Novel Concepts for GaAs/LiNbO$_3$ Layered Systems and Their Device Applications

Markus Rotter, Werner Ruile, Gerd Scholl, and Achim Wixforth

***Abstract*—Thin semiconductor quantum well structures fused onto LiNbO$_3$ substrates using the epitaxial lift-off (ELO) technology offer the possibility of controlling the surface acoustic wave (SAW) velocity via field effect. The tunability of the conductivity in the InGaAs quantum well results in a great change in SAW velocity, in general, accompanied by an attenuation. We show that an additional lateral modulation of the sheet conductivity reduces the SAW attenuation significantly, enhancing device performance. At high SAW intensity, the bunching of electrons in the SAW potential also leads to a strong reduction of attenuation. These effects open new possibilities for voltage-controlled SAW devices. We demonstrate a novel, wireless, passive voltage sensor, which can be read out from a remote location.**

I. GaAs/LiNbO$_3$-Hybrids

The propagation velocity of SAW is strongly affected by the electrical boundary condition on the surface of the piezoelectric material. In conventional SAW devices, the surface impedance is fixed by the design and usually cannot be tuned externally. The combination of a piezoelectric material with the voltage-tunable surface impedance of a semiconductor device, however, allows for continuous change of the velocity. A great change in SAW velocity can be achieved on a material with a large electromechanical coupling coefficient K^2, e.g., LiNbO$_3$. We demonstrated a quasi-monolithic combination of LiNbO$_3$ and a GaAs quantum well structure for controlling the SAW velocity [1], [2].

This combination is achieved using the ELO, which was developed by Yablonovitch *et al.* [3]. The first use of this hybridization technique for SAW devices has been reported by Hohkawa *et al.* [4]. To fabricate the hybrids, a semiconductor-layered system is grown by molecular beam epitaxy, starting with an AlAs sacrificial layer on top of the GaAs substrate. This layer is followed by a modulation doped In$_{0.2}$Ga$_{0.8}$As quantum well structure containing a two-dimensional electron system (2DES) (see Fig. 1). After covering the semiconductor structure with a black wax called Apiezon W, the AlAs layer is etched selectively in hydrofluoric acid. Then, the active layer system containing the 2DES is removed from the substrate and transferred onto the LiNbO$_3$ chip (128° rotation Y-cut, X-prop.) with the SAW transducer structure. The ELO film is tightly fixed only by van der Waals' forces. After this ELO process, the semiconductor film, which has a thickness of 0.5 μm, is patterned as shown in Fig. 1. Typical values for carrier concentration and room temperature mobility are $n_s = 5 \times 10^{11}$ cm^{-2} and $\mu = 4000$ cm^2/Vs. Because the 2DES is very close to the LiNbO$_3$ surface (the distance is only 32 nm), the conductivity of the electron system strongly influences the SAW propagation velocity v.

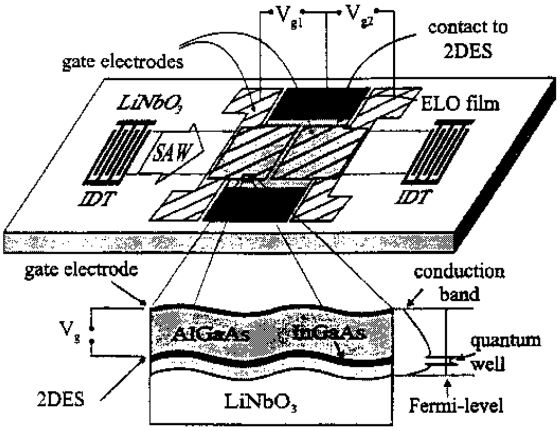

Fig. 1. Schematic sketch of the hybrid device (not drawn to scale) with two gates on top of the ELO film. The thickness of the ELO film is 0.5 μm, and the distance between LiNbO$_3$ and 2DES is just 32 nm. An RF signal is applied to one IDT to generate SAW. The lower part of the figure shows a schematic cross-section revealing the layer configuration and the energy of the conduction band in the semiconductor with respect to the Fermi level.

II. Attenuation and Velocity Change in the Hybrid

The interaction of the SAW and the 2DES results in a change of SAW phase velocity v and an attenuation Γ of the transmitted SAW intensity $I = I_0 \exp(-\Gamma l)$, where I_0 denotes the intensity of the SAW just entering the ELO film, and l is the length of the ELO film in the direction of SAW propagation [5], [6]. For our hybrid system, the sheet

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M. Rotter and A. Wixforth are with Sektion Physik der LMU and CeNS, Geschw.-Scholl-Platz. 1, D-80539 München, Germany (e-mail: achim.wixforth@physik.uni-muenchen.de).

W. Ruile and G. Scholl are with Siemens AG, Corporate Technology, D-81730 München, Germany.

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conductivity σ of the 2DES influences Γ and v as follows:

$$\begin{aligned} \Gamma &= K_H^2 \frac{\pi}{\lambda} \frac{\sigma/\sigma_m}{1+(\sigma/\sigma_m)^2} \\ \frac{v - v_{\mathrm{sc}}}{v_{\mathrm{oc}}} &= \frac{\Delta v}{v_{\mathrm{oc}}} = K_H^2 \frac{1}{2} \frac{1}{1+(\sigma/\sigma_m)^2} \end{aligned} \tag{1}$$

where λ is the SAW wavelength in the hybrid, v_{sc} denotes the hybrid velocity for the highly conductive electron system, and v_{oc} denotes the hybrid velocity for a depleted electron system. K_H^2 is the effective hybrid coupling coefficient, which is smaller than K^2 of LiNbO$_3$ because the gate electrode on top of the ELO film causes the velocity for a depleted electron system to be smaller than the velocity for a free LiNbO$_3$ surface. For a frequency of $f = 340$ MHz and $f = 434$ MHz and the described layered structure, the hybrid coupling coefficient is $K_H^2 = 3.3\%$ and $K_H^2 = 3.8\%$, respectively [2]. The coefficient σ_m denotes the conductivity at which maximum attenuation occurs and is approximately given by $\sigma_m = v\varepsilon_0 \left(\varepsilon_s \coth(2\pi h/\lambda) + \sqrt{\varepsilon_{11}^T \varepsilon_{33}^T - \varepsilon_{13}^T \varepsilon_{31}^T}\right) = 3.6 \times 10^{-6}\Omega^{-1}$ for a frequency of $f = 340$ MHz. ε_{ij}^T is the dielectric constant of LiNbO$_3$ under constant stress conditions. ε_s is the dielectric constant of the semiconductor film, and h is the distance between the gate electrode and the 2DES. If a voltage is applied to the gate electrode, the quantum well is depleted via field effect, resulting in a reduction of the sheet conductivity σ. This leads to an increase in SAW velocity.

If the gate voltage is applied homogeneously across the whole area of the ELO film, the change in SAW velocity is accompanied by a relatively large attenuation according to (1), which can be observed in Fig. 2 (see traces '$V_{g1} = V_{g2} = V_g'$'; dashed lines). The insertion attenuation at $V_g = 0$ can be attributed to the bare SAW chip and the mechanical attenuation caused by the ELO film [2]. The attenuation maximum at $\sigma = \sigma_m$ limits device performance in the corresponding range of the gate bias. To overcome this drawback, we developed new concepts for the reduction of this attenuation.

III. MULTIPLE GATE STRUCTURES

In principle, the idea is to distribute the attenuation over the whole range of gate bias, reducing the maximum attenuation. This can be achieved by dividing the ELO film into separated areas at different gate potentials and, correspondingly, different sheet conductivities. Fig. 1 shows the geometry of a hybrid device with two gate electrodes on top of the ELO film. The experimental results for this geometry are displayed in Fig. 2. If the gate voltage is applied to only one gate, with zero bias on the other, a phase shift and an attenuation of the transmitted RF signal can be observed (traces gate 1 and gate 2 in Fig. 2). Both gates show similar behavior. If the same gate voltage is applied to both gates at same time, attenuation and phase shift are added, resulting in a large phase shift and a nearly doubled attenuation at $V_g = -7.7V$ (dashed traces; '$V_{g1} = V_{g2} = V_g'$').

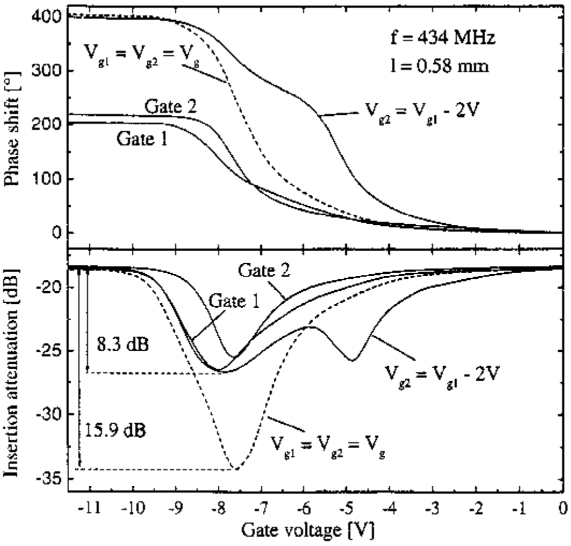

Fig. 2. Insertion attenuation and phase shift of the transmitted signal in a hybrid with two gates on top of the ELO film (according to Fig. 1) for different gate bias configurations. The traces labeled by Gate 1 and Gate 2 display the phase shift and attenuation of the device with only one gate swept (namely Gate 1 or Gate 2); the corresponding gate is grounded. The quantity l denotes the length of that part of the ELO film, which is covered by gate electrodes. All measurements are at room temperature.

This maximum attenuation can be reduced significantly when different voltages are applied to the gates. In Fig. 2, we show a particular measurement at which an additional offset bias of -2 V was applied to gate 2 (see traces '$V_{g2} = V_{g1} - 2V$'). This results in a shift of the attenuation and phase curves of gate 2. The total phase shift is the same as that for identical voltages. However, the total attenuation is much smaller when a gate voltage offset is applied because the overall attenuation is distributed over two different regions of the gate voltage.

A further reduction of insertion loss can be achieved by fabricating more than two gates on top of the ELO film. In Fig. 3, a hybrid with four gates is presented. The SAW characteristics of the four single gates were measured and are displayed in Fig. 3. Apart from slightly different threshold voltages, which can be explained by the fabrication process, all four gates show the expected behavior.

When the same gate voltage is applied to all gates, the phase shifts and attenuation curves are superposed. Because of the small offsets of the single gate traces, the total attenuation is slightly less than the sum of the maximum attenuation of the single gates. Further, the total attenuation can be distributed across a wider gate voltage range by applying different gate voltages. Here, gate bias offsets of 1, 2, and 3 V were applied to the respective gate. This reduced the total electronical attenuation by 15 dB, from -23.4 to -8.4 dB. In this multiple-gate device, the

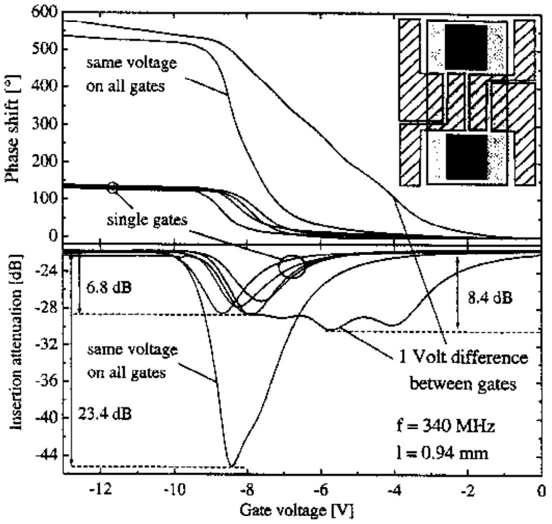

Fig. 3. Attenuation and phase shift in a device with four separated gate electrodes. The inset displays the geometry of the semiconductor structure. The ELO film is light gray, the Ohmic contacts are dark gray, and the gates are hatched.

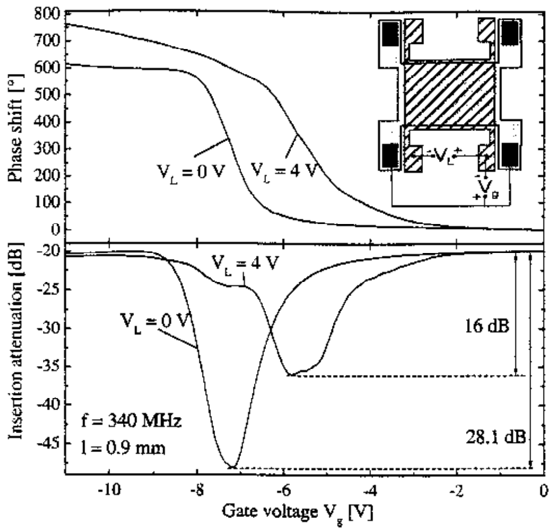

Fig. 4. Phase shift and corresponding insertion attenuation in a device with resistive (Ohmic) gate electrode. A longitudinal voltage V_L results in enhancement of SAW transmission.

phase shift is very close to a linear function of the gate voltage, which is very useful for most applications when a simple linear relationship between voltage and phase shift is desired. If a larger voltage offset is applied between the gates, the overall attenuation could be minimized further along a highly resistive gate electrode on top of the ELO film in the direction of SAW propagation, as displayed in the inset of Fig. 4. We realized this structure with a thin Ni/Cr gate electrode (thickness, 5 nm). In Fig. 4, we show the results of insertion loss and phase shift. If a longitudinal voltage V_L is applied, we achieve a continuous