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Transport in a shunted surface superlattice with a perpendicular magnetic field

T. Feil*, H.-P. Tranitz, C. Gerl, W. Wegscheider

Institut für Experimentalphysik, Universität Regensburg, 93040 Regensburg, Germany

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Abstract

We experimentally investigate the transport through a shunted surface superlattice under the influence of a magnetic field applied perpendicular to the current direction. The current–voltage characteristics of these surface superlattices exhibit a peak which is followed by a wide region of negative differential resistance. The application of a transverse magnetic field has a profound influence on the position and height of this peak. The recorded shifts are compared to the predictions of different superlattice transport theories. Since these theories predict a different dependence on the magnetic field strength, the transport mechanism in the surface superlattice structures can be uniquely determined.

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1. Introduction

In their proposal [1] of the superlattice structure, Esaki and Tsu showed that a superlattice under homogeneous bias should exhibit negative differential conductivity (NDC) due to electrons performing Bloch oscillations in a cosine-like miniband. Based on their initial suggestions it was found that the superlattice is a potential active gain medium in the THz regime [2,3]. Unfortunately, it turned out that the NDC in the structure is unstable with respect to electric field domain formation. This problem is mainly responsible for the fact that no electrically driven active Bloch oscillator has been realized. In Ref. [4] we have suggested a superlattice structure which allows us to avoid electric field instabilities even at high carrier densities.

In this contribution we study the transport through such a surface superlattice (SSL) under the influence of a magnetic field that is applied perpendicular to the SSL. The magnetic field leads to a confinement which competes with the one induced by the electric field. In particular, the work on conventional superlattices (SL) showed that both the position and the height of the NDC peak are strongly influenced. Since the dependence of the shift of the NDC peak on the magnitude of the magnetic field is expected to be quadratic for sequential tunneling transport and linear for the semiclassical miniband transport, we can infer the adequate transport description for our structure from this position change.

2. The device

Fig. 1 shows the typical structure used for the realization of a shunted surface superlattice as investigated here. It is realized by the cleaved-edge overgrowth method [5], which combines two perpendicular growth steps with atomic precision. In the first step a nominally undoped $GaAs/Al_{0.3}Ga_{0.7}As$ SL, with two doped contact layers on each side is deposited on a semi-insulating [0 0 1] substrate. This structure is then cleaved in situ and is overgrown on the side with a GaAs well referred to as the cleaved-edge well (CEW), followed by an $Al_{0.3}Ga_{0.7}As$ barrier and a doped GaAs layer acting as a gate contact. The actual well and barrier thicknesses of the undoped SL are 12 and 3 nm, respectively, and the CEW has a width of 5 nm. The

*Corresponding author.
E-mail address: thomas.feil@physik.uni-regensburg.de (T. Feil).

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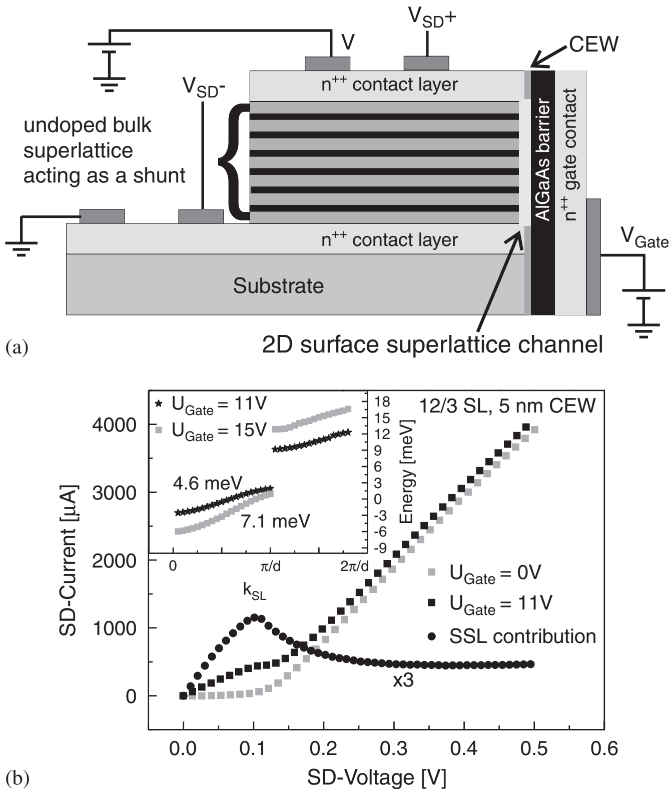

Fig. 1. In (a) a schematic drawing of the sample structure is shown. Part (b) shows the transport contributions of the combined SL/shunt system and also the individual transport characteristics. In the inset the bandstructure of the device for gate voltages of 11 and 15 V are shown.

operation of the device is similar to a field-effect transistor. A positive voltage is applied to the side gate contact which in turn leads to the formation of a two-dimensional electron system at the interface between CEW and gate barrier. The two-dimensional channel is subject to a strong modulation from the undoped SL, which leads to the formation of minibands separated by minigaps (cf. inset Fig. 1(b)) in the direction of the first growth step, just as in a conventional SL. Therefore, we will refer to the low-dimensional channel as a surface superlattice. The transport along this channel can then be studied by application of a voltage across the two contacts next to the undoped bulk superlattice.

At liquid helium temperatures and for a fixed gate voltage, the transport characteristics of the device are taken by sequentially sweeping the applied bias V while the voltage drop V_{SD} and the current are measured. The series resistance of the doped layers is determined from conductivity measurements at low magnetic fields and the current–voltage characteristics are corrected for the corresponding value.

In order to achieve an active shunting of the SSL, which is needed in order to avoid field instabilities [6], the doping profile in the contact layers of the first growth direction is chosen such that there is substantial current flow through the undoped SL. The undoped SL has a small unintentional carrier density, which means that the field distribution is almost homogeneous along the device [7,8] and the current–voltage characteristic increases monotonically (cf. Fig. 1(b), $U_{\mathrm{Gate}} = 0\,\mathrm{V}$). For positive bias, the SSL also carries current and its transport characteristic can be found as the difference between the two traces (cf. Fig. 1(b)). The SSL transport has the characteristic shape expected for a superlattice with a homogeneous field distribution [1]. From the position of the NDC peak we extract a relaxation time of about 0.8 ps. This rather long scattering time is a major difference to usual superlattice structures which typically have relaxation times of about 100 fs. A comparison between the miniband energies and the scattering-induced level broadening suggests [9] that our device is operated in the miniband transport regime.

3. Transport in a transverse electric field

The application of a magnetic field perpendicular to the current direction has a profound influence on the transport along a superlattice structure [10–13]. In Ref. [11] it was demonstrated that low-density SLs, which show a continuously increasing current, are expected to show a positive magnetoresistance for small electric field values, whereas a negative magnetoresistance should appear for larger bias. The cross over point between these two regimes is predicted to increase with the applied magnetic field strength. Such a behavior is also found for the transport characteristics of the shunting bulk SL as shown in Fig. 2. The explanation of this behavior completely relies on a semiclassical miniband transport picture. Therefore, the bulk SL transport in our device seems, even for a small miniband width of 3.3 meV, as found from a Kronig–Penney model calculation, to be best described by this description. This in turn suggests rather long relaxation times also for the carriers in the shunting SL.

For the rest of our discussion we will now solely focus on the magnetic field-induced changes in the current–voltage characteristics of the SSL. Since the SSL is a SL structure with homogeneous field distribution the changes in the velocity–electric field characteristic are directly seen in the current–voltage traces. For a gate voltage of 15 V, which corresponds to a density of $2.5 \times 10^{11}\,\mathrm{cm}^{-2}$, the corresponding data are shown in Fig. 3. Two main features are observed for increasing magnetic field strength. First, the overall transport decreases continuously and second the NDC peak position is shifted to higher applied biases. A shift in the NDC peak position towards higher applied bias is expected for both the miniband transport [10,14] and the sequential resonant tunneling regime [15]. In the first case the magnetic field induces an additional confinement along the SL axis which competes with the localization due to the electric field, which itself is responsible for the NDC. Therefore, for increasing magnetic field strength, meaning stronger additional confinement, it takes larger electric fields for the carriers to feel the NDC inducing localization effect. Above a certain threshold magnetic field