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Tunneling effects in short period strained AlN/GaN superlattices

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We study electronic conduction of short period strained GaN/AlN superlattices. The mechanisms of current transport perpendicular to the layers were studied, with an emphasis on the elastic and inelastic tunneling through the AlN barriers. Electron transport as a function of temperature is examined in I-V, G-V (first derivative dI/dV). The current and the conductance show nonlinear oscillatory character. The observed characteristics are interpreted as sequential resonant tunneling through AlN barriers and reveal negative differential conductivity (NDC).

1 Introduction Efficient perpendicular transport (electrical transport along the growth direction) in AlGaN/GaN or AlN/GaN superlattices (SLs) is critical to the operation of many GaN-based devices, including heterobipolar transistors, light-emitting diodes, hot electron transistors, etc. The properties of AlGaN/GaN SLs related to the feasibility of a terahertz-range oscillator are under discussion [1].

Tunneling effects and intersubband absorption in AlN/GaN superlattices or double-barrier structures have been the subject of a few investigations and the results were either controversial or unreproducible. As pointed out by Baumann et al., [2] in the majority of the experiments, the effects were observed purely optically [3] and no vertical current transport was demonstrated. Just a few studies to our knowledge were reported on vertical current transport through thin AlN barriers in a resonant tunneling diodes [4, 5]. Clearly pronounced negative differential resistivity (NDR) in current-voltage (I-V) characteristics as an indication of resonant tunneling was reported [4] and was subjected to extensive discussion [6, 7] because of the sensitivity of the results on the direction of the voltage sweep and the reproducibility. Golka et al. [8] observed NDR in AlGaN/GaN double-barrier diodes, but it disappeared after the first trace of the I-V curves. Room temperature intersubband electroabsorption modulation in AlN/GaN coupled quantum wells was investigated in [9].

Perpendicular transport characteristics of $Al_xGa_{1-x}N$/GaN SLs was studied both theoretically and experimentally [10] based on sequential tunneling. The model showed that short superlattice periods are required to minimize the perpendicular resistivity. However, NDR in the current–voltage data was not observed.
To enable high tunneling probability and efficient perpendicular transport the barriers should be kept sufficiently thin. This requirement appears crucial since the epitaxial growth of AlN layer thicknesses in the 15–30 Å range is still quite a challenging task because of the appearance of defects and cracks. Other drawbacks are increased interface roughness scattering and the inherent polarization fields in nitrides.

In this work we study electronic and conduction properties of short period strained AlN/GaN superlattices. Specifically, the mechanisms of current transport perpendicular to the layers were studied, with an emphasis on the elastic and inelastic tunneling through the AlN barriers. For these specific SLs, the band gap difference between the barrier and well reaches 2.7 eV, which tends to reduce the thermally activated escape of electrons and holes, even at room temperature. The main results of this study are concerned with the observation of resonance tunneling cur-

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rents in AlN/GaN superlattices and inelastic transport. Perpendicular electron transport as a function of temperature is examined in current-voltage I-V and conductance-voltage G-V (first derivative dI/dV) characteristics. If the dominant transport mechanism is tunneling, the I-V curve reflects mostly the elastic currents. When the barrier is thin enough, there is a finite probability for the electrons to tunnel elastically through it. The elastic component gives an insight in the barrier properties being dependent on its thickness, height, doping etc. The appearance of a structure in the derivatives indicates the presence of an inelastic and/or resonance process. The inelastic processes lead to different tunneling paths and give additional current contributions when the tunneling electrons lose energy through fundamental excitations, charge trapping, or charge – assisted conduction.

2 Samples and experimental procedure The samples were grown undoped ($N_D \sim 5\times10^{16}$ cm^{-3}) on (0001) sapphire substrates by MOCVD [11]. On top of the substrate, a 30 nm thick AlN layer and a 2-µm-thick nominally undoped GaN buffer layer were grown, followed by a ten period AlN/GaN structure. No additional capping layer was present. The well/barrier thickness ratio is approximately 3:1, given the well/barrier thicknesses are 45.4/14.3 Å. An Au Schottky contact of Ø = 500 µm was evaporated on top of the structure and an In Ohmic contact was formed to the GaN buffer. The mesa structure was 1mm^2. The samples were placed in an ARC closed-cycle cryostat allowing change of the temperature between 10 and 300 K. Measurements were done in the dark by means of HP 4140B pA-meter/dc voltage source at applied voltages in the range -2 V – +2 V.

In all samples, the AlN barriers are tensile strained with an in-plane strain of about 2x10^{-2}. The built-in electric field in the wells 2.7 MV/cm is estimated according to the approach in [12, 13]. As a result a bound positive sheet charge occurs at the AlN/GaN interface, which attracts mobile electrons, and a two-dimensional electron gas (2DEG) is formed even in the absence of any intentional doping.

The conduction band profile for this particular sequence of 10 AlN/GaN periods is calculated (not shown) together with the electron wavefunction of a state from the middle of the first miniband without and with increasing the internal polarization field. The results clearly show that the state is localized. The expected at zero external bias SL miniband is broken due to the internal polarization field.

Photoluminescence measurements [13] reveal emission below the GaN band gap, which reflects the high built-in field in the AlN/GaN system. The measured transition energy is influenced by the competition between the blue shift induced by quantum confinement and red shift influenced by polarization. The conduction band edge profile created for the whole structure (Fig. 1) including the surface contact places the outermost wells in a depletion while the reminder of the wells reach the Fermi level. Depletion acts opposite to the polarization field and slightly decreases it. Thus we cannot neglect the fact that nearest QW's to the surface of the SL are modified and assume the wells in the SL no identical.

3 Results and discussion The I-V curves reveal a typical diode character. In Fig. 2 a set of experimental dc I-V curves versus temperature is shown. The current and the conductance characteristics (Fig. 3) under forward biasing show nonlinear and oscillatory behavior. Negative differential conductance (NDC) reveals at certain voltage values which are relatively temperature insensitive. It is observable up to 150 K, being increasingly pronounced at lower temperatures. The appearance of NDC is a clear indication of resonance tunneling. The current peak-to-valley ratio is 3.2. We note that the measurements were made by a single trace at a particular temperature. However, the temperature was changed sequentially by 10 K and the tunneling effects appeared reproducibly as seen in the figures. The pronounced effect in the whole set of curves and the measurement sequence gives us a confidence that there is no bistable behavior as reported in [6, 7].

Similar perpendicular transport in SLs on arsenides was reported more than 30 years ago by Esaki et al. [14].

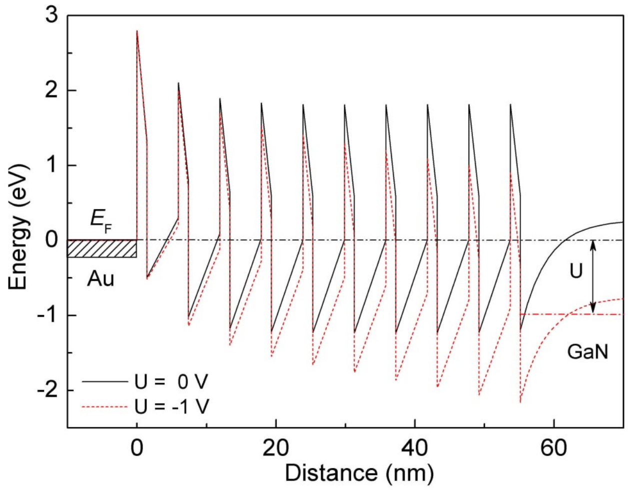

Figure 1 Conduction band profile of the 10 period SL structure at U = 0 V (solid line) and at U = -1 V (dotted line).

At a certain voltage drop in the wells the transport through SL minibands is quenched because it causes localization of the carriers in a separate quantum well. The condition for appearance of localization and onset of tunneling is the voltage drop at a well qFL_w to exceed the SL miniband width ΔE; L_w is the well width and F is the applied field modified by the intrinsic built-in polarization field. Thus the two-dimensional carrier density is available for tunneling to adjacent quantum well. This condition is readily satisfied in our case. At a subsequent resonant voltage drop conduction through a bound state appears. According to Esaki [14] the period of the appearance of NDC corre-

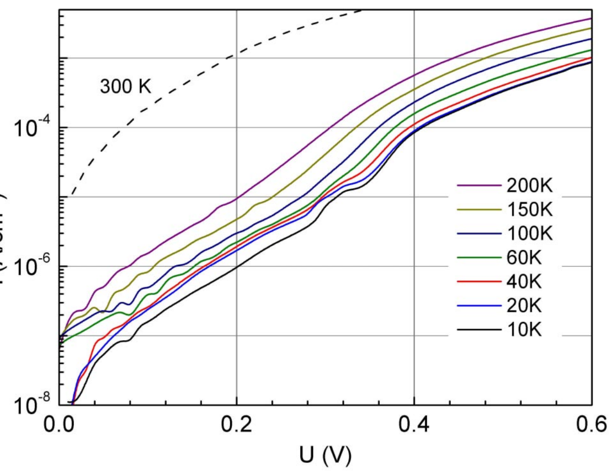

Figure 2 Current-voltage characteristics of a forward biased AlN/GaN SL at different temperatures.

sponds to the energy difference between the first and second electron minibands *E2- E1*.

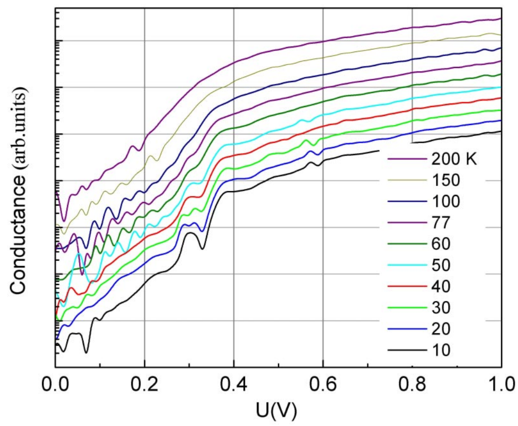

Figure 3 Conductance of the AlN/GaN SL showing negative resistance regions due to resonance tunneling. The characteristics are shifted along the y-axis.

A minimum in conductance was determined from the 10 K characteristics at 328 mV (Fig. 3) which possibly corresponds to the position of the first confined electron state. The bias is such that the Fermi level is aligned with the quantum level of an unoccupied state in a quantum well. According to the band diagram in Fig. 1 a candidate is the nearest well to the surface being the one that could have its *E1* level at zero bias higher than the Fermi level. In order to calculate the bound state energies for electrons and holes the envelope function approximation was used in the quantum confined Stark effect (QCSE) regime. The AlN/GaN conduction-band offset was taken to be 1.75 eV [15]. The energy difference between the first and the second electron levels was calculated as *E2- E1* = 0.583 eV. This value corresponds to optically measured intersubband transitions bellow 0.6 eV for short period GaN/AlN SLs [3]. Additional higher energy resonant current features and NDC is not observable in the I-V and G-V curves.

It should be noted that the well and barrier thicknesses are nominal and some fluctuations and interface roughness are expected to influence the real confinement energies. Also, the non-equivalence of the distribution of the field over the SL will give slightly different energies from our calculations.

Except the NDC region oscillatory structure is present reproducibly with temperature change. The features are nearly evenly repeated with a period of 80-90 meV. An explanation could be the involvement of optical phonons in inelastic tunneling processes [16] through coupling with the tunneling electrons. Such observations of inelastic tunneling currents due to excitation of phonons are expected to occur at voltage drops proportional to the optical phonon frequency.

4 Conclusions Electron transport perpendicular to the AlN barriers was studied as a function of temperature in AlN/GaN 10-period superlattices. NDC was observed indicating the presence of resonant tunneling effects. Both elastic and inelastic tunneling processes were involved. The results are important as NDC in semiconductor superlattices is the origin of various proposals for compact submillimeter wave sources.

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