Spatially Resolved Surface Acoustic Wave Studies For Image Processing

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Abstract— The interaction between a surface acoustic wave (SAW) and photogenerated charge carriers in a piezoelectric semiconductor substrate leads to pronounced changes in the transmission properties of the SAW. Depending on the charge carrier density one observes an attenuation and a change in sound velocity in a SAW delay line comprising a light sensitive semiconductor film. Using specially designed surface acoustic wave transducers, we are able to spatially resolve this interaction. The transducers used for this purpose consist of fan shaped interdigated metal fingers, which show a broadband frequency transmission. It turns out, that for such transducers the excited SAW propagates on a narrow path, whose position can be controlled by the driving frequency. We are able to reconstruct a 2D charge distribution by applying a tomographic technique or by nonlinear interaction between a probe and a perpendicular pump SAW crossing each other in the area where charge carriers are generated.

I. Introduction

Sophisticated surface acoustic wave (SAW) device technology together with well defined electronic properties of a semiconductor leads to very interesting applications of optical signal processing.

In a piezoelectric crystal the SAW is accompanied by electric fields. The coupling is summarized in the electromechanical coupling coefficient K^2_{eff}. Mobile charge carriers move in the electric field and alter the velocity as well as the energy of the SAW due to finite resistance. For a conducting sheet close to the surface having a sheet conductivity σ the relative change in velocity $\Delta v/v$ and the attenuation Γ can be described by the following equations [1]

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

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$$\Gamma = \frac{K^2_{eff}}{2}k_{SAW}\frac{\sigma/\sigma_m}{1+(\sigma/\sigma_m)^2}. \qquad (2)$$

In these equations σ_m denotes a critical sheet conductivity and k_{SAW} the wave vector of the SAW. The largest energy transfer from the SAW to the charge carrier system occurs at $\sigma = \sigma_m$. In a hybrid system consisting of a submicron thick semiconducting AlGaAs/InGaAs-heterostructure on top of a strong piezoelectric substrate, like e.g. $LiNbO_3$, attenuations of about 20 dB and phase shifts of several hundred degrees have been demonstrated [2]. Therefore, SAW measurements are a very sensitive tool to determine fundamental properties of semiconductors and have been used to investigate e.g. two-dimensional electron systems in the quantum hall regime and the fractional quantum hall regime [3, 4]. With increasing potential amplitude Φ_{SAW} the SAW modulates the homogeneous charge carrier system. In this regime the SAW velocity and damping respond in a nonlinear way since it differs from the linear regime described by equations (1) and (2) [5].

In an illuminated semiconducting substrate, charge carriers are generated if the photon energy of the light is larger than the energy gap between valence and conductance band. If this is ensured, e.g. with a laser, the number of photogenerated charge carriers is proportional to the light intensity, which is in turn proportional to the conductivity σ. We investigated the interaction between SAWs and photogenerated charges in the linear as well as in the nonlinear regime in regard to its applicability to imaging devices.

II. Fan-shaped Interdigital Transducer

Spatial resolution is achieved by using so called fan shaped interdigital transducers, first introduced by Van de Heuvel [6]. In this special design of IDT the finger period is decreased monotonously along the aperture of the IDT

[7]. This causes an increase of the SAW frequency along the aperture. Hence, the resulting SAW intensity transmission signal of a delay line consisting of two fan-shaped IDTs is a frequency bandpass. For a frequency within such a bandpass the IDT matches the resonance only in a confined part of the aperture and launches a SAW only on a narrow path. If multiple split fingers are used, internal reflections are reduced and one has the opportunity to work also with higher harmonics of the resonant ground frequency with one single delay line. The value $bandpass/middle\ frequency$ is approximately the tapering factor which represents a constant value. Therefore, the absolute value of the bandpass spreads with higher harmonics. A typical transmission signal of this design is shown in fig. 1.

The width of the SAW path limits the spatial resolution. It was already shown that the width decreases with increasing tapering factor before it reaches a minimum and then increases again due to diffraction [8]. Diffraction gains in importance, if the confinement reaches the order of the wavelength. Sauer et al. have been able to directly demonstrate diffraction for GaAs by X-ray imaging [9]. The typical width of a SAW path for an IDT with a tapering factor of 10%, an aperture of 450 µm and a driving frequency of 600 MHz is approximately 50 µm.

In the case of a GaAs(001) surface the symmetries along the [110] and [-110] axis are equivalent. Therefore the transmission signals of perpendicular SAW delay lines are the same. The transmission signal in x and the perpendicular direction of a $LiNbO_3$ 128° rot. Y-cut surface is different. On the last-mentioned substrate and for our delay line layout the transmission in x-direction is 10 dB higher than in the perpendicular one.

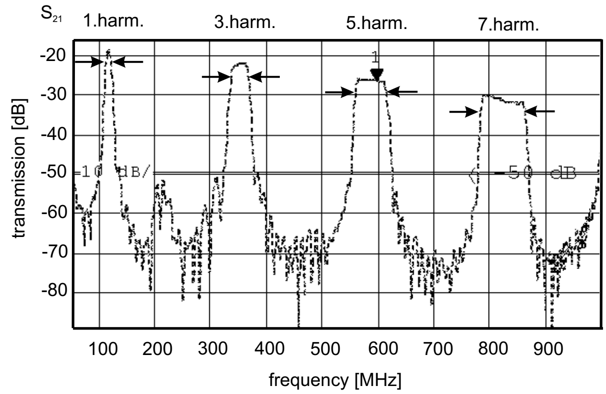

Fig. 1. Transmission signal S_{21} of a delay line with fan shaped split 4 IDTs. The taper factor is 10%. Maximum transmission occurs at the odd harmonics of the IDT periodicity. Here, we show the odd harmonics 1 through 7.

III. Sensitivity of Different Materials, the Linear Regime

We measure amplitude and phase of the transmitted SAW signal with and without illumination of a spot being 5 µm in diameter on our SAW delay line. The light source is an Argon laser (λ=488 nm). The SAW signal changes for frequencies and a corresponding SAW path intersecting the area where light induced charge carriers are present. We measure a peak in the relative change of phase and amplitude vs. the frequency bandpass. The FWHM of this peak corresponds to a larger spot size in real space than the spot of the light. The difference between the measured and the real spot size is due to the finite width of the SAW path (as shown in section II) and the diffusion of charge carriers.

The relative change in phase and amplitude of the transmitted SAW signal changes with different material properties and different driving frequencies of the device. In this work we present three different GaAs devices. The first one is pure GaAs, which is characterized at the two different driving frequencies 440 and 825 MHz. With increasing frequency more wavelenghts fit into the illuminated area and hence the sensitivity of the device increases (compare triangled symbols in fig. 2). In GaAs grown at low temperatures (LT-GaAs) the mobility of electrons is lower (μ_e in the order of $10^2 \mathrm{cm}^2/\mathrm{Vs}$) as compared to the electron mobility in GaAs grown at higher temperatures ($\mu_e = 8{\cdot}10^3 \mathrm{cm}^2/\mathrm{Vs}$). To reach the same sheet conductivity $\sigma = en_e\mu_e$, where e is the elementary charge, one has to increase the two dimensional electron density n_e. Consequently one has to generate more charge carriers to get the same conductivity. This is shown in fig. 2 squared data

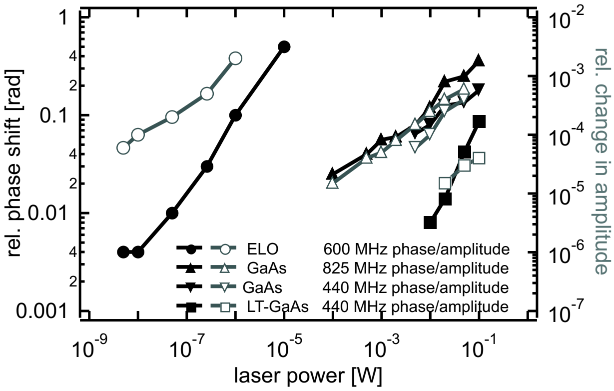

Fig. 2. Dependence of maximum change in phase and amplitude of the SAW signal on different laser intensities and light sensitive GaAs films. The diameter of the laser spot at the surface is about 5μm.

IV. Novel SAW-Camera by Using Nonlinear Interaction

To image a 2D charge carrier distribution with SAWs different approaches are possible. For measurements as described above the signal is a 1D projection of a 2D distribution. To reconstruct a 2D image, one can apply tomographic techniques [7] as used in the x-ray absorption tomography of solid objects [11]. For this purpose one has to record a set of 1D projections for different angles between SAW path and the pattern of illumination. We break new ground in using two perpendicular SAWs interacting with each other via the electron-hole plasma. The transmission properties of a SAW with low intensity (probe SAW) changes with the intensity of the perpendicular SAW (pump SAW) in presence of charge carriers. We proofed the existence of this nonlinear regime (described in section I) for single delay lines as well as for two perpendicular ones. All devices are hybrid systems similar to what is described in section III. With fan-shaped IDTs we limit the SAW path in both directions and are therefore able to locally restrict the interaction to a small area of our device. This small area represents a pixel. The device consists of a 350 nm thick ELO film (InGaAs-AlGaAs-GaAs heterostructure) a tapered IDT split 4 delay line in x-direction and a tapered IDT split 1 delay line in the perpendicular direction on the $LiNbO_3$. For these experiments we used a pulsed laser diode at 670 nm to illuminate the ELO film. The diode was operated with a pulse repetition rate of 1 to 10 kHz and a pulse width of 10 to some hundred nanoseconds. The first experiments were done using a network analyzer measuring the difference of the probe SAW signal with and without a continuous pump SAW (see fig. 3 (a) and (b)). For a better understanding we then altered our setup to do time resolved experiments. We are able to select the particular pulse time and pulse width of the light as well as of the two SAWs. We distinguish two different methods to image the charge carrier distribution.

In the first case the pump SAW interacts with attendant charges before the probe SAW travels across the ELO film. The probe SAW signal is taken with and without pump SAW. The difference of both signals is non-zero when the pump SAW modifies the conductivity of the probe delay line (compare fig. 3 (c) and (d)). We believe that the pump SAW alters the conductivity by transporting some charges out of the sensitive area.

In the second case both SAWs are launched at the same time and we used a lock-in technique by modulating the pump SAW with a square wave. We measured the modulation of the amplitude of the probe SAW fig. 3 (e) as well as the modulation of the cosine of the phase difference between probe SAW and corresponding reference frequency $cos(\Delta\phi)$ (shown in fig. 3 (f)). $cos(\Delta\phi)$ is different for each step of the frequency sweep. The reason is as follows. The number of acoustic wavelengths fitting in the delay line increases with the driving frequency. Hence, the phase of the transmitted SAW signal changes, while the phase of the corresponding reference frequency remains constant. The measuring technique is the most sensitive if $cos(\Delta\phi) = 0$. If $cos(\Delta\phi) = 1$ the modulation is very small and hardly to measure. The last-mentioned is responsible for the dark horizontal stripes in fig. 3 (f).

The performance of each IDT changes with the driving frequency and the ELO film is not perfectly homogeneous. Therefore the sensitivity changes with each pixel of our device. Despite this fact we are able to clearly interpret the 2D structure of the photogenerated electron-hole plasma with a grey scale plot of the raw data.

V. Conclusion

Surface acoustic wave devices are a very sensitive tool to detect changes in the charge carrier system. We investigated the sensitivity of semiconducting SAW devices to illumination. The tested materials cover a range of over seven orders of magnitude in laser intensity from $2.5 \cdot 10^{-2}$ to $5 \cdot 10^5\,\mathrm{W/cm^2}$. It turns out that a semiconducting piezoelectric hybrid structure consisting of a submicron thick GaAs layer on top of a $LiNbO_3$

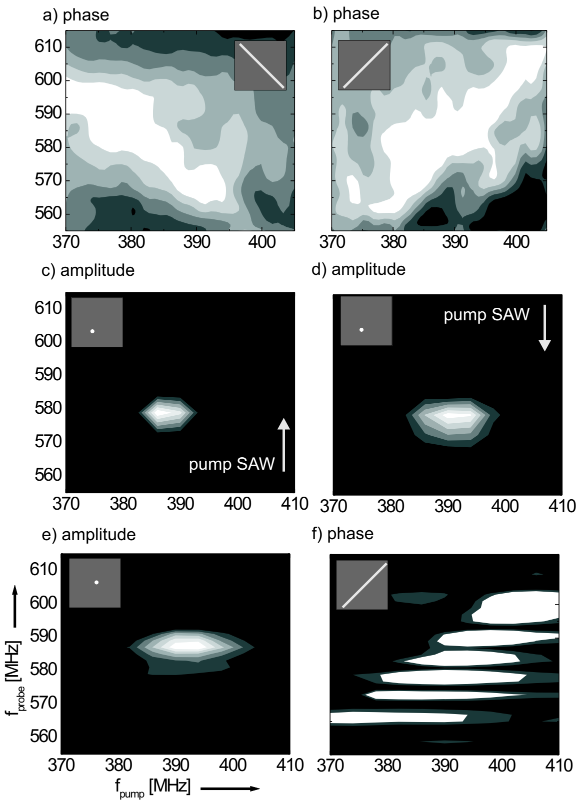

Fig. 3. (a) and (b) illustrates the signal of the probe SAW, measured with a network analyzer. The difference of the phase between pump SAW (continues wave) on and off is shown. (c) and (d) shows the difference of the amplitude of the probe SAW with pump SAW on and off. Both SAWs are pulsed. (e) and (f) illustrates the modulation of the probe SAW signal by modulating the intensity of the pump SAW with a lock-in technique. The insets of all figures sketch the pattern of the light on the semiconducting surface. For details see text.

crystal is a very sensitive tool to detect small light intensities due to the large coupling coefficient K^2_{eff}. The adequate substrate to detect large light intensities is GaAs grown at low temperatures. This crystal has a lower charge carrier mobility because of a bigger defect concentration than GaAs grown at higher temperatures. For high SAW intensities the conductivity depends on the SAW amplitude due to the strong piezoelectric fields and hence a band modulations in the semiconductor. The behavior for two perpendicular SAWs is similar. We demonstrated, that in the presence of photogenerated charge carriers the transmission properties of one SAW depends on the intensity of the perpendicular one.

To receive spatial resolution we use fan-shaped IDTs. With this kind of IDT we make the SAW paths narrower and limit the area of interaction. This limited area represents a pixel of our SAW-camera and gives us the possibility to generate images of simple patterns of light induced charge carriers.

Acknowledgment

This work has been sponsored in part by Advalytix AG, Brunnthal, Germany, and in part by the Bayerische Forschungsstiftung. Fruitful discussions with Prof. J.P. Kotthaus, and S. Manus (all University of Munich) are gratefully acknowledged.

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