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Shock waves in suspended low-dimensional electron gases

Florian W. Beil[a], Nakul Shaji[b], Felix Schoefer[a,b], Achim Wixforth[c], Werner Wegscheider[d], Dieter Schuh[d], Max Bichler[e], Robert H. Blick[b,*]

[a]*Center for NanoScience, University of Munich, 80539 Munich, Germany*
[b]*Electrical & Computer Engineering, University of Wisconsin-Madison, Madison, WI 53706, USA*
[c]*Lehrstuhl fuer Experimentalphysik I, University of Augsburg, 86135 Augsburg, Germany*
[d]*Institut fuer Angewandte & Experimentelle Physik, University of Regensburg, 93040 Regensburg, Germany*
[e]*Walter-Schottky-Institut, Technical University of Munich, 85748 Garching, Germany*

Abstract

We study the formation of shock waves in a suspended two-dimensional electron gas using surface acoustic waves. The mechanical displacement of the nano-resonator is read out via the induced acoustoelectric current. Applying acoustical standing waves, we are able to determine the anomalous acoustocurrent. This current is only obtained in the regime of shock wave formation. We find very good agreement with model calculations.

Keywords: Suspended low-dimensional electron gas; Electron–phonon interaction

During the last years, structuring of electron systems progressed to a point where the dimensionality of the electron gas as well as that of the surrounding phonon system can now be altered. An example for this is the freely suspended two-dimensional electron system (2DEG), for which the phonon modes can be tailored [1]. The combination of low-dimensional electron gases and a mechanical, that is 'phonon', degree of freedom is interesting for several reasons, the most obvious being the ability to enhance or reduce dissipation of heat in these systems, when applied as high-electron mobility transistors. The second important aspect is the study of the electron–phonon interaction for quantum computation purposes, i.e. to study this mechanism in the limit of single electrons exchanging energy with discrete vibronic modes of the suspended electron system [2]. Finally, suspended 2DEGs will be of considerable importance for approaches to metrology [3].

The main limitation encountered so far is the fact that the phonon system, in contrast to the electronic one, could not be actuated directly. Nevertheless, the method of choice for generating such an acoustic actuation is readily available; surface acoustic waves (SAW) are a proven tool for investigating non-suspended 2DEGs already [4]. Hence, we set out to combine low-dimensional electron systems embedded in a thin slab of AlGaAs with SAW generators, such as interdigitated transducers (IDTs). In early work, we demonstrated how to achieve acoustical coupling of an ordinary suspended beam without electron gas to SAWs [5,6].

Here, we present acoustical excitations of a suspended 2DEG by SAW, leading to the formation of shock waves in the phonon system. Shock wave formation is probed with the help of the so-called anomalous acoustoelectric effect, one of the manifestations of the electron–phonon interaction. Acoustoelectric effects have up to now been mainly studied in quantum wells, where the mechanical properties are determined by the bulk [7]. It should be noted again that suspending low-dimensional electron systems leads to a very strong mechanical deformation of the slab, as

*Corresponding author. Tel./fax: +1 608 262 1952.
E-mail address: blick@engr.wisc.edu (R.H. Blick).

compared to a ‘bulk 2DEG’. Hence, the interaction of electrons and acoustical phonons is extremely enhanced.

In the following, we will describe how SAWs mechanically excite the suspended electronic specimen and how acoustic currents are observed. The measured current consists of two components of which one is an anomalous current. This current directly traces the shock wave formation in the nano-resonator. As shock wave, we define the transition from a linear response such as a sinusoidal excitation towards non-linear waveforms.

The processing follows standard techniques for suspended 2DEGs [1,2], with the difference that we integrate IDTs for SAW generation on the sample. The lateral structures of the suspended 2DEGs and the IDTs are then defined via electron beam lithography. In a further step, anisotropic reactive ion etching (RIE) is applied to mill out the lithographically defined structure.

In Fig. 1, a scanning electron micrograph of the sample is shown. The inset presents the suspended beam of length 1.2 μm, width 300 nm and height 200 nm used in the experiments. The suspended sample is placed between two IDTs forming an acoustic delay line. In the following, the two IDTs are excited with continuous waves from two synthesizers.

For shock wave probing, we couple both IDTs to generate an acoustical standing wave pattern and then trace the induced direct current. The transducers generate a coherent acoustic sound wave via the inverse piezo effect, at the lithographically defined center frequency f_{saw}. The SAW frequency and wavelength are connected via $f_{\mathrm{saw}} = v_{\mathrm{saw}}/\lambda_{\mathrm{saw}}$, where $v_{\mathrm{saw}} = 2865\,\mathrm{m\,s^{-1}}$ is the surface wave velocity on GaAs in the [0 1 1] direction. In order to measure the acoustoelectric effects in the 2DEG in a two-point fashion. In Fig. 2(a), the measured magnetoresistance of the suspended 2DEG is shown. We find a sheet carrier density of $6.6 \times 10^{11}\,\mathrm{cm^{-2}}$ and a mobility of $3000\,\mathrm{cm^2\,V^{-1}\,s^{-1}}$. Also shown in Fig. 2(b) is a numerical simulation of the three fundamental mechanical modes of the suspended semiconductor beam.

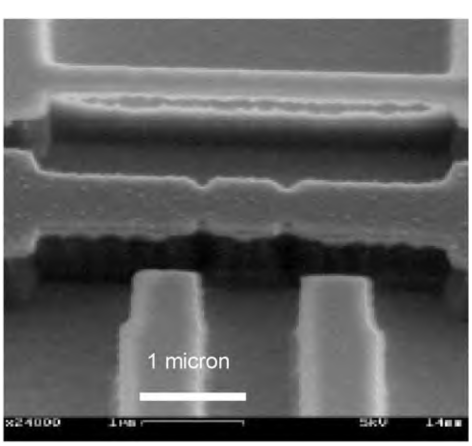

Fig. 1. Suspended slabs of 2DEG, which are placed between two SAW generators for probing the induced acoustoelectrical current.

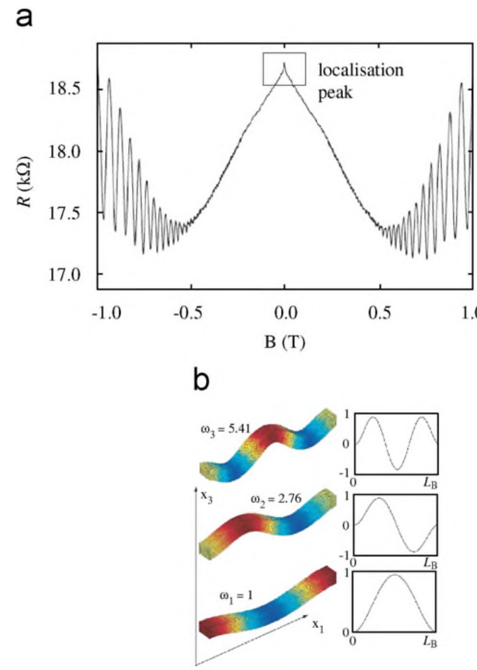

Fig. 2. (a) Magneto-transport data of the suspended 2DEG and (b) finite element simulation of suspended acoustically modulated semiconductor slab. Shown is the fundamental mode and the next to higher modes.

In order to read out the acoustoelectrical current, we conducted acoustic standing wave experiments; a standing wave is formed by applying phase-locked RF signals to both IDTs, left and right of the sample. Shifting the relative phase ϕ of the driving signal at one IDT, with respect to the other, results in a lateral shift of the standing wave pattern. If a perfect standing wave is formed, the total wave vector equals to zero and the only contribution to the measured acoustoelectric current is the anomalous component I_{an} [8].

In other words, the normal acoustoelectric current depends only on the propagating part, whereas the anomalous current depends on the mechanical deformation induced in the suspended 2DEG. Thus, we have a direct relation between the mechanical deformation and the relative phase ϕ, which allows us to map the mechanical mode of the suspended beam. By varying ϕ, we shift the maxima and minima of the acoustic wave through the resonator, thus mapping the deformation of the resonator directly in the current response.

In Fig. 3, the standing wave pattern of the anomalous current is shown. Evidently, the initial trace with moderate power levels applied to the IDTs is a fundamental mode of the suspended 2DEG, forming a sinusoidal trace. Increasing the acoustic power leads to a larger current, i.e. the trace is increased towards more negative currents. The deviation from the sinusoidal waveform shows up as a pronounced peak around $\phi = 180^\circ$. This is the transition from linear to non-linear response, where the steepening of the trace indicates *shock wave formation*. In other words, all of the energy of the SAW is compressed around $\phi = 180^\circ$, resulting in this non-linear waveform [9].

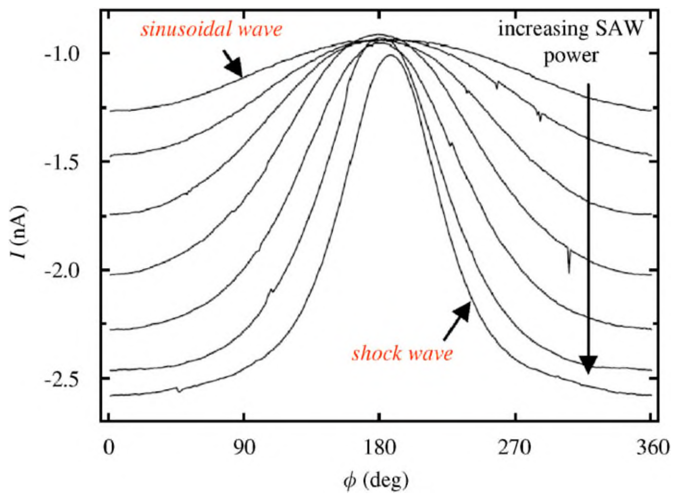

Fig. 3. Standing wave pattern in the induced anomalous acoustoelectric current vs. phase variation ϕ. With increasing SAW power (arrow), the pattern changes from a sinusoidal response to a shock wave.

In summary, we have shown that shock waves can be generated in suspended low-dimensional electron systems. The acoustoelectric effect is applied to map the mechanical deformation of the semiconductor beam containing the electron gas. In tracing the anomalous acoustoelectric current, we find the transition from a mechanical ground mode to a shock wave.

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