Ferroelectrics, Vol 318, July 2005 , pages 11-22

Pyroelectric Arrays Using Ceramics and Thin Films Integrated Radiation Collectors: Design Fabrication and Testing

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Abstract

Pyroelectric infra-red detectors have been of-interest for many years because of their wide wavelength response, good sensitivity and lack of need for cooling. Arrays of such detectors, comprising a pyroelectric material interfaced to an application specific integrated circuit for signal amplification and read out, provide an attractive solution to the problem of collecting spatial information on the IR distribution in a scene. Sol gel deposition provides an excellent technique for the growth of ferroelectric thin films and Mn-doped PZT30/70 films can be grown at 560ºC with F_D=3.85X10^{-5} $Pa^{-1/2}$. A new concept is presented here: the use of arrays of thin film pyroelectric detector elements with integrated radiation collectors designed to enhance the intensity of the radiation falling on the element. Two collector designs are presented, one based on the use of wet-chemically-etched pyramidal cavities, the second based on the Compound Parabolic Concentrator (CPC). Approximations to truncated CPC structures were SF_6-dry-etched into a silicon wafer, upon which had been defined pyroelectric IR sensors with low thermal conductance (spiral leg structure) fabricated in a high sensitivity PZT thin film. First experimental assessment of the performance of these structures is presented.

1 Introduction

Uncooled pyroelectric infra-red detectors have been in use for many years and their applications range from intruder sensing through environmental monitoring to flame and fire detection [1]. In the last 15 years there has been a growth of interest in using 2D arrays of very small pyroelectric elements for uncooled thermal imaging [2,3]. A range of pyroelectric materials have been used for these devices and some of the most sensitive are ceramics such as those based on solid solutions in the lead zirconate titanate ($PbZr_xTi_{1-x}O_3$ – PZT) system [4]. These arrays are microsystem-type devices in which each pyroelectric element is interfaced to its own integrated FET amplifier, these being linked by arrays of switches for

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multiplexing. These devices have been made possible through the flip-chip hybridisation of thin wafers of bulk materials (particularly ferroelectric ceramics) with silicon application specific integrated circuits (ASICs) – known as read-out integrated circuits (ROICs). They have developed remarkable performances, and arrays have been demonstrated possessing 388x284 elements and noise equivalent temperature differences of ca 140mK [2]. There has been an interest for a long time in the possible use of thin pyroelectric films, because of their potential for making low thermal mass elements [5]. Arrays that have been demonstrated include: linear arrays fabricated using bulk micromachining techniques with sputtered $PbTiO_3$ on (100) silicon [6], La-$PbTiO_3$ on MgO [7], P(VDF-TrFE) on silicon [8] and sputtered films of $Pb(Zr_{0.15}Ti_{0.85})O_3$ on (100) silicon [9], the latter for use in infra-red gas spectrometers [10]. In all these the bulk micromachining has been used to remove the silicon from behind the pyroelectric film, leaving a thin, low thermal mass membrane. The development of fully integrated 2D arrays has been encouraged by the low temperature (<550°C) growth of ferroelectric thin films such as PZT directly onto active silicon devices [11]. Surface micromachining is the preferred route for the manufacture of 2D integrated arrays and single elements employing a polysilicon supporting membrane under a $PbTiO_3$ film were demonstrated more than 10 years ago [12]. Workers have employed different strategies to obtain good thermal isolation. Koehler et al [12] have evacuated and sealed the cavity under the element. Other groups [11] evacuate the whole package and use long legs supporting the active element to provide the best possible thermal isolation. Clearly, the subject of integrated pyroelectric IR detector arrays covers a wide range of materials and device technologies. This paper describes a new way in which the ferroelectric thin film and micromachining technologies can be combined to produce a novel detector array concept employing micromachined structures as radiation collectors to give a significant increase in sensitivity.

2 Integrated Radiation Collectors

The basic concept of the non-imaging radiation collector has been described in considerable detail by Welford and Winston [13] and Winston et al [14]. The idea is to define a reflective re-entrant cavity with a shape such that as much as possible of the radiation entering through one aperture will emerge from a smaller aperture at the other end, being concentrated in the process. The simplest concentrator is the light collecting cone [15] and this suggests a possible use for a bulk micromachined pyramidal cavity in silicon as a means for concentrating some of the radiation falling into the cavity onto a sensitive pyroelectric area in the centre as shown schematically in Fig. 1, with a sensitive pyroelectric area at the centre of a supporting membrane at the base of the cavity. The sensitive area can be defined either by an absorber on the front of the membrane or by an electrode pattern, or by a combination of the two. It is clear that radiation incident on the cavity can arrive at the sensitive area either by a direct path, or by reflection from the walls. Geometry and the Fresnel equations for reflection at a dielectric surface can be used to calculate the collecting power of a bare silicon cavity compared with one plated with, for example, reflective gold. Fig. 2 shows the variation of the ratio of the total radiation intensity to that arriving directly at the sensitive area, plotted as a function of ϕ, assuming that the off-axis angle is in the (110) plane. (The parameters used in this example are m=65microns, s=22.5 microns with a 180 micron thick silicon wafer.) The model incorporates effects of obscuration of the sensitive area by the edge of the cavity (for ϕ>ca45°) and the fact that for ϕ>ca20° we progressively lose reflections from the walls. We can average the relative intensity arriving at the sensitive area for all sagital angles, as also shown in Fig. 2, and conclude that for incident angles (ϕ) up to 25°, the intensity of radiation arriving at the detector should be at least 50% greater with a collector than without.

The pyramidal etch pit will thus work as a radiation collector, albeit a rather inefficient one. However, Winston et al [17] have shown that much greater collection efficiencies can be obtained by using a Compound Parabolic Concentrator (or CPC). These authors have analysed the properties of such cavities in great detail and their analysis will not be repeated here. However, the basic principle is shown in Fig. 3a. The cavity is created to have a parabolic cross section such that the focus of the parabola falls at the opposite edge of the exit aperture. In this case, well over 90% of the radiation falling into the entry aperture within a cone of semi-angle θ will emerge through the exit aperture. To find the optimal design for the integrated collectors we have analysed the collection efficiency of various profiles, using a two dimensional model. A CPC was chosen with dimensions compatible with the pitch of the array (500μm). The CPC design has two degrees of freedom: in our case the profile is determined by the choice of the entry aperture half-extent (a = 300 μm) and the exit aperture half-extent (a' = 75 μm). An acceptance angle of 14.48 degrees results, meaning that this CPC design would collect all radiation at the incidence angle (relative to the normal to the CPC) within 14.48 degrees. Since the full length of such concentrator is 1452μm, truncation is necessary to reduce it to a conventional silicon wafer thickness. The upper part of the CPC can be truncated without a major reduction in collection efficiency. In our design, the length was reduced to 580 µm (corresponding to the thickness of the Si wafer), leading to an entry half-aperture of 254 µm. Models were made for versions of all profiles compatible with a subsequent reduction of the active areas by etching into the membranes thermally-isolated elements suspended on microbridges. The theoretical performances of the above profiles were assessed assuming ideally-reflecting surfaces. The calculations were performed partly analytically (by identifying the boundary rays between regions of total rejection and total acceptance) and partly by ray-tracing. First we considered a CPC with acceptance angle equal to ~ 14.48 degrees. We then compared its performance with the truncated CPC and CPC's enlarged to permit the introduction of pyroelectric elements with extended legs. The collection efficiencies of elliptical collectors (Fig 3b) were also modelled. These profiles were modelled on the average dimensions of collectors experimentally achievable by pure SF_6 dry etching (see below). The results showed that the CPC always offered the maximum collection efficiency, giving factors of 3.5 to 4 increases in power, while the elliptical concentrators showed a significantly-poorer concentration power for all cut-off angles, but even here a 2x increase should be achievable. A schematic of the complete device structure is shown in Fig 4, including the design of the infra-red elements incorporating long microbridge legs for the purposes of thermal isolation. The incident IR is absorbed in a thin film absorber structure consisting of a 0.5 to 1µm thick layer of SiO_2 coated with 377Ω/square NiCr on the IR absorbing face. The SiO_2 also supports the thin PZT pyroelectric layer which is deposited on a 5nmTi/100nmPt, which doubles as the back electrode for the pyroelectric and the reflector at the back of the thin film absorber.

3 Radiation Collector Fabrication

The fabrication of the pyramidal collectors by wet chemical etching has been described in detail elsewhere [16]. Here we will describe the fabrication of approximations to the CPC structures by dry etching. Inductively Coupled Plasma (ICP) etching has been extensively developed for the fabrication of structures in silicon with steep sidewalls [17]. This process involves exposing the silicon sequentially to an SF6 plasma, followed by a step where the silicon is exposed to a passivating gas (C4F8). Different approaches were taken to attempt to produce the ideal CPC profile. "Grey-scale" lithography was used to define a contour in a polymer mask, followed by standard unidirectional DRIE [18]. This was unsuccessful in that it could not produce the high aspect ratio structures required. Partially anisotropic etching in which the ratio of etch to passivation time was varied produced deep cavities, but with very rough sidewalls. A fully isotropic etch process was investigated, as shown in Fig 5a. Here, the vertical etch rate was higher than the lateral etch rate. The cavities were characterised by taking replicas with silicone rubber (PDMS) and some examples of these are shown in Fig 5b. The shapes are the result of a complex kinetic mechanism in a regime where the diffusion of the radicals to the etching front represents the slower step in comparison with the surface reaction. A large number of samples were produced under different conditions of pressure and platen power: the contours produced were all roughly similar in shape. In fact, for all the features produced, the etch factor – the ratio between the etch depth (ED) and the undercut or lateral etch (EL) – lay between 1.7 and 2.4 regardless of any process parameters or feature size. SEM of cavity cross sections and replicas offers a qualitative idea of the nature and extent of surface roughness (Fig 6), enough to estimate that this process offers a reasonable surface quality. The cavity roughness appears to be below one micron (rms), which is probably adequate for use as a reflector of 10μm wavelength radiation. The typical dimensions of the profiles obtained in this way are only approximations to the ideal CPC profile, i.e. they can approximate the bottom of a CPC. For example, a cavity etched for ~ 4 hours in pure SF_6 from an original aperture diameter of 85 μm in a 250 μm thick silicon wafer may approximate the bottom sixth part of the CPC with θ ~ 14 degrees. This is illustrated in Fig. 7. If a second wafer were to be aligned and bonded to produce an additional cavity on top of the first one, as also shown in Fig. 7, then about one third of the CPC profile could be approximated. Ray tracing software has been used to calculate the relative increase in power that would be incident on the pyroelectric element at collector exit aperture and the results are shown in Fig 8 in comparison with an ideal truncated CPC of the same overall height. These calculations assume a uniform irradiance over the collection angle indicated. It can be seen that a single elliptical collector should approximately double the radiation power reaching the detector element while the double collector should allow a further 50% increase. An ideal CPC profile would allow a factor of 4 increase in radiation power reaching the detector element.

4 Device Fabrication and Testing

Several sets of arrays of 16x16 elements on 500μm pitch were produced to the two basic designs (pyramidal collectors and single elliptical collectors using the isotropic SF_6 etch process). Highly 111-orientated Mn-doped $Pb_{1.1}(Zr_{0.3}Ti_{0.7})O_3$ (PM01ZT) films 700 ~ 1000nm thick were prepared on the Pt/Ti electrode by a chemical solution deposition method as has been described elsewhere [19, 20]. The properties and pyroelectric performances of the films are given in Table 1, where F_D is defined by $F_D = \frac{p}{c'\sqrt{\varepsilon\varepsilon_o}\tan\delta}$ and p=pyroelectric coefficient, c'=volume specific heat, ε=material permittivity, ε_o= permittivity of free space, $\tan\delta$=material loss tangent. Note that the dielectric properties are measured at sub-100Hz frequencies, where any practical pyroelectric device will be used. Several PZT compositions and processes were explored, including the use of Mn doping at levels between 0.02 and 2mole %. It was found that a 1% Mn doping level had a marked positive effect upon the dielectric and pyroelectric properties, leading to an excellent value of F_D that considerably exceeds any value reported elsewhere for a thin film at such low frequencies. The first devices were a set using wet anisotropic etching in TMAH [16] to give pyramidal radiation collectors as shown schematically in Fig 1. Photomicrographs of these are shown in Fig. 9. The second set of arrays used DRIE employing isotropic etching in SF_6, together with dry etching of the membrane structure to fabricate thermally isolated detector structures in the base of the collector. Photomicrographs of these devices are shown in Fig 10. The arrays were tested by setting-up a demountable probe system which permitted contact to a selection of the array elements, which could be sequentially connected to a single output FET. This was shielded by a Ge window, through which the array was permitted to view an IR source (a hotplate held at 380ºC). A rotating chopper was interposed between the source and the array. Two stages of collimation were used to restrict the angle over which the array elements could view the source. Firstly, an aperture was placed at the chopper which restricted the angle of view to ca 25º. (This was roughly equivalent to the acceptance angle corresponding to a f/2 lens being used to image onto the array.) Secondly, two sets of micro-collimator array were made by using DRIE to etch sets of cylindrical holes in a 260 micron thick silicon wafer. Each collimator in the first set was 125 microns in diameter, approximately the size of the detector elements in the base of the collectors. Each collimator in the second set was 410 microns in diameter. By using the first set of collimators, clamped against the detector wafer, it was possible to restrict the radiation acceptance angle so that none fell on the collector side-walls. The second collimator was then used to allow the collector side-walls to come into play in a well-controlled fashion. In this way, it was possible to assess the efficacy of the collector designs. Both coated and non-coated collectors were assessed.

The results of these tests are summarised in Table 2. Consider first the pyramidal cavity design. Here, tests were carried out with the 410μm collimator. An increase of 40% in response was seen when gold-coated sidewalls were compared with non-coated sidewalls. This is the first positive evidence that the collectors are performing as predicted. The second set of tests involved comparing the responses of the detectors when looking through the

125μm collimator arrays with the responses when looking through the 410μm collimator arrays. Here, it was found that the pyramidal collector performed slightly better than expected, giving a factor of 7 increase in response. The DRIE elliptical collector gave a response increase of 7 times, within experimental error of the prediction. (In both cases, a factor of 3.2 increase in response would have been expected if the collectors had been entirely non-functional – the increase being due to the larger collection aperture). It has, therefore, been demonstrated that the principle of the non-imaging radiation collector can be combined with an array of pyroelectric elements and provide a useful increase in the power reaching an element. In this case, a factor of two increase in power has been demonstrated for radiation illuminating the array over a collection angle equivalent to a f2 lens. This would be expected to give an equivalent detectivity of about $4x10^{8}cmHz^{1/2}W^{-1}$ using the thermally-isolated element design employed in the final device.

It is clear that there is great scope for further work along the lines described here. The collectors made in these devices are non-ideal. Their shape only approximates that of an ideal CPC and a further factor-of-two increase in radiation power collected would be expected if the ideal shape could be obtained. Recent work using a "two stage" etch process has shown some promise in this direction. In this [18], a vertical side-walled cavity is etched first and then opened-up with an isotropic etch process. This is versatile, but requires optimisation to obtain the required profile. The cavities made by dry etching are quite rough and it is probable that better performance could be achieved if much smoother surfaces could be obtained. Ultimately, a better approach might be to use a micro-machining process to fabricate a male mould and then to make the female cavities in plastic by micro-injection moulding, following this with a metal plating process.

5 Conclusions

In conclusion, the principle of integrating a radiation collector with a pyroelectric detector array has been demonstrated successfully. It has been shown that both pyramidal and hemi-elliptical collector cavities can be made in silicon substrates using wet and dry etching respectively can be used to usefully collect the radiation falling onto a pyroelectric array and to concentrate this radiation onto detector elements placed at the cavity bases. 16x16 arrays have been made using a high-performance pyroelectric thin film material and it has been demonstrated that both gave approximately a factor-of-two increase in signal.

6 Acknowledgements

The financial support of EPSRC through grant number GR/N06113/01 is gratefully acknowledged. The assistance of Dr. Chris Carter, Dr. Steve Porter and Mr Paul Osbond at IRISYS plc with the fabrication and testing of the arrays is also gratefully acknowledged.

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Whatmore, Roger W.

2005-07

Whatmore RW, Landi S, Shaw CP; KirbyPB. (2005) Pyroelectric arrays using ceramics and thin films integrated radiation collectors: design fabrication and testing. Ferroelectrics, Volume 318, July 2005, pp. 11-22

http://hdl.handle.net/1826/1701