ISCMP Varna'82

Edited by M Borissov

Optical and Acoustic Waves in Solids — Modern Topics

Proceedings of the 2nd International School on Condensed Matter Physics

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World Scientific Publishing Co Pte Ltd
P O Box 128
Farrer Road
Singapore 9128

ISBN 9971-950-61-8
9971-950-62-6 pbk

P R E F A C E

The Second Meeting of the permanent International School on Condensed Matter Physics (ISCMP) was held from 23 Sep . to 1 Oct., 1982 in Varna. This School is sponsored by the Institute of Solid State Physics of the Bulgarian Academy of Sciences with the collaboration of the Academies of Sciences of the USSR and the other socialist countries. Honorary chairman is Prof. A.M. Prohorov, Nobel prize winner.

Meetings of the School are being held every two years. The subject of the 1982 meeting was "Optical and Acoustic Waves in Solids - Modern Topics" and its scientific program was prepared with the assistance of an International Scientific Council consisting of Profs.: V.Agranovich (USSR), G.Albrecht (GDR), M.Borissov (Bulgaria), V.Ginzburg (USSR), J.Gyulai (Hungary), F.Koch (FRG), A.Maradudin (USA), V.Pokrovski (USSR), A.Prohorov (USSR), and V.Shikin (USSR).

134 scientists (44 from abroad) took part in the School. 18 lectures were given in 37 lecture hours and 3 poster sessions with 15 communications were organized.

These Proceedings contain most of the lectures read during the School. The contents follow the order of the lecture school program. For one reason or another the following lectures could not be included: F.F.Beleznay (Hungary) "Surface Acoustic Waves - a New Tool to Characterize Semiconductor Crystals and Surfaces", Yu.Gulyaev (USSR) "Interaction of Acoustic Waves with Electrons", Yu.Gulyaev (USSR) "Advances in Surface Acoustic Wave Devices", A.Kaplyanski (USSR) "Optical Investigations of Acoustic Phonons in the 10^{12} Hz Frequency Range", L.Keldysh (USSR) "Semiconductors under High Intensity Excitations".

The Organizing Committee wishes to express its profound gratitude to all lecturers who kindly agreed to take part in our 1982 meeting and contributed to its successful work.

Sofia, Prof.M.Borissov

10 January, 1983

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ACOUSTIC AND OPTICAL WAVES IN SOLID STATE ELECTRONICS

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1. Introduction

Solid state physics has distinguished itself in last decades as a highly developed scientific field. Being closely related with other basic physical disciplines as well as other fields of natural science such as chemistry and biology, it provides powerful means for studying the complicated processes in condensed matter. This is the main reason why solid state physics now proves to be the basis and accelerator of contemporary advance in technology. One remarkable manifestation of this link is the development of solid state electronics with its most progressive trend - microelectronics.

This lecture aims at giving a general survey on the contemporary status of wave microelectronics - a modern and promising field in which acoustic and optical waves in condensed media are used as information carrier. The analogy between microelectronic devices using both types of waves is followed to illustrate a formal analogy between acoustics and electromagnetism. The place of microwave acoustics and optics amongst other fields of wave and solid state electronics is discussed and some of their modern trends are considered. Microwave and integrated optical sensors are particularly emphasized.

2. Major stages in the development of solid state electronics

Modern electronics is a wide and complex field of science and techniques with great importance for economics.

Its name is due to the fact that information processing has for a long time been performed with electron beams in vacuum and solids. Recently, such fields of electronics were developed in which the electronic processes do not play an important role. In a broad sense of the word electronics now includes the whole technical basis of modern informatics and more precisely - modern communication and computer techniques, automatics and robotics.

The general field in the development of modern electronics as technical basis of informatics is microelectronics. Its most important trends are: further miniaturization of elements; more complex functions performed by an element; higher speed of operation; consumed power reduction; integration of elements by means of an unified technology; higher reliability and price reduction.

In the above definition of electronics, as will be further understood in the lecture, we do not include the so called high power macroelectronics. This has recently been developed for use in energetics, new technologies and power machines in a direction which is in a sense opposite to that of microelectronics.

The information carriers in electronics are electron beams or waves. So, if we exclude the magnetic discs, we can consider electronics, in a narrow sense of the word, as composed of two parts: electron beam electronics and wave electronics (Fig.1). However, this partitioning is not absolute: the electron beams are known to possess wave properties which are also used in some devices of modern electronics. Also, new electron elements are being developed, the performance of which is based on interactions of electrons with acoustic waves.

The modern development of the two parts of electronics is based mainly on using solid state materials. Until recently the most common materials used in electron beam electronics were semiconductors. For that reason this is usually called semiconductor electronics. In the second part of solid state electronics the main materials are dielectric crystals and that is often called dielectronics. However, such a classification cannot be considered as rigorous. In fact, in solid state electron beam electronics

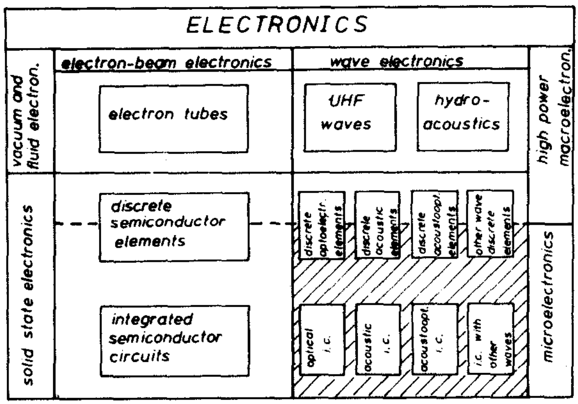

Fig. 1

we often use dielectrics, superconductors, magnetic materials etc. next to semiconductors, while in solid state wave electronics semiconductors also find some application.

The development of semiconductor microelectronics has passed through two major stages. In the first one electronic circuits have been realized by means of discrete electron elements. Its development began in 1952 (Fig.2) with the rapid replacement of electron tubes by transistors in home and digital electronics.

With the invention of the first bipolar semiconductor integrated circuits in 1963 and the first MOS integrated circuits in 1966 began the second, integral stage in the development of semiconductor electronics.

The large variety of applications of modern digital electronics is mainly based on the use of semiconductor integrated circuits. Their integration already exceeds one million elements per chip (Fig.3). Nevertheless, despite of being more complicated, integrated circuits have reliability much higher than that of discrete elect-

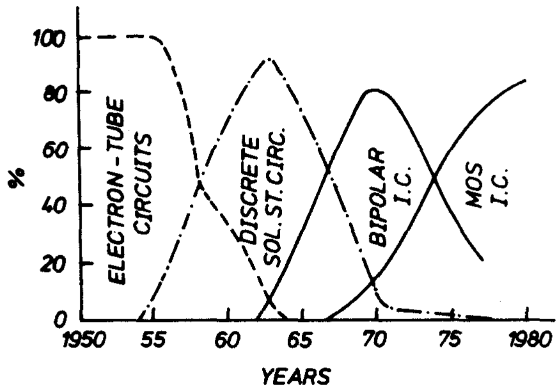

Fig.2 . Electronic circuits in digital electronics

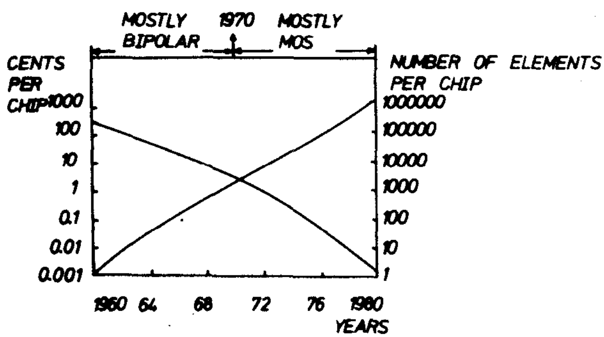

Fig.3 . Integration and price of integrated circuits

ronic circuits. The modern technology for fabrication of integrated circuits provides element prices as low as one thousandth of cent per element. The speed of operation of the active elements reaches the order of several nanoseconds for power of 10^{-4} W and one microsecond for 10^{-9} W (Fig.4).

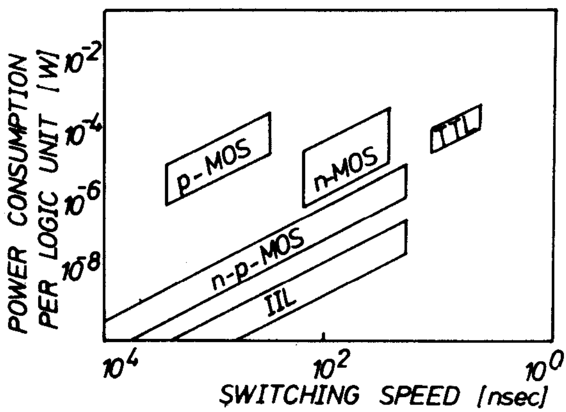

Fig.4. Speed of operation

The use of new materials and technologies and particularly the development of integrated circuits with submicron element technology provide the possibility to increase further the integration and speed of operation. At present the semiconductor integrated circuits find such a wide application that we usually identify them with solid state microelectronics. It is thus not astonishing that most publications in distinguished international journals on solid state electronics such as Solid State Electronics, Solid State Circuits, Microelectronics etc., as well as those of firms producing electronic devices are almost entirely devoted to semiconductor microelectronics.

The first wave electronic devices were constructed even before the invention of electronic tubes. They used high and ultrahigh radiofrequency electromagnetic waves as well as low frequency ultrasound waves in fluids. Radiotechniques and hydroacoustics were followed by the development of solid state acoustoelectronics and optoelectronics. These two parts of wave electronics started developing in the 60-ies, almost simultaneously with the creation of the first semiconductor integrated circuits. They are still in progress, find wide applications and open new possibilities for receiving, translating and processing of information.

The solid state microelectronics, including acoustoelectronics, optoelectronics, acoustooptics as well as this based on use of other waves in solids still remain in the stage of discrete elements. New trends towards element miniaturization, decrease of consumed power, and integration of elements into integrated wave electronics circuits by means of an unified technology are now observed. These give rise to solid state wave microelectronics. We shall confine our lecture to this latter field only since it is the most perspective.

Other fields of solid state wave electronics such as high power acoustooptics (acoustooptical deflectors and modulato-s), some coherent optics and holography devices for pattern recognition, high power ultrasound transduction elements etc. are also in progress now. However, these devices either cannot be miniaturized or do not need so. Therefore, we shall consider them as high power wave macroelectronics elements which, as specified above, will be excluded from this discussion.

One feature by which solid state wave microelectronics devices are better than semiconductor circuits is their increased functionnality. It means that a single element can perform functions which are otherwise realizable by using a whole circuit. This is achieved by appropriately exploring the complicated physical properties and processes in the solid medim the element is fabricated of. A simple example of a microwave acoustic device with increased functionnality as compared with conventional semiconductor microelectronic devices is the surface acoustic wave (SAW) intermediate frequency (IF) filter for colour TV receivers (Fig.5). Two SAW interdigital (ID) transducers, one of which appropriately wheighted through the varying overlap length of electrodes, are deposited on the polished surface of a single piezoelectric crystal plate. The transfer function characteristics of the filter, which is the product of the

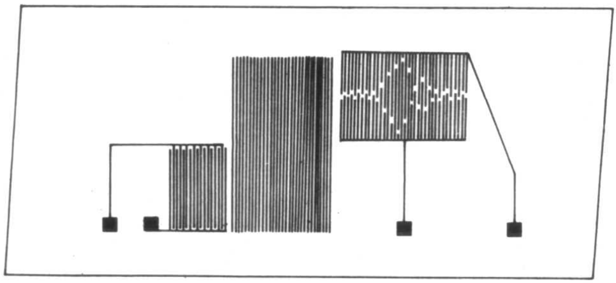

Fig.5 . Schematic diagram of a SAW IF filter for colour TV

transfer functions of individual transducers, is shown in Fig.6. This characteristics is also achievable by use of conventional discrete elements circuits (Fig.7). It is not difficult to see the advantages of the SAW filter in number of elements, size and reliability.

From the viewpoint of integration and miniaturization of elements, solid state wave microelectronics is so far behind semiconductor circuits. Also, active microwave solid state elements for use in the HF and UHF ranges have not yet reached a satisfactory stage of development if one excludes the integrated optical lasers. However, many potential capabilities have not been explored in this direction. As regards passive electronic elements microwave electronics already exhibits some advantages over semiconductor circuitry.

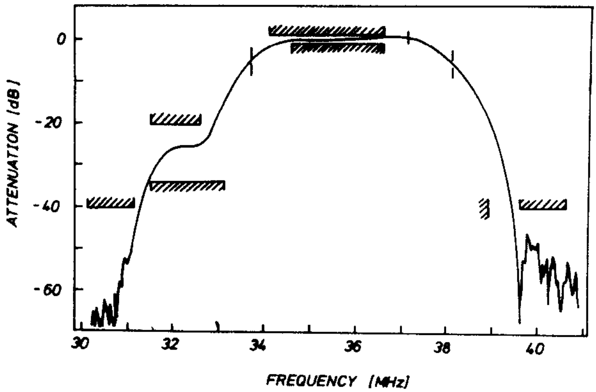

Fig.6 . Attenuation of a IF TV SAW filter

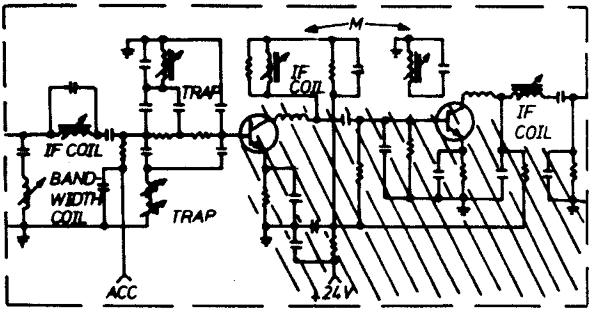

Fig.7 . Part of conventional IF TV channel block (unshaded) which can be replaced by a single SAW filter

One of the main reasons for the relatively slow progress suffered by microwave solid state electronics is that it possesses yet little capability to compete with semiconductor integrated circuits in the field of digital electronics. It is hard to beleive that this situation might change considerably in next future. However, parallelly with progressing in the digital aspect, microelectronics is now being in increasing need of high performance analog devices. The disproportion in the development of these two types of devices is strongly undesirable since it has an adverse effect on the compex introduction of electronics into industry and life. This is of partcular importance in connection with the application of microprocessors. For such reasons large efforts are being made nowadays toward increasing the rate of progress of wave microelectronics.

Several examples of such devices already having found application or being in progress now will be considered in the second part of our lecture. However, before proceeding with this, we shall be concerned breafly with the analogy, distinction and interaction between acoustic and optical waves used in solid state wave microelectronics.

3. Acoustic and optical waves in solids and their interaction

3.1 Acoustic and optical waves in unlimited crystals

There are different types of waves which are usable for purposes of microelectronics because of having relatively low attenuation and small wavelength. Such are: acoustic, optical, magnetostatic and plasma waves etc. However, among these, the acoustic and optical waves are most widely used. Besides the small wavelength permitting to realize very small sized devices, these waves can easily be excited and detected. In addition, they are extremely sensitive to geometrical, electrical and mechanical effects, thus allowing one to guide them and change technologically their parameters.

The parallelism observed in both the importance of acoustic and optical waves for microelectronics and the features of microwave acoustic amd optical devices is a manifestation of an analogy between the two types of waves. Above all, this analogy shows out from a striking similarity between the basic equations of electromagnetism and acoustics [1] (Table 1). Optical waves are governed by Maxwell's equations. Acoustic waves are des-

Table 1 . The electromagnetic-acoustic analogy

Maxwell's equations	Acoustic field equations
$-\nabla \times E = \mu \cdot \frac{\partial H}{\partial t}$	$\nabla \cdot T = \rho \frac{\partial v}{\partial t} - F$
$\nabla \times H = \varepsilon \cdot \frac{\partial E}{\partial t} + \sigma E + J_s$	$(1 + \tau : \frac{\partial}{\partial t}) \nabla_s v = s : \frac{\partial T}{\partial t}$
E electric field	T stress
H magnetic field	v velocity
J_s source current density	F body force density
ε permettivity	s compliance
μ permeability	ρ mass density
σ conductivity	τ relaxation
$\nabla \times = \begin{pmatrix} 0 & -\frac{\partial}{\partial z} & \frac{\partial}{\partial y} \\ \frac{\partial}{\partial z} & 0 & -\frac{\partial}{\partial x} \\ -\frac{\partial}{\partial y} & \frac{\partial}{\partial x} & 0 \end{pmatrix}$	$\nabla \cdot = \begin{pmatrix} \frac{\partial}{\partial x} & 0 & 0 & 0 & \frac{\partial}{\partial z} & \frac{\partial}{\partial y} \\ 0 & \frac{\partial}{\partial y} & 0 & \frac{\partial}{\partial z} & 0 & \frac{\partial}{\partial x} \\ 0 & 0 & \frac{\partial}{\partial z} & \frac{\partial}{\partial y} & \frac{\partial}{\partial x} & 0 \end{pmatrix}$
$-[\nabla \times] = [\widetilde{\nabla \times}]$	$\nabla_s = [\widetilde{\nabla \cdot}]$
Poynting's vectors	
$E \times H$	$-v \cdot T$

cribed with the acousic field equations. If one compares the two kinds of equations (appropriately written) as well as the relations for Poynting's vectors, one immediately sees that they perfectly parallel each other. A formal analogy thus establishes between the electric and magnetic fields of the electromagnetic wave on one hand and the mechanical stress and velocity of the acoustic wave on the other.

Furthermore, Maxwell's equations lead to two kinds of electromagnetic uniform plane waves that propagate along a given direction in a crystal. These are transverse waves with mutually perpendicular polarization directions. Polarization and velocity can be deduced from the optical indicatrice tensor which is geometrically represented by the index ellipsoid (Fig.8). Along the optical axis of uniaxial crystals (the main rotation axes of hexagonal,

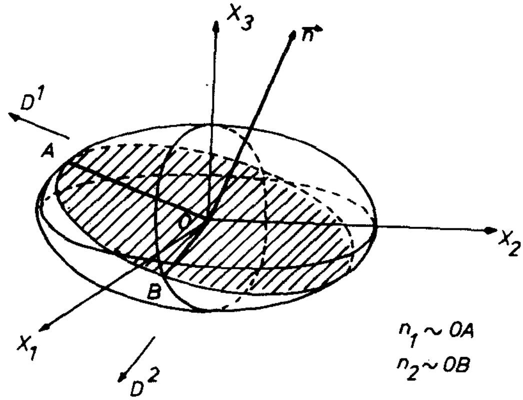

Fig.8 . Index ellipsoid

tetragonal and trigonal crystals) both waves are degenerate, i. e. propagate with equal velocity. In noncentrosymmetrical crystals can occur, under specific conditions, the so called optical rotary activity which causes the polarization plane to rotate as the wave propagates in the crystal.

From the acoustic field equations it follows that three uniform plane acoustic waves with mutually perpendicular polarizations can propagate along a given direction in a crystal. The velocities and polarizations of these waves result from Christoffel's equations (Table 2). However, by contrast with the electromagnetic case, acoustic waves can be longitudinal. In general, they are linearly polarized along directions which neither coincide with the propagation vector nor are perpendicular to it. Only along

Table 2 . Acoustic plane wave equations in solids

$u_j = \hat{u}_j \exp[ik(n_k x_k - vt)]$	Plane wave propagating along a direction with unit vector $n(n_1, n_2, n_3)$, phase velocity v and wavenumber $k=\omega/v$
$\rho \frac{\partial^2 u_j}{\partial t^2} - c_{ijkl} \frac{\partial^2 u_k}{\partial x_i \partial x_l} = 0$	Wave equations c_{ijkl} stiffness tensor ρ mass density
$(\Gamma_{jk} - \delta_{jk} \rho v^2) \hat{u}_k = 0$	Christoffel equations $\Gamma_{jk} = n_i n_l c_{ijkl}$
$\lvert \Gamma_{jk} - \delta_{jk} \rho v^2 \rvert = 0$	Three phase velocities $v^{(n)}$, three eigenvectors $\hat{u}_j^{(n)}$

some specific directions, called pure mode axes, they transform into one longitudinal and two transverse waves. Along the three-, four-, and sixfold axes both transverse waves have equal velocity. Such are called acoustical axes. By analogy with the electromagnetic case, the propagation of a degenerate transverse wave along an acoustic axis in a noncentrosymmetrical crystal can be subjected to rotary activity. In piezoelectric crystals acoustic waves can be acompanied by electrostatic waves travelling with the same velocity. To illustrate the above considerations the electromagnetic and acoustic waves which can propagate along the X-axis of a hexagonal crystal are shown in Fig.9.