Anderson-Blount transition. Based on experiments in a large number of samples, we believe that (II) is the dominant effect and is probably responsible for all the observed ν_B saturation.

Regardless of whether or not this transition strictly belongs to the Anderson-Blount class, it is of particular interest for at least two additional reasons. First, it lies entirely outside the framework of our present understanding of $PrAlO_3$ and therefore possibly of other cooperative Jahn-Teller systems. Additional symmetry complications in $PrAlO_3$ uncovered by this work pose challenges to the proper extension of these theories. Because Brillouin experiments cannot give unambiguous determination of crystal symmetry, careful neutron or x-ray studies near 118 K are needed. Second, and of perhaps wider interest, is the generality of the occurrence in perovskite-like lattices of this type of transition. Certainly it has not yet been observed in any other such material, but could easily have been missed because of the negligible coupling of the order parameter to other than acoustic probes. Although the electronic and optical phonon modes play no direct role in this transition, does it occur because of a particular set of anharmonic circumstances which themselves result from the higher temperature exciton-phonon–driven transitions in $PrAlO_3$? Unless this rather unlikely situation is indeed the case, it is quite reasonable to suppose that there are other pure-strain structural transitions in perovskite-like materials awaiting discovery.

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Note added.—Recent neutron diffraction studies (P. G. Woralton and R. A. Byerlein, to be published) of the pressure-induced phase transition[12] in TeO_2 confirm that this transition is also of the Anderson-Blount type.

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New Transport Phenomenon in a Semiconductor "Superlattice"*

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We report electronic transport properties in a GaAs-AlAs periodic structure known as a "superlattice" prepared by a molecular-beam epitaxy. Its differential conductance in the superlattice direction first gradually decreases, followed by a rapid drop to negative values, then, at high fields, exhibits an oscillatory behavior with respect to applied voltages. This observation is interpreted in terms of the formation and expansion of a high-field domain. The voltage period of the oscillation provides the energy of the first-excited band which is in good agreement with that predicted by the theory.

It has been proposed[1,2] that quantum states with desirable energies or bandwidths can be created in monocrystalline semiconductors, once a well-defined structure with extremely narrow potential barriers and wells is achieved in a controlled manner: The transport of electrons in the structure is then expected to be largely governed by such quantum states.

In this Letter, we report transport properties in a periodic structure known as a "superlattice."

The current and conductance as a function of applied voltage show nonlinear characteristics and exhibit an oscillatory behavior beyond a certain threshold voltage. The observed period of the oscillation in terms of applied voltage appears to coincide with the energy difference between the quantized states or bands. This result, we believe, not only suggests the formation of a high-field domain but also confirms the creation of the ground and first-excited bands in the superlattice.

The superlattice used in the present experiments typically comprises fifty periods. Each period has a thickness of 85 Å, consisting of 45 Å GaAs and 40 Å AlAs. The latter provides a potential barrier of a height of 0.4–0.5 eV. The structure has been grown on GaAs substrates by the advanced facilities of computer-controlled molecular-beam epitaxy.[3] The conduction-electron density is $\sim 10^{17}$ cm^{-3} in the superlattice region and $\sim 10^{18}$ cm^{-3} in contacting GaAs regions, the substrate on one side and an overlaid layer on the other. The formation of such a superfine structure has been verified by a combined technique of Auger electron spectroscopy and argon-ion sputter etching,[4] and more recently by small- and large-angle x-ray scattering techniques.[5]

The allowed energy bands in a superlattice can be calculated from the following expression, assuming a one-dimensional, periodic square-well potential.[6]

$$-1 \leq \cos\frac{a(2mE)^{1/2}}{\hbar}\cosh\frac{b[2m(V-E)]^{1/2}}{\hbar} + \left(\frac{V}{2E}-1\right)\left(\frac{V}{E}-1\right)^{-1/2}\sin\frac{a(2mE)^{1/2}}{\hbar}\sinh\frac{b[2m(V-E)]^{1/2}}{\hbar} - 1,$$

where E is the electron energy in the superlattice direction, V the barrier height (0.4 eV), a the well width, b the barrier width, and m the effective mass ($0.1m_0$). The hatched region in Fig. 1 indicates the two energy bands, E_1 and E_2, as a function of well width, with the barrier width constant at 40 Å. In the present case with a well width of 45 Å, the widths of the ground and first-excited bands, E_1 and E_2, are as narrow as 5 and 40 meV, respectively. Such narrow bandwidths are a result of the relatively tight-binding potential in the present structure,[7] as compared with that previously investigated.[8] Thus the locations of E_1 and E_2 in this case are essentially the same as those of discrete energy levels in a single square well. Since the scattering time τ is estimated to be of the order of 10^{-13} sec in our epitaxial structure,[8] an inherent broadening even for these discrete levels is expected to be 6–7 meV. Therefore, in order to test these theoretical curves, we have employed the method of the previously reported resonant tunneling in double barriers.[9] The energies, E_1 and E_2, for three different well widths, 40, 50, and 65 Å, were obtained from a large number of double barriers. Although there is some understandable spread, as shown in Fig. 1, because of thickness fluctuation and other imperfections, the measured values generally fall on the calculated curves, particularly well for the ground state.

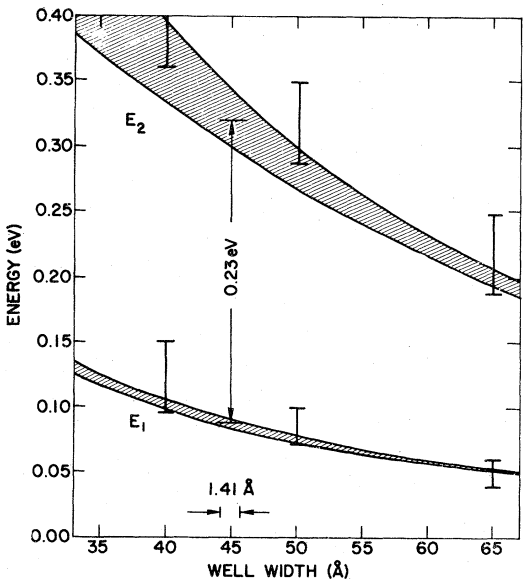

FIG. 1. Two superlattice energy bands, E_1 and E_2, calculated as a function of well width with a barrier width of 40 Å. Each range indicates some spread of experimental values taken from double barriers. Distance of 1.41 Å represents the spacing between (100) atomic planes in GaAs or AlAs.

Transport measurements were made on the present superlattice with two-terminal specimens of an area of about 10^{-7} cm^2. The current is found to increase smoothly with applied voltages up to a few tenths of a volt. Subsequently it starts to saturate or decrease and at high voltages a fine oscillatory behavior is developed. Results of 50-nsec pulsed measurements remain essentially the same. Figure 2 illustrates the differential conductance as a function of applied voltage at four different temperatures: 65, 125, 210, and 300°K. At room temperature, the conductance neither becomes negative nor shows any

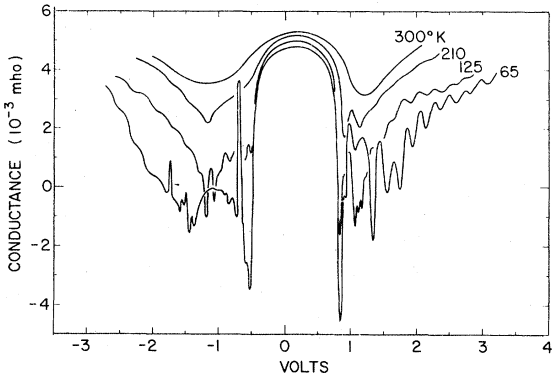

FIG. 2. Differential conductance versus applied voltage in a superlattice at four specified temperatures.

fine structure. The oscillatory behavior is observable at 210°K and becomes increasingly pronounced at lower temperatures. On the other hand, both the conductance near zero bias and a threshold voltage where the conductance begins to drop sharply are relatively insensitive to the temperature variation. Instabilities sometimes exist in the negative-conductance range which give rise to spurious conductance curves. The asymmetric characteristic with respect to polarity, as seen in Fig. 2, is fairly common in many specimens, and is likely due to an asymmetry in the potential profile, although its origin is not clear at this moment. In measuring over 20 specimens, the general features of the conductance, however, are quite reproducible: The onset voltage for the negative differential conductance ranges from 0.4 to 0.8 V and the period of the oscillation falls between 0.21 and 0.24 V.

The observed characteristics are interpreted as schematically illustrated in Fig. 3. At low applied fields, a marginal band-type conduction probably governs the electron transport. The mobility deduced from the conductance near zero voltage is of the order of 50 cm^2/V sec in the direction of the superlattice. After showing a slow decrease as in Fig. 3(a), the conductance starts to drop rapidly at a field of $\sim 10^4$ V/cm: The voltage drop per unit cell (per one period) approaches about 8 meV, if a uniform field distribution is assumed. Beyond this point it seems reasonable to assume that the band conduction fails to be sustained throughout the entire superlattice region and a narrow high-field domain is spontaneously generated. Although the domain region may initially extend only to one barrier [Fig. 3(b)] or two [Fig. 3(b′)], a substantial fraction of

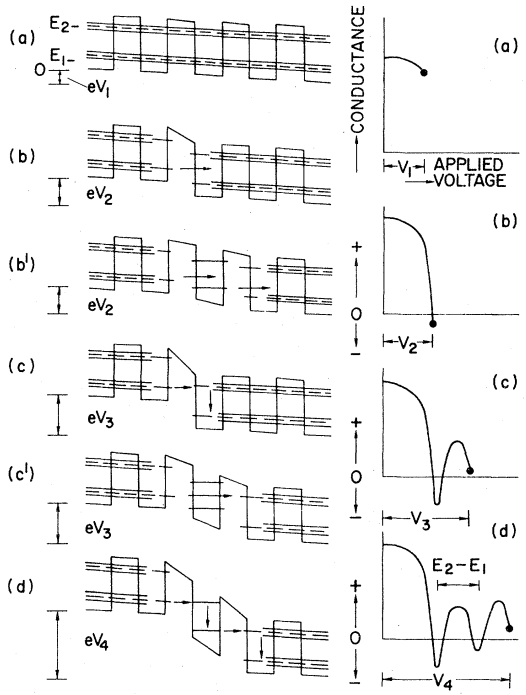

FIG. 3. Schematic energy diagrams (left-hand side) and corresponding conductances (right-hand side): (a) band conduction; (b) and (b′) spontaneous generation of a domain; (c), (c′), and (d) development of domain expansion.

the total voltage will be applied across it. This will leave intact the band conduction in the rest of the superlattice region. It should be pointed out that the high-field domain formation, initiated possibly by a random noise fluctuation or more likely an unavoidable nonuniformity in the superlattice structure, is indeed an inherent feature of the voltage-controlled negative-conductance medium.[10]

We proceed to analyze tunneling characteristics across the high-field domain, because it will dominate the total conductance characteristic of the superlattice system. As shown in Figs. 3(b) and 3(c) or in Figs. 3(b′) and 3(c′), one may realize that this situation is somewhat analogous to the double-barrier tunneling.[9] In the most simple case, a single barrier is sufficient to provide a current peak or a negative conductance arising from matching or mismatching of energy levels on both sides of the domain, as shown in Fig. 3(c), because all involved electrons here are two dimensional in nature. In this domain tunneling, the current peak or dip is expected to be just as sharp as that in the case of the double-

barrier where electrode electrons are three dimensional, if the transverse-momentum conservation of electrons is invoked.[11] The tunneling current across the domain will increase at the matching condition when the applied voltage across it reaches a value corresponding to the difference between E_1 and E_2, as shown in Figs. 3(c) and 3(c'). With further increase in applied voltage, the domain region will be expanded to the adjacent barriers, one by one, and, correspondingly, off- and on-matching conditions will be alternately repeated. Figure 3(d) shows that both barriers in the domain are simultaneously at the matching condition. This discrete nature in the domain expansion will give the oscillatory behavior in the conductance curve, as illustrated sequentially from top to bottom on the right-hand side of Fig. 3. Therefore, the observed voltage period (0.21–0.24 V) will provide the experimental value for $E_2 - E_1$, which is in good agreement with the estimated value (0.23 eV) shown in Fig. 1.

The observed negative conductance is not due to the Gunn effect, because the onset voltage (0.4–0.8 V) for the negative conductance, the electron mobility (50 cm^2/V sec), and the electron mean free path (a few hundred angstroms) in the structure are much too low to activate the electron transfer mechanism.[12] Furthermore, the observation of the oscillatory effect will exclude the possibility of the involvement of hot electrons. The involvement of the optical phonons, $\hbar\omega_0$, is also clearly denied because, in that case, the oscillation peaks are predicted to occur at fields F given by $eFd = \hbar\omega_0/n$, where n is an integer and d is the superlattice period.[13]

In the proposed model, we have used simplified assumptions[14] such as a square-well potential profile, a constant effective mass, ignoring a number of possible effects such as the upper valley in GaAs, band bending, junction problems between the superlattice region and the heavily doped contact regions, etc. These, however, are believed to play rather minor roles and will be required only for further refinement of the theory. The suprisingly good agreement between the calculated and experimental values of the location of the first-excited band seems to support our model and elucidates the most fundamental aspects of the transport characteristics in the superlattice.

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