State-of-the-art surface acoustic wave linear motor and its future applications

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Abstract
Two merits of the surface acoustic wave (SAW) device are its high energy density and small size. However, the driving frequency is around 10 MHz or higher. In spite of the difficulties involved with high frequency, the high energy density is attractive for actuator applications. The SAW linear motor's no load speed and maximum output force were 1.1 m/s and 3.5 N using a silicon slider. The silicon slider dimensions were 4 x 4 x 0.3 mm³. We made a lot of 30 µm diameter projections on the silicon surface. The acceleration was 1000 m/s². The SAW motor is expected to be a high speed, quick response, high resolution micro-actuator, and much more. High driving voltage was a problem. Our newly designed electrode proved that the driving voltage was reduced to less than 10 V to excite the traveling wave. For actual applications, the SAW device will be placed in a slider. This design is effective in terms of performance and cost. The nanotribology of the SAW motor is also an important and interesting subject. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction
Previously, the realization of a friction drive motor with a surface acoustic wave at high frequency — e.g. 10 MHz — was considered to be almost impossible due to the small vibration amplitude, around 10 nm. However, the difficulties involved with the friction drive have been overcome by control of the contact pressure between a slider and a stator. We have proposed an X-Y linear motor that operates at 10 MHz Rayleigh wave in two dimensions using a LiNbO₃ wafer, three inches in diameter [1]. We have already demonstrated the operation of an HF band (3 to 30 MHz) ultrasonic motor at 10 MHz [2] and 20 MHz [3,4]. At high frequency operation, the vibration amplitude is very small. Hence, a high contact pressure of, for example, several hundred megapascals is required for the friction drive to avoid the influence of a squeeze film of air. The operating conditions and basic performance of ultrasonic motors under high-frequency operation have been investigated experimentally [5–7]. The most significant result of this research was the discovery of the high output force density of the friction drive. The output force density was 50 N/mm². However, the actual output force was 1 mN because the tested slider was one steel ball. The maximum speed and maximum acceleration were 0.8 m/s and 900 m/s². As a first step in the development of an actual linear motor, specially designed multi-contact point sliders [8,9] were examined to determine if they could provide sufficient thrust for practical use. A simplified simulation model [9,10] was used to estimate the available thrust. The result showed that a surface acoustic wave motor has significantly high potential to serve as a small linear motor. Recently, we proposed a low power driving method [11] and a cost effective design of the surface acoustic wave (SAW) transducer.

2. Principles and subject
The basic construction of the surface acoustic wave motor is shown in Fig. 1. The stator transducer is a surface acoustic wave device which is made of lithium niobate. At each end, interdigital transducers are deposited. The Rayleigh wave is excited by the interdigital
transducer with a high frequency electrical power source. The driving frequency is the resonance which is fixed by the electrode pitch of the electrode. The driving frequency is currently about 10 to 100 MHz. There is an ability for much higher frequency application.

The surface particle elliptical motion of the traveling Rayleigh wave is applicable to a traveling wave type ultrasonic motor as shown in Fig. 2. The basic principle is the same as the traveling wave type ultrasonic motor, however, the vibration displacement of the wave is extremely different. Due to high driving frequency, the displacement is about 20 nm or much smaller. This value is the same as the stator transducer surface roughness. We have already determined that the most important point for success is control of the contact condition between the stator and the slider.

Recently, we tried to find the optimum design of the contact surface of the slider. For this purpose, silicon based microfabrication technology is utilized. It is convenient to fabricate various types of contact surface. They can have a different diameter contact area and different distributions of silicon projections. With these parameters, the elastic deformations of the stator and slider are changed. We then find appropriate conditions as we did with a single ball slider [7].

Performance tests of the surface acoustic wave motor are being undertaken. The potential of the motor was pointed out by preliminary experiments [7–9]. We should demonstrate the available performance of the motor. Tentative data on motor performance are shown in this paper. However, they are not the best.

Basically, the high power density of the surface acoustic wave device is of merit for a high output power actuator. However, it is not only of merit, but also demerit now. Because the transducer requires a high input power to drive it. Consequently, the driving electrical source is high voltage and high power. To reduce the driving voltage and improve the efficiency, we have to save the wasted power in the transducer. In the case of the linear motor, as shown in Fig. 1, the traveling vibration power is not circulated in a wave guide, such as in a rotary motor whose wave guide is circular. Therefore, an energy circulation system is required. This system is proposed and tested.

For commercial products, the device should be easy to apply for mechanical systems and cost effective. We propose several new design concepts of the surface acoustic wave motor for this purpose. The surface acoustic wave motor is applicable to one-dimensional and two-dimensional thin flat actuators. These new design actuators will be suitable for next generation advanced electromechanical systems.

3. Silicon slider motor

A photograph of a surface acoustic wave linear motor is shown in Fig. 3. The silicon slider is pushed by a spring which is fixed to a linear ball bearing guide. The dimension of the piezoelectric substrate for the stator transducer was $60 \times 15 \times 1 \text{mm}^3$. The traveling wave of the Rayleigh wave at 9.6 MHz was generated by interdigital transducers. The weight of the moving part of the motor was about 3.1 g.

A slider fabricated with silicon has a lot of microcontact points on the surface in order to control contact conditions for the stator transducer. We tried several diameters of contact points, from 10 to 50 μm. The
dimension of the slider was $4 \times 4 \times 1.5 \text{mm}^3$. These sliders were tested by using another testing setup 'swing arm type', as in Ref. [9].

4. Performance of 10 MHz motor

At first, the output force of the motor was measured from the transient curve of the step motion using a swing arm type setup. We derived a lot of data from the measurement. But the answer to 'optimize the surface of the slider' is not yet clear. It seems that smaller diameter, high density silicon projections are better. The maximum output force was 3.5 N when using a 30 μm diameter projection slider.

We also measured the transient response, stepping motion and high frequency response up to 130 kHz. The silicon slider had 20 μm diameter projections, of which the center interval was 30 μm. The pre-load was about 30 N.

The transient response of the slider is shown in Fig. 4 at several driving voltages. The starting acceleration was greater than 1000 m/s$^2$. From this value, the output force was about 3 N. The no-load speed was more than 1 m/s. Step motion by 80 V driving voltage and 30 waves was measured. The distance of each step was about 40 nm. When we decreased the number of driving waves by 20, the mean traveling distance was 25 nm. This was the technical limit of the measuring equipment, whose resolution was 4 nm. We have a possibility of nanometer or subnanometer stepping motion resolution with the surface acoustic wave motor.

By changing the driving IDT alternately, the response of the slider was measured. At the alternate frequency of 130 kHz, the motion of the slider was observed. The vibration amplitude of the slider at 130 kHz was 30 nm p-p.

5. Energy circulation

The surface acoustic wave motor shown in Fig. 3 required a high driving voltage of 100 V or more and 100 W for high speed operation. This is because the transducer did not circulate the power in the device. Almost all the driving power was absorbed at the absorber. For high efficiency driving, we developed a new IDT design as shown in Fig. 5 [11]. The new transducer requires two driving IDTs and two unidirectional IDTs for circulation. We need two electrical sources whose phase difference is 90°. We have succeeded in exciting a traveling wave and driving the slider [12]. Using this driving method, the driving voltage has been greatly reduced, to around 5 V.

6. Future work

For industrialization of the new actuator, the cost of the elements is very important. Element designs such as those in Figs. 1, 3 and 5 are wasteful in using the material, because the element size is too large compared with the friction drive area. Expensive material such as lithium niobate should be saved.

A new cost effective transducer design for energy saving is shown in Fig. 6. This transducer is able to work as a slider and a stator. The whole surface of the
wave guide is useful for the friction drive. The friction drive area is not required to be so large, and hence the device size is reduced. This design has the merit of improving the performance of the actuator, since a quick build up of the wave is possible.

A similar design for a two-dimensional actuator is also available, as illustrated in Fig. 7. This transducer has energy circulation electrodes for both directions of wave propagation in a small element. With four RF driving sources, two-direction forward and reverse motion is possible. As shown in Fig. 8, the transducer moves in the x-y plane. The traveling distance of the motor is only limited by the dimension of the guide surface, not the transducer size.

7. Physical interest and conclusions

The physical phenomenon of the driving boundary is attractive from the view point of tribology. We know that the elastic deformation of the slider and stator surface due to pre-load should be controllable to obtain superior driving conditions for large thrust and less slip. In the case of the high frequency surface acoustic wave motor, elastic deformation of nanometer order should be estimated, as illustrated in Fig. 9.

The limitation of high frequency is not yet clear. If the surface roughness is fine, the frequency limitation will be higher. We predict that a driving frequency of 100 MHz will be possible. An example of the 100 MHz SAW motor is shown in Fig. 10. Since the dimensions of the device depend on the wavelength, namely on the driving frequency, the motor is miniaturized with high frequency. A high performance surface acoustic wave motor was demonstrated. The no-load speed was 1.1 m/s, the acceleration was 1000 m/s$^2$ and the output force was 3.5 N. A low voltage driving method was developed. With this method, battery drive will be possible.

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