Process Technologies for High-Resolution Infrared Detectors based on $LiTaO_3$

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Infrared system designers increasingly demand pyroelectric detectors demonstrating on the one hand a geometry and number of responsive elements, which are highly user-specific, and a very high signal-to-noise ration on the other. This paper describes the principal design of high-resolution single-element detectors and arrays based on the pyroelectric material lithium tantalate ($LiTaO_3$) together with subtechnologies for manufacturing. It is shown that the production of self-supporting responsive elements with a thickness smaller than 5 µm will be feasible by applying a combined chemical and mechanical polishing (CMP) together with ion beam etching. In the attempt to increase the absorption coefficient of these elements special silver black coatings are deposited, which result in an absorption coefficient $\alpha \geq 0.92$ in the wave range 2…20 µm. When the responsive elements of linear arrays were electrically bonded with the read-out circuit, minimum pitches of 50 µm were reached for ultrasonic bonding processes.

Selected detector parameters are used to prove the potential advancement of detector characteristics, which will be feasible by applying these technologies.

1 Introduction

IR semiconductor detectors (CMT, PtSi, InSb, InGaAs) are known to have an excellent signal-to-noise ratio and to be very fast. The major drawback to these detectors is the generally inevitable cooling (–20 to –196 °C) and, as a consequence, high costs.

Uncooled thermal detectors may be a budget-priced alternative, their signal-to-noise ratio is however smaller by some (2…4) orders. This drawback may be compensated by the advantages that their spectral responsivity is extremely homogenous in the technically interesting wave range of 2…20 µm, that they are exceedingly sturdy as well as compact and small. As a result of the development of purpose-made technologies for the manufacture of thermally well isolated responsive elements with an extremely low heat capacity and a high absorption coefficient at the same time, the thermal resolution capacity of these detectors has been consistently increased over the past years. Particular progress has been made with pyroelectric detectors [1, 2] and bolometer structures [3].

The Institute for Solid-State Electronics at Dresden University of Technology has been working in the field of pyroelectric single-element detectors and arrays for about 20 years. Particular attention has been paid to the development and construction of user-specific detectors [4] with high thermal and spatial resolution capacities (linear arrays) based on lithium tantalate. Essential fields of application of these detectors are pyrometry, gas analysis, spectrometry and security equipment.

2 Detector Architecture

$LiTaO_3$ detectors are hybrid components. They consist of the pyroelectric chip with the responsive elements and a first read-out circuit. The two subcomponents are placed in a hermetic housing with an infrared-transmissive window. Figure 1 shows the diagrammatic internal set-up of a linear array. The responsive elements of the pyroelectric chip are electrically bonded to the bond pads of the read-out circuit. The shortest possible distance between the responsive elements is determined by the minimum bond pitch, among others. The area that is overlapped by the front and back electrodes determines the dimension of the responsive elements. The electrodes are structured ultrathin metal systems with various thicknesses (7…150 nm).

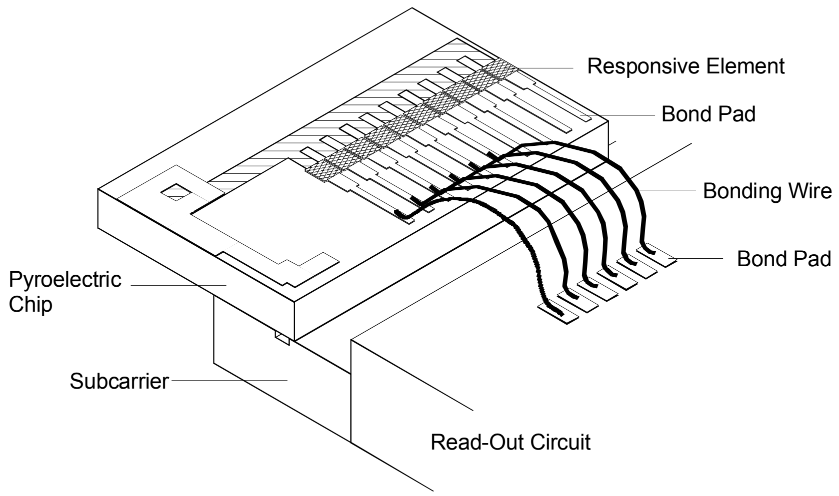

Figure 1: Schematic architecture of a hybrid linear array

For the single-element detectors and arrays the signal-to-noise ratio increases with the thickness d_P of the responsive element getting smaller [4, 5]. The responsivity grows with the absorption coefficient increasing. For the layer system used here, front electrode-$LiTaO_3$-back electrode, the band absorption coefficient is $\alpha \approx 0.6$ (2…20 µm). To obtain good thermal isolation the responsive element is placed in the housing as a self-supporting construction, i.e., the heat flow is laterally from the element into the bordering pyroelectric material, and normally to the chip surface into the surrounding inert gas. The lateral heat flow in the pyroelectric material causes undesirable thermal cross-talk between the neighbouring responsive elements of arrays, which makes the modulation transfer function (MTF) decrease. The MTF may be improved considerably by the application of grooves between the elements. Figure 2 shows the planned chip layouts for single-element detectors as well as for a linear array. The required chip dimensions for linear arrays are typically $[14{,}500_{-100} \times 1{,}600_{-100} \times 20_{\pm 1}]\ \mu m^3$ for a plan parallelism of ± 1 µm.

3 Process Technologies

The following process sequences are essential for the manufacture of a pyroelectric detector:

- Detector simulation and determination of the chip layout
- Manufacture of the $LiTaO_3$-chip
- Manufacture of the read-out circuit (e.g., CMOS multiplexer)
- Packaging and housing
- Determination of detector parameters.

A selection of subtechnologies will be described in the following chapters. These subtechnologies considerably influence the thermal and spatial resolution capacity of the infrared detectors.

3.1 CMP and Ion Beam Etching

$LiTaO_3$ is grown by the Czochralski method of pulling crystals, afterwards it is polarised. The crystal diameter that has been made feasible is presently 3". The z-cut is applied for pyroelectric materials. There are current commercial production techniques to coat chips that are polished on both sides with a layer of about 80 µm of minimum thickness, which is not sufficient for the manufacture of detectors with a higher signal-to-noise ratio. For this reason, a production technology has been developed for the manufacture of self-supporting responsive elements with a thickness smaller than 5 µm. Figure 3 demonstrates the technological production process of thin $LiTaO_3$-chips in accord with Figure 2 (a).

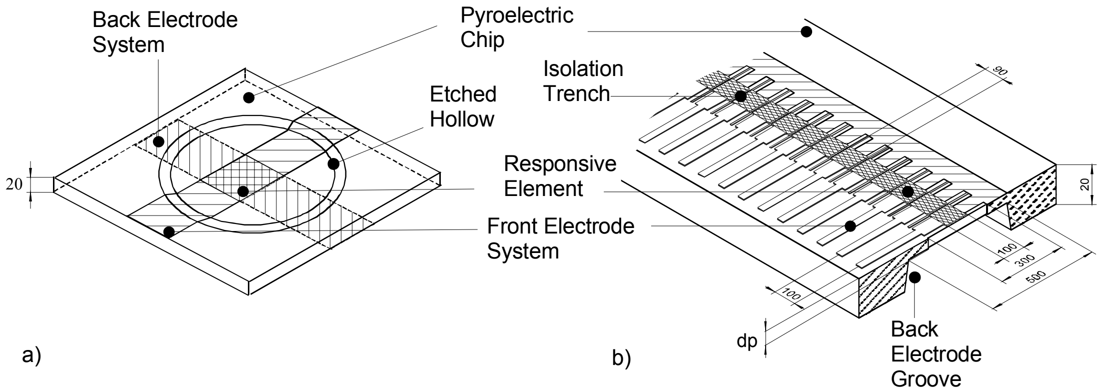

Figure 2: Layout of different $LiTaO_3$-chips, ion beam etched single-element detector chip (a), ion beam etched chip for a linear array (b)

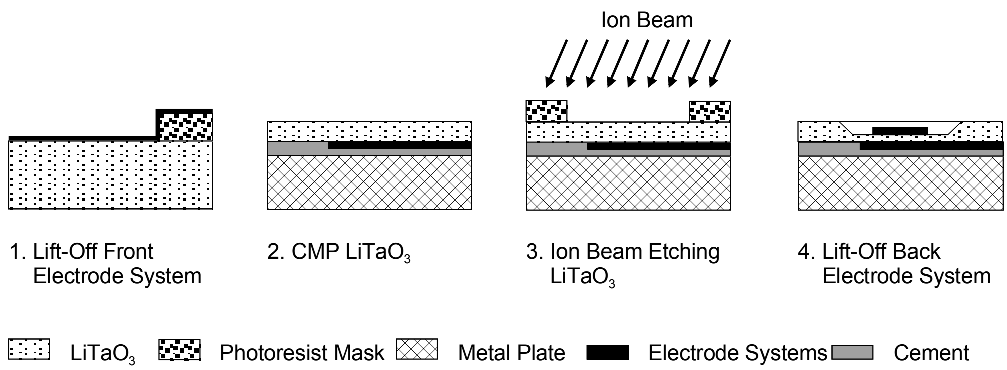

Figure 3: Process technologies for $LiTaO_3$-chips

The production starts on polarised, monocrystal $LiTaO_3$-wafer with a diameter of 2.5" and a thickness of about 500 µm. One side is polished. The other side is lapped.
On the basis of the user-specific number and geometry of elements a detector simulation (thermal, electric) is carried out and the necessary chip layout is determined. First, the lift-off technique is applied to structure the front electrode system photolithographically on the polished wafer side. There are two levels of structuring: front electrode and front electrode reinforcement outside the responsive element. A photoresist mask of the type AZ 1514 H has been used. The front electrode is made of NiCr 80/20 with a thickness of about 10 nm. A layer system made of NiCr 80/20 and gold of a total thickness of about 50 nm is used to reinforce the front electrode. This lift-off technique is applied to obtain minimum structure widths of 5 µm for array pitches of 10 µm. As a result of the surface charges, which are brought about when the pyroelectric material $LiTaO_3$ slightly changes its tempera-

ture, and the possible spark discharges as well problems may occur during the photolithographic process, which in turn determines the element efficiency of arrays.

After the front electrode has been structured, the polished side of the $LiTaO_3$ disc is cemented onto round metal precision plates with a plan parallelism better than ± 1 µm. A special cement is used for this. The cement thickness is smaller than 5 µm. Mechanical and chemical-mechanical polishing (CMP) methods together with ion beam etching are used for thinning. The mechanical and chemical-mechanical processing is carried out with a precision polishing jig to which the round metal plates with the $LiTaO_3$ wafers are mounted. Figure 4 shows the polishing jig with the round metal plates with $LiTaO_3$ samples.

Figure 4: Polishing jig with LiTaO3-samples

Up to a thickness of about 40 µm, lapping with silicon carbide (5 µm) on a cast iron plate forms the major part of abrasion. The thickness is then reduced to about 30 µm by a mechanical polishing procedure using a diamond paste (grain size 3 µm) on a polishing cloth. A final gentle CMP procedure is carried out on the basis of an acid SiO_2-solution to obtain a thickness of 20 µm.

The mechanical processing is followed by ion beam etching to reduce the thickness of the responsive elements [5]. Ion beam etching is a dry etching process, in which the etching parameters may be very well adapted to the structuring aim. Essential process parameters are the ion current density, the ion energy, the bombardment angle, the etching gas and the residual gas pressure. To etch the material locally on the responsive elements a photoresist mask is applied. The masks of the type AZ 4562 were used, which were approximately 20 µm thick. With the chosen process parameters an etching rate ratio $LiTaO_3$: AZ 4562 = 1.2 : 1 could be obtained. The thicker chip edge ensures the mechanical stability that is necessary for handling, in particular for assembly and bonding. In this way, the production of chips with responsive elements thinner than 2 µm has become feasible. The minimum usable thickness of the responsive elements depends on the plan parallelism obtainable for crystal processing and the required responsivity homogeneity and is determined for arrays by the number of elements. Thermal isolating grooves have been etched between the responsive elements in the attempt to reduce thermal cross-talk in linear arrays. In $LiTaO_3$ areas of 5 µm thickness the grooves are typically 5…10 µm wide and 300 µm long. Figure 5 shows SEM pictures of ion beam etched chips for single-element chips and thermal isolation trenches in a linear array chip in the pitch 50 µm.

Table 1 gives an overview of typical abrasion rates for the various subprocesses of the overall $LiTaO_3$ processing. After ion beam etching the remaining masking lacquer is removed. Then the back electrode system is structured by the lift-off technique. A diamond saw separates the wafers in the chips. After the chips have been detached and cleaned, an annealing process is started, i.e., the damages that were caused by the ion beam etching process in the crystal structure are being reduced.

Process	Lapping	Polishing with diamond	Polishing with silica sol	Ion beam etching
Abrasion rate [nm/min]	3,000...6,000	100…200	20…50	40…100

Table 1: Typical abrasion rates for the various subprocesses of the overall $LiTaO_3$ processing

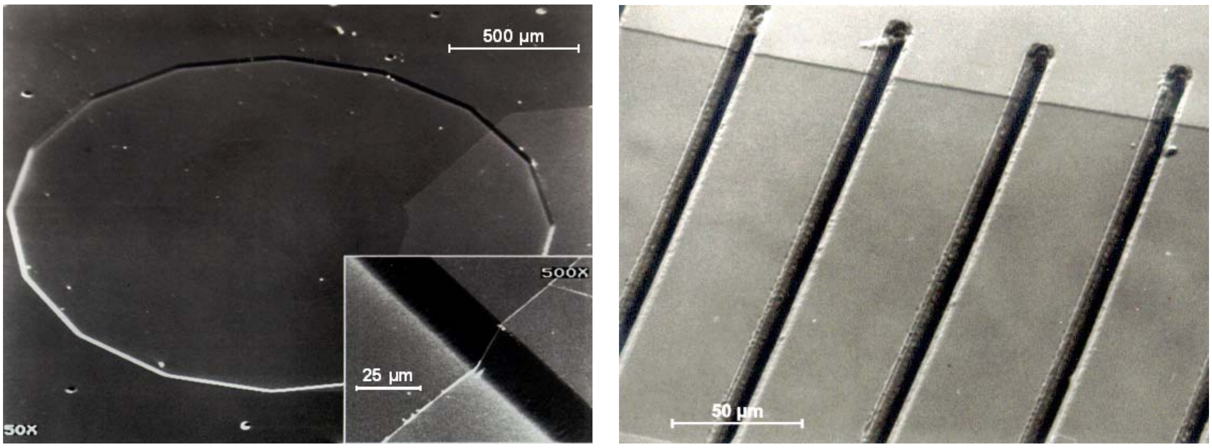

Figure 5: SEM pictures of ion beam etched single-element chip ($d_P \approx 4$ µm) (a)
and thermal isolation trenches in a linear array chip (pitch 50 µm) (b)

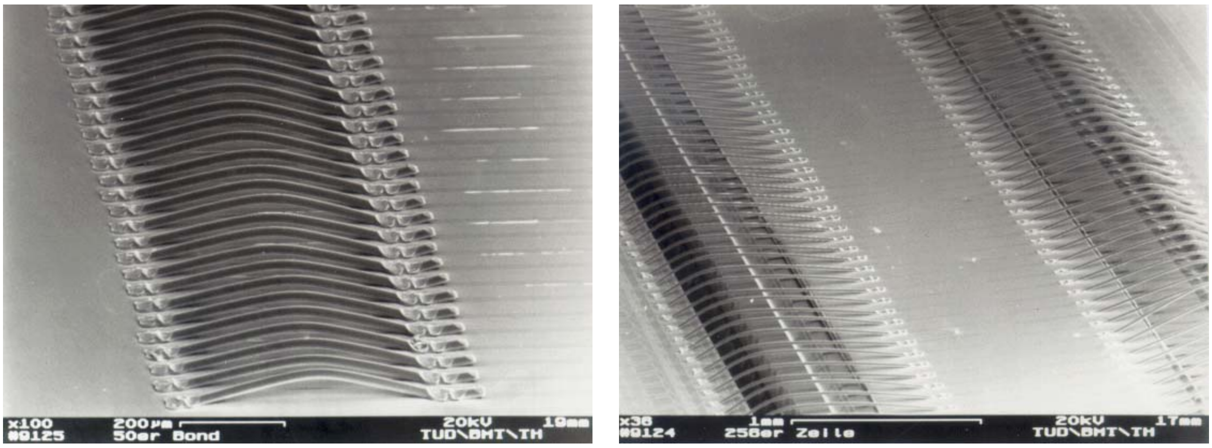

Figure 6: SEM pictures of bonds on LiTaO3 with 50 µm pitch (a) and
bonds between circuits and pyrochip in a 256 element linear array (b)

3.2 Fine Pitch Bonding

Packaging and housing of the pyroelectric detectors is of decisive importance for the manufacture of long-term durable and reliable components. The electric connection between the responsive element on the pyroelectric chip and the input structure on the read-out circuit is of particular significance for arrays. Thanks to the high flexibility and reliability for the $LiTaO_3$ detectors developed wire bonding techniques may be applied. As a rule, thermal compression bonds and thermosonic bonds, respectively or ultrasonic bonds can be used. The first two methods suffer the disadvantage that the minimum temperature of the bond elements is relatively high (100…350 °C) and that the bonding area is relatively large, which is needed by the deformed bond ball. As a result, bond pitches smaller than 100 µm are hardly feasible.

Ultrasonic wire bonding implies mechanical friction under pressure, which brings about the connection between bonding wire and bonding area. There is no need to heat the bond elements. The bonding wire is precisely guided in a bonding wedge. The possible minimum bond pitches basically depend on the diameter of the bonding wire used and the bonding wedge geometry. Silicon-alloyed aluminium leads are the major choice for the bonding wires.

On the background of the $LiTaO_3$ array production, the current US bonding technique and technology has been optimised such that now reliable bondings between the thin metal layer on the pyroelectric chip and the aluminium bond pad on the read-out circuit can be manufactured. A special bonding wedge was used together with an AlSi wire with a diameter of 17.5 µm to produce bonds with 50 µm pitches. Thus it has become possible to manufacture linear arrays with 256 elements and 50 µm pitches using a read-out circuit. The application of two read-out circuits in the future (on both sides of the pyroelectric chip) might allow the development of linear arrays with 512 elements and 25 µm pitches. Figure 6 shows SEM pictures of bonded $LiTaO_3$ chips.

3.3 Black Coating

A special layer deposited onto the front electrode of the responsive element may considerably improve the absorption behaviour of the latter. This layer absorbs the incident infrared radiation in a spectrally homogenous and wideband manner. It brings about a temperature alteration in the pyroelectric material due to the downward heat conduction into the $LiTaO_3$, which finally results in a signal voltage. This principle and the chip technology described in chapter 3.1 determine the requirements made on this type of black coating:

- High and steady radiation absorption [$\alpha(\lambda) \rightarrow 1$] in the technically interesting wavelength range 2…20 µm
- Minimum heat capacity
- High thermal conduction
- Good long-term stability and reproducibility of the layer features

May be deposited as well as structured on thin chips or is compatible with numerous technologies. Black metal coatings fulfil the requirements mentioned above best. Their structure is light, fluffy and porous. They consist of very small particles [6] (1…30 nm). Most frequently, black coatings on the basis of gold or silver are used. To produce black metal coatings metals are evaporated in a special residual gas atmosphere at pressures of 0.07…0.7 mbar. The evaporated particles precipitate as a black deposit in the vacuum chamber and cover large surfaces of the chip to be coated. The lateral structuring is obtained by means of variable metal masks. Owing to the relatively high evaporation pressure and the related short mean free lengths of path of the evaporated metal particles, under-evaporation of the mask are likely. This limits the lateral resolution of the structuring (about 20 µm). Black metal coatings are electrically conductive. The layer deposition shows some essential process parameters, such as evaporation temperature, evaporation material, pressure and composition of the residual gas and the chip temperature.

A black coating has been optimised on a silver basis to produce $LiTaO_3$ detectors. The procedure described was applied to manufacture black coatings with a thickness of ≈ 5 µm, which demonstrate a band absorption rate of about 0.92 for a 500 K radiator in the wave range 2…20 µm. A major drawback of the layers developed is that they are not stable against wiping and that they cannot be treated wet-chemically. This means that they can be deposited on the responsive elements only after the pyroelectric chips have been detached.

4 Detector Properties

The single-element detectors consist of the pyroelectric chip, a low-noise SFET and a ultra-high Ohm resistor. They are placed in a TO 39 or TO 8 housing with a suitable infrared-transmissive window. Table 2 shows the essential parameters of the detectors developed. It becomes apparent that very thin responsive elements result in a considerably improved specific detectivity D^*, which is a measure for the signal-to-noise ratio. At the same time, it can be seen that the detector responsivity S_V is about one and a half times higher thanks to the black absorptive coating applied. Figure 7 demonstrates the spectral responsivity of single-element detectors with and without black coating.

Figure 8 shows a comparison between the measured dependence of the responsivity on the responsive element thickness and the calculated values for a linear array [7]. The arrays contain 128 responsive elements with a pitch of 100 µm. The size of the responsive element is [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 $LiTaO_3$ [$\alpha_{LiTaO_3} = f(d_P)$].

Type of sensor	LT	LT-I	LTS*	LTS*-I	LT-I	LTS*-I
d_P [µm]	20	5	20	**5**	5	5
A_S [mm^2]	2 × 2	2 × 2	2 × 2	2 × 2	1 × 1	1 × 1
S_V [V/W]	380	350	540	500	1200	1750
D^* [10^8 cm Hz$^{1/2}$ W^{-1}]	5	8	8	**12**	8	12

S* Black coating
A_S Size of the responsive element

Table 2: Properties of single-element detectors [500 K radiator, 10 Hz, 1 Hz bandwidth]

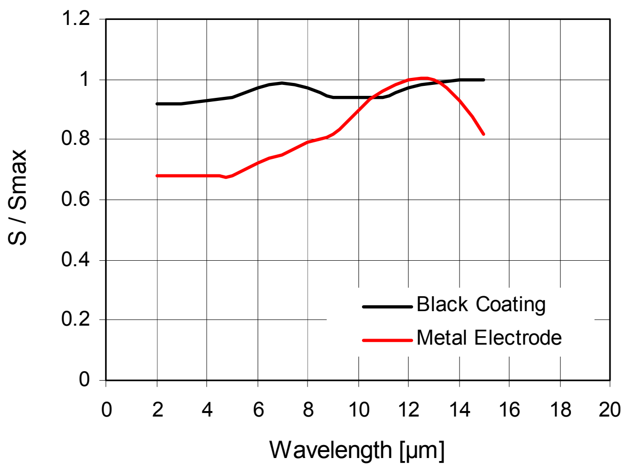

Figure 7: Relative spectral responsivity of single-element detectors with and without black coating

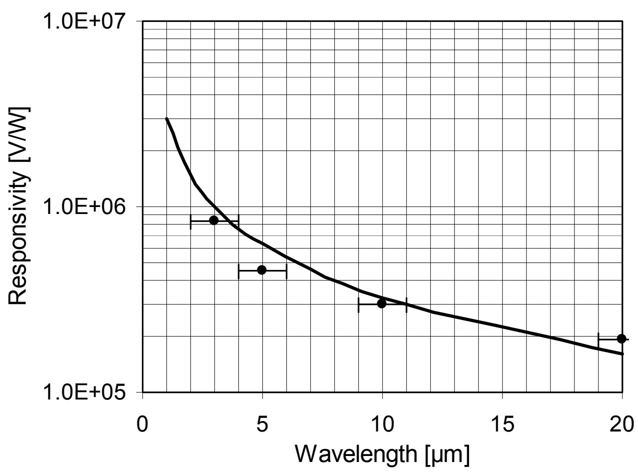

Figure 8: Measured dependence of responsivity S_V on the thickness d_P of the responsive elements compared to the calculated values

5 Conclusion

The consistent efforts to develop special subtechnologies for the production of pyroelectric infared detectors on the basis of $LiTaO_3$ resulted in components demonstrating a high signal-to-noise ratio. The high flexibility of the technology as a whole allows the production of very specific detectors for a wide range of applications even in small numbers and at reasonable cost.

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