A 3×1 integrated pyroelectric sensor based on VDF/TrFE copolymer

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Abstract

This paper presents an integrated pyroelectric sensor based on a vinylidene fluoride–trifluoroethylene (VDF/TrFE) copolymer. A silicon substrate that contains field-effect transistor (FET) readout electronics is coated with the VDF/TrFE copolymer film using a spin-coating technique. On-chip poling of the copolymer has been applied using a step-wise poling at room temperature. The copolymer deposition and polarization are compatible with semiconductor technology. An array of 3×1 integrated pyroelectric sensor has been realized. The current and voltage sensitivities and noise of this sensor have been measured. Voltage noise decreases with increasing frequency, and it is $2 \text{ nV (Hz)}^{-1/2}$ at 100 kHz.

Keywords: VDF/TrFE copolymer; Pyroelectric sensors; Infrared sensors

1. Introduction

A vinylidene fluoride–trifluoroethylene (VDF/TrFE) copolymer has been applied as a pyroelectric detector [1–5]. An advantage of this copolymer compared with the polymer PVDF is that the copolymer is pyroelectric without mechanical stretching [1]. A very thin copolymer film ($1\text{--}10 \mu\text{m}$) is deposited on silicon using a spin-coating technique [3]. This technique gives the possibility of placing the sensing element (VDF/TrFE copolymer) near to the readout electronics to minimize the interference. The thermal conductivity of the VDF/TrFE copolymer is much lower than that of other ceramic or single-crystal pyroelectric materials. Therefore, the VDF/TrFE copolymer is a suitable candidate for a matrix IR image sensor.

Aluminium electrodes are present on both sides of the copolymer film. The bottom electrode is connected to the gate of a field-effect transistor (FET) as part of the readout circuit. By applying an electric field between the top and bottom electrodes, on-chip poling of the copolymer can be achieved at room temperature and without damaging the readout electronics. The deposition and poling processes are compatible with semiconductor technology.

FETs are used in the readout electronics because of low noise. The properties of FETs will be presented. In this paper

we describe the deposition of the copolymer on the silicon substrate. On-chip poling of the copolymer will be discussed. Electrical properties of the VDF/TrFE copolymer are presented. Finally, current and voltage sensitivities and noise of this sensor will be discussed.

2. Technology

A pyroelectric material such as VDF/TrFE copolymer generates an electric charge when it is subjected to a temperature change. This charge is directly supplied to the gate of an FET. Therefore, the distance between the sensing element and the electrical signal-conditioning circuitry is minimum and there is almost no deterioration of the signal due to external interferences.

The impedance of the sensing element (VDF/TrFE copolymer) is extremely high and consequently cannot be used for biasing the gate of the FET to supply the gate leakage current. Therefore an extra impedance R_{bias} is connected to the gate of the FET. The FET is biased with an external voltage source V_{bias} . The pyroelectric charge of the sensing element will modulate the drain current of the FET, which is then converted to a change in the output voltage V_{out} by the resistor R_{load} . The pyroelectric sensor can be operated by connecting two resistances: R_{bias} for biasing the gate of the FET and R_{load} for converting the drain current of the FET to an output voltage. A schematic of the sensor element is given in Fig. 1.

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Fig. 1. Schematic of a pyroelectric sensor element.

This circuit can be described by the electrical analogue of Fig. 2.

A charge that is generated by the pyroelectric effect is represented by a current source. The generated charge will slowly leak away through the electrical impedance of the VDF/TrFE sensing element and the gate biasing resistance R_{bias} , which is connected in parallel to this impedance. The impedance of the VDF/TrFE sensing element consists of R_p (resistance of the VDF/TrFE copolymer) and C_p (capacitance of the VDF/TrFE copolymer), both connected to the FET, whose input impedance will mainly consist of a capacitance C_{gs} . Finally, the right-hand part of the circuit represents the amplification of the FET and the load resistor R_{load} .

The transfer function of this sensor element can be calculated as a function of the chopper frequency ω and is given by

$$V_{out}(\omega) = \frac{pA\Delta\bar{T}\omega g_m R_{load} R_E}{(1 + j\omega R_E C_E)(1 + j\omega R_{load} C_{gd})} \quad (1)$$

where $\Delta\bar{T}$ is the temperature change in the sensing element per time unit, which depends on the chopper frequency ω , p the pyroelectric coefficient of the VDF/TrFE, A the sensing element area, R_E the parallel resistance of R_p and R_{bias} , C_E the parallel capacitance of C_p and C_{gs} , R_{load} the load resistor, g_m the transconductance of the FET, and C_{gd} the gate-drain capacitance of the FET.

The resistance R_E depends mainly on the gate biasing resistance R_{bias} due to an extremely high value of the resistance of the VDF/TrFE copolymer R_p . The capacitance C_E , however, depends on both the capacitance of the VDF/TrFE C_p and the capacitance of the FET C_{gs} . The first time constant (left part) in Eq. (1) is much lower than that of the second time constant (right part). Therefore, the electric cut-off fre-

Fig. 2. Electrical analogues describing electric behaviour of the sensor.

quency is mainly set by the first time constant, and depends on the gate biasing resistance R_{bias} . The influence of the variation of R_{bias} on the output voltage and the electric cut-off frequency will be examined.

2.1. FET readout electronics

The FET readout electronics have been realized in the DIMES01 double metal layer process at the DIMES Laboratory of the Delft University of Technology. Parameters of the FET are given in Table 1. Fig. 3 shows the vertical cross section of the layout of a single pyroelectric sensor (not to scale). The gate of each readout FET is connected to a larger piece of aluminium bottom electrode (the so-called extended gate), located on the chip surface and defining the pixel area. This extended gate has an extra external connection, allowing polarization of the copolymer, measuring the electrical properties of the VDF/TrFE copolymer and measuring the current sensitivity of the pyroelectric sensor element. The dimensions of these extended gates, which serve to collect enough charge, are $200\ \mu\text{m} \times 200\ \mu\text{m}$. The inter-pixel distance is $200\ \mu\text{m}$. The top electrode of the VDF/TrFE sensing element is connected to ground. This is achieved by gluing a bonding wire from the chip housing to the aluminium top electrode using conductive adhesive.

The biasing resistor R_{bias} is outside the chip area. It is not integrated on the chip, for two reasons: the desire to vary the value of R_{bias} and the difficulty in realizing a high R_{bias} . We

Table 1
Properties of the FET readout

Property	Size	Units
Gate area	400	μm^2
Extended gate-oxide thickness	0.3	μm
Extended gate area	200×200	μm^2
I_{DSS}	0.8	mA
g_m ($I_D = 0.4\ \text{mA}$)	0.76	mA V^{-1}
W/L	100	
β	0.36	mA V^{-2}
f_0	1	kHz
V_p	1.5	V

Fig. 3. Vertical cross section of the layout of a single pyroelectric sensor. The load resistor, which is shown here in discrete form for clarity, is also integrated on the chip.

want to vary the value of R_{bias} to investigate its influence on the output voltage and on the electric time constant. The amplification resistor R_{load} of 10 k Ω is located near to the extended gate array at the top side of the chip

2.2. Deposition of the VDF/TrFE copolymer

A copolymer sample was formed using 65 mol% vinylidene fluoride and 35 mol% trifluoroethylene, supplied by Solvay and Cie, Brussels, Belgium, in powder form. 9.0 ml of methyl ethyl ketone at 80 °C was used as a solvent. 1 g of VDF/TrFE is dissolved in the hot methyl ethyl ketone solvent, resulting in a 10% concentration VDF/TrFE copolymer solution. During stirring, the solution sample is heated up to 100 °C. After the copolymer is completely dissolved, the solution is filtered and cooled down to room temperature.

The filtered solution is spun on the silicon substrate that contains FET readout electronics by using spin-coating. With this technique, a 1 μm thick copolymer film with a uniformity of 5% is obtained. The sample is annealed as follows: first, the sample is kept for 24 h at 25 °C. Then, the annealing temperature is increased to 100 °C. The sample is kept at this temperature for 6 h, and an anneal for 10 min at 160 °C follows. Finally, the annealing temperature is slowly decreased to 25 °C in 4–5 h. This annealing is done to recover the local stresses, to enhance the crystallization, to improve the adhesion between the copolymer and the aluminium, and to evaporate the remaining methyl ethyl ketone solvent.

The adhesion between the copolymer and the aluminium layers is further improved by a vapour deposition of HMDS (hexamethyl disilazane). This process is performed twice, first before spin-coating of the copolymer and secondly after the annealing step. Finally, a 250 nm aluminium top electrode is deposited.

The copolymer film is poled by step-wise poling, which is described in the next section. A d.c. field is applied between the bottom electrode (extended gate) and the top electrode. This on-chip poling treatment is carried out at room temperature. After the poling treatment, each chip is glued to a DIL 40 housing and aluminium wire bonded.

The absorption of an aluminium electrode is very low. Therefore, it is necessary to deposit an absorbing layer on the top electrode. Here, one has to be sure that the heat capacity of the absorbing layer is small compared with the heat capacity of the top electrode.

2.3. Poling treatment

In order for VDF/TrFE copolymer to be useful as a transducer material, the copolymer must be oriented and polarized. Typically, the larger the degree of orientation in a VDF/TrFE film, the higher will be the resultant activity. The orientation and polarization of VDF/TrFE copolymer films can be accomplished by various methods, all of which include the application of a high electric field across the polymer layer. The larger the applied electric field, the higher the pyroelec-

Fig. 4. Step-wise poling treatment.

tric coefficient. The upper limit of the applied electric field is determined by the electric breakdown strength of the VDF/TrFE polymer film.

A poling method for thin copolymers has to be developed, compatible with IC technology. Criteria for the choice of a poling technique include homogeneous polarization, high pyro-activity of the resulting film, low failure rate due to electrical breakdown during poling, long-term stability of activities and compatibility with semiconductor technology.

Step-wise poling will meet these criteria. The probability of electrical breakdown during poling decreases due to the relatively low applied field. Moreover, the step-wise poling is carried out at room temperature. With step-wise poling, about 30 min are needed to polarize the copolymer, instead of the 5–10 min for 'regular' thermal poling [6].

The step-wise poling is performed by a series of pulses lasting several minutes, and with increasing height. The pulse width is 4 min and the interval between two pulses is 2 min. The maximum applied field strength is 100 V μm^{-1} , with a constant increase of 20 V μm^{-1} . Fig. 4 shows the step-wise poling treatment. More details of this poling method are described elsewhere [7].

2.4. Noise sources

There are several noise sources in the pyroelectric sensor. They can be modelled by three sets of equivalent noise sources, for respectively the detector noise of the pyroelectric sensor element, the readout FET noise and the noise of the additional circuitry.

2.4.1. Detector noise

There are three main noise sources of the pyroelectric detector itself.

2.4.1.1. Thermal fluctuation noise

Thermal fluctuation noise results from energy exchange between the detector and the environment at temperature T . The mean power spectrum density ΔP_T is written as

$$\Delta P_T = (4kT^2G)^{1/2} \quad (2)$$

where G is the real part of the thermal admittance of the pyroelectric detector.

The thermal fluctuation noise is calculated as an equivalent thermal input signal.

2.4.1.2. Johnson noise

The Johnson noise is a random voltage fluctuation caused by the thermal motion of electrons in a resistive element, and is expressed as

$$\Delta V_J = (4kTR_p)^{1/2} \quad (3)$$

with k is Boltzmann's constant, T is the temperature and R_p is the parallel resistance of the VDF/TrFE copolymer sensing element.

2.4.1.3. Dielectric loss noise

The dielectric noise is caused by the thermal motion of electrons in a capacitance C_p with a dielectric loss $\tan \delta$ of the pyroelectric detector. It is expressed as

$$\Delta V_D = (4kT\omega C_p \tan \delta)^{1/2} \quad (4)$$

2.4.2. FET noise

An FET contains three dominant noise sources.

2.4.2.1. Gate-current shot noise

The gate-current shot noise, caused by the charge within the transistor being quantized (as electron and holes), is expressed as

$$\Delta i_g = (2qI_g \Delta f)^{1/2} \quad (5)$$

with q = the electronic charge, 1.6×10^{-19} C.

2.4.2.2. Channel thermal noise

The channel thermal noise is caused by the thermal vibrations of the atoms, and is expressed as

$$\Delta i_{ch} = \left[\frac{\omega(C_{gs} + C_{gd})}{g_m} \right] (4kT \frac{2}{3} g_m \Delta f)^{1/2} \quad (6)$$

with g_m = the transconductance of the FET.

2.4.2.3. Flicker noise

The flicker noise or $1/f$ noise is caused by the presence of surface traps in the transistor:

$$\Delta V_{1/f} = \left(4kTf_0 \frac{2}{3} \frac{1}{g_m} \frac{\Delta f}{f} \right)^{1/2} \quad (7)$$

with f_0 as a process-dependent parameter.

2.4.3. Noise of the additional circuitry

The biasing resistance R_{bias} connected to the gate of the FET and the load resistance R_{load} connected to the drain will give rise to thermal noise.

Fig. 5. Equivalent noise circuit present in a pyroelectric sensor element.

2.4.3.1. Thermal noise of R_{bias}

$$\Delta V_{R_{bias}} = (4kTR_{bias})^{1/2} \quad (8)$$

2.4.3.2. Thermal noise of R_{load}

$$\Delta V_{R_{load}} = (4kTR_{load})^{1/2} \quad (9)$$

The total noise measured at the output of the sensor can be calculated as the quadratic sum of the various contributions of the individual noise sources. The location of these noise sources is shown in the equivalent noise circuit of Fig. 5.

3. Experimental results

The performance of the integrated pyroelectric sensor depends on some parameters. First, it depends on the electrical properties of the 65/35 VDF/TrFE copolymer as sensing element. These properties have been measured after all step processes. Secondly, it depends on the sensitivity of the pyroelectric sensor. Thirdly, it depends on the noise of the pyroelectric sensor.

The sensitivity of the integrated pyroelectric sensors depends on the thermal behaviour of the sensor and the electrical transfer function of the readout electronics. The thermal behaviour is determined by the structure of the sensor [8]. Moreover, it depends on the chopper's modulation frequency. The electrical transfer function of the readout electronics depends on the properties of the FETs and the additional circuitry (R_{bias}).

3.1. Electrical properties of VDF/TrFE

The electrical properties of the VDF/TrFE copolymer, such as dielectric loss, dielectric constant and pyroelectric coefficient, which are related directly to the pyroelectric activity, have been measured. Table 2 show the electrical properties of the 65/35 VDF/TrFE copolymer. Those values have been measured at 22 °C.

3.2. Current sensitivity

The current sensitivity is the ratio of output current to the incident radiation power and is given by

Table 2
Electrical properties of the 65/35 VDF/TrFE copolymer

Property	Size	Units
Pyroelectric coefficient	2	nC cm ⁻² K ⁻¹
Dielectric constant	13.1	
Dielectric loss	0.034	

$$F_i = \frac{I_{out}(\omega)}{P_i} = \frac{pA\Delta\bar{T}\omega}{P_i} \quad (10)$$

where P_i is the incident radiation power, $\Delta\bar{T}$ the temperature change per unit time (which depends on the chopper frequency), p the pyroelectric coefficient of the VDF/TrFE and A the sensing element area. Because of the multilayer structure, the current sensitivity consists of the primary and secondary thermal cut-off frequencies, respectively [9].

The current sensitivity of the pyroelectric sensor element has been directly measured on-chip by connecting an extra external connection of the extended gate. So, the current sensitivity of each pyroelectric sensing element can be measured independently of the amplifier circuitry.

Fig. 6 shows the measured and calculated current sensitivities of a pyroelectric sensor sensing element as a function of the chopper's modulation frequency. It agrees with the previous work [8]. At low frequencies (below 20 Hz), the influence of the silicon substrate is dominant. In this range, the thermal wave penetrates into the structure down to the silicon substrate and therefore the influence of the silicon substrate is large. The secondary thermal cut-off frequency was measured as 7 Hz. It is less than the calculated value. The first thermal cut-off frequency is much lower, 10^{-9} Hz [9].

At high frequencies, the thermal wave does not fully penetrate into the VDF/TrFE copolymer. So, the current sensitivity decreases with increasing frequency. An improvement of the current sensitivity will be achieved by etching the silicon substrate under the sensing element [8].

3.3. Voltage sensitivity

The voltage sensitivity is the ratio of the output voltage to the incident radiation power and is given by

$$F_v = \frac{V_{out}(\omega)}{P_i} = \frac{pA\Delta\bar{T}\omega}{P_i} \frac{g_m R_{load} R_E}{(1 + j\omega R_E C_E)(1 + j\omega R_{load} C_{gd})} \quad (11)$$

or

$$F_v = \frac{g_m R_{load} R_E}{(1 + j\omega R_E C_E)(1 + j\omega R_{load} C_{gd})} F_i \quad (12)$$

So, the voltage sensitivity equals the current sensitivity multiplied by the current-to-voltage transfer function of the FET readout electronics. If the structure of each sensor element is the same, the voltage sensitivity is only attributed to the readout electronics. It increases with increasing param-

Fig. 6. Measured and calculated current sensitivities of the pyroelectric sensor element as a function of the frequency.

Fig. 7. Measured and calculated voltage sensitivities of the pyroelectric sensor element for $R_{bias} = 1$ and $10 \text{ M}\Omega$ as a function of the frequency.

ters g_m , R_{load} and R_E . The g_m of the FET is 0.76 mA V^{-1} . With R_{load} of $10 \text{ k}\Omega$, a readout amplification of 7.6 is obtained. As mentioned in the previous section, the resistance R_E depends mainly on the gate biasing resistance R_{bias} , and the electric cut-off frequency is mainly set by the first time constant $(1 + j\omega R_E C_E)$, and depends on R_{bias} . A linear transfer function of the voltage sensitivity is obtained by the coincidence of the secondary thermal and electric cut-off frequencies, respectively. The influence of the variation of R_{bias} on the voltage sensitivity and the electric cut-off frequency can be examined.

Fig. 7 shows the measured and calculated voltage sensitivities of the single pyroelectric sensor as a function of the chopper's modulation frequency. It is found that the voltage sensitivity increases with increasing R_{bias} (the voltage sensitivity with $R_{bias} = 10 \text{ M}\Omega$ is ten times greater than with $R_{bias} = 1 \text{ M}\Omega$).

The electric cut-off frequency also depends on R_{bias} . For $R_{bias} = 10 \text{ M}\Omega$, it was measured to be located at $\approx 20 \text{ Hz}$ and increases with decreasing R_{bias} , as we expected (see also Eq. (12)). For $R_{bias} = 10 \text{ M}\Omega$, the electric cut-off frequency coincides with the secondary thermal cut-off frequency.

3.4. Noise

Here, we measure the total voltage noise, composed of the detector noise, the readout FET noise and the noise of the

Fig. 8. Measured voltage noise of the pyroelectric sensor element for $R_{\text{bias}} = 1 \text{ M}\Omega$ as a function of the frequency.

additional circuitry. Fig. 8 shows the measured voltage noise of the pyroelectric sensing element for $R_{\text{bias}} = 1 \text{ M}\Omega$ as a function of the frequency. It is found that the voltage noise decreases with increasing frequency, from $200 \text{ nV (Hz)}^{-1/2}$ at 10 Hz to $2 \text{ nV (Hz)}^{-1/2}$ at 100 kHz. It can be concluded that the flicker noise dominates the noise sources. This agrees with noise calculations.

3.5. Specific detectivity

The performance of the integrated pyroelectric sensor is often expressed in term of the specific detectivity $D^* [\text{cm (Hz)}^{1/2} \text{ W}^{-1}]$,

$$D^* = \frac{\Delta V_{\text{total}}}{F_v} \quad (13)$$

where ΔV_{total} is the total voltage noise and F_v the voltage sensitivity.

A specific detectivity of $1 \times 10^5 \text{ cm (Hz)}^{1/2} \text{ W}^{-1}$ at 10 Hz is obtained. It increases with increasing frequency. It equals that of an integrated pyroelectric sensor based on PVDF for much smaller R_{bias} (factor 2×10^4) [10]. By increasing the value of R_{bias} , a higher specific detectivity can be reached. A higher specific detectivity can also be obtained by etching the silicon substrate under the sensor element (an improvement of a factor of 100) and enlarging the pyroelectric coefficient.

4. Conclusions

A 3×1 integrated pyroelectric sensor based on VDF/TrFE copolymer has been realized. On-chip poling of the copolymer film at a relatively low voltage has been achieved. The current sensitivity depends on the chopper modulation frequency. The influence of the silicon substrate is noticeable at low frequencies. The voltage sensitivity depends on R_{bias} for low frequencies ($< 1 \text{ kHz}$). The electric cut-off frequency of the sensor also depends on R_{bias} . The voltage noise decreases with increasing frequency, and it is $200 \text{ nV (Hz)}^{-1/2}$ at 10 Hz. The specific detectivity is $1 \times 10^5 \text{ cm (Hz)}^{1/2} \text{ W}^{-1}$ at 10 Hz.

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