 - \Delta d)^2} V^2 = k_{\text{sys}}\, \Delta d$$
$$\Delta d = \frac{\epsilon A}{2k_{\text{sys}}(d_0 - \Delta d)^2} V^2 = \frac{\epsilon A}{2k_{\text{sys}} d_0^2} V^2. \tag{3}$$

Since the spring constant k_{sys}, the plate area A, and ϵ are constants depending on the geometry and material properties, the displacement is linearly proportional to the square of the input signal V. This squaring is realized by the attracting Coulomb force between the electrodes and obeys a fundamental law; hence it can be very accurate. When a fluctuating signal $V(t)$ is applied, the Fourier transform of the squared input signal contains a dc component and higher harmonics. This dc component gives the plate a dc deflection, and the higher frequency terms are damped by the squeezed film damping of the structure, or by an extra low-pass filter in the electronic readout circuit. Therefore, the mechanical and electronic damping performs the integration of the squared signal, resulting in a steady state signal proportional to the square of the rms value of the input signal. The displacement of the structure can be measured capacitively.

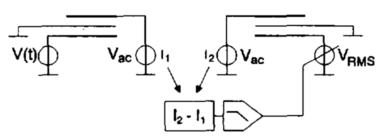

Fig. 2. rms converter measurement system.

IV. Measurement System

A measurement system based on one single bridge structure has the disadvantage that second-order effects limit the accuracy of the rms value of the input signal. These effects are edge and bending effects, which make the plane plate approximation invalid. Also, the spring constant is not really constant, which gives an extra error for increasing signal levels. These effects can be compensated by using a second bridge structure, which is driven by a dc voltage and which should give the same deflection as the one driven by the input signal. Both bridges suffer from the same nonlinearities, which compensate each other and result in a more accurate result. The system uses two identical double bridge structures with three electrodes each (see Fig. 2).

The upper and lower electrodes are fixed, but the middle electrode is flexible. One structure is activated by the fluctuating input signal, and the other structure is driven by a dc voltage that is equivalent to the generated rms value. When a voltage is applied between the bottom and the middle electrode, the latter is attracted, and this results in a displacement as given by (3). This displacement changes the capacitance between upper and middle electrodes, which can be measured capacitively. A voltage source V_{ac}, of fixed frequency, drives the top electrode, and therefore the capacitance change results in a current change. The frequency of this signal should be much higher than the bandwidth of the mechanical structure itself, but within the bandwidth of the standard readout electronics. Although this voltage generates an attracting force between the middle and upper electrodes, this does not disturb the measurement because both structures have the same attractive force and this disturbing effect is compensated. The current of both structures is compared, the difference is amplified and, after low-pass filtering, the resulting dc signal is applied to the second structure. The dc signal is equal to the rms value of the input signal. The signal-to-noise ratio can be increased using synchronous detection, thereby introducing a low-pass filter in the loop.

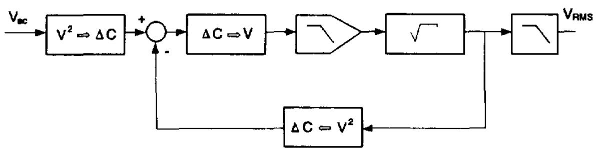

Fig. 3. Simulation model.

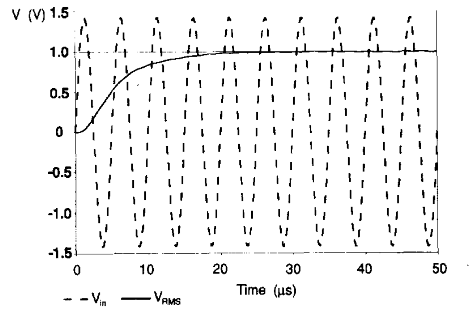

Fig. 4. Simulation result with sinusoidal 200 kHz input signal.

V. Simulation Results

The simulation model of the measurement system of Fig. 2 is given in Fig. 3. The bridge structures are modeled by blocks converting the input voltage V into a capacitance change ΔC. To keep the loop gain constant, an electronic (low-frequency) square rooter circuit is inserted, to compensate for the squaring of the V_{rms} in the feedback bridge. An electronic low-pass filter is inserted after the ΔC to voltage conversion because this conversion is realized using synchronous detection, using the drive voltage V_{ac} and the measured current difference between the two structures.

The accuracy of the V_{rms} is determined by the loopgain, which can be controlled by the low-frequency amplifier. The ac ripple that is still present on the output signal can be reduced without increasing the response time significantly by using an external low-pass filter.

The damping of the structure is mainly squeezed film damping [6], [7]. The dynamic behavior of the mass, spring, and damper system can be described by a second-order differential equation. This behavior can be simulated using an electrical circuit simulator (SPICE) and a parallel RLC network, where R, L, and C are given by the inverse damping, inverse spring constant, and mass, respectively. The measurement system of Fig. 3 is simulated, using the following properties of the mechanical structure and time constant of the electronic loop filter: $l = 100\mu$m, $w = 30\mu$m, $h = 500$ nm, $d_0 = 500$ nm, and $\tau_{RC} = 1.6 \times 10^{-6}$. The equivalent electrical parallel RLC circuit is $R = 15.68\ \Omega$, $L = 2$ mH, and $C = 17.25$ fF.

Fig. 4 gives the result of a sinusoidal input signal of 200 kHz and amplitude $\sqrt{2}$V. The accuracy of the output V_{rms} is about 0.5%.

VI. Fabrication of the Device

In order to take full advantage of integration techniques, surface micromachined structures must be combined with standard electronic circuits. This can be achieved only when the surface micromachining steps, which are carried out after processing of the electronics, are fully compatible with the electronic process. This gives several limitations on the materials deposited and the temperatures used during the post-processing. A special surface micromachining process module has been designed [8], which is compatible with a standard bipolar process. This process module uses two sacrificial PSG layers [9], two low-stress nitride layers, and two low-stress polysilicon layers, as can be seen in Fig. 5.

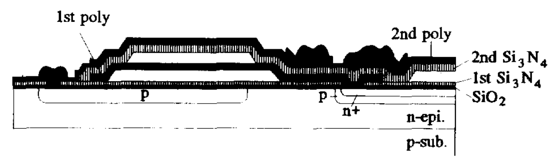

Fig. 5. Cross section of the micromachined structure.

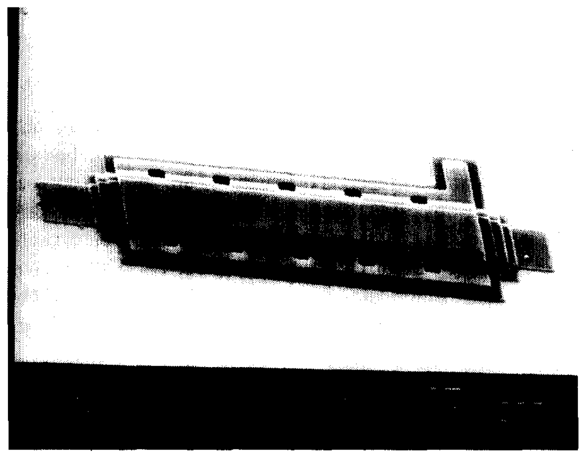

Fig. 6. SEM photograph of the rms converter.

The maximum temperature used during this post-process is less than 850°C, which is low enough to ensure that the transistor characteristics are not altered. Also, the polysilicon films are deposited in such a way that no high-temperature annealing is required to lower the intrinsic stress in the film. The film has a small tensile stress just after deposition and donor activation annealing, which ensures that the mechanical structures remain flat.

A photograph of a fabricated converter is shown in Fig. 6. The picture was taken before the metallization step, and therefore the sacrificial layer has not yet been etched away. From left to right, the middle polysilicon electrode can be seen. Orthogonal on this electrode, the second nitride, and on top of that the second polysilicon layer, can be seen. In these layers etch holes are created to ensure that the etchant reaches the inside PSG layers. The bottom electrode is created in the epilayer and therefore cannot be seen.

VII. Conclusions

Using a compatible post-process surface micromachining module with a standard bipolar process, an integrated electrostatic rms converter can be fabricated. The electrostatic rms converter has a high 1% bandwidth, which is limited by the RC time constant from the source impedance and the very small input capacitance (several fF) of the structure. This bandwidth can be as high as 100 MHz, which is much higher than can be achieved with fully electronic rms converters. Compared with thermal rms converters, the electrostatic converter has a much higher input impedance, and therefore it does not load the source. Overloading the structure does not damage the converter as is the case with thermal converters. Removing the input voltage after exceeding the pull-in voltage of the bridge structure causes it to return to its original position.

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