Atomically precise modulated two-dimensional electron gas exhibiting stable negative differential resistance

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In 1969 Esaki and Tsu [1] proposed that an artifical superlattice should exhibit negative differential conductance (NDC) due to Bloch oscillations and could therefore be used as an active mm-wave device. But although Bloch oscillations were experimentally confirmed in superlattices [2], the phenomenon of charge domain formation inhibited the realization of an active Bloch oscillator. The formation of such domains is suppressed in the structure we investigate due to the reduction of dimensionality. Our device (fig. 1) is realized with the Cleaved-Edge-Overgrowth method [3]. It consists of an undoped GaAs/AlGaAs superlattice sandwiched between two highly doped contact layers, that is cleaved in situ and then overgrown with an AlGaAs barrier and a highly doped gate contact.

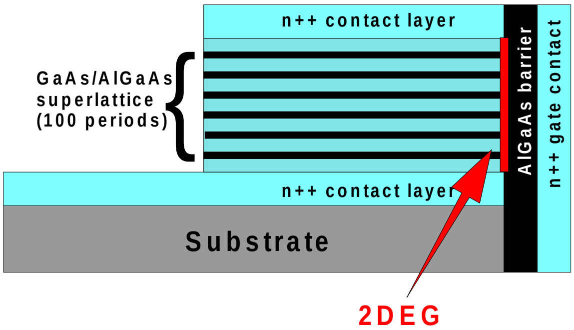

figure1: device structure

Selfconsistent calculations show that for positive gate voltages, the electrons are confined to a triangular potential at the barrier and occupy only the lowest cosine-like miniband. The other minibands are energetically far enough removed, so that tunneling into them can be neglected. The transistor like realization also allows us to change the electron density in our system by simply changing the applied gate voltage.

At liquid helium temperature the I-V-traces of the device (fig. 2) clearly exhibit a large region of NDC which is attributed to Bloch oscillations of the miniband electrons. But unlike in conventional superlattices where the phenomenon of charge domain instabilities leads to an unstable region exhibiting hysteresis, the traces of our device are fully stable and reproducible for low gate voltages. For larger electron densities the NDC peak shows a steep linear drop which indicates an unstable region in which the device jumps to the next stable voltage point of operation. This result is expected from numerical calculations carried out applying the Drift-Diffusion-Model and the Boltzmann equation. They show that for smaller carrier densities the diffusion is strong enough to suppress charge domains. For increasing densities the term responsible for the growth of carrier fluctuations becomes dominant and the I-V-traces show an instability. A simple stability criterion can be derived from a

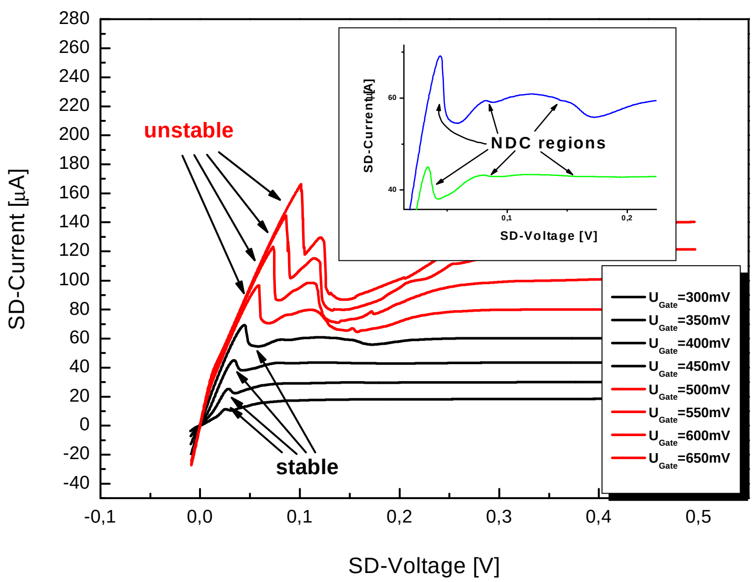

figure2: I-V-characteristics

small signal analysis and is in good agreement with the experimentally measured carrier densities. The difference to conventional superlattices lies in the reduction of the dimensionality of the system (fig. 3). In conventional superlattices the carriers can move freely in both directions perpendicular to the superlattice axis and therefore carrier fluctuations form a charged dipole layer. The accompanying electric field is constant in the transport direction. In our system where the electrons are confined at the cleavage plane carrier fluctuations have a wire-like geometry and the resulting electric field falls off like 1/r along the superlattice.

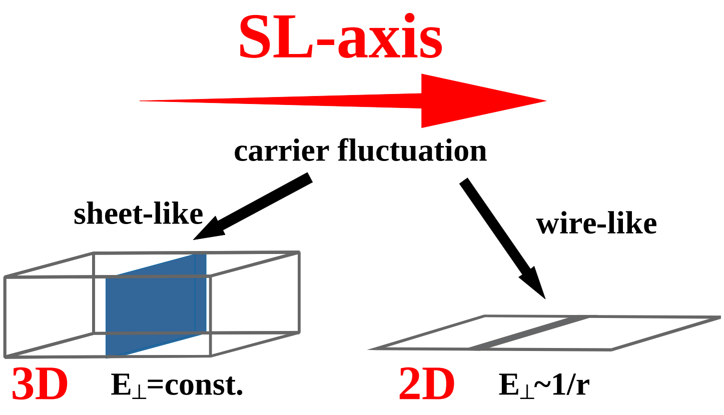

figure 3: 3D-2D difference in carrier fluctuations

The stable NDC regions of our device offer the possibility to build an active emitter based on Bloch oscillations. The accessible frequency range of our current device lies around 100 GHz. It is expected that the structural parameters in principle allow the realization of oscillation frequencies up to 1 THz. Such an oscillator can also be expected to be tunable in a wide frequency interval.

Experiments studying the inverse effect of subjecting the device to an external high frequency electric field confirm the Bloch oscillation dynamics. A high frequency electric field is guided into the liquid helium reservoir along a rectangular waveguide and is coupled to the sample via a small antenna. For frequencies $f < f_{Bloch}(V_{crit})$ the I-V-characteristics show a clear suppression and shift to higher SD-Voltages for the NDC peak. With increasing AC power both the suppression and the shift are also increased. The shift in peak position rules out an increasing electron temperature for the current decrease, as a higher electron temperature should not affect the voltage position of the NDC peak. The measured behavior qualitatively also agrees well with the theoretically expected changes in the I-V-traces (cf. fig. 4). Beside the realization of an active emitter our device also allows interesting studies of the interactions between oscillating electrons and lattice excitations (cf. structures in I-V-traces in the inset of fig. 2). The different peak structures indicate a strong energy dependence of the momentum scattering time τ_m.

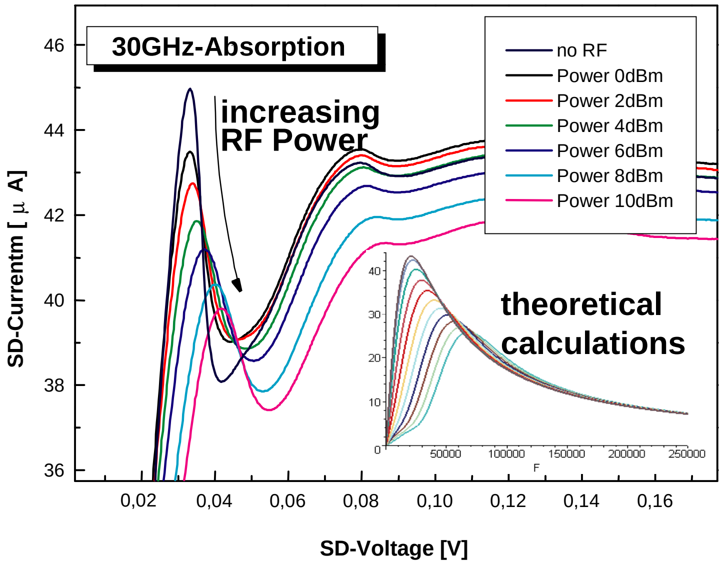

figure 4: I-V-characteristics with RF-Field

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