Materials Research Bulletin 48 (2013) 3420–3423

Contents lists available at SciVerse ScienceDirect

Materials Research Bulletin

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

Kerf profile and piezoresponse study of the laser micro-machined PMN-PT single crystal using 355 nm Nd:YAG

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ARTICLE INFO

Article history:
Received 31 January 2013
Received in revised form 24 April 2013
Accepted 8 May 2013
Available online 15 May 2013

Keywords:
A. Electronic materials
C. Atomic force microscopy
D. Ferroelectricity

ABSTRACT

A systematic study on laser micro-machining of PMN-PT single crystals has been performed. The PMN-PT single crystal has been micromachined using a 355 nm Nd:YAG laser. The kerf profile and cutting quality of the laser micro-machined PMN-PT single crystal were studied as functions of the laser process parameters. It was found that the direct proportional relationship between the depth of the kerf and the laser power provides an effective reference to determine the depth required to be ablated. It is significant for fabricating micro-devices using the single crystal by laser micro-machining. Besides the physical behavior, the piezoresponse of the PMN-PT single crystal has also been investigated by PFM. The results reveal that the laser micro-machining would not affect the macroscopic piezoelectric performance of the PMN-PT single crystal. The present work shows the feasibility of micro-patterning the PMN-PT single crystal into any geometry using a Nd:YAG laser.

1. Introduction

Relaxor-based ferroelectric $Pb(Mg_{1/3}Nb_{2/3})$-$PbTiO_3$ (PMN-PT) single crystals have attracted considerable attention because of their ultrahigh electromechanical coupling factors and piezoelectric coefficients near the morphotropic phase boundary (MPB) composition [1]. Based on their outstanding performance, various electromechanical applications have been studied and reported [2–4]. Recently, PMN-PT single crystals have attracted considerable interest in the applications of micro-electrical systems [5,6]. Due to the fragile nature of the single crystals, thermal or mechanical stress has to be avoided during the micro-fabrication processes. Dry and wet chemical etching techniques have been commonly utilized in the micro-fabrication of the PMN-PT single crystals. The dry etching processes are time consuming and expensive, especially for relatively thick crystals [6]. Although the wet etching techniques have been widely used in micro-patterning [7], the processes are complicated with sophisticated skill and experience required. Besides the etching techniques, laser micro-machining has also been used in micro-patterning of metals, ceramics, diamond and semiconductor materials [8–14]. Compared to the etching techniques, laser micro-machining is simple, non-contact, mask-free and highly effective. The micro-pattern can be fabricated without any geometry restriction. With the demand growth of piezoelectric microdevices such as micro-cantilever [15], ultrasonic array [16] and micro-pump [17], it is highly desired to apply the laser micro-machining technique on micro-patterning the piezoelectric single crystals. Nevertheless, no systematic study on laser micro-machining of PMN-PT single crystals has been reported in literatures.

Among various kind of lasers, CO_2 and Nd:YAG are the most popular ones to be utilized in industries [18]. As the wavelength of the Nd:YAG solid state laser is much shorter than that of the CO_2 gas laser, the Nd:YAG laser is ideally suited for micro-machining. With smaller pulse duration and better focusing behavior, the Nd:YAG laser machining can produce narrower kerf and heat affected zone (HAZ) with less dross. To achieve better quality, the effect of input parameters (including beam parameters, material parameters and machining parameters) on process performance is required to be known. The aim of the present work is to investigate the laser micro-machining of the PMN-PT single crystal using a 355 nm Nd:YAG laser. The values of process parameters were determined to yield the desired product quality (such as kerf width and depth) so as to maximize the process performance. Besides, the effect of the laser micro-machining on the ferroelectric domain configuration in the PMN-PT single crystal was also studied by means of piezoresponse force microscopy (PFM).

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http://dx.doi.org/10.1016/j.materresbull.2013.05.025

Table 1
Specifications of the laser system.

Parameters	Specifications
Wavelength	355 nm
Maximum average power	2.0 W
Frequency	Single shot to 20 kHz
Focus length	40 mm

2. Experimental

The PMN-28%PT single crystal was grown in the Shanghai Institute of Ceramics by the modified Bridgman method [19]. Before the laser machining, the crystals were diced into a size of $10 \times 10\ mm^2$. They were then ground and polished to 0.5 mm thickness. The laser-machining experiments were carried out using a Q-switched diode-pumped solid state Nd:YAG laser (ESI 5200) system. The laser specifications are listed in Table 1. The laser scanned the crystal surface with a single 3 mm-long line. Each trial ran three times. The single pulse energies used ranged from 0.2 to 1.0 W with a constant frequency of 3 kHz. All the experiments were carried out using a constant effective spot size of 25 μm.

The surface and geometry of the micro-machined crystal were observed using an optical microscope. A 50× microscope with 1 μm resolution positioning stages was used to measure the geometry features. The kerf width was defined as the maximum width of the kerf. All the data were the average values of three readings.

PFM is known as a powerful tool for probing local piezoelectric and ferroelectric properties of materials at nanoscale [20]. With the PFM technique, the ferroelectric domain structure of the target sample can be imaged. To investigate the effect of the laser micro-machining on the domain structure, the PFM images were studied as a function of the distance away from the kerf. For PFM imaging, Cr/Au were coated on one side of the micro-machined crystal as bottom electrode. The domain images were obtained by piezo-response force microscope (Nanoscope V, Digital Instruments) using a conductive tip coated with Al/Pt. During the imaging, a modulating voltage of 6 V (peak-to-peak) with 11 kHz was applied to Cr/Au bottom electrode while the tip was electrically grounded. The out-of-plane-polarization images were obtained by collecting the piezoelectric response signal demodulated by a lock-in amplifier.

3. Results and discussions

The mechanism of the laser cut is mainly dependent on the thermophysical properties of the material and the specifications of the laser. As shown in Fig. 1, a laser micro-machined PMN-PT single crystal kerf with an elliptical paraboloid shape is shown. In general, the ablated depth, z, and the width, r, are proportional to the laser power. Fig. 2 shows the laser power dependence on the width r and depth z of the PMN-PT single crystal in a single pass process. It was found that the laser micro-machined width increases with the laser power. The effect is much significant when the laser power is low. Besides, the depth is directly proportional to the laser power. This direct relationship provides a fast and effective reference to determine the depth required to be ablated especially for thin crystal samples.

Since the depth is limited using a single pass process, multi-passes are required to produce the deeper depth in the laser micro-machining process. During the multi-passes process, the laser beam is supposed to be focused exactly on the surface at the first pass. Fig. 3 shows the relationship between the ablated depth, width and the pass number. The experiments were carried out

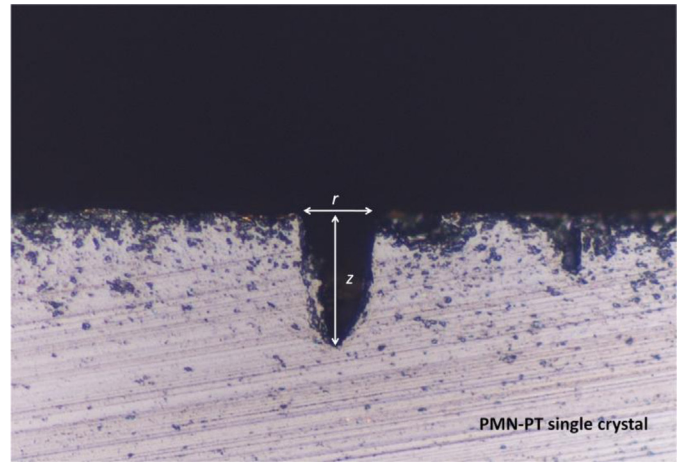

Fig. 1. An optical photograph of the cross-section of the laser micro-machined kerf of the PMN-PT single crystal (laser parameters: 0.6 W, 3 kHz, 6 mm/s, 5 passes).

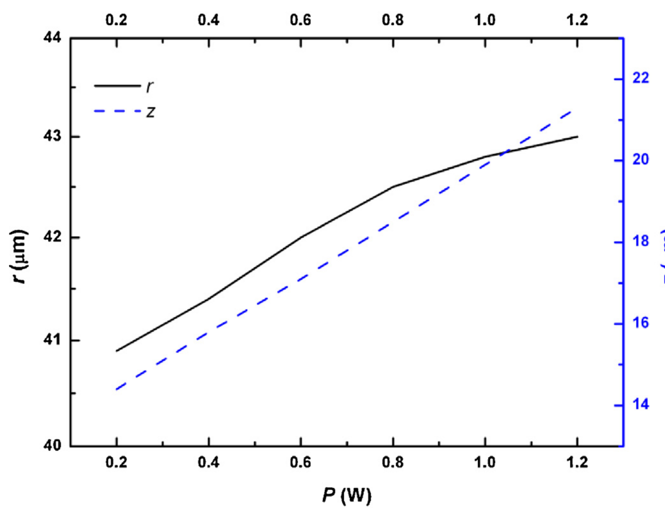

Fig. 2. Single pulse energy dependence of the width r and depth z of the PMN-PT single crystal.

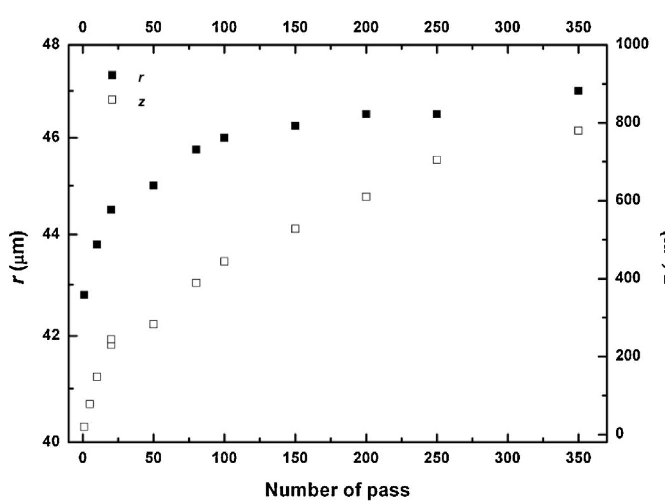

Fig. 3. Dependence of the pass number on the width r and depth z of the PMN-PT single crystal.