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Magnetotransport investigations of structural irregularities in a weakly coupled GaAs/AlAs superlattice under domain formation

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Irregular current branches have been observed experimentally in the I-V characteristics, when static electric-field domains are formed in a weakly coupled GaAs/AlAs superlattice. The origin of these irregularities has been investigated by applying a magnetic field B perpendicular to the layers. With increasing B, the maximum value and the width of different current branches become more and more regular. At $B=9$ T, most current branches are extremely regular indicating that the irregularities are induced by scattering processes, which determine the current in the nonresonant tunneling regime. However, some branches are not affected by the magnetic field demonstrating that they are completely induced by the deviation from an ideal periodicity or by the inhomogeneities at the contact.

Under static domain formation in weakly coupled semiconductor superlattices (SL's), the electric field distribution inside the SL breaks up into two regions of constant field, which are separated by a domain boundary. With increasing external bias, the domain boundary moves period by period through the SL thereby producing a series of current branches separated by discontinuities in the I-V characteristics.[1–3] For a perfect SL, the current branches are regular having a constant width and the same maximum current as previously demonstrated by the theoretical studies.[1,2] However, experimental investigations of real SL's usually exhibit current branches with variable width and maximum current. Theoretical investigations have shown that these irregularities may be induced by imperfections of the SL in the growth direction, i.e., the deviation from ideal periodicity. These imperfections can be caused by fluctuations of the doping density, the well, or the barrier width.[2,4,5] Although the theoretical simulations can reproduce irregular branches, it is still difficult to identify the origin of the imperfections, which account for the irregularities, by simply comparing the experimental I-V characteristics with the calculated results. Furthermore, transfer of carriers by nonresonant tunneling assisted by scattering processes varies from period to period and has been neglected in previous calculations.

In this paper, we will experimentally study the origin of the irregularities of the current branches by applying a magnetic field B perpendicular to the layers. With increasing values of B, most of the branches become more and more regular. Since scattering-assisted transport varies from period to period and is influenced by the perpendicular magnetic field, the corresponding irregularities at $B=0$ T are caused by scattering-assisted nonresonant tunneling. However, the irregularity of one particular branch in the center of the current plateau is not affected by the magnetic field, indicating that it is induced by a structural deviation from ideal periodicity. Near the edge of the current plateau, irregularities are also present at higher magnetic fields, showing that they are related to inhomogeneities at the contact. Therefore, by applying a perpendicular magnetic field, different origins of irregularities can be identified.

The investigated sample consists of a 40-period, weakly coupled SL with 9.0-nm GaAs wells and 4.0-nm AlAs barriers grown by molecular-beam epitaxy on a (100) n^+-GaAs substrate. The central 5 nm of each well are n doped with Si at 3.0×10^{23} m^{-3}. The SL is sandwiched between two highly Si-doped $Al_xGa_{1-x}As$ contact layers forming an n^+-n-n^+ diode. The sample is etched to yield mesas with a diameter of 120 μm. For recording the experimental data, the sample is cooled down to 1.5 K in pumped He^4 within a superconducting magnet, which allows a maximum magnetic field of 9 T. Both the electric and the magnetic field are applied perpendicular to the SL layers. The time-averaged current-voltage characteristics are recorded with a Keithley SMU 236.

Figure 1 shows the time-averaged I-V characteristics for a voltage sweep from 0 to -5.2 V at several magnetic fields. A series of current branches separated by discontinuities is observed in the plateaulike region for all I-V characteristics. This plateaulike region originates from static domain formation as described in Ref. 6. The current discontinuities are

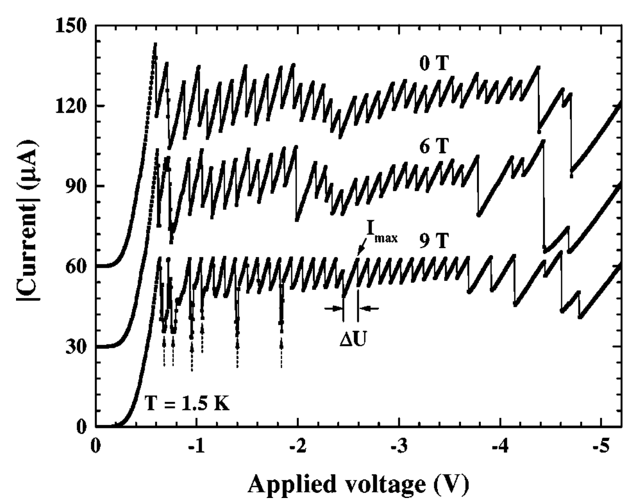

FIG. 1. Time-averaged I-V characteristics at 1.5 K for several magnetic fields as indicated. The solid lines are a guide to the eye. For clarity, the traces at 6 and 0 T have been shifted upwards by 30 and 60 μA, respectively.

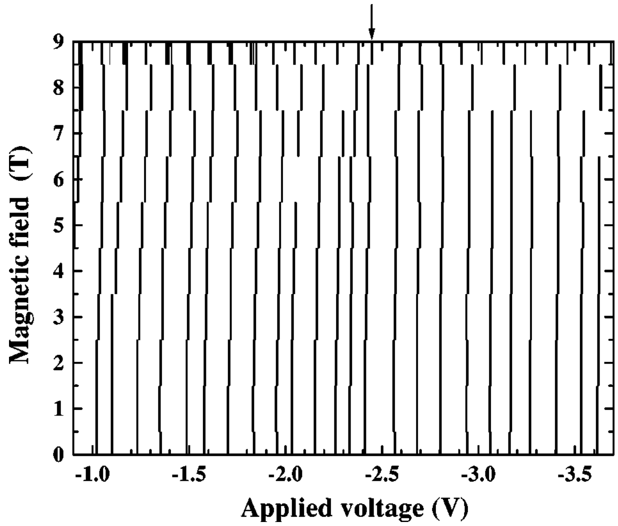

FIG. 2. Grey scale plot of the differential conductance dI/dV versus applied voltage and magnetic field. dI/dV has been obtained numerically from the I-V characteristics recorded for the same condition as in Fig. 1. The darker areas indicate the regions of negative differential conductance.

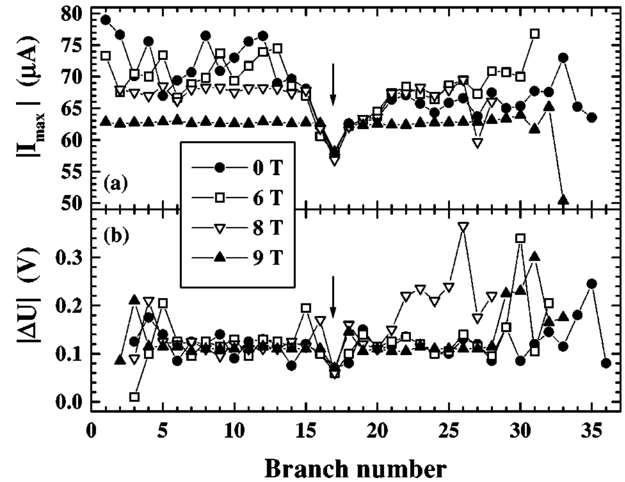

FIG. 3. Variation of I_{max} (a) and ΔU (b) as a function of branch number for 0, 6, 8, and 9 T.

induced by a jump of the domain boundary across one SL period. In contrast to a theoretical study of a perfect SL,[5] the experimentally observed branches at $B=0$ T are rather irregular. It has been previously shown that the maximum current and the voltage width of each branch depend sensitively on the location of the domain boundary in the SL.[2,4,5] In this paper, we will therefore characterize the regularity of each current branch by its maximum current I_{max} and its voltage width ΔU (cf. Fig. 1). In addition to the more regular current branches at $B=9$ T, also some very sharp dips appear in the I-V characteristics indicated by the dashed arrows in Fig. 1. The origin of these dips is presently not understood.

The effect of B on the variation of I_{max} and ΔU varies for different current branches. In the following, the current branches will be labeled by a number, which is determined by counting the branches from low to high field. At $B=0$ T, there are 34 current branches separated by 35 discontinuities, which is of the same order as the number of the SL periods. With increasing values of B, the fluctuations of I_{max} become smaller and smaller as shown in Fig. 1 for $B=6$ and 9 T. At the same time, the fluctuations of ΔU are also reduced. Figure 2 shows a gray-scale plot of the numerically derived differential conductance dI/dV as a function of applied voltage for the bias range from -0.9 to -3.7 V and magnetic field. The darker areas correspond to the bias position of the current discontinuities. The horizontal separation between two adjacent lines determines ΔU. With increasing values of B, ΔU becomes more and more regular for most branches except at about -2.4 V (cf. arrow in Fig. 2), where a large value of ΔU remains for all magnetic field values. For $B=8$ T, there appears to be a deviation from this behavior at larger biases.

The regularity of I_{max} and ΔU with increasing magnetic field becomes even more evident in Fig. 3, where I_{max} and ΔU are plotted as a function of the branch number for $B=0$, 6, 8, and 9 T. At 0 and 6 T, both I_{max} and ΔU display a significant variation with the branch number. When B is increased to 8 T, I_{max} becomes almost constant for small branch numbers, while for large branch numbers it still varies to some extent. At 9 T, I_{max} is constant for almost all branches except for two bias regions [cf. Fig 3(a)]. For the 16th branch, which is located in the center of the current plateau, indicated by the arrow in Fig. 3(a), I_{max} does not change at all between 0 and 9 T and differs from the constant value of almost all other branches. For a branch number larger than 30, which corresponds to a bias region near the edge of the current plateau, two branches disappear and the variation in I_{max} actually increases.

ΔU exhibits a similar behavior as shown in Fig. 3(b), i.e., the width of most branches becomes more and more regular with increasing magnetic field. However, the effect is not as pronounced as for I_{max}. Again, the width of the 16th branch in the center of the plateau is not affected by the magnetic field. For $B=8$ T, the values of ΔU at large branch numbers fluctuate much more than for other magnetic field values. Furthermore, even for 6 T, the deviation at large branch numbers occurs already at a value of 27 and is even more pronounced. Finally, there is also some irregularity for small branch numbers.

We believe that the regularity of the branches at high magnetic fields is connected with an occupation of a low number of Landau levels for the quantum well at the domain boundary. If only the lowest two Landau levels are occupied and the spacing between these levels is much larger than the thermal energy, scattering between different Landau levels is strongly suppressed. Since the wells are directly doped, we do not expect spin splitting of the Landau levels. The two-dimensional doping density is 1.5×10^{15} m^{-2}, which corresponds to a magnetic field of about 1.5 T for a Landau-level filling factor of two, since each Landau level is doubly degenerate. However, due to the domain formation, a charge accumulation layer occurs at the domain boundary with a density of about 5.9×10^{15} m^{-2} as determined from the field difference in Ref. 7, which is about a factor of four higher than the doping level. This density clearly corresponds to a magnetic field of 6 T for a Landau-level filling factor of two. At the same time, the Landau level spacing for $B\geqslant6$ becomes larger than 10.5 meV, which is about two orders of magnitude larger than the thermal energy at 1.5 K (0.13

meV). Therefore, for $B \geqslant 6$ T, the probability for inter-Landau-level scattering in the quantum well at the domain boundary is strongly reduced. In addition, with increasing magnetic field, the electrons become more and more localized in lateral potential fluctuations due to the doping inside the wells, which also reduces the scattering probability of electrons.

From the above experimental observations, the irregularities of the current branches appear to have different origins. In theoretical investigations on a perfect SL, the characteristic of the tunneling current vs the electric field between two adjacent quantum wells is assumed to be the same for all SL periods so that I_{max} and ΔV are identical for all branches.[1,2] However, for experimentally studied SL's, this characteristic can vary between different parts of the SL. The current through the superlattice is mainly determined by the nonresonant tunneling process at the domain boundary,[6] which can vary because of fluctuations in the well width, barrier width, doping density, or interface quality between different periods. The first three types of fluctuations will not be affected by the application of a perpendicular magnetic field. However, the interface quality will mainly influence the scattering-assisted nonresonant tunneling process. The scattering can be induced by interface roughness, impurities, or phonons. Therefore, in the experimentally studied sample, the tunneling current vs electric field characteristics may change from period to period resulting in irregular current branches. Since irregular branches can only be observed for voltages, where the domain boundary crosses the imperfect SL periods,[5] these irregular branches can be used to detect structural imperfections inside the SL. The perpendicular magnetic field splits each subband of the wells into a series of Landau levels. With increasing magnetic field, the in-plane part of the wave function becomes more and more localized resulting in a strong reduction of the nonresonant tunneling rate assisted by scattering processes.[8] Therefore, the scattering-induced irregularities of the current branches should be removed by a perpendicular magnetic field. Since the experimental results show that most current branches become more and more regular with increasing values of B, we conclude that the dominant mechanism for the observed irregularities at 0 T are related to different scattering matrix elements in the nonresonant tunneling process, when the domain boundary is located in different SL periods.

For the 16th branch, I_{max} and ΔV do not change with magnetic field. This observation clearly indicates that the irregularity of this branch is solely due to a structural deviation from perfect periodicity. A structural parameter for one period in the center of the SL differs from that of all other periods. It has been demonstrated previously that the fluctuations of the barrier width have a large effect on the I-V characteristics.[5] For a single barrier being 20% thicker than all others, the I-V characteristics already changes from a single current plateau to two plateaus.[9] Previous theoretical simulations show that, even when a single barrier is only one monolayer thicker than all other barriers, the current branches exhibit already significant fluctuations.[5] If a single barrier is one monolayer thinner than all others, I_{max} for the corresponding branch will be larger than for all other branches,[5] which is not observed in our experiment. We can also exclude well width fluctuations for the 16th branch using the same arguments as in Ref. 5. This leaves us with a localized variation of the doping density as the most possible origin for the observed irregularity of the 16th branch.

For the branches with numbers larger than 30, the irregularity may be induced by doping inhomogeneities near the contact layer. For these branches, the domain boundary is close to the edge of the SL so that it becomes very sensitive to the details of the contact layer. Previous theoretical studies have already shown that I_{max} of the last branch can be larger or smaller than for all other branches,[2] depending on the carrier densities at the contact layer. We believe that this is the reason for the variation of I_{max} of the last branch at 9 T. The broadening of these branches at large magnetic fields is currently not well understood. However, it could also be induced by doping inhomogeneities near the contact layer. At very low or very high bias near the edge of the plateau, the spatial extent of one of the two domains becomes very small. Therefore, several SL periods can be crossed by the domain boundary during a current jump over one discontinuity as shown previously.[10] This effect can also account for the fact that the number of the experimentally observed branches are always smaller than the nominal number of SL periods.

In summary, the effect of a magnetic field applied perpendicular to the layers on static domain formation has been studied in a weakly coupled SL. For most branches, the fluctuations of the current branches at 0 T are removed by the application of the magnetic field. This observation indicates that these irregularities are connected with the nonresonant tunneling process at the domain boundary. For the 16th branch, the irregularity does not change with magnetic field demonstrating that it is induced by a structural imperfection inside the SL. For the branches near the edge of the current plateau in the I-V characteristics, the fluctuations of the band width become more pronounced with increasing magnetic field, which could be accounted for by assuming inhomogeneities near the contacts. In conclusion, by applying a perpendicular magnetic field, different origins of irregularities in the I-V characteristics can be distinguished.

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