Electric field domains in intentionally perturbed semiconductor superlattices

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Simulations based on a rate equation model for high-field transport through a doped semiconductor superlattice are presented for the case that one barrier is chosen significantly wider than the others. The distinct impact of that local perturbation on the overall shape of the current–voltage characteristic is discussed and related to the spatial field distribution. The measured current–voltage characteristic of a superlattice, which was intentionally grown with one thicker barrier, confirms the strong asymmetry predicted by the model calculations. [S0003-6951(96)00731-0]

In weakly coupled doped semiconductor superlattices electric field domains form if a sufficiently high bias is applied in the growth direction.[1,2] In the current–voltage characteristic these show up as a sequence of current branches,[3] each of which is associated with a different position of the domain boundary, i.e., with a different spatial extension of the high-field domain. The number of branches is roughly equal to the number of superlattice periods. Numerical simulations based on the extension of a simple quantum mechanical transport model[4] suggest that one can use such macroscopic current measurements to detect and localize single microscopic growth-related defects in a sample, since with increasing applied voltage the domain boundary ''scans'' the superlattice structure well by well.[5,6] While previous experimental results have been in support of the theoretical model calculations, which explain many of the features observed, a direct confirmation is only possible by growing samples with specific, intentionally included perturbations.

It is the purpose of this letter to demonstrate, based on predictions of our model calculations, that specifically tailored current–voltage characteristics can be obtained by intentionally introducing structural imperfections into the superlattice. Our simulations show that a single wider barrier should have a significant impact on the overall shape of the characteristic. It is even possible to pinpoint its location within the sample. The theoretical predictions are verified through a comparison with the measured characteristic of a sample grown with one barrier significantly wider than the others.

The superlattice structure considered here consists of $N=40$ GaAs wells with a (3D) doping density N_D with $N-1$ undoped AlAs barriers in between (plus one additional AlAs barrier at each end separating the superlattice from the substrate layers). We simulate sequential charge transport through the superlattice structure by a set of rate equations for the electron densities in the different bound states in the wells.[6] The transport coefficients for the tunneling processes between neighboring wells are derived from a simple microscopic model. They are functions of the local electric field $F^{(i)}$ and depend on the widths of the ith barrier, b_i, and of the adjacent wells, l_{i-1} and l_i, respectively.[4,6] For a given applied voltage U the electric field F_i across the ith barrier can be calculated self-consistently from the charge distribution using Poisson's equation. In our simulations we use the parameters $l=90$ Å and $b=15$ Å for the widths of the wells and barriers, respectively, of the structurally perfect superlattice, as well as a doping density of $N_D=6.7\times10^{17}$ cm^{-3}.[6]

Figure 1 shows the calculated current–voltage characteristic of a superlattice whose 32nd barrier (counted from the cathode for positive U) is thicker than the others by 20%. The up-sweep is displayed for both directions of the applied voltage U. Both contacts, whose influence on the current–voltage characteristic appears to be of minor importance,[7] are modeled identically using discrete Dirichlet boundary conditions.

For both bias directions, with increasing voltage we first obtain a sequence of short current branches with a low current density of about 2.5 kA/cm^2. It is followed by a single long ascending branch leading to another sequence of nota-

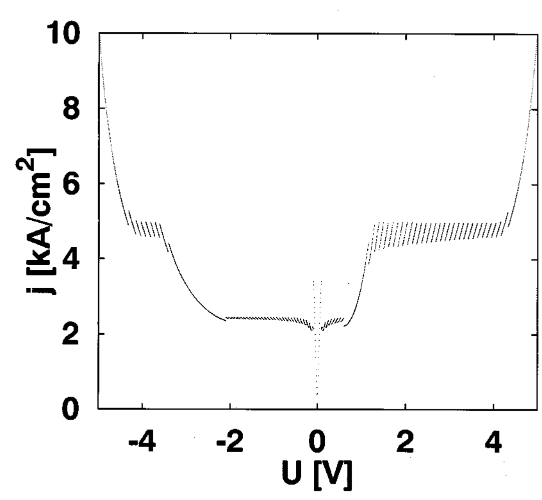

FIG. 1. Simulated current–voltage characteristic of a superlattice with 40 periods and $N_D=6.7\times10^{17}$ cm^{-3} (sweep-up). The 32nd barrier of the superlattice has been chosen 20% wider than the others.

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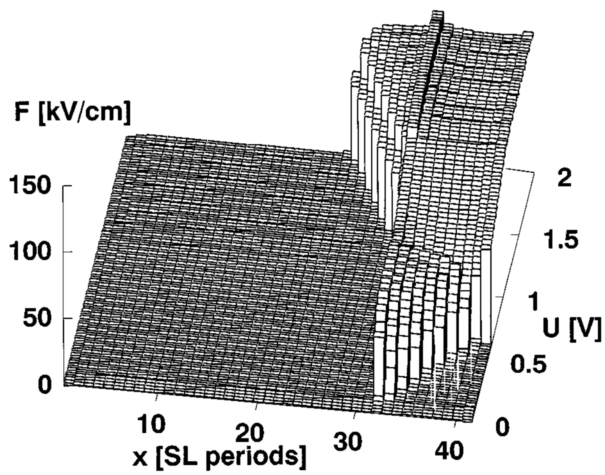

FIG. 2. Simulated spatial profiles of the electric field F across the superlattice (SL) structure for positive voltages (Fig. 1). The SL periods are numbered starting from the cathode.

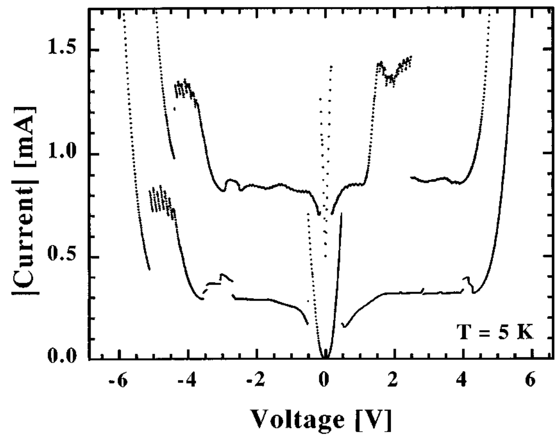

FIG. 3. Measured current–voltage characteristics in the dark (lower curve) and under illumination (upper curve) of a GaAs/AlAs superlattice with an intentional substantial increase of the thickness of one AlAs barrier layer. For both bias directions the absolute value of the current for the sweep-up direction is displayed. The upper curve is vertically shifted by 0.5 mA.

bly longer current branches at about $j=5$ kA/cm^2. The lengths and current density of the latter branches are identical to those of the characteristics obtained in simulations of ''perfect'' or weakly disordered superlattices of the same doping density.[6] The characteristics of both bias directions differ in the voltage at which the long ascending branch is located, i.e., the number of branches in the ''lower'' and ''upper'' sequences. For positive U the lower current sequence consists of 8, the higher one of 29 branches, while for reverse bias the ratio is 30 to 7.

This asymmetric behavior can be explained with the help of the spatial field distribution across the sample, which for positive bias is displayed in Fig. 2 for voltages U up to 2 V. For very small voltages U the electric field is distributed virtually homogeneously across the sample (corresponding to the initial sharp rise of the current–voltage characteristic). At ~0.1 V this homogeneous field distribution breaks up, and a high-field domain forms across the 32nd and 33rd barriers. This can be easily understood if one keeps in mind that for stationary states of the system the current across each barrier must be identical. To meet this condition the electric field across the thicker 32nd barrier, $F^{(32)}$, must be higher than elsewhere. However, the total voltage U is not yet high enough for the high-field domain to extend over more than two superlattice periods. For the resulting ''inverse'' field domain boundary, a local carrier depletion, i.e., an electron density n_i in the 33rd well smaller than the doping density, is required due to Poisson's law $\epsilon(F^{(i+1)}-F^{(i)})=e(n_i-N_D)$, where e is the elementary charge and ϵ is the dielectric constant. As a result, the current density, which equals the local electron density times the field-dependent transport coefficient summed up over all transport processes, and thus the total current through the sample is small compared to the case of a ''perfect'' or weakly disordered superlattice of the same doping density, where only charge accumulation occurs.

Our simulations show that with further increase of U the high-field domain expands towards the anode period by period, creating the small discrete branches in the characteristic. When the anode has been reached, the current is no longer limited by electron depletion; it grows with rising U up to the value of the branches in the characteristic of a ''normal'' superlattice. The high-field domain now expands towards the cathode across the remaining superlattice periods the same way it would throughout a sample without the wider barrier. The remaining current–voltage characteristic is therefore effectively that of a ''perfect'' superlattice with a smaller number of periods (30) and a respective voltage offset. For negative bias, the same mechanism applies. However, the thicker barrier is located at a different position with respect to the cathode resulting in the asymmetry of the $I-U$ characteristic.

The predictions of the theoretical investigation have been tested using a 40 period GaAs/AlAs superlattice with 90 Å wells and 35 Å barriers grown by molecular beam epitaxy (MBE). The 32nd AlAs barrier layer (counted from the cathode for positive voltages) has been chosen to be significantly wider being 42 Å. The central 50 Å of each GaAs layer were doped with 5×10^{17} cm^{-3}. The current–voltage characteristics were obtained in a He-flow cryostat at 5 K using a Hewlett Packard (HP) 3245A voltage source and a HP 3458A multimeter.

Figure 3 shows the measured current–voltage characteristics of this sample in the dark (lower curve) and under illumination (upper curve) using 50 mW of a Ti:sapphire laser at 1.65 eV. Apart from the initial steep rise of the current for very small voltages (corresponding to a homogeneous field profile), the dark characteristic is mostly flat and rather unstructured. Only for negative voltages beyond $U=-4$ V, the current sharply increases by a factor of about 1.5 followed by a sequence of seven branches typical for domain formation in superlattices. This part of the characteristic is similar to the simulated one (Fig. 1). The characteristic changes drastically under laser illumination with an energy above the superlattice energy gap, in particular for the positive bias direction. A sudden increase of the current occurs at about $U=1.5$ V, which is followed by a sequence of ~10 (long) branches. At about $U=2.4$ V the current drops again to the low value of 0.3 mA, which is similar to the current level before the strong increase and also to the negative bias direction.

A closer look at the characteristic under illumination reveals that for both bias directions the flat parts of the dark characteristic now consist of a series of small current branches. Between -0.2 V and -3 V there are ~ 25 branches, while between $+0.2$ V and $+1.5$ V there are about 7 branches. The effect of visualizing static domain formation in the $I-V$ characteristic by laser illumination has been previously demonstrated in undoped as well as doped samples.[8,9] Without optical excitation, the charge in the superlattice regime is not sufficient to form stationary domains.

The current measurements thus confirm the effects predicted by our model simulations. In both bias directions for small U, the current exhibits a series of short branches at a low value resulting from the charge depletion associated with an ''inverse'' domain boundary. At large voltages, a sharp rise of the current and another series of considerably longer branches is observed. The most important difference between both bias directions is the position of the steep increase in the current, which is directly related to the location of the thicker AlAs barrier layer. This can be consistently explained using the field profiles in Fig. 2. A full quantitative agreement of theory and experiment cannot be expected at this stage because of the simplicity of the employed model. The irregularities observed in the current–voltage characteristic, e.g., at -3 V, might be due to other defects or growth-related disorders such as doping fluctuations in the sample, which can also cause the disappearence of some of the current branches from the characteristic.[6] Such additional perturbations might also be responsible for the drop of the current at about $+2.4$ V.

In summary, we have shown that the measured current–voltage characteristic of a superlattice sample, which was grown with a single significantly wider barrier, is in agreement with the theoretical predictions from a simple microscopic transport model. We conclude that the presence of a single thicker barrier leads to the formation of an ''inverse'' domain wall associated with a charge depletion and is responsible for a drastic reduction in the absolute current as well as the lengths of the branches in the respective part of the $I-U$ characteristic. Thus, specific features of the current–voltage characteristic can be related to intentional, localized perturbations of the perfect superlattice structure. Current measurements of a specifically grown sample have confirmed our theoretical results giving insight into the details of domain formation such as the location of the high-field region within the sample and the direction of the domain wall translation.

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