Uncooled linear arrays based on $LiTaO_3$

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Numerous applications in the field of infrared measurement technology demand uncooled linear arrays which show such qualities as high signal-to-noise ratio, appropriate spatial resolution, reasonable costs as well as reproducible detector parameters that are stable in the long run.

This paper gives a survey of both the design and essential properties of recently developed pyroelectric linear arrays with integrated CMOS multiplexer made on the basis of lithium tantalate ($LiTaO_3$). There are up to 256 responsive elements with a minimum pitch of 50 µm in the linear arrays. Thanks to the development of a flexible manufacture technology as well as to the further development of sub-technologies there has been a permanent improvement of the thermal and spatial detector resolution capacity. At the same time it has become possible to adapt the detector layout and design to the planned application to a large extent even for a small number of items. The paper demonstrates that reducing the thickness of the responsive elements and providing good thermal isolation at the same time is a way to improve the signal-to-noise ratio many times.

Some of the applications of $LiTaO_3$-linear arrays are infrared line cameras for the non-contact temperature measurement as well as spectrometers in the wavelength range of 0.8…25 µm.

1 Introduction

Pyroelectric infrared detectors along with thermopiles and bolometers belong to the group of thermal detectors. The advantage of these detectors is that they can be operated at room temperature, additionally they show a very homogenous spectral responsivity in the wavelength range of 0.8…25 µm compared to semiconductor detectors. The spectral ranges 3…5 µm and 8…14 µm are of particular technical importance.

Figure 1 shows the principal design of a pyroelectric linear array. Its essential components are the pyroelectric chip and the read-out circuit, where each of the individual responsive elements is connected with an input structure of the circuit. The incident radiation flux $\Phi_S(t)$ is absorbed by the responsive element with the area A_S and causes a temperature change $\Delta T(t)$ in the pyroelectric material. This results in a change of the spontaneous polarisation in the material (pyroelectric effect), which causes charges to build up at the electrodes. These charges are read into the circuit and generate a signal voltage u'_S at the circuit output. Along with the signal voltage u'_S a noise voltage u'_R occurs at the output. The latter is generated by internal noise sources in the pyroelectric chip as well as in the circuit. It limits the least detectable radiation flux.

Some detector parameters can be used to quantitatively describe the performance of linear arrays [1]. The responsivity S_V describes the dependence of the signal voltage u'_S on the incident radiation flux $\Phi_S(t)$ for the spatial frequency $R=0$:

$$S_V = \frac{\Delta u'_S}{\Delta \Phi_S} \ . \tag{1}$$

The noise equivalent power (NEP) is the least detectable change of the radiation flux $\Delta\Phi_S$, which generates a signal voltage change $\Delta u'_S$ at the detector output, which corresponds to the effective value of the noise voltage u'_R :

$$\mathrm{NEP} = \frac{\Delta\Phi_S\, u_R'}{\Delta u_S'} = \frac{u_R'}{S_V} \ . \tag{2}$$

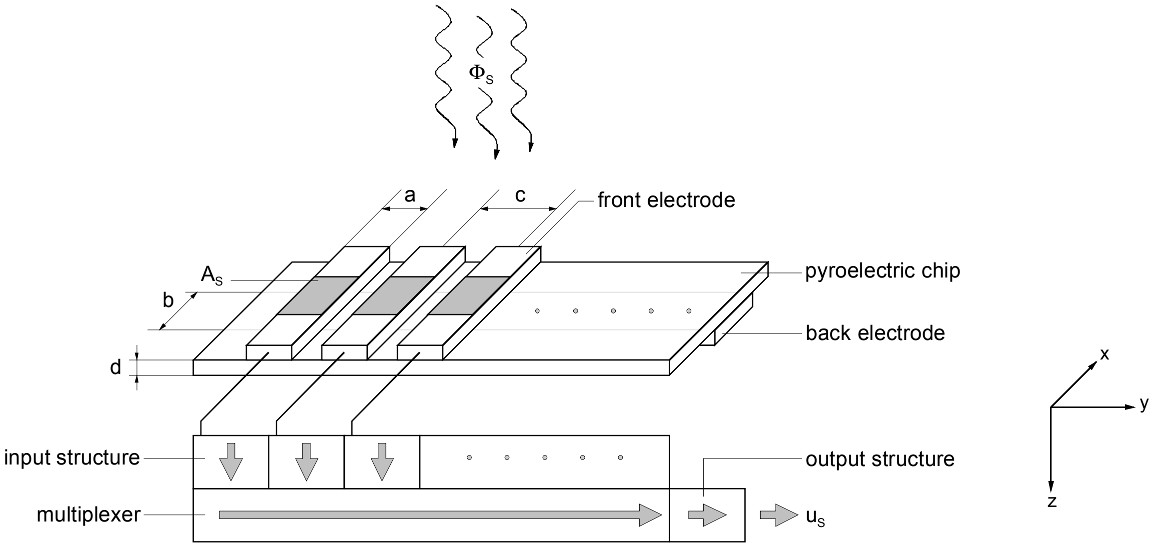

Figure 1: Principal design of a pyroelectric linear array

The modulation transfer function MTF describes the spatial resolution capacity of an array:

$$\mathrm{MTF}(R) = \frac{S_V(R)}{S_V(R=0)} \ . \tag{3}$$

Ideally the MTF is 1 and the product of the individual modulation transfer functions of the array. Here the thermal MTF is of particular importance. It is caused by the thermal cross-talk between the responsive elements as a result of thermal conduction processes in the pyroelectric material. The detector qualities that can be obtained are mainly determined by the properties of both the pyroelectric material and the electrode system, the geometry of the responsive elements, the thermal contact of the responsive element with the environment, the transfer qualities as well as the noise of the read-out circuit.

For the arrays described we get the following equation for the responsivity S_V:

$$S_V = \frac{\tau_F\ \alpha\ p\ v}{c_P'\ d_P\ 2\ C\ f_{Ch}} \tag{4}$$

with:		
	τ_F	transmittance of the optical window
	α	absorption coefficient of the responsive element
	p	pyroelectric coefficient
	c_P'	volume-specific heat of pyroelectric material
	v	amplification factor
	C	integration capacity
	f_{Ch}	chopping frequency.

From these facts it is clear that a reduced thickness d_P of the responsive elements results in an increase of the responsivity.

2 Linear array based on $LiTaO_3$

The research work done in the field of pyroelectric detector development and applicable materials at our institute over many years has shown that $LiTaO_3$ is an excellent and proven material for the manufacture of infrared detectors. It is easy to treat this material mechanically and its chemical resistance is very good. There are single-crystalline polarised $LiTaO_3$ wafers on the market, which have a diameter of up to 3" and thicknesses of 40…80 µm as a minimum.

Table 1 shows measured properties of $LiTaO_3$ that are detector-specific. Arrays based on $LiTaO_3$ demonstrate excellent long-term durability and reproducibility of detector qualities as well as a very small dependence of the responsivity upon the ambient temperature.

p	c_P'	ε_P'	tan δ(1 kHz)	a_P
$1{,}8 \times 10^{-8}$ C cm^{-2} K^{-1}	3,2 J cm^{-3} K^{-1}	43	5×10^{-4}	$1{,}8 \times 10^{-2}$ cm^2 s^{-1}

Table 1: Measured properties of $LiTaO_3$ ($T = 25$°C)

2.1 Pyroelectric chip

In the past years was made an extensive work for the development and optimization of numerous subtechnologies for the reproducible and high-yield production of self-supporting $LiTaO_3$ chips with up to 256 responsive elements and a thickness of the responsive elements smaller than 10 µm [2] [3]. The methods comprise mechanical and mechanical-chemical polishing and ion-beam etching as well [4]. Figure 2 shows the typical layout of two different chip types.

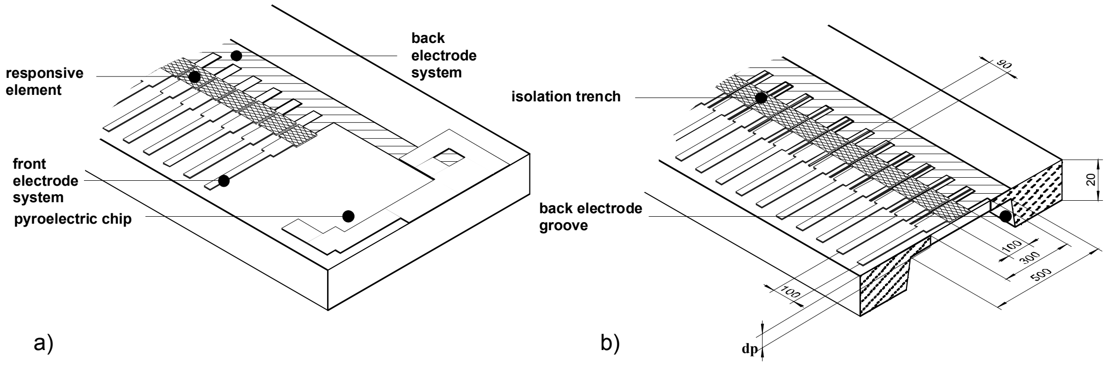

Figure 2: Chip layout with typical dimensions (µm) a) standard chip (only mechanical polishing)
b) ion-beam-etched chip

After the front electrode systems have been structured the $LiTaO_3$ wafers of about 500 µm thickness are thinned to a thickness of about 30 µm by mechanical lapping and polishing processes. After that the wafers are mechanically and chemically polished to a final thickness of about 20 µm. The chip surface is of optical quality. The chips demonstrate a typical plane parallelism that is better than ± 1 µm. For the manufacture of standard chips the back electrode system is photolithographically structured after the treatment. After the chips have been detached from the machining carrier they show the dimensions $[14{,}500_{-100} \times 1{,}600_{-100} \times 20_{\pm 0}]$ µm^3 and are ready for further packaging processes.

To produce chips with even thinner responsive elements ion-beam etching (IBE) is carried out after polishing. Ion-beam etching is a dry-etching technique, whose process parameter may excellently be adjusted to the specific structuring task. While the back electrode trench is being etched (see figure 2), the chip edge area is covered by a photoresist mask. The thicker chip edge area provides the mechanical stability necessary after etching for the handling of the self-supporting chips, in particular for packaging and bonding. For the process parameters applied typical etching rates for $LiTaO_3$ are 40…100 nm/min. Using the ion-beam etching technique linear arrays with a responsive element thickness of less than 2 µm were produced. The feasible minimum thickness of the pyroelectric material in the trench area is primarily determined by the obtained plane parallelism of the polished chips as well as by the user request for the responsivity homogeneity over all responsive elements. For the reduction of the thermal cross-talk between the responsive elements and – as a result – for the MTF improvement thermal isolation trenches can be etched between the responsive elements. Typical trench widths are 5…10 µm for a length of 300 µm [5].

2.2 Packaging & housing

The packaging & housing of the individual detector components is of decisive importance for the manufacture of long-term durable and reliable infrared detectors. The linear arrays with chip lengths up to 14,500 µm are placed in a 16-pole hermetic metal housing with the dimensions [22 x 32 x 3.5] mm^3. A hybrid arrangement is applied for the linear arrays. The read-out circuit and a subcarrier with the pyroelectric chip are placed on a thick-layer wiring carrier. The chip's responsive elements are arranged in the centre of the housing. The individual elements on the chip are electrically bonded with the bond pads of the read-out circuits by ultrasonic wire bonding. At the time being the minimum bond pitch is 50 µm. At present we use a CMOS-analogue switch structure with C/V converter and with low-noise preamplifiers, which has been especially developed for the read-out circuit.

Moreover, a temperature detector is integrated in the housing. The infrared-transmissive window is chosen in dependence of the array application. Applications of very broad bands call for calcium fluoride (0.1…9 µm), KRS-5 (0.65…30 µm) and sapphire (0.4…5 µm) for example. For wave lengths of 3…5 µm and 8…12 µm bandpass filters are used.

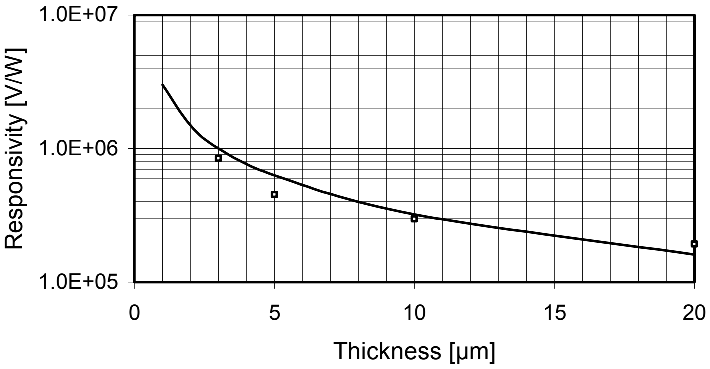

Figure 3: Measured dependence of responsivity S_V on the thickness d_P of the responsive elements compared to the calculated values

2.3 Array properties

Figure 3 shows a comparison between the measured dependence of the responsivity on the responsive element thickness and the calculated values. The arrays contain 128 responsive elements with a pitch of 100 µm. The responsive surface covers an area of [90 x 100] μm^2. The measurements were carried out with a germanium window bloomed for 8…14 µm. The mean absorption coefficient α of the responsive element amounted to 0.61. The measurements were performed at ambient temperature ($T = 25$ °C) using rectangular chopping at 128 Hz. Deviations result from the measuring errors in the determination of the thickness of the responsive elements and the reduction of the overall absorption coefficient of the radiation-sensitive elements due to the reduced self-absorption of $LiTaO_3$ [$\alpha_{LiTaO_3} = f(d_p)$].

Number of Elements	Pitch c [µm]	Size of Element a x b [μm^2]
1 x 128	100	90 x 100
1 x 128	100	90 x 500
1 x 128	100	90 x 1000
1 x 128	100	90 x 1500
1 x 128	100	90 x 2300
1 x 256	100	90 x 100
1 x 256	50	40 x 50

Table 2: Typical configurations of linear arrays

Number of Elements	1 x 128	1 x 128	1 x 128	1 x 256
Size of Elements [μm^2]	90 x 100	90 x 100	90 x 2300	40 x 50
Pitch [µm]	100	100	100	50
Element Thickness [µm]	20	5	20	5
Responsivity S_V [VW^{-1}]	200 000	500 000	200 000	500 000
Variation S_V	1…2 %	2…5 %	1…2 %	3…6 %
NEP [nW]	5 (2.5)	2 (1)	6 (3)	2 (1)
NETD (300 K, F/1-optic) [K]	0.8 (0.4)	0.3 (0.15)	0.04 (0.02)	1.4 (0.7)
MTF (R = 3 lp/mm)	0.6	0.6	0.6	0.7

( )-values: additional 4 accumulations (frame rate 32 Hz)

Table 3: Typical properties of linear arrays
(rectangular chopping with 128 Hz, array temperature 25 °C, Ge*)

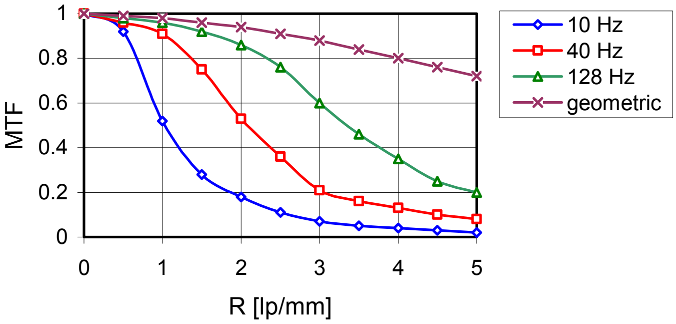

Figure 4: Frequency dependence of the MTF for a linear array without isolation trenches

Table 2 shows a survey of linear arrays built so far and their element geometry. A special packaging and structuring technique facilitates the manufacture of very long linear arrays with more than 256 elements in the pitch ≥ 50 µm. Table 3 shows essential properties of different detector types. Figure 4 shows the frequency dependence of the MTF for a 128-element linear array without thermal isolation trenches. It clearly shows that the MTF of the linear array improves with the chopping frequency increasing, since the thermal diffusion length of the temperature wave in the pyroelectric material decreases. What is important for the user is that by an increased chopping frequency within certain limits the spatial detector resolution can be improved at the expense of the thermal resolution (with the responsivity decreasing).

The etching of thermal isolation trenches brought about an enormous improvement of the MTF of arrays with 256 elements [5].

Long-term investigations that had been carried through over up to five years showed that there were no changes of the array parameters within the accuracy limits of the measuring set-ups.

3 Array applications

Various types of the linear arrays presented are applied in infrared systems for non-contact temperature measurement. These are on the one hand line cameras such as the PYROLINE system made by the DIAS Angewandte Sensorik GmbH [6] and on the other hand scanning systems, too [7]. Together with dispersing optical elements (prisms, gratings) the arrays are applied in infrared spectrometers [8]. At present investigations are carried out to test their application in systems for the filling level measurement in optically non-transparent vessels. For a quick and efficient array operation by the user a special sensor module has been developed, which comprises the chopper, a low-noise signal processing with digitalisation, a computer interface as well as the required clock and power source.

4 Conclusions

The manufacture of pyroelectric linear arrays based on $LiTaO_3$ with thicknesses of the self-supporting responsive elements of less than 5 µm has become possible by the development of special thinning techniques (ion-beam etching). It has been demonstrated that as a result the signal-to-noise ratio can be improved many times in correspondence with simulation calculations. The minimum value of the NEP achieved so far for a detector with responsive elements of the dimensions $[90 \times 100]\ \mu m^2$ was 0.2 nW for a chopping frequency of 40 Hz. Since the read-out circuit presently determines the detector noise, there will be a further reduction of the NEP by a new noise-optimized design in the next future.

These newly developed linear arrays based on $LiTaO_3$ are rugged and long-term durable components with both thermal and spatial resolution, which makes them a good choice for the efficient application in systems for non-contact temperature measurement and process monitoring as well as in spectrometers and security systems at reasonable costs.

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