ELSEVIER
Physica E 7 (2000) 294–298
PHYSICA E
www.elsevier.nl/locate/physe

Negative differential resistance of a 2D electron gas in a 1D miniband

R.A. Deutschmann[a,*], W. Wegscheider[a,b], M. Rother[a], M. Bichler[a], G. Abstreiter[a]

[a] Walter Schottky Institut, Technische Universität München, Am Coulombwall, 85748 Garching, Germany
[b] Universität Regensburg, Universitätsstr. 31, 93040 Regensburg, Germany

Abstract

We experimentally investigate the miniband transport in a novel kind of superlattice fabricated by the "cleaved edge overgrowth" method. The structure represents a field effect transistor, where the channel consists of an MBE-grown superlattice perpendicular to the current flow. By means of the gate the Fermi energy can be adjusted between the bottom of the first miniband and into the minigap. We observe pronounced negative differential resistance at electric fields across the superlattice as low as 160 V/cm. From magnetotransport measurements a relation between the applied gate voltage and the position of the Fermi energy in the artificial band structure is established. Electron mobility depending on the Fermi energy is deduced separately from Shubnikov–de Haas oscillations, from the voltage at the peak current and from the low-field resistance.

Keywords: Superlattice; Miniband transport; Negative differential resistance; Bloch oscillations

1. Introduction

Man made periodic potentials have long been of great interest for fundamental research and in view of applications. On the one hand epitaxially grown semiconductor superlattices (SLs) have revealed a large variety of effects in electronic transport [1], but so far research has mainly concentrated on systems with Fermi energy close to the miniband minimum. Additionally for a given sample the Fermi energy is usually fixed. On the other hand in surface lateral superlattices the Fermi energy is adjustable, but at the price of a rather large periodicity and shallow potential modulation which leads to a large number of occupied bands [2]. We have extended a sample structure developed by Störmer et al. [3] to combine attractive features of both: A two-dimensional electron system (2DES) resides in an atomically precise superlattice, the Fermi energy of which can continuously be adjusted over a wide range by a gate, and the bandstructure of which can be engineered by heterostructure MBE growth. This sample design allows us to study superlattice DC transport as well as magnetotransport properties of a single partially or fully filled band.

2. Sample design and measurement technique

Our samples consist of an MBE grown undoped 100×119 Å GaAs/31 Å $Al_{0.32}Ga_{0.68}As$ SL sand-

* Corresponding author. Tel.: +49-89-28912756; fax: +49-89-3206620.
E-mail address: rainer.deutschmann@wsi.tu-muenchen.de (R.A. Deutschmann)

1386-9477/00/$ - see front matter
PII: S1386-9477(99)00312-4

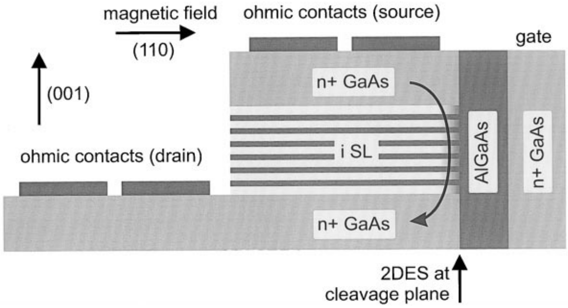

Fig. 1. Sample structure. First in the (0 0 1) direction the undoped SL is grown between two n+ GaAs contacts. After cleaving the sample, on the (1 1 0) face the gate is grown. At positive gate voltages a two-dimensional electron gas is induced in the SL at the interface to the AlGaAs. The magnetic field is applied perpendicular to the 2DES.

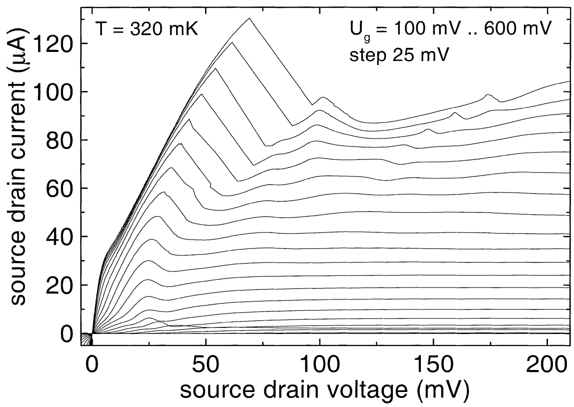

Fig. 2. Current voltage relation for gate voltages between 100 and 600 mV. A region of negative differential resistance at very low electric fields across the SL is observed, the position of which depends on the gate voltage.

wiched between two 100 nm undoped GaAs layers and two 1 μm n+ GaAs layers grown on semi-insulating (0 0 1) GaAs substrate, as shown in Fig. 1. The two doped layers serve as source and drain contacts. After in situ cleaving the sample, an $Al_{0.32}Ga_{0.68}As$ spacer layer is grown on the freshly exposed (1 1 0) plane, followed by a 15 nm undoped and a 100 nm n+ GaAs layer, which serves as a gate. After wet chemical etching source, drain and gate are finally contacted by evaporating GeAu.

Experiments were performed at liquid helium temperatures in a four point contact measurement scheme with two contacts each on source and drain. The samples have to be cooled below liquid nitrogen temperatures to avoid thermally activated bulk leakage currents between source and drain. By applying a positive voltage U_g to the gate with respect to source and drain a two-dimensional electron gas can be induced in the SL below the gate. Electrons thus travel in an *undoped* SL from source to drain, while their density can continuously be controlled by the gate. These features make our samples distinct from conventional MBE grown GaAs/AlGaAs SLs used for transport experiments. On the other hand our samples can be viewed as surface lateral SL with strong potential modulation and shorter period as can conventionally be obtained. In DC measurements one set of contacts was used to apply the voltage and measure the current I_{sd}, with the other set of contacts the true voltage drop U_{sd} across the SL was measured. Additionally the sheet resistance of the GaAs contact layers was accounted for by subtracting the appropriate voltage drop. Magnetotransport measurements were also performed in four point geometry with the magnetic field oriented perpendicular to the 2DES.

3. Experimental results

The DC current voltage relation of the transistor for U_g between 100 and 600 mV is shown in Fig. 2. At first sight the curve resembles that of a conventional transistor, with an ohmic current increase at low source drain voltages, saturation at high source drain voltages, an orderly increase of the saturation current with gate voltage, but with an additional region of negative differential resistance (NDR). A closer look reveals four different regimes depending on the gate voltage. For $U_g < 170$ mV no NDR is present. For U_g between 170 and 240 mV NDR develops, the peak current I_{peak} increases, the peak voltage U_{peak} decreases. Subsequently up to $U_g = 400$ mV the voltage U_{peak} remains almost constant at about 25 mV. Finally for even higher U_g the voltage U_{peak} increases again, and instability is observed for $U_{sd} > U_{peak}$ which causes I_{sd} to drop and U_{sd} to rise abruptly. Additionally a kink is observed in I_{sd} at $U_{sd} = 5$ mV, the origin of which is unclear.

As a first remark we note that for $U_g = 0$ mV practically no leakage current I_{sd} is detected for voltages U_{sd} we are concerned with here. However, for $U_{sd} > 1.1$

V, a gate voltage independent sudden increase of I_{sd} is observed, followed by an instability similar to the one discussed above. This effect is attributed to electrons being injected into the bulk SL from the contact at large U_{sd}. A second remark is concerned with the energetic barrier between source and drain, which prevents bulk leakage current and is determined by the energetic position of the first miniband with respect to the Fermi level in the doped GaAs contacts. At low electron densities ($U_g < 200$ mV) and small U_{sd} this barrier is significant also in the electron channel and causes non-ohmic increase of I_{sd} with U_{sd}.

Information about the relation between U_g and the electron density in the channel n_s was obtained by magnetotransport measurements. We found clear Shubnikov–de Haas (SdH) oscillations in the longitudinal magnetoresistance ρ_{xx} from which three kinds of information can be deduced. First, from the periodicity of the oscillations the electron density was determined to $n_s = (5.7 \pm 0.1) \times U_g 10^{11}\ \mathrm{V}^{-1}\ \mathrm{cm}^{-2}$ which agrees reasonably well with the result obtained from a capacitor model. The spacing between the maxima of ρ_{xx} was perfectly constant for all U_g when plotted against inverse magnetic field. Second, from the onset of the SdH oscillations a rough estimate of the electron mobility in the SL can be obtained, which will be discussed below. Third, a characteristic positive magnetoresistance and a quenching of the SdH oscillations are observed in the SdH curves when U_g is raised above a critical voltage. This behavior is expected for a system with open electron orbits [4].

4. Discussion

The one-dimensional band structure of the given SL is readily obtained by a Kronig–Penney calculation, which yields a width for the first miniband of $\Delta = 3.8$ meV, separated from the second miniband by a 60 meV one-dimensional minigap. The first excited level of the triangular field effect potential is expected at about 15 meV above the first miniband. Since there is still free electron movement possible perpendicular to the SL parallel to the cleavage plane, the energy-momentum relation is given by

$$E(k_x, k_z) = \frac{\hbar^2 k_x^2}{2m^*} + \frac{\Delta}{2}(1 - \cos(k_z d)),$$

where $d = 150$ Å is the SL period, k_x and k_z are the electron momenta in the free and SL direction, respectively. In order to establish a relation between the Fermi energy E_f and n_s we have determined the density of states (DOS) numerically, which is displayed together with the first miniband in Fig. 3. The DOS has a logarithmic singularity at the top of the miniband, but there are states in the minigap [5].

Experimentally, the onset of the positive magnetoresistance occurred at $U_g = 450$ mV, corresponding to $n_s = 2.5 \times 10^{11}\ \mathrm{cm}^{-2}$. On the other hand, given the DOS, we can calculate n_s for $E_f = \Delta$ and we find $n_s = 2.3 \times 10^{11}\ \mathrm{cm}^{-2}$ in quite good agreement with the experiment. Thus we know that for any $U_g < 450$ mV, E_f will be in the first miniband, whereas for $U_g > 450$ mV the minigap will be occupied.

We now proceed to extracting the apparent electron mobility depending on U_g from the data, which can be done in three different ways. First the condition $\omega_c \tau \geqslant 1$ for the appearance of SdH oscillations, with ω_c the cyclotron frequency and τ the scattering time, yields a lower bound of the electron mobility $\mu_{SdH} = 1/B_c$ given the critical magnetic field B_c at the onset of the SdH oscillations. It is well known that this procedure considerably underestimates the true mobility of the carriers [6]. Second in the Esaki and Tsu model [7] the expression $\mu_{ET} = e\Delta\tau d^2/2\hbar^2$ is found where τ can be determined from $U_{peak} = l\hbar/e\tau d$, where $l = 1.5$ μm is the SL thickness. Although the low temperature may justify the use of the Esaki–Tsu model over more sophisticated models, again the obtained mobility will likely be underestimated. This is because the finite Fermi energy has not been taken into account in the calculation. Third we can estimate the mobility from the slope $1/R$ of the ohmic increase of I_{sd} at small U_{sd} from $\mu_R = l/Rn_s eb$, where $b = 240$ μm is the channel width.

In Fig. 4 we have plotted the values of μ obtained as described above. Both μ_{SdH} and μ_{ET} are of the same magnitude and have qualitatively the same behavior with U_g. For small band filling μ_{SdH} and μ_{ET} first increase, then remain constant, and decrease for E_f close to and in the minigap. μ_R in contrast is drastically smaller and shows a very different dependence on U_g with three different linear regimes. The small magnitude of μ_R explains why I_{peak} is much smaller than expected from the Esaki–Tsu model. So far we do not have an appropriate model for these findings.

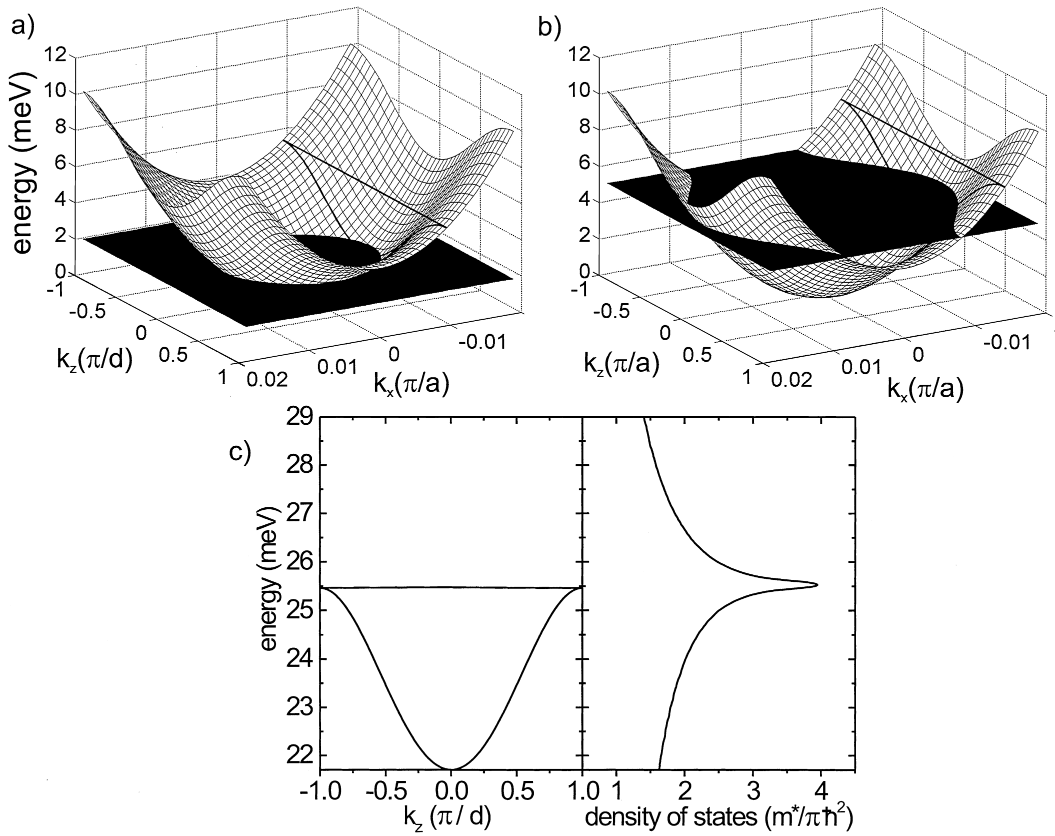

Fig. 3. Shape and density of states of the first miniband: (a) Situation for $E_f = \Delta/2$. Schematically the trajectory of one electron for an electric field along the SL and long scattering time is depicted. a is the lattice constant of GaAs. (b) Situation for $E_f > \Delta$. It can be seen that electron transport and NDR is still possible. (c) Band structure along the SL direction and density of states, normalized to the DOS of a 2DES.

Electrons in a SL are expected to perform Bloch oscillations (BO) when $\omega_{BO}\tau \geqslant 1$, where $\omega_{BO} = eFd/\hbar$. For $U_g = 375$ mV we have found $\mu_{SdH} = 4$ m^2/Vs, from which follows $\tau = m^*\mu/e = 1.5$ ps, with $m^* = 0.067m_e$ conservatively taken. BOs can thus be expected for $U_{sd} > 43$ mV with a minimum frequency of $f_{BO} = 100$ GHz, assuming a constant electric field in the SL. The localization length $\lambda = \Delta/eF$ in this case is 9 periods of the SL, thus ensuring to be far away from Wannier–Stark localization. Of course the problem of incoherent radiation remains.

In conclusion we have presented a novel SL device which gives control over the electric field across the SL as well as the position of the Fermi energy of a 2DES in the SL. Starting at electron densities as low as 0.9×10^{11} cm^{-2} NDR is observed. The electric field across the SL at the peak current remains approximately constant at 160 V/cm as long as E_f lies in the miniband, and increases when E_f is raised above the miniband. Surprisingly even when E_f lies in the minigap NDR is persistent. From U_{peak}, from SdH measurements and from the low-field resistance the electron mobility is deduced, respectively. It is found that μ_{ET} and μ_{SdH} both have a maximum when E_f lies in the miniband, whereas μ_R develops a much smaller maximum when E_f lies in the minigap. The presented device may serve as textbook example for 2D electronic transport in a partially or fully filled miniband.

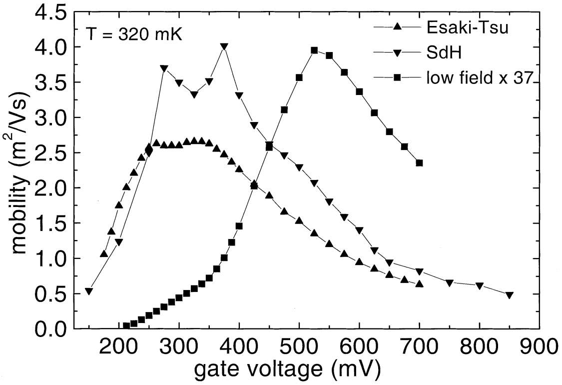

Fig. 4. Electron mobility determined from the position of the current maximum, from the onset of the SdH oscillations, and from the low-field resistance. Note that the low-field resistance is enhanced by a factor of 37.

Acknowledgements

We gratefully acknowledge the support by the DFG via SFB 348 and the BMBF through contract 01 BM 630/1.

References

[1] H. Grahn (Ed.), Semiconductor Superlattices, Growth and Electronic Properties, World Scientific, Singapore, 1995.
[2] R.R. Gerhardts, D. Weiss, K. von Klitzing, Phys. Rev. Lett. 62 (1989) 1173.
[3] H.L. Störmer et al., Appl. Phys. Lett. 58 (1991) 726.
[4] R.A. Deutschmann et al., Physica E 6 (2000) 561.
[5] T. Ando, J. Phys. Soc. Japan 47 (1979) 1595.
[6] S. Das Sarma, F. Stern, Phys. Rev. B 32 (1985) 8442 and references therein.
[7] L. Esaki, R. Tsu, IBM J. Res. Dev. 14 (1970) 61.