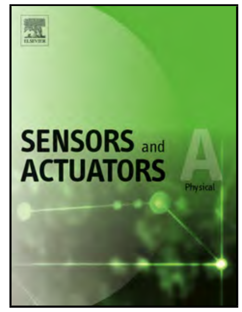

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Self-powered Flexible Touch Sensors based on PZT Thin Films using Laser Lift-Off

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Research Highlights

- PZT based Self-powered flexible touch sensors are fabricated using the laser lift-off technology.
- Flexible piezoelectric touch sensors can be applied to detect the specific touch position and distingush between touch-induced and bending induced signals via signal position, signal shape, and duration.
- The developed flexible piezoelectric touch sensors may be fabricated in high resolution, with suitable fabrication techniques.

Abstract

Touch screens have become an inherent part of the user interface in many electronics applications such as smartphones. The two types of developed touch sensors, the resistive and capacitive sensing devices, may face several difficulties when applied to flexible device applications such as touch signals arising from bending motions. In this study, we assess the feasibility of flexible touch sensors based on piezoelectric $PbZr_{0.52}Ti_{0.48}O_3$ (PZT) thin films. Piezoelectric ceramic based flexible touch sensors possess unique advantages including scalable fabrication, fast response time, durability, and being self-powered. A demonstration device has been fabricated with a sandwich structure consisting of Pt electrode/functional PZT/Pt electrode/flexible substrate structure using laser lift-off (LLO) method. In order to anneal the functional PZT layer at high temperature (600 degree Celsius), the device was first fabricated on the sapphire substrate and transferred via melting sacrificial PZT layer with an excimer laser. We demonstrate the detection of x- and y-axis touch location via piezoelectric materials and confirm that the flexible piezoelectric touch sensors can distinguish between touch-induced and bending-induced signals via signal location, signal shape, and duration time. A notable feature of this fabrication technique involves its possibility to be fabricated in high resolution. This device may potentially achieve high resolution with suitable fabrication techniques, thus, providing the possibility for the next generation touch sensors.

Keywords: Flexible piezoelectric touch sensors; Laser lift-off (LLO); PZT

1. Introduction

Flexible display, one that can be folded, wrapped and bent like a piece of paper, has received a significant amount of research attention.[1–5] Some key criteria for flexible displays include lightweight, thinness, toughness to fracture and rollability. Successful implementation of these qualities may provide electronics with yet-to-be-realized applications, such as electronic paper (e-paper) and next-generation smartphones. For such applications, an input device such as touch screen that possesses the same criteria as those mentioned above may also prove essential.

Currently, there are two types of touch sensors available for flat-screen electronics, the resistive and capacitive types. In resistive sensors, [6] sensing elements are realized by the resistive-metal-based mechanism. When the surface is pressed, two different metallic layers make contact due to the strain applied by the touch and make an electric connection between the two layers at the location of the touch. Since the method relies on mechanical contact between two metallic layers, the tracking resolution is limited and device lifetime is short. Capacitive sensors consist of a dielectric material inserted between electrode layers, and an alternating voltage is applied to both electrodes. [7,8] Bringing a finger close to the surface changes the local electrostatic field near the touch location and the capacitance change on the grid can be measured to determine the touch location. Since the dielectric response is measured, the device does not operate when the local electrostatic field is interrupted by other media at the surface, such as a dust particle or water bubble on the surface. For the same reason, only specific materials can be used as a stylus. It is noted that both resistive and capacitive methods can only measure the contact location without the information on the amount of pressure applied. [9]

While the two methods serve as key technologies for modern electronics such as smartphones, these techniques have technical difficulties to be applied in flexible devices. Flexible touch sensors may undergo frequent bending as well as touch and it is crucial to distinguish between the bending and multi-touch motions. For instance, in resistive types, bending may result in signals at untouched regions because the two metallic layers may contact each other during bending. In capacitive type, a clear distinction between touching and bending may be difficult to incorporate, for the touch sensor may not distinguish between bending-induced electrostatic field change and touch-induced field change.

One potential candidate for the next-generation touch sensors is based on piezoelectric materials. [9–11] Piezoelectric materials generate voltage signals proportional to the amount of pressure applied to the material. The technology would, therefore, be unaffected by foreign substances on the surface including dust and water bubbles. Other advantages include its demonstrated ability to sense complex deformations and potential high-resolution application. The duration of touch can be estimated since removing the stress generates a negative peak. The time interval between a positive and the following negative peak, therefore, indicates the duration of a touch. Building a touch sensor based on piezoelectric materials may potentially overcome the malfunction during bending, since the device may distinguish between the signals during touching and bending. Specifically, touching a specific location is expected to generate sharp and frequent signals, while bending generates relatively weak and broad signals from the continuous strain. The duration of bending is also expected to be larger than that of touching. The relatively easy fabrication in large area, durability, and fast touch response time serve as other potential advantages. The sensors may serve as active sensors because the signals can be self-generated without external energy input from energy harvesters and batteries. [12]

The research effort on flexible piezoelectric devices largely focused on piezoelectric polymers due to their inherent flexibility and durability. [11] However, piezoelectric-polymer based touch sensors exhibit low touch sensitivity due to the low piezoelectric constant (d_{33}) of available piezoelectric polymers such as PVDF-TrFe (13~19 pC/N). [13] Ceramic piezoelectric materials such as $PbZr_xTi_{1-x}O_3$ have a d_{33} value of approximately 400 pC/N [14] and thus, high touch sensitivity can be obtained. It is noted that the piezoelectric output voltage is proportional to the amount of force with piezoelectric coefficient as the proportionality constant:

$$V = \frac{F \cdot d_{33} \cdot T}{W \cdot L}$$

where V stands for the output voltage, F the pressure force, d_{33} the piezoelectric coefficient, T the thickness of the piezoelectric layer, W the width, and L the length of the piezoelectric layer.

[21] However, the high piezoelectric constant of PZT is achieved only when the material is annealed above 600℃ because high crystallinity is required for strong piezoelectric effect. This processing temperature is higher than the melting point of most flexible substrate materials such as PTFE (260℃), PVDF (40-120℃), ETFE (50-150℃), or Polyimide (350℃). Thus, an efficient methods to transfer high-temperature annealed ceramics onto flexible substrates such as wet etching or laser lift-off (LLO) are essential. [15,16]

In this study, we assess the feasibility of flexible piezoelectric touch sensors based on $PbZr_{0.52}Ti_{0.48}O_3$ thin films, fabricated via laser lift-off method. We first demonstrate that the ferroelectric properties of PZT do not change during laser lift-off and transfer onto PI substrate. We then show the touch sensing properties of PZT thin films on both rigid sapphire and PI substrate. We finally demonstrate that piezoelectric based touch sensors can distinguish between touching and bending signals via their peak duration and amplitude. Based on these results, we argue that piezoelectric ceramic thin films can be a competitive material choice for flexible touch sensors and discuss potential directions for successful implementation into real life applications.

2. Experimental

2.1. PZT device fabrication on sapphire substrate

Fig. 1 shows a schematic for the fabrication process of the devices. First, the sacrificial $PbZr_{0.52}Ti_{0.48}O_3$ (52/48) thin films of 200 nm were deposited using by reactive RF-sputtering on double-side polished R-plane sapphire substrates. This layer prevents any damage that may arrive from laser damage to the functional PZT layer (52/48). [17,18] $PbZr_{0.52}Ti_{0.48}O_3$ +PbO (10 wt % excess) sputtering target was synthesized using the bulk process. The sacrificial PZT thin films were annealed using rapid thermal annealing (RTA) process at 650℃ in the O_2 atmosphere for 10 min. The horizontal Pt patterns of 1 mm width and 3 mm gap were deposited on sacrificial PZT/sapphire using DC sputtering. After patterning the electrodes, the functional PZT (52/48) layer of 800 nm thickness was deposited using reactive RF sputtering. The thin films were annealed using RTA for 10 min at 650℃ in the O_2 atmosphere. The vertical Pt electrode patterns with 100 nm thickness were deposited on top. The electrodes on top and bottom form a mesh-like structure so that we may specify x- and y-axis positions of a touch signal. The sacrificial PZT and Functional PZT thin films deposition conditions were different as shown Table 1.

2.2. Laser lift-off onto flexible substrate

For the lift-off process, we placed the flexible Polyimide (PI) substrate on top of the device using polyimide epoxy. A KrF excimer laser pulse (λ=248 nm and energy density=350 mJ/cm^2) was shone on the backside of the sapphire substrate. At the laser radiation, the temperature at the interface between the sacrificial PZT thin film and sapphire substrate rises rapidly and melts the interface. The multilayered Pt/functional PZT/Pt/Ti/sacrificial PZT device was then transferred to PI substrate. The functional PZT thin film was poled at 100℃ and 100 kV/cm for 2h for a sufficiently strong piezoelectric response. (Premier Ⅱ, Radiant) A poling process with the heating is reported to be effective in obtaining the strong piezoelectric effect. [19,20]

2.3. Structural and electrical characterization

To identify the crystallinity of the functional PZT thin films, we carried out the X-ray diffraction (Rint/Dmax 2500, Rigaku Co., Japan) analysis for a PZT thin film deposited on sapphire and PI substrate (before and after LLO). XRD analysis was performed with the 2θ scan ranging between 20° and 60° with the CuKα X-ray. A field emission scanning electron microscopy (FE-SEM, FEI, and Inspect F50) was used to observe the surface and measure the thickness of functional PZT thin films on a sapphire substrate and surface of the functional PZT thin films on PI substrate (after LLO). Ferroelectric properties of the functional PZT thin films before and after laser lift-off were measured using ferroelectric tester (Premier Ⅱ, Radiant). The P-E loop of the functional PZT thin films was collected via AC bias sweep from -60 kV/cm to 60 kV/cm.

2.4. Bending and touching output signals analysis

The touch output signals from the piezoelectric touch sensor were measured before and after laser lift-off. For the sapphire substrate based device, the functional PZT thin film was poled under the same condition. After the laser lift-off, bending and touching output signals were measured using an oscilloscope (Tektronix, DPO4014B). A touch force using a pen is applied to the touch sensors. The touch force is measured to be approximately 0.25 N using a force meter (Imada DPS-110). The value and shape of the output signals were analyzed, in order to assess the potential distinction between the touching and bending signals.

3. Results and discussion

Fig. 2 illustrate the surface morphology, cross-sectional image, X-ray diffraction peaks and the PE loop measurement of the functional PZT layer. The deposition conditions for sacrificial PZT and functional PZT thin films were shown in Table 1. It was confirmed from the SEM images that the functional PZT thin films were well crystallized and had 800 nm thickness. The XRD patterns in Fig. 2c exhibit strong crystallinity of the transferred PZT film on PI substrate using LLO. The diffraction peaks could be indexed with a tetragonal phase of $PbZr_{0.52}Ti_{0.48}O_3$ with lattice constants $a = 4.036$ Å, $b = 4.036$ Å, $c = 4.146$ Å (JCPDS Card No. 33-0784).

The ferroelectric properties of the functional PZT thin films were characterized. Fig. 2d illustrates the Polarization-Electric curve hysteresis loop for the functional PZT layer before and after laser lift-off (LLO). The functional PZT thin film on a rigid substrate and that on PI substrate have approximately identical hysteresis curve. The film on rigid substrate has a saturation polarization (P_{sa}) of $53.25\ \mu C/cm^2$ and a remnant polarization (P_r) of the $22.5\ \mu C/cm^2$, while that on flexible substrate after LLO possess the saturation polarization (P_{sa}) of $52.6\ \mu C/cm^2$ and a remnant polarization (P_r) of the $21.2\ \mu C/cm^2$. The coercive field (E_c) of the films before and after LLO are both approximately 4.3 kV/cm. These results indicate that the ferroelectric properties of functional PZT layer do not get damaged during the LLO method.

Fig. 3 illustrate the response signals from the touch sensor when pressed gently by a pen. Fig. 3a and Fig. 3b depict the schematic and real pictures of the devices before and after LLO. Fig. 3c shows that output signal of the X1 point, which indicates the base noise information. The noise peak amplitude on X1 is 15.3 mV on average when the points nearby (X2 and X3) are pressed. The noise peaks on X2 and X3 reach up to 29.3 mV when the points nearby are pressed. Fig. 3d illustrates the touch sensing properties of the device on flexible substrates. The output signals of X1 indicate the base noise information with an average peak amplitude of 11.8 mV. When the X2 and X3 are touched with a pen, higher amplitude signals than those observed with rigid touch sensors are observed, with average peak amplitudes of 342.9 mV and 418.0 mV for X2 and X3, respectively. The noise peaks on X2 appear similar to those observed in X1 while the noise peaks on X3 appear higher than those observed in X2. This difference in touch peak amplitudes and noise peak amplitudes is understood in terms of electrode reliability.

As can be seen in the image of Fig. 3b, the electrodes undergo a level of degradation during laser lift-off, in terms of their structural integrity and adhesion to the substrate.

The increased pressure sensitivity on flexible substrate arises from the increased amount of strain applied at the touch location on the PZT layer. The touch signal-to-noise ratio improves by a factor of about 4.5 times at X2 point and ten times at X3 when using a flexible substrate. On rigid substrates, the strain is not localized to the touch location due to the rigid substrate. On flexible substrates, however, the strain is strongly localized to the touch location, increasing the touch sensitivity.

A crucial feature of this touch sensor is its capability to distinguish between voltage peaks arising from bending and touching. Fig. 4 illustrate the peaks arising from the two possible input sources. Bending the device generates small, yet clear peaks on all points affected by bending, as observed in Fig. 4a. The output signals from all points have approximately the same intensity and the same distance between positive and negative peaks. This is because the amount of strain applied to the points by bending is approximately identical. In many bending cases, this is true. Comparing the output signals in Fig. 3d and Fig. 4a, we find that the bending induced peaks involve multiple connected points in a line, with similar peak characteristics such as peak heights, peak widths and the distance between positive and negative peaks. Fig. 4b and 4c illustrate the zoomed-in view of the touch and bending signals. We find that the peak widths of touch signals are in general smaller than those of bending signals. The peak widths of the touch signals are approximately 0.05 seconds while those of bending signals is approximately 0.2 seconds. The reason for this difference may be due to the continuous bending motion as opposed to the fast, quick touch motion. Based on these characteristics, we can supposedly resolve between touching and bending peaks.

One additional feature involves the capability to identify the duration of a single touch. This, as mentioned briefly above, can be done via identifying the interval between the positive and negative peaks, since piezoelectric sensors always involve both peaks at the time of touch and release. We demonstrate this in Fig. 5. A positive pulse occurred at the onset of touch, and noise signals were generated when the duration of the touch. With the pen detached from the touch sensor, the negative releasing peak is observed.

A notable feature of this fabrication technique involves its possibility to be fabricated in high resolution. The limit in resolution comes either from the characteristic length scale of fundamental strain field of solid this films or the feature size of electrode patterns. This device may potentially achieve high resolution with suitable fabrication techniques, thus, providing the possibility for the next generation touch sensors.

4. Conclusion

In this study, we demonstrate and characterize a piezoelectric PZT based sensors. The PZT thin film has been transferred to flexible substrates via laser lift off after suitable high-temperature annealing process. We confirm that the P-E hysteresis of the PZT thin films remain identical before and after the laser lift off, indicating that the functional PZT active layer is undamaged during the laser lift-off. The touch sensing properties on flexible substrate improves meaningfully over that on a rigid substrate, and we demonstrate the sensing of the specific touch position. Through comparing the peak width, peak amplitudes and the distance between two peaks, we provide a guideline for distinguishing between peaks arising from bending and touching. The duration of a single touch can be identified by the distance between the positive and negative peaks. The developed flexible piezoelectric touch sensors may be fabricated in high resolution, with suitable fabrication techniques.

Acknowledgements

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Dr. Sangtae Kim received his Ph.D. from Department of Materials Science and Engineering at Massachusetts Institute of Technology in 2016. He is now a researcher at Korea Institute of Science and Technology (KIST). His research interest includes mechanical energy harvesting, electrochemical devices and actuators.

Dr. Do-Kyung Hwang received his Ph.D. degree in applied physics from Yonsei University, Korea (2008). From 2008 to 2009, he was a postdoctoral associate at Korea Institute of Science and Technology (KIST). From 2009 to 2012, he was a postdoctoral fellow at Georgia Institute of Science and Technology. He is currently a senior researcher in KIST. His current research interests include fundamental and applied aspects of organic/metal oxide semiconductors and low dimension nanostructured semiconductors based electronic/optoelectronic devices.

Dr. Chong-Yun Kang received his Ph.D. from the Department of Electrical Engineering of Yonsei University in 2000. Now he is a Principal Research Scientist in KIST from 2000 and a professor of KU-KIST Graduate School of Converging Science and Technology in Korea University from 2012. His research interests include smart materials and devices, especially, piezoelectric energy harvesting and actuators, electrocaloric effect materials, and nanostructured oxide semiconductor gas sensors.

Fig. 1. Schematic of the fabrication process for the flexible piezoelectric touch sensors based on PZT thin films

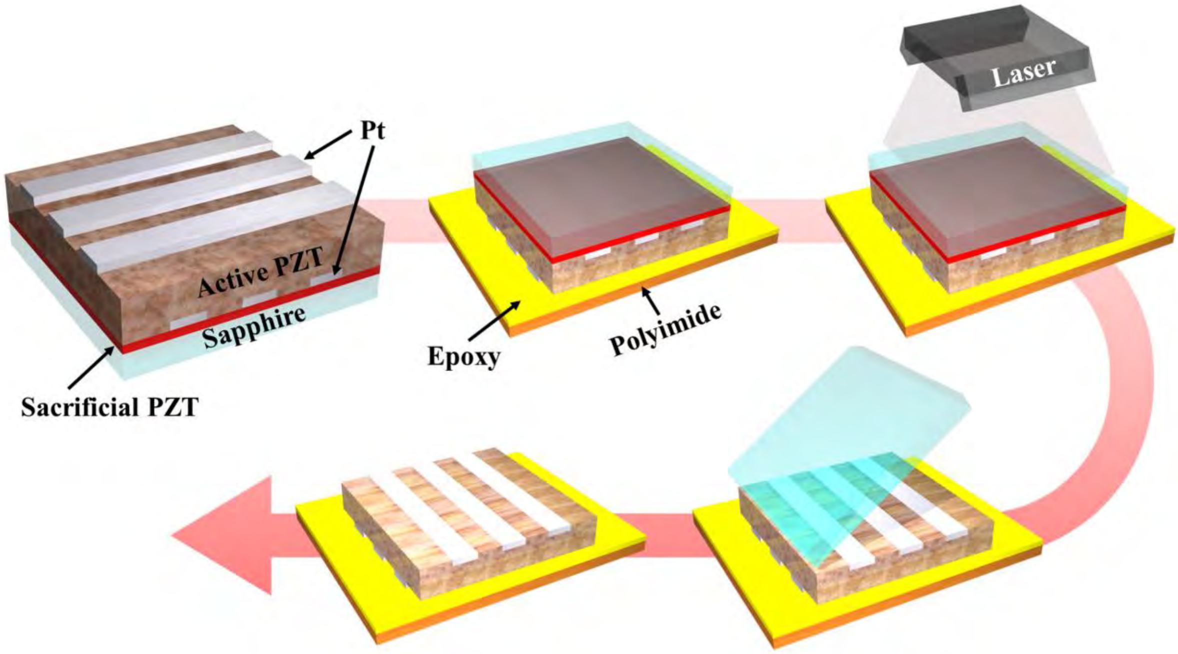
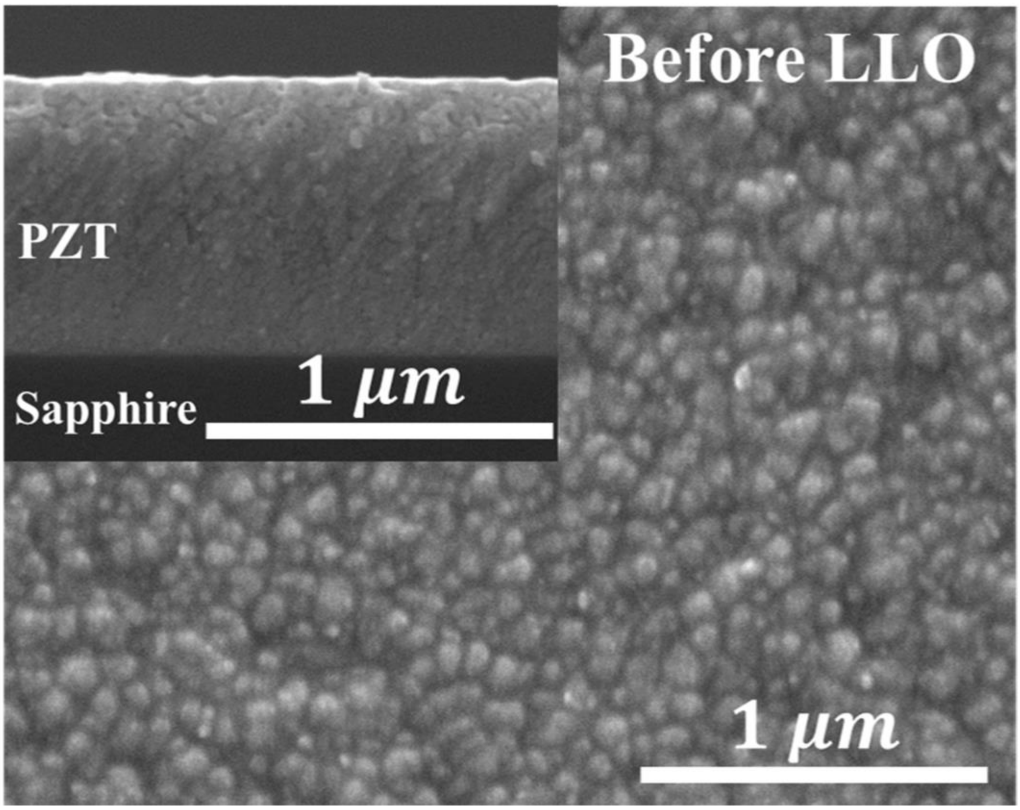
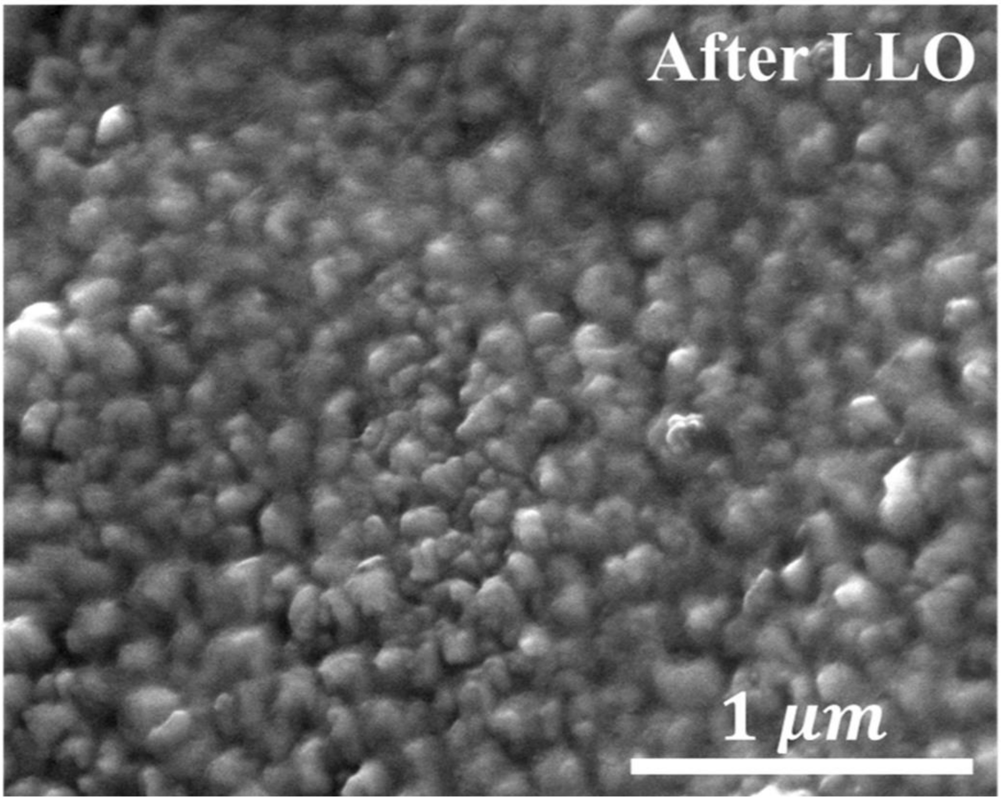


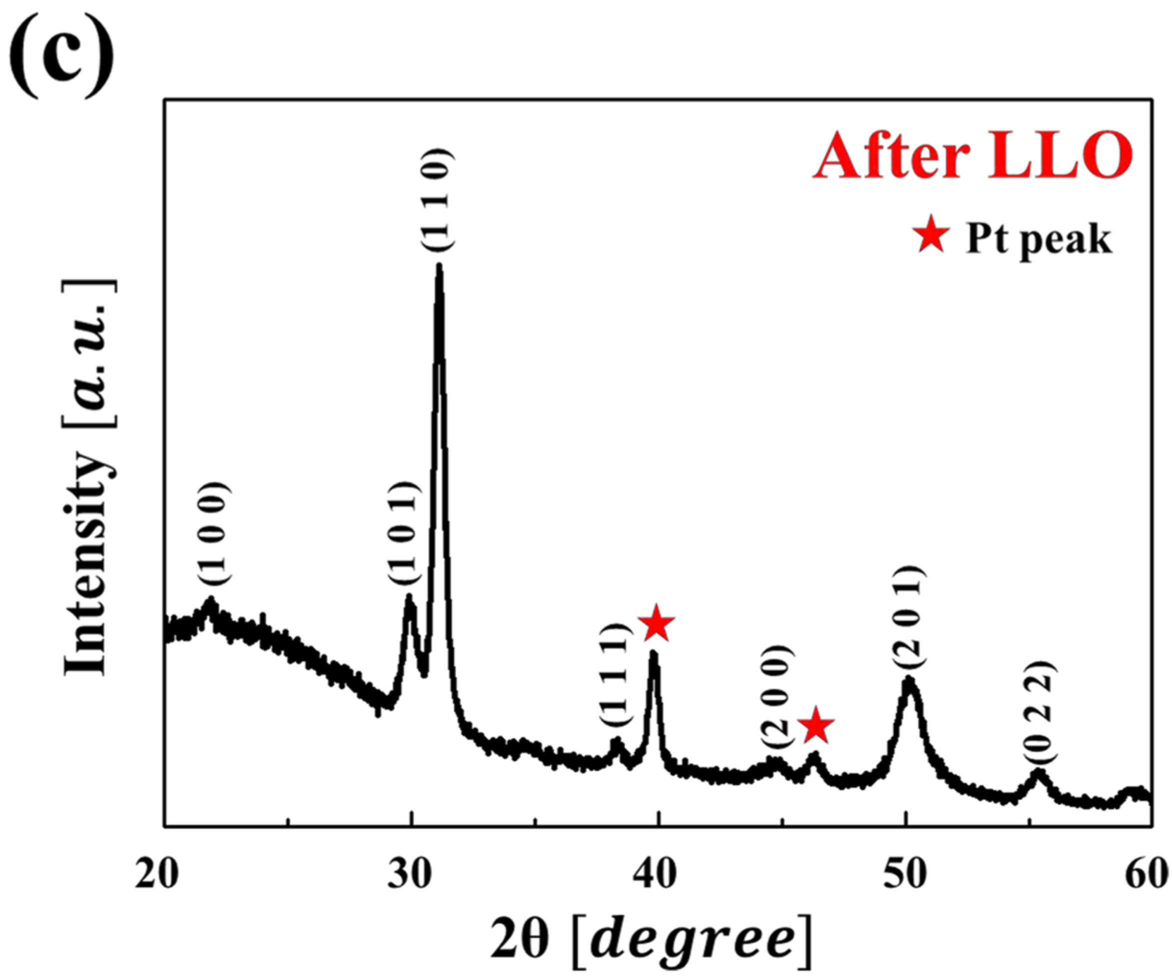
Fig. 2. (a) Top-view and cross-sectional (inset) SEM images of the functional PZT thin film on sapphire substrate (before laser lift-off) (b) Top-view SEM image of the functional PZT thin film on polyimide substrate (after laser lift-off) (c) XRD patterns of the functional PZT thin films after laser lift-off (d) Ferroelectric properties of the PZT thin films before and after laser lift-off.

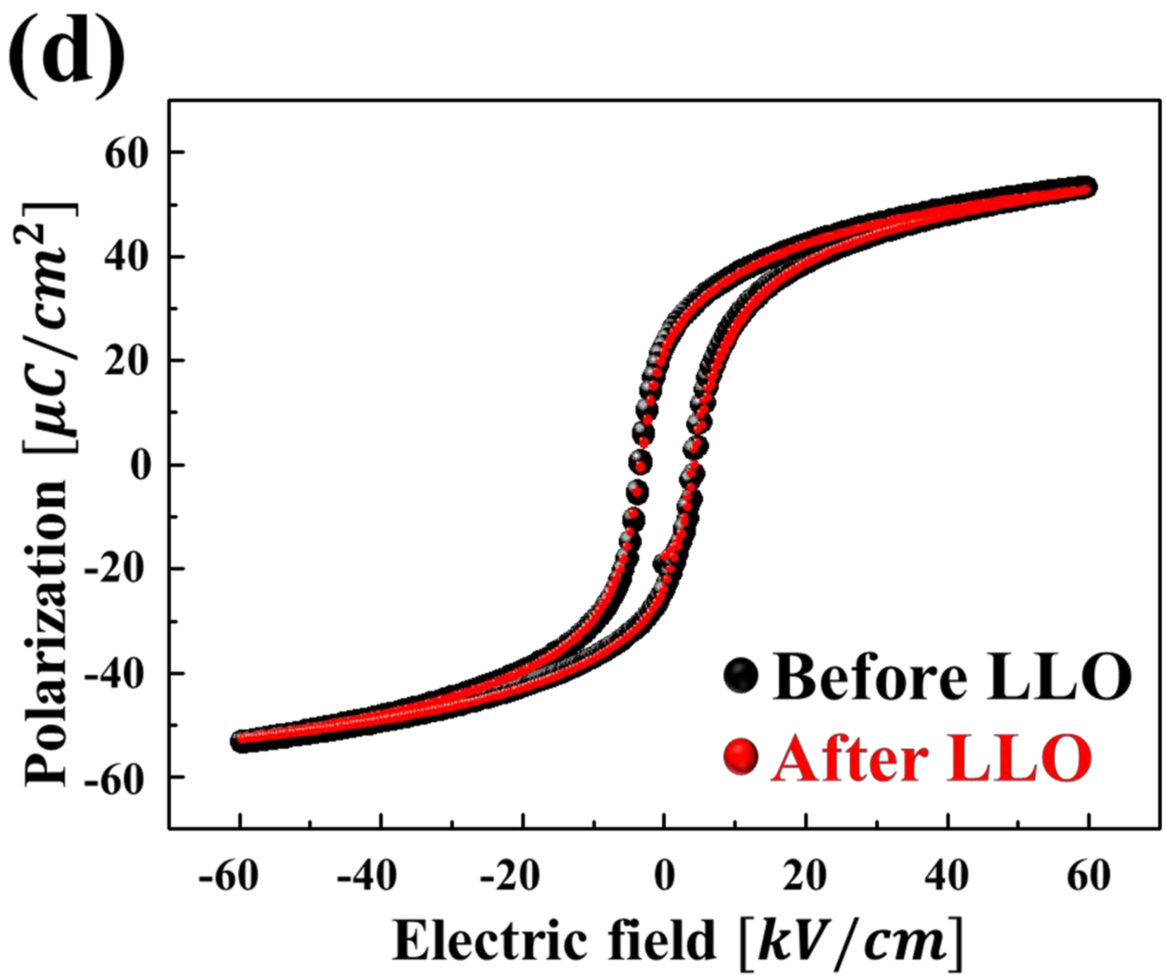
(a)



(b)

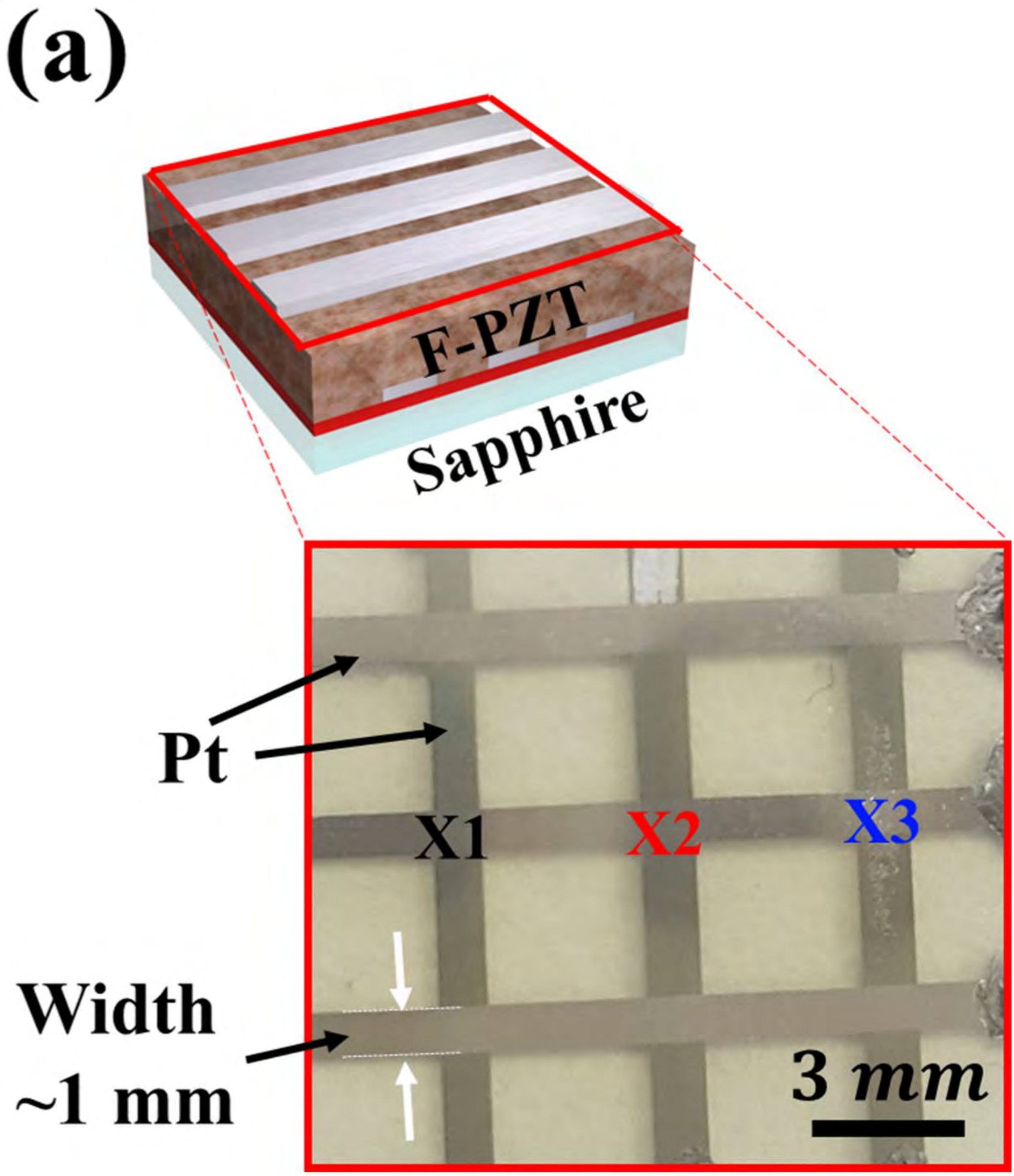


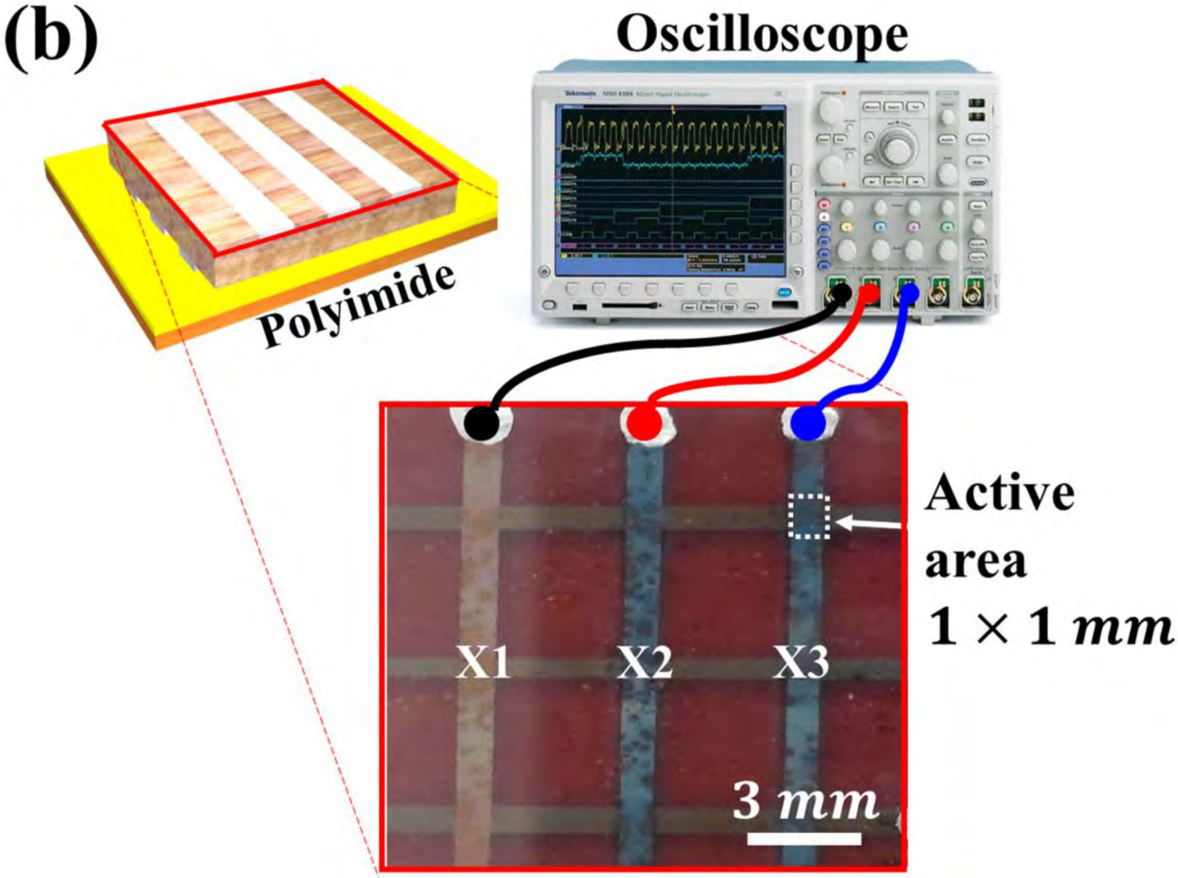

(c)
After LLO
★ Pt peak
Intensity [a.u.]
(1 0 0)
(1 0 1)
(1 1 0)
(1 1 1)
(2 0 0)
(2 0 1)
(0 2 2)
20
30
40
50
60
2θ [degree]

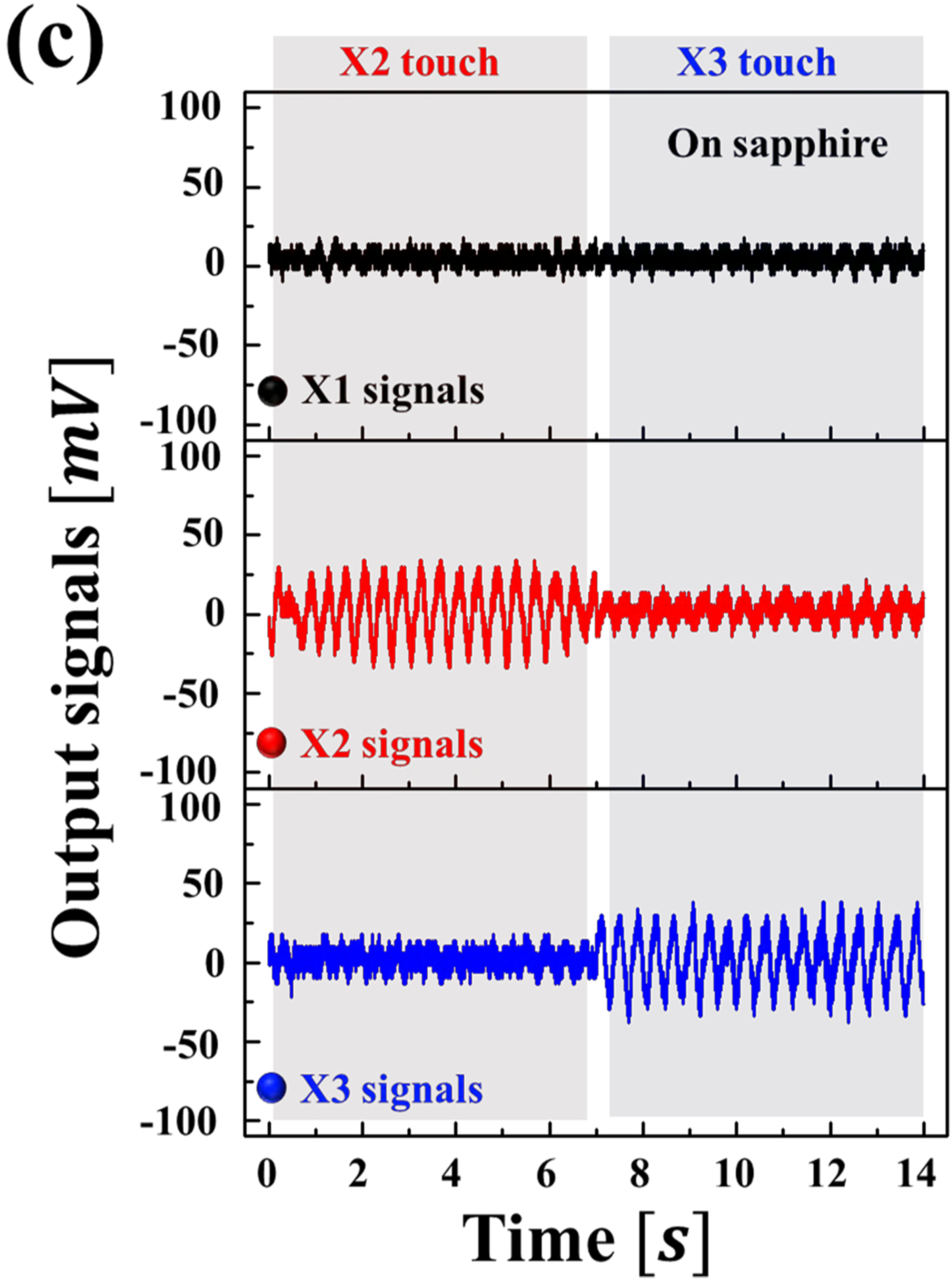


(d)
60
40
20
0
-20
-40
-60
Polarization [μC/cm²]
Before LLO
After LLO
-60
-40
-20
0
20
40
60
Electric field [kV/cm]

Fig. 3. Schematics and real device images of touch sensors (a) on rigid sapphire substrate and (b) on flexible polyimide substrate, connected to measurement system. Touch sensing properties of touch sensors on the rigid sapphire substrate and (d) on the flexible polyimide substrate




(b)
Oscilloscope
Polyimide
Active
area
1 × 1 mm
X1
X2
X3
3 mm


(c)
X2 touch
X3 touch
On sapphire
X1 signals
X2 signals
X3 signals
Output signals [mV]
Time [s]
100
50
0
-50
-100
0
2
4
6
8
10
12
14

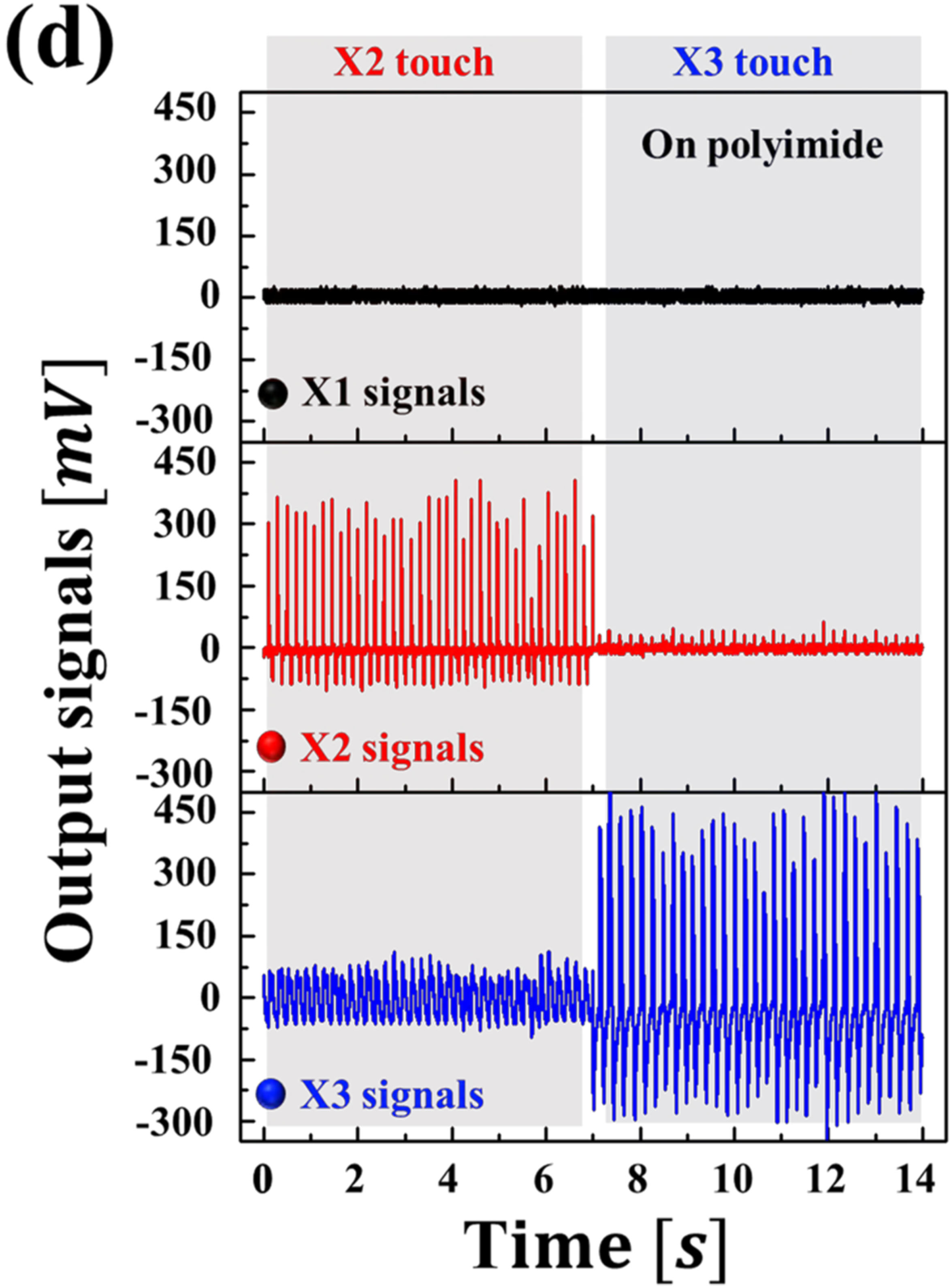
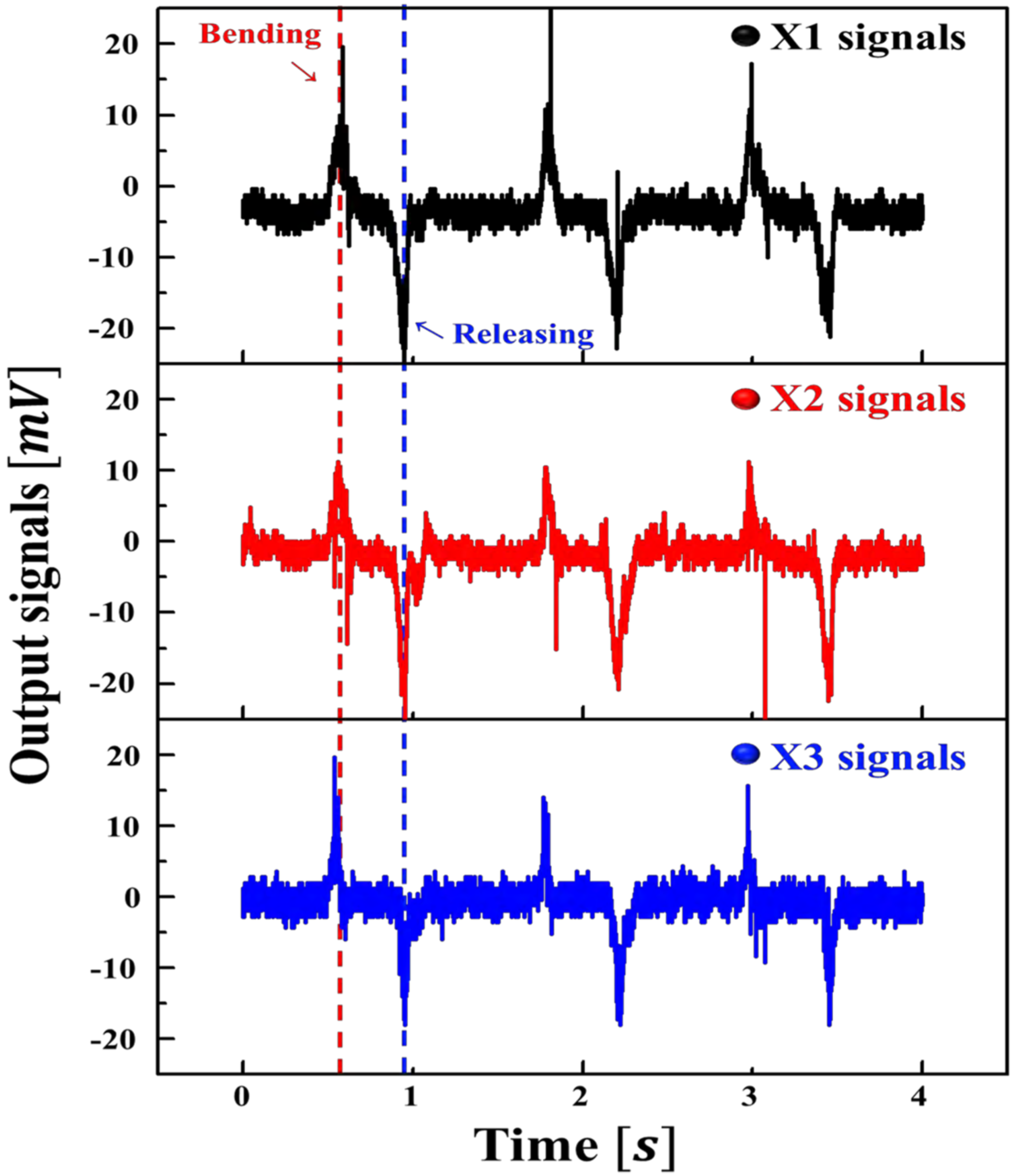
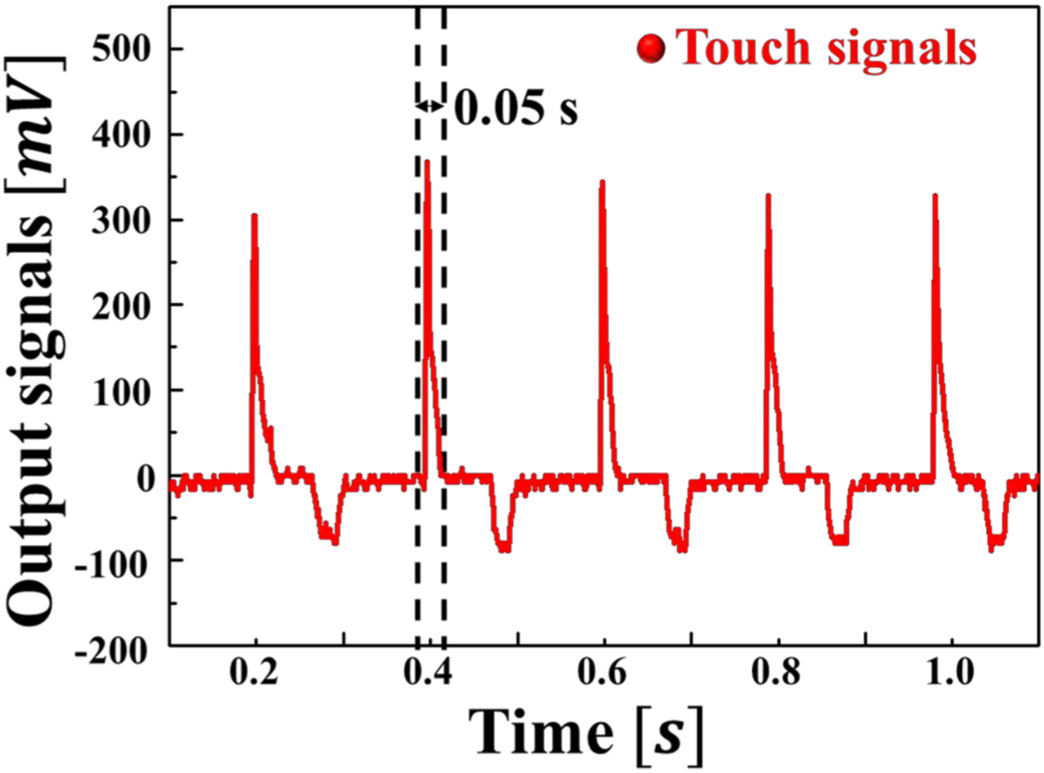

(d)
X2 touch
X3 touch
On polyimide
X1 signals
X2 signals
X3 signals
Output signals [mV]
Time [s]
450
300
150
0
-150
-300
0
2
4
6
8
10
12
14

Fig. 4. (a) Bending signals of the flexible piezoelectric touch sensor. We observe that the magnitude of the bending signal is approximately one order lower than those of touch signals. (b) Signals of the touch motions and their duration (c) Signals of the bending motions and their duration

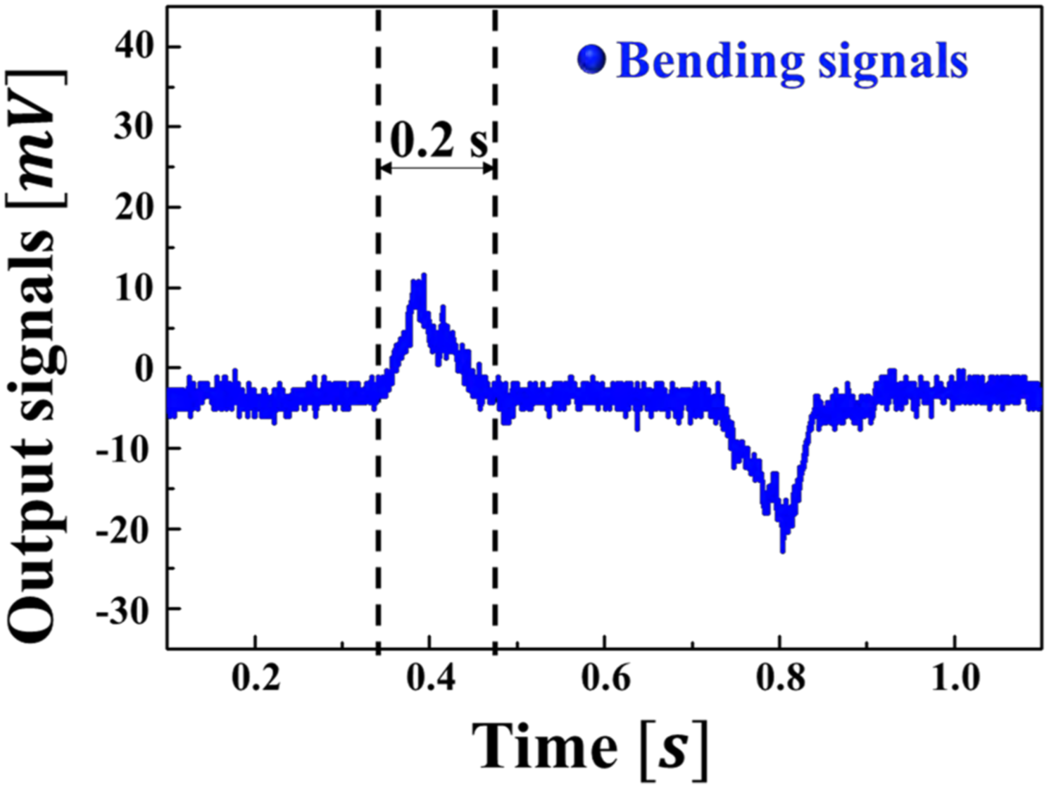
(a)



(b)


Touch signals
0.05 s
Output signals [mV]
500
400
300
200
100
0
-100
-200
0.2
0.4
0.6
0.8
1.0
Time [s]

(c)



Bending signals
0.2 s
Output signals [mV]
Time [s]
40
30
20
10
0
-10
-20
-30
0.2
0.4
0.6
0.8
1.0

Fig. 5. Signals from touching the piezoelectric flexible touch sensors

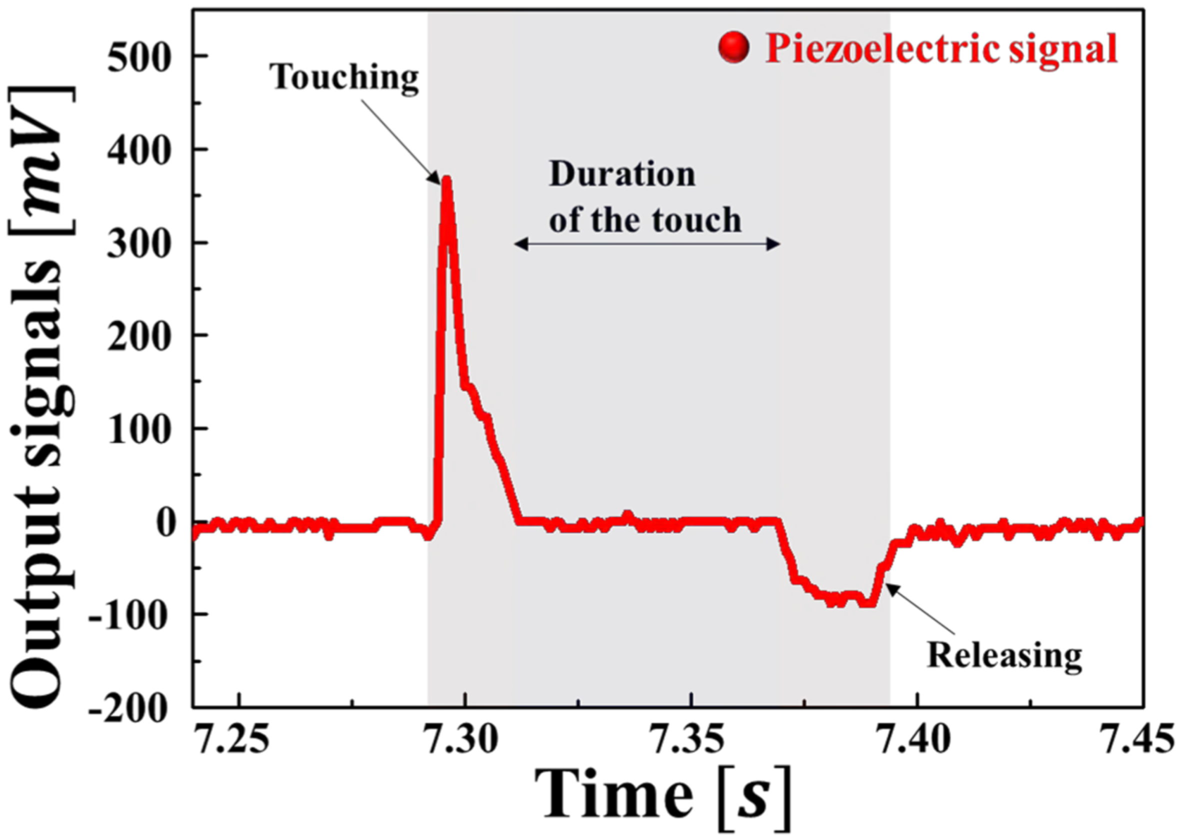


Table 1. Deposition conditions of the sacrificial PZT, functional PZT, and Pt electrodes

	Target	**Base pressure (Torr)**	**Working pressure (Torr)**	**RF & DC power (W)**	**Gas ratio Ar/O_2 (sccm)**	**Deposition temp. (℃)**
Sacrificial PZT	$Pb_{1.1}Zr_{0.52}Ti_{0.48}O_3$	2 x 10^{-6}	3 x 10^{-3}	RF, 80	20/0	R.T
Functional PZT	$Pb_{1.1}Zr_{0.52}Ti_{0.48}O_3$	2 x 10^{-6}	3 x 10^{-3}	RF, 80	19/1	500
Pt	Pt metal	4 x 10^{-6}	3 x 10^{-3}	DC, 30	20/1	R.T