Sensors and Actuators A 261 (2017) 140–150

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Investigation of pyroelectric fields generated by lithium niobate crystals through integrated microheaters

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ARTICLE INFO

Article history:
Received 27 October 2016
Received in revised form 5 May 2017
Accepted 5 May 2017
Available online 8 May 2017

Keywords:
Pyroelectric fields
Lithium niobate
Joule effect
Thermal effect analysis

ABSTRACT

We present a deep investigation of pyroelectric fields generated by lithium niobate crystals through integrated microheater structures. The microheaters are made of highly compact titanium microcircuits able to dissipate heat through a low-power consuming Joule effect. Microheaters with diverse geometries were designed and fabricated on the +*Z* face of lithium niobate crystals, in order to characterize pyroelectric fields with different distributions. The pyroelectric effect was studied under ambient conditions analysing the current impulses detected using a metallic probe connected to an oscilloscope. The current impulses were related to the air breakdown induced by the electric field arising between the −*Z* face of the crystal and the metallic tip. We show that the fabrication technique is relatively easy to accomplish and we analyse the thermal behaviour of the microheaters both theoretically and experimentally. The results show how such microheaters are able to control the intensity and the spatial distribution of the pyroelectric fields at microscale.

1. Introduction

Pyroelectricity is the ability of certain materials to generate an electrical potential in response to a temperature change. The change in temperature induces a slightly movement of the molecules within the material that changes their dipole moments. Thus, two oppositely charged faces are created and an electrical field across the material is established. In other words, the pyroelectric effect is due to the dependence of the spontaneous polarization P_s, the dipole moment per unit volume of the material, on the temperature. Historically, the most important applications of the pyroelectric effect have been related to the possibility to measure the power generated by a radiation source, such as pyrometry, infrared imaging, radiometry [1–4]. However, there are other applications that are attracting great interest, including lithography [5,6], electrohydrodynamic effect based devices [7], electron emission devices [8,9], ion source spectrometry [10,11], alignment of nano-particles under electrode-free approaches [12], nano droplet drawing [13,14], self-trapping of optical beam in a photorefractive medium [15]. These applications made use of easy to use but macroscopic thermal sources such as CO_2 laser heads, hot plates, Peltier modules and soldering iron tips. Recently, we have demonstrated the possibility of controlling the pyroelectric field even at microscale through the Joule effect developed by microscopic electrical circuits fabricated onto the surface of lithium niobate (LN) crystals [16]. The micro-heater (μH) configuration enabled us to electrospin bending-free fibres generating well-ordered spiral patterns.

Here, we present a deep characterization of such μHs fabricated onto the surface of +*Z* cut LN crystals, in order to demonstrate the reliability and the effectiveness of these microdevices for all of those applications where compact and low-power consuming electric field sources are highly desirable. Moreover, the microscale nature of the μH allows one stimulate the crystal locally, thus opening the route even to the development of array pyroelectric sources. The fabrication procedures make use of skills established in the past for a different class of applications including thermo-optical switches, chemical sensors, gas sensors, flow sensors and MEMS [17–19]. Four different μH configurations are analysed here in order to investigate and exploit different electric field distributions: 1) the 'meander'; 2) the 'fan'; 3) the 'spiral'; 4) the 'S-shape'[20]. Both the thermal and the electrical behaviour of the μHs were

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http://dx.doi.org/10.1016/j.sna.2017.05.010
0924-4247/

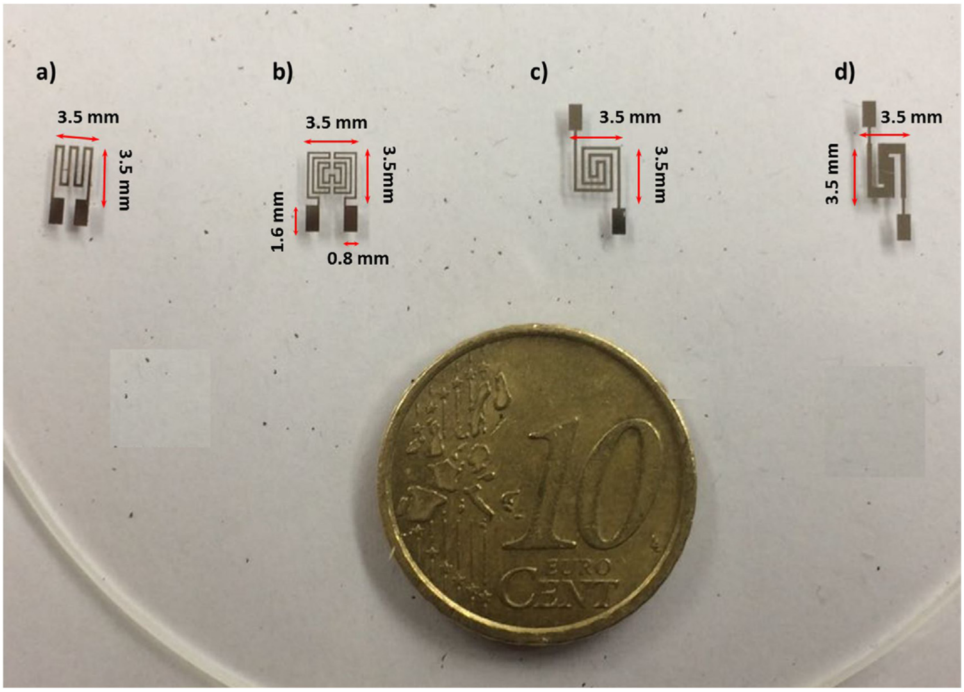

Fig. 1. Four different micro-heater geometries: a) Meander, b) Fan, c) Spiral, and d) S-shape.

investigated theoretically and experimentally for fully understanding their operation modes and, consequently, for opening the route to new potential applications. The pyroelectric effect activated by the µH was investigated analysing the pyroelectrical current impulses detected using a micrometric metallic probe connected to an oscilloscope [21]. In particular, the temperature variation due to the µH induces a spontaneous polarization change, which produces a redistribution of the bound charges on the crystal surface. The electrical field generated between the crystal surface and the metallic probe causes an air breakdown that appears as an impulse on the oscilloscope. Generally, when a $LiNbO_3$ crystal is heated under ambient conditions, free charges in the air will readily compensate the change in the polarization, thereby avoiding the creation of an electric field [22]. Although, when the probe is few hundreds of microns far from the crystal surface where the air acts as a thick dielectric layer and the generated electric field strength between tip and surface is great enough for inducing an air breakdown. In this paper, the pyroelectric current impulses were analysed for different µH designs and operating conditions in order to demonstrate the effectiveness of the µH as thermal tool for activating the pyroelectric effect. In particular, we validate that the threshold electric field strength required to generate the current impulses at oscilloscope is approximately 3×10^6 V/m (dielectric breakdown of air). Current impulses with larger amplitude is detected above this threshold field strength while the impulses gradually disappear below the afore-mentioned threshold.

The carried out results could be partially useful for applications that exploit the activation of an pyroelectric field between the crystal surface and non-conducting region; such as: 3D lithography [23], aligning nano particles in electrode free [12], nano-droplet drawing [13,14].

2. Method and fabrication

Fig. 1 shows the four µHs investigated here in order to test and characterize configurations with different distributions of the thermal stimulus. The µHs were fabricated on the *+Z* face of LN crystal samples (both sides polished, 500 µm thick and purchased from Crystal technology Inc.) using titanium (Ti) as a joule heating resistor material. This material has been chosen because the nanometric spontaneous titanium oxide layer formation on exposed surfaces allow to passivate the heating resistor and thus thermally and electrically stable µHs are achieved [24]. Moreover, its conductivity allows using low drive voltage for effective heat generation. Fabrication of the µHs on the +Z surface instead of −Z face is a purely conventional approach. As the pyroelectric field arises specularly on both +Z and −Z surface of LN once the µH is switch on. The possibility to realize the µH directly on the surface of the pyroelectric material allows one to maximize the heat transmission to the LN crystal, thus minimizing heat conduction losses.

2.1. Numerical simulation of µHs

The electro-thermal analysis of the µHs was performed by COMSOL^{TM} Multiphysics [25]. The µHs cover an area $(3.5 \times 3.5)\,mm^2$ with a titanium thick layer of 300 nm. In the full 3D numerical model, a LN substrate with a size of 10 mm × 10 mm × 500 µm was considered (see Fig. 1).

The simulations were performed by coupling the power generation, due to the joule heating, with the heat conduction and dissipation into the device considering also the heat exchange with the surrounding air. The multiphysics simulation uses the electric current module in combination with the heat transfer module. The joule heating was calculated as a consequence of the input voltage (V_{pot}) applied to the µH pads. In particular, the electrical conductivity of the µH (σ) was modelled using a temperature dependent equation:

$$\sigma = \frac{1}{\rho_o * (1 + \alpha(T - T_0))} \tag{1}$$

where, ρ_0 is the resistivity at a reference temperature T_0, and α is the temperature coefficient of the resistivity that takes in account the dependence of the resistivity on the temperature. In order to evaluate the heat transfer in the pyroelectric material, several material properties both of the LN and Ti are required. Moreover, since the electrical and thermal properties of thin film materials