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PMN–PT (lead magnesium niobate–lead titanate) piezoelectric material micromachining by excimer laser ablation and dry etching (DRIE)

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ABSTRACT

In the attempt to find the appropriate micromanufacturing technology of PMN–PT (lead magnesium niobate–lead titanate) piezo material, whose MEMS-related applications look promising, two methods are investigated: excimer laser ablation (using KrF gas) and inductively coupled plasma (ICP) dry etching, also known as DRIE (using Ar/C_4F_8 gases). The paper quantitatively reports the optimal parameters for PMN–PT micromachining and compares both methods. KrF excimer laser ablation threshold fluence is of 14 J/cm^2, the etching rate may reach 100 μm/min (50 nm/pulse) but the ablated surfaces are cone-shaped restricting thus the method to cutting/drilling 2D shapes. Excimer ablation method is found to be more convenient for rapid prototyping with less precise features requirements (>10 μm). On the other hand DRIE method on PMN–PT is time-consuming, requires a hard mask deposition but is cleaner and more precise. Dry etching maximum recorded speed is of 0.19 μm/min. The nickel hard mask selectivity varies around 8:1. In exchange this method provides flatter surfaces with no etched material redeposition.

1. Introduction

In the recent years there has been an increasing interest in growing and characterizing $x\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3$–$(1-x)\text{PbTiO}_3$ [1] and $x\text{Pb}(\text{Zn}_{1/3}\text{Nb}_{2/3})\text{O}_3$–$(1-x)\text{PbTiO}_3$ [2] also known as PMN–PT and PZN–PT respectively. Initially used as ceramics, they were grown into single crystals by modified Bridgman or solid-state single crystal growth methods and have become commercially available. Those materials exhibit outstanding piezoelectric properties (e.g. d_{33} = 3500 pC/N, d_{13} = −1200 pC/N, k_{33} = 0.95 etc.) that considerably surpass the PZT ceramics by a factor of 4–5 [1].

During the last decade, the applications of PMN–PT increased dramatically, including high frequency bulk and surface resonators and filters, sensors and actuators, ultrasonic transducers, energy harvesters.

The ability to fabricate well-defined structures on the surface of the substrates, with near vertical sidewalls, a high aspect ratio, and a relatively low surface roughness, is a key factor for many applications, like MEMS, NEMS and integrated optical devices. High depth, high aspect ratios, good uniformity over the wafer, vertical wall profiles and reasonable etching selectivity, i.e. the ratio of the etch rates of the substrate and the mask are the actual challenges. However, for the PMN–PT material, most applications rely on classical mechanical machining methods (saw dicing, lapping etc.). Few recent papers document some PMN–PT MEMS microdevices. For instance, one of the early patented micromachined devices is a PMN–PT composite ultrasound transducer (PC–MUT). The fabrication technology is shown in [3] but with undisclosed quantitative parameters regarding DRIE method. In [4] arrays of etched cantilevers were reported to serve as acoustic sensors; equally lacking parametric details. Finally, in the recent topic review article [5] that reveals the state of the art in piezoelectric MEMS, the dry etching characteristics of most piezoelectric materials are summarized, except for the ones of PMN–PT. As consequence, investigating the micromachining possibilities of this innovative material seems topical. The research is related to the authors' mainstream activities in piezoelectric micro-actuators and tweezers for micromanipulation/microassembly. More recently, integrated PMN–PT piezo-actuators raised our interest, provided the improved performance [6].

Two separate methods will be addressed: excimer (or exciplex) laser ablation and ionic dry etching. The nanosecond ultraviolet (UV) excimer laser pulses are suitable for the UV photolithography or micromachining [7] a large panel of materials [8]. Other complementary application of excimers include piezoelectric materials is the thin films deposition by ablating targets like PZT [9]. Excimer

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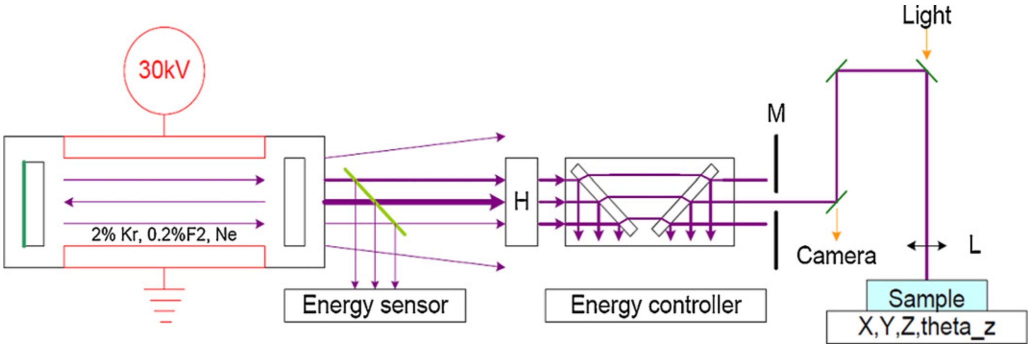

Fig. 1. The excimer laser ablation micromachining unit.

lasers provide high power, wide and homogenous beams for micromachining quite large surfaces. They seem the compromise between the classical YAG laser workstations where large heating transfer occur and the femtosecond lasers that are cold, precise but time-consuming.

Plasma-based reactive ion etching (RIE) is a controllable dry process exploiting both chemical and physical processes to remove solid material locally [10].

Deep reactive ion etching (DRIE) using inductively coupled plasma (ICP) RIE system has demonstrated its potential in batch fabrication of deep anisotropic microstructures in Silicon. The technology is also used for highly directional and precise micro-scale etching of materials including piezoelectric. The interest is in highly integrated piezoelectric and piezo-on-silicon microsytems (from resonators and transducers to actuators and energy harvestors) [5] where traditional methods fail (e.g. mechanical lapping and trenching, ultrasonic etching).

Dry etching of piezoelectric materials is not new issue, researches being reported in quartz [11], AlN [12], $LiNbO_3$ and PZT ceramics [13] where etching is mainly obtained by a rather physical sputtering with insignificant chemical contribution. Quite similar to PZT, the PMN–PT should be also compatible with DRIE.

Unlike PZT, the appropriate micro-technologies for PMN–PT based Piezo-MEMS are not fully documented in the literature; this paper attempts to fill a gap by quantitatively reporting the etching of PMN–PT. It extends some previous results of the PMN–PT material dry etching [14] and subsequently presents the first quantitative information about PMN–PT micromachining tests by excimer laser ablation.

The paper is organized as follows. After the introductory part which presented the brief information about the PMN–PT and its applications for micro devices, the second section details the experimental plan and the related facilities for both the laser ablation and plasma etching set-ups. The third section reports the experimental results for the excimer laser ablation of the PMN–PT while the fourth section documents the ion etching, depicting graphical and numerical results. Finally, a conclusions section is dedicated for several comparative remarks.

2. Micromachining methods

2.1. PMN–PT samples

The material samples used during these experiments were TRS-X2C plates of 200 μm thickness supplied by TRS Technologies (http://www.trstechnologies.com/). The material concentration is 68% of PMN and 32% of PT; the cut and poling was performed in <0 0 1> direction for an optimised out-of-plane (*Z*-axis) operation. This type of plate possesses a very large longitudinal d_{33} piezoelectric coefficient: between 2300 and 3300 pC/N. The k_{33} coupling factors range from 0.90 to 0.97. The transverse coefficients d_{31} are isotropic for this type of cut, varying from −700 to −1200 pC/N according to some intrinsic or external parameters such as material concentration, crystallographic defects and operating temperature.

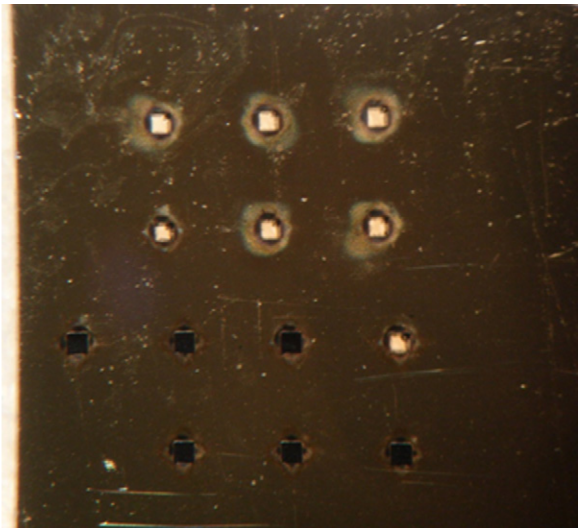

Fig. 2. Photography of an excimer-ablated sample, notice that some holes are completely perforated. The halos around the holes are caused by some ablated material redeposition (larger for the drilled holes, as the PMMA glass underneath was subsequently ablated).

2.2. Excimer laser ablation setup

The Excimer laser ablation setup consists in an excimer laser source, the adequate optics and a 4 degrees-of-freedom positioning table allowing to program complex designs, as in the Fig. 1.

The excimer gas is excited by an electric field: the resulting ultraviolet laser beam is homogenized by (H), leading to a homogeneously intense beam. A fraction of this energy can be removed by the energy controller, before the beam passes through a mask (M). The length of the optical path between the mask and the sample can be tuned in order to adjust both the focus and the demagnification (lens L) up to 14× of the image projected by the mask. The focus is done manually with the aid of a visible light beam.

The laser beam is area is around 3 cm^2. Depending on the demagnification rate, a mask may release one entire device, or even several ones; in this case the patterning is called static. For larger objects, a computer-aided scanning technique is employed, by accurately moving the substrate under basic mask shapes: circles, squares, rectangles etc (Fig. 2).