Tunneling between Two Strongly Coupled Superlattices

R. A. Davies, M. J. Kelly, and T. M. Kerr
GEC Research Limited, Wembley, Middlesex, United Kingdom

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When two semiconductor superlattices are separated by a moderately thick tunneling barrier, one might expect novel features in the electronic transport associated with tunneling between the different superlattice minibands. We report on the highly anomalous electronic conduction in such a structure, and interpret the data in terms of energy filtering by the superlattice minibands.

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The idea of using composition modulation to create new materials with novel electronic properties was proposed several years ago. Perhaps the best known example is the superlattice[1] in the GaAs/AlGaAs system grown by molecular beam epitaxy (MBE). In the superlattice, bound states in wells of GaAs confined by AlGaAs barriers overlap, forming "minibands" of typical widths and separations of tens of millielectronvolts. Under an applied electric field, it should be possible to inject electrons into regions of negative effective mass in the minibands, giving negative differential conductivity and Bloch oscillations.[1] Two effects can obscure the phenomenon: Zener tunneling into higher minibands, which was observed in the original experimental work of Esaki and Chang,[2] and Anderson localization induced by deviations from perfect periodicity with conduction occurring by hopping.[3] It should still be possible to exploit the miniband structure of imperfect superlattices to produce novel transport phenomena.

We report here the observation of strongly non-Ohmic conduction in a structure which consists of two superlattices coupled by a moderately thick tunnel barrier. The structure was grown in a Vacuum Generators MBE system, with Si as the *n*-type dopant, on a semi-insulating (100) GaAs substrate. In order of growth the layers were (i) 500 nm of GaAs, (ii) 1 nm AlAs (to act as a barrier to defect diffusion from the substrate), (iii) 1 μm GaAs (doped at 10^{18} cm^{-3}), (iv) 40 nm GaAs (10^{17} cm^{-3}), (v) 2 nm GaAs, (vi) a superlattice section consisting of 21 layers of 3-nm $\mathrm{Al_{0.25}Ga_{0.75}As}$ and 20 layers of 6-nm GaAs (doped at 4×10^{17} cm^{-3} over the central 2 nm), with the central AlGaAs layer thickness set to 8 nm rather than 3 nm, (vii) 2 nm GaAs, (viii) 40 nm GaAs (10^{17} cm^{-3}), and (ix) 100 nm GaAs (10^{18} cm^{-3}).

The main design considerations of the superlattices were the following: (i) Given a Kronig-Penney model, a 70%–30% bandgap offset,[4] and the GaAs effective mass ($0.067m_e$), the width of the first miniband was ~30 meV (to inhibit optic phonon scattering within the band) with a gap to the second miniband of ~100 meV. (ii) The mean doping level was chosen to put the Fermi level near the center of the first miniband, and was spaced away from the AlGaAs to minimize problems associated with deep donors.[5] The adjacent GaAs layers had the same doping level followed by outer layers of higher doping to improve contact formation and reduce series resistance.

A transmission electron microscopy image[6] of the actual structure revealed random fluctuations of up to ~0.5 nm from the specified thicknesses, with slight differences in the average periods of the two halves of the superlattice. Calculations of the electron transmission probability, by use of an extension of the method of Tsu and Esaki,[7] and the measured layer thicknesses, show the existence of minibands of resonant tunneling at energies similar to those of the design structure. The main effect of the thick barrier and superlattice thickness variations is to reduce the maxima in transmission within the minibands.

Diodes were fabricated by etching to the lower contact layer leaving 100-μm dots, with Ohmic contacts made to top and bottom by use of a conventional AuGe:Ni:Au metallization followed by infrared transient alloying. A second control structure, containing only one well and two barriers in the "superlattice," but otherwise identical, was grown and processed in the same way to investigate the role of contact and series resistances, and the heterojunctions between the GaAs contact layers and the superlattices.

In Fig. 1 representative results of the static current-voltage (I-V) characteristics at several temperatures are shown, along with a corresponding result for the control structure. [Because of their low impedances (~4 Ω), a four-terminal, current-biased measurement was made, but results are presented in the more conventional I-V form.] The most notable features are the discontinuous voltage steps at certain currents, which exhibit a hysteresis dependent upon the direction of the current sweep. Measurements of the derivative $\partial V/\partial I$ (made with conventional ac modulation techniques) show that this diverges as the discontinuity is approached, i.e., that the slope $\partial I/\partial V$ becomes zero. Such behavior suggests very strongly that the true I-V curve is N shaped with a region of negative differential conductivity[8]; discontinuities and hysteresis are expected from an element with this form of I-V characteristic if measured by use of current biasing. Measurements using voltage biasing reproduce

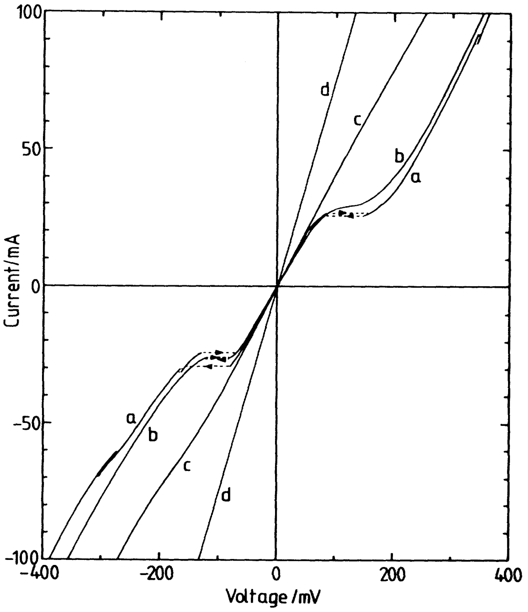

FIG. 1. The current-voltage characteristics of conduction through the superlattice at several temperatures: (a) 100 K (there is no change to 4 K), (b) 175 K, and (c) 295 K. Broken lines show a discontinuous change with arrows indicating hysteresis. Curve (d) is for the double-barrier control structure (at 295 K although almost independent of temperature).

the *I-V* curve except in the unstable region where oscillations are observed, the nature of the oscillations depending strongly on the external circuit. Such oscillations are inherent to *I-V* instabilities and result from resonances in the circuit, which does not act as a perfect voltage source at high frequencies. The large step is quite reproducible between different samples, although the fine structure and the amount of hysteresis vary, possibly because of small variations in the layer thicknesses across the wafer.

The *I-V* characteristics are temperature independent below ~100 K (to 4.2 K, the lowest temperature used). Above this the voltage steps decrease, and the hysteresis loops shrink and eventually disappear, leaving a smooth characteristic which is only slightly non-Ohmic at room temperature. In the Ohmic regions away from the steps the resistances are very similar and almost independent of temperature. The above measurements, taken in the dark, are unchanged in normal illumination. The control structure is Ohmic, with a resistance in good agreement with that calculated for the contact layers. Resonant tunneling[9, 10] might be expected in this structure but, because the barriers are thin, conduction is dominated by the series resistances. If we use the control structure to estimate the series resistance of the superlattice structure, the voltage drop across the superlattice itself is ~40 mV at the onset of the discontinuity, with a step height of ~100 mV. The close agreement of these values with the designed miniband energies is discussed below.

Pulsed measurements were also performed. For this the devices were mounted in microwave diode packages and matched to a 50-Ω coaxial circuit. *I-V* characteristics, measured with a 1-μs pulse with a 1:100 mark:space ratio, were identical to the static measurements which indicates that lattice heating is absent, although electron heating is likely with the electric fields present in the superlattice. Measurements of the voltage drop across the device during the leading edge of a current pulse showed that switching across the voltage step was at least as fast as the instrumental resolution of 100 ps.

While our superlattice structure and our transport measurements differ in many respects from those studied by Esaki and Chang,[2] some features of their explanation still apply here. We have several new pieces of supporting evidence and, furthermore, our explanation suggests new lines of research. (Intervalley transfer, which gives rise to negative differential conduction in bulk GaAs,[10] is precluded in our structure by the low energies involved.) In the development of our argument, it is convenient to consider the case of ideal voltage biasing. The structure may be considered as two ten-period superlattices, separated by a tunnel barrier of 8 nm of $Al_{0.25}Ga_{0.75}As$. In each superlattice section metallic conduction occurs in the first miniband with most of the applied bias dropped across the thick tunnel barrier. (Although the fluctuations in layer thickness might introduce some form of localization,[3] the absence of any temperature dependence below 100 K shows that this is not so and hence that we are justified in describing the transport as metallic. Furthermore, the superlattice is, of course, an anisotropic three-dimensional system, so that arguments about short localization lengths in one-dimensional disordered systems do not strictly apply.) At low values of bias, carriers can tunnel from the first miniband on one side to the first miniband on the other, so that the conduction appears Ohmic. However, once the voltage drop across the tunnel barrier exceeds the width of the first miniband (~30 meV), conduction is only possible if electrons lose energy by emitting phonons, and a drop in current is to be expected. Because of voltage drops in the superlattice regions the applied bias at this point will be slightly larger than the miniband width, consistent with the observed behavior. The current will increase again only when the bias is increased by an amount equal to the separation of the first and second minibands (giving our voltage step of ~100 meV). At this point electrons may tunnel elastically from the first miniband on one side to the second on the other. From here the electrons are free to relax back to the first miniband by phonon emission. When operated under current-bias conditions, and at the relevant current densities, the space charge required to support this high-field domain can be established in less than 100 psec, consistent with the pulsed measurements.

In contrast to the earlier work of Esaki and Chang,[2] we have an obvious location for the high-field domain in which interminiband tunneling occurs. Voltage drops in the rest of the structure remain small and the differential conductance does not vary appreciably until close to the onset of the instability. Further support for the model comes from the temperature dependence of the I-V data; the voltage step is constant below ~ 100 K while above it drops as $\exp(-T/T_0)$ with $T_0 \sim 70$ K (~ 6 meV). This is not inconsistent with phonon-assisted tunneling across the gap between the minibands occurring at the thicker barrier.

We note that our model requires a miniband structure on both sides of the thicker barrier and so would not apply if it were towards either end of the superlattice. The calculations of resonant tunneling for each of the two superlattice sections show small differences in the sets of miniband energies, and these may contribute to the observed asymmetry in the I-V data, along with the asymmetry in interface quality and dopant distribution inherent to MBE growth.[2,9,10]

Fine structure, including secondary hysteresis loops both within and beyond the main feature, is found in some samples. The calculations of transmission probability referred to earlier show sharp resonances near the miniband edges which may account for this. These resonances are very sensitive to the details of layer thicknesses and so will vary between samples.

In a further publication we shall present results including the magnetoresistance (which is anisotropic), detailed studies of the unstable regions of the I-V characteristics (including high-frequency behavior), structural studies, and attempts to reproduce the phenomenon in other superlattice structures.

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