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Realization of the Esaki-Tsu-type doping superlattice

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A type-*A* (Esaki-Tsu-type) doping superlattice has been obtained by using the δ-doping technique and employing very small superlattice periods, on the order of the electron de Broglie wavelength. Such superlattices exhibit quantum-mechanical coupling of electron and hole wave functions in adjacent quantum wells resulting in finite z dispersion. Clear experimental evidence of having realized an Esaki-Tsu type of doping superlattice is supported by optical emission and absorption properties, from photoluminescence and photoconductivity measurements, as well as perpendicular transport properties. The measurements reveal (i) stable emission and (ii) absorption of radiation below the bulk band gap of GaAs. Efficient transport in the superlattice growth direction is found for doping superlattices with small periods. These results are interpreted as direct evidence for the realization of a type-*A* doping superlattice, whose properties deviate significantly from the type-*B* doping superlattice with long periods.

Seventeen years ago, Esaki and Tsu[1] proposed to superimpose a one-dimensional periodic potential onto the lattice potential of a semiconductor. If the carrier mean free path exceeds the period length of such a superlattice the entire electron system will enter a quantum regime with reduced dimensionality. One attractive feature of the Esaki-Tsu superlattice (SL) is the synthesis of new artificial materials with properties otherwise not derived from bulk or alloy form. In their original proposal, Esaki and Tsu[1] proposed two alternative procedures to obtain a modulated periodic potential, namely, by changing the material type or doping species resulting in compositional and doping superlattices, respectively. The idea of a tailored novel material has attracted numerous scientists throughout the last 17 years with exclusive emphasis on compositional Esaki-Tsu superlattices.[2-6]

An Esaki-Tsu-type doping superlattice, which we will refer to as a type-*A* doping superlattice, has to fulfill two requirements. First, the superlattice potential modulation needs sufficient strength to couple the modulation periodicity to the electron wave vector, thus inducing minizone formation in the Brillouin zone. Second, the superlattice period has to be on the order of the de Broglie wavelength. In their original publication, Esaki and Tsu[1] proposed homogeneous alternating n- and p-type doping. However, homogeneous doping causes the solubility limit of impurities to be the limiting factor for large modulation on a short length scale; either a strong modulation on a large length scale, or a weak modulation on a short length scale is feasible. The solubility limit of impurities thus constrains a strong modulation on a short length scale. It is therefore very difficult to realize the superlattice idea by the originally proposed structure. In this Rapid Communication, we show that employment of a new doping concept enables us to realize the original idea of Esaki and Tsu. To achieve this goal we employ the new δ-doping technique.[7] A Dirac-δ-function-like doping profile can be obtained by epitaxial growth methods such as molecular-beam epitaxy; a distribution of impurity atoms in one single monolayer is achieved by suspending the crystal growth and evaporating the dopant on the nongrowing crystal surface. Subsequently, regular crystal growth is resumed. We have shown that the δ-doping technique allows us to localize impurity atoms on a lattice-constant length scale[8] and to locally exceed the solubility limit of Si and Be in GaAs.[9] The n- and p-type δ-doped superlattice will be referred to as sawtooth superlattice (STS) due to the sawtooth-shaped conduction- and valence-band edges.

Our present work emphasizes the experimental verification of the type-*A* superlattice by optical and transport measurements. Hitherto homogeneously doped doping multilayers with typical periods $z_p > 500$ Å have been investigated.[10,11] It was shown that the n-i-p-i superlattice has interesting properties such as the tunability of the energy gap.[11] Even though the n-i-p-i is a superlattice in a structural sense it is not a superlattice in that electronic properties do not evolve according to the ideas of Esaki and Tsu. In fact, the tunability of the energy gap relies on long carrier lifetime ($\tau \cong 1000$ sec), i.e., on noninteraction, decoupled multiple-quantum wells,[11] which does not conform to the seminal superlattice proposal.[1] We will therefore refer to long-period doping superstructures as type-*B* doping superlattices.

The epitaxial layers used in this study were grown by molecular-beam epitaxy and consist of layers of alternating n- and p-type doped impurity sheets. Si and Be are used for n- and p-type doping, respectively. High doping concentrations $N_D^{2D} \geq 1 \times 10^{13}$ cm^{-2} and short superlattice periods of 75–200 Å are used for the type-*A* superlattice. Such extreme design parameters have not been used previously. Longer periods and smaller doping concentrations are used to demonstrate the differential physical properties between type-*A* and type-*B* doping superlattices.

Experimental results from photoluminescence measurements are displayed in Fig. 1. The top part of Fig. 1 shows the two doping-superlattice concepts, i.e., the long-period-length and the Esaki-Tsu (ET) types. The latter has minibands of finite width and a stable superlattice

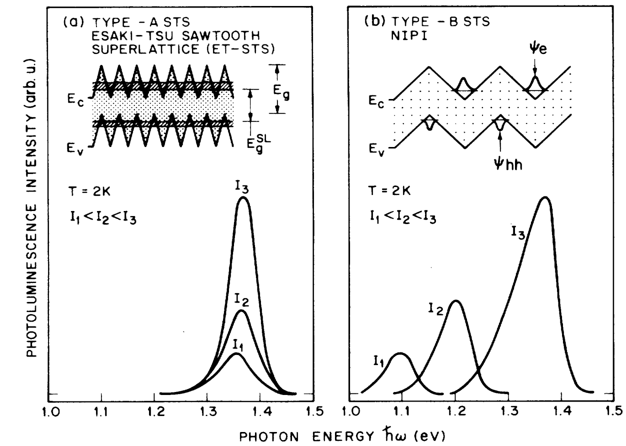

FIG. 1. Top: Schematic illustration of an Esaki-Tsu sawtooth superlattice (STS) (left) with minibands in superlattice direction and of a long-period-length sawtooth superlattice, (right) with no coupling of states in adjacent quantum wells. Bottom: Photoluminescence spectra of an Esaki-Tsu type ($N^{2D}=1\times10^{13}$ cm^{-2}, $z_p=150$ Å) and of a long-period-length doping superlattice ($N^{2D}=1\times10^{13}$ cm^{-2}, $z_p=600$ Å).

band gap which is smaller than the GaAs bulk band gap.[9] We calculated the energetic width of the electron miniband (coupling strength) according to the Kronig-Penney model, finding $\frac{1}{10}$ to several meV for the sample used in this work. The coupling strength of our doping superlattice is thus comparable to the coupling strength of a $Al_xGa_{1-x}As$/GaAs compositional superlattice with the same period. Furthermore, we have grown long-period superlattices ($z_p \geq 300$ Å) as shown at the top right of Fig. 1. Photoluminescence spectra of the type-A SL show an emission peak energy of 1.37 eV. The peak energy of 1.37 eV is significantly smaller than the bulk band gap of GaAs (1.512 eV at 2 K). Furthermore, the peak energy does not shift significantly with the variation of the excitation intensity. The three photoluminescence spectra of Fig. 1(a) clearly reveal the stable energy gap of the superlattice which is independent of the excitation intensity. The invariance of the SL energy gap is observed in type-A superlattices, but not in long-period superlattices. The stability of the energy gap can be explained by the strong coupling of adjacent quantum states. In this case the electron and hole wave functions do not decay appreciably in the barrier regions and thus the recombination probability[12] is not reduced significantly. From a single-particle point of view one can state that a stable type-A SL band gap requires that the "tunneling time" through a barrier, Δt,[13] be shorter than the bulk GaAs recombination lifetime τ_N. The mean time of an electron within one well Δt can be inferred from the miniband width ΔE, according to $\Delta t = \hbar/\Delta E$.[14] With a miniband width of $\Delta E = 1$ meV, Δt amounts to 10^{-12} sec and is indeed shorter than the bulk recombination lifetime $\tau = 10^{-9}$ sec, thus confirming our experimental results.

Photoluminescence results of a long-period sawtooth superlattice (type B) exhibit a tunability of the emission wavelength due to the pure two-dimensional character of the system, i.e., decoupled electron and hole states.[11] The corresponding estimate for Δt for the long-period sawtooth superlattice yields $\Delta t > 1$ sec, i.e., more than 10 orders of magnitude larger than for a type-A sawtooth superlattice.

Photoconductivity measurements performed on type-A sawtooth superlattices are depicted in Fig. 2(a). A lateral p-n junction configuration has been used for the study.[15] The photoconductivity can be shown to be directly proportional to the absorption coefficient α for the lateral p-n junction configuration used in this study. The striking feature of the type-A superlattice is the large photoconductivity observed below the bulk band gap of GaAs because of enhanced absorption. At energies $E < 1.1$ eV, i.e., below the superlattice gap the photoconductivity decreases. The energy of $E = 1.1$ eV is attributed to the superlattice band-gap energy. For comparison, the photoconductivity of a high-purity GaAs sample is shown in Fig. 2(a), with an absorption edge of $E = 1.42$ eV at $T = 300$ K. Comparison of the photoconductivity of the doping superlattice and the high-purity GaAs sample reveals that strong absorption occurs in the superlattice at energies 1.1 eV $\leq E \leq 1.4$ eV. The data of Fig. 2(a)

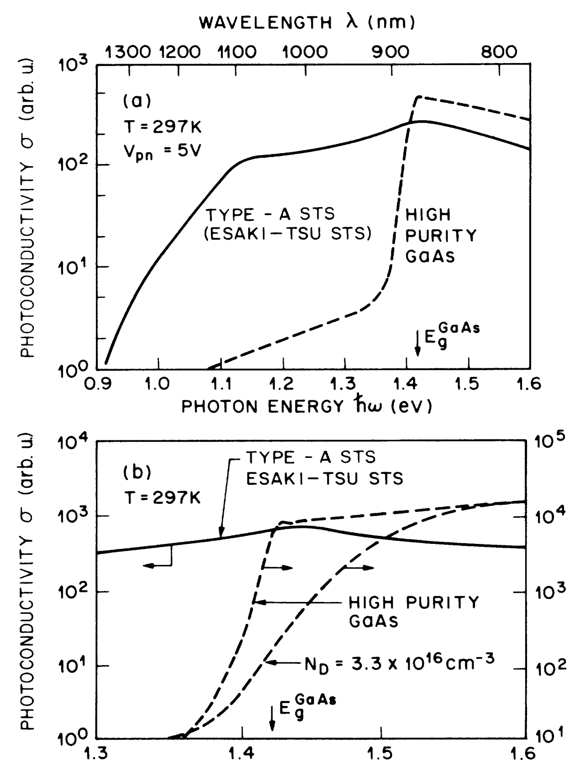

FIG. 2. (a) Photoconductivity of an Esaki-Tsu-type doping superlattice ($N^{2D}=1\times10^{13}$ cm^{-2}, $z_p=150$ Å, lateral p-n junction with 5 V applied in reverse direction). For comparison the photoconductivity of a high-purity n-type GaAs sample is shown. (b) Comparison of a photoconductivity spectrum of an Esaki-Tsu-type doping superlattice (solid line) with absorption spectra on high-purity and doped GaAs (dashed line) obtained by Casey *et al.* (Ref. 16).

show that the absorption edge is shifted to lower energies in the type-A doping superlattice. Our experimental finding cannot be fully explained by the theory of absorption in conventional doping superlattices.[11] These theoretical considerations predict an exponential tail[11] of the absorption for $E < E_g$. Such an exponential tail which should exist for $E < 1.4$ eV does, however, not occur in the photoconductivity data shown in Fig. 2(a).

In Fig. 2(b) we compare the photoconductivity of the type-A sawtooth superlattice with absorption data of n-type GaAs by Casey, Sell, and Wecht.[16] The photoconductivity data of high-purity GaAs grown for this study [Fig. 2(a)] compare well with the absorption results on high-purity GaAs [Fig. 2(b)]. Again, the superlattice shows a strong photoconductive response at energies below the bulk band gap of GaAs. The strong absorption of the superlattice is probably caused by two factors. First, absorption between minibands contributes to the total absorption in an Esaki-Tsu-type doping superlattice (miniband absorption). Second, Franz-Keldysh absorption due to the high built-in electric field of the superlattice is expected. We point out that high built-in electrostatic field of $E = eN_D^{2D}/2\epsilon \cong 10^7$ V/cm has never before been achieved.

Finally, we performed perpendicular electronic transport measurements to confirm the Esaki-Tsu superlattice character of the small-period-length sawtooth superlattices due to the pure two-dimensional properties of the system (i.e., flat dispersion relation or infinitely large confinement mass). In other words, the thick barrier causes the tunneling probability to be negligibly small. If, however, the superlattice period is compressed such that the tunneling probability becomes appreciable, a finite derivative of the perpendicular dispersion relation (i.e., finite confinement mass) and efficient vertical transport result. Perpendicular superlattice transport has been theoretically discussed in terms of miniband conduction and sequential tunneling in the literature.[17] It has been postulated theoretically[18] that perpendicular transport in superlattices should result in Bloch oscillations due to the reflection of carriers at the miniband edges. Such Bloch oscillations have, however, not been experimentally identified unambiguously.[19]

Figure 3 shows two current-voltage characteristics of (a) a type-A sawtooth superlattice and (b) a long-period doping superlattice at room temperature. The epitaxial layers used for the transport measurement are grown on an n^+-type GaAs substrate. Nonalloyed Ohmic contacts are used[9] to avoid diffusion of impurities into the superlattice. The Esaki-Tsu superlattice shows a linear current-voltage characteristic. Efficient transport is observed at voltages which are even smaller than the potential modulation of the superlattice [modulation of band edges is approximately $eN^{2D}z_p/(4\epsilon) \cong 300$ meV], indicating that tunneling dominates the current flow at small deviations from thermal equilibrium. A clear qualitative and quantitative change of the current-voltage characteristic is observed in the long-period type-B sawtooth superlattice. A

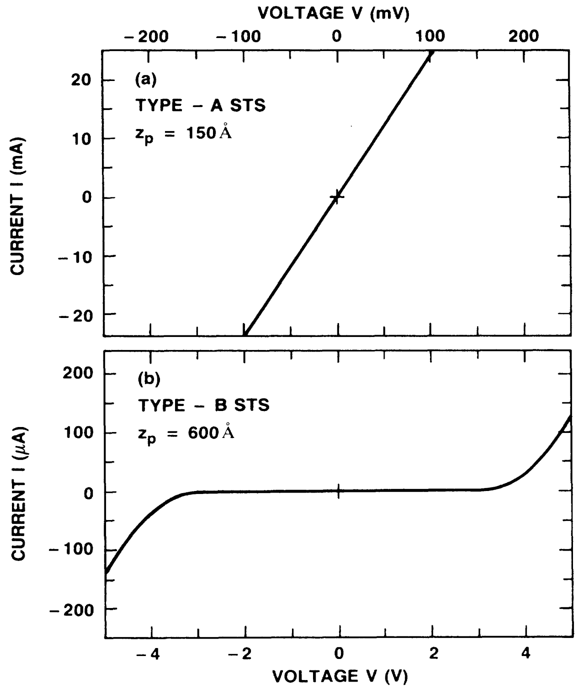

FIG. 3. Current-voltage characteristics of (a) an Esaki-Tsu sawtooth superlattice ($N^{2D} = 1 \times 10^{13}$ cm^{-2}, $z_p = 150$ Å) and of (b) a long-period-length doping superlattice ($N^{2D} = 1 \times 10^{13}$ cm^{-2}, $z_p = 600$ Å) at room temperature. The current ratio at $V \cong 0$ V is $t > 10^6$.

blocking characteristic is measured for this type of superlattice at voltages $|V| < 4$ V. The currents through the two different superlattices differ by a factor of at least 10^6. A symmetric exponential current increase is observed at higher voltages, when the carrier energies are sufficient to overcome the thick barriers by thermionic emission.

In conclusion, we have realized a type-A (Esaki-Tsu-type) doping superlattice. The difficulties associated with the originally proposed homogeneously doped superlattice were overcome by the use of the δ-doping technique. This technique allows us to obtain simultaneously a high potential modulation ($\gtrsim 300$ meV) and a short superlattice period ($\lesssim 200$ Å) simultaneously. The realization of an Esaki-Tsu-type doping superlattice is experimentally demonstrated by optical as well as transport measurements. Photoluminescence measurements show an energy gap independent of excitation intensity, which demonstrates the three-dimensional character of the superlattice. Strong photoconductivity is observed at energies below the bulk band gap of GaAs. Efficient perpendicular transport is observed in short-period Esaki-Tsu-type doping superlattices. A suppression of perpendicular current flow by a factor of $> 10^6$ occurs in long-period sawtooth superlattices.

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[12]The radiative recombination probability can be described by the optical matrix element $\langle \Psi_i, r, \Psi_f \rangle$ where the subscripts i and f stand for the initial (electron) and final (hole) state. A large amplitude of Ψ within the barriers consequently results in a short recombination lifetime.

[13]Accurately defining, Δt is the mean time of a carrier remaining within one well before tunneling to one of the adjacent wells.

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[15]In the lateral p-n junction configuration an n- and a p-type contact are alloyed adjacent to each other into the sample. The gap between the contact is illuminated with chopped monochromatic light. The current-voltage characteristic of such a lateral p-n junction configuration is diodelike with a threshold voltage of $V = +1$ V and a reverse breakdown voltage of $V = -6$ V. Under illumination, the photocurrent increases linearly for increasing negative bias and saturates at $V = -3.5$ V.

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