SURFACE ACOUSTIC WAVE DEVICE

This invention relates to surface acoustic wave (SAW) devices, and more particularly to a SAW device based on piezoelectric thin films.

SAW devices and related subject matter are described in the following publications:
Patent US 3 955 160;
Patent US 4 437 031;
Patent US 4 456 847;
Patent US 4 491 811;
Patent US 4 507 581;
Patent US 4 531 107;
Dransfield *et al.*, "Excitation, Detection and Attenuation of High-Frequency Elastic Surface Waves", Physical Acoustics, Principles and Methods, W. P. Mason and R. N. Thurston ed., Vol. VII, pp. 219-272, Academic Press, 1970; and
Shih *et al.*, "Theoretical Investigation of the SAW properties of Ferroelectric Film Composite Structures", IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, Vol. 45, No. 2, pp. 305-316, March 1998.

A SAW device is constructed so that electrical signals are transformed into acoustic surface waves by a transducer formed on a piezoelectric substrate, and the acoustic surface waves propagate on the surface of the substrate. The device is fabricated using piezoelectric materials, such as a piezoelectric crystal, $LiNbO_3$, Quartz, etc., piezoelectric ceramic material, $Pb(ZrTi)O_3$ (PZT), ZnO, etc., or a piezoelectric thin film deposited on a non-piezoelectric substrate, such as ZnO on silicon. The SAW device comprises a pair of electro-SAW transducers and a SAW propagation path established therebetween. Usually, the SAW propagation path is constituted by a part of the polished piezoelectric substrate which is used in common for both transducers.

An acoustic wave with a frequency as high as several gigahertz travels on the substrate surface at a velocity which is about 10^{-5} times that of electromagnetic waves. A surface acoustic wave thus has the slow travel property of sound while retaining the microwave frequency of its source. SAW devices utilizing these properties can be used in delay lines, filters, pulse processors and other microwave devices and circuits.

In a SAW delay line, the delay time is determined by the velocity of the surface acoustic wave and the distance travelled by the surface acoustic wave on a piezoelectric surface.

In a SAW filter, the frequency characteristics of the filter are determined mainly by the sound velocity of the SAW and the electrode patterns of the input and output transducers.

Generally, the electrode pattern of a transducer includes a plurality of parallel electrode strips. The orientation of the strips determines the direction of a wave front.

In a single-phase transducer, all the electrode strips are maintained at a single phase, with one electrode strip and one gap region between electrode strips defining a region for one wavelength.

In an interdigital transducer, electrode strips are formed at an interval of ½ wavelength, and two-phase control is carried out. More particularly, two comb-shaped electrodes each having a plurality of electrode fingers (strips) are opposed and interlocked and maintained at opposite phases. This is known as alternate-phase mode. Two electrode strips and two gap regions between the strips define a region for one wavelength. Typically, the electrode strips and the gap regions all have the same width l which is $\lambda/4$, where λ represents the wavelength of a SAW.

Generally, conventional transducers can be operated in only one mode, either single-phase mode or alternate-phase mode. An object of the invention is to combine these

two modes and develop a new type of SAW device that can be operated at two different frequencies.

According to a first aspect of the invention, there is provided a surface acoustic wave device, comprising: an electrode layer patterned as two electrodes with an interdigital arrangement; a piezoelectric layer; an elastic substrate layer; means for providing electrical connection of both electrodes to the same end of an electrical source to operate the device in single-phase mode; and means for providing electrical connection of each electrode to a different end of an electrical source to operate the device in alternate-phase mode.

According to a second aspect of the invention, there is provided a method of operating a surface acoustic wave device, the device comprising an electrode layer patterned as two electrodes with an interdigital arrangement, a piezoelectric layer and an elastic substrate layer, the method comprising: connecting both electrodes to the same end of an electrical source to operate the device in single-phase mode; and connecting each electrode to a different end of the electrical source to operate the device in alternate-phase mode.

The patterned electrode layer may be a top electrode layer located on the side of the piezoelectric layer away from the substrate layer. The device may further include an underlay electrode layer located between the piezoelectric layer and the substrate layer.

The patterned electrode layer may be an underlay electrode layer located between the piezoelectric layer and the substrate layer, and the device further comprising a top electrode layer located on the side of the piezoelectric layer away from the substrate layer.

The device may further include a buffer layer located between the underlay electrode layer and the substrate layer.

A suface acoustic wave device based on a piezoelectric thin film deposited on a non-piezoelectric substrate has been designed. The device can be operated in alternate-phase mode or single-phase mode, and thus the device can generate surface acoustic waves at two different frequencies. The device has been termed a "single-phase/alternate-phase SAW device".

For a better understanding of the present invention, specific embodiments will now be described, by way of example, with reference to the accompanying drawings, in which:

Fig. 1 is a top view of a known interdigital transducer configuration;

Fig. 2A is a top view of a known single-phase transducer configuration with conductive and non-conductive strips of width $\lambda/2$;

Fig. 2B is a side schematic view to illustrate a typical electric field pattern for a ZnO/Si single-phase transducer;

Fig. 2C is a side schematic view to illustrate a typical electric field pattern for a single-phase $LiNbO_3$ transducer;

Fig. 3A is a side schematic view of a substrate that is suitable for single-phase/alternate-phase SAW device fabrication;

Fig. 3B is a side schematic view of another substrate that is suitable for single-phase/alternate-phase SAW device fabrication;

Fig. 3C is a side schematic view of another substrate that is suitable for single-phase/alternate-phase SAW device fabrication;

Fig. 4A is a side schematic view showing a typical electric field pattern for the single-phase mode of a first embodiment of a single-phase/alternate-phase SAW device;

Fig. 4B is a side schematic view showing a typical electric field pattern for the single-phase mode of a second embodiment of a single-phase/alternate-phase SAW device;

Fig. 5A is a side schematic view showing a typical electric field pattern for the alternate-phase mode of the first embodiment of a single-phase/alternate-phase SAW device;

Fig. 5B is a side schematic view showing a typical electric field pattern for the alternate-phase mode of the second embodiment of a single-phase/alternate phase SAW device;

Fig. 6A is a plan view of the patterned electrode layer of an embodiment, showing the electrical connections for the embodiment when operating in alternate-phase mode; and

Fig. 6B is a plan view of the patterned electrode layer of an embodiment, showing the electrical connections for the embodiment when operating in single-phase mode.

As shown in Fig. 1, a conventional interdigital transducer consists of two electrodes 1 and 2, each comprising an arm having a plurality of fingers 3 and 4. The fingers are electrode strips extending from the arm, and are alternately spaced with respect to one another along a non-conductive surface 5, with non-conductive gap regions between the fingers. As indicated in Fig. 1, the width of each of the conductive fingers and the non-conductive gaps therebetween is equal to $\lambda/4$ where λ is the SAW wavelength. The upper limit of the operating frequency of a SAW device is determined by the capability of the photolithographic techniques being used to define the transducer.

A single-phase transducer configuration, as shown in Fig. 2A, doubles the operating frequency possible for a given photolithographic capability. In Fig. 2A, a single-phase transducer includes a conducting arm 6 having a plurality of conductive fingers 7 extending from the arm, with non-conductive gap regions 8 between the fingers. As indicated, the spacing between the fingers, as well as the width of each finger is $\lambda/2$, where λ is the SAW wavelength.

A side view of a single-phase transducer in a layered configuration is shown in Fig. 2B. The transducer includes a top electrode layer patterned as shown in Fig.2A with fingers 7. Below this, the transducer includes ZnO layer 9, Al underlay electrode layer 10, SiO_2 buffer layer 11, silicon layer 12 and Al electrode layer 13. The electric field lines are generally parallel since the thickness of the ZnO layer 9 is typically three to ten times smaller than the spacing between the electrode fingers 7.

In contrast, a single-phase transducer in a single crystal configuration is shown in Fig. 2C. In this case, the spacing between the electrode fingers 7 is much smaller than the crystal thickness. Therefore, fringing of the electric fields occurs as depicted. In Fig. 2C, the single-phase patterned electrode layer with conductive fingers 7 is positioned on a $LiNbO_3$ substrate 14, and a back electrode 15 is deposited at the back side of the $LiNbO_3$ substrate. The inherent difference in the field pattern between the layered crystal structure and the single crystal structure makes the single-phase transducer in the layered configuration much more efficient than its counterpart in the single crystal configuration.

Figs. 3A, 3B and 3C show side schematic views of substrates that are suitable for embodiments of single-phase/alternate-phase SAW device fabrication. In Fig. 3A, the substrate includes the top electrode layer 16 (Al, Au, etc.), the piezoelectric thin film layer 17 (ZnO, PZT, $LiNbO_3$, $LiTaO_3$, etc.), the underlay electrode layer 18 (Al, Au, etc.), the buffer layer 19 (SiO_2, Si_3N_4, diamond, etc.), the elastic substrate layer 20 (sapphire, Si, GaAs, InP, fused silica, glass, etc.),and the back electrode layer 21 (Al,

Au, etc.). In Fig. 3B, the buffer layer 19 is absent, whilst in Fig. 3C, both the underlay electrode layer 18 and buffer layer 19 are absent.

The term "elastic substrate layer" means any substrate which has a linear relationship between its stress and strain. Thus, an elastic SAW can travel on it.

An underlay electrode was described by Shih *et al.* in "Theoretical Investigation of the SAW properties of Ferroelectric Film Composite Structures", IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, Vol. 45, No. 2, pp.305-316, March 1998. Shih *et al.* used the underlay electrode as a floating electrode to enhance the electro-mechanical coupling efficiency of a device. Thus, the transducer only operates in alternate-phase mode.

Figs. 4A, 4B, 5A and 5B are side schematic views showing embodiments of single-phase/alternate-phase SAW devices.

For the first embodiment, shown in Figs. 4A and 5A, the substrate of Fig. 3A has been used, and the top electrode layer 16 patterned with the interdigital electrode pattern shown in Fig. 1, including conductive fingers 3 and 4. Underlay electrode layer 18 is unpatterned. Fig. 4A shows the electric field pattern for the first embodiment operating in single-phase mode, i.e. all the conductive fingers 3 and 4 are maintained at the same phase. Fig. 5A shows the electric field pattern for the first embodiment operating in alternate-phase mode, i.e. alternating conductive fingers 3 and 4 are maintained at opposite phases.

For the second embodiment, shown in Figs. 4B and 5B, the substrate of Fig. 3A has been used, and the underlay electrode layer 18 patterned with the interdigital electrode pattern shown in Fig. 1, including conductive fingers 3 and 4. Top electrode layer 16 is unpatterned. Fig. 4B shows the electric field pattern for the second embodiment operating in single-phase mode, while Fig. 5B shows the electric field pattern for the second embodiment operating in alternate-phase mode.

Fig. 6A is a plan view of the patterned electrode layer (which may be either layer 16 or 18) of the embodiments showing the electrical connections for an embodiment operating in alternate-phase mode. The two comb-shaped electrodes are connected to the two different ends of an electrical source 22. The surface acoustic wavelength is λ_o and the operating frequency is $f_o=v/\lambda_o$, where v is the velocity of the surface acoustic wave.

Fig. 6B is a plan view of the patterned electrode layer (which may be either layer 16 or 18) of the embodiments showing the electrical connections for an embodiment operating in single-phase mode. The two comb-shaped electrodes are connected to the same end of an electrical source 22. The other end of the electrical source 22 may be connected to the underlay electrode 18, for example as in the first embodiment (Fig. 4A), or the top electrode 16, for example as in the second embodiment (Fig. 4B).

For single-phase mode compared with alternate-phase mode, the surface acoustic wavelength is halved, $\lambda=\lambda_o/2$ and the frequency is doubled, $f=2f_o$.

A single-phase/alternate-phase SAW device may be fabricated using any of the substrates illustrated in Figs. 3A to 3C. Either the top electrode layer 16 is patterned or the underlay electrode layer 18 is patterned, for example, in the manner illustrated in Fig. 1.

The piezoelectric layer 17 may be a polycrystalline or single crystal material. The piezoelectric layer 17 may be formed of, for example, ZnO, PZT, $LiNbO_3$, $LiTaO_3$, etc.

The buffer layer 19 is a dielectric thin film, such as SiO_2, Si_3N_4, diamond film, etc. This layer is generally included to improve the crystallinity or texture of the piezoelectric layer. It can also be used to increase the speed of the SAW.

Each electrode layer may comprise a thin metal film, such as Al, Au, Ag, Ti, or a conductive thin oxide film, such as Al:ZnO, ITO, ATO, or a semiconductor film, such as p-type silicon.

The elastic substrate layer 20 may be a crystalline material, such as sapphire, $SrTiO_3$, etc. or a non-crystalline, acoustically isotropic material, such as fused silica, glass, etc. or a conductive material such as aluminium, tungsten, etc. or a semiconductor material such as Si, Ge, GaAs, InP, AlN, GaN, etc.

In the case where a single-phase/alternate-phase SAW device is fabricated using the substrate of Fig. 3C, then the substrate layer will be either a conductive or semiconductor material, and the top electrode layer 16 will be patterned. To operate this device in single-phase mode, the top electrode 16 is connected to one end of the electrical source 22 and the back electrode 21 is connected to the other end of the electrical source 22. The substrate 20 serves as the floating electrode to enhance the electro-mechanical coupling efficiency of the device.

These single-phase/alternate-phase SAW devices can use the substrate more efficiently and are more versatile than conventional SAW devices. They can be used in SAW delay lines, resonators and filters. By using semiconductors as the substrate, it is also possible to integrate SAW devices and electrical circuits on the same chip.

CLAIMS:

1. A surface acoustic wave device, comprising:

an electrode layer patterned as two electrode with an interdigital arrangement;

a piezoelectric layer;

an elastic substrate layer;

means for providing electrical connection of both electrodes to the same end of an electrical source to operate the device in single-phase mode; and

means for providing electrical connection of each electrode to a different end of an electrical source to operate the device in alternate-phase mode.

2. A device according to claim 1, the patterned electrode layer being a top electrode layer located on the side of the piezoelectric layer away from the substrate layer.

3. A device according to claim 2, the device further including an underlay electrode layer located between the piezoelectric layer and the substrate layer.

4. A device according to claim 1, the patterned electrode layer being an underlay electrode layer located between the piezoelectric layer and the substrate layer, the device further comprising a top electrode layer located on the side of the piezoelectric layer away from the substrate layer.

5. A device according to claim 3 or 4, the device further including a buffer layer located between the underlay electrode layer and the substrate layer.

6. A method of operating a surface acoustic wave device, the device comprising an electrode layer patterned as two electrodes with an interdigital arrangement, a piezoelectric layer and an elastic substrate layer, the method comprising: connecting both electrodes to the same end of an electrical source and the other end of the electrical source being connected to the underlay electrode to operate

the device in single-phase mode; and connecting each electrode to a different end of the electrical source to operate the device in alternate-phase mode.

7. A method according to claim 6, the patterned electrode layer being a top electrode layer located on the side of the piezoelectric layer away from the substrate layer.

8. A method according to claim 7, the device further including an underlay electrode layer located between the piezoelectric layer and the substrate layer.

9. A method according to claim 6, the patterned electrode layer being an underlay electrode layer located between the piezoelectric layer and the substrate layer, the device further comprising a top electrode layer located on the side of the piezoelectric layer away from the substrate layer.

10. A method according to claim 8 or 9, the device further including a buffer layer located between the underlay electrode layer and the substrate layer.