

Ga_{1-x}Al_xAs, as the "barrier" material, mainly because these two semiconductors are extremely closely matched in lattice constant. The method of choice for depositing the layers was in each case that of molecular-beam epitaxy, a method that permits the accurate (within a few atomic layers) deposition of strata as thin as 10 Å (the equivalent of 6-7 atomic layers).

The theory of one-dimensional square wells may be found in the early pages of any elementary quantum-mechanics text. For the infinitely deep well the energy spectrum of the bound states is given by

$$E_{zn} = (\pi^2 \hbar^2 / 2m)(n/L_z)^2$$

where n is the quantum number, L_z the thickness of the layer in which the particle is confined and m its effective mass.

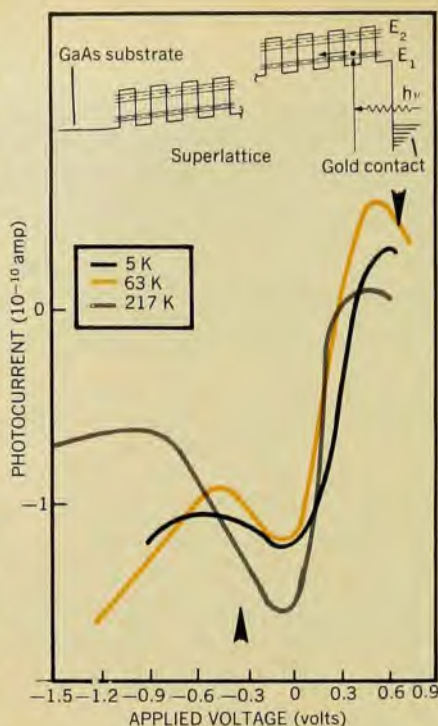
For a well of finite depth the energy levels are given by a transcendental equation, which must be solved graphically or by iteration with a computer. The solid-state configuration also presents other complications:

► There are two wells, not just one. The electron is excited from the valence band to the conduction band, both of which exhibit square-well behavior. In an earlier work with Charles Henry (Bell Labs) the Bell group found that, when the x in Ga_{1-x}Al_xAs is 0.2 ± 0.01 , 88% of the energy gap lies in the conduction band, with the remaining 12% in the valence band. They did this by matching experimental data on light-absorption peaks with the standard theory mentioned; Dingle indicated that the squareness of the semiconductor wells is supported by the fit obtained.

► There are two kinds of carriers, electrons and holes. When an electron is promoted from the valence band to the conduction band, a positively charged hole is left behind; together these constitute an exciton. Data obtained by the Bell Labs group shows how the "two-dimensionality" of the excitons increases with progressively narrower wells.

► A selection rule restricts optical transitions to states of like quantum number. Thus an $n = 2$ valence electron can be excited to an $n = 2$, but not 1 or 3, conduction-band state. The number of states available depends on the well depth and the well-layer thickness.

Dingle, Gossard and Wiegmann have now conducted a systematic series of investigations³ on heterostructures ranging from 50 to 200 Å in well width, from 12 to 18 Å in barrier width and from 0.19 to 0.27 in atomic concentration x of aluminum, and with a number of wells that progresses from 1 to 2 to 3 to 10, the superlattice case. Their absorption spectra are interpreted as showing the existence of light and heavy holes as



Photocurrent versus applied voltage at three temperatures in a superlattice of alternating 50-Å layers of Ga_{0.8}Al_{0.2}As and GaAs. The inset shows the energy diagram, indicating the photon energies of the two transitions E_1 and E_2 . The graphs are for the first peak, E_1 , which is at 1.55-1.58 eV depending on temperature. Arrows point out the two regions of negative differential conductance. (Ref. 2.)

well as evidence of tunneling between wells, which gives rise to symmetric (bonding) and antisymmetric (antibonding) states in the coupled double-well case. As the number of coupled wells increases, individual levels merge into a band for the superlattice configuration.

In a 1974 report of resonant tunneling Chang, Esaki and Tsu observed quantum states from peaks in the current-voltage characteristics of double barriers. In their studies of optical properties, Tsu, Atsushi Koma and Esaki have measured reflection rather than absorption of light.

For measurements of the transport of carriers across it, the superlattice must be provided with electrical contacts. In their photocurrent studies, the IBM group used the GaAs substrate and a semitransparent gold film about 100 Å thick for these. The transport properties are determined by the energy-wavevector relationship, which in a crystal repeats with Brillouin-zone periodicity. The superlattice structure further breaks into minizones, leading to new properties not found in the host crystal. One of these, the so-called "Bloch oscillation," is due to reflection at the minizone boundaries, provided the electron-scattering time is sufficiently long. An alternative way of

seeing how these high frequencies become possible is that the greater coherence distance of the electrons lowers the capacitance of the structure.

While terahertz frequencies have so far eluded the experimenters, another predicted property, negative differential conductance, has been observed. Theoretically this relates to the fact that the effective mass of the electron becomes negative close to the minizone boundaries. In graphs² showing the variation of the photocurrent with applied voltage for a superlattice two regions of negative differential conductance are visible. (There is also a dark current an order of magnitude higher, because of the contact potential with the gold electrode.)

Esaki and Chang⁴ were surprised to find, when the voltage increased beyond that for negative conduction, an oscillatory current-voltage characteristic. This the IBM group attributed to the formation of domains of one or a few periods upon which the entire potential difference collapses and across which resonant tunneling may occur. Other IBM superlattice studies include those of phonon and polariton modes (with Sudhanshu Jha), Auger-electron spectroscopy (with Rudolph Ludeke), x-ray analysis (with Armin Segmüller), hopping conduction (with Gottfried Döhler) and magnetic quantization (with James Janak); in the latter case the superlattice potential was found to introduce Van Hove singularities.

One possible difficulty with heterostructures are the stresses induced by differential thermal contraction of the layers; recent work by Dingle and Wiegmann indicates, however, that these have a minimal effect on the properties of the structure.

How soon superlattices will prove their mettle in optical communications or high-speed computers is too early to say, but they have already found one unintended application: As a byproduct of their accuracy, superlattices are now used to study the resolution of scanning electron microscopes. —HRL

References

1. J. P. van der Ziel, R. Dingle, R. C. Miller, W. Wiegmann, W. A. Nordland Jr, Appl. Phys. Lett. 26, 463 (1975).
2. R. Tsu, L. L. Chang, G. A. Sai-Halasz, L. Esaki, Phys. Rev. Lett. 34, 1509 (1975).
3. R. Dingle, A. C. Gossard, W. Wiegmann, Phys. Rev. Lett. 34, 1327 (1975).
4. L. Esaki, L. L. Chang, Phys. Rev. Lett. 33, 495 (1974).

Continental drilling program recommended

Even though there have been offshore and deep-sea drilling projects in recent years, a comprehensive continental

drilling program in the United States has not been started. The Carnegie Institution (Washington, D.C.) has just released a report that includes recommendations for such a program, to last ten years and cost over \$110 million.

Key areas of investigation, the report says, are the active geophysical processes taking place in the continental crust and the crustal state and structure. Aside from the value of basic research in such a project, other implications are clear: It is hoped that the science of earthquake prediction and control would be advanced and that new geothermal resources could be tapped efficiently. It is also important to learn what effect this geothermal exploitation will have on the underground geothermal reservoir.

Most continental drilling in the US (especially deep drilling) has been done where an economic return was expected. More than two million holes have been made in the search for oil and additional ones made for ore deposits, but many areas of scientific interest have not been penetrated and even extant holes have not been optimally instrumented to collect geophysical data. This is not to say that existing holes cannot be used or extended, the report notes, but certain scientific questions can only be answered by drilling new holes in specific locations.

This drilling is proposed to be done in two phases; first, a series of many shallow holes (30 to 300 meters) followed by the selected drilling of intermediate and deep holes (300 to 9000 meters). The shallow-hole investigations together with regional studies of heat flow, thermal structure and state of stress in the crust could be started immediately at an annual cost of about \$2 million. The bulk of the effort and cost, however, is associated with three main projects that need deep holes: the study of mechanism of faulting and earthquakes; hydrothermal systems and active magma chambers; and the extent, regional structure and evolution of the crystalline continental crust. Each of the three efforts would cost \$20-30 million and take from four to seven years to complete.

Earthquake prediction and control can be implemented along an active zone such as those in California only after a more complete understanding of the earthquake mechanism is achieved. To do this, the report says, the physical properties of the rock at various depths near an active fault zone must be recorded *in situ* and knowledge of other parameters is also needed—measures of shear stresses, pore pressure, permeability and fluid chemistry. Many researchers believe that control of fluid pressure within several kilometers of a fault zone is the key to earthquake control and direct field measurements of

rock permeability are necessary for this to be done.

Experimentally, these objectives can be reached by drilling at an appropriate site (such as the Bear Valley region of the San Andreas system) to depths of three, six and nine kilometers. The shallow hole would serve to monitor an area of low seismicity and low brittleness; the zone six kilometers down is the area of maximum earthquake frequency and probably dominated by brittle behavior; and at nine kilometers, the zone is largely aseismic, and the rock is characterized by ductile behavior. Drilling part of the way at a 45-degree angle will enable monitoring of both the rock adjacent to a fault and the material in the fault zone itself.

Hydrothermal magmatic systems. Great economic benefit can easily accompany scientific gains by drilling into and near hydrothermal and magmatic areas. Such zones fall into two categories—vapor-dominated (or dry-steam) systems and hot-water systems. Deep drilling will be necessary to determine if they are fundamentally different.

Geothermal energy (more easily extracted from vapor systems) and exploration for mineral deposits have their direct monetary payoff, but this type of drilling could have more profound ramifications—a sufficient gain in knowledge about magmatic systems could lead to predicting the time, location and violence of volcanic eruptions.

The experimental procedure for hydrothermal-magmatic system investigations would extend over a five to seven year period, involving geophysical reconnaissance to select appropriate sites and the various stages of drilling that extend into

- ▶ the shallow hydrothermal zone ($\frac{1}{3}$ to 3 km), the level of commercial drilling in recent years.

- ▶ deep hydrothermal or conductive-transfer zone (2-3 km), which is at the edge of the contact zone between the magma and the country rock. Almost nothing is known of this zone—its temperature and pressure gradients and fluid content.

- ▶ the magma chamber-country rock contact zone (3-6 km), where the temperature is 800-1000°C and major emphasis will be placed on *in situ* analysis of chemical gradients.

- ▶ the magma zone, should it prove to be feasible.

Major advances in drilling techniques and instrumentation are necessary for the hotter parts of the deep hydrothermal zone, and the layers below.

State and structure. Understanding the dynamics of plate movement is dependent on learning more about regional heat flow, the state of stress and the broad structure of the crust's crystalline basement. The analysis of stresses and forces will be much advanced, the re-

port says, even with a modest drilling program. Also, data are needed to define the extent and nature of various heat provinces—now more possible because of the recently established relationship between heat flow and radioactive heat production in near-surface crystalline rocks.

Goals for this exploration include measuring spatial, time, temperature, pressure and chemical parameters of crustal evolution; defining of the external configuration and internal structure of the basement rock; investigating mechanisms of how basement rocks are formed and modified; and testing of models for the interactions between continental plate margins, and between oceanic plate margins and the continental crust.

The Carnegie report is an outgrowth of a workshop on continental drilling held during June 1974 at Abiquiu, New Mexico. The gathering was designed to provide recommendations for the US Geodynamics Committee, the group responsible for developing a US program for its participation in the 52-nation International Geodynamics Project (see PHYSICS TODAY, December 1973, page 19).

Satellite and observatory will study x-ray sources

A satellite launched in May and a new observatory at Kitt Peak, Arizona will provide astrophysicists with a dual means to observe x-ray sources. The satellite is Explorer 52, the third in the NASA Small Astronomy Satellite series; it has four experiments that make up a research package developed at MIT's Center for Space Research. The package includes

- ▶ a galactic absorption experiment, to monitor the absorption of low-energy diffuse x-ray background interstellar matter in the galaxy,

- ▶ a Scorpio monitor experiment, to view the time variations of x-ray activity in the x-ray source Sco X-1,

- ▶ a galactic monitor experiment, to help locate x-ray sources in the Milky Way to a precision of 15 arcsec and

- ▶ an extra-galactic experiment, which will monitor weak x-ray sources outside our galaxy.

The Earth-bound observatory to be used in conjunction with this satellite will be operated by scientists from the University of Michigan, Dartmouth and MIT. Money for the building was provided by McGraw-Hill Inc and the instrument housed therein is the 52-inch Cassegrain Coudé telescope, moved recently from the Michigan campus at Ann Arbor.

Data from the x-ray instruments on Explorer 52 will be radioed to Earth, analyzed and made available to astron-