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Angaben zur Veröffentlichung / Publication details:

Müller, C., A. A. Nateprov, Günter Obermeier, Matthias Klemm, Vladimir Tsurkan, Achim Wixforth, Reinhard Tidecks, and Siegfried R. Horn. 2007. "Surface acoustic wave devices." In *Zinc oxide materials and devices II: Integrated Optoelectronic Devices, 21 - 24 January 2007, San Jose, California, USA*, edited by Ferechteh Hosseini Teherani and Cole W. Litton, 647415. Bellingham, WA: SPIE. https://doi.org/10.1117/12.714700.

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ABSTRACT

Starting with an introduction to surface acoustic waves, their generation and detection using interdigital transducers (IDTs) on piezoelectric materials (e.g. $LiNbO_3$ and ZnO) will be reviewed. Then the application of surface acoustic waves in electronic devices will be presented. Moreover, recent studies, using the technique of attaching the material of investigation onto the sound path of the acoustic delay line between the IDTs is discussed.

Keywords: Surface acoustic wave (SAW) devices, SAW-sensors, materials science with SAW

1. SURFACE ACOUSTIC WAVES

The phenomenon of surface acoustic waves (SAW) was first theoretically described by Lord Rayleigh [1]. His theory was then applied by geologists in the field of earthquakes [2], because he proposed that surface acoustic waves could be an important contribution to this phenomenon. Actually, this kind of earthquake waves are much better modelled having components in form of the later discovered Love waves, a special type of shear polarized surface acoustic waves, which propagate in layered structures.

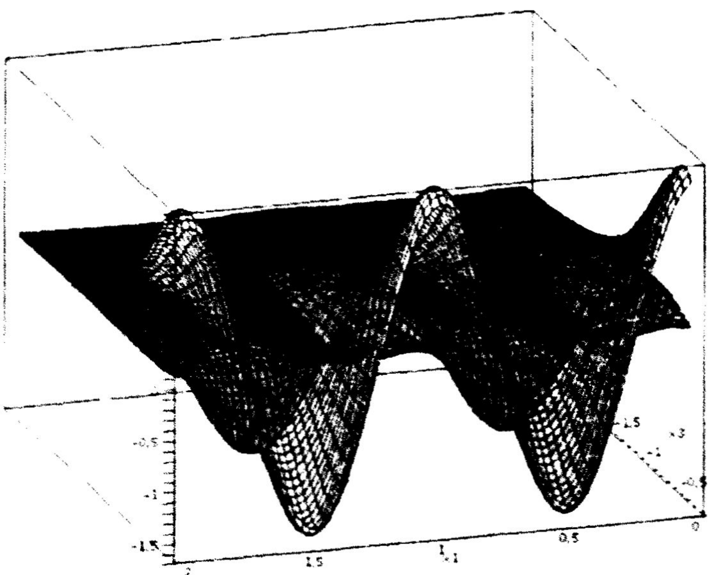

Fig.1: *Sketch of the displacements in a Rayleigh surface acoustic wave, according to the mathematical formulation given in Ref. 3. For details see the text.*

Zinc Oxide Materials and Devices II, edited by Ferechteh Hosseini Teherani, Cole W. Litton,
Proc. of SPIE Vol. 6474, 647415, (2007) · 0277-786X/07/$18 · doi: 10.1117/12.714700

In Fig. 1 a sketch of the displacements occurring in a SAW is shown. The figure gives the displacement of a particle from its equilibrium site due to the SAW in an isotropic medium. The front view is on the surface of the medium extending into the -x3 direction. The SAW is propagating in the x1 direction. Plotted is the (x1,x3) plane of the medium. In the absence of the SAW, all particles would be at a position on zero height in this plane. Two informations about the actual position have been plotted in the figure.

Firstly, the curve in red (that one with the smaller amplitude) gives information about the longitudinal shift of the particle along the propagation direction x1. If the red curve is above the plane (i.e. represents a positive value), the particle is shifted into the propagation direction. If it is below the plane (i.e. represents a negative value), the particle is shifted against the propagation direction. The absolute value of the shift depends on the amplitude of the red curve.

Secondly, the green curve gives information how far the particle is shifted perpendicular to the propagation direction, i.e. parallel to the x3 direction. If the curve is above the plane, the particle is shifted into the positive direction of the x3 co-ordinate. If the curve is below the plane the particle is shifted into the negative direction. The absolute value of the shift depends on the amplitude of the green curve.

Both shifts together describe a point on the well known elliptical movement of a particle in a Rayleigh wave (see e.g. Fig 10.23 on page 92 of Ref. 5).

There are a lot of more types of surface acoustic waves (e.g. Love waves in layered structures, shear waves, surface skimming bulk waves (SSBW), etc.[4 ,5]). The one which Rayleigh described, is polarized transversal out of plane of the medium the surface acoustic wave travels on. This type of surface wave, when travelling on an isotopic media, is labelled by his name, and called the Rayleigh wave.

A Rayleigh wave behaves similar to a usual water wave, which has most of its energy deposited on the surface of the water. When diving underneath the wave, one hardly can feel the movement of the wave. The same holds true for a surface acoustic wave: The amplitude of this wave is maximal in the direct vicinity of the surface and decays exponentially into the material which the wave travels on. The decay length is about the wavelength, λ_R. So it behaves like a 2 dimensional wave. The trajectory of a particle in the wave is an ellipsoid, when looking into the direction perpendicular to the propagation direction of the SAW and perpendicular to the direction of the polarisation. So the surface acoustic wave cosists of two wave components: One is longitudinal polarized along the wave propagation direction and the other one perpendicular to the propagation direction, i.e. like a shear wave polarization.

The sound velocity of the Rayleigh wave, v_R is around 10% lower than for a bulk shear wave and around 50% lower than for a bulk longitudinal wave of the medium travelling in the same direction. [4]. This is why a Rayleigh wave cannot excite a bulk wave and the energy is left concentrated at the surface. Lord Rayleigh calculated the sound velocity for an isotropic medium for a surface acoustic wave. The calculation of the sound velocity of a surface acousitc wave in an anisotropic medium can not be done analytically but only numerically, using a computer [6].

When the Rayleigh wave travels along a piezoelectric material, it generates, due to the compression and elongation, an electric field, accompanying the elastic wave. This electric field decays extremely fast perpendicular to the propagation direction of the wave. Following an argumentation given by Lewis [4] one can imagine that this electric field is radiated as an electromagnetic wave into the vacuum above the surface. For an electromagnetic wave it is $\lambda \cdot f = c$, with λ the wavelength, f the frequency, and c the speed of light. Using that $\omega=2\pi f$ is the angular frequency and $k=2\pi/\lambda$ the wave number vector, we get $\omega^2 = c^2 k^2$, or, in the three dimensional case

$$\omega^2 = c^2(k_1^{\ 2} + k_2^{\ 2} + k_3^{\ 2}) \qquad (1)$$

Here, k_1, k_2, k_3 are the Cartesian components of the wave number vector of the electromagnetic wave and ω is the angular frequency of the SAW. If one imagines that the SAW propagates along the x_1 direction it is $k_1 = k_R = \omega / v_R$. Since, in the direction x_2 the wavefront of the SAW is constant, that means $k_2 = 0$, eq. (1) yields

$$\frac{\omega^2}{c^2} - \frac{\omega^2}{v_R^{\ 2}} = k_3^{\ 2} \qquad (2)$$

Since, the sound velocity of the surface acoustic wave, v_R, is around 5 orders of magnitude smaller than the speed of light, c, it is $k_3^{\,2} \approx -\omega^2 / v_R^{\,2}$, that means $k_3 \approx \pm\, i\omega \,/ v_R = \pm\, ik_R$. The minus sign has to be chosen, because the potential Φ, generating the electric field of the radiated electromagnetic wave, has to be zero for going to infinity

So the potential Φ is given by

$$\Phi = \Phi_0 \exp\left(i(\omega t - k_R x_1)\right)\ \exp(-k_R x_3) \qquad (3)$$

Thus, the electric potential decays exponentially with the decay length $\lambda_R = 2\pi / k_R$, on going above the piezoelectric material, which the surface acoustic wave travels on.

The same argument can be applied for the elastic wave, which decays exponentially into the material. The decay for the longitudinal and transversal components of the Rayleigh wave (both propagating with v_R) occurs due to the higher velocities of the longitudinal and shear bulk waves, as mentioned above. Since the longitudinal bulk wave is faster than the longitudinal shear wave, the longitudinal component of the Rayleigh wave decays more strongly.

The sound velocity v_R itself does not depend on the frequency or wavelength, i.e. we have an acoustic wave. As there is no dispersion, the shape of a SAW is maintained [7]. This is in contrast to the surface waves propagating as seismic waves, which show a dispersion due to the inhomogeneity of the earth material. Waves with a longer wavelength go deeper into the earth material, which has a higher elastic constant than the surface, and travel, therefore, faster than waves with a smaller wavelength.

2. GENERATION AND DETECTION OF SURFACE ACOUSTIC WAVES USING INTERDIGITAL TRANSDUCERS

It took 80 years from the first theoretical description of surface acoustic waves, until their generation and detection in a miniaturised version was possible in an electrically controlled way, as necessary for an application in devices.

In 1965 White and Voltmer [8] developed the idea to employ the piezoelectric effect (found in 1880 by Pierre and Jacques Curie), more exactly the inverse effect, to ***generate*** surface acoustic waves: By applying a voltage between two electrodes, placed on top of a piezoelectric substrate, a distortion of the surface can be produced electrically. This elastical deformation travels with the surface acoustic wave velocity, v_0, of the substrate along the surface. If the distortion arrives at a further electrode pair, it can be amplified by applying a voltage between this pair, too. This can be repeated at an additional third electrode pair, and so on.

This was the basic idea of White and Voltmer, when applying a rf voltage on a periodic structure of fingers, yielding a sinusoidal shaped distortion. The interdigital transducer (IDT) was designed. It consists of fingerpairs which are equally spaced. It looks like the structure one gets if one puts the fingers of his two hands between each other. So every second finger is connected to the same palm, i.e. potential pad, or so called bus bar.

Fig. 2 shows an IDT structure consisting of 11 fingerpairs. It should be added that the IDT structure itself was originally applied for a bulk wave device developed by Mortley.

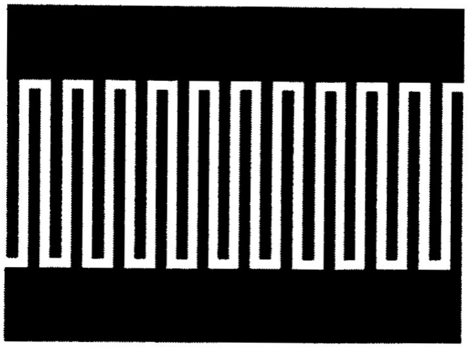

Fig.2: *An interdigital transducer (IDT) for generating surface acoustic waves on a piezoelectric material.*

The distortion generated by the IDT experiences not only an amplification, but also a sinusoidal shaping. This is caused by the two adjacent electric fields of an electrode, which have opposite direction: So, one electric field stretches the material, whereas the neighbouring field, showing into the opposite direction, compresses it. The reason for the opposite elastic effect is that the inverse piezoelectric effect only occurs in a material without an inversion centre of symmetry in its crystalline structure.

The amplitude of the emitted SAW depends on the frequency of the rf voltage applied to the IDT. The amplitude is proportional to the Fourier transform of the charge distribution along the IDT [9]. The most simple model to describe this behaviour of the IDT is the so called delta-function-model for the IDT, proposed by R.H. Tancrell and M.G. Holland [10].

According to Ref [9], the following factor enters the expression for the amplitude:

$$A(f) \approx \left| \frac{\sin x}{x} \right| \tag{4}$$

with $x = \frac{f - f_0}{f_0} N\pi$, where N is the number of fingers and f_0 the centre frequency of the IDT. Here, f_0, is related to the wavelength λ of the SAW by, $\lambda f_0 = v_0$, where v_0 is the sound velocity of the SAW on the piezoelectric material and λ is determined by the geometry of the IDT, in the sense that the periodicity of the finger structure of the IDT fits λ. The bandwidth Δf between the first zeros of the function in eq. (3) depends reciprocally on the number of the fingers, that means

$$\Delta f = \frac{2}{N} f_0 \tag{5}$$

These results are valid for equally spaced pairs of fingers. Moreover, the overlap of fingers at different potential must be equal for all fingerpairs.

By a variation of the geometry of the IDT, e.g. by changing the overlap of pairs of fingers, i.e. the region of electro-acoustic interaction, it is possible to get different frequency responds (appodized IDT [11]). There are different models allowing to design an IDT with a desired frequency respond, e.g. a network model by Smith et. al. [12]. In this model, one finger pair is described by an equivalent circuit. The N finger pairs, which the IDT consists of, are then just added. Another methode, the so called normal mode method [9], uses the conservation of energy and gets the design parameters out of this principle. All these methods only approximate the real behaviour of the IDT. A very general and complete description of the IDT which, however, is very complex, can be achieved using field theory [13].

The ***detection*** of a propagating surface acoustic wave can be done in a similar manner as the generation. The elastic surface acoustic wave propagates with its sound velocity on the substrate (e.g. ZnO or $LiNbO_3$.). This elastic wave, is due to the piezoelectric effect of the substrate, accompanied by an electric field This electric field is used for the detection of the SAW, by detecting the electric field with a second, receiving IDT. Thus, a seismograph for the miniaturised earthquake is realized.

The electrical generation of a SAW is realized by a frequency generator, and the detection with a spectrum analyser. Usually, we used an equipment, which combines both features, the so called networkanalyzor. The frequency of the rf voltage, which has to be applied for an optimal emission of the surface acoustic wave, can easily be calculated from the geometry of the IDT that emits a SAW of a certain wavelength, λ, defined by the spacing of the finger electrodes, as already mentioned above. The best emitted frequency, the so called fundamental frequency, f_0 is then given by:

$$\lambda \cdot f_0 = v_0 \quad \textbf{(6)}$$

Here, v_0 is the sound velocity of the piezoelectric substrate and λ the structural periodicity of the IDT.

To excite the SAW electrically, a radio frequency voltage with the fundamental frequency of the IDT (typically in the 100 MHz range) has to be supplied to one of the IDT.

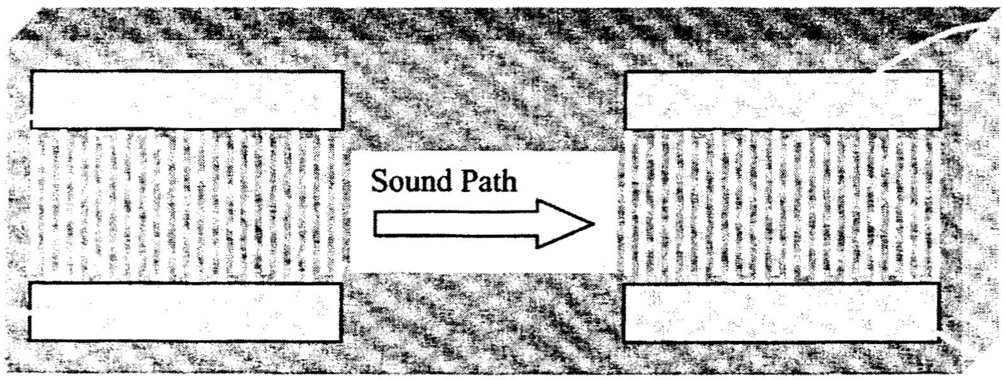

Fig.3: *Sketch of a surface acoustic wave delay line.*

The SAW propagates along the substrate from the sending IDT to the identical receiving IDT, i.e. along the "sound path" or " delay line" (typically about 5mm long) of the surface acoustic wave device, seen in Fig. 3.

3. SURFACE ACOUSTIC WAVE DEVICES

3.1 Filters, sensors and actuators

There is a big body of applications of SAW devices as high frequency filters in electronic circuits. Furthermore, surface acoustic waves have been applied in highly sensitive sensors. Finally, it is possible to use the electrical and mechanical part of the SAW in actuators. Some examples demonstrating the main applications are given in the following.

Since, the transfer function of the surface acoustic wave device can be adjusted precisely by designing the IDTs, makes the device to a very often applied filter in cellular phones and also in television (TV) electronics [9].

Nowadays a surface acoustic wave device is an industrial product, which can be built highly reproducible, using the very common and cheap lift off technique widely applied by the chip industry.

Apart from this area of applications using an empty delay line, we can apply the sound path region for sensing and actuating:

There is a big area of applications for gas- [14,15,16] and bio-sensors [17,18]. Here, a specific, very often chemically active, interface is used (see Fig.4) at which, in the optimal case, only one sort of atoms, molecules or biomolecules, which one wants to sense, is able to dock (Fig.4).

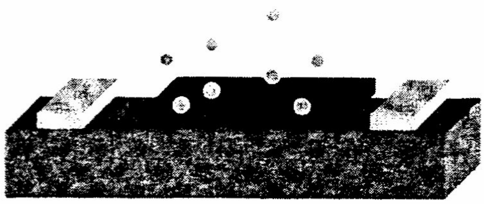

Fig 4.: SAW-*delay line with a sensitive layer (dark blue) for a specific interface with gas molecules.*

During this docking process, a parameter like the viscosity, elasticity, conductivity, or mass at the surface of the SAW device changes, which can be detected by a change of the surface acoustic wave parameters, e.g. the sound velocity or attenuation [19]. During this process only one parameter should change, while the others have to be held constant, e.g. the temperature needs to be controlled. So, it is important for this sensor approach to have a specific interface for the material to be detected, only one parameter should change during the sensoring process.

Surface acoustic waves can be also used as an actuator, e.g. to transport some liquid in form of nanodrops from one place to another one [20]. Thus, one gets, what is called a "lab on a chip" [21].

Another possibility for a SAW actuator is to use the electric field or potential, travelling together with the elastic distortion, to separate photo-generated excitons by blocking the electron-hole recombination. The separated charges travel with the electric potential. At a certain region of at the sound path which is metallized, so that the surface is short circuited there and the electric field accompanying the SAW vanishes, the holes and electrons can recombine by emitting light. With this method is possible to "transport" light from one place to the other [22,23]

It is also possible to read out the properties of a surface acoustic wave device contactless, which is, e.g,. applied to identify trains or to sensor the air pressure in a tire of a car [24].

3.2 Recent examples of solid state physics research using surface acoustic wave devices

Surface acoustic wave devices are widely applied in solid state physics research. To cover all activities is beyond the scope of this talk. Instead, we focus on very recent applications to investigate the interplay of lattice, electronic, and magnetic degrees of freedom during phase transitions.

For this purpose the material under investigation is attached at the sound path of the SAW device. This influences the propagation parameters, i.e. the sound velocity and the attenuation, of the surface acoustic wave. If there is a change of the physical properties of the material, this is observed as a change of the influence on the SAW and ,therefore, a change of the sound velocity and attenuation. Thus, phase transitions in the material induced by external parameters, such as the temperature T, can be studied using surface acoustic wave devices.

3.2.1 The ferrimagnetic semiconductor $FeCr_2S_4$

The first example is the study of changes of elastic and magnetic properties of the ferrimagnetic semiconductor $FeCr_2S_4$ [25].

For this purpose, a thin (20 μm) single crystalline plate of the material was placed directly onto the sound path between the sending and receiving IDT of a delay line (see Fig 5).

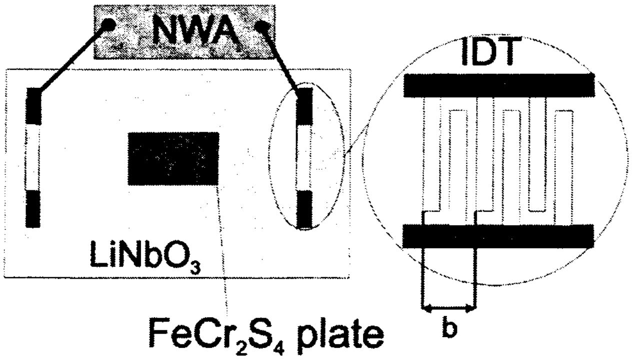

Fig. 5. *Surface acoustic wave (SAW) delay line with a thin single crystalline $FeCr_2S_4$ plate on the sound path, bet ween the interdigital transducers (IDTs). One IDT is viewed in lager magnification. The distance b of the two finger electrodes with the same electric potential is indicated, where b= λ. The measurements were performed using a vector network analyzor (NWA) [25].*

The first trial of the experiment did not work. The reason was a too weak coupling of the single crystal to the surface of the delay line. For a more intense mechanical coupling we then used, in a second trial, diluted General Electric (GE) varnish to glue the $FeCr_2S_4$ plate on the sound path.

The measurements were performed in a cryostat with a variable temperature insert (VTI), allowing measurements in the temperature range from room temperature to 4.2 K.

By measuring the attenuation of the surface acoustic wave in the temperature range from 4.2 K to 200 K, the elastomagnetic coupling in the ferrimagnetic semiconductor $FeCr_2S_4$ could be studied. The data clearly display the anomalies also found in low-field magnetization measurements.

The temperature dependence of the attenuation for a sample with the normal of the (100) plane perpendicular to the substrate and the SAW propagating in the <110> crystallographic direction, is presented in Fig.6.

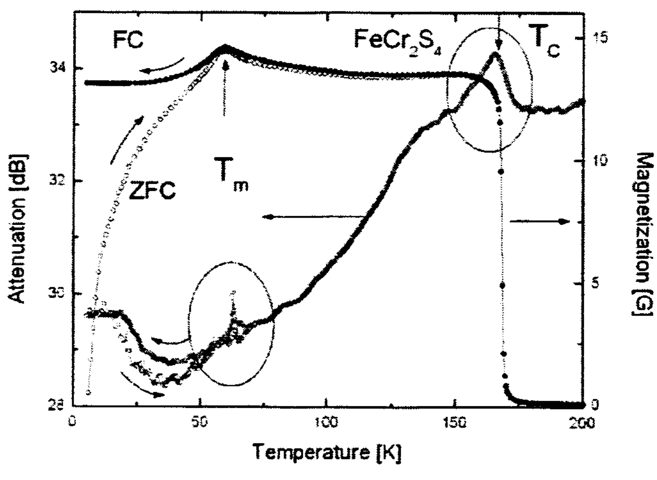

Fig. 6: *Attenuation of the surface acoustic wave as a function of the temperature, for a single crystalline thin plate of $FeCr_2S_4$ on the sound path of a $LiNbO_3$ surface acoustic wave device. The full red curve shows an average of several measurements for decreasing temperature. Open squares represent an attenuation measurement for increasing temperature. In addition, the low-field magnetization (measured as described in Ref. 26) of a single crystal of the same material is shown (FC: field cooled, measured at decreasing temperature; ZFC: zero field cooled, measured at increasing temperature). The thin line is a guide to the eye [25].*

At around 170 and 60 K the attenuation shows a non-monotonic behaviour with pronounced anomalies, correlating well with the changes of the low-field magnetization. The attenuation shows a maximum at the Curie temperature, T_C and then decreases until the temperature reaches ~40K. The attenuation shows a sharp peak at the temperature T_m (indicated in Fig. 6), which is assigned to a spin-glass like magnetization anomaly. Below this temperature, an irreversible behaviour similar to the hysteretic behaviour of the magnetization is observed. The fact that the attenuation mirrors the anomalies of the magnetization indicates a strong coupling between spin and lattice degrees of freedom in $FeCr_2S_4$.

3.2.2 The metal-insulator transition in V_2O_3 thin films

In the last experiment we learned that the coupling of the investigated material to the delay line is of first priority. Therefore, we performed a new experiment in which the material, to be explored under varying physical conditions, was directly deposited on the delay line in form of a thin film.

Here, we matched two requirements at the same time. Firstly, an intense coupling between the piezoelectric material of the sound path and the material to be investigated was achieved. Secondly, we could adjust the thickness d of the material under investigation in the 100nm range. Thus, $d << \lambda / 2$, so that the electric field of the surface acoustic wave screens the whole material. (see the discussion in Chap. 1, where $\lambda = \lambda_R$).

For this thin film experiment [27] we used V_2O_3, a material, which is metallic at room temperature, but near to the edge of an insulating state. On lowering the temperature, the material changes from the metallic to the insulating state. However, this is not the only transition in this compound. At the same time, there is a change of symmetry in the crystalline structure from trigonal to monocline and, in addition, a magnetic transition from the paramagnetic state to an antiferromagnetic state at low temperature.

The thin films of V_2O_3 were produced by an electron-beam evaporation process from a V_2O_3 target under ultra high vacuum (UHV, 10^{-7}-10^{-8} mbar) conditions. The films (thickness ~ 370 nm) were deposited onto a 128° rot YX cut of a $LiNbO_3$ substrate.

DC conductivity measurements are done in parallel to the surface acoustic wave investigations (see. Fig. 7)

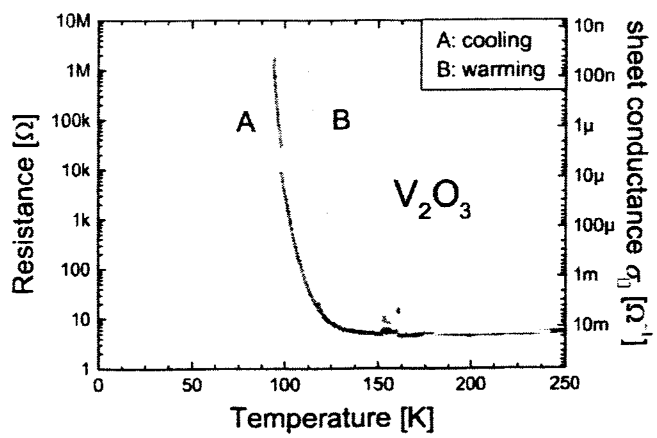

Fig.7: *Temperature dependence of the resistance of a V_2O_3 thin film. The scale on the right side shows the sheet conductance of the film. [27]*

At the metal to insulator transition, the resistivity increases by at least six orders of magnitude. For the cooling-warming cycle there is a hysteretic behaviour of the resistance, as well known for this compound.
The attenuation of the SAW is displayed in Fig. 8 and shows also a hysteretic behaviour.

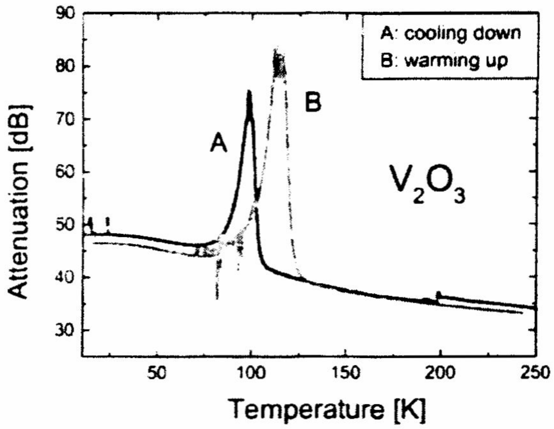

Fig. 8: *Temperature dependence of the attenuation of a SAW device at which the sound path is covered with a thin film of V_2O_3 [27]*

The attenuation maximum of the warming up curve is higher, than the one of the cooling down curve. The noise at around 10 K may be due to an adsoption of helium atoms at the layer, leading to an additional damping of the SAW.

Where does the damping of the surface acoustic wave come from? There is more than one contritution. First of all, we have an attenuation, which is due to the change of the conductance of the thin film on top of the sound path. The reason for the influence of the conductance is a more or less short-circuiting of the electric field generated by the piezoelectric effect. If the conductance of the film is high, the electrons in the metal, which are moved by the electric field of the SAW, experience low Ohmic losses resulting in a low attenuation. In contrast if the conductance of the film is low, there are only a few charge carriers present, which are moved by the wave, so that again the losses and, thus, the damping of the wave is low. With decreasing conductance, i.e. increasing resistance for decreasing temperature of the film, the attenuation first increases and, after passing a maximum, decreases again. This is just the behaviour of the attenuation observed experimentally.

If the electric field is shorcircuited by a metallic layer, the electrical restoring forces are weakened and the material becomes softer. This softening changes also the sound velocity of the surface acoustic wave travelling along the sound path.

The sound velocity shift Δv normalized to v_0 is plotted in Fig.9. Curve A2 shows the normalized measured sound velocity shift during cooling (a linear background of the measurement has been subtracted [27]).

In the same figure we plotted the theoretical prediction (curve T) of a model considering the influence of the conductance of the film on the sound velocity of the SAW. At around a temperature of 200 K, the data of curve A2 starts to differ from the theory. The deviation can be fitted by a polynom QF of second order. This fitting curve QF was then substracted from curve A2 only in the temperature range (200K-60K), where the curve was not horizontal as the model predicts, yielding curve A3.

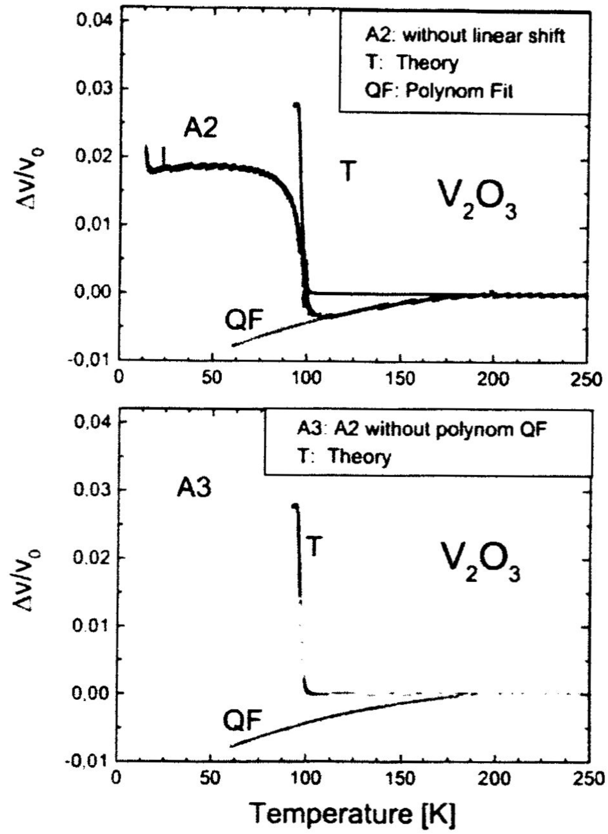

Fig. 9: *Velocity shift vs. temperature for a V2O3 thin film on the sound path of a surface acoustic wave device on cooling down, together with the theoretical prediction (curve T). For details see the text. [27]*

It is remarkable that the step height of the so generated curve A3 equals the expected height of the theory (curve T), which expresses nothing else but the difference of the velocities of $LiNbO_3$ covered with an insulating and highly conducting thin layer, respectively.

The attenuation and the sound velocity measured can be more or less described by a model of Ingebrigtsen [28] considering the interaction of a SAW with a thin conducting film on top of the sound path of a SAW device, elaborated for comparison with our experiments in Ref. 27, invoking results of Hutson and White given in Ref. 29. However, in this approximation, the model only considers the influence of conductance changes. The observed deviation between the model and our experiments indicate an influence of changes of elastic and dielectric properties of the V_2O_3 material during the metal to insulator transition.

4. CONCLUSIONS

The method, to attach a single crystalline plate or to deposit a thin film of the material under investigation onto the piezoelectric substrate on the sound path of a surface acoustic wave delay line, is a suitable technique for surface acoustic wave studies in solid state physics and materials science. However, for general purpose applications of this method, there is a strong withdraw, because not every material can be produced in form of a thin plate or a thin film.

This could be overcome by the fabrication a SAW device on top of the material to be investigated. This means to deposit a piezoelectric material onto the substance to be investigated, which now can be, e.g., a single crystal (see Fig.10,I) or a thin film on a non piezoelectric substrate, for which the growing conditions for the thin film may be more appropriate (see Fig.10,II).

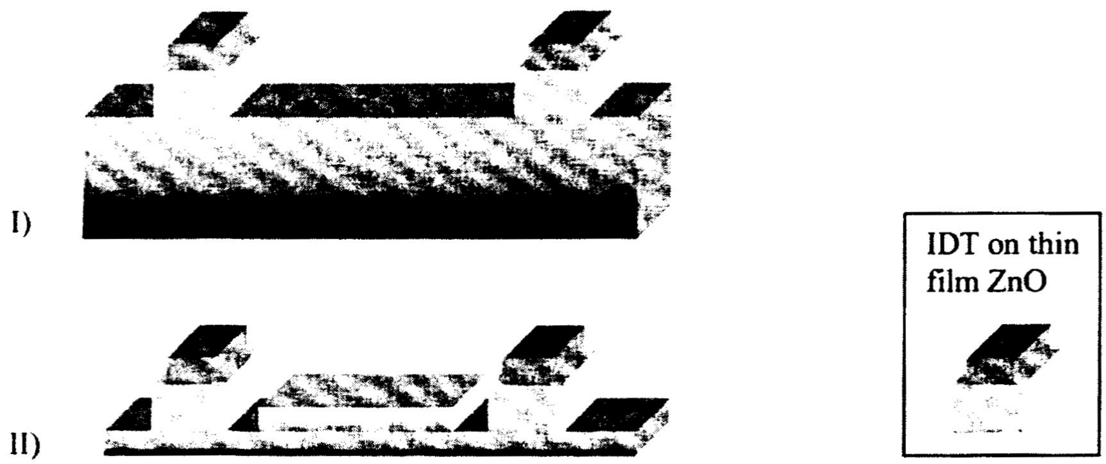

Fig. 10 *Principal setup for a ZnO based surface acoustic wave device for solid state physics and materials science investigation.*

A suitable piezoelectric material for such type of devices would be the piezoelectric binary compound ZnO. This material can be easily produced in form of a thin film by several deposition methodes, e.g. , sputtering (rf, dc) and pulsed laser deposition (PLD)

ACKNOWLEDGEMENTS

The authors want to thank Rolf Anders and Robert Horny for their assistance to prepare figure 1 of the present article. One author (C. M.) wants to thank Annegret and Ulrich Müller for financial support to enable the visit of this conference.

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