Voltage Controlled SAW Velocity in GaAs/LiNbO3-Hybrids

Markus Rotter, Werner Ruile, Achim Wixforth, and Jörg P. Kotthaus

Abstract—**The combination of the electronic properties of semiconductor heterojunctions and the acoustic properties of piezoelectric materials yields very promising surface acoustic wave (SAW) hybrid systems. Quasi-monolithical integration of thin GaAs/InGaAs/AlGaAs-quantum well structures on $LiNbO_3$ SAW devices is achieved using the epitaxial lift-off (ELO) technique. The conductivity of the two-dimensional electron system in the quantum well, which can be controlled via field effect, modifies the velocity of the SAW. Due to the high electromechanical coupling coefficient of $LiNbO_3$ a large phase shift can be obtained. As an example for this new class of voltage-tunable single chip SAW devices, a voltage-controlled oscillator (VCO) is presented in which the output frequency can be tuned by an applied gate voltage.**

I. Introduction

The propagation velocity of surface acoustic waves (SAW) on strong piezoelectric materials depends very much on the electric boundary condition: a conductive surface prohibits the effect of piezoelectric stiffening thus reducing the velocity of the SAW. For various applications a continuously tunable velocity would be desirable. Up to now, different approaches were made to combine conventional SAW devices with the electronic properties of semiconductor materials. For example, earlier proposals are based on the voltage-controlled width of a depletion layer in a semiconductor bulk diode [1]–[3]. However, the interaction between SAW and a quasi two-dimensional electron system (Q2DES) in semiconductor heterojunctions recently has attracted interest [4], [5]. Nevertheless, on most high electron mobility materials, the piezoelectricity is weak, and the effect of the electron system on the SAW is usually small. Therefore, quasi-monolithic hybrids with strong piezoelectric substrates combined with suitable semiconductor layers yield a promising approach to achieve a large tunability of the SAW velocity [6], [7].

II. Interaction Between SAW and Q2DES

The interaction of a SAW and a Q2DES on the surface of the piezoelectric substrate results in a change of SAW phase velocity $\Delta v/v_0$ and an attenuation Γ of the SAW intensity $I = I_0 \exp(-\Gamma x)$ along the propagation path x. This can be described by a simple relaxation model [4], [8]:

$$\begin{aligned}\Gamma &= \frac{K_{\text{eff}}^2}{2}\frac{2\pi}{\lambda}\frac{\sigma/\sigma_m}{1+(\sigma/\sigma_m)^2}\\ \frac{\Delta v}{v_0} &= \frac{K_{\text{eff}}^2}{2}\frac{1}{1+(\sigma/\sigma_m)^2},\end{aligned} \quad (1)$$

where σ is the sheet conductivity and σ_m denotes a critical conductivity in which maximum attenuation occurs; K_{eff}^2 is the electromechanical coupling coefficient and λ is the wavelength of the SAW. In contrast to bulk semiconductor structures where $\Delta v/v_0$ is a function of λ, the velocity change caused by a two-dimensional electron system on the surface of the piezoelectric substrate is independent of wavelength.

Both attenuation and velocity change scale with the coupling coefficient K_{eff}^2. However, in common semiconductor materials the coupling coefficient is very low [i.e., for the GaAs (100) surface: $K_{\text{eff}}^2 = 6.4 \times 10^{-4}$]. Therefore, the maximum change in SAW velocity is not large enough for most applications. The combination of the electronic properties of GaAs and the strong piezoelectric $LiNbO_3$ solves this problem. The coupling coefficient of $LiNbO_3$ (128° rot. YX-cut) $K_{\text{eff}}^2 = 5.6\%$ is nearly two orders of magnitude higher than for GaAs. One approach toward this combination was a sandwich-like structure [9], [10], where a GaAs structure was brought into close contact with a $LiNbO_3$ delay line. A residual gap between the two substrates, however, limits the reproducibility of the coupling between electron system and SAW. Moreover, in this system the sheet conductivity of the Q2DES is not easily tuned.

III. Hybrid Technology

Here we demonstrate a quasi-monolithic hybrid system that can be realized using the epitaxial lift-off technique (ELO) introduced by Yablonovitch *et al.* [11], [12]: a thin GaAs/AlGaAs-structure containing a Q2DES is lifted off the growth substrate and can be transferred on nearly arbitrary host substrates. We use a GaAs/AlGaAs/InGaAs-system that is grown by molecular beam epitaxy (MBE). The GaAs substrate is followed by an AlAs sacrificial layer that afterward is etched away during the lift-off process. The active layer system consists of

Manuscript received November 26, 1997; accepted June 20, 1998.
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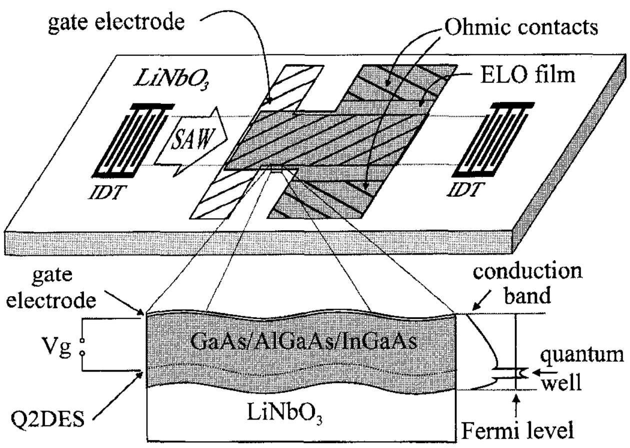

Fig. 1. Schematic geometry of a typical hybrid device. A negative bias between the gate electrode and the Ohmic contacts to the quasi two-dimensional electron sytem (Q2DES) is used to tune the in-plane conductivity and, hence, the SAW velocity. A schematic of the conduction band edge forming the modulation doped quantum well structure is shown next to the layer system. A typical length of the ELO film in the SAW propagation direction is 2 mm.

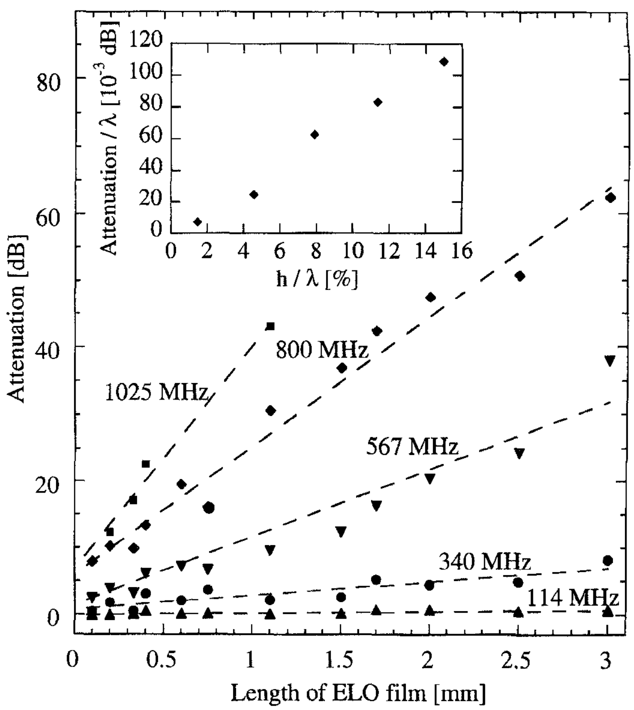

Fig. 2. Mechanical attenuation of an ELO film as a function of the film length. Every symbol reflects the average of about five samples. The inset shows the attenuation per wavelength as a function of h/λ ($h = 0.5$ μm).

modulation-doped $Al_{0.2}Ga_{0.8}As$-barriers with an embedded $In_{0.2}Ga_{0.8}As$ quantum well. Instead of the InGaAs well, we also used a structure with a GaAs quantum well which showed similar results. The distance between quantum well and AlAs layer is just 30 nm. After the diffusion of Ohmic contacts to the Q2DES, the structure is covered with a black wax (Apiezon) acting as a stabilizing layer during the ELO process. Then the AlAs-layer is selectively etched away in hydrofluoric acid and the remaining ELO film is transferred onto a $LiNbO_3$ SAW device. The thickness of the semiconductor film is $h = 0.5$ μm. After some heating procedures this ELO film is tightly fixed on the $LiNbO_3$ only by the van-der-Waals-forces. The GaAs film is then patterned and covered by a thin NiCr gate which acts as a field-effect electrode. The geometry of the complete hybrid SAW device is shown in Fig. 1.

Detailed investigations of the electronic properties of the ELO films in magnetotransport measurements, photoluminescence, and far infrared spectroscopy at $T = 4.2$ K show no degradation of the Q2DES after the ELO process. Recent work on the epitaxial lift-off technology reveals that mass production of ELO devices could be feasible soon [13], [14].

IV. Experimental Results

The ELO film affects the SAW propagation in two different ways: first, it changes the mechanical properties, and second, the electrical boundary conditions are modified. Mechanically the film produces an attenuation and a velocity change of the SAW. The attenuation as a function of film length is shown in Fig. 2. With increasing frequency, the ratio h/λ between film thickness h and wavelength λ also increases. This results in a larger attenuation with increasing frequency. Two reasons for the mechanical attenuation have to be considered: intrinsic losses within the ELO film, and reflections and bulk mode conversion at its edges perpendicular to the propagation direction. Fig. 2 reveals that the attenuation increases linearly with the film length. Therefore, the major part of the attenuation is due to a loss of SAW intensity during propagation in the ELO film itself. The linear regression of the curves was used to calculate the attenuation per wavelength λ. These values are shown in the inset of Fig. 2 as a function of h/λ. For larger h/λ the attenuation per wavelength increases. The extrapolated value of the attenuation for zero film length that is given by the linear regression in Fig. 2 estimates the attenuation due to the film edges. This contribution to the attenuation is also a function of the step height h/λ.

The mechanical load of the GaAs film also modifies the SAW velocity in the film. Experimentally, we obtain a change of the phase velocity for different excitation frequencies as shown in Fig. 3. The SAW group velocity is measured via the delay time of the hybrid system at zero gate bias $V_g = 0$. Due to the dispersive behavior of the semiconductor film, this velocity differs from the phase velocity. From the measured values of the group velocity, we calculated the phase velocities, which are shown in Fig. 3. The effect of the SAW velocity change by the Q2DES can be neglected at $V_g = 0$, because the sheet conductivity σ is large compared to σ_m. As the SAW velocity of GaAs ($v_0 = 2864$ m/s) is much smaller than the corresponding value on $LiNbO_3$ (128° rot. YX-cut, $v_0 = 3980$ m/s), the

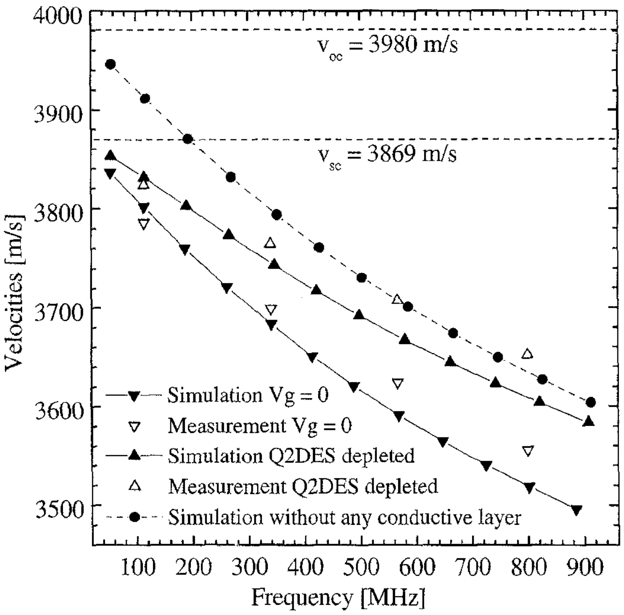

Fig. 3. Measured and simulated SAW phase velocity at different frequencies in GaAs/LiNbO$_3$ hybrids. The phase velocity was calculated from delay time measurements of the group velocity. The dashed line shows the simulated velocities for an ELO film without a Q2DES and without a gate electrode.

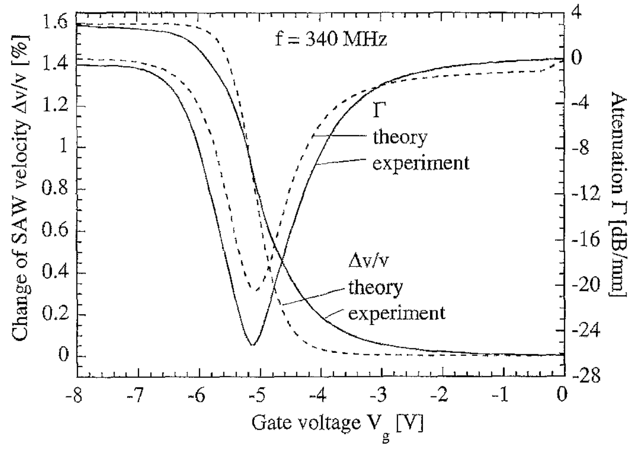

Fig. 4. Change of the phase velocity and attenuation of the SAW as a function of the voltage between gate and Q2DES together with the respective model calculations.

hybrid velocity is lower than on a free LiNbO$_3$ surface. The SAW velocity decreases with increasing frequency because of the higher ratio h/λ. The phase velocity also is calculated using a finite element method [15], [16]. Here, the GaAs structure is assumed to be mechanically homogenous with a conductive layer at the position of the quantum well. Strain induced in the film during the ELO process also is neglected in the simulation. Despite these assumptions and the small number of experimental data points for the calculation of the phase velocity, the agreement between simulation and experiment is good.

When a gate voltage is applied to the GaAs system, the carrier density of the Q2DES is reduced, and the change in conductivity influences the SAW velocity significantly. In Fig. 3 we also show the measured and simulated velocities when the quantum well is depleted. The gate electrode on top of the hybrid structure screens the SAW potentials. This also reduces the electric potentials at the position of the Q2DES [17]. For low frequencies and hence long wavelength, this screening is very strong, resulting in a SAW velocity close to the one at $V_g = 0$. For higher frequencies this effect decreases; therefore, the velocity approaches the simulated curve for an ELO film without any conductive layer (dashed line). Our simulations thus reveal the maximum achievable velocity change $\Delta v/v = (v(\text{depl}) - v(V_g = 0))/v(\text{depl})$ in the hybrid. This velocity change can be used to define a new hybrid coupling coefficient $\overline{K}^2_{\text{eff}} := 2\Delta v/v$ being a function of h/λ. Other approaches to determine this coupling coefficient in semiconductor/piezoelectric-structures can be found in [18], [19].

In Fig. 4 we plot the experimentally obtained velocity change $\Delta v/v$ and the attenuation Γ of the SAW as a function of the gate bias together with a calculation according to (1). $\Delta v/v$ is calculated from the measured phase shift $\Delta\varphi$ via:

$$\frac{\Delta v}{v} = \frac{\Delta\varphi \cdot \lambda}{360° \cdot L} \qquad (2)$$

where L denotes the length of the ELO film. Maximum attenuation and maximum differential velocity change occur at $V_g = -5.1$ V where the critical conductivity σ_m is reached. At $V_g = -7$ V the electron system becomes depleted and the remaining conductivity is at such a low level that the electric SAW attenuation is negligible [see (1)]. At this low electron concentration the SAW velocity reaches its maximum, as expected. As both voltages scale with the actual distance between gate and Q2DES, a proper semiconductor layer design allows for a flexible adjustment of the voltage range to application needs.

In order to compare these measurements with the simple relaxation model (1), the sheet conductivity σ of the Q2DES was measured as a function of gate voltage in four point geometry on the same sample. The coupling constant in (1) is replaced by the effective hybrid coupling constant $\overline{K}^2_{\text{eff}}$ as experimentally measured above. For a frequency of $f = 340$ MHz, we obtain $\overline{K}^2_{\text{eff}} = 0.033 = 0.58K^2_{\text{eff}}$. The critical conductivity σ_m is approximately given by $\sigma_m = v\varepsilon_0\left(\sqrt{\varepsilon^T_{11}\varepsilon^T_{33} - \varepsilon^T_{13}\varepsilon^T_{31}} + 1\right) = 2.1 \times 10^{-6}\Omega^{-1}$ for $f = 340$ MHz, with ε^T_{ii} denoting the dielectric constants of LiNbO$_3$ (128° rot. YX-cut) at constant stress. In contrast to a three-dimensional electron system, σ_m is in two dimensions only a very weak function of the frequency f; the only parameter that changes slightly with frequency according to the dispersion curve in Fig. 3 is the velocity v. As can be seen in Fig. 4, the agreement between measurement and the model is good.

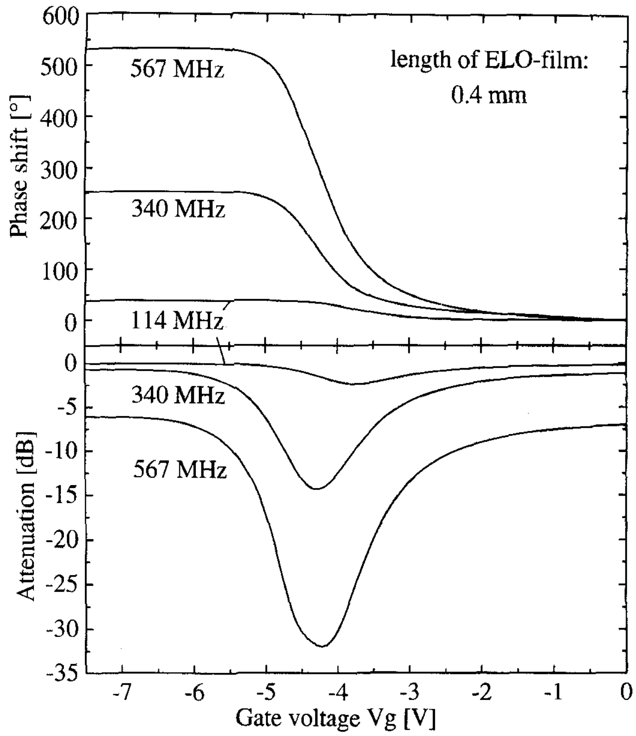

Fig. 5. Phase shift and attenuation of the surface acoustic waves at different frequencies. The insertion losses of the $LiNbO_3$ structure without ELO film are subtracted.

In Fig. 5 we show the same experiment at different frequencies. A split finger transducer geometry is used for the generation of multiple harmonics in these experiments. We display the phase shift and the attenuation for a sample with an ELO film length of 0.4 mm. The insertion losses of the $LiNbO_3$ device without film are subtracted so that only the mechanical and electrical influence of the ELO film are shown. The mechanical attenuation increases with higher frequencies according to Fig. 2. $\Delta\varphi$ as well as Γ increase with shorter wavelength. This is explained by (1) and (2) and the increase of $\overline{K}^2_{\text{eff}}$ for higher frequencies. Fig. 5 also reveals the weak dependence of σ_m on the frequency. With increasing SAW frequency, the hybrid SAW velocity is decreasing, resulting in a reduction of σ_m. This leads to a shift of the points of maximum attenuation toward lower conductivities, i.e., larger negative gate bias.

V. Applications

For several applications, a large tunable phase shift is desirable. As $\Delta\varphi$ is proportional to the ELO film length L (2), devices with longer films yield larger effects. For example, we could demonstrate a phase shift of $\Delta\varphi = 1046°$ at $f = 340$ MHz and $\Delta\varphi = 1320°$ at $f = 434$ MHz for samples with $L = 2$ mm. This large tuning range of the propagating surface acoustic waves is very promising for new devices.

One possible application of these hybrids is a voltage-controlled delay line oscillator, in which the resonance frequency can be tuned by an applied gate voltage. In Fig. 6 we show the device geometry used in our experiments. The operating frequency is $f = 434$ MHz. On a $LiNbO_3$ substrate two transducer structures are fabricated: a short single phase unidirectional transducer (IDT 1) and a long transducer (IDT 2). The acoustical path length is equal to the length of IDT 2 in order to achieve mode selection. An ELO film with $L = 470$ μm is placed in between both IDTs.

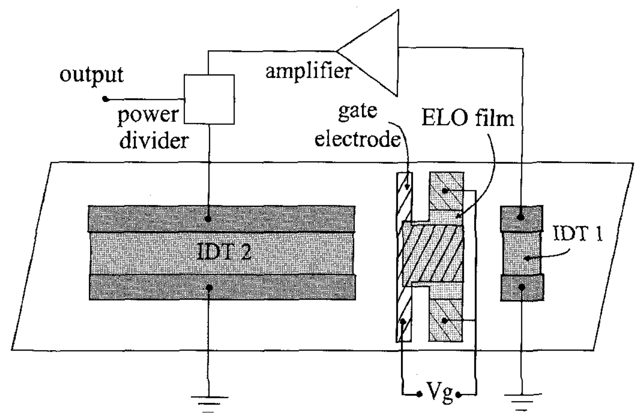

Fig. 6. Schematic sketch of the voltage controlled oscillator.

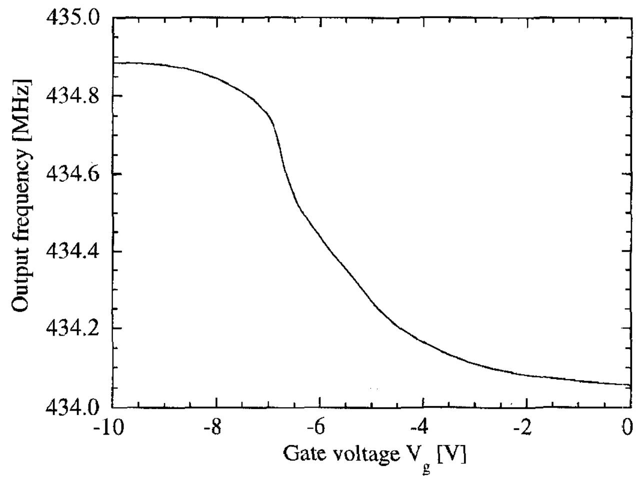

Fig. 7. Measured output frequency of the VCO as a function of the applied gate voltage.

For a loop gain larger than one, the total phase of the loop must be zero and the total losses must be compensated by the amplifier. The output frequency is only an unambiguous function of the gate voltage if the maximum phase shift caused by the ELO film is below 360°. Therefore, we choose a length of the ELO film such that it produces a phase shift of $\Delta\varphi = 355°$. Hence, the film covers about one quarter of the free distance between the transducers. The output frequency of this device as a function of the applied gate bias is displayed in Fig. 7. For this geometry a maximum frequency tunability of 0.82 MHz is achieved. Theoretically, the maximum frequency shift Δf in this oscillator geometry is given as $\Delta f = 1/\tau$ for a phase shift of $\Delta\varphi = 360°$, where τ is the acoustic delay time of the device. Considering the different SAW velocities in the corresponding device areas, the delay time is calculated to $\tau = 1195$ ns. This leads to $\Delta f = 0.84$ MHz ($\Delta\varphi = 360°$), in good agreement with the measured value for $\Delta\varphi = 355°$. A larger frequency tuning range can be achieved if the delay time τ is decreased.

Future phase noise measurements will show how the phase noise properties of the hybrid chip compare to common oscillators, including an external phase shifter. The excellent electronic properties of the semiconductor film allow for future integration of rf circuitry on the same chip, for example, the amplifier in the VCO could be integrated on the hybrid itself.

Also for wireless SAW sensing [20], the hybrid devices are very suitable. For this application the ELO film is placed between a transducer with attached antenna and a reflector structure. The ELO film changes the delay time of a remote radio sensing signal in the device. Therefore, any sensor providing a DC voltage can be read out from a remote location. As the large dynamic electric fields also affect the optical properties of the GaAs structure [7], acousto-optic applications of the hybrids also could be possible.

VI. Conclusions

$LiNbO_3$/GaAs hybrid systems fabricated by the epitaxial lift-off technology open a large field for novel voltage-tunable SAW devices. In order to characterize the acoustic properties of this layer system, detailed experiments and calculations show the mechanical effects of the ELO film on the SAW. Due to the high coupling coefficient of $LiNbO_3$, the acousto-electric interaction between the Q2DES and the SAW is very large. Compared to monolithic GaAs SAW devices, a velocity change being two orders of magnitude larger is achieved in the hybrid system. The experimental results are in good agreement with calculations based on a simple relaxation-type model. With an ELO film of 2 mm length, we reach a phase shift of 1320° at $f = 434$ MHz. The range of the applied voltage is about 7 V and thus compatible with IC voltages. As the interaction is controlled via field-effect, the operation of the device is nearly powerless. As an initial example for possible applications we present a voltage-controlled hybrid oscillator with a frequency tuning range of 0.82 MHz at $f = 434$ MHz. The excellent electronic properties of the GaAs/AlGaAs/InGaAs-heterostructure material allow for the integration of rf amplifiers or integrated circuits on the same hybrid chip. Other possible applications are broadband single-chip voltage-tunable delay lines and hybrids for wireless SAW sensing. Also the excellent acousto-optic properties of $LiNbO_3$ might be combined with the electro-optic properties of layered GaAs heterojunctions, which also could lead to new acousto-optic applications.

Acknowledgment

We would like to thank D. Bernklau and H. Riechert for the excellent GaAs structures grown by MBE, and S. Berek for the fabrication of the $LiNbO_3$ devices. We gratefully acknowledge the $LiNbO_3$ VCO design by W. Neumayer and the technical assistance by S. Manus and T. Ostertag.

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Dr. Kotthaus was elected a Fellow of the American Physical Society in 1989, received the 1991 Gentner-Kastler-Prize of the French and the German Physical Societies, and in 1995 a Max-Planck Research Prize.