Resonant tunneling in semiconductor double barriers*

L. L. Chang, L. Esaki, and R. Tsu

IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598

(Received 18 March 1974)

Resonant tunneling of electrons has been observed in double-barrier structures having a thin GaAs sandwiched between two GaAlAs barriers. The resonance manifests itself as peaks or humps in the tunneling current at voltages near the quasistationary states of the potential well. The structures have been fabricated by molecular beam epitaxy which produces extremely smooth films and interfaces.

The phenomenon of resonant transmission of electron waves through potential barriers is a familiar one. The Kronig-Penney model of a one-dimensional crystal consists of a series of barriers which exhibits allowed bands of perfect transmission separated by forbidden bands of attenuation. The situation of double barriers has been discussed by Bohm[1] and Iogansen[2] using the WKB approximation and by Kane[3] using the method of wave-function matching. Recently, Tsu and Esaki[4] have treated the general case of multiple barriers in the framework of tunneling formalism, considering the realistic three-dimensional problem. The voltage dependence of the tunneling current has been calculated by assuming the conservations of the total electron energy and its momentum transverse to the direction of tunneling.[5] Resonance is shown to give rise to current maxima at such applied voltages that the Fermi energy of the electrode coincides with the quasistationary states of the potential well. However, it has been generally accepted that this kind of effect is very difficult to realize experimentally because of structural fluctuations in both the potentials and the thicknesses. On the other hand, resonant tunneling of field-emitted electrons through atoms absorbed on metal surfaces has been treated by Gadzuk[6] to interpret the experimental results by Plummer and Young.[7]

In this letter we report clear evidence of resonant tunneling in double-barrier structures made of monocrystalline semiconductors. We chose n-type GaAs as a host semiconductor in which potential barriers with the height of a fraction of 1 eV were formed by introducing epitaxial layers of $Ga_{1-x}Al_xAs$. Because of the similar properties of the chemical bond of Ga and Al, together with their almost equal ion size, the introduction of Al makes the least disturbance to the continuity and thus the quality of the epitaxial films. These multilayer structures have been prepared with the most advanced technique of molecular beam epitaxy in ultrahigh vacuum where precise control of thickness and composition is achieved by using a mass spectrometer in combination with a process control computer.[8] A unique feature of this technique is the extreme smoothness of the resulting films, as evaluated by both electron diffraction measurements and transmission electron microscopy.[8,9] This is undoubtedly the most important requirement for the observation of resonant tunneling. Recently, we have succeeded in profiling these epitaxial layers by a combined technique of ion sputter etching and Auger electron spectroscopy,[10] indicating the existence of unprecedented superfine structure on a thickness scale of 50 Å.

We have made such double-barrier structures of two different configurations with the same materials: one has a GaAs well of 50 Å sandwiched between two $Ga_{0.3}Al_{0.7}As$ barriers of 80 Å and the other has a 40-Å well between 40-Å barriers, as shown schematically in the insets of Figs. 1 and 2, respectively. These multilayers were successively grown on GaAs substrates, ending with a thick GaAs as the top electrode. The electron concentration in both the substrate and the electrode is 10^{18} cm^{-3}, corresponding to a Fermi energy of 40 meV. The Al composition and the thickness in each region have been determined from the beam intensities and the durations of growths together with calibrations obtained from relatively thick films. The two-terminal devices for transport measurements have an active area of 6-μ-diam circles, achieved by several photoresist processes involving etching, oxide deposition, and metallization.[8] The current-voltage and conductance-voltage characteristics for the two configura-

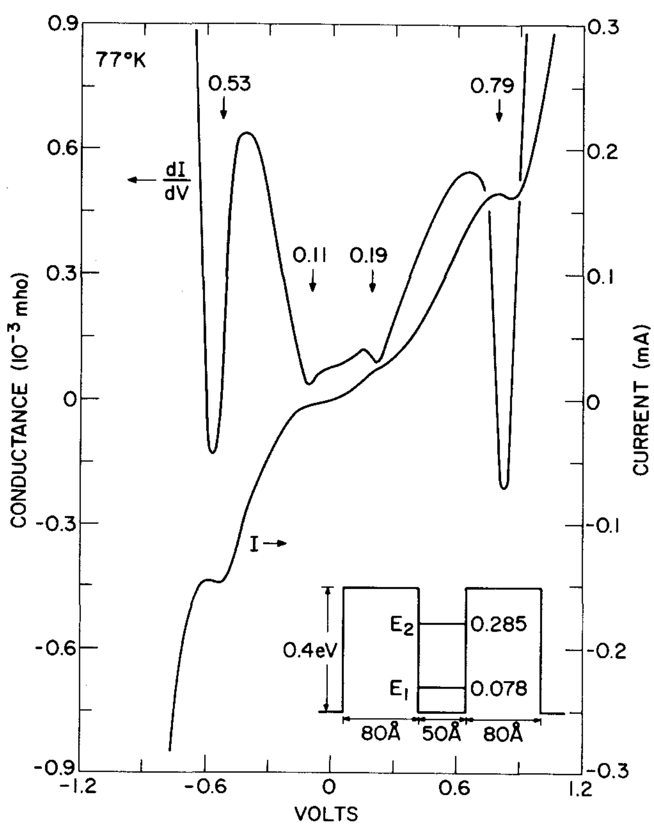

FIG. 1. Current and conductance characteristics of a double-barrier structure of GaAs between two $Ga_{0.3}Al_{0.7}As$, as shown in the energy diagram. Both the thicknesses and the calculated quasistationary states of the structure are indicated in the diagram. Arrows in the curves indicate the observed voltages of singularities corresponding to these resonant states.

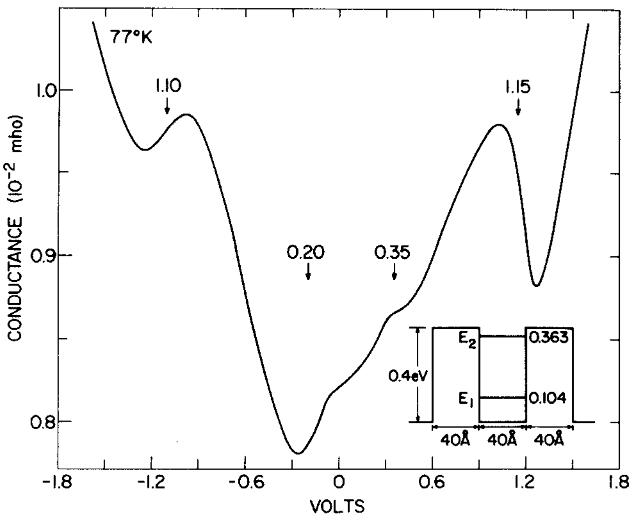

FIG. 2. Conductance characteristics of a double-barrier structure similar to that shown in Fig. 1. The various thicknesses are changed, resulting in different quasistationary states, as indicated in the energy diagram.

tions are shown in the figures. The voltage polarity refers to that applied to the top electrode. The conductance results were taken with a 2-mV peak-to-peak ac signal at 1 kHz. It is noted that the two conductance curves have the same general shape, each showing two sets of singularities as indicated by arrows: $V_1 = +0.19$ and -0.11 V, $V_2 = +0.79$ and -0.53 V in Fig. 1; and $V_1 = +0.35$ and -0.20 V, $V_2 = +1.15$ and -1.10 V in Fig. 2. The singularities at the higher voltages in Fig. 1 actually exhibit a decrease in current, giving rise to a negative resistance.

The quasistationary states for the two configurations are calculated using the transmission expression derived by Tsu and Esaki.[4] Two of the lowest energy states are shown as E_1 and E_2 in the inset diagrams for the two cases, respectively. The barrier height and the effective electron mass used in the calculation are taken to be 0.4 eV and 0.1 m, respectively. These values probably represent reasonable estimates: the effective mass at the bottom of Γ_1 in GaAs is 0.072 m; and the energy difference between $\Gamma_{15} - X_1$ in $Ga_{0.3}Al_{0.7}As$ and $\Gamma_{15} - \Gamma_1$ in GaAs is about 0.55 eV[11] of which a small portion would appear in the valence band. The applied voltages at which maximum transmissions occur due to the states E_1 and E_2 are approximately twice their values. They are 0.16 and 0.57 V for the configuration in Fig. 1 and 0.21 and 0.73 V for that in Fig. 2. Their comparison with the observed values averaged to 0.15 and 0.66 V, and 0.28 and 1.12 V for the two cases are considered satisfactory in view of the simplified square-potential model and the fact that the parameters used in the calculation are not intended for a quantitative agreement. The relatively large observed voltages for the thin-well configuration in Fig. 2 are caused by a small series resistance that becomes relatively important at high currents.

To illustrate the degree of reproducibility, conductances from different samples of the same configuration as in Fig. 1 are plotted in Figs. 3(a) and 3(b) at different temperatures. The results at 77 °K are very similar to those in Fig. 1 in terms of both the general shape and the energies at which the singularities occur, although the conductances do not always become negative. The result at room temperature shows a smooth curve monotonically increasing with voltage as shown in Fig. 3(a). This indicates severe thermal smearing at this temperature and implies a relatively small barrier height. The relatively small decrease of conductance from 300 to 77 °K is the result of thermal-assisted tunneling,[12] and could be accounted for by including the Fermi distribution function in the integration of the tunneling expression.[4] The conductance curve at 4.2 °K, as shown in Fig. 3(b), remains essentially the same except for the appearance of the familiar zero-bias anomaly. The fact that the structure does not become more sharpened suggests the existence of structural fluctuations and impurity scattering in our samples.

The experimental characteristics of relatively pronounced singularities at the second quasistationary states but only slight ones at the first are not difficult to understand, in light of the theoretical calculations.[4] The first state could be considered to be close to a real bound state that would give rise to a strong but narrow

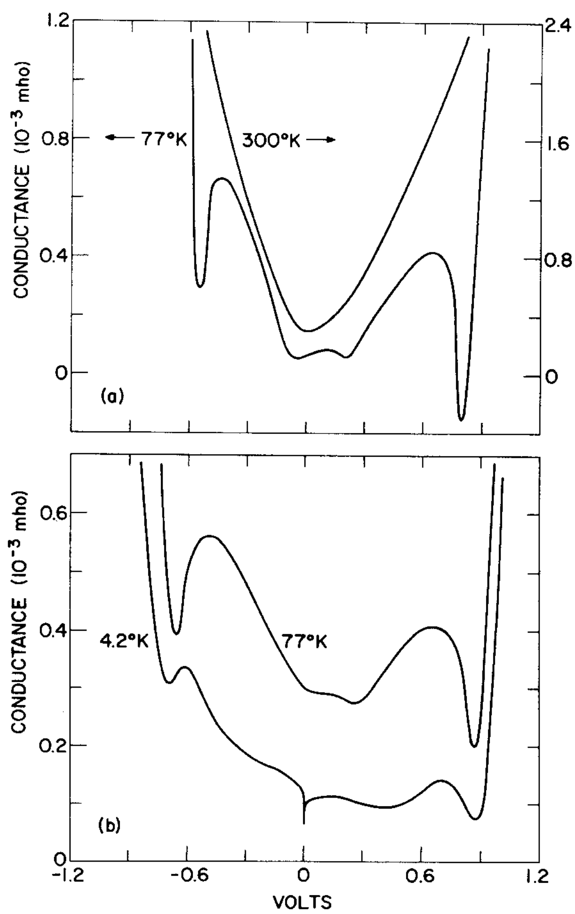

FIG. 3. Conductances of different samples at specified temperature to illustrate the degree of reproducibility. The configuration of the samples is the same as that shown in Fig. 1.

peak in transmission, as such it is more subject to structured fluctuations; while the second state, being high in energy, is rather broad. The observed asymmetry of the characteristics with respect to the applied voltages could easily be caused by an asymmetry of the barrier structure. The dependence of the conductance on the thickness of the barriers is very strong, as can be seen from Figs. 1 and 2, resulting in an increase of 2 orders of magnitude for a thickness reduction by a factor of 2. The strong thickness dependence and the weak temperature dependence as mentioned earlier are, of course, characteristic of the tunneling process of electron transport.

In conclusion, we believe that resonant tunneling in double barriers of semiconductors has been observed. It results in peaks or humps in the tunneling current at resonant energies which increase as the width of potential well is reduced. The advanced facilities with proper choice of materials for the formation of the structure enabled us to observe the effect that has hitherto eluded experiments.

The authors acknowledge technical assistance from L. Osterling, C. Periu, and M. Christie.

*Research sponsored in part by the Army Research Office, Durham, N. C.

[1]D. Bohm, *Quantum Theory* (Prentice-Hall, Englewood Cliffs, N. J., 1951), p. 283.
[2]L. V. Iogansen, Zh. Eksp. Theor. Fiz. **47**, 270 (1964); [Sov. Phys.-JETP **20**, 180 (1965)].
[3]E. O. Kane, in *Tunneling Phenomena in Solids*, edited by E. Burstein and S. Lundqvist (Plenum, New York, 1969), Chap. 1.
[4]R. Tsu and L. Esaki, Appl. Phys. Lett. **22**, 562 (1973).
[5]W. A. Harrison, Phys. Rev. **123**, 85 (1961).
[6]J. W. Gadzuk, Phys. Rev. B **1**, 2110 (1970).
[7]E. W. Plummer and R. D. Young, Phys. Rev. B **1**, 2088 (1970).
[8]L. L. Chang, L. Esaki, W. E. Howard, R. Ludeke, and G. Schul, J. Vac. Sci. Technol. **10**, 655 (1973).
[9]D. B. Dove, R. Ludeke, and L. L. Chang, J. Appl. Phys. **44**, 1897 (1973).
[10]R. Ludeke, L. Esaki, and L. L. Chang, Appl. Phys. Lett. **24**, 417 (1974).
[11]H. C. Casey and M. B. Panish, J. Appl. Phys. **40**, 4910 (1969).
[12]F. A. Padovani and R. Stratton, Solid-State Electron. **9**, 695 (1966).

Effect of doping on degradation of GaAs-Al_xGa_{1-x}As injection lasers

P. G. McMullin, J. Blum, K. K. Shih, A. W. Smith, and G. R. Woolhouse

IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598
(Received 28 February 1974)

The influence of the active layer dopant on the degradation of GaAs-Al_xGa_{1-x}As double-heterostructure lasers has been studied using pulsed excitation. Compensated p-type dopants give the slowest degradation, while n-type dopants give the most rapid. These results can be understood on the basis of arsenic vacancy migration and the formation of arsenic vacancy-acceptor complexes.

The noncatastrophic degradation of GaAs-Al_xGa_{1-x}As double-heterostructure injection lasers has been intensively studied recently.[1-9] The short lifetime of these lasers, typically 10–100 h of continuous operation, has greatly restricted their use. Several factors affecting lifetime have been noted, such as strain due to the mounting process,[3] growth perfection and impurity contamination in the epitaxial growth,[4] and the Al content of the active region.[7]

The importance of nonradiative recombination centers due to impurities or crystal imperfections on the degradation of light-emitting diodes and injection lasers has previously been recognized.[10] An increase in the number of nonradiative recombination centers during device operation has been attributed to the diffusion of impurities or an increase in the number of crystal imperfections, such as Frenkel defects. One specific degradation mechanism has been identified in the double-heterostructure lasers, namely, the growth of dark lines in the active GaAs layer.[2] These are regions of low emission associated with dislocation networks in the epilayers.[6] The dislocation networks appear to grow by the emission or absorption of point defects, and to originate at threading dislocations passing through the epilayers. The dark lines usually appear in less than 100 h of continuous operation and cause rapid degradation of the laser.

In this letter we report another factor which greatly affects laser lifetimes: the doping of the active region. Lasers in which the active region is compensated p-type material doped with Si or Ge last much longer than similar units with undoped or n-type active regions. These results can be qualitatively explained by assuming that dark-line defects grow primarily by incorporation of arsenic vacancies. The longer life of p-type units is then due to formation of acceptor-arsenic-