Infrared sensing using pyroelectric polymers

A F Armitage, K Benjamin, D Setiadi, H Weller & T D Binnie

Napier University, Electrical & Electronic Engineering Dept., 219 Colinton Road, Edinburgh, EH14 1DJ
email: a.armitage@napier.ac.uk

Abstract: This paper describes a programme of work intended to develop inexpensive infrared imagers. The technology is based on the pyroelectric effect in the polymer PVDF, and a copolymer of VDF and TrFE. Early work used films of the polymer on simple ceramic substrates. While this continues to be a useful approach, the use of silicon integrated circuit substrates provides possibilities of amplification as close as possible to the signal source. Several integrated circuits have been fabricated and tested, and some results are presented for these. A brief description is also provided of the thermal and electrical modelling.

1. Introduction

Infrared sensors can be categorised a number of ways. One way is to class them according to whether they are based on a single element detector, such as photodiodes sensitive to the IR range of wavelengths, and those based on multiple pixels as used in infrared astronomy and night vision systems. This latter type of sensor has often been based on exotic ternary semiconductors, such as mercury cadmium telluride (HgCdTe). Requiring cooling, they are expensive specialist devices

There have been a number of developments to try and provide sensors in the middle of this range [1,2,3,4]. These tend to be based on relatively inexpensive thermal technologies (such as the pyroelectric effect or thermopiles) in order to provide cheap infrared imaging capabilities. The success of single element PIR (Pyroelectric Infra Red) detectors in burglar alarms and intruder detectors suggests that low-cost infrared detection based on similar principles should be feasible. The resolution and sensitivity might not match that of the traditional infrared imagers, but if the cost can be kept low numerous applications become feasible. For instance, health (monitoring of vascular circulation), safety and reliability (plant defects, circuit board characterisation), night vision, traffic applications and so on.

Signal levels in these systems can be low, so amplification as near as possible to source is desirable. For this reason, a number of groups are looking at pyroelectric coatings laminated directly onto silicon substrates. For large arrays, this will also provide advantages in multiplexing and addressing. However, for low-cost applications, and for experimental purposes, cheaper substrates can be useful. We have been looking at ceramics of the type used for hybrid circuit construction. This gives the advantage that we can make the amplification circuitry using standard thick-film and surface-mount techniques.

2. The pyroelectric effect

Pyroelectric materials are polar and respond to thermal energy by a change in spontaneous polarisation. This process is dependent on the change in temperature induced in the material. The change in polarisation results in charge separation; the charge can be transferred to an ac electrical signal in an external circuit. In order to produce the change in temperature, the incoming radiation is usually chopped using a rotating slotted disc. The common PIR security detectors work in a slightly different way. The radiation is not chopped directly. As a person moves across the field of view of the single element detector, fresnel lenses or a faceted mirror modulate the incoming radiation so that a temperature change is induced, typically in differential elements.

A number of pyroelectric materials are available. Some of these are single crystal ($LiTaO_3$, $NaNO_2$[7], Triglycine Sulphate: TGS) or ceramic ($PbTiO_3$, modified lead zirconate[3],). A typical imaging detector uses a ceramic disc; this is bump-bonded to a read-out chip which contains the necessary amplification and multiplexing[3]. This is a relatively expensive solution. Films and crystals of pyroelectrics are available which can be bonded capacitively to substrates, avoiding the complications of bump-bonding techniques. Single crystals can be difficult to handle but can give good responsivities. Films are the easiest to handle, though there is a limited range of materials available. PVDF can be obtained as free-standing films. The copolymer P(VDF/TrFE) can be spin-coated from solution. The pyroelectric coefficient of these materials is approximately one tenth of that of the ceramic and crystal materials[8], but their ease of processing makes them a convenient choice. Other properties, such as the dielectric loss, give them figures of merit that are comparable with other pyroelectrics.

The applications envisaged for these sensors use medium wavelength infrared in the 4-12 micron range. For instance, detection of people relies on the fact that humans radiate at approximately 10 microns. This also corresponds to a window of low atmospheric absorption. In our experiments, the response of the sensors in this range is measured by using an infrared lamp, an optical chopper, and a lock-in amplifier. A monochromator can also be used to select specific wavelengths.

3. PVDF on ceramic

Both PVDF and P(VDF/TrFE) consist of a crystalline and an amorphous fraction. Unless treated, the crystalline fraction tends to be randomly oriented, resulting in no net polarisation vector. In a sensing system, the polarisation vector in the pyroelectric layer has to be perpendicular to the substrate. This can be achieved by stretching a polymer film, or by applying a d.c. voltage across the layer (poling).

Films of PVDF are available commercially for use in infrared detection. These can be pre-poled, and coated with metal on top and bottom surfaces if this is needed. Different thicknesses are available, with 9 micron being the thinnest practical. Thicker films are easier to handle, but have slower responses, due to the different thermal capacities.

Attaching the film to the substrate can be done by a variety of methods. Bauer & Ploss[4] used polyisobutylene to bond PVDF layers. Okuyama[5] interfaced $LiTaO_3$ on Si using glycerine. We have developed a simple method using a thin film of UV curing epoxy. The properties of this layer are important, as the electrical and thermal behaviour of the detector stack is influenced by the glue layer[9].

We have been using commercially available PVDF films to make small IR detectors on 96% pure alumina thick film substrates. Contacts have to be made to the top and bottom of the PVDF. In the simplest detector structure (figure 1), the metal coating is left on one surface of the PVDF film. This becomes the top contact. The bottom contact is made by patterning the ceramic with a metallic thick film ink, which is processed as normal for thick film circuits. The layout of the ink is used to determine the pixel shape.

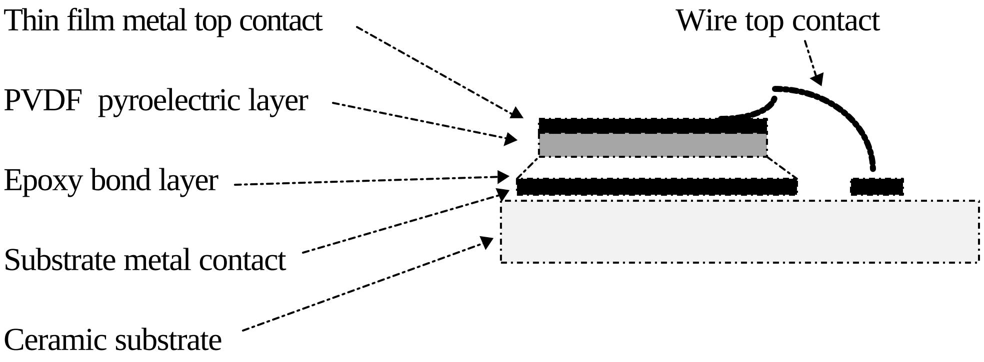

Figure 1: Construction of the PVDF on ceramic sensor

By using different types of epoxy, we have been able to investigate the effect of bonding with a conductive layer, or using a dielectric layer that gives capacitive coupling. Typical performances, plotted as a function of chopping frequency, are shown in Figure 2. In this case the sensor is connected to the gate of a FET. Theoretical predictions for the performance[10] agree well with the experimental measurements.

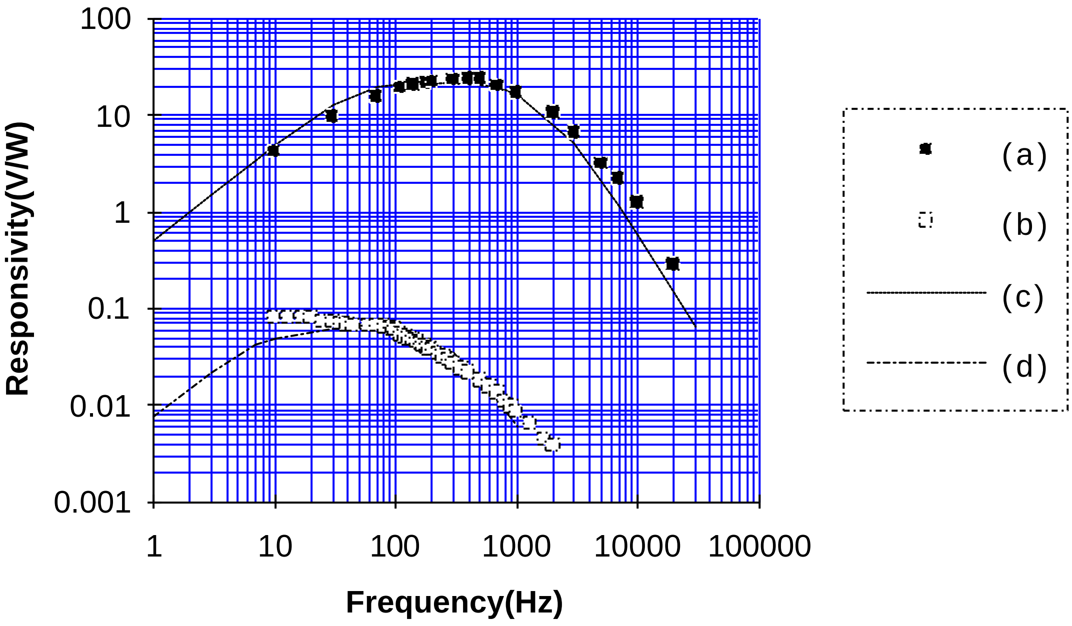

Figure 2: Frequency response of 9 micron PVDF with (a) capacitive and (b) conductive bonding. Theoretical predictions are shown in (c) and (d).

The response for the capacitively coupled sensor is better, due to the superior thermal insulation of the dielectric bond layer compared with conducting bond layer. We are currently investigating multi-pixel sensors in order to look at the effects of cross-talk, bonding layer thickness, and substrate properties. The substrate is important because the thermal conductivity and thermal capacitance affect the time constants for the temperature change within the layered system. Ideally, the sensing layer would be isolated so that heat was not dissipated in the substrate, or carried from pixel to pixel resulting in cross-talk. This is not possible in practice, but correct choice of bonding and substrate properties and thicknesses can go some way towards an optimum solution.

4. PVDF and copolymer on integrated circuits

In order to minimise the pickup of noise, it is preferable to amplify the signal as close to the source as possible. This can be achieved by bonding PVDF films directly to a silicon integrated circuit using the same sort of bonding techniques developed for the ceramic substrates (figure 3). Also, it is possible to spin-coat the copolymer of VDF and TrFE, which is soluble in 2-butanone (Methyl Ethyl Ketone). This is done by mixing 65 mol% Vinylidene Fluoride (VDF) and 35 mol% Trifluoroethylene, then dissolving the mixture in 2-butanone at 80^{o}C to achieve a 10% wt. concentration. The solution is filtered and spin coated onto a silicon integrated circuit substrate. Varying the concentration of the solution, the spin rate, and the spin time permits some control of the film thickness[8]. Typical film thicknesses of 0.5 to 1.5 micron are prepared in this manner (figure 3). Figure 4 shows the chip layout.

Once the copolymer has been spin-coated, it must be poled. There are a number of techniques available using electron beams and corona discharges. A relatively simple method using a stepped application of d.c. electric fields has been developed [8]. This provides good results provided the spin-coated film shows good uniformity. As with other methods, imperfection in the films can lead to localised breakdown. For this reason, care must be taken in the preparation and handling of the films.

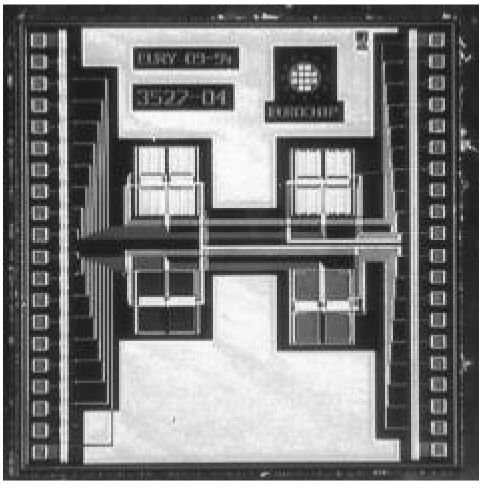

Figure 4. Layout of the chip

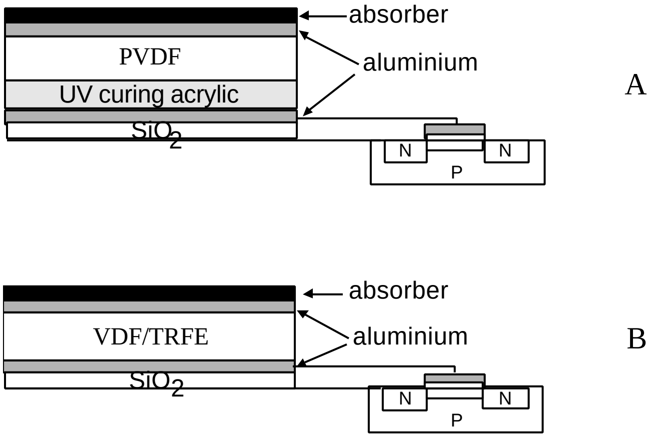

Figure 3. Vertical cross-section of the layout of pyroelectric sensors based on (a) PVDF and (b) VDF/TrFE copolymer

Comparative measurements were made for the sensors based on PVDF polymer and VDF/TrFE copolymer. The frequency responses are shown in Figure 5. The measured values are compared with theoretical calculation [11]. The curves in Figure 5 show the output voltage of the sensor prior to the readout MOSFET. A good relationship between the measured and the calculated values is found. In the simulation, we assume that only 30% of the incident radiation is absorbed by the sensor. Responsivities of 4.3 V/W and 0.5 V/W at 400 Hz have been achieved for the pyroelectric sensor based on PVDF and VDF/TrFE copolymer, respectively.

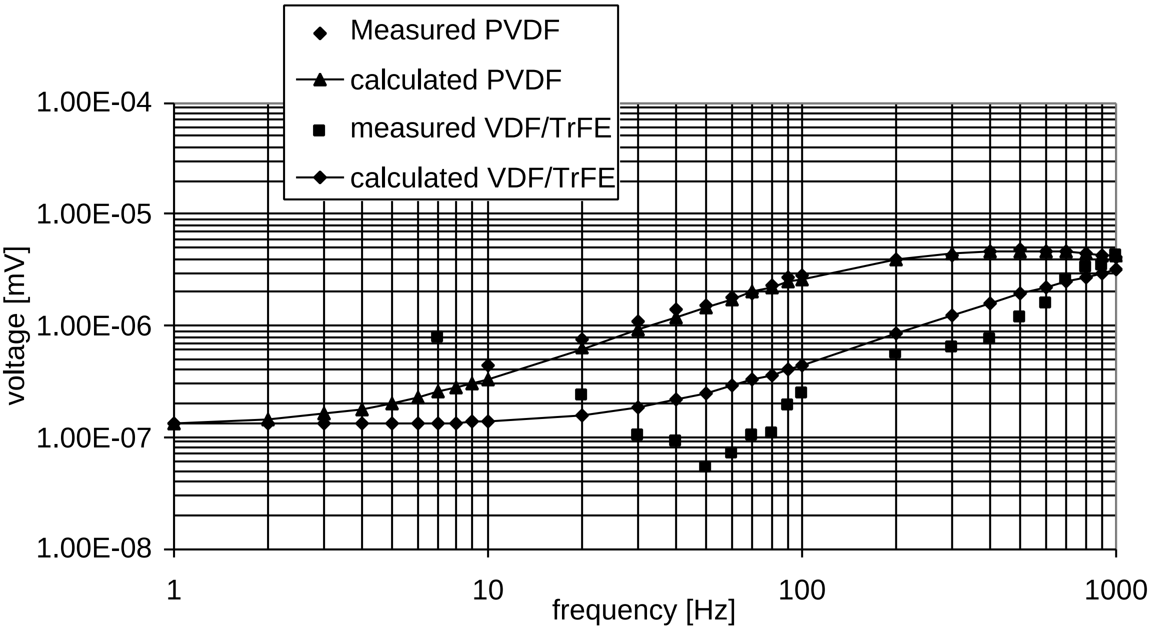

Figure 5: Response of PVDF and copolymer (VDF/TrFE) on silicon.

5. Modelling

Modelling of the system involves two aspects. The absorption of the infrared radiation, and the subsequent heat diffusion is undoubtedly the most important feature. The actual temperature changes induced will depend on the thickness of the layers, the thermal conductivities and the thermal capacities. Cross-talk between pixels will degrade performance, and must also be considered. However, the electrical behaviour of the amplification system also needs to be considered. The peak response tends to be at a chopping frequency of 100-1000Hz, so there is no need to use high-frequency techniques. Low-noise amplification is more important, and this is not trivial when using standard production CMOS that is not optimised for low-noise design. Initially, thermal and electrical modelling was done separately. A variety of computer aided maths packages have also been used.

Recently, we have been using a circuit simulation package (Tina) to model the thermal and electrical behaviour together. The thermal behaviour has to be modelled as an electrical analogue, with electrical capacitances and resistances replacing thermal capacitances and resistances (figure 6). This requires care with scaling factors, but seems to be capable of producing an accurate model that is easier to manipulate than the two stage thermal/electrical model.

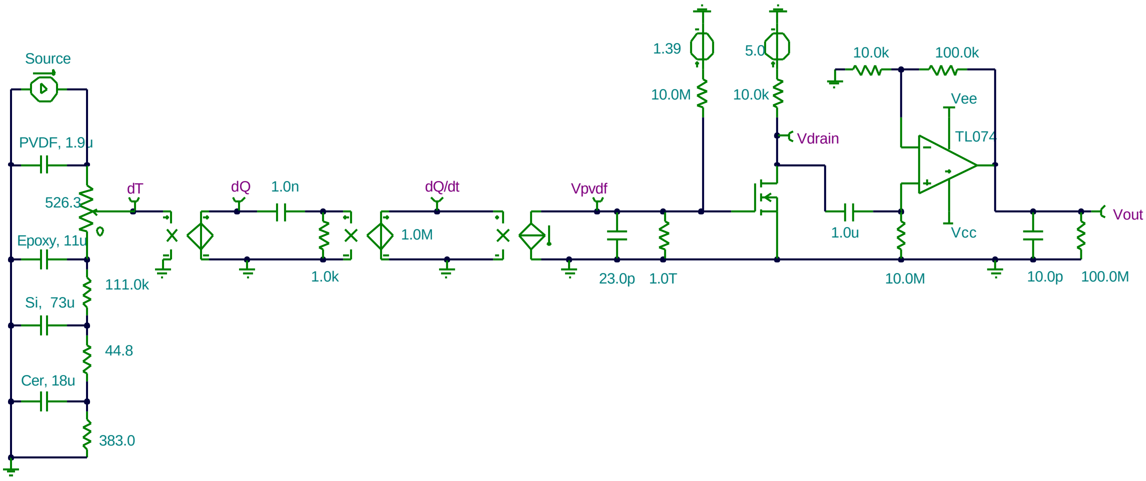

Figure 6: Thermal/electrical model of integrated sensor

6. Discussion

Useful responses have been demonstrated for a variety of systems. Inexpensive ceramic substrates have been used to investigate a wide range of parameters, such as coating thickness, pixel geometry and amplifier type. On ceramic substrates we have produced arrays of up to 8 X 8 pixels. On silicon, the on-chip amplification should lead to better performance, with smaller devices. The present objective is to optimise the low-noise amplification. A number of amplifier structures have been investigated, with current designs aiming for low-noise circuitry on standard CMOS technology

Optimising the response will involve many more stages. Presently, we know that our structures are relatively inefficient absorbers of infrared. The upper metallic contact reflects more than half the incoming radiation. The polymer layer is too thin to absorb all the remaining infrared. Further work needs to be done on anti-reflection coatings. However, this is not trivial as any added layers slow the response of the sensor. Complete systems will also need suitable optics, including lenses and a chopping mechanism

7. References

1.Whatmore 1986 *Rep prog phys* **49** 1335-1386
2.Watton R 1989 *Ferroelectrics* **91** 87-108
3.Munch W von and Thiemann U 1991 *Sensors and Actuators A* **25-27** 167-182
4. Ploss B & Bauer S 1991 *Sensors and Actuators A* **25-27 407-411**
5.Okuyama M, Togami Y, Ohnishi J, Hamakawa Y, Kimata M and Denda M 1989 *Ferroelectrics* **91** 127-139
6. Lock P J 1971 *Appl Phys Lett* **19** 390-391
7. Engelhardt C, Wurfel P and Ruppel W 1986 *Ferroelectrics* **69** 223-230
8. Setiadi D, 1995 *PhD thesis* Universiteit Twente **ISBN 90-9008925-X**
9. Webster S & Binnie T D 1995 *Sensors and Actuators A* **49** 61-65
10 Hammes P P A & Regtien P P L 1992 *Sensors and Actuators A* **32** 396-402
11. Setiadi D & Regtien P P L 1995 *Sensors and Actuators A* **46-47** 408-412