Large-Area Single-Crystal Actuator for Multifunctional Haptic Displays

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Abstract

Haptic interface is essential for improved user interaction with various displays by the sense of touch. However, current haptics in most displays provide limited tactile feedbacks due to their narrow operating frequencies. We present a multifunctional haptic display with a large-area single crystal actuator which allows more diverse user experiences with a broad range of frequencies. The haptic actuator composed of the single crystal leads to high vibrational performance originated from its superior electromechanical properties. Furthermore, the automotive "Smart Surface" organic light-emitting diode (OLED) display integrated with the actuator suggests a new direction for future interactive display applications.

Author Keywords

Haptic display; Piezoelectric; Single crystal; Multifunctional; OLED

1. Introduction

Haptic feedback meets recent demand of various display applications to enhance their immersive and interactive user experiences [1]. Especially, organic light-emitting diode (OLED) displays need smaller, thinner and lighter components with their improved design flexibilities compared to liquid crystal displays (LCDs) [2]. To address these needs, piezoelectric haptic actuators have been considered as potential alternatives to commercially widespread electromagnetic motors because the piezoelectric actuators do not require a thick and heavy permanent magnet. The piezoelectric actuators generate vibrational displacements caused by the mechanical strain from the power-efficient inverse piezoelectric effect upon applied voltages. Furthermore, they can offer a wide range of haptic experiences including audible sound and ultrasonic tactile response [3].

Representative piezoelectric properties (*e.g.*, piezoelectric coefficient (d_{33}), mechanical quality factor (Q_m)) of piezoelectric materials play a crucial role in the vibrational performance of the actuators [4]. As such, there have been tremendous attempts to improve the piezoelectric properties, for instance, compositional changes [5]. Single crystal piezoelectric materials such as $Pb(Mg_{1/3}Nb_{2/3})$-$PbTiO_3$ (PMN-PT) and $Pb(In_{1/2}Nb_{1/2})O_3$-$Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ (PIN-PMN-PT) are highly promising candidates due to excellent electromechanical properties compared to those of conventional polycrystalline piezoelectric ceramics [6]. Here, we present a piezoelectric actuator with a large-area single crystal film grown by Bridgman method, which has the high d_{33} and Q_m parameters for improved vibrational displacement outputs. We demonstrate the multifunctional performance of the haptic actuator induced by its broad operating frequencies (*i.e.*, from low to ultrasonic frequencies) with an OLED display panel. Furthermore, audible sound levels of the actuator were characterized with a monitor display mock-up model. Finally, we highlight the automotive "Smart Surface" OLED display integrated with the single crystal haptic actuator to show its promise as the multifunctional haptic display producing low frequency tactile haptic and audible sound performance for future interactive display applications.

2. Results and Discussion

Fig. 1(a) shows that a large-area single crystal thin film was successfully fabricated by Bridgman method and cut into a size of 60×60 mm^2. The thin film was designed with the PIN-PMN-PT composition for high thermal stability, and the size is the largest to maintain the compositional uniformity across the whole area. Fig. 1(b) clearly proves the excellent piezoelectric parameters of the fabricated single crystal thin film compared to commercially available piezoelectric ceramic films based on polycrystalline lead zirconate titanate (PZT). The d_{33} and Q_m parameters of the single crystal have ~2 times and ~15 times higher than those of the widely commercialized soft PZT (PZT-5H), respectively [7]. Particularly, the product of d_{33} and Q_m parameters of the single crystal film, which represents its vibrational performance, is significantly enhanced in comparison with the commercialized soft ceramic PZT-5H and hard ceramic PZT-8 [8]. It is evident that the vibrational performance of the single crystal is superior to that of polycrystalline piezoelectric materials. Additionally, the curie temperature (T_c) of the single crystal is competitive to the soft PZT, therefore, the thin film is thermally resistant for a wide variety of display applications.

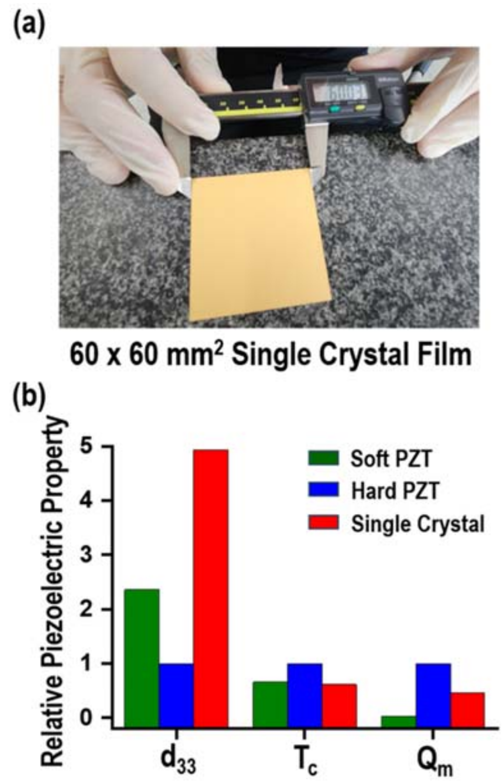

Figure 1. (a) A large-area single crystal thin film (60 x 60 mm^2) for a multifunctional haptic actuator. (b) Relative piezoelectric properties of the single crystal compared to commercialized soft PZT (PZT-5H) and hard PZT (PZT-8).

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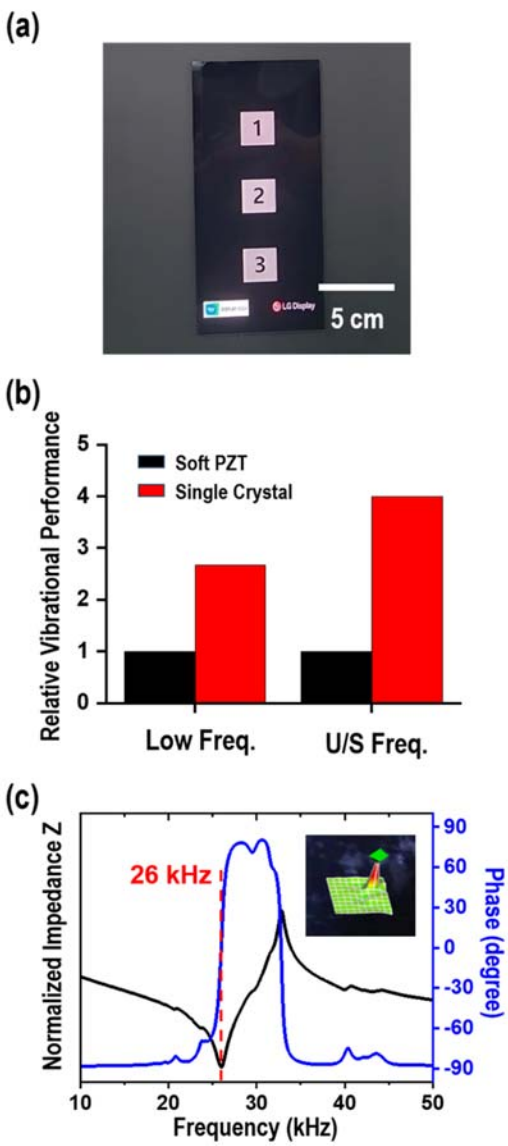

Figure 2. (a) A 7.2-inch OLED display panel to characterize the performance of the single crystal actuator. (b) Relative vibrational performance of the actuator compared to the soft PZT (PZT-5H) at low (130 Hz) and ultrasonic (26 kHz) frequencies. (c) Resonant frequency of the single crystal actuator applied to the OLED display panel, (Inset) ultrasonic vibrational displacements of the single crystal actuator.

Next, the multi-haptic performance of the actuator composed of the single crystal thin film was characterized with an application to an OLED display. As shown in Fig. 2(a), the 7.2-inch OLED display panel was used to evaluate the vibrational performance of the actuator. The vibrational outputs were obtained by the average values of 3 points (*i.e*., upper (1), middle (2), lower (3)) on the display panel. The vibrational displacements at a low frequency (130 Hz) and an ultrasonic frequency (26 kHz) were measured by an accelerometer using Ni-PlXe (National Instruments Co., Austin, TX, USA) and a scanning laser Doppler vibrometer (SLDV) (Optomet GmbH, Darmstadt, Germany), respectively. The high vibrational performance of the single crystal actuator was verified compared to the soft PZT (PZT-5H).

Fig. 2(b) presents the low frequency vibrational acceleration of the single crystal actuator has ~2.5 times higher than the value of the commercial soft PZT-based actuator. Furthermore, the ultrasonic displacement of the actuator is ~4 times higher than the soft PZT-based actuator. Fig. 2(c) is the resonant frequency of the single crystal actuator applied to the OLED display. The normalized electrical impedance data and phase angle spectrums of the single crystal-based actuator were obtained from the E4990A Keysight impedance analyzer (Keysight Technologies, Santa Rosa, CA, USA). The inset of Fig. 2(c) exhibits the ultrasonic vibrational displacements of the actuator. Especially, the ultrasonic vibrational performance cannot be achieved by the commercial magnet-based motors (*e.g*., voice coil motors) due to their limited operating frequencies. As such, this clearly proves the single crystal actuator has a promising potential for the multifunctional haptic display which can generate vibrational outputs in a wide range of frequencies.

Additionally, sound pressure level (SPL) of the single crystal actuator was characterized for speaker applications operated in audible frequencies (*i.e*., 100 ~ 20,000 Hz). We demonstrate a monitor display mock-up to evaluate the SPL of single crystal actuators (Fig. 3(a)). Two actuators with the size of 60×60 mm^2 were attached to the back of the display mock-up. The SPL of the actuators was characterized by the APx525 audio analyzer (Audio Precision, Beaverton, OR, USA). It is obvious that the single crystal actuators generate sufficient sound level which is relatively higher than the reference of the normal conversation sound (*i.e*., 60 dB) [9] (Fig. 3(b)). As such, the single crystal-based actuators can be applied to display applications as thin film speakers.

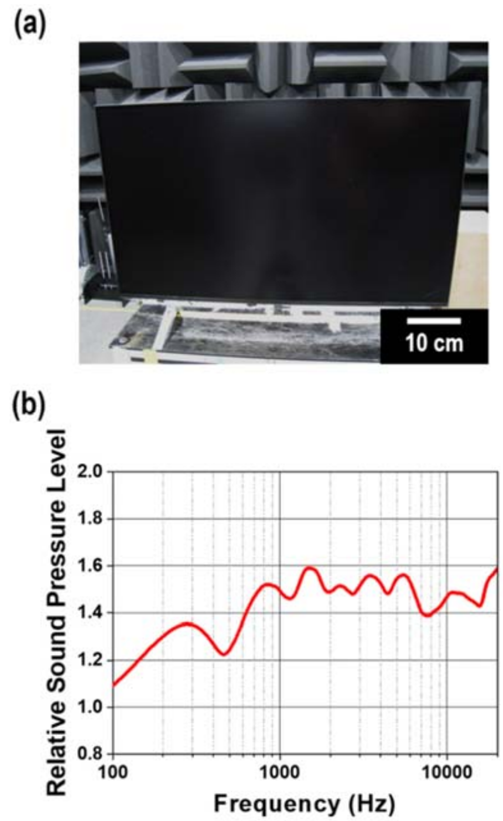

Figure 3. (a) A monitor display mock-up to evaluate the SPL of single crystal actuators. (b) Relative SPL of single crystal actuators integrated into the monitor display mock-up.

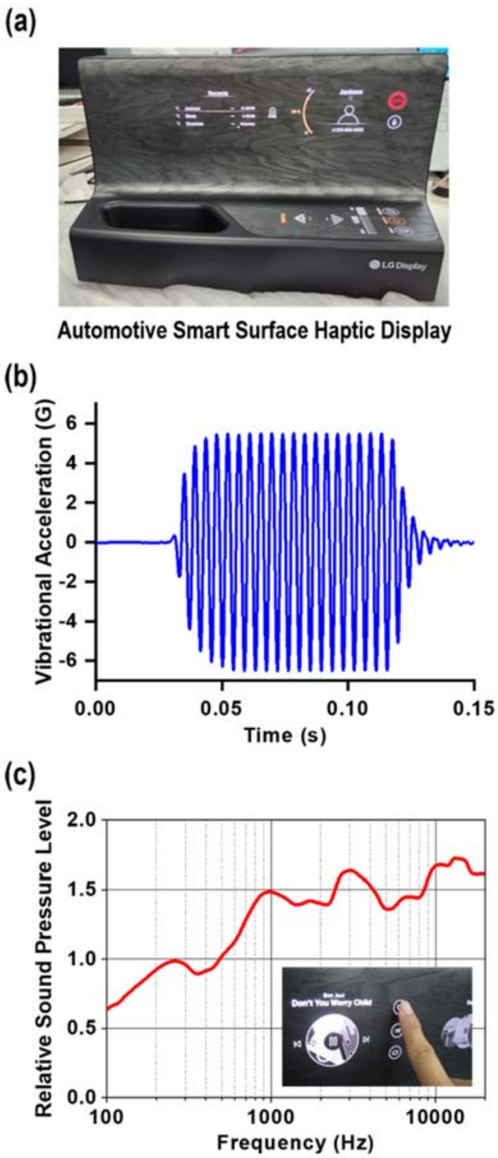

Figure 4. (a) "Smart Surface" haptic display integrated with the single crystal actuator. (b) Vibrational acceleration of the actuator. (c) Relative SPL of the single crystal actuator, (inset) representative user interface of the haptic display.

Finally, we introduce the "Smart Surface" haptic display integrated with the single crystal actuator for automotive applications. Recently, the smart interactive surfaces called "Shy Tech" with displays have attracted growing attention as a new trend with seamless integration of user interfaces into the interior surfaces of vehicles [10]. The combination of decorative elements and actuator technologies could open up the new possibilities for future automotive haptic displays allowing for diverse and immersive experiences. The smart surface haptic display was designed for automotive applications (Fig. 4(a)). The decorative seamless film with wood texture and color was applied to the OLED display with the single crystal haptic actuator. Fig. 4(b) demonstrates the vibrational acceleration of the actuator operated at a low frequency (130 Hz). It is clear that the vibrational performance is significantly high with fast response. Both the 10 % to 90 % rise time and the 90 % to 10 % fall time of the single crystal actuator are shorter than 10 ms in the vibrational acceleration. Additionally, the single crystal actuator can produce sufficient sound level compared to the reference sound level (*i.e.*, 60 dB) for the speaker function in the smart surface haptic display (Fig. 4(c)). The inset of Fig. 4(c) is an example of user interface of the smart surface display.

3. Conclusion

We developed the high performance piezoelectric actuator based on a large-area single crystal film for multifunctional haptic display applications. The vibrational performance of the single crystal actuator in a broad range of operating frequencies is superior to the conventional polycrystalline PZT ceramics. Obviously, the multifunctional properties and miniaturization cannot be achieved by the commercial magnet-based motors because of their limited operating frequency and thickness. The vibrational outputs at a low frequency and an ultrasonic frequency are considerably improved compared to those of the commercial soft PZT-based actuators. Furthermore, the actuator can generate sufficient sound level as the speaker function for thin display applications. The promise of the actuator was clearly demonstrated as a multifunctional haptic component in the automotive smart surface haptic display. We believe the single crystal actuator can be one of the potential candidates for multifunctional interactive haptic displays.

4. Acknowledgements

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