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PZT actuator applied to a femto-liter droplet ejector

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Abstract

Since the rapid advancement of the ink-jet printing technology, microdroplet ejectors have been developed into one of the essential fluid handling devices for delivering miniature liquid droplets in accurate dosage control. The applications of micro-droplet ejectors are increasingly prevalent in various emerging areas, for instance organic/polymer lighting emitting displays, liquid crystal display, optical communication, biochemical sample transport and screening and integrated circuit cooling devices. Among different inkjet printing technologies, piezoelectric driven droplet ejectors have shown their potential in dispensing diverse liquids. In this article, a novel femto-liter droplet ejector is proposed using a shear-type PZT actuator. To assure the workability of the ejector, the characteristics of the actuator were well investigated. Before integrating into the vibration plate of the ejector, the response of the rectangular plate-shaped actuator was evaluated by suspending the actuator on a fixture with both ends fixed. With a pre-specified driven waveform, the actuator vibrates to achieve satisfactory responses of displacement and velocity. Subsequently, the actuator was attached to the vibration plate as an actuating module for the ejector. The vibration plate has the design feature of a pillar on a diaphragm. The actuator pushed the pillar and thus deflected the diaphragm. The dimensions of the actuating module have been optimized by numerical simulations. The properties of diaphragm deformation and actuator transient response of the actuating module were simulated and measured for comparison purpose as well.

Keywords: PZT actuator; Driving waveform; Droplet ejector

1. Introduction

With the booming development of the drop-on-demand (DOD) piezo-driven ink-jet printing technology, the droplet ejector not only plays an important role in the customary printer market, but also weighs heavily in several leading-edge industries. During the process of manufacturing organic light emitting display (OLED), for instance, the traditional spin coating method has the following drawbacks: material-wasting, high sensitivity to substrates, and complex manufacture procedure. The ink-jet printing technique progressively attains advantages in fabrication for the crystal deposition of liquid crystal display (LCD), polyimide alignment layer, chromatic filter and in the biotechnology [1], drug dispenser [2], fuel injector of car engine, tin solder of electrical manufacture [3], optical interconnects, switch, lens, waveguide [4], and OLED [5, 6]. To design droplet ejectors, it is desirable to reduce droplet size, enhance droplet consistency, and remove satellite droplets. However, the applications of advanced industries are often limited in the drop size. For example, the resolution of the MEMS/NEMS devices fabricated by the ink jet technology is much inferior to that by the lithography technology. Unfortunately, this is beyond

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the limitations of current fabrication technology. With rapid growth of application areas as stated above, the necessity for understanding and modulation of drop generation in drop-on-demand printing has drawn attention of researchers. In the microdroplet-formation technology, the piezo-driven inkjet printing is the most valuable application. According to the deformation modes of piezoelectric (PZT) actuators, the commercial piezoelectric inkjet-printing technologies are divided into four main types including bend mode [7], push mode [8], squeeze mode [9] and shear mode [10, 11]. The piezoelectric actuators for all actuating modes is demanded to actuate large displacement and force output. For the shear-mode PZT actuator, the conventional design has the poling direction along the plate-thickness direction of the actuator. However, the current special design makes the active region poled along the lateral direction parallel to the plane of plate actuator, which can greatly improve the actuated displacement of shear-mode PZT actuator. This paper aims to present the design, analysis, fabrication, and measurement of a novel femto-liter droplet ejector comprising the shear-mode PZT actuator and the vibration plate with the feature of a bulge diaphragm.

2. Design

The present microdroplet ejector has a novel actuating design by a shear mode bulk PZT actuator prepared by poling the PZT powder compact that had been sintered and polished. The PZT powder (PCM55) is commercially available from PIEZO-CERAM Company [12]. Fig. 1 shows the schematic drawing of a proposed microdroplet ejector. It comprises a vibration plate, a channel plate and a nozzle plate in addition to the PZT actuator. Those nickel-made components were assembled to complete the ejector by gluing. The vibration plate has a two-level structure including the diaphragm and on which a bulge piled up. The thickness of the bulge is 60 μm, and the thickness of the diaphragm is less than 7 μm. The shear mode PZT actuator was glued on and suspended between the bulge and the surface of the vibration plate. As an external field (normal to the poling direction) is applied to the actuator, the induced shear effect makes the deflection of the diaphragm through the rigid bulge. This design can enlarge the volume sweep of the diaphragm, and in turn produce a higher pressure (i.e. a stronger ejecting force) in the chamber for expelling liquid droplets through the orifice. The advantage of this actuating mode is its larger actuating force due to the highest shear piezoelectric coefficient, d_{15}, among the piezoelectric coefficients. Moreover, because the size of the actuator is not restricted to the dimensions of the diaphragm on the pressure chamber, it is much easier to assemble the actuator to the vibration plate compared to the conventional design of the push or bend design.

3. Nickel components

The three quasi-3D components in the microdroplet ejector were fabricated by the multilevel electroforming technology. Referring to Fig. 1, the channel plate, vibration plate and nozzle plate were all electroformed with two-level structure. The polished stainless steel was adopted as a substrate for developing components. The AZ9260 series positive tone photoresist was used as electroforming moulds, and nickel was the electroforming material. Two repeated steps including the mould patterning and the nickel electroforming were the main processes to construct levels of the component. Firstly, the substrate was patterned with photoresist as a mould. Secondly, the electroforming was performed by depositing nickel in the opening of the photoresist mould. The photoresist mould for each level cannot be removed until finishing the final level. After removing the mould by acetone, the electroformed components on substrate can be easily taken off due to the medium adhesion. The photoresist was coated on the stainless-steel substrate by spin coater with both spreading step and thinning step. The photoresist

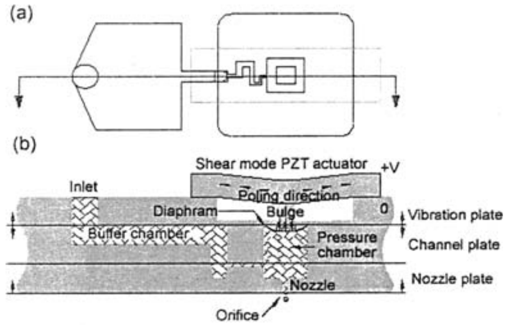
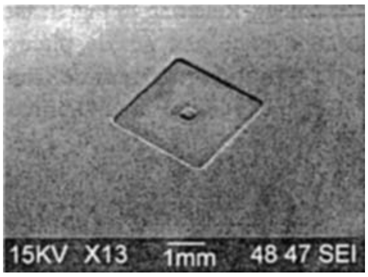
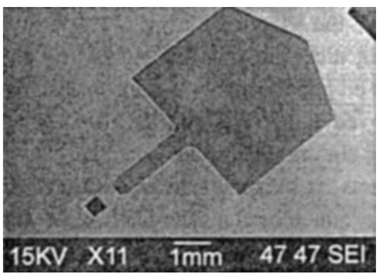


Fig. 1. Schematic diagram of proposed microdroplet ejector.

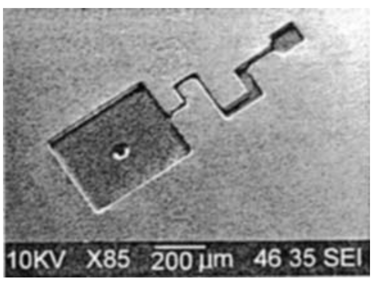
on substrate was baked on a hot plate or in an oven, and then exposed by a stand UV mask aligner (Karl Suess MA-6). The UV exposure process was performed under the hard contact mode with the intensity of 6 mW/cm^2 and the wavelength of 365 nm. Subsequently, the exposed photoresist was developed in an immersion process by using AZ400K diluted developer. The structure of components was further observed and checked by SEM (JEOL JSM-6360). Fig. 2 reveals the SEM photographs of the vibration plate, the channel plate, and the nozzle plate with the two-level structure. For the vibration plate, the bottom level was the diaphragm on which the bulge was placed. The channel plate consists of the buffer chamber and the pressure chamber. For the nozzle plate, the first level was constructed with the nozzle structure; whereas the second-level was fabricated to form the front part of the pressure chamber and the inlet channel connecting to the buffer chamber.



(a)



(b)



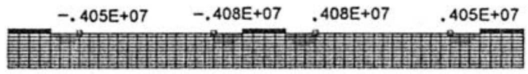
(c)

Fig. 2. SEM photographs of (a) vibration plate; (b) channel plate; (c) nozzle plate with two-level structure.

4. Piezoelectric actuator

4.1 Poling analysis

To provide uniform and adequate remnant pol-

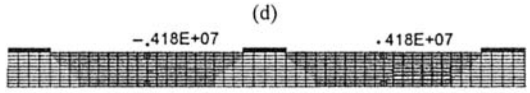


(a)

(b)

(c)

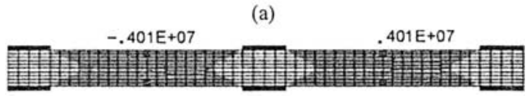
(d)



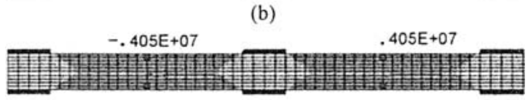
(e)

Fig. 3. A succession of contour plots of the fully poled region in single-surface poling design at various poling voltages of (a) 6000 V, (b) 6200 V, (c) 6218 V, (d) 6250 V and (e) 6500 V (the values shown indicate the Ex there in V/m).

(a)



(b)



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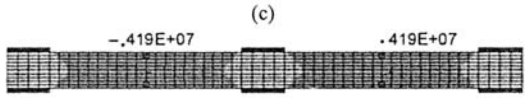
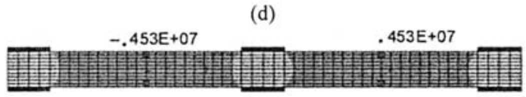


(d)



(e)

Fig. 4. A succession of contour plots of the fully poled region in dual-surfaces poling design with increasing poling voltages of (a) 5700 V, (b) 5750 V, (c) 5800 V, (d) 6000 V and (e) 6500 V (the values shown indicate the Ex there in V/m).

arization of the shear mode PZT actuator, the electrode design and the poling electric field should be thoroughly analyzed. In this study, the well-known FEM software ANSYS was utilized to analyze the poling field distribution under the poling process. For observing the development of completely poled region with the increase of the poling voltage, Fig. 3 shows a succession of the contour plots of the fully poled region in the 250-μm thickness sample by the *single-surface poling design*, which appears at the poling voltages of 6000 V, 6200 V, 6218 V, 6250 V and 6500 V, respectively. For the *dual-surfaces poling design*, Fig. 4 also displays a succession of the contour plots of fully poled region with the enlargement of the poling voltages including 5700 V, 5750 V, 5800 V, 6000 V and 6500 V, respectively. From the analysis, it can be evidently observed that the present *dual-surfaces poling design* has the advantage of applying lower poling voltages to achieve the same extent of remnant polarization with the *single-surface poling design*.

4.2 Sample Preparation

The ferroelectric PZT disc for the shear mode actuator was prepared using the commercially available PZT powder (PIEZOCERAM Company) through the dry powder pressing technique. This type (PCM55) of soft PZT powder is widely used to formulate actuators because of its high electromechanical coupling coefficient [12]. Before compacting, the powder had been heated in an oven at 120 ℃ for more than 4 hours to remove the moisture. The powder mixture was placed into a die and compacted by applying a uniaxial pressure of 90 MPa to produce powder compact. Next, the powder compact was put into a furnace with an oxygen environment heating to remove its polymer binder. It was then placed in a closed alumina crucible, in which the green compact was embedded in coarse ZrO_2 powders and surrounded by the PZT powder as a PbO atmospheric buffer. The sintering process was performed in a tube furnace under a quiescent air atmosphere by a heating rate of 90 ℃/min to the peak temperatures of 1250 ℃ for maintaining times of 3 hours, which followed by cooling rate of 90 ℃/min to intermediate temperature of 780 ℃ for holding around 20 minutes, and then cooling to the room temperature. The original dimensions of the

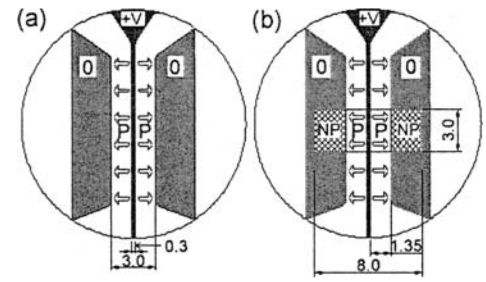


Fig. 5. Ferroelectric PZT disc (a) poling electrode pattern (b) shear mode PZT plate-shaped actuator diced from poled PZT disc (dimension in mm).

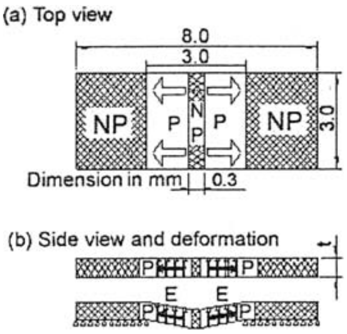


Fig. 6. Schematic of actuator for droplet ejection (a) dicing pattern (b) shear-mode deformation (dimension in mm).

green compact, 20 mm in diameter and 1 mm in thickness, was shrunk by 15 % after sintering. Then it was thinned to 250 μm in thickness by polishing. The poling electrodes were patterned by the screen-printing technique by using the silver paste and the pattern as shown in Fig. 5(a). After the PZT disc was poled, it was diced to form the shear mode actuator shaped like the rectangular plate with the dimensions of 8×3 mm. As depicted in Fig. 5(b), some regions including middle or outer non-poled zones (NP) and two poled zones (P) were defined. Two poled zones separated by the middle non-poled zone have symmetrical and opposite polarization directions parallel to the plane of the plate. Fig. 6 presents the schematic diagram illustrating the dicing pattern and the shear-mode deformation of actuator for droplet ejection. When the actuating electrodes is attached to the top and bottom surfaces of the plate actuator, the actuating electric field (E) perpendicular to the polarization direction (P) can lead to shear deformation and out-of-plane displacement under the actuation state.

5. Assembly

After electroforming all levels of the components for the ejector, a SEM (JEOL JSM-6360) was used to inspect and examine structure integrity of components. The epoxy adhesive (CIBA-GEIGY, AV 119) was applied on the attached surfaces by screen printing, and three components with aligned marks were assembled by a CCD aligning system. First, the channel plate was attached to the nozzle plate. The vibration plate was then appended to complete the three-layered droplet ejector. After that, the adhesive was cured in the oven kept at 110 °C for 2 hours. Next, the PZT actuator was attached by another epoxy adhesive (3M, DP-460) cured at 60 °C to evade from depolarization. Finally, the microdroplet ejector module was placed into housing by the same epoxy adhesive (3M, DP-460) for attaining a prototype of the ejector, as shown in Fig. 7.

6. Pzt actuator performance

Fig. 8 shows the schematic of experimental apparatus for measuring the actuated displacements. The middle displacement of the actuator was measured using the laser vibrometer system (Polytec MSV300). Fig. 9 illustrates the schematic of the test fixture of displacement measurement for the PZT actuator. The nickel substrate with 3-mm wide trench was utilized as the testing fixture to measure the displacement. During the test, the actuator was placed over the trench in the span-wise direction with both edges attached to the substrate firmly. The actuator was driven by the AC voltage at the frequencies of 1, 3 and 5 kHz, which were much less than its resonant frequency. Each data point was the mean value from the measured records of three to five samples with the deviations below 5 %. The middle maximum displacement (W_c) was obtained as well as the shear piezoelectric coefficient (d_{15}) was further computed by the equation, $W_c = d_{15}L(V/t)$. Fig. 10 shows the calculated shear piezoelectric coefficients with respect to the actuating field at three different actuating frequencies. It is observed that raising the frequency tends to lower the d_{15} value. And the d_{15} value does not keep constant at certain frequency. It increases linearly with the increasing actuating field. Two segments with linear regression function are obtained in each curve. Between two segments, a threshold field exists above which the d_{15} value is highly improved. In order to evaluate the transient response of the shear mode actuator, the waveform (exhibited in Fig. 11) was adopted to drive the actuator. Both the resulting displacement and the velocity responses measured at middle point were acquired and compared with the ANSYS simulation, as demonstrated in Figs.11(a) and (b). The displacement and velocity responses initially follow the driving waveform and oscillate in a convergent manner with a natural frequency afterward. In general, the simulations agreed reasonably well with the measured profiles.

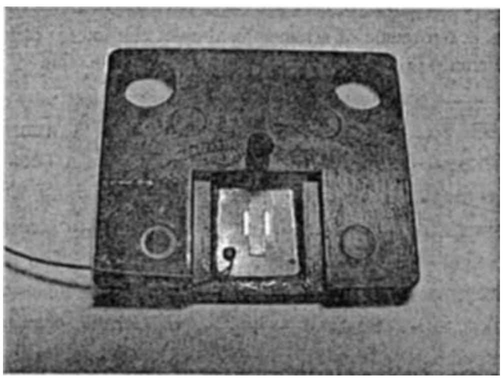


Fig. 7. Magnified photograph of prototype of microdroplet ejector.

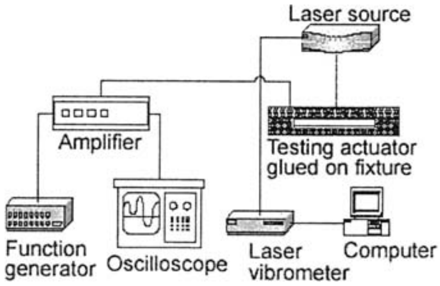


Fig. 8. Schematic of experimental apparatus for measuring actuated displacements.

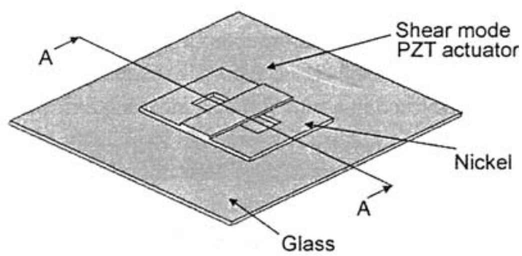


Fig. 9. Schematic of the testing fixture of displacement measurement for the PZT actuator.

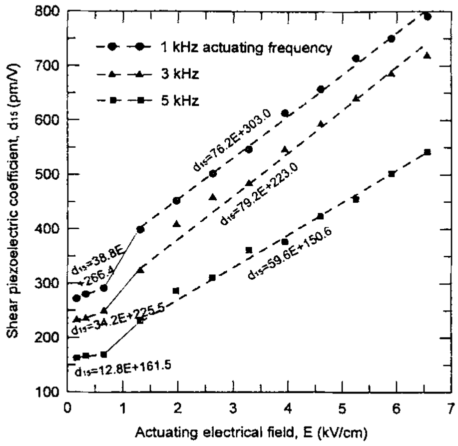
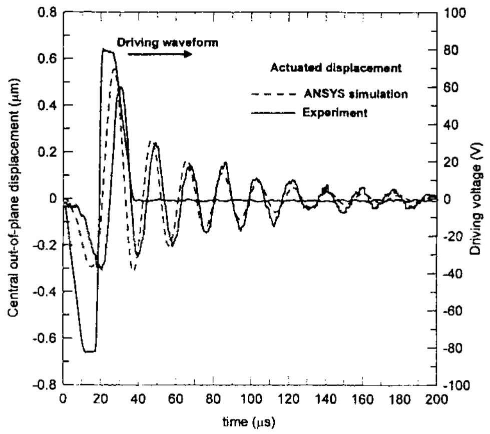
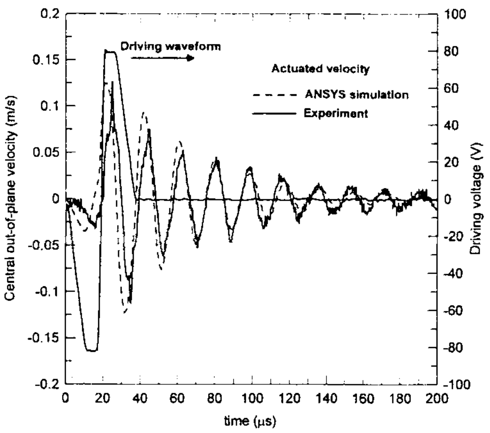


Fig. 10. Relationship of d_{15} and actuating electrical field.



(a)



(b)

Fig. 11. Comparison of experiment and simulation for the transient responses of the actuator under specific driving waveform (a) central displacement response, (b) central velocity response.

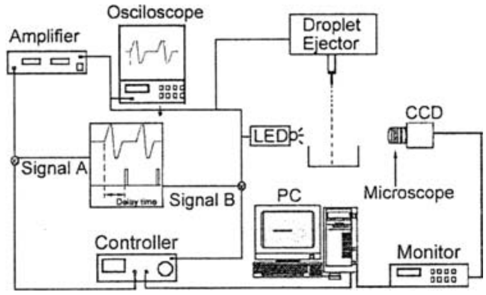


Fig. 12. Schematic of experimental system for visualizing droplet ejection.

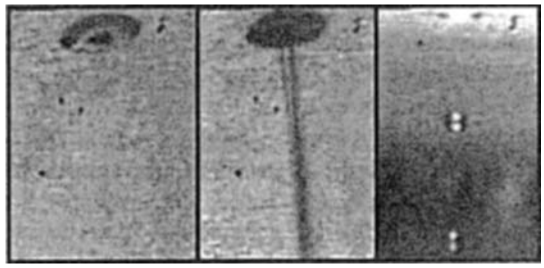


Fig. 13. Visualized micro-images of (a) nozzle; (b) ejecting liquid stream; and (c) 12-μm diameter droplet for one ejection cycle.

Fig. 12 presents the schematic of experimental system for visualizing droplet ejection. A light emitting diode (LED) was placed under the droplet ejector to illuminate the ejected droplets. Two signals, for driving the ejector with the voltage of 160 Vpp (signal A) and the LED (signal B), were synchronized with adjustable time delay. The images were recorded by the flash light from the LED at the specified delay time. Fig. 13 shows the visualized micro-images of (a) nozzle; (b) ejecting liquid stream; and (c) 12-μm diameter droplet for one ejection cycle. The diameter of the nozzle orifice was 15 μm. The observed images reveal that the proposed novel ejector can effectively achieve the droplet ejection process. In addition, the droplet volume was around 905 fL (femto-liter) with the diameter of 12 μm.

7. Conclusions

The present paper describes the design and assembly of components for a novel femto-liter droplet ejector actuated by a shear mode PZT actuator. The three quasi-3D components in the proposed ejector were successfully fabricated by the multilevel electroforming technology. Those components were further assembled by aligning system applying the epoxy glue by screen printing. Both poling designs, the *single-surface poling* and the *dual-surface poling*, were analyzed via the simulation of poling electric field. Numerical results indicate that the *dual-surfaces poling design* has the advantage of using lower poling voltages to achieve the same extent of remnant polarization with the *single-surface poling design*. The middle out-of-plane displacement and velocity responses of the shear mode PZT actuator was also examined by ANSYS simulations and measurements by the laser vibrometer system. By the driving voltage of 160 Vpp, the resulting volume displacement of the proposed novel ejector can well build a high chamber pressure for accomplishing the droplet ejection process. The liquid stream or droplet ejection was demonstrated by a visualization system. It was evidently observed that the droplet size was 12 μm in diameter; whereas the droplet volume was around 905 fL.

Acknowledgements

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