Single-chip fused hybrids for acousto-electric and acousto-optic applications

M. Rotter, C. Rocke, S. Böhm, A. Lorke, Achim Wixforth, W. Ruile, L. Korte

Angaben zur Veröffentlichung / Publication details:

Rotter, M., C. Rocke, S. Böhm, A. Lorke, Achim Wixforth, W. Ruile, and L. Korte. 1997. "Single-chip fused hybrids for acousto-electric and acousto-optic applications." *Applied Physics Letters* 70 (16): 2097–99. https://doi.org/10.1063/1.118960.

Applied Physics Letters

Single-chip fused hybrids for acousto-electric and acousto-optic applications

Cite as: Appl. Phys. Lett. **70**, 2097 (1997); https://doi.org/10.1063/1.118960
Submitted: 17 January 1997 • Accepted: 21 February 1997 • Published Online: 04 June 1998

M. Rotter, C. Rocke, S. Böhm, et al.

ARTICLES YOU MAY BE INTERESTED IN

Single-chip fused hybrids for acousto-electric and acousto-optic applications

M. Rotter,[a] C. Rocke, S. Böhm, A. Lorke, and A. Wixforth
Sektion Physik der LMU, Geschw.-Scholl-Platz 1, D-80539 München, Germany

W. Ruile and L. Korte
Siemens AG, Corporate Research and Development, D-81730 Müchen, Germany

(Received 17 January 1997; accepted for publication 21 February 1997)

The combination of the electronic and optical properties of a semiconductor hetero-junction and the acoustic properties of a piezoelectric substrate material yields a new class of very promising hybrids for potential acousto-electric and acousto-optic applications. $LiNbO_3$/GaAs hybrids have been fabricated using the epitaxial lift-off technique resulting in unusually large acousto-electric and acousto-optic interaction between the quasi two-dimensional electron system in the semiconductor and surface acoustic waves on the piezoelectric substrate. Field effect tunability of the interaction at room temperature is demonstrated and possible device applications are discussed. Photoluminescence measurements show the influence of the acousto-electric fields on the optical properties of quantum well structures.
[S0003-6951(97)q36716-4]

High frequency signal processing by means of acoustic methods is rather advanced and widely used today.[1,2] The use of surface acoustic wave (SAW) filters and delay lines has had a strong impact on both the miniaturization as well as the versatility of high frequency circuitry. Also, acousto-optical effects using SAW on dielectrics for Bragg modulators, interferometry, and related topics have been employed frequently and are well understood.[4] Most of these applications rely on the fact that the frequency response of SAW filters can be tailored in most any desired fashion and that nowadays many different strong piezoelectrics are available with technological attractive properties. Except for a few cases, the SAW devices reported so far are passive devices in a sense that for a given design and for a given set of material constants no real tunability of the acoustic or optical properties can be achieved.

On the other hand, the interaction between SAW and quasi two-dimensional electron systems (Q2DES) in semiconductor heterostructures has attracted great interest over the last decade.[5–7] It could be shown that piezoelectric fields accompanying a SAW on a piezoelectric substrate couples strongly to the Q2DES. The mutual interaction is used as a very sensitive tool for the investigation of the properties of the Q2DES.[7] Both the integer and the fractional quantum Hall effect[6] have been the subject of intensive investigations where basically the dynamical conductivity $\sigma(\omega,k)$ was probed by SAW transmission experiments. Also, SAW induced lateral superlattice effects have been reported[8] which might serve as an alternative way for the formation of dynamical quantum structures like quantum wires or even quantum dots.

As has been shown before,[9] the interaction between a SAW and mobile charges in a bulk piezoelectric semiconductor scales with a material parameter, namely K^2_{eff}, the electromechanical coupling coefficient of the respective substrate. For the special case of a Q2DES, the attenuation of the transmitted SAW intensity $I=I_0\exp(-\Gamma x)$ and the velocity shift $\Delta v/v_0$ is calculated in terms of conductivity dependent elastic constants of the piezoelectric substrate and turn out to be given by[4]

$$\Gamma=\frac{K^2_{\mathrm{eff}}}{2}k\frac{\sigma/\sigma_m}{1+(\sigma/\sigma_m)^2}\quad\text{and}\quad\frac{\Delta v}{v_0}=\frac{K^2_{\mathrm{eff}}}{2}\frac{1}{1+(\sigma/\sigma_m)^2},\tag{1}$$

where σ is the sheet conductivity and σ_m denotes a critical conductivity where maximum attenuation occurs; $k=2\pi/\lambda$ is the wave vector of the SAW and v_0 is the sound velocity for a free surface.

For most of the usual semiconductors on which high quality electron systems can be defined, this material parameter is a small quantity [for the GaAs (100) surface: $K^2_{\mathrm{eff}}=6.4\times10^{-4}$]. Hence, the acousto-electric effects being related to the interaction between the SAW and the Q2DES are weak. Both from the physical as well as from the technological point of view a piezoelectric substrate combining high coupling efficiency and the superior electronic properties of modern semiconductor heterostructures would be highly desirable. One attempt in this direction was the use of a sandwichlike hybrid structure[10,11] consisting of a strong piezoelectric substrate and a semiconductor structure containing the Q2DES being brought into close contact. There, it was shown that the SAW/Q2DES interaction is considerably enhanced as compared to the monolithic case. The existence of a residual airgap between the substrate and the semiconductor, however, limits the use of the sandwich hybrids to the lower frequency regime.

Here, we demonstrate that a quasi monolithical hybrid system can be realized using a crystal fusing technique that is usually referred to as ''epitaxial lift-off'' (ELO) introduced by Yablonovitch *et al.*[12] Using this method, the active GaAs/$Al_{0.3}Ga_{0.7}As$ layers of a semiconductor heterojunction containing the high quality electron system, were transferred and fused to a strongly piezoelectric $LiNbO_3$ substrate providing the desired high coupling constant $K^2_{\mathrm{eff}}=0.046$. In this process, a 100-nm-thick AlAs layer below the active semi-

[a]Electronic mail: markus.rotter@physik.uni-muenchen.de

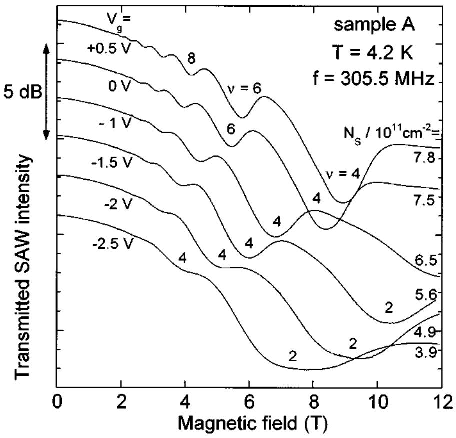

FIG. 1. SAW transmission through the heterojunction containing a Q2DES at low temperatures and in high magnetic fields. Giant quantum oscillations reflect the attenuation of the SAW according to Eq. (1) and the Shubnikov–de Haas oscillations of the magnetoconductivity (see Ref. 5) with ν denoting the Landau level filling factor. The length of the Q2DES is 1.7 mm. Parameter is the gate bias V_g between the Q2DES and a metallic field effect electrode on top of the structure. Negative bias V_g leads to a reduction of the free carrier density N_S.

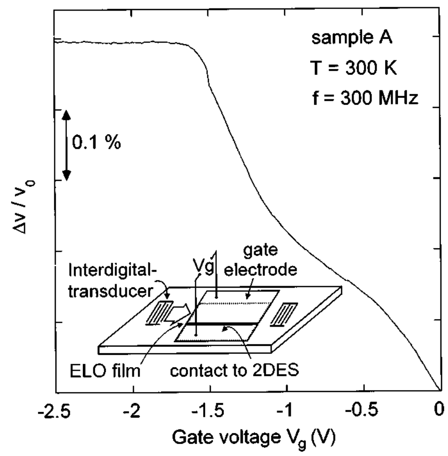

FIG. 2. Room temperature measurement of the change of the SAW velocity caused by the interaction with the mobile carriers in the semiconductor heterojunction as a function of the gate bias V_g. At $V_g \approx -1.5$ V the electron system in the heterojunction becomes depleted, indicated by no further change of the velocity. The inset sketches the sample geometry.

conductor layers is selectively removed using hydrofloric acid. The remaining 500-nm-thick ELO film is then transferred onto a YZ-$LiNbO_3$ substrate forming a SAW delay line (see also inset of Fig. 2). After some pressing and heating procedures that are described in detail elsewhere,[12] the van der Waals forces yield robust quasimonolithical structures. Here, we report on the transfer of a $GaAs/Al_{0.3}Ga_{0.7}As$ heterojunction forming a Si-doped and 100-nm-wide quantum well (sample A) containing a quasi two-dimensional electron system and a 15-nm-wide undoped $GaAs/Al_{0.3}Ga_{0.7}As$ quantum well structure (sample B), respectively. The structures have been grown either by molecular beam epitaxy (sample A) or by metal organic vapor phase epitaxy (sample B).

Typical results of the SAW/Q2DES interaction for the hybrid system in an external magnetic field are shown in Fig. 1. Here, we plot the transmitted SAW intensity as a function of the applied magnetic field. Giant quantum oscillations reflecting the Shubnikov–de Haas oscillations of the diagonal component σ_{xx} of the magnetoconductivity tensor are observed which are similar to those reported before on monolithic GaAs/AlGaAs structures.[4] However, the coupling constant in $LiNbO_3$, which is approximately two orders of magnitude higher than in GaAs, leads to much larger amplitudes of the oscillations than those previously reported. To estimate the effective *hybrid* coupling constant, the velocity shift which is caused by a conductive layer at the location of the Q2DES is calculated in a perturbation approach.[13] Important parameters are the distance between the $LiNbO_3$ surface and the electron system as well as the SAW wave vector k. These calculations yield a hybrid coupling constant $\overline{K}^2_{\mathrm{eff}} = 0.038$ for a SAW frequency of 300 MHz. The critical conductivity σ_m is then given by[11] $\sigma_m = v_0 \varepsilon_0 (\sqrt{\varepsilon_{xx}\varepsilon_{zz}} + 1) = 1.1 \times 10^{-6}\ \Omega^{-1}$, with ε_{xx} and ε_{zz} denoting the dielectric constants of $LiNbO_3$. These parameters together with the longitudinal magnetoconductivity σ_{xx} from transport measurements allow a direct comparison between the calculated SAW transmission according to Eq. (1) and the experiment, resulting in an excellent agreement (not shown).

The conductivity of the Q2DES can also be tuned using the field effect. A gate electrode on the top of the hybrid structure, however, reduces the hybrid coupling constant because of partial screening of the SAW potential.[7,14] In order to achieve a strong influence of the Q2DES on the SAW, the gate electrode must have a considerable distance to the Q2DES and the $LiNbO_3$ surface.[14] Including the influence of the gate electrode, we end up with a hybrid coupling constant of $\overline{K}^2_{\mathrm{eff}} = 0.022$.

In Fig. 1, the parameter between the traces is the gate bias V_g that has been applied between the Q2DES and the thin metal gate electrode on top of the structure. Application of a negative voltage V_g to the gate leads to a depletion of the Q2DES and a reduction of the carrier density N_s in the quantum well. This results in a shift of the oscillations to smaller magnetic fields.

In Fig. 2 we show the corresponding renormalization of the sound velocity of the SAW caused by the interaction with the Q2DES at room temperature. For the geometry of sample A, which has not yet been optimized, a change of about 0.5% of the SAW velocity can be realized. This strong modulation of the sound velocity is technologically very attractive, as it can be used for the realization of widely tunable delay lines, oscillators, and resonators around the center frequency of the SAW.

Also, the optical properties of a semiconductor quantum well can be altered acoustically in our hybrid system. The SAW propagating on the $LiNbO_3$ is accompanied by both vertical and lateral fields of appreciable strength that can couple to the semiconductor layers. Three major interactions between the piezofields and the optical properties of a quantum well are realizable:

(i) The strong vertical fields of the SAW lead to a tilt of the band edges of the well and hence to a shift of the

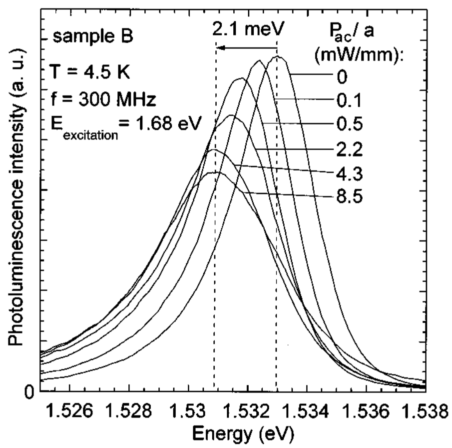

FIG. 3. Photoluminescence (PL) spectra of an undoped 15-nm-wide $GaAs/Al_{0.3}Ga_{0.7}As$ quantum well under the influence of a SAW propagating through the hybrid. With increasing SAW power the PL line shifts towards lower energies and loses intensity. The effects are understood in terms of the quantum confined Stark effect (QCSE) and a dissociation of the photogenerated excitons, respectively. P_{ac}/a denotes the acoustic power per unit beam path. The laser excitation intensity was 8.2 mW/cm^2.

quantum well state energies [quantum confined Stark effect, (QCSE)]. The observed PL in this case is red-shifted towards smaller energies.

(ii) The lateral electric field components associated with the SAW lead to a polarization of the photogenerated excitons and, above a critical field strength, may result in an exciton dissociation.[15] Hence, the observed PL is quenched above this critical field.

(iii) The strong piezoelectric fields may also lead to the occurrence of a lateral Franz–Keldysh effect that has been observed.[17]

In Fig. 3 we depict the result of a PL measurement taken on a 15-nm-wide GaAs/AlGaAs quantum well under the influence of a SAW propagating through the hybrid structure. As the SAW intensity is increased, we observe a pronounced red shift of the PL, in accordance with (i) as well as a decrease of the PL intensity which can be related to (ii). In our experiment, the maximum acoustic SAW power $P_{ac}/a = 8.5$ mW/mm (a being the width of the acoustic beam) corresponds to vertical and lateral fields of the order 1.3×10^4 V/cm and the 0.5×10^4 V/cm, respectively. As the period of the oscillating electric fields (τ=3.3 ns) is larger than the mean exciton lifetime which is of the order $\tau_{ex}\approx 1$ ns, radiative exciton recombination is possible at different spatially separated amplitudes of the electric fields. This results in a broadening of the PL signal.

Detailed investigations and extensions of the above acousto-optic effects are presently carried out. In addition to the reported effects, one can also imagine optical signal processing by the creation of lateral refractive index gratings or the modulation of the optical properties by SAW. Also, the possibility of the hybridization of, for instance, active semiconductor laser structures with strong piezoelectrics should be emphasized here.

In summary, we demonstrated a new class of semiconductor-piezoelectric hybrid structures that provide very promising properties for future acousto-electric and acousto-optic applications. Also for basic research these structures are of great value as the SAW provides an effective tool for the investigation of the dynamical electric and optical properties of quantum structures in semiconductor layer systems. Using fused hybrids, the resulting interaction between the SAW and the electron system in semiconductor quantum well structures is enhanced by nearly two orders of magnitude as compared to the monolithic case. At room temperature a very large modulation of the SAW velocity has been achieved which is very interesting for novel tunable SAW devices. By further optimization of the hybrid systems considerably higher electric fields can be reached, resulting in a strong modulation of the carrier density and the optical properties. This way, well defined dynamic lateral superlattices and carrier transport in the SAW field are accessible. The hybrid structure presented here could also be exploited for combination of the excellent acousto-optic properties of $LiNbO_3$ and the electro-optic properties of layered semiconductor structures. Our studies thus mark only the beginning of a new field of investigations and technological applications of the SAW/Q2DEG interaction.

The authors would like to thank J. H. English for his help and providing his growth expertise. They gratefully acknowledge fruitful discussions with J. P. Kotthaus and B. Borchert, and the technical assistance by S. Manus, W. Kurpas, and A. Kriele. M.R. acknowledges financial support of the Siemens AG, Munich. This work has been partially sponsored by the Deutsche Forschungsgemeinschaft (SFB 348) and in part by the Bayerischer Forschungsverbund FOROPTO.

[1] C. C. W. Ruppel, R. Dill, A. Fischerauer, G. Fischerauer, W. Gawlik, J. Machui, F. Müller, L. Reindl, W. Ruile, G. Scholl, I. Schropp, and K. C. Wagner, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **40**, 438 (1993).
[2] C. Campbell, *Surface Acoustic Wave Devices and their Signal Processing Applications* (Academic, New York, 1989).
[3] W. J. Stewart and I. Bennion, in *Rayleigh-Wave Theory and Application*, edited by E. A. Ash and E. G. S. Paige, Springer Series on Wave Phenomena (Springer, Berlin, 1985), pp. 341–356.
[4] A. Wixforth, J. P. Kotthaus, and G. Weimann, Phys. Rev. Lett. **56**, 2104 (1986).
[5] R. L. Willet, R. R. Ruel, M. A. Paalanen, K. W. West, and L. N. Pfeiffer, Phys. Rev. B **47**, 7344 (1993).
[6] R. L. Willet, R. R. Ruel, K. W. West, and L. N. Pfeiffer, Phys. Rev. Lett. **71**, 3846 (1993).
[7] A. Wixforth, J. Scriba, M. Wassermeier, J. P. Kotthaus, G. Weimann, and W. Schlapp, Phys. Rev. B **40**, 7874 (1989).
[8] J. M. Shilton, D. R. Mace, V. I. Talyanskii, M. Pepper, M. Y. Simmons, A. C. Churchill, and D. A. Ritchie, Phys. Rev. B **51**, 14770 (1995).
[9] A. R. Hutson and D. L. White, J. Appl. Phys. **33**, 40 (1962).
[10] A. Wixforth, J. Scriba, M. Wassermeier, J. P. Kotthaus, G. Weimann, and W. Schlapp, J. Appl. Phys. **64**, 2213 (1988).
[11] A. Schenstsrom, Y. J. Qian, M.-F. Xu, H.-P. Baum, M. Levy, and B. K. Sarma, Solid State Commun. **65**, 739 (1988).
[12] E. Yablonovitch, T. Gmitter, J. P. Harbison, and R. Bhat, Appl. Phys. Lett. **51**, 2222 (1987); E. Yablonovitch, D. M. Hwang, T. J. Gmitter, L. T. Florez, and J. P. Harbison, *ibid.* **56**, 2419 (1990).
[13] B. A. Auld, *Acoustic Fields and Waves in Solids* (Wiley, New York, 1973), Vol. II, p. 291.
[14] C. Rocke, S. Manus, A. Wixforth, M. Sundaram, J. H. English, and A. C. Gossard, Appl. Phys. Lett. **65**, 2422 (1994).
[15] A. Schmeller, W. Hansen, J. P. Kotthaus, G. Tränkle, and G. Weimann, Appl. Phys. Lett. **64**, 330 (1994).