Electric-Field Domains in Semiconductor Superlattices: A Novel System for Tunneling between 2D Systems

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The boundary between electric-field domains in semiconductor superlattices represents a tunneling barrier. While most of the superlattice is coupled resonantly the current through the superlattice is limited by *nonresonant* tunneling at the domain boundary. The emitter and collector are purely two dimensional and the system therefore acts as a model system for tunneling between 2D systems. For magnetic fields applied parallel to the layers the average current through the single barrier *increases*, in contrast to 3D and quasi-2D emitters.

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Tunneling experiments in a magnetic field parallel to the layers have been performed on single-barrier structures (SBS) [1-5] with 3D or quasi-2D contact regions. In these cases the electrostatic confinement is very small, leading already above a magnetic field of 1 T to a dominating magnetic-field confinement. In all these experiments a decrease of the tunneling current with increasing magnetic field was observed above 1 T. Theoretical calculations of tunneling through SBS in parallel magnetic fields also predicted a decreasing current with increasing magnetic field [6].

Tunneling resonances are observed in semiconductor superlattices with several subbands of energy E_i ($i=1,2,\ldots$) when an electric field $F_i=(E_i-E_1)/ed$ is applied perpendicular to the layers, where d is the superlattice (SL) period [7,8]. At large carrier densities the applied voltage breaks up into domains of resonant coupling between different subbands in adjacent wells with electric-field strength F_i separated by a domain boundary [9-12]. Although most of the SL is resonantly coupled, the transport at the domain boundary is *nonresonant* and limits the current. The domain boundary has a spatial extent of the order of one SL period and constitutes a single-barrier structure with purely 2D emitter and collector contacts. Because of the strong confinement of the quantum wells a magnetic field applied parallel to the layers reaches a comparable confinement only at field strengths above 12 T.

The samples are GaAs-AlAs SLs grown by molecular-beam epitaxy with a well width $d_W=9$ nm (GaAs), a barrier width $d_B=4$ nm (AlAs), and $N=40$ periods sandwiched between two highly doped layers of $Al_{0.5}Ga_{0.5}As$. In the n^+-n-n^+ diode each GaAs well is Si doped at 3×10^{17} cm^{-3} in the central 5 nm, while two other samples with undoped SLs in n^+-i-n^+ and p^+-i-n^+ configurations are used as reference samples. The diodes are processed into mesas of 0.01 mm^2 area and Cr/Au contacts are alloyed on the top and AuGe/Ni contacts on the substrate side. The energy spacing between the first and second conduction subband is calculated with a Kronig-Penney model to be 135 meV, in agreement with photocurrent spectra [13] obtained on the p^+-i-n^+ diode. The width of the lowest electronic miniband is well below 1 meV. The current-voltage characteristics are recorded with a Hewlett Packard 4140 pA meter. For zero magnetic field the experiments are performed at 6 K, while for the magnetic-field experiments the sample is at 1.8 K. The photoluminescence (PL) experiments are done at 6 K with the 647-nm line of a Kr^+ laser in single-line mode.

In Figs. 1(a) and 1(b) the dark currents of the n^+-i-n^+ and n^+-n-n^+ diodes at 6 K are plotted versus the applied voltage V_A. The applied electric field F_A is calculated from the applied voltage by $F_A=|V_A|/Nd$. The dark current of the n^+-i-n^+ diode [Fig. 1(a)] is continuously increasing as the applied electric field becomes larger. The I-V characteristic of the n^+-n-n^+ diode [Fig. 1(b)] exhibits a totally different behavior, a plateau-like region between −0.6 and −4.6 V with 35 very regularly spaced discontinuities. The number of jumps in the current is comparable to the number of periods of the SL. The jumps in the current can be understood as a movement of the boundary between electric-field domains by one SL period. At the domain boundary a certain charge

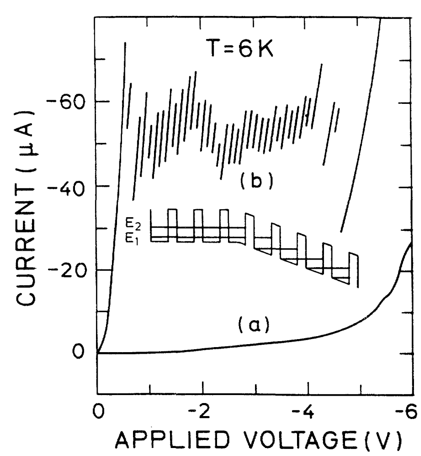

FIG. 1. Dark current of the (a) n^+-i-n^+ diode and (b) n^+-n-n^+ diode vs applied voltage. Inset: Schematic diagram of the voltage distribution in the presence of domains.

density is needed to account for the change in the electric field. In the n^+-n-n^+ diode the doping of the wells supplies the space charge, while the undoped n^+-i-n^+ diode does not exhibit domain formation in this field range. The maximum field strength of the plateau region in Fig. 1(b) ($V_A = -4.6$ V) divided by the number of jumps results in a voltage drop of 131 mV per period, in excellent agreement with the spacing between the first and second conduction subband.

The conclusion of the existence of two regions with different, but well-defined electric-field strengths is so far rather indirect. PL spectroscopy gives a more direct identification of the regions away from the domain boundary [11,12] because of the quantum-confined Stark effect (QCSE) [14]. In an electric field the band-gap transition is shifted to lower energies. If two regions with distinctly different electric-field strengths are present in a SL, two PL lines should be observable. In Fig. 2 the PL spectra of the n^+-n-n^+ diode are shown for the same field range as in Fig. 1. The optically excited carrier density is well below the doping level. The relatively large linewidth is due to the doping level. Two distinct PL lines are observed which do not shift in energy, but only change their relative strength. Comparing the energy positions of these lines with the Stark shift of the band-gap transition as determined by photocurrent spectroscopy in the p^+-i-n^+ diode, the electric-field strengths of the domains are identified as F_1 and F_2 in agreement with the indirect conclusion drawn from the I-V characteristic. However, in the n^+-i-n^+ diode only one PL line is observed in this field range at low photoexcited carrier density, and it shifts quadratically in energy, indicating a homogeneous field distribution.

The existence of the plateau region in Fig. 1(b) indicates that the current is limited by the domain boundary. Taking the numerical derivative of the logarithm of the current with respect to the applied voltage [$d\ln(I)/dV = I^{-1}dI/dV$, the conductivity normalized by the current] leads to 35 spikes with a rather constant value between the spikes, varying from 2.9 to 1.3 V^{-1} as the applied voltage is changed from -0.6 to -4.6 V [cf. Fig. 1(b)]. If the current is limited by the domain boundary, it should be described by *nonresonant* tunneling [15],

$$I = I_0 \exp\{-2d_B[2m_B^*(V_B - E_1)]^{1/2}/\hbar\}, \quad (1)$$

where m_B^* is the effective electron mass of the barrier material and V_B is the barrier height. An increase of the electric field between two discontinuities only affects the barrier height at the domain boundary, i.e., $V_B(F) = V_B(0) - eFd_B$. Assuming a width of the domain boundary of 1 SL period the electric field becomes $F = V/d$, where $V = V_A - mF_2 d$ and m is the number of periods already in the high-field domain. Since V_B is very large in AlAs ($V_B = 0.982$ eV), the derivative of the logarithm of I/I_0 can be approximated by

$$\frac{d\ln(I/I_0)}{dV} = \frac{ed_B^2}{\hbar d}\left(\frac{2m_B^*}{V_B(0) - E_1}\right)^{1/2}. \quad (2)$$

Inserting the parameters of the GaAs-AlAs SL into Eq. (2) with $m_B^* = 0.15m_0$ and $E_1 = 44$ meV results in a value of 2.52 V^{-1}, in excellent agreement with the experimental values of 2.9–1.3 V^{-1}. We conclude that the current is limited at the domain boundary by *nonresonant* tunneling, while most of the superlattice is resonantly coupled. The experimentally observed variation of the derivative leads to a width of the domain boundary between 0.9 and 1.8 SL periods (note that $1.7d = 2d_W + d_B$), corresponding to a single barrier at the domain boundary. At a minimum of the absolute current in the plateau region the barrier does not exhibit a significant voltage drop, while at a maximum of the current the voltage drop across the barrier is the largest.

The tunneling through SBS is strongly influenced by a magnetic field applied parallel to the layers [1–5], i.e., the electric and magnetic fields are perpendicular to each other. The I-V characteristic of the n^+-n-n^+ diode for 0, 9, and 12 T at 1.8 K is shown in Fig. 3. For 0 T the domain formation sets in at a larger electric field compared to Fig. 1(b) because the contacts display a higher resistance, i.e., the system has a lower conductance [e.g., $d\ln(I/I_0)/dV = 1\ \mathrm{V}^{-1}$] than in Fig. 1(b). There are three significant effects of the magnetic field on the I-V characteristic displayed in Fig. 3. The curves shift to higher electric fields, the plateau current increases, and the fine structure disappears around 12 T. While the origin of the change in the periodicity at 9 T is not very well understood, the disappearance of the fine structure at 12 T can be directly related to the cyclotron radius $r_c = \sqrt{\hbar/eB}$, which has a value of 7.4 nm at 12 T. *Resonant* coupling between adjacent wells is expected to be

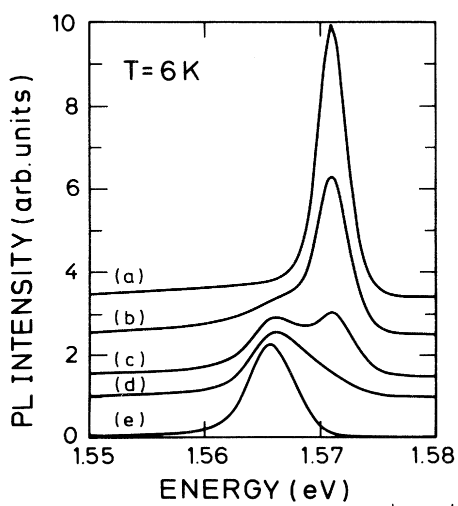

FIG. 2. Photoluminescence spectra of the n^+-n-n^+ diode at different applied voltages: curve a, -1 V; curve b, -2 V; curve c, -3 V; curve d, -4 V; and curve e, -5 V. The spectra are shifted vertically for clarity.

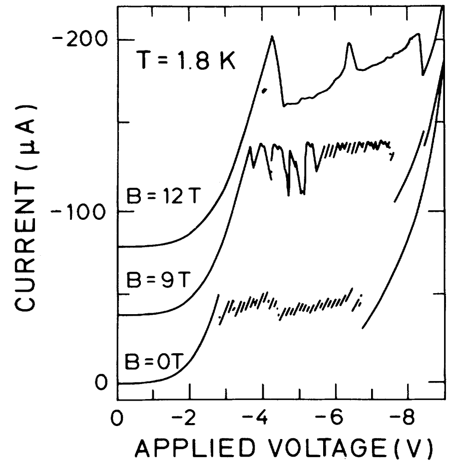

FIG. 3. Dark-current characteristic of the n^+-n-n^+ diode for several magnetic fields parallel to the layers ($B \perp I$). The characteristics for $B=9$ and 12 T are shifted by -40 and -80 μA, respectively. For $B=0$ T the onset of electric-field domain formation is shifted to larger electric fields as compared to Fig. 1(b) because of a higher contact resistance.

suppressed when r_c becomes of the order of half the SL period, in agreement with the observation. The shift of the I-V characteristic can be understood within a perturbative treatment of the magnetic field leading to a detuning of the energy levels in neighboring wells of [16]

$$\Delta E = \frac{e^2 \langle z^2 \rangle}{2m^*} B^2, \tag{3}$$

where $\langle z^2 \rangle = d^2$, since the expectation value has to be taken in the neighboring well, i.e., one period away from the center of the wave function. Because most of the SL is resonantly coupled, an additional field $\Delta F = \Delta E/ed$ is necessary to achieve the same situation as without the magnetic field. This leads to a shift of the onset voltage

$$|\Delta V| = \frac{Ne^2 d^2}{2m^*} B^2. \tag{4}$$

The experimentally observed $|\Delta V|$ is plotted in Fig. 4(a) as a function of the square of the magnetic-field strength. The shift is quadratic in B as predicted by Eq. (4) and the slope has a value of 9.9×10^{-3} V T^{-2} in excellent agreement with the slope of 8.9×10^{-3} V T^{-2} calculated from Eq. (4). At a fixed applied voltage on a branch in Fig. 1(b) the magnetic field reduces the voltage drop at the domain boundary by an amount given by Eq. (4).

In Fig. 4(b) the saturation current I_{sat}, i.e., the maximum current, of the plateau region is plotted versus the square of the magnetic field. Two regimes are present, between 0 and 6 T and from 6 to 11 T. The derivative $d\ln(I_{sat}/I_0)/dB^2$ has a value of 1.2×10^{-2} T^{-2} between 0 and 6 T and of 4.3×10^{-3} T^{-2} between 6 and 11 T, as determined from least-squares fits to the data points. The increase in the current and the existence of the two regions can be understood in terms of the dependence of the

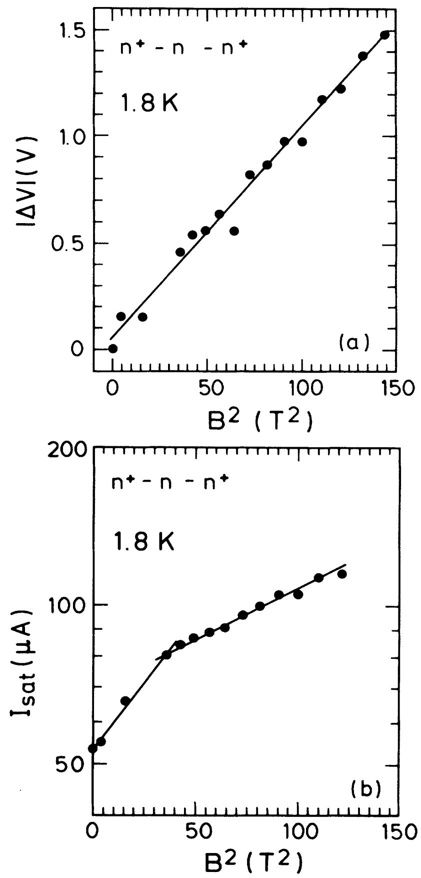

FIG. 4. (a) The voltage shift of the onset of domain formation and (b) the maximum current in the plateau region vs the square of the magnetic field for the parallel configuration. The solid lines are least-squares fits to the data points. The values of the slopes are given in the text.

subband energies on the center coordinate z_0 in a parallel magnetic field [16]:

$$E_1(B) = E_1(0) + \frac{e^2}{2m^*}(\langle z^2 \rangle + z_0^2) B^2. \tag{5}$$

For zero electric field the parabolic dependence of the energy on the center coordinate [Eq. (5)] leads for adjacent wells to an intersection of the magnetic dispersions of the two wells at the center of the barrier for all magnetic-field strengths. However, for a finite electric field across the domain boundary the intersection point of the magnetic dispersions is not fixed at the center of the barrier anymore, but depends on the electric- and magnetic-field strengths. In our sample, the magnetic dispersion below 6 T is not sufficient to cause the energies between the two wells at the domain boundary to intersect. Nevertheless, a channel for tunneling between two wells separated by more than one barrier is opened when the magnetic field is turned on. This does not contradict the earlier statement that the domain boundary only involves one barrier. The magnetic field opens up new tunneling channels

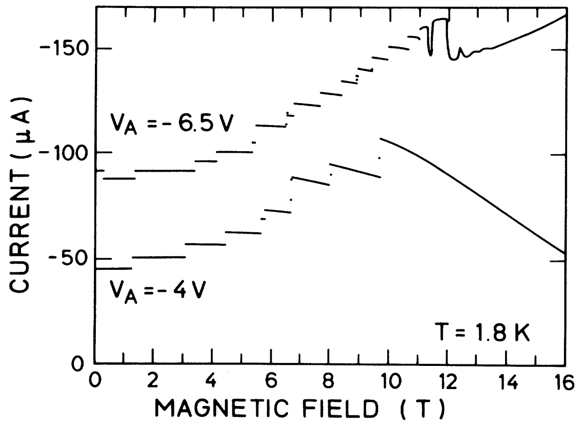

FIG. 5. Magnetic-field sweep of the dark current for two applied voltages. The curve for $V_A=-6.5$ V is shifted by -40 μA.

which lead to a larger current than the nonresonant tunneling through the single barrier at the domain boundary. Above 6 T the magnetic field leads to a restriction of tunneling at the domain boundary of less than 2 SL periods, i.e., only one barrier is involved again.

In Fig. 5 a magnetic-field sweep at two applied voltages is shown. Again two regions are observed. Between 0 and 6 T very flat steps are seen with a relative variation of less than 1%. Above 6 T the steps become curved. The magnetic field, on the one hand, increases the current at the domain boundary as discussed above $[d\ln(I_{sat}/I_0)/dB^2>0]$. On the other hand, it shifts the I-V characteristic to larger electric fields, i.e., for a fixed bias voltage on a branch in Fig. 1(b) the current decreases $[d\ln(I/I_0)/dV>0$ and $dV/dB^2<0]$. These two effects compensate each other between 0 and 6 T. The experimental values for these derivatives demonstrate this compensation in this magnetic-field range since $d\ln(I_{sat}/I_0)/dB^2=1.2\times10^{-2}\ \mathrm{T}^{-2}$ and the product

$$[d\ln(I/I_0)/dV]dV/dB^2=-9.9\times10^{-3}\ \mathrm{T}^{-2}.$$

For $B>6$ T the quantity $d\ln(I_{sat}/I_0)/dB^2$ is about a factor of 3 smaller and the decrease of the current dominates.

In summary, we have demonstrated that electric-field domains in GaAs-AlAs superlattices can be employed to study tunneling through a single-barrier structure with purely 2D emitter and collector. The domain boundary between the different electric-field regions acts as the barrier system which limits the current by *nonresonant* tunneling. Magnetic-field experiments in the parallel configuration lead to an *increase* in the current, in contrast to observations with 3D or quasi-2D emitters. Furthermore, to maintain resonant coupling within the domains the electric field at the domain boundary is reduced. A cancellation between the increase of the current and the reduction of the electric field at the domain boundary is observed in magnetic-field sweeps between 0 and 6 T.

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