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An integrated charge amplifier for a pyroelectric sensor

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Abstract

This paper presents an integrated charge amplifier that measures a small charge. This charge is generated by a pyroelectric detector. The charge amplifier consists of a single-stage common source configuration with a passive feedback network. The charge amplifier has a bandwidth of 700 kHz and an output noise voltage of 20 nV $Hz^{-1/2}$ at 1 kHz. A 2×2 integrated pyroelectric sensor based on VDF/TrFE copolymer has been realized. The voltage response of this sensor–amplifier is reported

Keywords: Charge amplifiers; Pyroelectric sensors; VDF/TrFE copolymers

1. Introduction

In the last two decades integrated single, linear array or matrix pyroelectric sensors on silicon have been developed. The advantage of these integrated sensors, in which the sensing element is placed near to the readout electronics, is minimized interference. Much research activity is concentrated on developing new and composite materials, deposition of the material on a silicon substrate, and new device configurations for pyroelectric sensors [1]. Conversely, the readout electronics get less attention. Hammes et al. discussed three designs of readout electronics for a pyroelectric sensor based on JFET and MOSFET processes [2–4]. This work highlighted the major problem of the realization of an integrated high impedance R_{bias} for biasing the FET.

One of three major parameters that determine the sensitivity of an integrated pyroelectric sensor is the electrical transfer function of the readout electronics [5]. Furthermore, the noise of the pyroelectric sensor is dominated by the noise of the pre-amplifier, particularly in the case of a matrix sensor in which the size of the pixels is small [4,5]. Therefore, to achieve a sensitive integrated pyroelectric sensor with a low noise equivalent power (NEP), we have studied and designed a new pre-amplifier for an integrated pyroelectric sensor.

When the temperature of a pyroelectric material is changed, an electric charge is generated. The relation between the primary information, temperature change T and the charge q is linear. The internal impedance of a pyroelectric detector is a capacitance C_{pyro}. The capacitance C_{pyro} is not accurately defined. It depends on constructional variation; it is non-linear and temperature dependent. Consequently, the voltage $v_{pyro}=q/C_{pyro}$ is not an accurate representation of the primary information. In the Norton representation, $i_{pyro}=dq/dt$ holds. Hence, the short-circuit current does not depend on the unreliable value of C_{pyro}. Therefore, i_{pyro} is an accurate analogue of the primary information. Hence, for accurate information transfer, a current amplifier is required, i.e., the input impedance of the amplifier has to be as low as possible, ideally zero. Other requirements for the amplifier are circuit simplicity, due to the large number of elements in a matrix sensor, and low noise, which preferably must be lower than the noise produced by the sensing element itself

In this paper we shall discuss the charge amplifier. The characteristics of the amplifier, such as bandwidth and noise, will be presented. A 2×2 matrix VDF/TrFE copolymer-on-silicon pyroelectric sensor using the charge amplifier has been realized. Sensitivity and noise will be presented. These values will be compared with those of a voltage amplifier.

2. Charge amplifiers

In this primary design we use a single common source configuration with feedback provided by a capacitor C_f and T-form R_1, R_2 and C_x, as shown in Fig. 1. An equivalent circuit of the sensing element is represented by the current source $I_{pyro}=pA\omega T$, where p is the pyroelectric coefficient of

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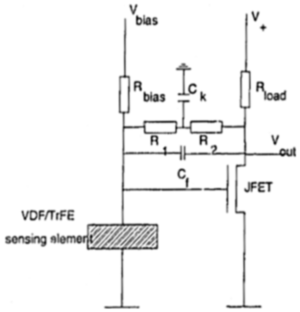

Fig. 1. A charge amplifier of a pyroelectric sensor.

the pyroelectric material, A the area of the sensing element, T the spatial average of the temperature in the pyroelectric layer, ω the angular modulation frequency and C_{pyro} the internal impedance.

The transfer function of the charge amplifier is

$$V_{out}=\frac{Z_i R_{load}(1-g_m Z)}{Z_i+R_{load}+Z+g_m Z_i R_{load}} pA\omega T$$

with

$$Z=\frac{R_1+R_2+j\omega C_k R_1 R_2}{1+j\omega C_f(R_1+R_2)-\omega^2 C_k C_f R_1 R_2}$$

and

$$Z_i=\frac{R_{bias}}{R_{bias}+j\omega C_{pyro} R_{bias}}$$

where g_m is the transconductance of the FET.

From the above equations, clearly an electric transfer function of the charge amplifier is set by R_{load}, the transconductance of the FET, the input impedance Z_i and the feedback impedance Z. The bandwidth of the amplifier is determined by Z_i and Z. Unlike the voltage amplifier as described in previous publications [4,5], we can increase the amplification factor without decreasing the bandwidth. Moreover, variability of R_{bias} does not directly influence the amplification factor of the pre-amplifier. We choose the components of the charge amplifier as follows: $R_1 = 10$ kΩ, $R_2 = 10$ kΩ, $R_{load} = 10$ kΩ, $R_{bias} = 10$ kΩ, $C_k = 10$ pF and $C_f = 10$ pF. A transfer function V_{out}/I_{pyro} of 1.10^4 V A^{-1}, and an input impedance of 3 kΩ are obtained. Resistors and capacitors are formed in a separate isolation island so that they are independent of other devices on the chip. The resistors are fabricated by making two contacts to the epitaxial layer. The capacitors are formed in an emitter–base junction.

The JFET charge amplifier has been realized in the DIMES01 double-metal-layer process at the DIMES Laboratory of Delft University of Technology. The parameters of the JFET are given in Table 1. Fig. 2 shows a microphotograph of a single cell of the 2×2 integrated charge amplifier

Table 1
Parameters of the JFET readout

Property	Size	Units
Extended gate area	500×500	μm²
I_{DSS}	8×10^{-4}	mA
g_m (I_D = 0.4 mA)	7.6×10^{-4}	A V⁻¹
W/L	100	
β	3.6×10^{-4}	A V⁻²
f_0	1	kHz
V_p	1.5	V

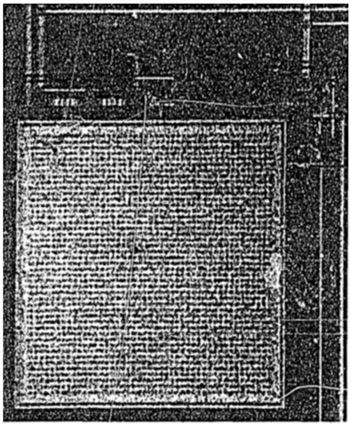

Fig. 2. A microphotograph of a single cell of the 2×2 integrated charge amplifier with an extended gate of 500 μm×500 μm.

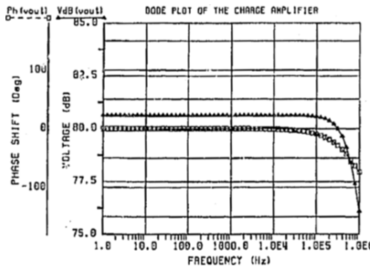

Fig. 3. Frequency and phase characteristics of the charge amplifier.

with an extended gate of 500 μm×500 μm². Fig. 3 shows the frequency and phase characteristics of the charge amplifier. The bandwidth of the charge amplifier is around 700 kHz and there is no phase shift under frequencies of 100 kHz.

The main noise sources of the charge amplifier are (1) gate current shot noise of the JFET, (2) the channel thermal noise of the JFET, (3) the flicker or $1/f$ noise of the JFET and thermal noise of R_{bias}, R_{load}, R_1 and R_2. Furthermore, since

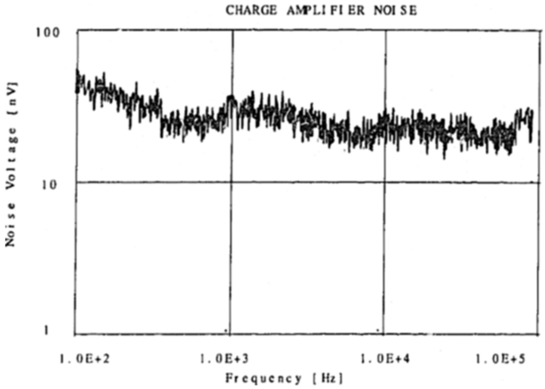

Fig. 4. Noise of the charge amplifier as a function of frequency

the pixel is small, dielectric loss noise from the sensing element (VDF/TrFE copolymer) can be neglected.

Fig. 4 shows the output voltage noise of the charge amplifier as a function of frequency. Up to 100 Hz, the $1/f$ noise gives the largest contribution to the total noise; the total output voltage noise decreases with increasing frequency. It is 25 nV $Hz^{-1/2}$ at 100 Hz. The thermal noise of R_{bias} dominates the noise sources at frequencies between 1 kHz and 0.3 MHz, the total output voltage noise is 20 nV $Hz^{-1/2}$ at 1 kHz. It is less than that of a voltage amplifier [4,5].

3. Pyroelectric sensor

The gate of each JFET is connected to a large piece of aluminium bottom electrode (the so-called extended gate) on the chip surface and the defining pixel area. This extended gate has an extra external connection that allows poling of the copolymer. The pixel pitch is 300 μm. Fig. 5 shows a vertical cross section of the layout of a single pyroelectric sensor. The resistors and capacitors, which are shown here in discrete form for clarity, are also integrated on the chip. VDF/TrFE copolymers are deposited on the silicon substrate that contains readout electronics using the spin-coating technique.

After annealing, a 100 nm aluminium top electrode is deposited. The aluminium electrode is also used as a mask for etching the copolymer. To avoid the adhesion problem between the electrodes and the copolymer, the top aluminium electrode is deposited directly by using a shadow mask.

To allow aluminium wire bonding and IC packaging, the copolymer has to be removed from the bonding pads There-

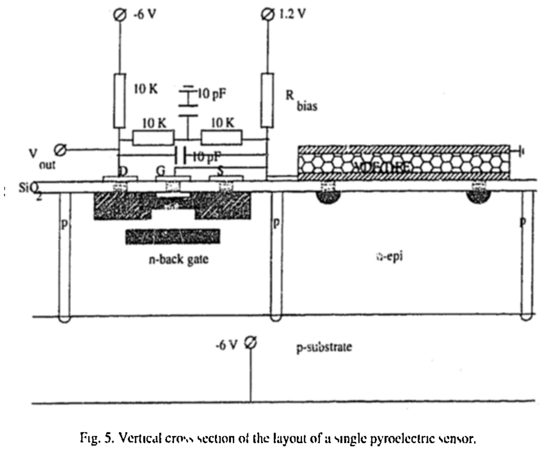

Fig. 5. Vertical cross section of the layout of a single pyroelectric sensor.

fore, some area of the copolymer has been etched. The selective etching of VDF/TrFE copolymer is done by wet etching with 2-butanone. A post anneal is carried out before the etching process. Finally, this top electrode is connected to ground by gluing a bonding wire from the chip housing to the aluminium electrode, using conductive adhesive.

The VDF/TrFE copolymer is poled by step-wise poling. This is performed by a series of pulses 8 min long of an electric field between the electrodes and with increasing height. Between two pulses, the electric field is zero (short circuit) for 2 min. The number of pulses is five, with a constant increase of 20 V μm^{-1}. This poling treatment is carried out at room temperature. The step-wise poling method is described in more detail elsewhere [4].

4. Experimental results

Fig. 6 shows the experimental set-up of the output voltage measurement. A chopper modulates the beam to provide an a.c. signal for the pyroelectric sensor and a reference signal for the phase-sensitive readout of the sensor output (lock-in amplifier). A germanium filter was used for screening ambient visible light from the sensor. A frequency response for the sensor was then determined by varying the chopper frequency. The heat source has been calibrated using a power measurement instrument. Therefore, we are able to calculate the sensitivity of the sensor.

There is inevitably some variation between pixels. If this system is to be extended to arrays containing more pixels, then the repeatability must be such that it is still possible to capture images without serious variation from pixel to pixel. Experimental results confirm that the basic circuitry shows little variation across pixels Fig. 7 shows the output voltage of all cells of the pyroelectric sensor using the charge amplifier as a function of the chopper frequency.

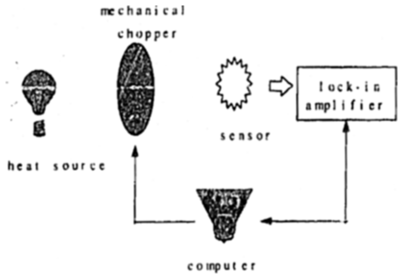

Fig. 6. Experimental set-up for the pyroelectric sensor measurement.

In order to facilitate a comparison between the voltage and charge amplifier configurations, both were realized on the same chip. The voltage sensitivity of the sensor using the voltage and charge amplifiers is shown in Fig. 8. The sensitivity of the sensor using the voltage amplifier is larger than that of the charge amplifier at low frequencies (below 100 Hz).

5. Conclusions

A simple integrated charge amplifier for a pyroelectric sensor has been realized. The charge amplifier has a bandwidth of 0.7 MHz and an output noise voltage of 20 nV $Hz^{-1/2}$ at 1 kHz. A 2×2 matrix integrated pyroelectric sensor has been made. A voltage sensitivity of 0.76 V W^{-1} at 100 Hz is achieved. Since the noise of the sensor is dominated by the noise of the charge amplifier, the voltage noise decreases with increasing frequency, for frequencies up to 100 Hz. It is 25 nV $Hz^{-1/2}$ at 100 Hz and is constant for frequencies between 1 kHz and 1 MHz. The noise equivalent power of the inte-

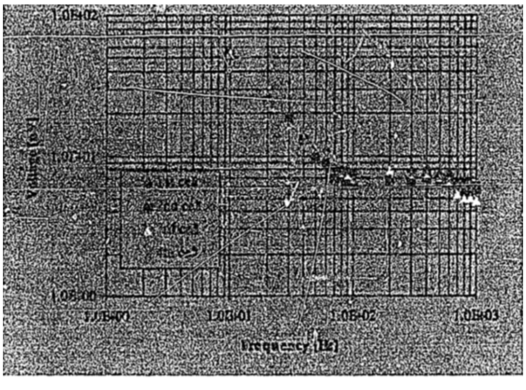

Fig. 7. Output voltage of all cells of the pyroelectric sensor using the charge amplifier as a function of the frequency.

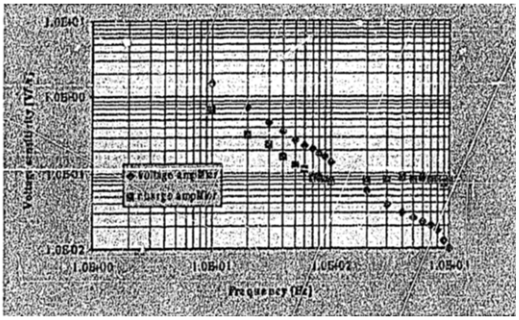

Fig. 8. Voltage sensitivity of the pyroelectric sensor using the charge and voltage amplifiers.

grated pyroelectric sensor is 3.3×10^{-8} W $Hz^{-1/2}$ at 100 Hz.

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Biographies

Dadi Setiadi was born in Palembang, Indonesia, in 1965. He received his M.Sc. degree in electrical engineering in 1991 from Delft University of Technology. In 1995, he received the Ph.D. degree in electrical engineering at the University of Twente, his thesis dealing with integrated VDF/TrFE copolymers-on-silicon pyroelectric sensors. In 1996, he became a post-doctoral fellow in the Sensor System Group, Napier University, UK.

A.F. Armitage obtained a Ph.D. in surface physics from Warwick University in 1981. He then worked on microprocessor-based plant instrumentation with British Nuclear Fuels Ltd. He moved to Edinburgh, and continued working on microprocessor systems, this time for a servo design company. In 1986 he joined Napier University as a lecturer in electronic engineering. He has collaborated with the Royal Observatory, Edinburgh, on the development of adaptive optics systems, some of which incorporated artificial neural networks. His main research interest, as part of the Sensor Systems Group, is the development of low-cost infrared imaging systems.

T.D. Binnie obtained a Ph.D. in solid state physics from Heriot Watt University before employment as a development engineer for Hughes Microelectronics Europe Ltd. Since joining Napier University as a lecturer in electronic engineering in 1986, he has worked on many research and development projects. In 1991 Dr Binnie set up the Sensor Systems Group at Napier University to work on a variety of academic and commercial contracts. The group consists of four academic staff and three full-time research staff. Dr Binnie is a co-holder of SERC Grant Award (GR/H81016) 'Traffic Representation by Artificial Neural Systems', and programme leader of EPSRC Grant Award (GR/K17224) 'Infrared Sensor Arrays'. He has also held commercial research contracts with Shell Exploration and Production (UK) Ltd., Shell Research Ltd. and Hewlett-Packard Research Laboratories and is a consultant to Vision Group plc. Dr Binnie was appointed reader in sensor systems in 1996 and is a member of the EPSRC College of Peers for Control and Instrumentation. He was joint winner of the Enterprise Oil–Heriot Watt University Environmental Award in 1995.

Paul P.L. Regtien was born in Boxmeer, The Netherlands, in 1946. He received the M.Sc. and Ph.D. degrees from Delft University of Technology in 1970 and 1981, respectively. Since 1970 he has been with the Department of Electrical Engineering of that university. Since 1994 he has been a full-time professor at the University of Twente, Department of Electrical Engineering. His current research activities lie in the fields of measurement transducers, robotic instrumentation and mechatronics.

Pasqualina M. Sarro received her 'Laurea' degree (cum laude) in solid-state physics from the University of

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