

# A VDF/TrFE copolymer on silicon pyroelectric sensor: design considerations and experiments

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## Abstract

For an optimal design of a VDF/TrFE (vinylidene fluoride trifluoroethylene) copolymer-on-silicon pyroelectric sensor, the one-dimensional diffusion equation is solved for the pyroelectric multilayer structure. Output current and voltage of the sensor are calculated. Improvement of the sensor can be obtained by: (a) etching the silicon substrate under the sensor element and (b) an additional VDF/TrFE copolymer layer as thermal isolation. Different noise sources for a pyroelectric sensor have been calculated. The dielectric noise dominates the noise sources. This conclusion has been verified by measured values.

*Keywords:* VDF/TrFE copolymer; Silicon pyroelectric sensor; Design

## 1. Introduction

Thin films offer the added advantage that pyroelectric detector elements can be directly integrated with IC technology. The VDF/TrFE (vinylidene fluoride trifluoroethylene) copolymer film was reported to be pyroelectric without stretching [1]. This means that the VDF/TrFE copolymer is a suitable candidate for an imaging sensor. Neumann et al. have produced 0.8–2.5  $\mu\text{m}$  thick VDF/TrFE copolymer films on a silicon substrate for pyroelectric detectors [2].

Unfortunately, the substrate influences the voltage sensitivity of the pyroelectric detector. In the literature, the effect of the substrate on the voltage sensitivity of the pyroelectric detector has been studied [3]. The numerical solutions demonstrated that the voltage sensitivity of a thin pyroelectric detector on a substrate is worse than that of a thicker detector.

The VDF/TrFE copolymer is deposited on a silicon substrate that will contain the readout electronics. The advantages of this pyroelectric smart sensor are ease of manufacturing and a large signal to noise ratio. A disadvantage is the decrease of sensitivity due to the silicon substrate. To diminish this disadvantage one must carefully design the pyroelectric sensor, in which the thickness of VDF/TrFE copolymer, the silicon substrate, the thermal isolation and electrodes must be considered.

## 2. Theoretical calculation

### 2.1. Pyroelectric detector

The VDF/TrFE copolymer pyroelectric sensor consists of 5 layers; two aluminium electrode layers, a pyroelectric (VDF/TrFE copolymer) film, and two substrate layers (silicon dioxide and p-type silicon). A thick masking dioxide layer reduces the parasitic thermal and electrical capacitance. The thickness of aluminium electrodes in a standard IC process is 600 nm. Thermal conductivities, the specific heat and densities of these materials are listed in Table 1.

The front face of the pyroelectric sensor has a heat loss per unit area of  $g_H T_1(0)$  where  $g_H$  is the radiation heat transfer coefficient and  $T_1(0)$  is the temperature of the pyroelectric sensor relative to ambient. It is assumed that the heat loss per unit area of the back face of the pyroelectric sensor is  $g_H T_N(w_N)$  where  $T_N(w_N)$  is the temperature of the  $N$ th layer relative to ambient. It is also assumed that the heat capacity of an absorbing layer that is deposited on top of the pyroelectric sensor, is small in comparison with the heat capacity of the front electrode.  $P_1$  is the incident radiation power per unit area, and is assumed to vary according to a sine wave; the absorption coefficient of the top layer is  $\eta$ .

Table 1  
The material parameters of the pyroelectric sensor

Material	Heat conductivity (W m <sup>-1</sup> K <sup>-1</sup> )	Specific heat (J kg <sup>-1</sup> K <sup>-1</sup> )	Density (kg m <sup>-3</sup> )
Aluminium	237	896	2707
VDF/TrFE copolymer	0.1287	1223	1880
SiO <sub>2</sub>	1.3	750	2200
Silicon substrate	149	703	2330

2.2. Thermal diffusion equation

The diffusion equation for each layer is

$$\frac{\partial T(x, t)}{\partial t} = \frac{\delta_n}{c_n d_n} \frac{\partial^2 T(x, t)}{\partial x^2} \tag{1}$$

where  $\delta_n$  is the heat conductivity,  $c_n$  the specific heat and  $d_n$  the density of the layer.

A solution of this differential equation is:

$$T_n(x, t) = T_n(x) \exp(j\omega t) \tag{2}$$

This yields

$$T_n(x) = \frac{\delta_n}{j\omega c_n d_n} \frac{\partial^2 T_n(x)}{\partial x^2} \tag{3}$$

The general solution of Eq. (3) is

$$T_n(x) = A_n \exp[\alpha_n(x - h_n)] + B_n \exp[-\alpha_n(x - h_n)]$$

with  $\alpha_n = \left( \frac{j\omega c_n d_n}{\delta_n} \right)^{1/2}$  (4)

Using the boundary conditions, the thermal diffusion equation for  $N$  layers, results in the matrix (Eq. (5)) given at the foot of this page.

Now, one can use Eq. (5) for the case of the pyroelectric sensor that consists of five layers. Using data of the material parameters of the pyroelectric sensor as shown in Table 1, one calculates the complex coefficients  $A_n$  and  $B_n$  as a function of frequency, by using Gaussian elimination.

The spatial average of the temperature in the pyroelectric layer  $\bar{T}$  is:

$$\bar{T}(t) = \frac{\eta P_1}{\alpha_2 w_2} \{A_2[\exp(\alpha_2 w_2) - 1] + B_2[1 - \exp(-\alpha_2 w_2)]\} \tag{6}$$

where the coefficients  $A_2$  and  $B_2$  are a function of frequency, and can be calculated from Eq. (5).

2.3. Output current and voltage

If the pyroelectric coefficient is  $p$  and the area of the pyroelectric sensor  $A$ , the temperature change will produce an alternating charge  $pA\bar{T}$ , hence a current  $pA\delta\bar{T}/\delta t$ .

Using Eq. (6), the output current is

$$I_0(t) = \frac{\eta P_1 p A \omega}{\alpha_2 w_2} \{A_2[\exp(\alpha_2 w_2) - 1] + B_2[1 - \exp(-\alpha_2 w_2)]\} \tag{7}$$

and the output voltage is

$$V_0(t) = \frac{\eta P_1 p A \omega R_p}{\alpha_2 w_2 (1 + \omega^2 R_p^2 C_p^2)^{1/2}} \{A_2[\exp(\alpha_2 w_2) - 1] + B_2[1 - \exp(-\alpha_2 w_2)]\} \tag{8}$$

where  $R_p$  is the resistance and  $C_p$  is the capacitance of the pyroelectric detector. The product  $R_p C_p$  is the electric time constant  $\tau_E$  and it depends only on the

$$\begin{bmatrix} g_H - \delta_1 \alpha_1 & g_H + \delta_1 \alpha_1 & 0 & 0 & \dots & 0 & 0 \\ e^{\alpha_1 w_1} & e^{-\alpha_1 w_1} & -1 & -1 & \dots & 0 & 0 \\ -\delta_1 \alpha_1 \theta^{\alpha_1 w_1} & \delta_1 \alpha_1 e^{-\alpha_1 w_1} & \delta_2 \alpha_2 & -\delta_2 \alpha_2 & \dots & 0 & 0 \\ 0 & & & & & & \\ \vdots & & & & & & \\ \vdots & & & & & & \\ 0 & 0 & 0 & 0 & \dots & -(\delta_N \alpha_N + g_H) e^{\alpha_N w_N} & (\delta_N \alpha_N + g_H) e^{\alpha_N w_N} \end{bmatrix} \begin{bmatrix} A_1 \\ B_1 \\ A_2 \\ B_2 \\ \vdots \\ A_N \\ B_N \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{5}$$

physical parameter of the VDF/TrFE copolymer detector, namely the dielectric constant and resistivity.

In the next simulation, the incident radiation power per unit area  $P_1$  is  $1 \text{ mW mm}^{-2}$ .

### 2.3.1. Influence of the VDF/TrFE copolymer film

Fig. 1 shows the output current as a function of the frequency. The thickness of the VDF/TrFE copolymer is varied in the simulation: (a)  $1 \mu\text{m}$ ; (b)  $10 \mu\text{m}$ ; (c)  $100 \mu\text{m}$ ; (d)  $1 \mu\text{m}$  without silicon substrate. It is found for the pyroelectric sensor with silicon substrate (see lines (a), (b) and (c) of Fig. 1) that current is constant below a certain frequency, i.e. 20 Hz for the  $1 \mu\text{m}$  film. For a much thicker film, this frequency is lower. Below this frequency, the influence of the silicon substrate is noticeable. The current increases in proportion to frequency at much higher frequencies and it achieves a maximum at a frequency in which the thermal diffusion length equals the thickness of the film at that particular frequency, i.e. 34 kHz for the  $1 \mu\text{m}$  film. From the maximum frequency the heat does not fully penetrate the VDF/TrFE copolymer. Therefore, in that region, the current decreases with increasing frequency.

Fig. 2 shows the output voltage as a function of the frequency. The thickness of the VDF/TrFE copolymer is varied in the simulation: (a)  $1 \mu\text{m}$ ; (b)  $4 \mu\text{m}$ ; (c)  $10 \mu\text{m}$ ; (d)  $100 \mu\text{m}$ ; (e)  $1 \mu\text{m}$  without silicon substrate.

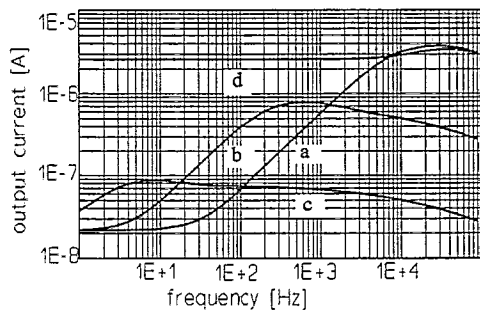


Fig. 1. Effect of the thickness of the VDF/TrFE copolymer on the output current. Film thicknesses are: (a)  $1 \mu\text{m}$ ; (b)  $10 \mu\text{m}$ ; (c)  $100 \mu\text{m}$ ; (d)  $1 \mu\text{m}$  without silicon substrate. The other parameters are 600 nm electrodes, a  $1 \mu\text{m}$   $\text{SiO}_2$  and a 0.5 mm silicon substrate.

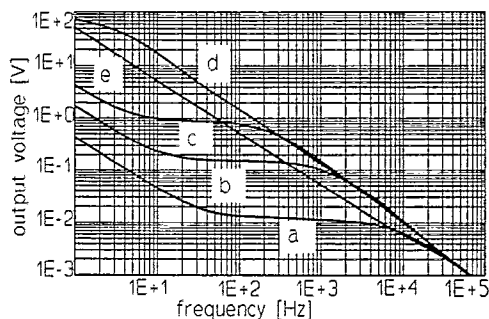


Fig. 2. Effect of the thickness of the VDF/TrFE copolymer on the output voltage. Film thickness are: (a)  $1 \mu\text{m}$ ; (b)  $4 \mu\text{m}$ ; (c)  $10 \mu\text{m}$ ; (d)  $100 \mu\text{m}$ ; (e)  $1 \mu\text{m}$  without silicon substrate. The other parameters are 600 nm electrodes, a  $1 \mu\text{m}$   $\text{SiO}_2$  and a 0.5 mm silicon substrate.

It is found that the output voltage of the pyroelectric sensor with the thicker VDF/TrFE copolymer is better than with the thinner one.

The electric time constant of the structure with silicon substrate is constant, around 200 s, regardless of the thickness of the VDF/TrFE copolymer. This electric time constant depends only on the physical parameters of the VDF/TrFE copolymer, namely the dielectric constant and the resistivity. The optimum electric time constant is equal to the inverse of the frequency in which the influence of the silicon substrate is noticeable. Therefore, a linear function of the output voltage versus frequency is achieved over a wide frequency range.

### 2.3.2. Silicon substrate

Now, by etching the silicon substrate under the pyroelectric sensor element, one can neglect this substrate. From Fig. 1 lines (a) and (d), it is found that the output current of the sensor is now much higher than that of the sensor with the silicon substrate for the same thickness of copolymer. So, a substantial improvement of a pyroelectric sensor can be obtained by etching the silicon substrate under the sensor element.

### 2.3.3. Influence of the VDF/TrFE copolymer thermal isolation

An additional VDF/TrFE copolymer layer has been deposited between the back aluminium electrode and the silicon dioxide. This layer serves only as thermal isolation. Therefore, it does not have to be pyroelectric.

Fig. 3 shows the effect of the thickness of the additional VDF/TrFE copolymer on the output current. The thickness of the additional VDF/TrFE copolymer is varied in the simulation: (a)  $1 \mu\text{m}$ ; (b)  $10 \mu\text{m}$ ; (c)  $100 \mu\text{m}$ . It is found that the frequency in which the output current achieves its maximum is still about 34 kHz for any thickness of the additional copolymer. The additional copolymer improves the output current of the sensor, but the output current is still below that of the sensor without the silicon substrate (see Fig. 3 line (d)), especially in the low frequency range. The influence of the silicon substrate cannot be neglected.

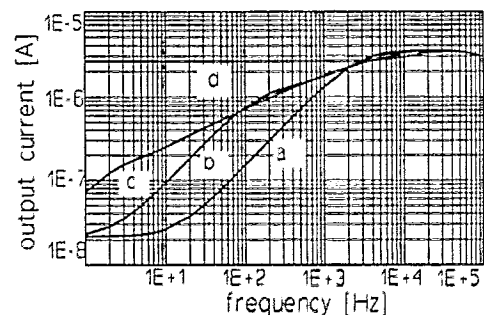


Fig. 3. Effect of the additional VDF/TrFE copolymer on the output current. Film thickness are: (a)  $1 \mu\text{m}$ ; (b)  $10 \mu\text{m}$ ; (c)  $100 \mu\text{m}$ ; (d)  $1 \mu\text{m}$  without silicon substrate. The other parameters are 600 nm electrodes, a  $1 \mu\text{m}$  VDF/TrFE copolymer, a  $1 \mu\text{m}$   $\text{SiO}_2$  and a 0.5 mm silicon substrate.

### 3. Experiments

Two kinds of samples were prepared; a pyroelectric sensor with the silicon substrate and a pyroelectric sensor with the removed silicon substrate under the sensing element. The last sample was prepared by etching part of the silicon substrate by KOH. A VDF/TrFE copolymer was deposited on the bottom aluminium electrode. The samples were annealed for 10 min at 160 °C, and then the temperature was slowly brought down to 25 °C over 4-5 h. After deposition of the top aluminium electrode, on-chip poling of the copolymer was carried out. The poling treatment was done at room temperature and using a step-wise poling. A vertical cross section of the pyroelectric sensor samples is shown in Fig. 4. The samples are mounted in a special sample holder. Fig. 5 shows the experimental set-up.

Fig. 6 shows the measured current sensitivity as a function of the frequency. The first two lines (□ and \*) show the measurement and calculation values for the case of the pyroelectric sensor without the silicon substrate. The other two lines (▲ and +) show the

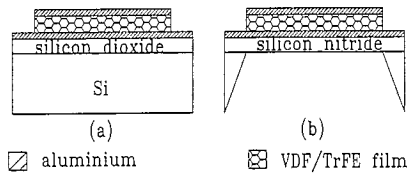


Fig. 4. Vertical cross section of the structure of the pyroelectric sensor: (a) with silicon substrate; (b) with etching silicon substrate under the sensor element.

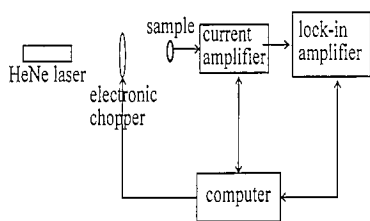


Fig. 5. Experimental set-up of the current sensitivity measurement.

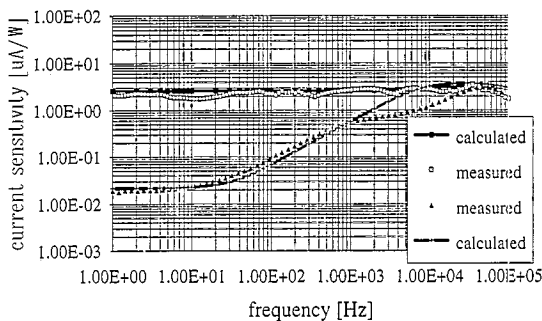


Fig. 6. The measured and calculated current sensitivity as a function of the frequency for the case of the pyroelectric sensor with the silicon substrate (□ and \*) and the pyroelectric sensor without the silicon substrate (▲ and +).

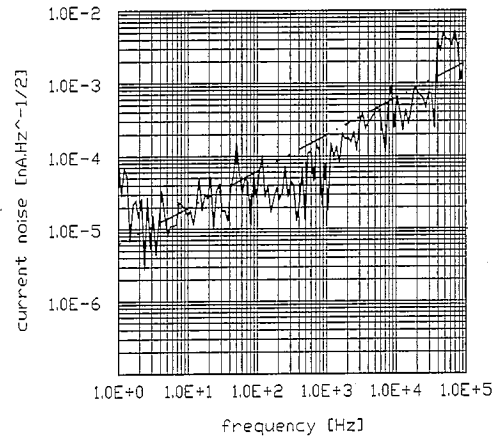


Fig. 7. The current noise as a function of the frequency. The broken line is calculation values and the dashed line is measurement values.

measurement and calculation values for the case of the pyroelectric sensor with the silicon substrate.

### 4. Noise sources

There are several noise sources in the pyroelectric sensor. The most important are Johnson noise, thermal fluctuation noise and dielectric loss noise. From the calculation, it is found that the dielectric loss noise dominates the noise sources. This conclusion has been verified by the measurement values as shown in Fig. 7, which shows the current noise of a single pyroelectric sensor as a function of frequency (calculation values for the broken line and measurement values for the dashed line). It is found that the total current noise increases with increasing frequency, according to the nature of dielectric loss noise which increases with increasing frequency.

### 5. Conclusions

The influence of the silicon substrate is measurable at low operation frequencies. Improvement of a pyroelectric sensor can be obtained by: (a) etching the silicon substrate under the sensor element and (b) addition of an extra VDF/TrFE copolymer as thermal isolation. The best improvement is obtained by etching the silicon substrate. The dielectric loss noise dominates the noise sources. The current noise increases with increasing frequency.

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## References

- [1] E. Yamaka, Pyroelectric IR sensor using vinylidene-trifluoroethylene copolymer film, *Ferroelectrics*, 57 (1984) 337-342.
- [2] N. Neumann, R. Köhler and G. Hofmann, Application of P(VDF/TrFE) thin films in pyroelectric detectors, *Ferroelectrics*, 118 (1991) 319-324.
- [3] A. Van der Ziel, Pyroelectric response and  $D^*$  of thin pyroelectric films on a substrate, *J. Appl. Phys.*, 44 (2) (1973) 546-549.