Comparative study on microfluidic performance of ZnO surface acoustic wave devices on various substrates

Wenbo Wang\textsuperscript{a}, Xingli He\textsuperscript{a}, Jian Zhou\textsuperscript{a}, Hang Gu\textsuperscript{a}, Weipeng Xuan\textsuperscript{a}, Jinkai Chen\textsuperscript{a}, Xiaozhi Wang\textsuperscript{a,*} and J.K. Luo\textsuperscript{a,b,*}

\textsuperscript{a}Dept. of Info. Sci. & Electr. Eng., Zhejiang University and Cyrus Tang Center for Sensor Materials and Applications, 38 Zheda Road, Hangzhou 310027, China.

\textsuperscript{b}Institute of Renewable Energy & Environ. Technol., University of Bolton, Deane Road, Bolton, BL3 5AB, United Kingdom

ZnO thin film-based surface acoustic wave (SAW) devices have been fabricated on Si, glass and polyimide (PI) substrates, and their microfluidic performances were compared. The Rayleigh and Sezawa mode waves were observed from the ZnO/Si devices, the Rayleigh and Lamb modes from the ZnO/PI, and only the Rayleigh mode from the ZnO/glass devices. The ZnO/Si devices have the best performance with the highest acoustic streaming velocity of about 10 cm/s and the shortest particle concentration time of less than 10 sec. The ZnO/glass SAW devices deliver comparable performances to that on Si substrate, while the ZnO/PI devices perform not as good as the devices on other two types of substrates due to the large acoustic attenuation, but still can deliver a streaming velocity up to 1.0 cm/s and reasonable particle concentration function with a particle concentration time of ~70 sec. Owing to its low cost, easy fabrication and compatible with traditional glass-based biochemical analysis systems, ZnO/glass SAW device is believed to have better potential for lab-on-a-chip application.
In recent years, lab-on-a-chip (LOC) technology has attracted great attentions for research and development, and has been widely utilized in chemical, biological and medical applications. Microfluidics including liquid transportation, pumping, mixing, digitizing, and sensors are the two main components of LOC microsystems. Various effects have been utilized to develop microfluidics such as bimorph structure, electrostatic and piezoelectric mechanisms. Moving part-free microfluidics based on kinetic energy such as electroosmosis, electrophoresis, dielectrophoresis etc are preferred owing to its advantages of excellent reliability, easy fabrication and operation etc.

Surface acoustic wave (SAW) device is one of the building blocks for electronics and microsystems, and can also be utilized for accurate sensing, efficient fluidic actuation and manipulation. Therefore SAW-based microfluidic devices and sensors will play an important role in single mechanism based-LOCs in the future. SAW-based microfluidics have the advantages of low cost, high stability, easy fabrication and operation, and have been intensively investigated and studied in recent years. Wixforth demonstrated the principle of SAW-based microfluidic. Li et al demonstrated the particle concentration effect on LiNbO3 substrate and Alghane et al conducted numerical simulation for liquid mixing and particle concentration. They also discussed the frequency effect and scaling effect on the performance of SAW-based microfluidics. Shi et al showed that standing surface acoustic wave (SSAW) can be used for particle sorting and manipulation. Reboud et al reported the ability to do cell lyses using SAW on LiNbO3 substrate.

One of the key issues for widespread application of LOCs and microfluidics is the cost of the materials and devices involved, which is the same for the SAW-based microfluidics and LOCs. At the early study, SAW-based microfluidic devices were all made on single crystalline bulk piezoelectric materials such as LiNbO3, LiTaO3, that are relatively expensive, and most importantly they can not be integrated with electronics on the same chip for control.
and signal processing. ZnO thin films on silicon (Si) substrate were then introduced for the development of thin film SAW-based microfluidics, and demonstrated its great potential for LOC application. Du et al demonstrated the thickness effect of the piezoelectric layer on the ZnO/Si-based SAW devices, and characterized its microfluidics performance. Recently, we have developed flexible ZnO thin film SAW devices on polyimide (PI) substrates and showed these devices can deliver the microfluidic functions as those by the ZnO/Si SAW devices. Furthermore, we have developed the transparent SAW devices using ZnO thin films deposited on glass substrates, demonstrated their comparable transmission properties to that on crystalline Si substrate. The materials for the PI and glass substrates are abundant and cheap; furthermore they are disposable, flexible or transparent, and thus have much better potential for LOC and microfluidic applications. In this work, we conducted a systematic investigation on SAW-microfluidics based on these three substrates (Si, glass and PI), and compared their performances.

**Experimental**

_Piezoelectric thin film deposition._— ZnO thin films were used as the piezoelectric layer, and were deposited on silicon, glass (Corning 2318) and polyimide (Kapton® polyimide film 100 H) substrates, with a direct-current (DC) magnetron sputtering deposition system. Si substrate was (100) orientation and 4 inch in diameter. The thickness of Si, glass and PI substrates was 500 μm, 500 μm and 100 μm, respectively. The deposition conditions used were optimized previously as follow: A zinc target with 99.999% purity was used for ZnO deposition; the chamber pressure was 1 Pa, and Ar/O2 mixture at a ratio of 100/50 (sccm) was used. The distance between the target and substrate was set to be 70 mm, and the substrate temperature was fixed at 200 °C. The sputtering power was set to be 200 W and the bias voltage was -75 V. The deposition rate was ~13 nm/min and the thickness of all the films used was approximately 4 μm which was controlled by the sputtering time.
Crystal structure characterization.— X-ray diffraction (XRD) (Panalytical Empyrean) with Cu-$k_a$ radiation ($\lambda_X = 0.154$ nm) at 40 keV and 40 mA was used for analyzing the crystalline structure, a diffraction pattern was obtained with a 25°-60° 2θ angle. Scanning electron microscope (SEM) (Hitachi S-4800) was used for cross-sectional structure analysis with a 3 keV acceleration voltage. For surface roughness characterization, atomic force microscopy (AFM) (SPI-3800N, Seiko Co.) in a tapping mode was used.

SAW device fabrication.— Ultraviolet light photolithograph and lift-off process were used to make interdigitated transducers (IDTs). An 80 nm thick Al film was used to fabricate IDTs which have 100 pairs of fingers, 12 $\mu$m wavelength ($\lambda$) and 3 mm aperture.

SAW device measurement and numerical simulation.— A network analyzer (E5071C, Agilent) was used to characterize the transmission and reflection property of the devices. Numerical study was also carried out to analyze the wave propagation mode with finite element analysis (FEA) using COMSOL MultiPhysics 3.5a (Comsol Ltd.) software. A model with the periodic boundary condition and ideal material properties was used for the modeling.

Acoustic microfluidics testing.— In this study, a signal generator (SMIQ 03B, ROHDER&SCHWARZ) connected to an RF amplifier was utilized to apply the RF signal to the device. Deionized (DI) water droplets mixed with polystyrene microparticles (~7 $\mu$m in diameter) were used for microfluidic measurement, and the volume was controlled by a micropipette ranging from 2 $\mu$l to 10 $\mu$l. It was loaded at the center of the SAW path when measuring acoustic streaming velocity and at the edge of wave path asymmetrically for particle concentration experiments. The movement of microparticles and fluid streaming were captured by a high speed camera (Grasshopper 03K2C, with 200 frames per second) for detailed analysis.

Results and discussions

ZnO films on different substrates.— It was found that the substrate has some effects on the
deposited film for the initial deposition at the thickness of a few tens of nanometers, but the films tend to be similar as they grow thicker. The crystal structures and properties of the ZnO films are hardly affected by the substrate material but by the deposition conditions owing to the thick ZnO layer used for all the samples. The ZnO films on different substrates show very similar properties with no noticeable difference. As a representative, Figure 1 shows the characterization results of ZnO thin film deposited on glass substrate. The SEM image illustrates that the ZnO crystal has a columnar grain structure, tightly packed with no void. The roughness of the ZnO films obtained by AFM measurement is 6 nm, 6 nm and 10 nm for the ZnO layers on Si, glass and PI substrates respectively, implying that all the ZnO thin films are suitable for fabricating devices by planar process. The XRD curves exhibit a strong and sharp peak at about 34.2° for the films on all three types of substrates, showing the excellent (0002) crystal orientation for all the films. The deviation of the peak positions from the standard 34.42° of monocrystal ZnO is caused by the in-film stress, which is in the order of 1.2~1.4 GPa for all the films used here. Although post-annealing at temperatures >200 °C could release the stress, we only compared the as-deposited films here due to the temperature limitation of the PI substrate. The full-width at half maximum (FWHM) for the (0002) ZnO peak is 0.18°, 0.19° and 0.18° for the ZnO films on Si, glass and PI substrates, respectively. The grain size of the ZnO films estimated by the Debye–Scherrer formula is 48.2 nm, 45.7 nm and 51.2 nm for the ZnO films on Si, glass and PI, respectively, that are comparable to those well-performed ZnO films reported in other works.

Transmission characteristics.— The ZnO thin film devices fabricated on three substrates are showed in Figure 2. It is apparent that SAW devices on both the glass and PI substrates have good transparency, while those on PI have excellent flexibility, showing these devices are suitable for the development of transparent and flexible electronics and LOCs. The transmission (S21) and reflection (S11) spectra of the SAW devices fabricated on three types
of the substrates are shown in Figure 3. For the ZnO/Si device, two resonant peaks can be observed from both the reflection and transmission spectra at the frequency of 260.3 and 424.4 MHz, respectively. The former is the Rayleigh (R) mode, and the peak amplitude is weak due to the high normalized thickness ratio of \( \frac{h k}{\lambda} \approx 2.09 \) \((h\) is the ZnO thickness and \(k = \frac{2\pi}{\lambda}\)). The higher frequency peak is the Sezawa (S) mode as expected from the structure with a higher acoustic velocity in the substrate than in the overlay. The S mode is much stronger than the R mode, indicating more acoustic energy could be obtained from the S mode wave for microfluidic application. For the ZnO/glass device, only the R mode wave (214.2 MHz) could be observed. This is because the acoustic velocity in the glass and ZnO are very close (~3200 m/s and ~2700 m/s) to each other. The devices on the ZnO/PI show resonant peaks at the frequencies of 150.4 and 414.3 MHz, respectively. The former one corresponds to the R mode wave, while the latter is the Lamb (L) mode wave as discussed in details in our previous work.

To further identify the wave modes of the devices, numerical simulation was carried out for these devices. The 2-dimensions FEA modeling uses the actual scale of the devices with periodic boundary. The deformation of the device structures at various resonant modes is shown in Figure 4. For the silicon and glass substrates, the deformation shape for the R mode is similar, acoustic waves mainly propagate on the surface layer (within about one wavelength depth), consistent with the feature of typical SAW. Owing to much higher acoustic velocity in Si than that in ZnO, a Sezawa mode could be found for the device on silicon, but not for that on glass. A large deformation occurs in the ZnO/PI for both the R and L modes due to the lower elastic modulus of the PI substrate. For the R mode, the largest deformation is confined in the surface, in agreement with the R mode on the Si and glass. In Figure 4(e), the deformation shape in substrate is symmetric, which is similar to the conventional Lamb wave, indicating it is more likely to be a plate wave, i.e. the L mode.
The detail analysis about wave velocity of the L mode for PI can be found in our previous paper ref.37.

Table I. Characteristics of ZnO based SAW devices on Si, glass and PI substrates

<table>
<thead>
<tr>
<th>Material</th>
<th>Density $\rho_0$ (g/cm$^3$)</th>
<th>Young’s modulus $E$ (GPa)</th>
<th>Poisson ratio $\sigma$</th>
<th>Phase velocity $v_p$ (m/s) (Theory)</th>
<th>Thermal expansion coefficient (ppm/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>2.33</td>
<td>131</td>
<td>0.28</td>
<td>4680</td>
<td>~3</td>
</tr>
<tr>
<td>Glass</td>
<td>2.39</td>
<td>69.3</td>
<td>0.22</td>
<td>3206</td>
<td>7.58</td>
</tr>
<tr>
<td>PI</td>
<td>1.42</td>
<td>2.5</td>
<td>0.34</td>
<td>754</td>
<td>~20</td>
</tr>
<tr>
<td>ZnO</td>
<td>5.61</td>
<td>110-140</td>
<td>~0.35</td>
<td>~2724</td>
<td>~2.9</td>
</tr>
</tbody>
</table>

The phase velocity, wavelength and resonant frequency are correlated by $v = \lambda f$. The phase velocity of all the wave modes can be calculated using this equation with the results summarized in Table II. For dual layer structures, acoustic waves propagate in both the ZnO layer and substrate as the thickness of ZnO is much less than one wavelength, therefore the phase velocity of the R mode is strongly affected by both the substrate material and ZnO film. The phase velocity of the fundamental mode (the R mode) in Si is 4680 m/s. These in Corning glass and PI substrates can be calculated by the following equation $^{37}$

$$v_p = 0.93 \sqrt{E/2(1+\sigma)}\rho_0$$  \hspace{1cm} (1)

where $E$ is the Young’s modulus, $\sigma$ presents the Poisson’s ratio and $\rho_0$ is the density of material. Those values could be found from the material datasheet (list in Table I),$^{33, 37, 46-50}$ and the calculated phase velocity for ideal bulk glass and PI is 3206 m/s and 754 m/s, respectively. The experimentally obtained phase velocity for the R-mode in the ZnO/Si is 3123, much smaller than the ideal case due to the influence of ZnO layer with slower phase velocity. For the SAW on PI, the velocity for the R-mode is larger than than in the PI layer as the velocity in the ZnO is much larger. The detailed discussion about the phase velocities in ZnO/PI SAW devices can be found from our previous publication ref.37.

Figure 5 is the comparison of transmission spectrum for the ZnO/glass SAW before and after
laoding a 4 μl droplet on the wave path, demonstrating that the acoustic energy is almost completely coupled into the fluid. For microfluidic application, it is apparent that SAW with larger signal amplitude and less insertion loss are desirable as more acoustic energy and large force can be utilized for application. The insertion loss of all the devices is summarized in Table II. The S mode of the ZnO/Si devices has a similar insertion loss to that of the R mode wave, but the peak amplitude is much larger, indicating the S mode is more suitable for developing microfluidic devices. Larger insertion loss is observed for the R mode of the ZnO/glass device as compared to those on Si substrate, but its resonant peak also has a large amplitude, implying a comparable performance with that of the ZnO/Si devices. For the ZnO/PI devices, both the R and L modes have large insertion loss (-45.815 dB and -43.647 dB, respectively), implying the energy transmission would be poor and may be inferior for microfluidic application. The electromechanical coupling coefficients ($k^2$) calculated from the reflection measurements are also presented in Table II for comparison. For the ZnO/Si devices, the $k^2$ value of the S mode is about 5.07%, much larger than that of the R mode, implying that the S mode can deliver better microfluidic function. For both the ZnO/glass and L mode of ZnO/PI devices, the $k^2$ values are around 1.0%, and the value of the R mode of the ZnO/PI is the smallest.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Wave mode</th>
<th>$f_0$ (MHz)</th>
<th>Insertion loss (dB)</th>
<th>$K^2$ (%)</th>
<th>TCF (ppm/K)</th>
<th>Phase velocity (m/s) (experim.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>Rayleigh</td>
<td>260.3</td>
<td>-8.448</td>
<td>0.66</td>
<td>-41</td>
<td>3123.6</td>
</tr>
<tr>
<td>Si</td>
<td>Sezawa</td>
<td>424.4</td>
<td>-8.659</td>
<td>5.07</td>
<td>-48</td>
<td>5092.8</td>
</tr>
<tr>
<td>Glass</td>
<td>Rayleigh</td>
<td>214.2</td>
<td>-14.596</td>
<td>1.05</td>
<td>-38</td>
<td>2570.4</td>
</tr>
<tr>
<td>PI</td>
<td>Rayleigh</td>
<td>150.4</td>
<td>-45.815</td>
<td>0.58</td>
<td>-310</td>
<td>1804.8</td>
</tr>
<tr>
<td>PI</td>
<td>Lamb</td>
<td>414.3</td>
<td>-43.647</td>
<td>1.06</td>
<td>-143</td>
<td>4971.6</td>
</tr>
</tbody>
</table>

Although the Young’s modulus is similar for silicon and glass, Si is monocrystal while glass is amorphous, there would be more acoustic attenuation in glass, which makes the
ZnO/Si devices work better than the ZnO/glass ones. The lower modulus of PI compared with those of Si and glass induces much larger acoustic attenuation in the PI substrate and acoustic impedance mismatch at the ZnO/substrate interface. Additionally, large roughness of the PI surface also makes stronger scattering of acoustic wave, which increases the loss. That makes the ZnO/PI devices not as good as the other two types. The above results clearly show that substrate has an obvious effect on the transmission performance of devices. The difference in material properties, hence the acoustic transmission would finally determines their microfluidic performance. In combination, it is clear that the ZnO/Si and ZnO/glass devices would be more competitive than that of the ZnO/PI devices for microfluidic applications.

**Temperature effect for different substrates.**— The resonant frequency shift versus temperature was investigated for all types of the devices with the results shown in Figure 6. The temperature coefficient of frequency (TCF), defined as \( \Delta f / \Delta T f_0 \), can be calculated from the gradients of the lines in Figure 6 and is presented in Table II. The TCF value is less than -50 ppm/K for both the wave modes of the ZnO/Si devices,\(^{51}\) and is about -38 ppm/K for the ZnO/glass devices, which is consistent with the result obtained from the Al-doped ZnO transparent SAW devices.\(^{38}\) The TCFs of the ZnO/Si and ZnO/glass are smaller than that (-75 \(-80 \) ppm/K) of LiNbO\(_3\) SAW devices,\(^{18}\) while those of the ZnO/PI are much larger.

The TCF is influenced by both temperature coefficient of acoustic velocity and thermal expansion coefficient, and is expressed as follows:\(^{52}\)

\[
\text{TCF} = \frac{1}{f} \frac{\partial f}{\partial T} = \frac{1}{v_p} \frac{\partial v_p}{\partial T} - \frac{1}{\lambda} \frac{\partial \lambda}{\partial T} = \frac{1}{v_p} \frac{\partial v_p}{\partial T} - \alpha
\]  

where \(f\) is the resonant frequency, \(T\) temperature, and \(\alpha\) the thermal expansion coefficient. The large TCF of the SAW on PI is mainly caused by the very large \(\alpha\) of the PI substrate. The velocity change with temperature is mostly determined by the temperature coefficient of elastic modulus (TCE)\(^{53}\) of the substrate material. Substrate with large Young’s modulus can
suppress thermal expansion of the ZnO thin film more effectively. As a result, SAW on Si and glass substrates have smaller TCFs than that of PI. It should be pointed out that residual stress (strain) in the film also plays an important role in TCF. But it seems to have limited or the same effect on the difference of the TCFs obtained as the residual stress is similar for all the devices as confirmed by the shift of the (0002) peak in the XRD curves.

Although high TCF is good for the development of high sensitivity temperature sensors, it is not desirable for microfluidic application as a part of acoustic energy will be wasted as the thermal energy; meanwhile it requires a tracking circuitry to monitor and adjust the RF frequency to match the frequency change caused by the raised temperature for applications.

Comparison of acoustic streaming.— It is well known that SAW could induce acoustic streaming when liquid is on the forward path of acoustic waves as schematically shown in Figure 7. Acoustic streaming is a basic but useful function of SAW-based microfluidics; it can pump and transport liquids, and provide efficient mixing, which is a very challenging task for micro-liter scale fluids.

The performances of ZnO-based SAW devices of different wave modes were measured and compared. The acoustic streaming as shown in Figure 7(c) can be seen from all our SAW devices. The variation of streaming velocity as a function of RF signal voltage is presented in Figure 8. With the same liquid volume of 2 \( \mu l \), the ZnO/Si device show the highest streaming velocity, especially for that by the Sezawa mode, consistent with the observation by Du et al. The ZnO/glass devices achieve a streaming velocity more than 5 cm/s, comparable to that of the ZnO/Si ones. The ZnO/PI devices exhibit the poorest performance among the three types of the devices, as expected from the transmission properties discussed above. The main reason is due to the large acoustic absorption by the PI substrate, which makes a remarkable attenuation of the transmission energy.

SAW devices based on single crystal materials, like LiNbO\(_3\), can deliver more than
15 cm/s streaming velocity in less than 2.5 V signal voltage. Compared with those, the ZnO devices showed above have poorer performance. However, except for special applications such as nebulization, droplet-ejection etc., microfluidic functions such as mixing and transportation etc. only need low fluid velocity, in the order of several tens to hundreds of micrometers per second. Thus the streaming performance of the ZnO SAW-based devices on all three substrates are competitive and promising for the microfluidic application.

Comparison of particle concentration.—— Controlled particle manipulation and concentration have a lot of applications in biochemical analysis and medical researches as it can significantly improve the sensitivity to target substances such as proteins, cells and bacteria. It has been well studied that asymmetric SAW induced streaming could induce micro or nano-particle concentration. Figure 9 illustrates the principle of the SAW-based microparticle concentration. With the droplet located on the edge of the wave path, the acoustic force would induce a single vortex streaming within the droplet, moving the microparticles toward the center of the vortex. The microimages in Figure 9(c) - 9(e) show that the polystyrene microparticles moved into the central area with an excellent efficiency after applying SAW at 0, 5 and 10 sec for the ZnO/glass SAW device.

The particle concentration on the ZnO/PI devices has been studied in our previous work. Due to the weak transmission of the SAW on PI substrate, the time for particle concentration is very long, typically over 50 sec, and the concentration efficiency is relatively poor compared to those induced by SAW on other two types of substrates. For example, as shown in ref.37, under an RF signal of Vpp (peak-to-peak voltage) 25 V, 70 sec were needed to concentrate the microparticles. Here we mainly discuss the particle concentration results from the ZnO/Si and ZnO/glass devices.

With a ~4 μl droplet and a 12.8 Vpp signal voltage, the particle concentration performance of ZnO/Si and ZnO/glass is shown in Figure 10. Here we use the diameter ratio between the
initial (the diameter of the droplet) and the concentrated particle distribution, $Dc/Dt$, to characterize the concentration process. We define the time at $Dc/Dt = 0.1$ as the concentration time. In Figure 10(a), it can be seen that for all the wave modes, the relationship between $Dc/Dt$ and time is nonlinear when the signal amplitude increases; $Dc/Dt$ decreases rapidly at the beginning and then slow down. The S mode of the ZnO/Si devices work the best for particle concentration owing to the low insertion loss and high $k^2$. Comparison of the devices on the two types of the substrates, it is clear that the ZnO/Si device has a higher efficiency, but the difference is quite small. Figure 10(b) shows the concentration time as a function of signal voltage. Note that for all the wave modes in both the substrates, even with the smallest signal voltage, the concentration time is less than 10 sec, that is very quick and sufficient for LOC application.

Since ZnO/glass devices worked well, detailed experiments were conducted to investigate the influence of droplet volume on the particle concentration performance. The liquid volume was varied from 4 $\mu$l to 10 $\mu$l with the results shown in Figure 11. The concentration time remain almost unchanged at about 10 sec when the liquid volume is changed from 4 to 10 $\mu$l. Hence, we can conclude that for particle concentration application, ZnO/glass devices have a comparable performance to the ZnO/Si devices, and may play more important role in LOC application as the glass substrate is cheap, disposable, and widely used for biochemical analysis.

In general, SAW devices based on bulk piezoelectric substrate perform better than those using piezoelectric thin films, and can deliver better functions in microfluidics such as high streaming velocity and short particle concentration time. For instance, LiNbO₃ SAW devices can concentrate microparticles at less than 20 dB power (~7 Vpp, estimation based on a 50 $\Omega$ matching resistor), but these reported here. However, as mentioned above, very high speed streaming is not necessary for liquid transportation and mixing etc. Also shifting
the wavelength of SAW can significantly improve the particle concentration efficiency as discussed with King’s equation\textsuperscript{63} by Rogers \textit{et al}.,\textsuperscript{62} and use of focused IDT SAW will also offer a better option for microfluidics.\textsuperscript{64} These can help to overcome the shortages of the thin film SAW devices.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Wave mode</th>
<th>Streaming velocity at 9.4 Vpp)</th>
<th>Concentration time (4 μl &amp; 12.8 Vpp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>Rayleigh</td>
<td>~7.7 cm/s</td>
<td>~5.8 sec</td>
</tr>
<tr>
<td>Si</td>
<td>Sezawa</td>
<td>~12.8 cm/s</td>
<td>~5.6 sec</td>
</tr>
<tr>
<td>Glass</td>
<td>Rayleigh</td>
<td>~5.8 cm/s</td>
<td>~8.5 sec</td>
</tr>
<tr>
<td>PI</td>
<td>Rayleigh</td>
<td>~1.5 cm/s</td>
<td>&gt; 50 sec</td>
</tr>
<tr>
<td>PI</td>
<td>Lamb</td>
<td>~1.8 cm/s</td>
<td>&gt; 50 sec</td>
</tr>
</tbody>
</table>

Table III is the comparative summary of the microfluidic performances of the SAW devices on three types of substrates. From performance point of view, the S mode of ZnO/Si SAW is the best, and is followed by the R mode of both the ZnO/glass and ZnO/Si SAW devices, and then those on PI substrate. The cost for Si substrate is higher than other two, but it has the advantages of the option for the integration with electronics on the same substrate. Glass substrate is one of the base materials for many biochemical analysis, DNA and protein microarrays, LOCs and microfluidics \textit{etc}. Effective utilization and integration of SAW-based microfluidics and SAW sensors on a glass substrate with other components would greatly increase and enhance many functions for biochemical analysis. For example, integrated SAW can be utilized to study cell growth and mutation under acoustic stimulation\textsuperscript{65}. Glass substrate also is transparent, a property Si lacks, which is very useful for biotechnology and medicine research. The main advantage of the PI substrate is the flexibility and disposability, enabling the development and exploration of many new functions and applications such as wearable and implantable microsystems \textit{etc}. Although its microfluidic performance is weak, SAW on PI can still deliver sufficient fluidic and sensing functions for LOC applications. In short, the
selection of substrate for SAW microfluidics and LOCs requires consideration and balance of the needs, costs, usability, performance etc as a whole, the low cost glass and polymers have certain advantages over Si substrate and piezoelectric bulk materials.

Conclusions
In summary, ZnO thin film based SAW devices have been fabricated on Si, glass and PI substrates, and their microfluidic performances have been studied and compared. High quality, c-axis orientation ZnO films can be obtained by magnetron sputtering deposition on all the substrates with no significant quality difference between them. The Rayleigh and Sezawa mode waves are observed from the ZnO/Si devices, the Rayleigh and Lamb mode from the ZnO/PI, and only the Rayleigh mode from the ZnO/glass devices. The ZnO/Si devices have the best transmission properties. For the microfluidic application, more than 5 cm/s acoustic streaming velocity and less than 10 sec particle concentration time have been achieved for both the ZnO/Si and ZnO/glass devices. The ZnO/PI devices work not as good as other two types of devices due to the large acoustic attenuation by the PI substrate, but still deliver a streaming velocity up to 1.0 cm/s and particle concentration function. Owing to its low cost, easy fabrication and compatible with traditional glass-based LOC systems, ZnO/glass based SAW devices have better potential for LOC application. If the flexibility is the priority concern, then SAW on PI can be the candidate for the application.

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References

Figure captions

Figure 1. An SEM image of the cross-section of the ZnO film (a); an AFM image of the film surface (b) for ZnO/glass structure; and a XRD pattern comparison for ZnO films on silicon, glass and PI (c).

Figure 2. ZnO film SAW devices on different substrates of Si (a), glass (b) and PI (c). The ZnO thickness is 4 μm and the IDTs hav 100 pairs of fingers for all the devices.

Figure 3. Reflection (S11) and transmission (S21) spectrum of the ZnO film SAW devices on different substrates of Si (a), glass (b) and PI (c).

Figure 4. Structural deformation at resonance obtained by FEA simulation for the R and S modes on Si (a), the R mode on glass (c) and the R and L modes on PI (d)(e) of ZnO thin film SAW devices.

Figure 5. Comparison of transmission (S21) spectrum for the SAW of ZnO/glass with and without loading a 4 μl droplet on the wave path.

Figure 6. Resonant frequency as a function of temperature for the R mode wave of the ZnO/Si, ZnO/glass and ZnO/PI devices. Resonant frequency decreases linearly when the temperature increases for all the device investigated.

Figure 7. Schematic drawings (a) (b) and a snapshot (c) of acoustic streaming in a liquid droplet, which was captured when a ~8 V RF voltage applied to the ZnO/glass device with a 2 μl droplet in the center of the propagation path.

Figure 8. Streaming velocity as a function of applied RF signal voltage for the ZnO/Si, ZnO/glass and
ZnO/PI SAW devices. All show a linear function with the RF signal voltage.

Figure 9. Schematic drawings of acoustic induced particle concentration (a) (b), and the single vortex could be utilized for particle concentration. Snapshots show microparticles aggregation when a 12.8 V RF signal is applied to the SAW device at 0, 5 and 10 s (c)-(e). The ZnO/glass SAW are used and the droplet in the snapshots is 4 μl.

Figure 10. Comparison of acoustic streaming-induced microparticle concentration for the devices on glass and Si substrates. The droplet is 4 μl and RF signal voltage is 12.8 Vpp. Diameter ratio Dc/Dt as a function of concentration time (a), and concentration time as a function of RF signal voltage (b) for both types of the devices.

Figure 11. Effect of liquid volume on particle concentration for SAW devices on ZnO/glass substrates. Diameter ratio Dc/Dt as a function of droplet volume: 4 μl (a); 6 μl (b) and 10 μl (c) and the relationship between the concentration time and RF signal voltage.