more Laboratory in January, fusion-reactor researchers now have access to 14-MeV neutron sources six times as intense as any previously available. The Rotating Target Neutron Source-II, replacing the RTNS-I, which has been used at Livermore for neutron damage studies since 1972, provides experimenters with two independent 10-mm wide, 14-MeV neutron sources, each providing a maximum flux of 10^{13} neutrons/sec cm^2.

Energetic neutrons damage reactor materials in several ways. Recoiling atoms produce cascades of vacancies and interstitial atoms in the lattice structure of crystalline materials. The neutron-induced production of hydrogen and helium in (n,p) and (n,α) reactions can lead to the formation of gas bubbles in the materials. Interstitial migration can change alloy microstructure, altering the electrical and mechanical properties of materials. Superconductors may fail, and radiological containment structures or insulators can be dangerously weakened. Surface damage may release material into the plasma, cooling it and thus quenching the thermonuclear burn.

One of the two RTNS-II sources has been available to experimenters since January, at which time a group from Argonne National Laboratory began a study of neutron-flux effects on the kind of fused silica windows that may be installed on the Princeton Tokamak Fusion Test Reactor. Three other neutron-damage studies were scheduled to begin in March. Groups from Brookhaven and Livermore are investigating the effect of 14-MeV neutrons on various superconducting materials being considered for confinement magnets. Detrimental changes in structural steels and other high-strength alloys are being looked for by a group from Pacific Northwest Laboratories.

The 14-MeV neutrons are released in the standard fusion reaction in which a deuteron and a triton combine to form a helium nucleus. At RTNS-II, a 150-milliamp beam of 400-keV deuterons impinges upon the titanium-tritide coating of a spinning copper target. The 1-cm-wide deuteron beam, accelerated by a Cockcroft–Walton accelerator, is so intense (75 kW/cm^2) that it would melt almost any material in its path. Therefore the tritium-containing target requires a very elaborate cooling system. The titanium tritide coats the face of a 50-cm-diameter copper-alloy disk, which spins at 5000 rpm and has an intricate and rather pleasing pattern of cooling channels etched into its rear surface. (See the cover of this issue of PHYSICS TODAY.) With a flat copper disk bonded to this etched surface, water must be forced through the channels at about a liter per second to dissipate the heat deposited by the deuteron beam.

The neutron flux emerging from the Rotating Target Neutron Source-II is still an order of magnitude less intense than what the inner walls of a fusion reactor will eventually have to suffer. Therefore the next generation neutron source is currently in the design stage at the Hanford Engineering Development Laboratory. This facility would use a 35-MeV deuteron linac and a liquid-lithium target to produce a total neutron source strength in excess of 10^{16} neutrons/sec with maximum flux of order 10^{15}/cm^2 sec. These neutrons will not however be monoenergetic, but will have a broad spectrum of energies up to 45 MeV. Design studies for the facility are underway. Construction would take about five years.

The Hanford facility would be able to undertake real lifetime studies of fusion-reactor materials. Jay Davis, who supervised the design and construction of the RTNS-II, told us that the emphasis of the Livermore facility is somewhat different. With its still limited flux it is intended primarily to provide data for comparison with theoretical models of fundamental damage processes initiated by 14-MeV neutrons. Frank Coffman, head of DOE's fusion technology program, points out that the flux of RTNS-II will be sufficient for lifetime studies of reactor components such as the magnet insulators, which are separated from the plasma by the inner walls. —BMS

Superlattices show quantum effects

Recent advances in controlling the epitaxial growth of semiconductor heterostructures have made possible the observation of man-made quantum-size effects in such structures. By sandwiching a layer of gallium arsenide about 100 Å thick between confining layers of aluminum–gallium arsenide, one creates a potential well about 300 milli-electron volts deep in which confined, discrete energy levels can be observed for electrons above the conduction band edge. By expanding this sandwich to hundreds of GaAs layers, with interspersed $Al_xGa_{1-x}As$ layers of comparable thickness, one has created a superlattice, with an artificial periodicity one or two orders of magnitude longer than the atomic spacing, superposed on the natural periodicity of the crystal (see PHYSICS TODAY, August 1975, page 17). This results in a splitting of the conduction bands into mini-bands corresponding to the mini-Brillouin zones of the longer periodicity. When such a superlattice is doped with donor impurities, a pseudo-two-dimensional electron gas will be confined in each GaAs layer.

In recent months a University of Illinois–Rockwell International collaboration has reported continuous-wave laser action from confined, discrete electron levels several hundred meV above the conduction band edge in quantum-well heterodiodes,[1] and a group at Bell Labs has found greatly enhanced electron mobility along the planes in periodically doped superlattices.[2]

Quantum wells. Daniel Dapkus and Russel Dupuis at Rockwell International have since 1977 been growing GaAs–$Al_xGa_{1-x}As$ quantum-well heterostructures by the epitaxial technique known as metallo-organic chemical-vapor deposition. The active GaAs layers, 50 to 200 Å thick, have proven so free of crystal defects that their collaborators at the University of Illinois, led by Nick Holonyak, have been able for the first time to achieve continuous-wave lasing transitions from high-lying discrete electron energy levels confined in the active layers. The bottom of the conduction band in GaAs lies about 300 meV below that in $Al_xGa_{1-x}As$, when x (the fraction of aluminum) is about 0.3. Thus each GaAs layer represents a 300-meV deep, one-dimensional potential well for electrons (and a shallower well for holes at the top of the valence band). When these wells are sufficiently thin ($\lesssim$300 Å), they generate an observable series of discrete quantum states for electrons and holes. Dapkus and Dupuis have produced heterostructures with single and multiple (up to six) GaAs layers. When the interleaved $Al_xGa_{1-x}As$ coupling layers are sufficiently thin ($\lesssim$100 Å), the coupling between confined quantum states results in a fine splitting. This splitting ultimately generates bands in the limiting case of an infinite superlattice, just as the coupling between discrete atomic electron levels generates bands in an ordinary crystal.

Conventional semiconductor heterodiode lasers, where the active central layer is thousands of angstroms thick, are usually grown by liquid-phase epitaxy. This technique grows crystals sufficiently free from lattice defects to allow continuous-wave laser action at room temperature. But with liquid-phase epitaxy one has not been able to produce the sharp interfaces required for the ultra-thin layers that can give rise to quantum-size effects. On the other hand, molecular-beam epitaxy, which was introduced at Bell Labs in 1969, can produce extremely sharp interfaces, with layer thickness down to mono-atomic dimensions (see PHYSICS TODAY, February 1977, page 17). But heterostructures grown by molecular-beam epitaxy have not yet proven capable of cw laser action at room temperature.

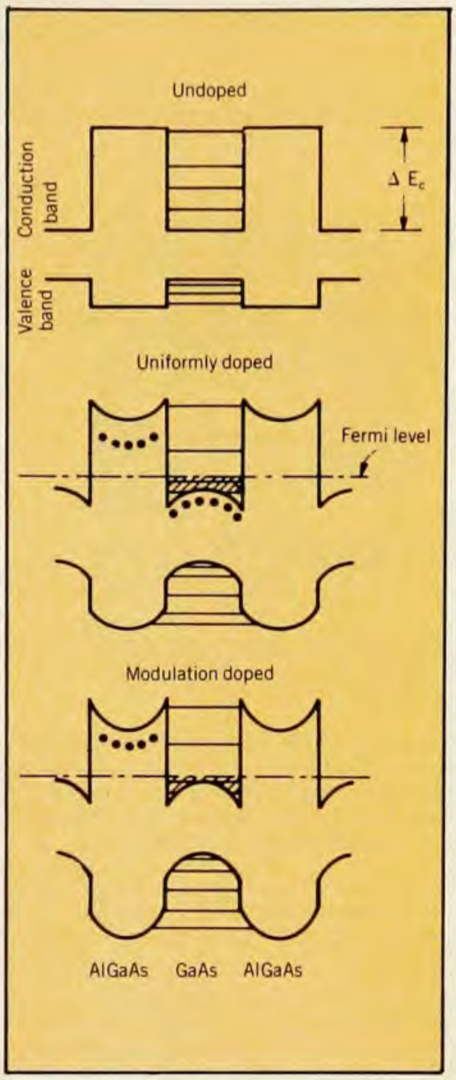
In the opinion of Charles Duke of Xerox, the Illinois–Rockwell results demonstrate that metallo-organic chemical-vapor deposition has to some extent combined the virtues of the other two epitaxial techniques, making possible for the first time practical quantum-well laser devices. In metallo-organic chemical-vapor deposition, the $Al_xGa_{1-x}As$ layer is epitaxially grown by passing a controlled mixture of trimethyl aluminum, trimethyl gallium and arsine (AsH_3), carried in a hydrogen-gas carrier flow, over a heated substrate. The organic radicals are pyrolized off by the heat from the substrate (700 K), and swept away by the carrier gas. The resulting crystals are extremely free from defects, which would tend to quench laser action. Being an atmospheric-pressure technique, this process requires a considerably less elaborate apparatus than does molecular-beam epitaxy, which needs a very high vacuum (10^{-10} torr).

Quantum-well lasers. A single GaAs quantum well will generate a series of discrete electron energy levels up to the energy of the edge of the conduction band in the neighboring $Al_xGa_{1-x}As$ layers. An additional, shallower well at the top of the valence band will generate a corresponding series of hole levels, more closely spaced than the electron levels. Radiative transitions will occur between the nth electron state and the nth hole state, where n is the principal quantum number of the state.

At 77 K the natural lasing wavelength in bulk GaAs crystal is 0.82 microns, in the near infra-red, corresponding to the 1.51-eV band gap between the conduction- and valence-band edges. But with the heterostructure potential wells providing an additional 300 meV, one has the possibility of laser emission all the way up to the visible. With a photopumped 200-Å single-well heterostructure at 77 K, Holonyak and coworkers have observed lasing transitions all the way up to $n = 5$. This 0.69-micron laser emission in the visible red corresponds to the 1.80-eV transition from the fifth confined electron state to the fifth hole state. This transition is 290 meV more energetic than the natural lasing transition of bulk GaAs, giving us a semiconductor laser with an extraordinary lasing range of $\Delta\lambda \approx 1300$ Å. In 1975 Jan Vanderziel and coworkers at Bell Labs[3] had seen pulsed laser emission from the $n = 1$ transition. The group had earlier studied the higher-lying states by absorption measurements.

The outer confining $Al_xGa_{1-x}As$ layers of these quantum-well laser heterostructures grown at Rockwell are of the order of a micron in thickness, and the cleaved crystal edges normal to the layers serve as reflectors for the light to bounce back and forth, permitting stimulated emission to occur in the active GaAs layer (or layers). The distance between reflecting edges is of the order of tens of microns. The Illinois–Rockwell group has obtained cw room-temperature laser action from a photopumped quantum-well laser only 10 microns long (edge-to-edge) and 1.3 microns thick. Holonyak describes this as the world's smallest cw room-temperature laser.

One can alter the lasing frequency by choosing a different thickness for the quantum well. With GaAs layers as thin as 50 Å, one needs to couple several active layers together with interleaved $Al_xGa_{1-x}As$ coupling layers ($\approx$70 Å), to prevent carriers from simply migrating across the tops of the wells from one confining outer layer to the other. By this means one can also increase the total thickness of active layers for opto-electronics applications without increasing the quantum thickness of the potential wells. For such applications a current-injection heterodiode is considered more interesting than a photopumped system. With both photopumped and injection-diode quantum wells, the Illinois–Rockwell group has achieved cw laser operation at room temperature, with threshold pumping power levels that Holonyak says are as low as those required by the best conventional double-heterodiode lasers.



Energy-band diagrams for undoped and n-doped GaAs-Al_xGa_{1-x}As superlattices, showing conduction and valence-band edges, with $\Delta E_c \approx$ 300 MeV for $x = 0.3$. The horizontal lines represent quantum-well discrete energy levels for electrons and holes confined in the GaAs layers. The dots indicate donor impurities, which are confined to the $Al_xGa_{1-x}As$ layers for modulation doping. Shaded areas up to the Fermi level indicate a confined two-dimensional electron gas.

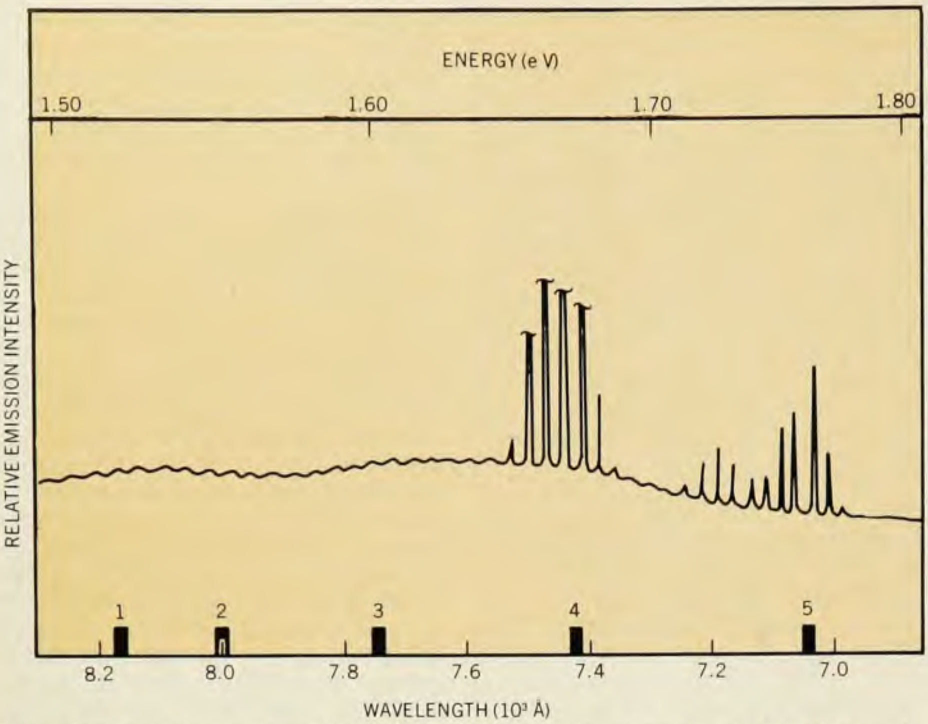
Because the active layer in the quantum-well diode is such a small fraction of the total light-guide volume, very little of the laser light will be reabsorbed. Holonyak estimates a quantum efficiency of about 80% for their quantum-well diode lasers.

Electron mobility in superlattices. In 1969 Leo Esaki and Raphael Tsu at IBM studied the solutions of the Schrödinger equation for conduction electrons in a periodic one-dimensional potential with periodicity of the order of a few hundred angstroms.[4] They pointed out that in a GaAs–$Al_xGa_{1-x}As$ superlattice the conduction electrons would concentrate in the GaAs layers. In doped semiconductors, the dopant sites are a major obstacle to the mobility of the carriers, which have a tendency to be scattered or trapped by the Coulomb well of the ionized doping atom. In an IBM internal report,[5] twice rejected for publication by *The Physical Review*, Esaki and Tsu suggested that if one were to confine n-type doping to the $Al_xGa_{1-x}As$ layers in the superlattice, one could achieve unusually high carrier mobility along the layers. The doping electrons would migrate to the GaAs layers, which, being free of donor impurity sites, would present fewer obstacles to the mobility of the electrons than is usually the case in doped semiconductors. This idea of modulated doping in superlattices was not pursued experimentally at IBM, Tsu told us.

Independently, Raymond Dingle, Horst Störmer, Arthur Gossard and William Wiegmann at Bell Labs, who were unaware of the Esaki–Tsu suggestion, grew the first modulation-doped superlattices last year at Bell Labs, by molecular-beam epitaxy, and they have been studying the mobility of electrons in such systems. They produced modulation-doped and uniformly doped $Al_xGa_{1-x}As$–GaAs superlattices with $x = 0.3$, and layer thickness ranging from 100 to 450 Å. Modulation doping was achieved by synchronizing the silicon and aluminum fluxes in the molecular beam, so that the dopant was distributed only in the $Al_xGa_{1-x}As$ layers and was absent from the GaAs layers.

The valence-four silicon impurity atoms replace either the aluminum or gallium atoms at the valence-three sites in the crystal, thus serving as electron donors. Because the conduction band edge in the GaAs layer lies about 300 meV below that in the $Al_{0.3}Ga_{0.7}As$ layers, the electrons from the donors will migrate to the GaAs layers. In both the uniformly doped and modulation-doped lattices, the $Al_{0.3}Ga_{0.7}As$ layers are depleted of carriers, and a confined, pseudo-two-dimensional Fermi gas of electrons will fill the GaAs quantum wells up to the Fermi level.

The Bell group doped the superlattices to various carrier densities of order 10^{17}–10^{18} electrons/cm^3 and measured



Stimulated-emission spectrum at 77 K from photopumped Illinois–Rockwell GaAs-$Al_xGa_{1-x}As$ heterostructures, with single 200-Å-wide quantum well. The two groups of peaks indicate the $n = 4$ and $n = 5$ electron-hole transitions. The individual peaks in each group are different standing-wave modes in the 25-micron-wide (edge-to-edge) lasing crystal. The natural lasing wavelength of bulk GaAs is 8.2 Å, corresponding to its band-gap energy (1.51 eV).

carrier mobility (defined as conductance per unit carrier density) along the superlattice layers as a function of density and temperature, using the Hall effect. They compared the measured mobilities with the upper limits predicted for bulk semiconductor crystals by the standard theory of Harvey Brooks and Conyers Herring. The Brooks–Herring upper limit for mobility decreases with increasing electron concentration, being about 3×10^3 per cm^2/V-sec for a carrier-electron density of 10^{18} per cm^3 in GaAs at room temperature.

Room-temperature mobilities measured for epitaxially grown bulk GaAs lie from 10 to 40% below the Brooks–Herring limit, and Dingle's measurements give mobilities lower still for uniformly doped GaAs–$Al_{0.3}Ga_{0.3}As$ superlattices at comparable carrier densities. But with modulation-doped superlattices, the Bell Labs group found electron mobilities up to 50% above the theoretical limit for bulk GaAs at room temperature. In other words, the mobility of electrons in the modulation-doped superlattice is as much as a factor of two greater than that in bulk GaAs. According to Dingle, this indicates that the interfaces between layers are extremely clean, because interface defects would introduce serious scattering problems.

Low temperatures. It is at low temperatures that the more dramatic mobility properties of modulation-doped superlattices emerge. At temperatures less than 100 K, scattering off ionized impurity sites is the dominant factor limiting carrier mobility in bulk semiconductors, and one expects a $T^{3/2}$ temperature dependence. This is in fact what one finds for bulk GaAs and (approximately) for the uniformly doped superlattices. In striking contrast, the Bell Labs group reports that the modulation-doped superlattices behave more like metals at low temperatures, with mobilities increasing smoothly as temperature is dropped. With impurity scatterers physically segregated from the carriers in these heterostructures, Dingle and coworkers report mobilities at liquid-helium temperatures 10 to 100 times those found in uniformly doped superlattices or bulk GaAs grown by molecular-beam epitaxy.

Additional evidence that these high mobilities do indeed come from confinement of the carriers in a two-dimensional electron gas comes from the anisotropic low-temperature behavior of the superlattice in a magnetic field. One can measure the mean time between scatters of a carrier electron by observing the oscillatory dependence of the lattice's magnetoresistance upon the applied field strength (Shubnikov–de Haas effect). By this technique the Bell Labs investigators found that for motion parallel to the superlattice layers the mean scattering time was about 10^{-12} seconds, one or two orders of magnitude longer than in comparably doped bulk GaAs. But for carriers moving perpendicular to the superlattice planes, no oscillatory dependence was observed up to 8 tesla, indicating a scattering time much shorter than 10^{-12} seconds. This is precisely what one expects if the donor impurities and carriers are indeed segregated in alternate layers.

Applications. Dingle likes to call the creation of these man-made quantum heterostructures "atomic architecture." Semiconductors being among our most useful technological materials, the possibilities indicated here for the manipulation of their characteristic parameters suggest a great variety of new applications.

The semiconductor laser diode is a central ingredient of fiber-optics communication systems (see PHYSICS TODAY, May 1976). Quantum-well lasers would have two significant virtues for such systems. First, they can be made to emit at chosen frequencies well above the natural lasing frequencies of semiconducting materials. Furthermore, the smallness of the active volume relative to the total light-guiding volume in such devices promises semiconducting lasers of very high quantum efficiency. The Illinois–Rockwell work makes clear that metallo-organic chemical-vapor deposition can produce quantum-well heterostructures of sufficient defect-free quality to permit lasing at frequencies hundreds of meV above the band gap, in a cw current-injection mode at room temperature. Very recently the Illinois–Rockwell group were surprised to see phonon sidebands in their quantum-well lasing spectra. Exploitation of this unexpected phenomenon, Holonyak told us, could lead to lasers of still greater quantum efficiency.

The increased carrier mobilities achieved in superlattices at Bell Labs, especially at low temperatures, hold promise for improved speed and reduced power requirements in complex switching systems, computers and other electronic devices. Dingle believes it may be possible to produce microwave devices, for example field-effect transistors, operating in the 100-gigahertz region.

These quantum-well structures can exhibit classes of physical phenomena not previously seen in semiconductors. The splitting of the conduction bands into minibands may make it possible, according to Esaki and Tsu, to attain regions of negative conductance (negative effective carrier mass) in the direction perpendicular to the superlattice planes, where the carrier will move in the direction opposite to its usual motion in an applied electric field. —BMS

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