budget will be under increased pressure. For the next five years NCAM would be likely to constrain funding of other new facilities for materials research, such as neutron scattering and submicrometer technology. She asked, if more money goes for synchrotron-radiation facilities construction, will there be enough money for research at the present facilities and for instrumenting additional ports at existing facilities and for operating existing facilities in other fields of materials research?

In testimony before the Fuqua committee in March, William Brinkman (Bell Labs), the chairman-elect of the Solid State Sciences Committee, said that to ensure programs involving small amounts of money "from the national point of view are initiated, it is essential that the climate in Washington should not be one where the only new initiatives that can be supported are those which cost hundreds of millions of dollars. One sometimes finds that it is easier to fund a large program, often with the simplest of goals, than to sell the continuous flexible funding of science where priority setting can be made at a level at which knowledgeable decisions are possible."

Lazarus told us, "Materials science fluorishes with diverse input, not with centralized funding and facilities. The Soviets already have the latter model—they have put much more money into materials science than the US has, but only through very concentrated, central laboratories that have produced almost no original research."

When the Fuqua committee ordered the authorization bill to the House at the end of April, its report contained a number of remarks concerning NCAM. Among them: "In its eagerness to move ahead aggressively with the Advanced Materials Research initiative, the Administration apparently has bypassed the preferred review process, which typically involved representatives of the research community."

"Given the possibility of revisions in the NCAM construction plan [as a result of the Narath panel's study], the Committee believes that it is prudent to slow the project during the first year. Consequently the Committee recommends a reduction of $5 million (approximately 20%) in FY 1984 construction funding.... No funds should be obligated for NCAM construction until the *ad hoc* committee has reported to DOE."

The Committee urged that "support for NCAM should not come at the expense of other worthy advanced materials research initiatives." But the Committee "believes that the Administration's LBL/NCAM proposal must be regarded also as an institution-building measure and not only as an enhancement for an important research field." Finally the Committee urged improved long-range planning and priority setting for the Basic Energy Sciences program including a clear delineation of the respective DOE and NSF responsibilities.

LBL director Shirley, replying to some of the criticisms of NCAM, told us, "We're seeking and receiving community input." Since January, he said, more than 60 letters firmly supporting NCAM and welcoming possible collaboration have been received from major universities and from industry. More than 175 scientists from 20 universities, seven national labs and a dozen industrial labs attended an ALS workshop 9–11 May to plan the insertion devices and beam-line designs. On 23 May scientists from Varian, Bell Labs, IBM Watson Research Center, Atlantic Richfield, Catalytica, Hewlett-Packard, Rockwell, Dow Chemical, Exxon, Union Carbide, Ford, Boeing, Chevron, Westinghouse and Xerox were to attend a workshop on industrial participation. During the summer LBL will begin seeking a director for NCAM with the hope of having the director begin work in the Fall. Also during the Fall workshops on each of the other parts of NCAM are to be held: the Surface Science and Catalysis Laboratory, the Advanced Materials Synthesis Laboratory, and the Advanced Device Concepts Laboratory. Shirley said that LBL has not yet developed a complete description of the NCAM scientific programs. "Our proposals are still tentative."

The Advanced Light Source, Shirley said, is optimized for high brightness in the vacuum uv and soft x-ray part of the spectrum. It is the first storage ring optimized for insertion devices. Instead of extracting radiation from the bending magnets, the radiation is generated in special magnetic devices located in the straight sections. Synchrotron radiation produced by these insertion devices can be significantly more brilliant than that produced by the bending magnets of the ring. From an accelerator-design point of view, Shirley said, "We know how to do that for this low energy range." But he said that the heat load from wigglers is a significant problem for higher-energy machines.

ALS has a circumference of 182 meters (about the same circumference as the NSLS 2.5-GeV ring), has been designed with low emittance, and will have 12 straight sections. These 12 straight sections can accommodate either wiggler or undulator insertions that can produce either very high intensity or very high brightness. (See the article on page 48 of this issue.) ALS is designed to provide pulses as short as tens of picoseconds.

Although ALS has been optimized for 1.3-GeV electrons, it can also operate at electron energies up to 1.9 GeV. By using undulators ALS can then produce 10-keV photons and by use of a superconducting wiggler, 40-keV photons. But at these higher energies, the emittance will be higher, spectral brilliance will be reduced and electron bunch lengths will increase.

Some critics had noted that the relatively low-energy ALS would be ideal for the research interests of David Shirley and not so well suited to most materials scientists. Others had noted that the LBL site could not accommodate a larger (and thereby higher-energy) storage ring. Shirley told us, "Of the thirty storage rings in the world, a sizable fraction are low-energy rings." These include Aladdin, the NBS source (280 MeV), the vacuum uv ring at NSLS and (the 800-MeV) BESSY in Berlin. Shirley believes Berkeley can do more science with a low-energy ring—covering four decades of the electromagnetic spectrum—from 0.1 to 5000 eV—across the K edge of most of the light elements, such as carbon, oxygen, nitrogen, sulfur and silicon. "The only way you can get to the edges you need is with low-energy, soft x rays."

As examples of ALS science, he cited EXAFS (not Shirley's speciality), all of photochemistry with optical and uv radiation, studies of transient phenomena taking advantage of the ALS picosecond pulses, and studies with a very bright infrared source (equivalent to 3×10^5 K).

Concerning the size limitations of the LBL site, Shirley said LBL had considered building a larger electron storage ring and had felt it could find a site for such larger ring in Berkeley. But it opted for the 1.3-GeV ring in the NCAM proposal. —GBL

Superlattices from mismatched materials

Leo Esaki and Raphael Tsu at IBM pointed out in 1970 that imposing an artificial periodicity one or two orders of magnitude larger than the natural lattice spacing on a semiconductor crystal ought to yield novel and potentially useful electrical and optical effects. Since then, considerable work has been done on fabricating and investigating the properties of superlattices—epitaxially grown stacks of alternating thin layers (on the order of a hundred angstroms) of two different semiconductor materials. But until

recently the requirement of good, defect-free crystal matching at the interfaces has severely restricted the choice of materials used to grow such artificially periodic structures. Almost all superlattices were grown with alternating layers of GaAs and $Al_xGa_{1-x}As$ with the lattice constants (spacings) of the two materials differing by only about a part in a thousand.

During the last year, however, Gordon Osbourn and his colleagues at Sandia have demonstrated[1] that one can grow good superlattices with much more severely mismatched semiconductor materials. For sufficiently thin layers—up to about 300 Å—it turns out that alternating materials with mismatched lattice constants differing by as much as a few percent will, if properly grown, accommodate themselves elastically to a compromise lattice constant. The Sandia group has shown, by structural, optical and electronic studies, that such "strained-layer superlattices" are astonishingly free of the interface dislocations one would have expected for heterostructures made from such badly mismatched materials—dislocations that would have destroyed the desirable optical and electrical properties one seeks from superlattices.

The Sandia results may be regarded as a confirmation of the pioneering work of Eugene Blakeslee and John Matthews at IBM in the mid-1970s. Working with Esaki and Tsu, they succeeded in growing strained-layer superlattices with very few defects. But the IBM group did not investigte the optical or electrical properties of these structures in detail, and the field lay dormant for the remainder of the decade. Attention was concentrated on the excellent results being achieved with well matched superlattices (PHYSICS TODAY, April 1979, page 19).

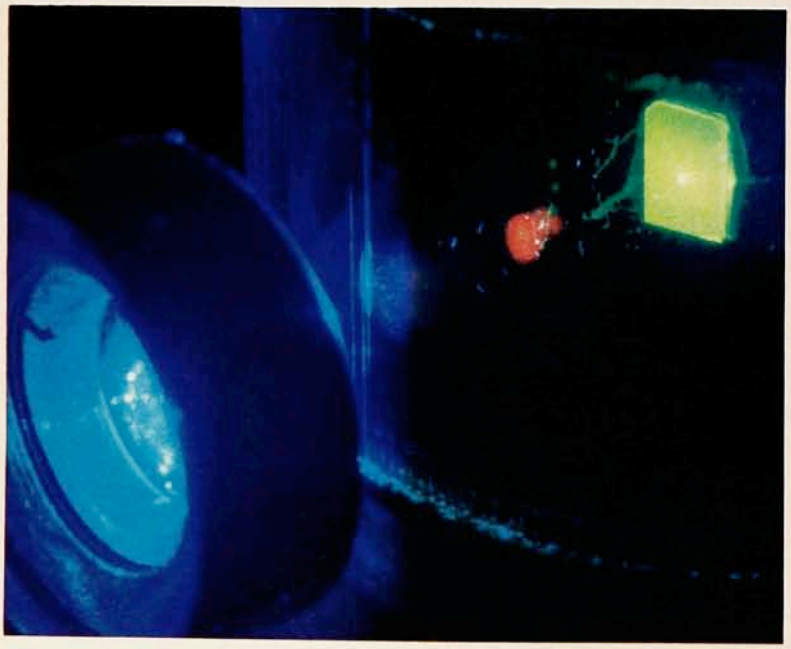
A severe test of the freedom from defects of the interfaces of such strained-layer heterostructures is their ability to sustain stimulated emission. With a strained-layer superlattice grown by Michael Ludowise and his colleagues at Varian, a University of Illinois group led by Nick Holonyak has recently been able to achieve continuous room-temperature laser action.[2] But, Holonyak told us, the large strain energy stored in such structures appears to render the superlattices unstable under the high pumping-power levels required for lasing. Although the superlattices grown at Varian by organometallic vapor-phase epitaxy start out quite defect-free, their stimulated emission deteriorates in a matter of minutes or hours, after which microscopic examination reveals an abundance of dislocations. There is, however, no reason to suppose that strained-layer superlattices would be unstable for lower-power applications such as photodetectors or field-effect transistors, Holonyak explained.

Theoretical and experimental analyses of strained-layer superlattices by the Sandia group indicate that by varying their layer thicknesses and compositions one can vary, *continuously and independently of one another*, the lattice constant, forbidden energy gap and transverse carrier mobility of the overall superlattice. The group has also predicted and presented evidence for the fabrication of direct-gap superlattices from indirect-gap bulk semiconductors. In a direct-gap semiconductor, the conduction and valence band structures permit the direct radiative recombination of electrons and holes; the resulting photon carries off the full energy of recombination. In indirect materials, on the other hand, the kinematics of recombination requires *phonon* intervention; some of the energy goes to the lattice itself.

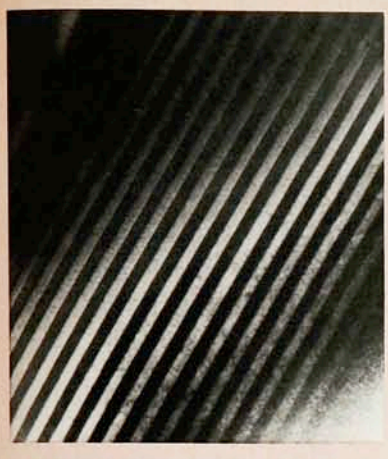
This ability to tailor the structural and electrical properties of semiconducting heterostructures at will should afford optical and electronic device designers unprecedented freedom from the bounds imposed by the constraints of bulk materials. Holonyak cautions, however, that strained-layer structures still have a long way to go before they achieve the performance levels of well-matched superlattices.

In 1970 Blakeslee used chemical vapor deposition to grow thin-layer superlattices that clearly showed elastic strain accommodation between the two mismatched materials. But the disappointing failure of these structures to exhibit the proposed novel effects appeared to indicate an excessively large number of interface defects. The subsequent work by Blakeslee and Matthews demonstrated that most of these defects could be removed by matching the compromise superlattice constant to that of the thick substrate on which it was grown.

In 1981, Osbourn undertook a theoretical study[3] of the electronic properties of strained-layer superlattices. By alternating different semiconductors with different conduction- and valence-band edges in interleaved layers thinner than the mean free paths of the electron and hole carriers, one presents the carriers with a periodic sequence of quantum potential wells whose periodicity is one or two orders of magnitude longer than the 2- or 3-Å spacing of the atomic lattice. This has the effect of generating mini-Brillouin zones that break up the conduction and valence bands of the bulk materials into superlattice minibands. Osbourn calculated that the superlattice band gap should depend not only on layer thickness and composition—the quantum-well effects one knows from well-matched superlat-



Fluorescence at 5660Å in the green is exhibited by this strained-layer supperlattice at liquid-nitrogen temperature in response to 100-mW laser irradiation at 4130Å. The superlattice was grown at Sandia with alternating thin layers of GaP and $GaAs_{0.2}P_{0.8}$. The superlattice strains elastically to compensate for the mismatch between the lattice constants of these two materials. The fluorescence tests how well the strain avoids dislocations at the mismatched interfaces. A Varian–University of Illinois group has achieved cw lasing at room temperature from similarly grown strained-layer structures.



Transmission electron micrograph of a $GaP/GaAs_{0.28}P_{0.72}$ strained-layer superlattice grown by metal-organic chemical vapor deposition at Sandia by Robert Biefeld and his colleagues. This edge-on view illustrates the uniformity of the 120-Å-thick layers and the lack of dislocations in the superlattice, despite the mismatch of the two materials.

tices—but also on the degree of strain in a superlattice made from mismatched materials. Thus lattice strain becomes an additional degree of freedom the device designer can play with. In a more recent theoretical analysis,[4] Osbourn points out that this extra freedom permits one to vary independently the lattice constant, band gap and transport properties of superlattices made with mismatched ternary semiconducting materials such as $In_xGa_{1-x}As$ or $GaAs_xP_{1-x}$. It may be, however, that the metastability of these strained structures will limit the exploitation of these attractive features to low-power applications.

Fabrication of strained-layer superlattices at Sandia by metal-organic chemical vapor deposition was begun late in 1981 by Robert Biefeld. He alternated 60-Å layers of GaP and $GaAs_{0.4}P_{0.6}$, materials whose bulk lattice constants have a 1.5% mismatch. Examination by electron microscopy, x-ray diffraction and ion channeling showed that the two materials had accommodated themselves elastically to a compromise lattice constant. Thus the crystal planes continue through the interfaces just as if the bulk materials had been well matched. In the direction normal to the layers, each material exhibits a strain of the opposite sign to its parallel strain; the layer contracted in the interface plane is dilated in the normal direction and *vice versa*. The strains were measured by ion-channeling techniques carried out by Thomas Picraux and coworkers.

Photoluminescence studies of this strained-layer superlattice by Paul Gourley appeared to support Osbourn's prediction that band-gap folding at the mini-Brillouin zone boundaries would render the superlattice "direct"—even though the constituent materials in bulk permit only indirect, phonon-assisted electron–hole recombination. The intensity of the luminescence was, however, considerably weaker than that produced by superlattices fabricated from direct materials, raising some doubts as to whether the predicted zone folding had in fact occurred. Holonyak believes that one will have to go to layer thicknesses of less than 30 Å to achieve adequate zone folding.

At the International Symposium on GaAs and Related Compounds in Albuquerque last September, the Sandia group presented further evidence of this indirect-to-direct conversion through zone folding from optical-absorption and photocurrent-spectroscopy studies of a number of strained-layer $GaAs/GaAs_xP_{1-x}$ superlattices with layer thicknesses up to 300 Å and mismatches up to a few percent. At Albuquerque the group also reported the molecular-beam-epitaxy fabrication of $In_xGa_{1-x}As/GaAs$ strained-layer superlattices grown by Ralph Dawson. They found the superlattice band gap measured by photocurrent and photoluminescence spectroscopy to be in good agreement with their theoretical calculations.

Recently the Sandia group has demonstrated the high electrical quality of these strained-layer superlattices, Osbourn told us, by low-temperature Hall-effect measurements and by the observation of large quantum oscillations in their high-field magnetoresistance.

Stimulated emission. Learning of the early Sandia results, Holonyak decided that the best way to determine just how defect-free these strained-layer interfaces really are was to try to generate laser action from strained-layer superlattices made with direct-bandgap materials. Even with zone folding, the intensity of recombination radiation from the indirect-bandgap materials used at Sandia is limited by the spatial separation of electrons and holes. The issue of defect freedom at the strained-layer interfaces is crucial for device applications because lattice dislocations serve as sites for competing nonradiative electron–hole recombination, and they degrade carrier mobility.

Using 75-Å strained-layer superlattices grown from direct-gap materials by organometallic vapor-phase epitaxy and metal-organic chemical vapor-phase deposition, the Varian–Illinois collaboration reported early this year that they had achieved continuous, room-temperature laser operation. But under the high pumping power levels needed for such stimulated emission—about 10^3 watts/cm^2—the structures proved unstable after minutes or hours.

Instability of strained-layer superlattices at high power levels is suggested by the abundance of dislocations seen as fine lines in this micrographic *top* view of a $GaAs/In_{0.2}Ga_{0.8}As$ superlattice grown at Varian. Dislocations appeared after it was run as a cw laser photopumped at about 10^3 W/cm^2. The rippled bands are an artifact.

Before being subjected to these high power levels, the strained-layer superlattice grown by Ludowise had looked extraordinarily good under the transmission electron microscope, Holonyak told us. Janet Brown, the microscopist of the Illinois group, was able to resolve individual lattice planes as they passed cleanly across interfaces between GaAs and $In_xGa_{1-x}As$ layers. "It was astonishing. I'd never seen such a thing," Holonyak recalls. Despite the fact that the lattice constants of materials in bulk are mismatched by 1.4%, "I could see no jogs or wiggles at the interfaces." When reexamined after the laser action had collapsed, however, the strained-layer superlattices showed an abundance of interface dislocations. The high pumping-power levels had apparently served to release the very considerable strain energy stored in these superlattices.

In spite of this apparent metastability at high power levels, Osbourn stresses the new opportunites: "We are no longer limited to the few well-matched systems Nature provides us. And we can selectively combine, squeeze and dilate these mismatched materials in superlattices to tailor their optical, electrical and structural properties to our liking." —BMS

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