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利用声表面波实现液体的二维驱动

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摘要:报道了利用声表面波实现水滴二维驱动的实验。在 127.8° Y 切 X 向传播的铌酸锂衬底上制作了 4 个叉指换能器。每个叉指换能器由 10 对电极构成, 其叉指周期为 $400\ \mu\text{m}$, 宽度为 $100\ \mu\text{m}$, 孔径为 $12\ \text{mm}$, 整个器件的尺寸为 $26\ \text{mm} \times 26\ \text{mm} \times 0.45\ \text{mm}$ 。由于铌酸锂晶体的各向异性, 叉指换能器沿 Y、X 方向的谐振频率不同, 分别为 $9.3\ \text{MHz}$ 和 $9.6\ \text{MHz}$ 。基于铜材料相对于铝材料的优点, 选用了铜材料并采用剥离工艺制作了电极, 得到了优化的工艺参数。最后, 用了超长时间超声波辅助方法彻底去除残胶, 实现了对水滴的二维驱动, 输入功率为 $9\ \text{W}$, 液滴运动的平均速率为 $5\ \text{mm/s}$ 。利用 ANSYS 软件分析了声表面波在铌酸锂衬底内的传播, 内部振动的模拟结果与理论分析一致。实验表明, 利用声表面波实现液体的二维驱动是可行的, 该液体驱动原型可用于片上系统和 $\mu\text{-TAS}$ 。

关键词:液体驱动; 声表面波; 剥离工艺; 有限元分析(FEA)

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Two-dimensional actuation of liquid using surface acoustic wave

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Abstract: This paper reports the two-dimensional actuation of a water drop by using a Surface Acoustic Wave(SAW). Four Interdigital Transducers (IDTs) is fabricated on a 127.8° rotated Y-cut X-propagation LiNbO_3 substrate. Each IDT is composed of 10 strip electrode pairs, which is $400\ \mu\text{m}$ in pitch, $100\ \mu\text{m}$ in electrode strip width and $12\ \text{mm}$ in aperture. The overall size of the device is $26\ \text{mm} \times 26\ \text{mm} \times 0.45\ \text{mm}$. Due to the anisotropy of LiNbO_3 crystal, the resonance frequencies of IDTs are in $9.3\ \text{MHz}$ along Y axis and $9.6\ \text{MHz}$ along X axis, respectively. Being superior in characteristics to aluminium, copper is used as the electrode material in fabrication process and the Lift-off process is adopted to fabricate electrodes, so that optimum process parameters are finally obtained. An ultra-long-time ultrasonic assistance is used to get rid of residues completely, finally, a two-dimensional actuation of the water drop is observed, which shows the input power is $9\ \text{W}$ and the average speed is drop movement is $5\ \text{mm/s}$. The propagation of SAW in LiNbO_3 substrate is simulated with ANSYS, simu-

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lation result agrees well with the calculation of theoretical vibration amplitude in LiNbO_3 . This research demonstrates that the two-dimensional actuation of a liquid drop by using the SAW is feasible. This prototype of liquid actuation is promising in lab-on-chip and μ -TAS applications

Key words: liquid actuation; Surface Acoustic Wave(SAW); lift-off process; Finite Element Analysis (FEA)

1 Introduction

The Surface Acoustic Wave (SAW) study stems from as early as more than 120 years ago when L. Rayleigh, after whom a kind of the surface acoustic wave was named, put forward the theory of SAW. The SAW is a particular kind of sound wave which is constricted at the very surface of a solid material while traveling^[1]. Due to fabrication limits, The SAW hardly found its way into industrial application in the early periods of the 20th century. Until 1960s, it was not applied in the field of communication, which attribute to the great booming of microfabrication at that time. Typical application fields of SAW devices include chemical vapor sensors, band-pass RF filters and so on.

Novel SAW actuation devices have high precision and high frequency^[2-3]. As we know, conventional ultrasonic motors use micrometer order vibration for frictional drive and can realize a sub-micrometer positioning. By contrast, SAW actuation device can realize a sub-nanometer positioning^[4] by using the surface friction force caused by Rayleigh wave. Besides, the SAW actuation is highly integrated and consumes much less spaces, which makes it promising in MEMS applications.

2 Actuation theory

An alternate electric field applied on a piezoelectric material surface produces both an electric field and a stress field. A convenient coupling of the electric field and stress field will cause points in the elastic medium move along an

elliptical locus, which engenders the SAW. If the propagation of SAW encounters the liquid on a surface, a leaky SAW is excited. The leaky SAW propagates along the boundary and excites the longitudinal wave into the liquid. The propagation constant k_L of the leaky SAW is a complex number. The particle displacement u_x can be expressed as follows^[5]:

$$u_x = A \exp(j\omega t) \cdot \exp(-jk_L x) \cdot \exp(-ak_L z), \quad (1)$$

Where A is the amplitude of SAW propagation, and

$$\alpha^2 = 1 - \left(\frac{v_s}{v_L}\right)^2, \quad (2)$$

v_s and v_L are the propagation speeds of the SAW along the substrate surface in the liquid, respectively. According to the general equation of hydrodynamics for viscous fluid

$$\mathbf{F} = \rho \frac{\partial \mathbf{v}}{\partial t} + \rho(\mathbf{v} \cdot \nabla) \mathbf{v}, \quad (3)$$

where \mathbf{F} is the net force per unit volume due to a stress, ρ is the liquid density, \mathbf{v} is the particle velocity.

The magnitude of x component net force per unit volume F_x can be expressed as

$$F_x = \rho \left(\frac{v_s}{v_L}\right)^{3/2} A^2 \omega^2 k_i \exp 2(-k_i x - k_i \alpha z), \quad (4)$$

Where k_i is the imaginary part of k_L .

In most cases, SAW is excited by an IDT with a RF electrical power source^[6].

3 Experiments

3.1 Preference of copper over aluminum

Most experiments done before have selected the aluminum as the IDT material of SAW device, for aluminum has comparatively high con-

ductance and is free from further oxidation due to the air isolation caused by the tight oxidation layer that covers it. However, copper has its own advantages over aluminum. To begin with, the resistivity of copper is merely $0.017 \Omega \cdot \text{m}$, approximately only two thirds of that of aluminum. Furthermore, the high-frequency performance of copper is much better than that of aluminum^[7]. Thirdly, copper deposition temperature is much lower than that of aluminum. This is vital for the performance of the SAW device, since high-temperature fabrication will more likely render the lattice of LiNbO_3 substrate to damage. In this research, the temperature of copper sputtering process is no higher than 150°C , while, by contrast, the normal temperature for aluminum sputtering ranges from 300°C to 600°C . In addition, samples in this research, of which the IDTs are made of copper, preserve well without apparent oxidation after they have been fabricated for half a year.

3.2 Device fabrication

A two-dimensional actuation stage is fabricated on a 127.8° rotated Y-cut X-propagation LiNbO_3 wafer. The LiNbO_3 wafer is 7.62 cm in a diameter and 450 μm in a thickness. As is shown in Fig. 1, the dimension of every electrode is 400 μm in pitch, 100 μm in electrode strip width and 12 mm in aperture.

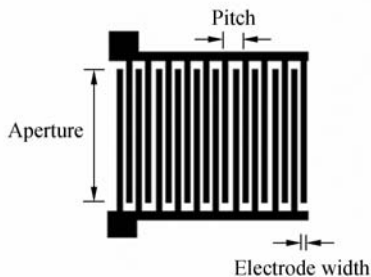


Fig. 1 Sketch of IDT

A standard lift-off process is adopted to fabricate the device, it goes as follows:

First, photoresist is spun onto the LiNbO_3 wafer and a UV exposure is conducted followed by a prebake. Second, the wafer is sputtered with copper at a low temperature of no higher than 150°C for 30 min and the thickness of copper is 130 nm. Finally, the fabricated wafer is rinsed in acetone to pattern IDT electrode pairs with ultrasonic assistance of 30 min. It is demonstrated that the usual way to get rid of residue by using acetone does not work; an acetone rinsing with ultra-long-time ultrasonic assistance is very effective.

In the process above, in order to enhance the adherence of copper to the LiNbO_3 substrate, a layer of chromium with a thickness of 10 nm is sputtered onto the substrate before sputtering of copper. It is also demonstrated that a photoresist of 17 μm , exposure of 170 s, development of 280 s, hardbake of 5 min, and removal of photoresist by using acetone rinsing with supersonic assistance for 30 min in series are convenient fabrication process parameters. The fabricated SAW actuator is shown in Fig. 2.

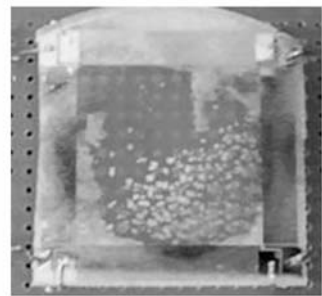


Fig. 2 Fabricated SAW liquid actuator

3.3 Result

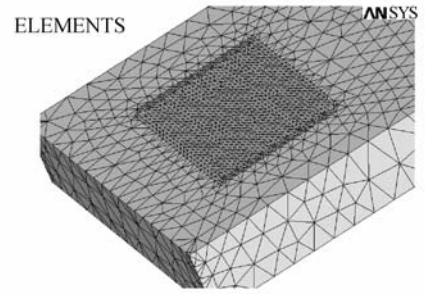
Due to the anisotropy of LiNbO_3 crystal, the resonance frequencies of four IDTs are in 9.3 MHz along Y axis and 9.6 MHz along X axis, respectively. By applying alternate voltage with different resonance frequencies on IDTs, the movement of a water drop is observed. The average speed is 5 mm/s and the input power is 9 W.

4 ANSYS simulation

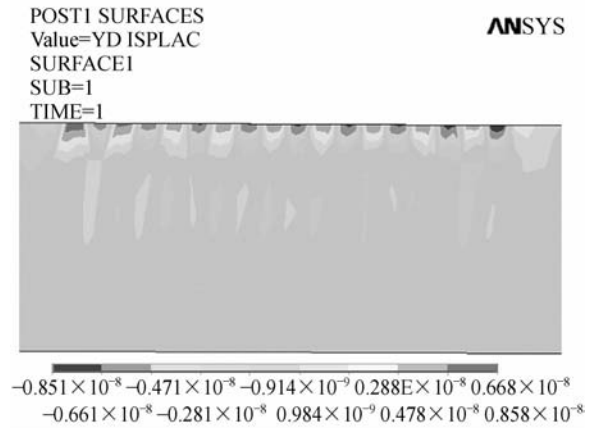
The simulation of vibration is done using ANSYS software. In the simulation process, SOLID 98 is adopted as the very element type, which is commonly utilized in piezoelectric coupling simulation analysis. SOLID98 is defined by ten nodes with up to six degrees of freedom at each node. It has three-dimensional magnetic, thermal, electric, piezoelectric, and structural field capability. The element has a quadratic displacement behavior and is well suited to model irregular meshes (such as produced from various CAD/CAM systems).

The meshed model with total of 79078 elements is shown in Fig. 3(a). The displacement perpendicular to the surface is simulated in Fig. 3(b) and simulated deformation in LiNbO_3 wafer is limited within a depth of $450\ \mu\text{m}$ to surface. To be specific, the distribution of vertical displacement can be divided into two strata. The first stratum is right beneath the surface and the second stratum is just below the first one. The displacement in the second stratum is smaller and much less regularly distributed than that of the first one. The distribution of vertical displacement in the second stratum is due to the combination of two kinds of body wave, one propagates from the top surface and the other reflects from the bottom surface.

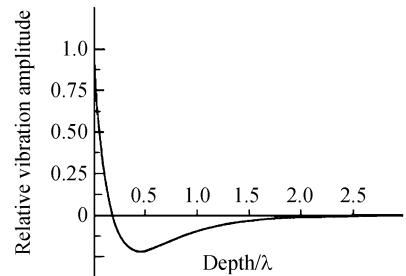
Simulation results agree well with the calculation of theoretical vibration amplitude in LiNbO_3 based on solid physics[Fig. 3(c)]. The first vibration amplitude peak appears at the very surface, the second peak appears at a depth of approximately half a wavelength $\lambda^{[8]}$. The amplitude of the first peak is larger than that of the second one. Simulation results prove to be correct.



(a) Meshed model



(b) Displacement perpendicular to surface



(c) Theoretical vibration amplitude

Fig. 3 ANSYS simulation results

5 Conclusion

This paper reports a two-dimensional actuation of a water drop by using SAW. A standard lift-off process is used to fabricate the actuation device and an ultra-long-time ultrasonic assistance is used to clear residues completely. The propagation of SAW on a LiNbO_3 substrate is simulated using the ANSYS, simulation results

agree well with the theory. This prototype of liquid actuation is very promising in lab-on-chip and μ -TAS applications. It can replace the tech-

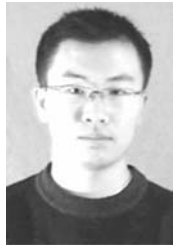
nologies of biochips or digital microfluidics devices in future. Its industrial application will be the focus of our future research.

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