Chapter 1. Introduction

1.1 Background of microfluidics

Microfluidics has been developed over the last 30 years in parallel with the advancement of microelectromechanical systems (MEMS) technology. Many different devices are under development, ranging from single components such as flow sensors, to complex microfluid handing systems for chemical analysis, consisting of pumps, mixer valves, flow sensors, separation capillaries etc.

The field of microfluidics is expanding rapidly with emerging products such as biological and medical platforms and micro-cooling devices that rely on micropumps as the core of their function. Micropumps are utilized in many applications including biological, chemical, and sensor network systems. Small volumes of fluids in these microsystems are often pumped, mixed, controlled or otherwise manipulated during operation. For example, biological samples must be moved through the components of miniature assay systems and react with reagents or biomarkers for detection and identification [1,2].

In 2002, the microfluidics market was estimated at \$3-4.5 billion and is increasing 25-35% annually [3]. A new field of research and products called a micro total analysis system (μTAS) is emerging that relies on micropumps for lab-on-chip devices [4]. There are several reasons that make microfluidic devices important.

(1) Miniaturized components and processes use small volumes of fluids, thus leading to reduced consumption of reagents and samples. This decreases costs and permits small quantities of precious samples to be utilised. Quantities of waste products

are also reduced.

(2) The small scale of microfluidic devices improves the efficiency and accuracy of biodetection. Reduced measurement times, improved sensitivity are also attainable.

(3) Many microfluidic technologies permit the construction of devices containing multiple components with different functionalities. A single integrated chip could perform a series of biological or chemical processes from beginning to end, for example, fluid transportation, mixing, sensing and measurement. Performing all fluidic handing operations within a single chip also reduces risk of sample loss and cross-contamination.

However, microfluidic applications are currently in limited use due to lack of research and development, and the high cost of production [5]. The most important components of microfluidics are the micromixer and the micropumps. The types of micropumps vary widely in design and applications, but can be categorized into two main groups: mechanical and non-mechanical pumps. Mechanical micropumps usually represent smaller versions of macro-sized pumps and include reciprocating, diaphragm, piston, and rotary designs. Mechanical micropumps have limited applications due to their high cost and difficulty of fabrication and are not detailed in this review. Non-mechanical pumps are unique to microfluidics because unlike most macro-scale pumps they have no moving parts involved. Non-mechanical micropumps can also be divided into two categories: continuous flow micropumps and digital micropumps. Continuous flow pumps include electrohydrodynamic (EHD), electro-osmotic (EO) and magnetohydrodrodynamic (MHD) micropumps. The latter includes electrowetting or dielectric (EW), optical electrowetting and electrostatic micropumps mostly relying on the alteration of surface tension. Recently there has emerged a new type of moving-part-free micropump utilizing a surface acoustic wave (SAW) as an actuation force. The research detailed in the thesis is to develop SAW-based micropumps and micromixers for lab-on-a-chip application, and the in the next section review will highlight the relevant technology development.

1.2 Piezoelectric interactions

Piezoelectric crystals play a dominant role in the communications and electronics industry, in which they are commonly used as filters, precision timers or for frequency control in oscillator circuits. Some materials, such as quartz, are naturally occurring piezoelectrics. Others, however, need to be polarized in order to make them piezoelectric. Polarization involves elevating the temperature while concomitantly applying an electric field across the sample, then cooling it down to room temperature with the electric field still applied [6]. The material then displays classical piezoelectric behavior.

Piezoelectricity is a coupling between a material's mechanical and electrical behaviour. The direct piezoelectric effect is present when a mechanical deformation of the piezoelectric material produces a change in the electric polarization of that material, with the change being proportional to the magnitude of the deformation. In other words, an electric charge appears on certain opposite faces of the piezoelectric material when it is mechanically loaded. The converse piezoelectric effect is the phenomenon whereby a mechanical stress that is proportional to an acting external electric field is induced in the piezoelectric material; the material is deformed when an electric voltage is applied [7, 8].

The piezoelectric effect can be demonstrated by applying either a compressive or tensile stress to the opposite faces of a piezoelectric crystal. Figure 3.2 shows that the resulting deformation of the crystal lattice produces a separation of the positive and negative charges.

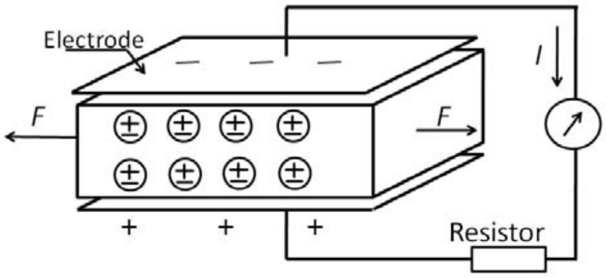

Figure 1.1 Transformation of mechanical energy into electrical energy

This effect results in electrical charge appearing on the surface of the electrodes. When the force is removed, the strain within the crystal lattice is released, causing charge to flow, thus re-establishing a zero potential difference between the electrodes. If a sinusoidal stress alternating between the tensile and compressive forces is applied to the opposite crystal faces, a sinusoidal piezoelectric voltage will appear across the electrodes. In this case, electrical energy is produced from mechanical energy. This process of crystal deformation can be reversed. When an external voltage is applied to the electrodes, the crystal lattice will deform by an amount proportional to the applied voltage. In this case, electrical energy is transformed into mechanical energy.

An ideal coupling mechanism between the electric circuit and the mechanical properties of the crystal ensures that the frequency of the mechanical acoustic wave is identical to the electric frequency. In other words, a distortion-free interface has extremely low dissipation.

1.3 Historical background of SAWs

Surface acoustic waves can be generated on the free surface of an elastic solid. This phenomenon has been exploited in electronic analog signal processing over the past 30 years, with the development of a host of devices and systems for consumer, commercial and military applications running at a multi-million-dollar annual rate. Although this is a comparatively new electronic technology, the scientific findings date back over the past 100 years. A mathematical discussion on the propagation of surface acoustic waves at the free surface of a homogeneous isotropic elastic solid was first reported by Lord Rayleigh in an address to the London Mathematical Society on 12 November 1855 [9]. He also discovered the phenomenon now called Rayleigh scattering, and predicted the existence of the surface waves now known as Rayleigh waves. Lord Rayleigh reported the surface acoustic wave mode of propagation, and in his classic paper, he predicted the properties of these waves. Named after their discoverer, Rayleigh waves have a longitudinal and a transverse shear component that can couple with a medium in contact with the device's surface. The coupling strongly affects the amplitude and velocity of the waves, allowing SAW sensors to sense mass and mechanical properties directly.

SAWs are mechanical (acoustic) rather than electromagnetic wave. The SAW travels along the surface of a material having some elasticity, with an amplitude that typically decays exponentially with the depth of the substrate. Much of an earthquake's destructive force is carried by this type of wave. SAWs achieved little recognition for their application in RF until three decades ago. It was not until 1965 that the phenomenon of surface acoustic wave propagation was first exploited for its applications to electronic devices with the invention of the interdigital transducer (IDT) by White and Volymer at the University of California [10]. It is the most efficient technique for the generation and detection of surface acoustic waves on a piezoelectric surface. The advent of the IDT made analog electrical filters operate at selected frequencies in the range from 10 MHz to 1 GHz or above.

SAW devices are an important class of piezoelectric devices, providing frequency control, frequency selection, and signal processing capabilities as filters, oscillators and transformers [11, 12]. SAW filters have enjoyed successful applications in the booming cellular telephone market and provided significant advantages in performance, cost, and size over other filter technologies.

Merits of SAW devices

SAW-based devices and systems have several excellent features. These include:

(1) With superimposed thin-film input and output interdigital transducers, SAW devices on a piezoelectric substrate can generally be designed to provide quite complex signal processing functions.

(2) SAW devices can be mass-produced using microelectronics fabrication techniques. As a result, they can be made to be cost-competitive in mass-volume applications.

(3) SAW devices can have outstanding reproducibility in performance.

(4) There are no moving parts that may suffer from wearing out during operation.

(5) SAW devices can be made to operate very efficiently at high-harmonic modes [13].

As a result, gigahertz-frequency devices can be fabricated using relatively inexpensive photolithographic techniques, rather than the significantly more expensive process involving electron-beam (E-beam) lithography.

1.4 Outline of SAW microfluidics

The signal processing and frequency response characteristics of a SAW device on a piezoelectric substrate are governed by the geometry of the metal-film IDTs deposited on the substrate. An IDT includes electrode bus bars and electrode fingers, extending from each electrode bus bar in an interdigitated configuration. The input and output transducers typically include interdigital electrodes formed on the top surface of the substrate. The shape and spacing of the electrodes determine the center frequency and the band shape of the acoustic waves produced by the input transducer. The amplitude of the surface acoustic waves at a particular frequency is determined by the constructive interference of the acoustic waves generated by the transducers. The geometry of the interdigital transducers (beam width, pitch, and number of fingers) on the piezoelectric substrate plays a significant role in the signal processing and frequency response characteristics of a SAW device.

Two IDTs are required in a basic SAW device configuration as depicted in Fig. 1.1. One of these acts as the device input and converts signal voltage variations into mechanical surface acoustic waves (utilizing the reverse piezoelectric effect). The other IDT is employed as an output electrode, the receiver, to convert mechanical vibrations back into output voltages (direct mode). Such energy conversions require the IDTs to be used in conjunction with elastic surfaces that are also piezoelectric.

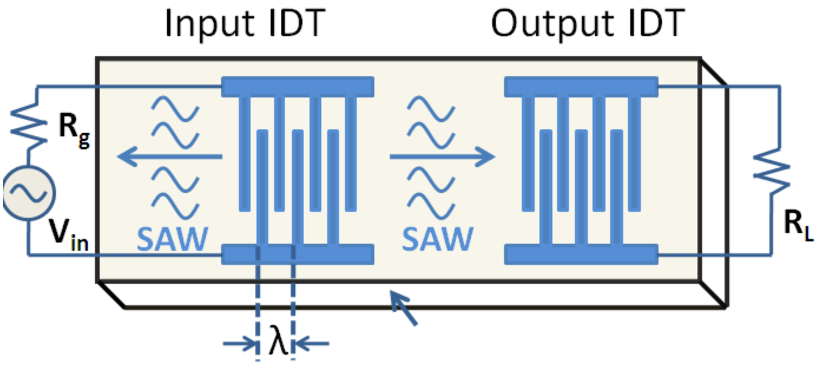

Figure 1.2 Basic SAW delay line fabricated on a piezoelectric substrate

1.5 Objectives of the research

Major electrical engineering product designs have been generated due to the development of the SAW. Currently, the largest markets for SAW applications are as filters in cell phones and in sensor applications. Recently, the extent of SAW device applications has rapidly expanded, including SAW-based microfluidics and SAW biochemical sensors. Most of the applications using SAW devices made from bulk substrates such as $LiNbO_3$ and $LiTaO_3$ and quartz which are expensive and fragile, and most importantly they cannot be integrated with electronics for control and signal process. This research focuses on the development of SAW-based microfluidics and their potential applications in biodetection, and clarifies the mechanism of acoustic pressure and interaction between the acoustic wave and liquids.

The primary intentions of this research are to develop a low-cost piezoelectric thin film based SAW technology, and to use this technology to develop SAW-based microfluidics and sensors, with the final target to develop SAW single-mechanism driven lab-on-a-chip with integrated microfluidics and sensors for biological and medical applications.

The thesis consists of 9 chapters. After a brief introduction in this chapter, Chapter 2 will focus on a review of microfluidics technologies, particularly the non-mechanical micropumps, and then goes on to surface acoustic wave based microfluidics.

Chapters 3 and 4 then detail the basic properties of the surface acoustic wave and an outline of the stress and strain relationships in piezoelectric solids is given in order to relate the material aspects of the SAW devices. The wave equation on the bulk substrate and layer structure of the SAW will be theoretically investigated. In chapter 5, different parameters of SAW device layout are proposed, and the subsequent section details the mask design and fabrication process flow.

Next in chapter 6, the wave mode on the $LiNbO_3$ substrate and a ZnO/Si layer structure will be investigated. Both designs have fundamental and higher modes; the higher mode wave is of great interest, since the higher operating frequency can be realized without high-resolution fabrication techniques. The higher modes of these two designs have completely different performance. Both the fundamental and higher modes exhibit the ability to stream within droplets, and is discussed in detail in Chapter 7.

Lastly, the report investigates the micropump that induces movement in a small droplet. For successful micropump applications, an hydrophobic coating is important to reduce the voltage needed to move the droplet. In chapter 8, the main focus is on the optimisation of the hydrophobic coating, which has a low surface energy and is bio-compatible and non-reactive. An experimental set-up was designed to test the force needed to move a droplet on differently-coated substrates with different surface treatments. Also, the mechanical wave of the SAW device causes a large increase in surface temperature which can quickly heat small liquid droplets and cause their evaporation; temperature-voltage curves are experimentally recorded and solutions are given to minimize this problem.

And finally the concluded work is in chapter 9, and highlights problems, shortages and possible future development.

Reference

---

[1] M. T. Taylor, P. Nguyen, J. Ching and K. E. Petersen. “Simulation of microfluidic pumping in a genomic DNA blood-processing cassette”. J. Micromech. Microeng. 13 (2003) 201.

[2] A. T. Woolley, D. Hadley, P. Landre, A. J. Demello, R. A. Mathies and M. A. Northrup. “Functional integration of PCR amplification and capillary electrophoresis in a microfabricated DNA analysis device”. Anal. Chem. 68 (1996) 4081.

[3] N.-T. Nguyen, X. Huang and T. K. Chuan. “MEMS - Micropumps: A Review”. J. Fliuds Eng. 124 (2002) 384.

[4] P. Woias. “Micropumps - past, progress and future prospects”. Sensors and Actuators B.105(2005) 28.

[5] N. T. Nguyen and Z. Wu. “Micromixers – a review”. J. Micromech. Microeng. 15 (2005) pp. R1.

[6] N. M. White and G. R. Leach. “Fabrication of a thick film sensor employing an ultrasonicoscillator”. IEE Proc. Sci. Meas. Technol. Vol. 142 (No.3) (1995) 249.

[7] D. Damjanovic. “Stress and frequency dependence of the direct piezoelectric effect in ferroelectric ceramics”. J. Appl. Phys. 82(Issue.4) (1997) 1788.

[8] N. W. Hagood, W. H. Chung and A. V. Flotow. “Modelling of piezoelectric actuator dynamics for active structural control”. J. Intell. Mater. Syst. Struct. Vol. 1(No. 3) (1990) 327.

[9] Lord Rayleigh. “On waves propagating along the plane surface of an elastic solid”. Proc. London Math. Soc. Vol.7 (1885) 4.

[10] R.M. White and F.W.Voltmer. “Direct piezoelectric coupling to surface elastic waves,” Appl. Phys. Lett., Vol.17,pp.314-316,1965.

[11] V.K. Varadan, W. D. Suh, P.B. Xavier, K.A.Jose and V. V. Varadan. “Design and development of a MEMS-IDT gyroscope”. Smart. Mater. Struct. 9 (2000) 898.

[12] D. T. Bell and C. M. Li. “Surface acoustic wave resonators”. Proc. IEEE 64 (1976) 711.

[13] R.C.Williamson. “Case studies of successful surface-acoustic-wave devices”. Proc.

1977 IEEE Ultrasonic Symposium, Oct.26-28,1977,Phoenix, AZ, IEEE Cat. No. 77CH1264-1SU (1977) 460.