NON-RECIPROCAL SAW DEVICES FOR RF APPLICATIONS

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Abstract - The combination of the electronic properties of a semiconductor heterostructure and the acoustic properties of strongly piezoelectric crystals yields promising hybrids for potential acousto electric applications. The nonlinear interaction between an intense SAW on a $LiNbO_3$ substrate and the free carriers in a semiconductor quantum well can be exploited to result in strongly non-reciprocal devices for RF applications.

I. HYBRID STRUCTURES

It has been known for quite some time that the electrical boundary conditions at the surface of a substrate on which a SAW is propagating strongly influence the propagation parameters of the SAW itself. In the literature, the limiting cases are often referred to as 'open' and 'shorted' boundary condition of the surface, depending on the conductivity of a thin layer on top of the substrate. To be able to deliberately switch between these two boundary conditions, we use a thin semiconductor layer forming a field effect transistor on top of a $LiNbO_3$ SAW delay-line.

The evanescent piezoelectric fields of the SAW on the $LiNbO_3$ may then couple to the free carriers in the semiconductor quantum well and induce the desired mutual interaction. The semiconductor thin film is grown by molecular beam epitaxy (MBE) and then transferred to the SAW substrate employing the 'epitaxial lift-off' process described elsewhere [1,2]. A thin metal electrode on top of the semiconductor film together with Ohmic contacts to the electron channel in a quantum well is used to electrically vary the carrier concentration in the electron channel by applying an appropriate gate bias to this electrode. This way, we are able to continuously change the in-plane conductivity of the electron channel and hence to electrically tune the SAW attenuation and the SAW velocity [3]. As has been shown before, such hybrid structures offer a great variety of possibilities for novel acoustoelectric devices [4] from electrically tuneable phase shifters to attenuators and remotely adressable sensor elements. In Fig. 1, we depict a sketch of such a hybrid device to illucidate the basic idea behind it.

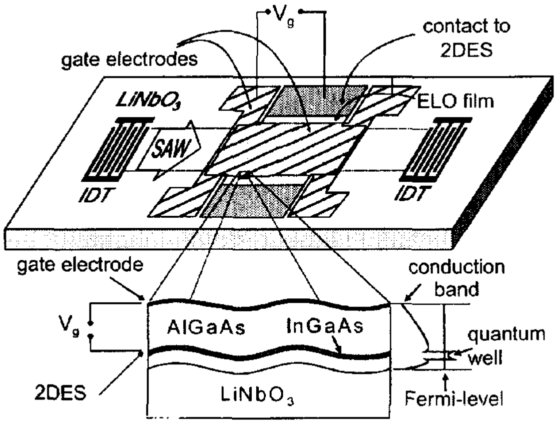

Figure 1: Sketch of a hybrid system consisting of a strongly piezoelectric substrate and a high mobility semiconductor heterojunction. The active semiconductor layers have been selectively removed from their natural substrate. The epitaxial lift-off (ELO) technique was used for this purpose.

Here, however, we would like to focus on the recently observed strongly non-linear interaction between intense SAWs and free charge carriers in such hybrid devices [5,6,7] and propose the exploitation of these effects to create novel, non-reciprocal devices for RF signal processing applications. This non-reciprocity is based on a strongly amplitude dependent SAW absorption caused by the nonlinear interaction between the SAW and the electron system in the quantum well.

II. NON-LINEAR INTERACTION

As has been discovered quite recently [5], the interaction between a SAW on a strong piezoelectric and a quasi two-dimensional electron system in close vicinity to the piezoelectric's surface can be very strong: An initially homogenously distributed electron system in the plane of a quantum well can be separated into well difined stripes of trapped charge, moving in the lateral potential wells of the SAW. Apart from this sound induced charge conveyance, another interesting effect occurs, being closely related to this spatial charge separation. As the interaction between a SAW and mobile carriers in close vicinity of the crystal surface is basically governed by the dynamic screening of the lateral dynamic piezoelectric fields accompanying the SAW at the speed of sound, the screening behavior of the electron system is of vital importance to the understanding of the interaction itself. In the small signal limit, where the lateral potential modulation of the SAW has only little effect on the electron system itself, a linear theory of the interaction can be quite easily derived. It results in the well known formulae for the conductivity dependent attenuation $\Gamma(\sigma)$ and the renormalization of the sound velocity $\Delta v/v_0\ (\sigma)$.

$$\Gamma = k\frac{K_{eff}^2}{2}\frac{(\sigma/\sigma_m)}{1+(\sigma/\sigma_m)^2} \qquad (1)$$

and

$$\frac{\Delta v}{v_0} = \frac{K_{eff}^2}{2}\frac{1}{1+(\sigma/\sigma_m)^2} \qquad (2)$$

Here, $k=2\pi/\lambda$ denotes the SAW wave number, K_{eff} the electromechanical coupling coefficient of the substrate and σ the in-plane conductivity of the electron system in the quantum well. Around a critical conductivity σ_m , the system switches between the 'open' and 'shorted' boundary conditions mentioned above, leading to a pronounced peak in the absorption and a steplike change of the sound velocity (piezoelectric stiffening).

The situation changes, however, if the SAW amplitude becomes so large that the parameter $\eta=e\Phi_{SAW}/\ \mu$ can no longer be disregarded. This parameter describes the ratio between the amplitude of the SAW piezoelectric potential Φ_{SAW} and the electrochemical potential or Fermi level μ_F of the electron system. Once η approaches unity, the sound induced lateral potential modulation leads to a significant modulation of the carrier density within the plane of the quantum well, eventually completely separating the formerly homogeneous layer into stripes. As long as the modulation is not complete, dissipative screening currents in the plane of the electron system lead to a sound absorption, as described by eq. (1) for very small η. However, once the density modulation becomes complete, such currents no longer exist and the SAW is no longer attenuated by dissipation within the electron system. as has been show before [5,7], this qualitative description of the nonlinearity can be well quantified in the framework of our theoretical model.

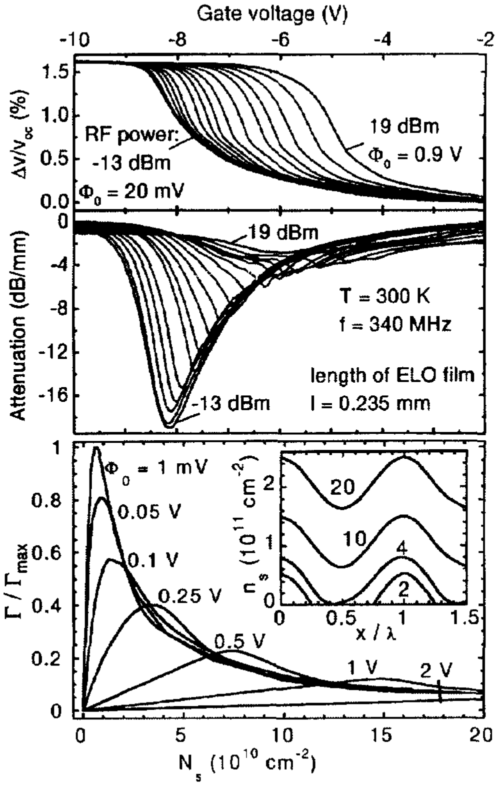

Figure. 2. Measured attenuation and velocity change of a SAW as a function of gate voltage for different RF power. The lower part shows the calculated attenuation as a function of the carrier concentration N_s. In the inset we plot the calculated local carrier concentration n_s as a function of the in-plane coordinate for different total carrier concentration N_s in units of 10^{10} cm^{-2} [5].

In Fig. 2, we depict the results of an amplitude dependent measurement of the SAW attenuation and velocity change in one of our hybrid strutures. In the experiment, a gate bias V was used to tune the total number of electrons and hence their in-plane conductivity in the well. At low SAW powers, a strong absorption peak at around V_g=-8Vand a step like increase of the sound velocity is observed, in accordance with eqs. (1) and (2). However, with increasing SAW amplitude one observes a significant reduction of the maximum attenuation, and a shift of the peak position towards more positive gate voltages. The change in sound velocity, on the other hand, remains nearly unchanged, while the position of the point of the largest slope follows the shift of the absorption peak towards more positive gate bias. The amplitude dependent change in the maximum absorption exceeds 10 dB/mm in this case. The lower panel shows the result of a semiclassical hydrodynamic calculation of the absorption [5]. We plot it as a function of the total carrier concentration in the quantum well, being proportional to the applied gate bias. The assumed SAW potentials Φ_{SAW} for each curve are attached to the lines. A clear correspondence between our experimental findings and the relatively simple calculation is obvious. In the inset of the lower panel in Fig. 2 we also plot the resulting lateral modulation of the carrier density as a function of the spatial coordinate along the plane of the well for different total densities N_s (indicated by the numbers attached to the lines). The SAW amplitude is fixed in this case. Here, we directly observe the increase of the parameter η with decreasing total carrier density or Fermi level μ_F.

III. NON-RECIPROCAL SAW DEVICES

As has been just described, the SAW absorption in the non-linear regime of interaction is strongly amplitude dependent. This effect can be positively exploited to realize non-reciprocal SAW devices. Such devices per definition exhibit a transfer function $S_{12} \neq S_{21}$, i.e., the SAW transmission strongly depends on the *direction* of the SAW propagation. For the sample as investigated in Fig. 2, a directionality of about 15 dB can be achieved if S_{12} and S_{21} differ by about 30 dB. These numbers are by no means representative, as the sample was not at all designed and optimized to operate as a non-reciprocal device. However, there is no technical reason against the design of a sample with a strongly asymmetric transfer function. Given the above non-linear behavior of our hybrid devices, one can for instance design a sample with, say, two SAW transducers of very different efficiency. In the simplest case, this can be achieved by just different numbers of finger pairs for both transducers. Another way would be to have one single phase uni-directional transucer (SPUDT) and one 'standard' bidirectional transducer with much less efficiency on the same chip. To illucidate our device proposals, we schematically depict in Fig. 3 those three different approaches to realize non-reciprocal SAW devices based on the non-linear interaction between SAW and a quasi two-dimensional electron system.

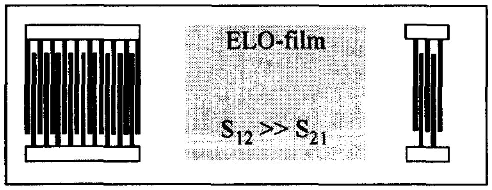

Figure 3: Schematic of a non-reciprocal SAW device based on the nonlinear interaction between a SAW on a piezoelectric substrate and free carriers in a semiconductor ELO film. As the SAW absorption is strongly intensity dependent, two different transducers with different conversion efficiency are used to provide the condition S_{12}>>S_{21}.

For completeness, we wish to also adress another possibility for the creation of non-reciprocal SAW devices, which, however, are based on yet another physical mechanism: It has been known for quite some time that during the interaction of a SAW on a piezoelectric and free carriers in a closeby semiconductor not only energy but also momentum can be transferred. The result of such momentum transfer from the SAW to the electron system is on the famous acoustoelectric effect [8] and on the other hand (momentum transfer from the electron system to the SAW) acoustoelectric amplification [9]. Our hybrid structures also allow for the investigations of these prominent physical phenomena. In this case, a current is imposed to the electron system in the ELO film, being directed either along the SAW propagation direction or opposite to it. in one case the momentum transfer from the drifting electrodes to the SAW is positive, resulting in an amplification of the SAW with respect to the case of zero current flow. In the other case, when the current flows against the SAW, a current induced additional attenuation is observed. In other words, here, too, a non-reciprocal behavior $S_{12} \neq S_{21}$ can be achieved. Without going into the details of this experiment [6], we show its results in Fig. 4. We depict the measured SAW transmission of our device as a function of a longitudinal voltage applied across the ELO film, directed parallel to the SAW propagation direction. S_{12} and S_{21} are measured by simply reversing the direction of SAW propagation but keeping the direction of the current flow fixed. The longitudinal voltage induces a current flow in the plane of the quantum well, which provides the desired momentum transfer to the SAW.

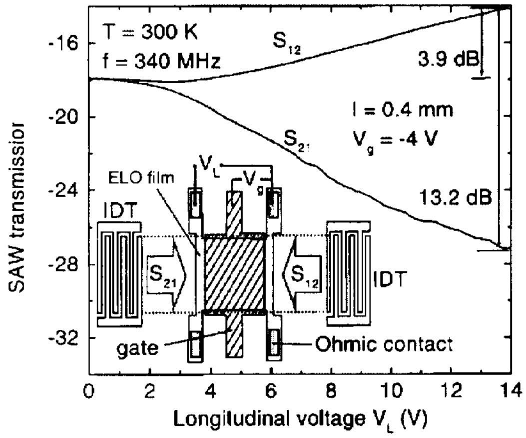

Figure 4: Non-reciprocal SAW device based on momentum transfer between the SAW and drifting electrons in the ELO film under the influence of a longitudinal voltage V_L [6]. Depending on the direction of SAW propagation with respect to the direction of current flow, either an additional attenuation or acoustoelectric amplification is observed. In the present device, a difference of 13.2dB for both cases could be observed for the highest longitudinal voltage applied.

IV. CONCLUSION

In summary, we have demonstrated that hybrid systems consisting of a strong piezoelectric and a thin semiconductor film containing free electrons in a quantum well offer new possibilities for the creation of non-reciprocal SAW devices. We have shown, that at least two different physical phenomena can be exploited for this task: On the one side this is the strongly nonlinear interaction as discussed in detail and on the other hand, a drifting electron system is used to create the desired non reciprocity.

V. ACKNOWLEDGEMENT

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VI. REFERENCES

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