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SURFACE ACOUSTIC WAVES AND DEVICES

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The purpose of this paper is to review the basic physics of surface wave propagation on piezoelectric substrates, and to survey the applications of these waves to various types of devices. Smooth, layered, and corrugated substrates will be considered. Methods of analysis will be reviewed, and general characteristics of the solutions (polarization, velocity, piezoelectric coupling, etc.) will be summarized. To conclude, a brief overview of the historical development of surface wave devices (delay lines, resonators, correlators, convolvers etc.) will be presented, and recent trends in applications will be described.

1. History and classification of wave types

The story of surface acoustic wave devices begins with the publication in 1885 of a paper by LORD RAYLEIGH that analyzed the propagation of waves along the plane surface of an isotropic elastic solid [12]. In this paper Rayleigh was influenced by earlier work of LAMB in a paper (1882) on the vibrations of an elastic sphere, and he predicted that these surface waves would probably play an important role in the study

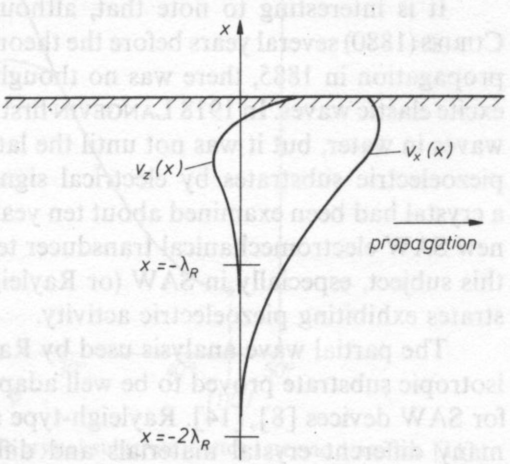

FIG. 1. Particle displacement components for Rayleigh surface wave (SAW) propagation along a smooth surface. (After AULD [17].)

of earthquakes. As will be seen in Section 2, Rayleigh's analysis solved the problem by combining appropriate longitudinal and shear vibrations to satisfy the boundary conditions, thereby anticipating the partial wave method that is now standard in the design surface acoustic wave devices. Figure 1 illustrates the depth variation of the two components of elastic displacement resulting from this combination of partial waves.

The last decade of the 19th century was a period of great activity in elastic vibration research. Rayleigh soon followed his surface wave paper with a second paper (based on the same analytical approach) on wave propagation along a free isotropic plate [13]. In this paper he identified the two families of plate solutions now known as horizontal shear (SH) and Lamb waves. The second wave type was named after Lamb, in recognition of his publication in the same year (1889) of a paper on flexural waves in an elastic plate [9], a member of one of the two classes of Lamb wave solutions. The surface wave solutions, now called surface acoustic waves (SAW) in the elastic device community, were named Rayleigh waves some time before 1925.

Rayleigh's prediction that elastic surface waves would play an important role in geophysics was quickly realized. A paper by LAMB in 1904 considered the propagation of tremors over an elastic surface [10]. Several years previously BROMWICH (1898) had introduced the concept of wave propagation on a layered half-space, motivated by the desire to model the effect of the earth's mantel on earthquake propagation. Waves on layered surfaces were the subject of intense investigation in the years to follow (LOVE (1911), STONELY (1924) and SEZAWA (1927)), and were later to prove to be of great practical importance in SAW devices. BREKHOVSKIKH published in 1960 a general reference work on propagation in layered solids [18]. During this same period, interest in the earthquake problem stimulated a series of papers on the excitation of waves on a half-space by localized mechanical surface and volume sources. The excitation problem (treated by LAMB (1904) and later, for example, by NAKANO (1925) and CAGNIARD (1939)) became the subject of renewed interest with the advent of SAW applications to nondestructive testing [27] and signal processing [14], beginning in the 1950's and 1960's.

It is interesting to note that, although piezoelectricity was discovered by the CURIES (1880) several years before the theoretical demonstration of elastic surface wave propagation in 1885, there was no thought until decades later of using this effect to excite elastic waves. In 1918 LANGEVIN first used piezoelectricity to excite acoustic bulk waves in water, but it was not until the late 1960's that SAW were excited directly in piezoelectric substrates by electrical signals. Wave propagation on the surface of a crystal had been examined about ten years previously [5]. But the emergence of this new SAW electromechanical transducer technology led to an explosion of interest in this subject, especially in SAW (or Rayleigh wave) propagation on anisotropic substrates exhibiting piezoelectric activity.

The partial wave analysis used by Rayleigh for surface wave propagation on an isotropic substrate proved to be well adapted to the piezoelectric substrates required for SAW devices [8], [14]. Rayleigh-type surface waves (SAW) were investigated for many different crystal materials and differently-oriented substrates. During these investigations it was discovered that anomalous behavior can occur for certain propagation directions. It was originally believed that SAW could not propagate in these directions. But more detailed calculations showed a more complex type of behavior (Fig. 2). At the critical direction ([110]) in the figure the normal surface wave becomes a bulk wave that propagates parallel to the surface without radiation (surface skimming wave). At this same point a nonradiating surface wave with a different velocity (pseudo surface wave) exists, but it propagates without radiation loss only in this one critical direction. Elsewhere the wave radiates energy into the substrate and becomes a leaky wave (leaky wave solutions were noted by RAYLEIGH in his 1885 paper but were discarded as nonphysical).

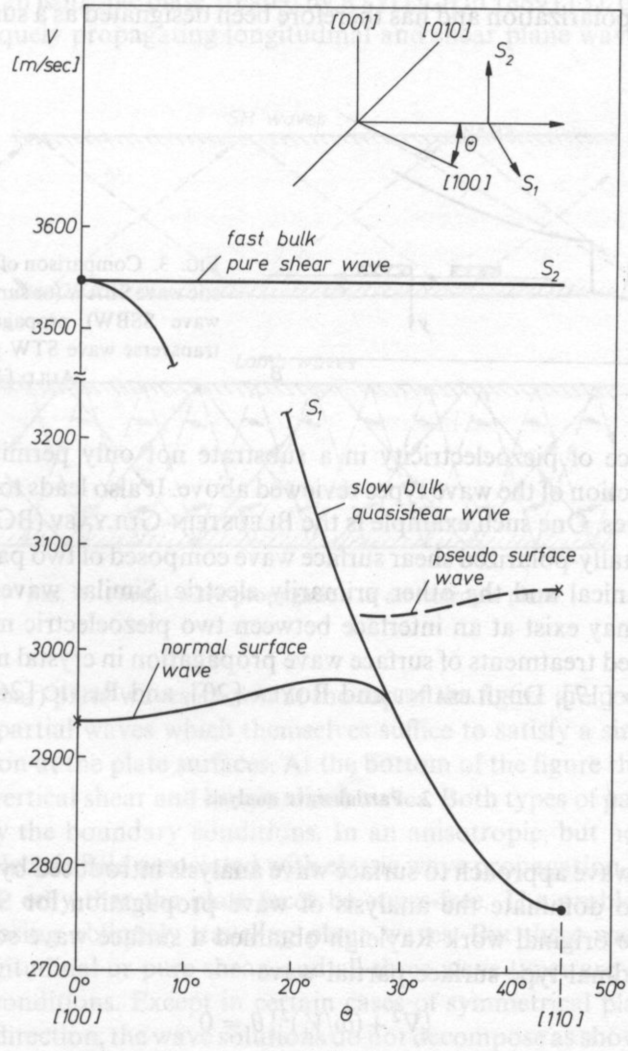

FIG. 2. Pseudosurface wave propagation along a single crystal substrate. (After LIM and FARNELL [11].)

In some crystals, surface skimming bulk waves, SSBW, (alternatively termed shallow bulk acoustic waves, SBAW) exhibit properties, such as a higher propagation velocity than a SAW, that are useful in practical devices. For this reason this type of wave is sometimes used in delay line applications, despite the fact that it is not closely confined to the surface. Confinement may be achieved by depositing a layer on the surface [21] to create a Love wave, or by fabricating a corrugated surface [1], [7], [15]. Figure 3 shows a corrugated surface created by depositing a periodic array of metal strips, where an SBAW stopband is created by BRAGG scattering due to the periodicity of the structure. As seen in the figure, the wave on the corrugated surface propagates at a lower velocity than the SBAW for frequencies below the stopband. Like the SAW, which is also a slow wave, this wave is a surface wave, Unlike the SAW, however, it has horizontal shear polarization and has therefore been designated as a surface transverse wave (STW).

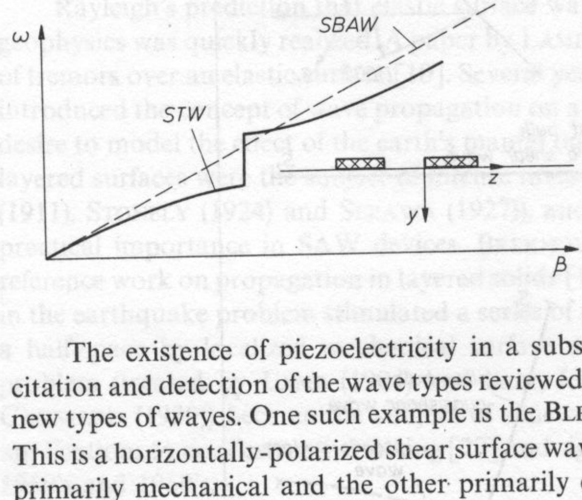

FIG. 3. Comparison of shallow bulk acoustic wave SBAW (or surface skimming bulk wave SSBW) propagation and surface transverse wave STW propagation. (After AULD [17].)

The existence of piezoelectricity in a substrate not only permits electrical excitation and detection of the wave types reviewed above. It also leads to the existence of new types of waves. One such example is the BLEUSTEIN-GULYAEV (BG) wave [4], [6]. This is a horizontally-polarized shear surface wave composed of two partial waves, one primarily mechanical and the other primarily electric. Similar waves, analogous to Stonely waves, may exist at an interface between two piezoelectric media.

More detailed treatments of surface wave propagation in crystal media have been published (AULD [17], DIEULESAINT and ROYER [20], and RISTIC [26]).

2. Partial wave analysis

The partial wave approach to surface wave analysis introduced by RAYLEIGH [12] has continued to dominate the analysis of wave propagation for SAW device applications. In the original work Rayleigh obtained a surface wave solution by combining a longitudinal-type surface partial wave

$$\{\nabla^2 + (\omega/V_l)^2\}\theta = 0 \tag{1a}$$

$$\theta \sim \exp(-\alpha_l z + i\beta x) \tag{1b}$$

and a shear-type surface partial wave

$$\{\nabla^2+(\omega/V_s)^2\}\,u_s=0 \tag{2a}$$

$$u_s \sim \exp(-\alpha_s z+i\beta x) \tag{2b}$$

to satisfy stress-free boundary conditions at the substrate surface. These boundary conditions require that the β's be the same in Eqs. (1) and (2). The relations between the depth decay factors α_l, α_s and β are obtained from the longitudinal and shear dispersion relations. Application of the zero stress boundary condition then leads to a condition linking ω, α_l, α_s and β, which must be solved simultaneously with the longitudinal and shear dispersion relations [16].

In the case of an isotropic plate, treated by RAYLEIGH in 1889 [13], the partial wave solutions are obliquely propagating longitudinal and shear plane waves (Fig. 4). The

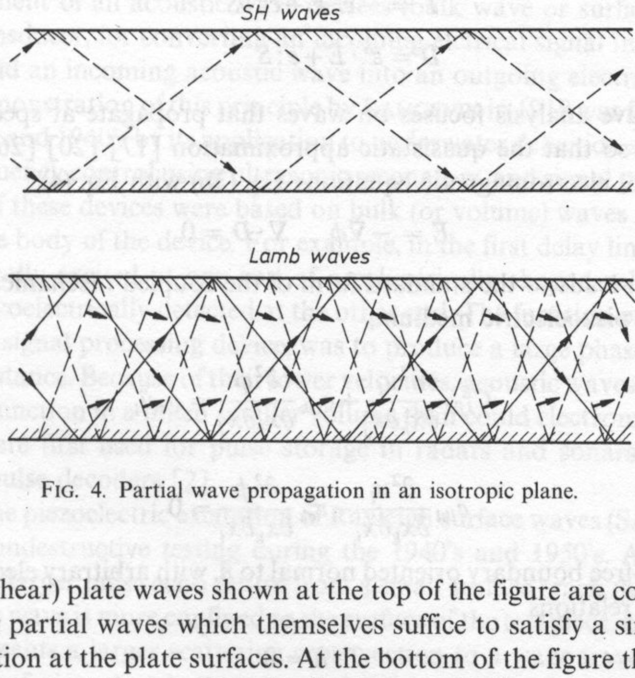

FIG. 4. Partial wave propagation in an isotropic plane.

SH (horizontal shear) plate waves shown at the top of the figure are constructed from horizontal shear partial waves which themselves suffice to satisfy a single zero stress boundary condition at the plate surfaces. At the bottom of the figure the Lamb waves are composed of vertical shear and longitudinal waves. Both types of partial waves are required to satisfy the boundary conditions. In an anisotropic, but nonpiezoelectric plate, there is no electric field associated with elastic wave propagation, and boundary conditions require only that the plate faces be stress-free. The problem can still be solved by superposing obliquely traveling plane waves. But these waves are not, in general, pure longitudinal or pure shear, and all three wave types are coupled by the stress boundary conditions. Except in certain cases of symmetrical plate orientation and propagation direction, the wave solutions do not decompose as shown in Fig. 4. To summarize, elastic wave solutions in nonpiezoelectric crystal plates are most generally constructed from three partial waves. A similar remark applies to SAW propagation on a nonpiezoelectric crystal substrate.

In the piezoelectric substrates required for SAW devices, coupling between the elastic and electromagnetic requires that both mechanical and electrical boundary conditions be satisfied at the substrate surface. (A similar remark would apply to the case of plate waves in a piezoelectric plate.) The partial wave method may still be applied, but the partial waves must now be solutions to the coupled elastic and electromagnetic equations

$$\nabla \cdot T = \varrho \frac{\partial^2 u}{\partial t^2} \tag{3a}$$

$$\nabla \times E = -\mu_0 \frac{\partial H}{\partial t} \qquad \nabla \times H = \frac{\partial D}{\partial t} \tag{3b}$$

$$\begin{aligned} T &= -e \cdot E + c^E : S \\ D &= \varepsilon^S \cdot E + e : S \end{aligned} \tag{3c}$$

Piezoelectric wave analysis focuses on waves that propagate at speeds close to the elastic velocity, so that the quasistatic approximation [17] [20] [26] can be made, replacing the full electromagnetic equations Eq. (3b) with Eq. (4).

$$E = -\nabla \phi \qquad \nabla \cdot D = 0 \tag{4}$$

Combining then leads to the standard form of the coupled mechanical and electrical equations for a piezoelectric medium,

$$C^E_{ijkl} \frac{\partial^2 u_l}{\partial x_k \partial x_j} + e_{ijk} \frac{\partial^2 \phi}{\partial x_k \partial x_j} = \varrho_m \ddot{u}_i \tag{5}$$

$$e_{ikl} \frac{\partial^2 u_l}{\partial x_k \partial x_i} - \varepsilon^S_{ek} \frac{\partial^2 \phi}{\partial x_k \partial x_i} = 0$$

At a stress-free boundary oriented normal to $\hat{n}$, with arbitrary electrical boundary conditions, the relations

$$T \cdot \hat{n} = 0 \tag{6a}$$

$$\begin{aligned} \Phi &= \Phi' \\ D \cdot \hat{n} &= D' \cdot \hat{n} \end{aligned} \tag{6b}$$

must be satisfied in general. In SAW device analysis, however, it is common to consider only short-circuit boundary conditions (where $\Phi = 0$) or open-circuit boundary conditions (where $D \cdot \hat{n} = 0$) at the surface of the substrate. There are then just four boundary conditions: three mechanical and one electrical. (The number may be further reduced, as noted above, for particular symmetric substrate orientations and propagation direction). As a consequence, four partial waves are required. Solution of Eq. (5) for plane waves always yields three solutions, corresponding to the three plane elastic wave solutions for a nonpiezoelectric material, but modified by the piezoelectric interaction. However, Eq. (5) also permits the existence of the four piezoelectric surface-type partial waves required to satisfy the four boundary conditions imposed in piezoelectric SAW analysis. Three of these solutions correspond to the three partial waves required for nonpiezoelectric SAW, but modified by piezoelectricity. The fourth solution corresponds to the Laplace solution for Φ in a nonpiezoelectric material, again modified by the piezoelectricity.

3. Surface wave transduction

A basic element of all acoustic wave devices (bulk wave or surface wave) is the piezoelectric transducer, for converting an incoming elctrical signal into an outgoing acoustic wave and an incoming acoustic wave into an outgoing electrical signal. The first practical demonstration of this principle by Langevin in 1918 was followed during the 1920's, 1930's and 1940's by its application to underwater detection systems (sonar), filtering and frequency control using ultrasonic resonators, and signal processing using delay lines. All of these devices were based on bulk (or volume) waves propagating in the interior of the body of the device. For example, in the first delay lines a bulk wave was piezoelectrically excited at one end of a cylindrically-shaped solid body (or in a liquid), and piezoelectrically detected at the other end. The function of the delay line, the first acoustic signal processing device, was to produce a large phase shift or delay time in a short distance. Because of their lower velocities, acoustic waves in solids could accomplish this function in a much smaller volume than could electromagnetic waves. These devices were first used for pulse storage in radars and sonars, as well as in computers and pulse decoders [2].

Interest in the piezoelectric excitation of Rayleigh surface waves (SAW) first arose in the field of nondestructive testing during the 1940's and 1950's. A surface wave generates a much larger pulse echo return from a small surface crack than does a bulk wave, because the wave is more confined to the surface of the test piece, and because the surface crack presents a larger scattering cross section to a wave traveling along the surface. A review of piezoelectric transducers for these applications was published in 1967 by Viktorov [27]. Typical transducer structures are illustrated in parts (a) and (b) of Fig. 5. These are based on the concept of exciting the wave by a distribution of forces applied to the surface of the solid, as in the earlier geophysical studies by Lamb (1904) and others. In both examples an external piezoelectric structure was used to generate such forces.

A second impetus to the development of piezoelectric surface wave transducers was provided by the recognition that an ability to tap into an acoustic delay line at

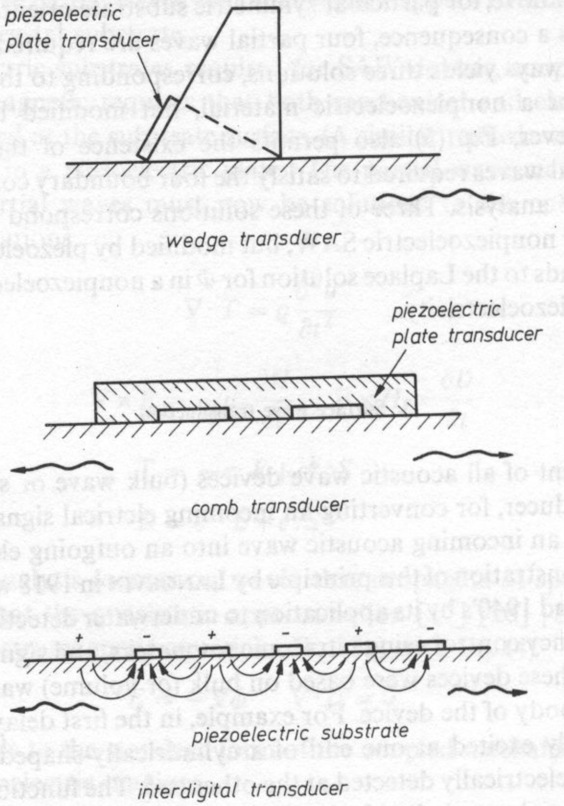

FIG. 5. Methods of surface acoustic wave SAW transduction (a) Wedge, (b) Comb, (c) Interdigital electrodes (IDT)

various points along the propagation path would vastly expand the signal processing capabilities of the device. Surface acoustic delay lines immediately attracted attention because of the ready accessibility of the wave at all points along its propagation path. The unsuitability of wedge and comb transducers for tapped delay lines led quickly to the invention and rapid development of the interdigital transducer, shown in part (c) of Fig. 5. Here, transduction and propagation occur in the same piezoelectric material. A periodic electric field, generated in the medium by a comb electrode structure, with alternate electrodes driven in phase opposition, creates a strain distribution that changes sign spatially with the same period as the surface wave to be excited.

The interdigital transducer (IDT) quickly assumed a major role in SAW technology, because of its suitability for tapped delay line applications and its planar character, which made it compatible with integrated circuit technology. A number of text and reference works dealing with the theory of these transducers appeared in the 1970's and 1980's [17], [20], [24], [25], [26].

4. Surface wave signal processing and resonators

After the perfection of the IDT SAW transduction technique there occurred a virtual explosion in SAW device development. A small sampling will serve to illustrate the richness and variety of the applications. Details may be found in reference works [14], [19], [22], [24], [25] and in the periodical literature.

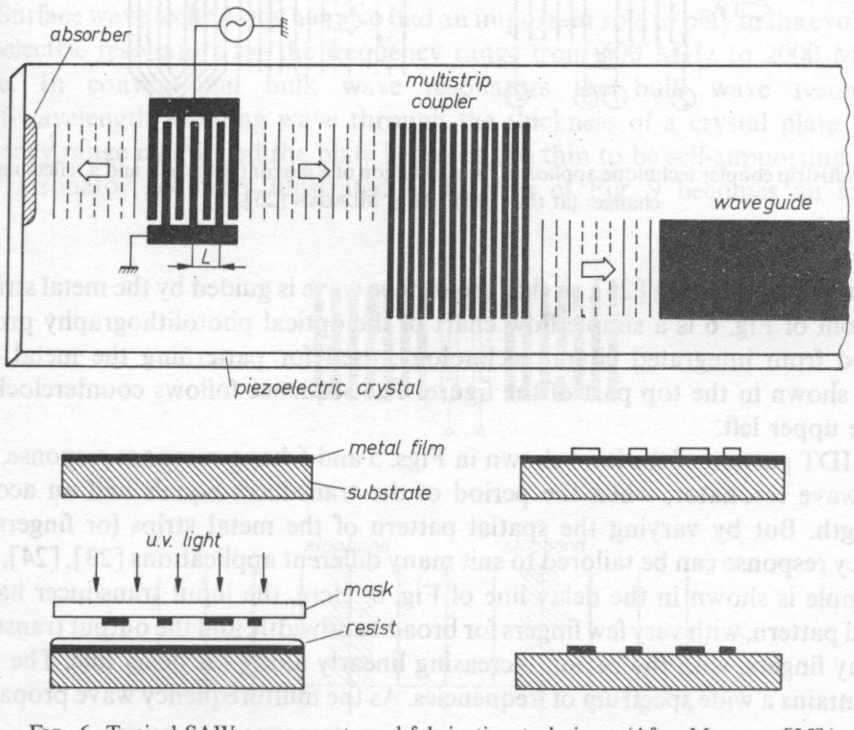

FIG. 6. Typical SAW components and fabrication technique. (After MORGAN [25].)

The top part of Fig. 6 illustrates several kinds of surface wave device components using the piezoelectric effect. They are all realized by depositing metal patterns on a piezoelectric crystal, either coupling to the surface acoustic waves by means of piezoelectrically generated electric fields or perturbing the piezoelectric surface wave by changing the electrical boundary conditions a the substrate surface. At the left is the interdigital transducer structure of Fig. 5 (c). In the center of the figure is a multistrip coupler. This functions essentially as an IDT receiver coupled directly, strip by strip, to an IDT transmitter. In this case it serves to laterally displace the surface wave beam, but many other applications developed from this simple concept [25]. (Figure 7 gives two examples.) At the right of Fig. 6 is a surface wave duct waveguide. The short circuit electrical boundary conditions under the film slow down the wave velocity and create

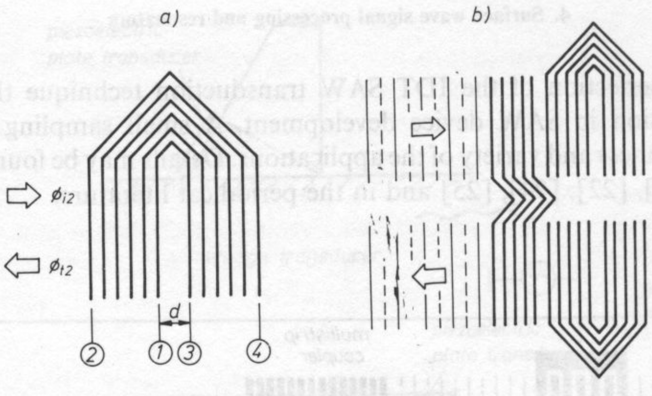

FIG. 7. Multistrip coupler technique applied to the realization of a mirror (at the left) and a reflecting track changer (at the right). (After MORGAN [25].)

a trapped wave condition [25], so that the surface wave is guided by the metal strip. At the bottom of Fig. 6 is a simple flow chart of the optical photolithography process, borrowed from integrated circuit technology, used for patterning the metal components shown in the top part of the figure. The sequence follows counterclockwise from the upper left.

An IDT pattern of the kind shown in Figs. 5 and 6 has a resonant response, as in a bulk wave resonator, when the period of the transducer equals half an acoustic wavelength. But by varying the spatial pattern of the metal strips (or fingers) the frequency response can be tailored to suit many different applications [23], [24], [25]. An example is shown in the delay line of Fig. 8. Here, the input transducer has the standard pattern, with very few fingers for broad bandwidth, and the output transducer has many fingers, with the period increasing linearly along the delay line. The input pulse contains a wide spectrum of frequencies. As the multifrequency wave propagates

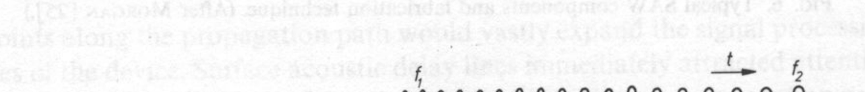

FIG. 8. "Chirp" waveform generated in a SAW delay line. (After MORGAN [25].)

under the output transducer the various frequency components couple out at points where wavelength-period matching to the IDT occurs. High frequencies arrive first and low frequencies last, so that the short input signal is converted into a long signal with a linear frequency modulation. Such so-called "chirp" waveforms are widely used in radar. If this same waveform is fed back into the output of a chirped delay line, with the chirp pattern reversed in time from that shown in the figure, the long waveform is compressed into a narrow pulse again.

Surface wave technology has also had an important role to play in the evolution of piezoelectric resonators for the frequency range from 500 MHz to 2000 MHz and above. In conventional bulk wave resonators the bulk wave resonates in a half-wavelength standing wave through the thickness of a crystal plate. For the frequency range mentioned the plate becomes too thin to be self-supporting, and the SAW resonator geometry illustrated at the top of Fig. 9 becomes an attractive

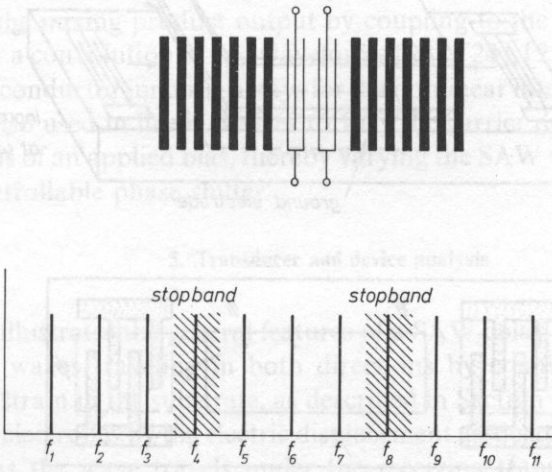

FIG. 9. SAW resonator structure and mode distribution. (After AULD [17].)

alternative. A standing SAW now resonates between two deposited metal strip gratings shown by the heavy vertical lines. These gratings act as strong reflectors within stopbands near the Bragg reflection frequencies, where the metal strip period is equal to a multiple of one-half a SAW wavelength. Standing wave resonances can occur only within a grating stopband. By making the stopband sufficiently narrow one single resonance can be selected in each stopband (Fig. 9, bottom). In this way the central (or resonator) part of the structure can be made long enough for convenience in fabrication and to permit insertion of IDT's. At the same time all but a few of the length resonances are suppressed by the discrete stopband frequency response of the grating mirrors. SAW resonators may also be realized with etched groove gratings, as shown in the top

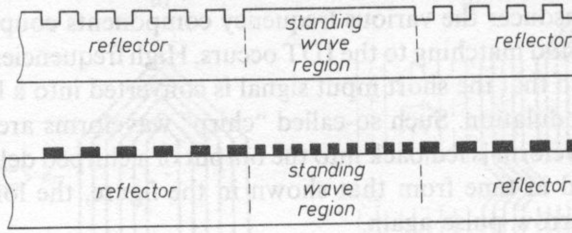

FIG. 10. STW resonator structure. (After AULD [17].)

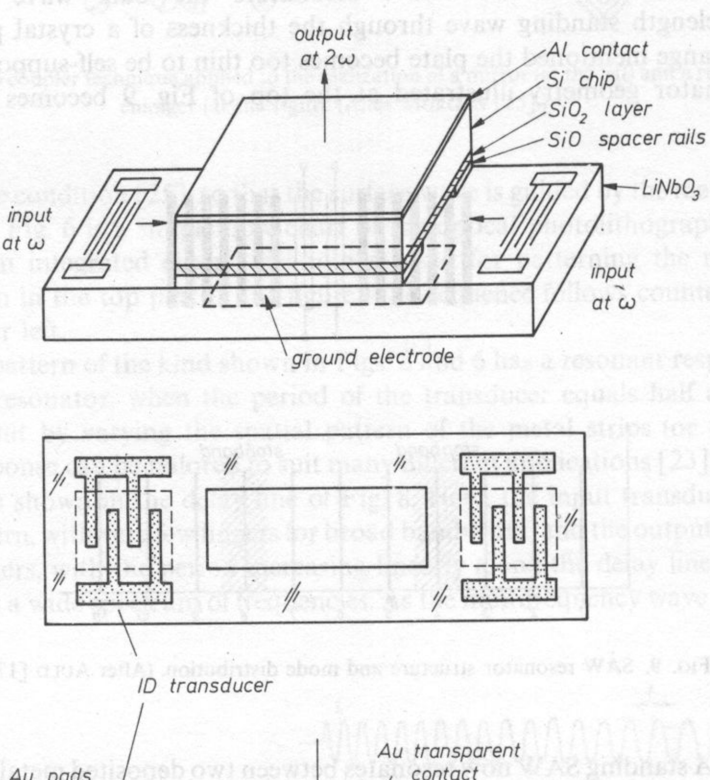

FIG. 11. SAW-semiconductor convolver. (After KINO [24].)

part of Fig. 10. Another alternative is to operate with the STW introduced in Section 1 (Fig. 10, bottom). These resonators are easier to fabricate because the STW wavelength can be longer than the SAW wavelength at the same frequency. They also have certain operational advantages [3].

Another class of SAW devices for signal processing exploits the piezoelectric interaction between surface acoustic waves and charge carriers in semiconductors. Both semiconductor substrates (gallium arsenide) and semiconductor overlays (silicon) on insulating substrates are used. The first efforts in this direction aimed at developing a SAW amplifier by interacting the wave with a stream of drifting carriers. Amplification was observed, but the overall transducer-to-transducer performance was not sufficiently good to make the device attractive for practical applications. A useful class of *nonlinear* SAW/semiconductor devices used the electric field associated with a piezoelectric surface wave to electrically mix two counterpropagating waves. Figure 11 illustrates one version of this type of device. Waves are excited at each end of the delay line, and distributed electrical mixing occurs in the silicon chip overlay. Spatial integration of the mixing product output by coupling to the top electrode generates a correlation or a convolution of two waveforms [23], [24], [25]. Some versions of this device use semiconductor junction arrays for the nonlinear interaction. Semiconductor junctions are also used in linear devices to vary the carrier density in the interaction region by means of an applied bias, thereby varying the SAW velocity and realizing an electrically-controllable phase shifter.

5. Transducer and device analysis

Figure 12 illustrates the general features of a SAW delay line. The IDT at the left excites surface waves traveling in both directions by creating a spatially periodic distribution of strain in the substrate, as described in Section 3. At the right, charge is induced on the electrodes by the electric displacement associated with the piezoelectric surface wave as the wave travels under the receiving transducer thereby creating a current through the electrical load Z_L. The power in the wave not converted to electrical power in the receiver load is transmitted past the transducer, where it must be absorbed by a lossy coating on the substrate to avoid reflection. A reflection of the incident wave also occurs at the front side of the receiving transducer, and this return wave is again reflected at the transmitting transducer. Care must be taken to minimize all these multiple reflections at the transducers, as well as those at the ends of the substrate.

Since the introduction of SAW technology in signal processing devices, a variety of methods have evolved for analyzing the surface wave components such as those in Figs. 6 and 12. It is convenient to unify this theory in a format analogous to that of microwave circuit theory. Microwave circuit formalism deals with ensembles of distributed electromagnetic components that are connected by wave propagation regions to form electromagnetic "circuits", analogous to the ensembles of SAW components in Figs. 6 and 12. It is customary in microwave theory to represent each subelement of the

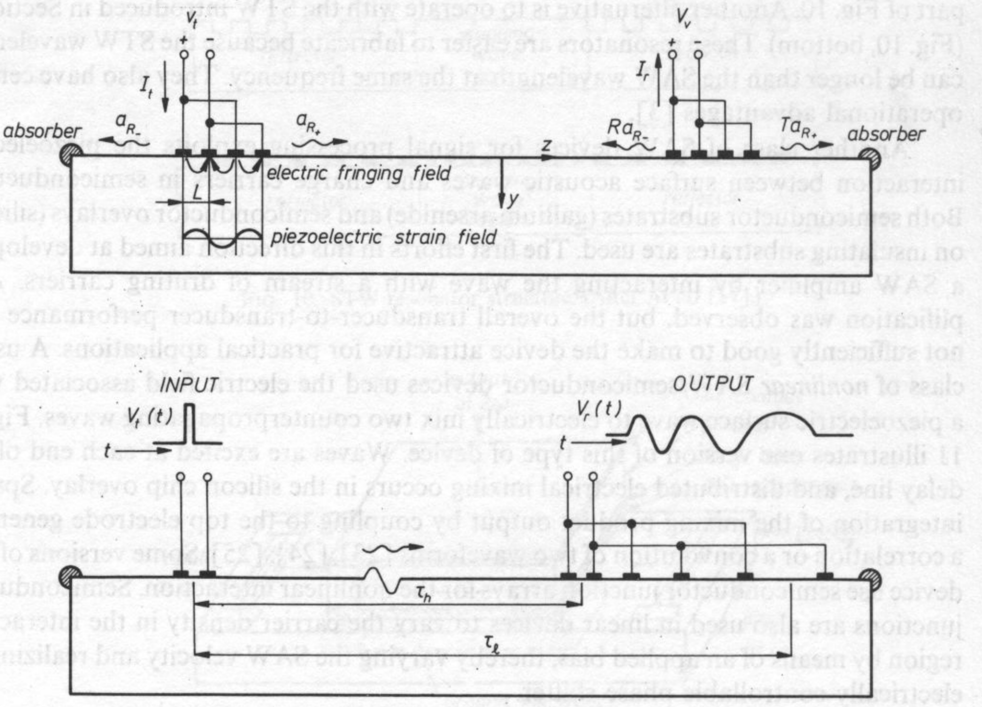

FIG. 12. SAW delay line, with IDT excitation and detection. (After AULD [17].)

ensemble by its scattering matrix. In this scattering matrix, the matrix elements (or S–parameters) relate the outgoing wave amplitudes [b] to the incoming wave amplitudes [a] at terminal planes defining the subelement in question (amplitudes are normalized so that unit amplitude corresponds to unit power). This S–parameter relation is written as

$$[b] = [S]\,[a] \tag{7}$$

In Fig. 12, for example, the outgoing waves are the surface acoustic waves emitted to the right and left of the left-hand (or transmitting) transducer by an electromagnetic wave incident at the electrical terminals. At the right-hand transducer the wave launched by the transmitter is an incoming wave and the wave passing beyond the transducer is outgoing.

Equation (8) shows a mathematical formulation of the distributed transducer principle briefly outlined in Section 3.

$$\begin{aligned} a_{\mathrm{R}+}(z) &= e^{i\beta_{\mathrm{R}}z}/4P_{\mathrm{R}}\int_{-\xi}^{+\xi} e^{i\beta_{\mathrm{R}}\zeta}\{\quad\}_{\mathrm{R}+}\cdot\hat{\mathbf{y}}\,d\zeta, \qquad z > +\xi \\ \{\quad\}_{\mathrm{R}+} &= \{\Phi_{\mathrm{R}+}^{\infty *}(0)\,(i\omega D_y(0,z))\} \end{aligned} \tag{8}$$

The amplitude of the emitted wave is expressed an integral over a distribution of sources defined by the driving charge distribution (equal to the normal electric displacement D_y) induced on the transducer electrodes by the incident electromagnetic wave. This result is derived from a general field theorem that constitutes a basic analytic tool in microwave circuit theory, but extended to include piezoelectric waves [17]. The modified theorem can be stated as

$$\nabla \cdot [\quad] = 0 \tag{9}$$

with

$$[\quad] = \mathbf{v}_1 \cdot \mathbf{T}_2 - \mathbf{v}_2 \cdot \mathbf{T}_1 \oplus \mathbf{E}_1 \times H_1 \ominus E_2 \times H_1 \tag{10}$$

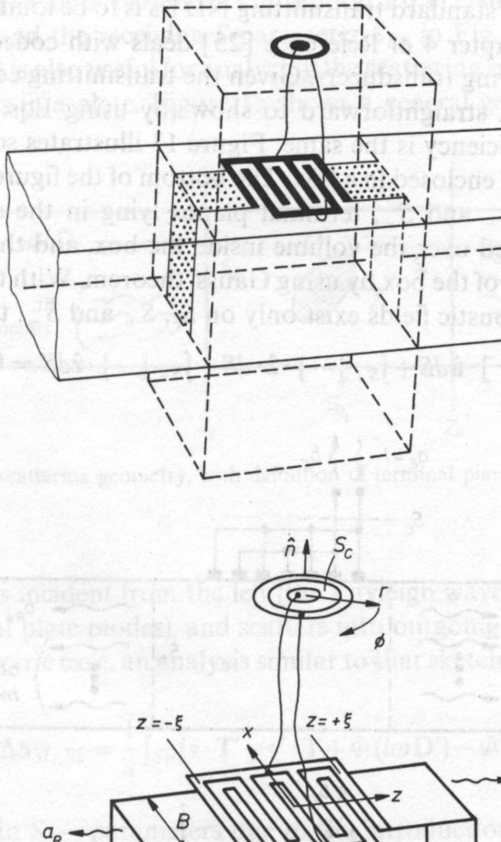

FIG. 13. Construction for proof of IDT reciprocity. General configuration (top). Definition of terminal planes $S \ldots S_-$ and S_c (bottom). (After AULD [17].)

In Eq. (10) the circled plus and minus signs apply for media where the electromagnetic coupling is due to piezoelectricity, as in the cases considered here. The signs are interchanged when the electromechanical coupling is due to magnetostriction (page 176, Vo. II in Reference [17]). For purely electromagnetic problems the displacement velocity and stress terms are suppressed, and Eqs. (9) and (10) reduce to the Lorentz reciprocity relation used in microwave theory. Another variant of Eq. (10), useful for purely piezoelectric problems, replaces Maxwell's equations by the quasistatic equations (Eq. (4)) and which replaces the square bracket in Eq. (8) by

$$\{\quad\} = \{\mathbf{v}_1 \cdot \mathbf{T}_2 - \mathbf{v}_2 \cdot \mathbf{T}_1 + \mathbf{\Phi}_1 (i\omega \mathbf{D}_2) - \mathbf{\Phi}_2 (i\omega \boldsymbol{D}_1)\} \tag{11}$$

Detailed analysis of standard transmitting NDT's is to be found in references such as [17], [24], [25]. Chapter 4 of Reference [25] deals with coded transducer finger patterns, and also receiving transducers. Given the transmitting conversion efficiency of an IDT it is, in fact, straightforward to show (by using Eqs. (9)–(11)) that the receiving conversion efficiency is the same. Figure 13 illustrates schematically, at the top of the figure, an IDT enclosed in a box. The bottom of the figure defines electric, S_c, and surface acoustic, S_+ and S_-, terminal planes lying in the surface of the box. Equation (9) is integrated over the volume inside the box, and then converted to an integral over the surface of the box by using Gauss' theorem. With the assumption that electromagnetic and acoustic fields exist only on S_c, S_+ and S_-, this reduces to [17]

$$\int_{S_c} [\quad] \cdot \hat{\mathbf{n}} dS + \int_{S_+} \{\quad\} \cdot \hat{\mathbf{z}} \cdot dS - \int_{S_-} \{\quad\} \cdot \hat{\mathbf{z}} dS = 0 \tag{12}$$

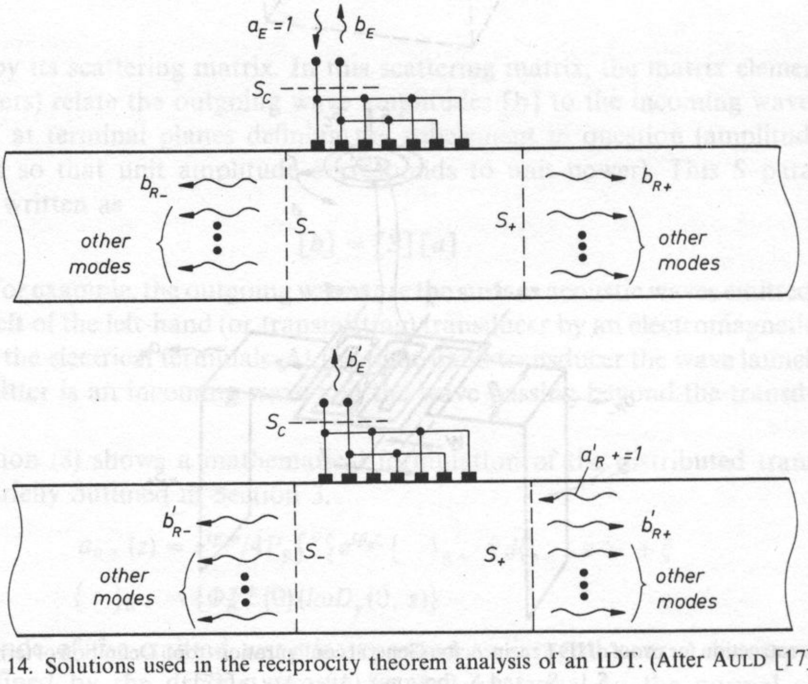

FIG. 14. Solutions used in the reciprocity theorem analysis of an IDT. (After AULD [17].)

At the acoustic terminal planes S_+ and S_- the quasistatic form (Eq. (11)) may be used, while the full electromagnetic form must be used at the electrical terminal plane S_c.

The solutions 1 and 2 in Eqs. (9)–(11) are now selected as in Fig. 14. It can be shown [17] that inside the brackets [ ] and { } cross products involving pairs of outgoing waves cancel, so that the integral over S_- is zero and

$$\begin{aligned} \int_{S_+} \{\quad\} \cdot \hat{\mathbf{z}}\, dS &= b_{\mathrm{R}+}\, a'_{\mathrm{R}+}\, (4P_{\mathrm{RR}}B) \\ \int_{S_c} [\quad] \cdot \hat{\mathbf{n}}\, dS &= -b'_{\mathrm{E}} a_{\mathrm{E}} \left(\int_{S_c} 2\,(E_r)_i\,(H_\phi)_i\, dS\right) \end{aligned} \tag{13}$$

When the power flow integrals on the right side of these relations are normalized to unity, according to the S–parameter convention, Eq. (12) shows that the transmitting S-parameter S_{RE} and the receiving S-parameter S_{ER} in Fig. 14 are equal.

Equation (9) is also useful for analyzing the scattering of elastic waves from internal inhomogeneities in a plate. Figure 15 shows a general geometry, where a particular

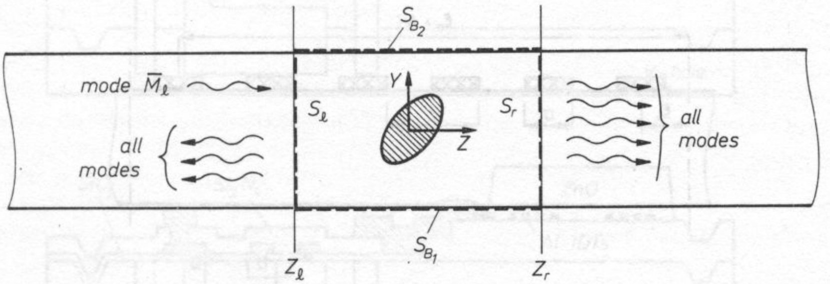

FIG. 15. General scattering geometry, with definition of terminal planes S_r and S_l. (After AULD [17].)

plate mode $\bar{M}$ is incident from the left (the Rayleigh wave, SAW, is in fact one of the family of general plate modes), and scatters into outgoing modes of all types. For the general piezoelectric case, an analysis similar to that sketched above yields the relation

$$\Delta S_{\overline{M_l},\overline{N_r}} = \frac{1}{4}\int_{S_F} \left(\mathbf{v}\cdot\mathbf{T}' - \mathbf{v}'\cdot\mathbf{T} + \Phi\,(i\omega\mathbf{D}') - \Phi'\,(i\omega\mathbf{D})\right)\cdot\hat{\mathbf{n}}\, dS \tag{14}$$

for the change in S – parameters due to the introduction of an inhomogeneity. The integral is over the surface S_F of the inhomogeneity. Primed fields are those existing when the inhomogeneity is present, and unprimed fields are those when it is absent. (Note that there are no reflections and no mode transmission couplings when the inhomogeneity is absent.) An analogous formula can be derived for the change in S–parameters due to a surface inhomogeneity (Fig. 16). That is

$$\Delta S_{Rl,Rl} = \frac{1}{4}\int_{\xi-a/2}^{\xi+a/2} (\mathbf{v}\cdot\mathbf{T}' + i\omega\Phi\mathbf{D}')\cdot\hat{\mathbf{n}}\, dz \tag{15}$$

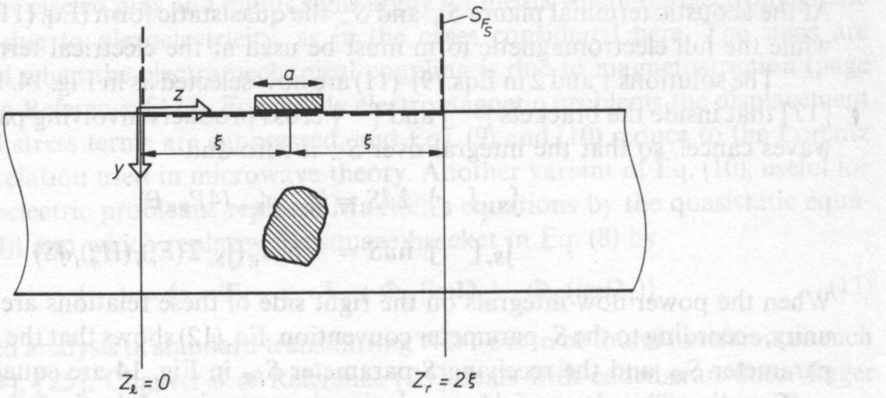

FIG.16. Surface and volume scattering of SAW. (After AULD [17].)

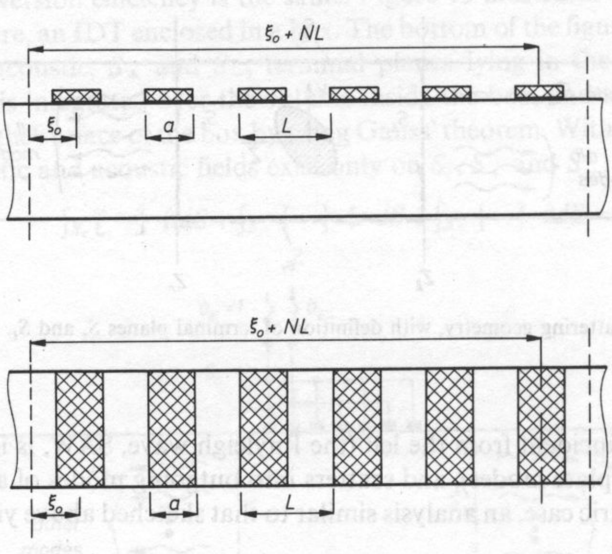

FIG. 17. Scattering of SAW by surface and volume gratings. (After AULD [17].)

The inhomogeneities need not be single, but may take the form of periodic gratings (Fig. 17). In this way Eq. (15) may be used to analyze surface wave scattering from an IDT (Fig. 12).

6. New techniques and future directions

The initial motivation for developing piezoelectric surface wave devices came from the need for better nondestructive testing and signal processing technologies. In these areas the use of SAW devices has become very sophisticated, with widespread ap-

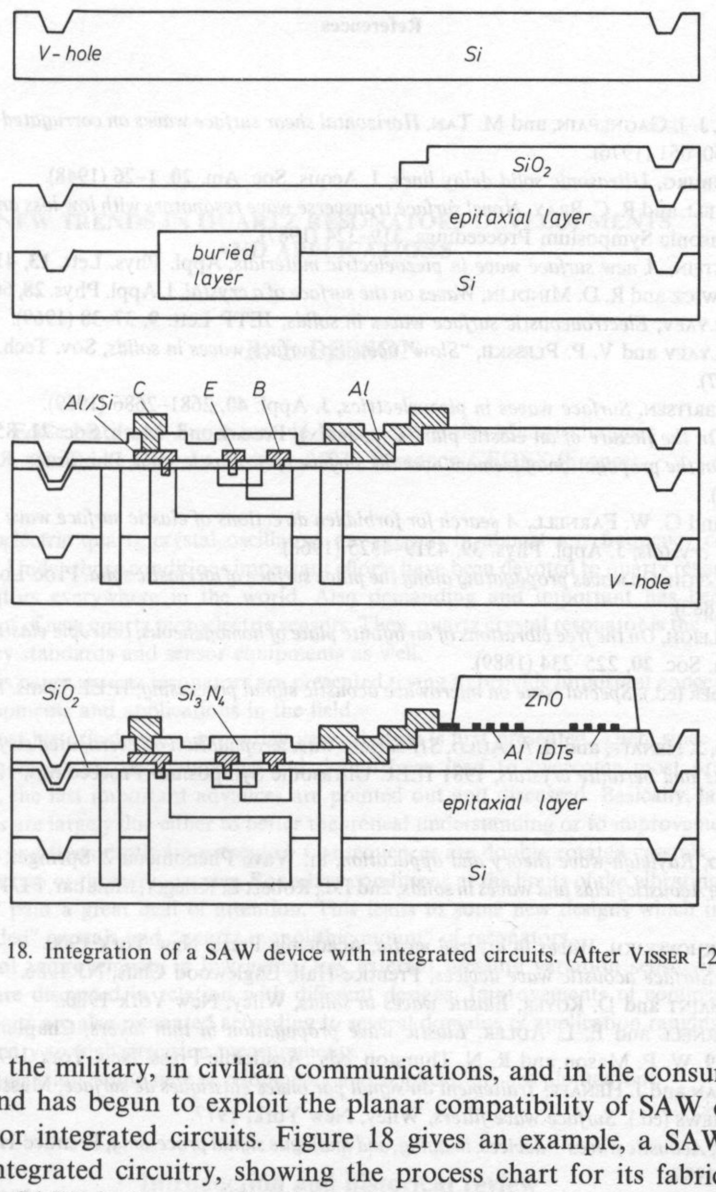

FIG. 18. Integration of a SAW device with integrated circuits. (After VISSER [28].)

plications in the military, in civilian communications, and in the consumer market. A recent trend has begun to exploit the planar compatibility of SAW devices with semiconductor integrated circuits. Figure 18 gives an example, a SAW filter with associated integrated circuitry, showing the process chart for its fabrication (after VISSER [28]). SAW devices are also beginning to play an important role in sensor technology. Delay lines have been deposited on microfabricated silicon diaphragms for pressure sensing. Surface acoustic wave temperature pressure and acceleration sensors utilize the temperature and strain sensitivity of surface acoustic waves on crystal substrates. The extreme sensitivity of SAW delay lines to surface conditions has led to their use in sensors for air pollution and for studies of adsorbed materials. Recent years have also seen a resurgence of interest in SAW/semiconductor devices for electrically controllable phase shifters and oscillators.

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(b)

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