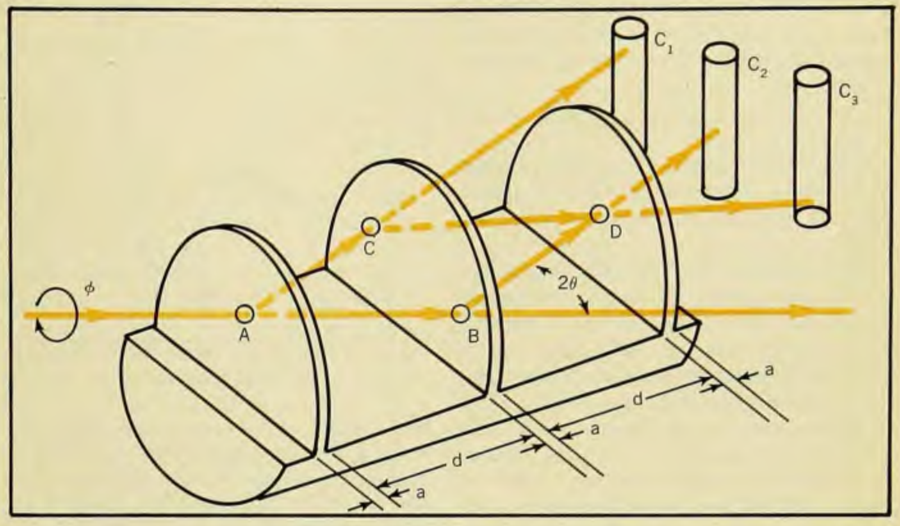
search & discovery

Go and catch a falling neutron . . .

A team of experimenters has used a neutron interferometer to observe the quantum-mechanical phase shift of neutrons caused by their interaction with the Earth's gravitational field. The experiment is one of the first (if not *the* first) observations of the principle of equivalence for a quantum-mechanical system. The experimenters, who reported their work in *Phys. Rev. Letters* on 9 June, are Roberto Colella and Albert W. Overhauser (Purdue University) and Samuel A. Werner (Ford Motor Company).

An x-ray interferometer became feasible about ten years ago, once the electronics industry was able to produce large single crystals of silicon without dislocations. One needs every atomic plane in the silicon to be on the average in the right position within 10^{-8} cm. Such an x-ray interferometer was reported in 1966 by Ulrich Bonse and Michael Hart (then at Cornell University). Then last year H. Rauch and W. Treimer (Atom Institut der Österreichischen Hochschulen, Vienna) and Bonse (now at Institut für Physik, Universität Dortmund) successfully constructed a neutron interferometer.



Neutron interferometer used to measure gravity-induced quantum interference. The high-pressure He^3 detectors monitor one noninterfering beam (C_1) and two noninterfering beams (C_2).

In the experiment done by Colella, Overhauser and Werner, neutrons from the Ford Nuclear Reactor at the University of Michigan strike a single crystal of silicon that has been cut to form three connected slabs (see figure on this page). The original crystal was a cylinder 2 inches in diameter and 3 inches long; after cutting it with a diamond saw the experimenters were left with three slabs on a base that is essentially half of the original cylinder.

The velocity-selected neutron beam is split into two partial beams, one moving uphill in the gravitational field. The neutrons are freely falling; they hit a Bragg-reflecting plane and again fall freely along the next path. After going through a sequence of three Bragg reflections, the two beams interfere. (The free fall of neutrons had been measured, earlier, first by Andrew W. McReynolds at Brookhaven National Laboratory in 1951, and then with much greater precision by John W. T. Dabbs, J. A. Harvey, D. Paya and H. Horstmann at Oak Ridge National Laboratory in 1965.)

The relative phase β of the two beams where they recombine and interfere, at point D of the figure, is varied by rotating the interferometer about the line AB of the incident beam. The phase is

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Man-made square wells offer insight and applications

Thanks to teams at two laboratories, that textbook abstraction of quantum mechanics, the one-dimensional square well, has become realized in a physical object. Known as a "heterostructure," this object consists of accurately deposited thin layers of two different semiconductors of matching lattice constants. When these man-made square wells are built up into stacks of 10–100 periods, they constitute essentially an infinite configuration (because of the finite mean free path of the carriers) known as a "superlattice" (PHYSICS TODAY, August 1973, page 20). These structures open the possibility of creating quantum states with predetermined energy levels and bandwidths.

Because of the unique characteristics of heterostructures and their related superlattices, including their unusual dimensions and negative-resistance regions, important devices are expected to result from this work, including terahertz oscillators, amplifiers, waveguides and greatly improved injection lasers. Laser oscillations from optically pumped multilayer structures of this type have already been reported.[1]

Considered as important as the potential applications, however, are the physical insights the study of these structures affords. These were explored in papers by Raphael Tsu, Leroy Chang, George Sai-Halasz and Leo Esaki[2] at the IBM Research Center, who investigated their transport properties, and by Raymond Dingle, Arthur Gossard and William Wiegmann[3] of Bell Laboratories (Murray Hill), who carried out a systematic determination of their energy levels by an optical-transmission method. Although much of this work was done at low temperatures (2–10 K), the IBM group studied photocurrents up to room temperature (300 K). Dingle told PHYSICS TODAY that the laser oscillations mentioned have also been observed at room temperature.

The techniques used by the two labs were similar in many respects: Both used gallium arsenide as the "well" material and gallium aluminum arsenide,

$Ga_{1-x}Al_xAs$, 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.

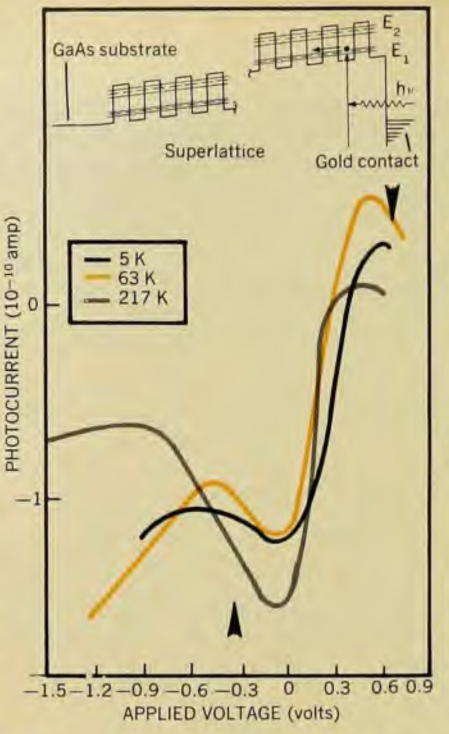
For a well of finite depth the energy levels are given by a transcendental equation, which must be solved graphically or by iteration with a computer. The solid-state configuration also presents other complications:

▸ 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 investigations[3] 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 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.



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.)

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 graphs[2] 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 Chang[4] 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

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Continental drilling program recommended

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