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A RIGOROUS FIELD ANALYSIS OF MULTILAYERED SAW DEVICES

Walter J. Ghijsen and Peter M. van den Berg

Delft University of Technology

Delft, The Netherlands

ABSTRACT

A rigorous analysis of the acousto-electric field in general multilayered SAW devices in the time Laplace-transform domain is outlined. The configuration of investigation contains an arbitrary number of homogeneous and reciprocal media of any kind of anisotropy and orientation. The basic equations of homogeneous media are solved using a spatial Fourier transformation. Using this solution and the boundary conditions at the interfaces, the total field problem is reduced to a boundary value problem of the electric potential and the electric surface charge density in the plane of the electrodes, and a relation between the Fourier transforms of these quantities. This dual boundary value problem is solved iteratively, by minimization of the root-mean-square error in one of the boundary conditions.

INTRODUCTION

Traditional Surface Acoustic Wave (SAW) devices consist of a number of electrodes on a piezoelectric substrate. Current technological developments however, involve SAW devices consisting of a number of electrodes in a multilayered environment, such as integrated SAW devices and chemosensors. In integrated circuits, a piezoelectric layer of ZnO is deposited on a Silicon substrate, and a typical SAW chemosensor consists of a gas sensitive layer on a piezoelectric substrate. These SAW devices exhibit a very complicated behavior, and a clear understanding of their physical operation is important to their design.

This paper summarizes a rigorous analysis of general multilayered SAW devices, in which the piezoelectric effect is fully taken into account. This research has been carried out to support the technical developments and applications of these devices. It is a continuation of former work (1), in which a method was presented to analyse configurations, in which the symmetry and orientation of all media was restricted. In the present work the analysis only uses the reciprocal properties of the homogeneous media. A more detailed description of this analysis is given in (2).

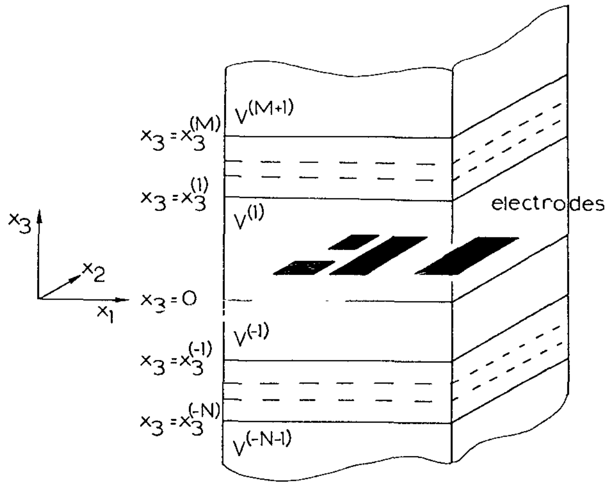

Fig. 1. The general configuration.

THE ACOUSTO-ELECTRIC FIELD DESCRIPTION OF THE GENERAL CONFIGURATION

We confine our attention to SAW devices that can be modelled by the general configuration of Fig. 1. This configuration consists of a number of perfectly conducting electrodes of vanishing thickness in a multilayered structure. The Cartesian reference frame $(\mathbf{i}_1, \mathbf{i}_2, \mathbf{i}_3)$ and pertaining spatial coordinates are chosen such that the plane $x_3 = 0$ is one of these interfaces. The electrodes are located in this plane $x_3 = 0$ (the electroded plane). The layered structure contains any number M of homogeneous layers above the electroded plane, and any number N of layers below it. All media are time-invariant, locally reacting, reciprocal and homogeneous. They may posses any type of symmetry and orientation. All sources in the configuration are electric surface charge sources in the electroded region of the electroded plane.

The field analysis of the general configuration is carried out in the time Laplace-transform domain. A quantity in this domain is obtained from its representation in the time domain by the Laplace transform. This transform takes advantage of the invariance of the configuration with respect to time, and the linear properties of the acousto-electric field. Causality of the field is enforced, by requiring all field quantities to be analytic in the right half of the complex plane

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of the Laplace variable. The frequency behavior of a configuration is obtained from this analysis in the limiting case of a vanishing positive real part of the Laplace variable.

In each homogeneous medium, the acousto-electric field is described by the basic equations in linear form; it is assumed that the amplitudes of the involved quantities are small enough such that the first order terms account for the studied effects sufficiently accurately. The basic equations are derived from the equations of elastodynamics, the quasi-static approximation (neglecting the magnetic field) of Maxwell's equations of electromagnetics and the constitutive equations. At the interfaces the basic equations do not hold and have to be supplemented by appropriate boundary conditions.

THE SPECTRAL FIELD ANALYSIS

The analysis takes advantage of the spatial invariance of the layered structure in all directions parallel to the interfaces. The field analysis in each homogeneous medium is performed in the spectral domain. The representation of a quantity in the spectral domain is obtained from its representation in the time Laplace-transform domain (or spatial domain) by a two-dimensional Fourier transform with respect to x_1 and x_2. In the spectral domain, the basic equations can be reduced to a linear, homogeneous first order differential equations for the field vector in the variable x_3. The eight elements of the field vector are the field quantities being continuous across the non-electroded interfaces.

In the spectral domain, the acousto-electric field of each homogeneous medium can be written as the general solution of the differential equation for this field vector. This solution can be written as the product of a 8x8 composition matrix and a wave vector. The columns of the composition matrix are the eigenvectors of the system matrix of the differential equation of the field vector. Each of the eight elements of the wave vector is the product of some constant and an exponential function of which the argument depends on one of the eigenvalues of the system matrix. For real and non-zero values of the spatial Fourier transform variables and for the time Laplace variable having a real part larger than zero, four of these eigenvalues of passive media have a real part larger than zero, and the other four have a real part smaller than zero. Consequently, the causality constraints exclude four of the eight wave vector components of the superstrate and substrate. The eigenvectors can all be taken orthogonal in the sense of the reciprocity theorem. As a consequence, the decomposition matrix, being the inverse of the composition matrix, can be obtained without carrying out matrix inversion.

The solution of each homogeneous medium and the continuity of the field vector across the interfaces outside the electroded plane, is the basis of the propagator matrix formalism and the scattering matrix formalism. In the propagator matrix formalism, the field vectors in two different locations are related. In the scattering matrix formalism, the wave vector in two different locations are expressed in each other. Both formalisms lead to the effective admittance relating the spectral electric potential and the spectral electric surface charge density in the electroded plane. The propagator matrix formalism is more straightforward, but is numerically instable. This problem is avoided in the more sophisticated scattering matrix formalism.

THE ITERATIVE SOLUTION OF THE DUAL BOUNDARY VALUE PROBLEM

The boundary conditions for the electric potential and the electric surface charge density in the electroded plane $x_3 = 0$ form, together with the spectral relation between these quantities, the dual boundary value problem. The acousto-electric field of the entire multilayered configuration can be found from the solution of this dual boundary value problem.

This effective admittance can be written as a quotient of the determinants of two 8x8 matrices. The elements of these matrices are finite for finite, non-zero values of the spatial Fourier variables and a finite value of time Laplace variable. The curves in the plane of the Fourier variables along which the numerator of the admittance is equal to zero, represents the freely propagating waves of the layered structure, such as surface waves. The curves along which the denominator vanishes, represents the waves for the multilayered structure in which the plane $x_3 = 0$ is taken perfectly conducting.

The dual boundary value problem is solved iteratively providing an estimate of the field in each step, satisfying the boundary conditions for the electric surface charge density. The electric potential of this field deviates from the prescribed value at the electrodes. The integrated square value of this deviation is introduced as an error criterion for the satisfaction of the boundary conditions at the electrodes. In each step, the improved estimate field is obtained as the superposition of the estimate field of the previous step and a correction field. The potential of this correction field is taken orthogonal to the correction potentials of all previous steps. This procedure leads to a minimum value of the integrated square value of the deviation at the electrodes. The correction field in each step is constructed from a variational field. At the electrodes, the variational surface charge density is taken equal to the surface charge density associated to the deviation of the estimated electric potential in the previous step, and outside the electrodes it is taken equal to zero. The variational potential is related to this variational surface charge density by the spectral relation. In the numerical Fourier inversion of the spectral potential, the contribution of the zero of the effective admittance has to be determined analytically, when this zero is located near the integration path.

NUMERICAL RESULTS

The general field theory for multilayered structures and the iterative techniques have been programmed in FORTRAN 77 on a VAX-11/750 computer. To keep the computational effort within reasonable limits, the configurations in the present computer program are taken invariant in the x_2-direction. This means that all electrodes in the plane $x_3 = 0$ are infinitely long and parallel to i_2. The configuration of Fig. 1 thus reduces to one with a two-dimensional character.

To obtain an impression of the performance of the present method, a configuration of ten infinitely long electrodes on a PZT-4 substrate has been considered (Fig. 2a). The c-axis of infinite symmetry is taken perpendicular to the electroded plane. The results of the present method as depicted in Figs. 2b and 2c, are in agreement with the results of a different, computational technique for single substrate configurations (3). The real part G and the imaginary part B of the admittance per unit length in the x_2-direction as function of the normalized frequency k are given in Fig. 2b. The normalized frequency k is given as $k = \omega L/v^{sw}$, with ω the radial frequency, v^{sw} the frequency independent surface-wave velocity of the PZT-4 substrate and L as indicated in Fig. 2a. The amplitude X of potential associated to the surface wave is depicted in Fig. 2c. The dashed curve in Fig. 2b represents the surface-wave contribution to the real part of the input admittance.

The present method of analysis has also been applied to the multilayered structure of Fig. 3a. This configuration consists of four electrodes in a ZnO-SiO_2-Si structure. This configuration represents practical integrated SAW devices. The orientation of the c-axis of the hexagonal ZnO is perpendicular to the plane of the electrodes, and the dimensions are chosen in accordance with a practical design. For the values of the material constants we refer to (2). In former work (1) this axis was taken parallel to the electrodes, which is not the practical situation in these integrated SAW devices. The real part G and the imaginary part B of the admittance per length unit in the x_2-direction as function of the normalized frequency k are depicted in Fig. 3b. The normalized frequency k is given as $k = \omega L/v^c$ with ω the radial frequency,

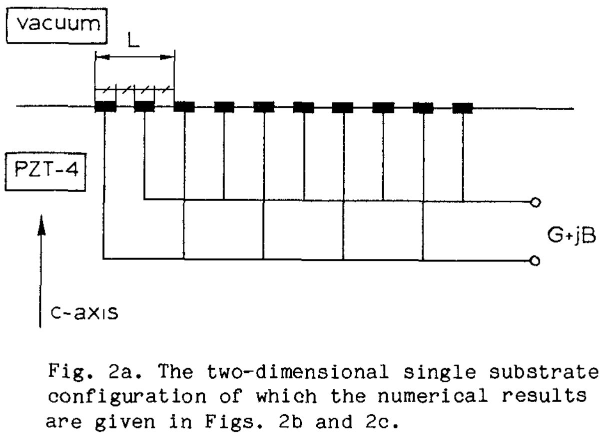

Fig. 2a. The two-dimensional single substrate configuration of which the numerical results are given in Figs. 2b and 2c.

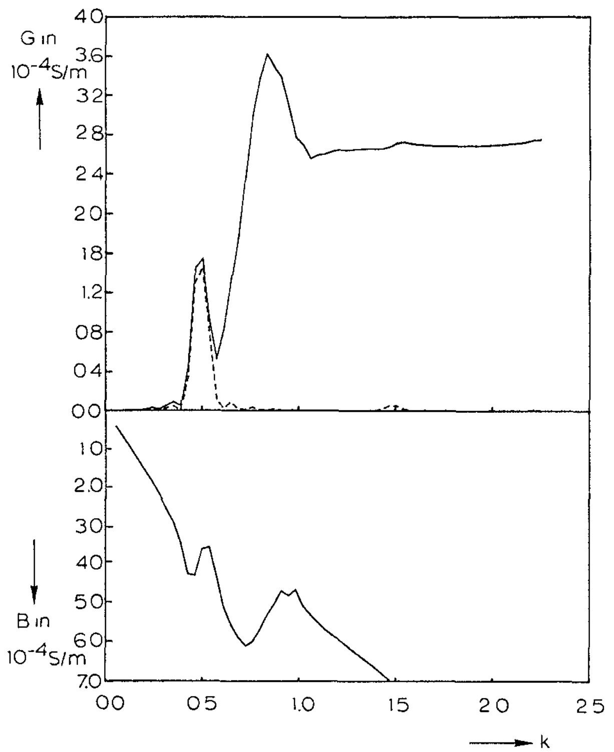

Fig. 2b. The real part G and the imaginary part B of the admittance of the configuration of Fig. 2a, as function of the normalized frequency k. The dashed curve is the surface wave contribution to the real part of the admittance.

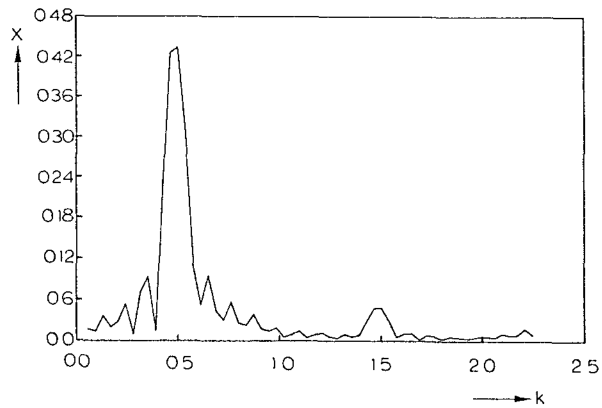

Fig. 2c. The amplitude X of the surface-wave potential of the configuration of Fig. 2a, as function of the normalized frequency k.

v^c the cutoff velocity and L as depicted in Fig. 3a. It is noted that the behavior of the input admittance is mostly capacitive. The amplitudes ϕ^{sw} of the potential associated to the surface waves of this configuration as function of the normalized frequency k are given in Fig. 3c. In contrast to single substrate structures, multilayered structures may have more than one surface wave

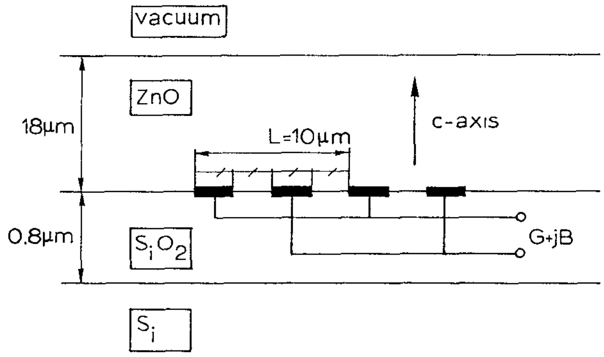

Fig. 3a. The two-dimensional layered configuration of which the numerical results are presented in Figs. 3b-3d.

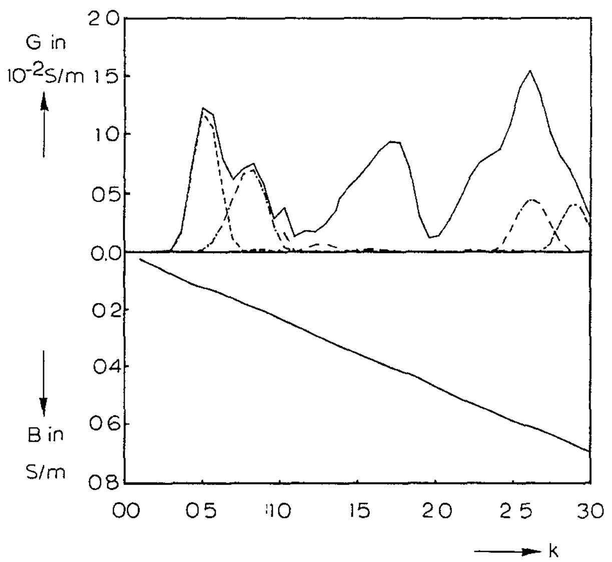

Fig. 3b. The real part G and the imaginary part B of the admittance of the configuration of Fig. 3a, as function of the normalized frequency k. The dashed curves are the surface wave contributions to the real part of the admittance.

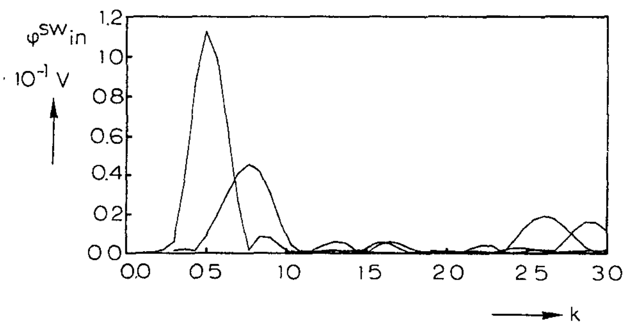

Fig. 3c. The amplitude ϕ^{SW} of the surface-wave potential of the configuration of Fig. 3a, as function of the normalized frequency k.

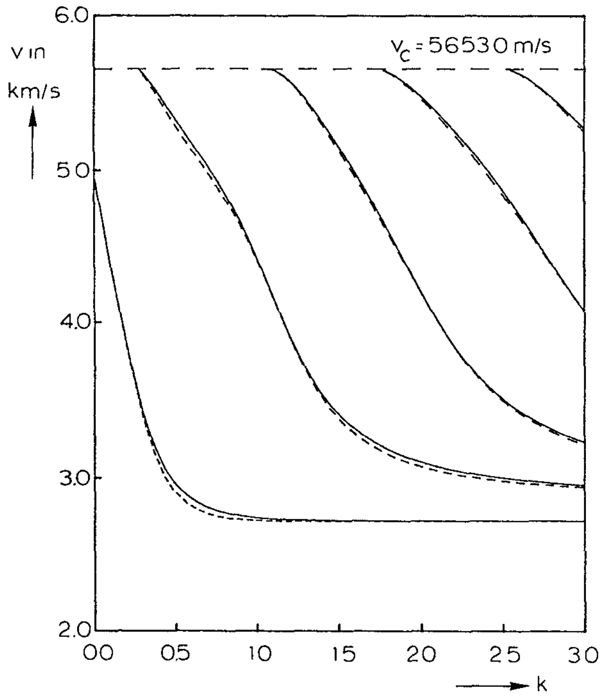

Fig. 3d. The surface wave velocities of the layered structure of Fig. 3a as function of the normalized frequency k. The solid curves are associated to the structure of Fig. 3a without the electrodes in the plane $x_3 = 0$, and the dashed curves are associated to the structure of Fig. 3a having a perfectly conducting plane $x_3 = 0$.

having velocities that vary with the frequency. The surface-wave velocities of the present multilayered structure as function of the normalized frequency k is shown in Fig. 3c.

CONCLUSIONS

The present analysis is able to determine the acousto-electric field of general multilayered SAW devices accurately. The proposed numerical technique enables the calculation of their field rigorously with reasonable computational effort.

REFERENCES

(1) W.J. Ghijsen and P.M. van den Berg, "A rigorous computational technique for the acousto-electric field problem in SAW devices," IEEE Trans. Ultrason., Ferroelectrics, Frequency Contr., vol. UFFC-33, pp. 375-384.

(2) W.J. Ghijsen, "The acousto-electric field analysis of multilayered Surface Acoustic Wave devices." Delft: Ph.D. Thesis of the Delft University of Technology, to be published in 1987.

(3) D. Quak, "Interdigital excitation of surfaces waves on the basal plane of a semi-infinite, hexagonal, piezoelectric crystal," Wave Electronics, vol. 3, pp. 107-123, 1977/1978.