Uncooled array IR sensors integrated with CCD analog processor

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Abstracts. The technological methods proposed above allow one to prepare integrated structures of multi-element heat detectors and special CCD. In thin structure the sensitive film is isolated from the substrate by means of a supporting membrane or serves as the membrane itself. Such a technology seems to be advantageous in further development of different MEMS structures. There is created a completely monolithic pyroelectric array of sensors 100×100 μm^2 based on a heat-sensitive film construction lifted slightly above the crystal and also detector specimens with NETD less than 0.2-0.5 K (8-12 μm at 300 K and 20-50 Hz of modulation frequency). Derived measurements and investigations allowed us to choose the structure of 2D analog CCD processor which now is under design and which will be integrated with pyroelectric membrane array.

Keywords: uncooled arrays, IR sensors, pyroelectric films, CCD analog processor

INTRODUCTION

The middle of nineties gave great achievements in the field of high sensitive, low cost and high technology leaner and matrix uncooled IR sensors. A lot of laboratories and research groups from USA, UK, France, Germany and Japan [1...3] have made efforts and reached great success in manufacturing solid state integrated uncooled matrix arrays with temperature resolutions less than 0.1 K, with f / 1 optics. There are functional base of these devices, are multi-element microbolometric and pyroelectric sensors. Their advanced technology allowed to design and produce uncooled focal plane arrays (UFPA) having up to 80.000...100.000 pixels and approximately 2mil centers.

Our research group applied first attempts in this field, in the early nineties beginning from works dealt with the technology of pyroelectric thin films integrated with silicon CMOS structures. This paper presents some our results and our seeing the problem of design, materials and performance of pyroelectric multi-element detectors integrated with schemes of signal processing. Finally, our point of view on future directions of research and development into UFPA are discussed.

DETECTOR STRUCTURE, MATERIAL AND FABRICATION

In order to achieve high results designing IR heat detectors one should make a construction with small thermal mass, suspended by low thermal conductance supports over heat sink. For IR bolometric detector arrays with integrated CMOS readout electronic this construction as a rule is fulfilled in the form of micro bridge located over silicon substrate as described for example in Ref. [4]. In case of pyroelectric matrix array integrated with readout circuit the construction is thin flex ribbon with reticulated thin ceramic pyroelectric pixels connected by bump bonding readout electronics [1].

In our case thin pyroelectric retina supported by low thermal conductance elements over silicon substitute was chosen as a detector structure. The calculations of heat balance equation yield that for typical time of 0.02s. the optimum heat transfer layer thickness is about 0.5...2.0μm. Looking for appropriate pyroelectric films we fabricated and studied a lot of non- organic ferroelectric thin films such as PZT, BST [1] and organic pyroelectric film of policyclic organic compound (TADPh) and of polyvinylidene fluoride (PVDF) [5]. Trying to achieve the UFPA manufacturing technology simplicity we fixed our choice on the construction described lower.

Of the most efficiency, to our opinion, appear to be the methods using achievements of the so-called micro-electromechanical systems (MEMS) technology [6, 7] improved for polyimide and PVDF films [5]. A schematic view of an example of the structure proposed is given in Fig. 1.

We developed fabrication process of uncooled pyroelectric IR sensor with photosensitive elements isolated from the substrate by an air or vacuum gap. As seen in Fig. 1, the photosensitive elements consisting of common top and readout bottom electrodes with a pyroelectric layer in between (this structure also serves as light absorber) are placed on vertical columns. To form the air gap a special buffer repeating the shape of the gap is formed and then removed through the holes in the covering membrane.

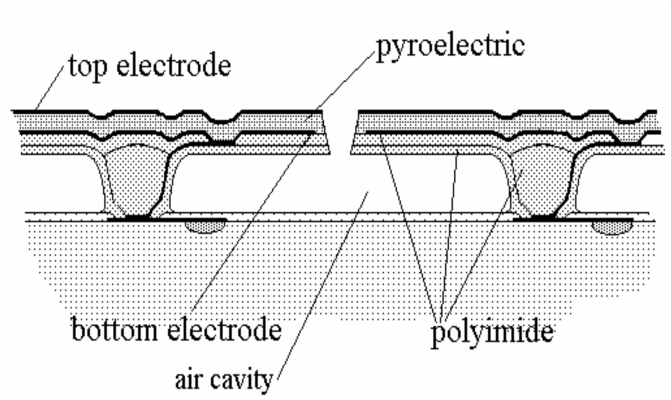

FIGURE 1. Schematic design of the multi-element integrated detector with polyimide membrane

A buffer layer 2-4 μm thick is first deposited on a substrate. Holes for the supporting columns are etched in the layer, which is then coated with polyimide about 0.5 μm thick. Holes are made in the polyimide film to provide wiring interconnections and subsequent removing of the buffer. Metal lead pattern is sputtered on the film. The holes in the buffer layer are filled with polyimide. Then the base 0.8-1.0 μm thick polyimide or PVDF layer is deposited. The base layer also has holes to provide connections and the etching off the buffer. A general view of heat-isolating polyimide membrane with holes is shown in Fig. 2. The bottom electrodes (they take up the whole area of the chip except the etching holes and interhole links) are formed on the membrane by 0.05 μm titanium layer sputtering and etching.

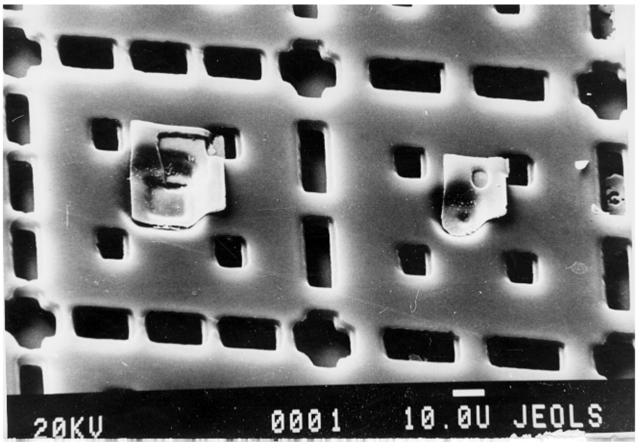

FIGURE 2. General view of heat-isolating polyimide membrane with the holes and with the metallization. The membrane is placed above IC signal processor, one element of the membrane being of the size of 100×100 μm^2

The next operation is the etching of the buffer layer. If the hole size is not less than 5×5 μm^2, the etching rate slightly depends on the size, but it drops considerably with the increasing interhole distance. The etched holes are located around the periphery of individual elements with narrow links between the elements. It should be noted that the links are used to provide the integration of the top electrode (they are not needed to hold the membrane).

To improve adhesion to the substrate hindered due to surface tension, the membrane was dried in isopropyl alcohol vapor. In the case of TADPh detector the heat-sensitive film and the top electrode are sputtered on the resultant structure through the mask. In the case of PVDF detector the heat-sensitive layer and the top electrode were prepared by lithography with oxygen gas plasmachemical etching. The PVDF film was polarized at about $2{\cdot}10^8$ V/m field strength. The sensitivity of the membrane structure for 25 Hz modulation frequency was at least $2{\cdot}10^4$ $V{\cdot}W^{-1}$.

MATRIX DETECTOR CONCEPTION

As usual advanced FPA are equipped with on clip readout integrated circuits (ROICs) implemented in CMOS technology. One can see such approach as for microbolometric UFPAs [4] as for pyroelectric UFPAs [1] CMOS ROIC filters, buffers and multiplexes the output signals.

In our investigations we emphasized our investment on analog processing in CCD structures. As it is well known CCD analog processors are commonly used in cooled FPAs fulfilling functions of storage, skimming, partitioning, antiblooming, amplifying and multiplexing [8]. And judging by the low meaning of minimum resolvable temperature (up to 40...20mK) for such devices this decision in quite satisfactory.

The main achievement of CCD approach from our point of view is parallel processing of the signal. Special 2D analog processor for operating with matrix pyroelectric arrays which construction is described above is under design now. This processor has interline structure with surface channel input elements and burried channel low noise multiplexing and output elements. It consists of two sections.

The first operates as storage section with fast frame transfer, the second one is memory section where we have, on one hand, positive pyrosignal, on the on other, negative pyrosignal. The construction of output structure allows to subtract these signals and double sensitivity. The storage section may operate in special regime in order to decrease modulation transfer function (MTF) in the region of high spatial frequencies. Matrix UFPA will contain 128×128 element on approximately 4-mil centers.

Obtained characteristics of thin films non organic pyroelectric and characteristics of proposed 2D CCD analog processor give us the hope to reach for such structure MPT not more than 0.1 K for low spatial frequencies.

PYROELECTRIC- CCD STRUCTURE MODELING

We put forward and investigated in detail new technological operations for preparation of thin pyroelectric organic films, the operation being compatible with basic technology of contemporary microelectronics. They made possible industrial production of thin films with pyroelectric coefficient in the range $(1...5){\cdot}10^{-5}$ $C{\cdot}K^{-1}{\cdot}m^{-2}$, and good figure of merit for applications to monolithic multi-element uncooled detectors.

In order to investigate the characteristics of array pyroelectric device the hybrid CCD structure was manufactured. Linear CCD burried-channel low noise multiplexor with direct pyroelectric signal injection was used for these experiments. The injection required can be efficiently provided through the sample intrinsic leakage currents under the applied voltage of several volts.

The input circuit of linear multiplexor was designed specially to allow all signal processing procedures we proposed for our advances matrix analog processor. Experimental measurements allow one to determine optimum values of signal storage period, modulation frequency, and bias voltage on the pyroelectric capacitor (see, e.g., Fig. 3).

There are created a completely monolithic pyroelectric sensor array based on a heat-sensitive film construction lifted slightly above the crystal. Detector specimens (2×128 elements of the area of

100×100 μm^2) with NETD less than 0.2-0.5 K (for 8-12 μm at 300 K and 20-50 Hz of modulation frequency) has been manufactured.

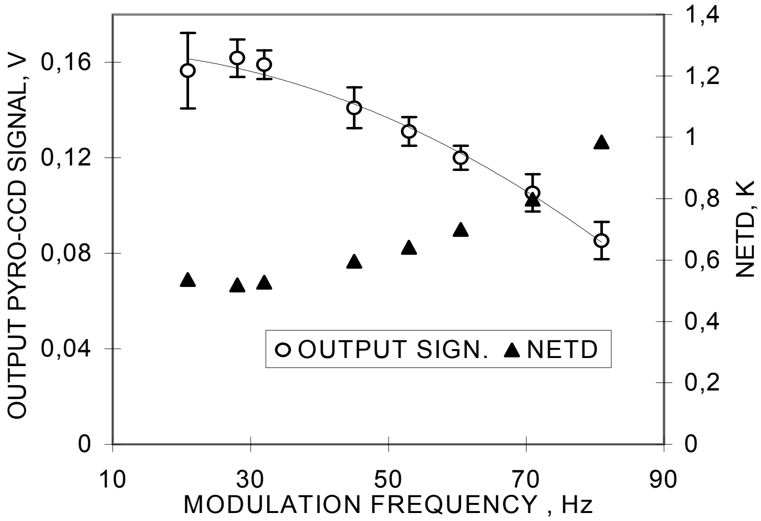

FIGURE 3. Output CCD signal vs. modulation frequency of incident IR radiation

FERROELECTRIC PHENOMENA AND "DEEP" ANALOG PROCESSING

One of the remarkable features of ferroelectric materials is the ability of changing their characteristic under the action of external conditions in particular being applied by electric field. We have fulfilled carefully investigations of pyroelectric coefficient dependence vs polarization conditions of thin ferroelectric films, PZT for example [9]. These studies showed that this dependence discovers practically linear character (Fig. 4), on the other hand due to the polycrystalline structure of ferroelectric thin films "soft" polarization switch is capable in this case. Appropriate characteristics have been watched under application of a symmetric scanning voltage so as under pulses switch of polarization for various amplitudes of switching pulses.

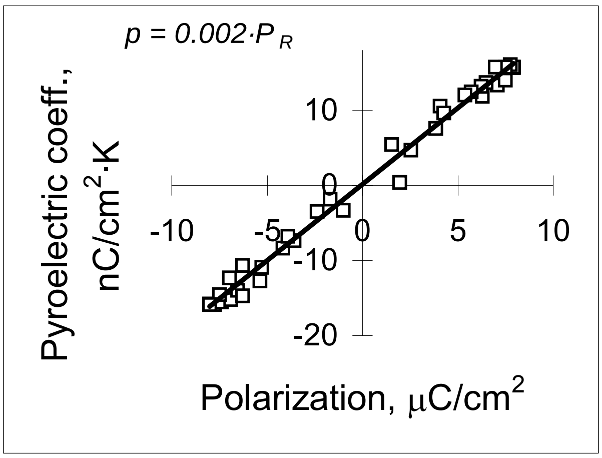

FIGURE 4. Polarization dependence of pyroelectric coefficient for PZT films. The 0.2 μm PZT films were prepared by the sol-gel techniques on oxidized silicon substrates with platinum electrodes at various temperature regimes

So it was shown that analog memory could be realized in thin ferroelectric films due to their stable state remainent polarization. The two phenomenon pointed out earlier may be used in the devices performing analog multiplication of two signals, one of them is incident radiation, the other is a priori storage information in the form of specially appropriately polarized pyroelectric detector elements. This can produce sensitivity non-uniformity compensation of the UFPA elements for the purpose of the spatial noise reduction.

Although the CCD readout is possibly not the optimum approach for thermal imaging arrays with fine pitch elements, we shall expose below some additional fusibilities of the integration of CCDs with ferroelectric films. As an example, let us take a look at the specific device that performs an analog multiplication of two signals. Concrete realization scheme of this procedure is discussed in [10]. The charges come to the CCD registers from an external device, according to a predetermined fashion, which yields a given voltage distribution applied to each pyroelectric detector, and consequently, causes its partial depolarization with corresponding change of sensitivity of each element of the detector array.

Assume that all pyroelectric elements are preliminary polarized alike, so that their pyroelectric coefficients are the same. As any input circuit of CCD, composed of the pyroelectric sensor element, input diode, and input gate, is in principle reversible, then an inverted charge transport under the input diode from a CCD register is feasible. Now, if one performs a transformation of the thermal image projected on the array, the resulting signal from each detector element should be proportional to the product $P_{ij} \cdot \gamma_{ij}$ (where P_{ij} is the incident irradiation flow projection onto the ij-th element of the array, and γ_{ij} is the pyroelectric coefficient of this element). Thus the image can be multiplied by a predetermined picture (see, e.g., Fig. 5).

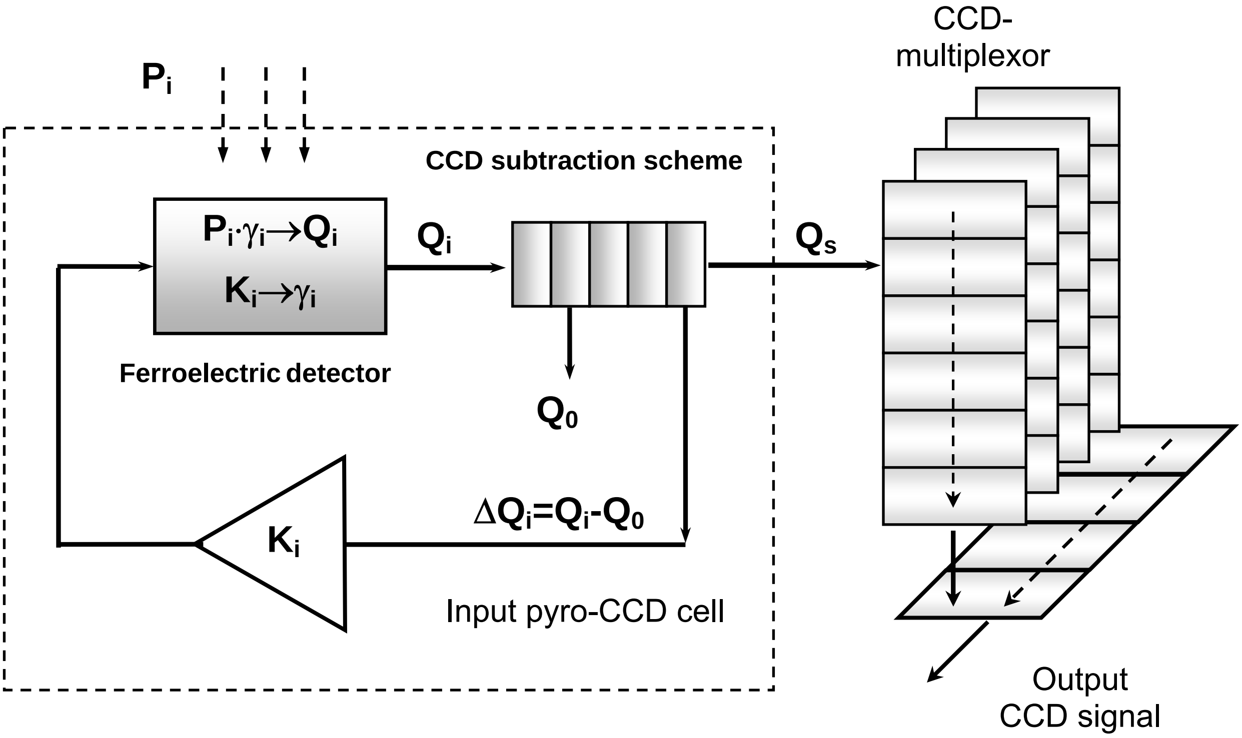

FIGURE 5. Scheme pyro-CCD for obtaining the correction nonuniformity of pixels and signals convolution

The other example of "deep " analog processing can be illustrated using phenomena in thin ferroelectric films for synthetic- aperture radar (SAR) processor, based on ferroelectric CCD TDI structure [11]. In this case the processor operation in each range channel results in multiplication of a sample, of a signal received from a phase sensitive detector by a reference function corresponding to a given range. This is followed by a shift of the resultant matrix of values by one line. Optoelectronic processor for the information in SAR images described in [11] has only one fixed matrix of reference signal and this greatly restrict the application of such device. In the case of ferroelectric-CCD structure one can change the reference coefficients according to the flight parameters.

CONCLUSIONS

We put forward and investigated in detail new technological operations for preparation of thin pyroelectric organic films, the operation being compatible with basic technology of contemporary microelectronics. They made possible industrial production of thin films with pyroelectric coefficient in the range $(1...5)\cdot10^{5}\ C\cdot K^{-1}\cdot m^{-2}$, and good figure of merit for applications to monolithic multi-element uncooled detectors.

The technological methods proposed above allow one to prepare integrated structures of multi-element heat detectors and special CCD readout circuits. In thin structure the sensitive film is isolated from the substrate by means of a supporting membrane or serves as the membrane itself. Such a technology seems to be advantageous in further development of different MEMS structures. Derived measurements and investigations allowed us to choose the structure of 2D analog CCD processor which now is under design and which will be integrated with pyroelectric membrane array described above.

2D analog CCD processor makes procedure of signal storage, skimming, antiblooming, memorizing of positive and negative pyroelectric signals and doubling output signals by subtraction of these components. It also can be used in special regime in order to decrease MTF at high spatial frequencies.

Ferroelectric-CCD structures may be applied for "deep" analog processing such as non-uniformity correction or vector-matrix multiplication with real time changing of matrix coefficients using the effect of "soft" polarization of ferroelectric thin films under appropriate electric fields.

There are created a completely monolithic pyroelectric sensor array based on a heat-sensitive film construction lifted slightly above the crystal. Detector specimens (2×128 elements of the area of $100\times100\ \mu m^2$) with NETD less than 0.2-0.5 K (for 8-12 μm at 300 K and 20-50 Hz of modulation frequency) have been manufactured.

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