to match the GaAs structure.) Paul Peercy, a spokesman at Sandia, said the transistors have no detectable change in their electronic characteristics after being lifted off and transferred to a new substrate.

The lift-off technique is analogous to building a house at one site, then picking it up off the ground and transporting it to a new lot. In this case, the ground is a GaAs substrate. A very thin layer—as little as 20 Angstroms thick—of aluminum arsenide (AlAs) is deposited over this, and a GaAs semiconductor device—the house—is built on that, using conventional thin film techniques such as molecular beam epitaxy. A waxy material is then placed over the finished semiconductor device. The wax pulls the device upward as dilute hydrofluoric acid etches away the AlAs layer, freeing the device. Since the bottom of the device is almost perfectly flat, it adheres firmly to the flat face of a new substrate through van der Waals bonding (bonding between the atoms on each surface). The bond is so strong "you need a razor to scrape the layer off, and even then you won't get all of it," Yablonovitch said.

Japanese scientists actually published a paper on a similar technique in 1978, Yablonovitch said, but they never followed up on it. Two factors allow the technique to succeed now that were not present in 1978: an improved acid etch and a careful pull by the wax. The acid eats away the AlAs layer and leaves the other layers untouched with a selectivity of as much as 100 million to 1, allowing the device to come through the process intact. The tension in the wax pulls up the edges of the thin film as the acid is working, allowing hydrogen gas—the by-product of the etching process—to escape from under the device without built-up pressure causing it to crack.

The importance of the lift-off technique is that it allows completely different materials to be used for the substrate and the thin film device. This may, for instance, solve the problem of short circuits in semiconductor devices caused by nuclear radiation, something the military is very concerned about. Devices placed on an insulator such as glass could be made immune to radiation.

Another use would be to speed signals in computers. The high dielectric constant of semiconductors slows down the speed at which signals are propagated in current electronic circuits. Using bases with a lower dielectric constant could double the speed of computer signals, Yablonovitch said. The technique could also be used to make less expensive solar cells, putting thin films of highly efficient but expensive GaAs on inexpensive bases, such as silicon.

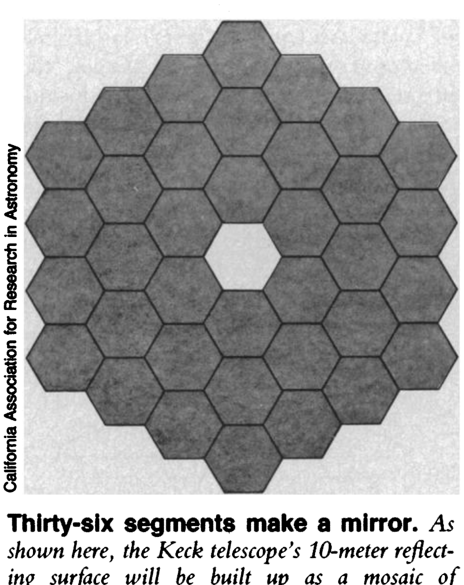
■ Robert Pool

Keck Telescope Mirror Is in Production

The goal is to turn 36 hexagons of high-grade ceramic into a single optical surface 10 meters across; the question is how?

Gliding across the glassy surface on a muddy film of water and polishing compound, a steadily spinning pad moves back and forth, back and forth. The motion is hypnotic. And for the astronomical community, it is rich with significance. On this polishing machine at the Itek Optical Works in Lexington, Massachusetts, production is finally under way for the mirror segments of the largest telescope in the world: the 10-meter Keck Telescope, which is being constructed by the University of California and the California Institute of Technology on the summit of Hawaii's Mauna Kea.

"We're on the order of a year behind our original schedule," says Gerald M. Smith, who manages the project on behalf of the California Association for Research in Astronomy (CARA), a nonprofit corporation formed by the two universities to build and operate the telescope. Smith also admits to being hard up against his $87-million budget ceiling ($70 million of which was provided by the W. M. Keck Foundation; thus the telescope's name). Developing the techniques to fabricate and test the Keck mirror has proved to be a much tougher job than anyone expected. Nonetheless, experiments completed this past autumn have convinced CARA researchers that the problems are now under control. "We still expect to have the telescope operational in 1991," says Smith.



California Association for Research in Astronomy

Thirty-six segments make a mirror. *As shown here, the Keck telescope's 10-meter reflecting surface will be built up as a mosaic of hexagons. The central segment is left out so that auxiliary reflectors can bounce starlight down to instruments located behind the main mirror. Neither the gaps between the segments nor the hexagonal shape will greatly affect the final image.*

A visit to the Itek facility shows what a challenge the Keck mirror really is. In four centuries of telescope-making, there has never been anything quite like it. Its 10-meter diameter, twice the size of the venerable Hale Telescope on Palomar Mountain, was chosen as a compromise between hubris, realism, and the astronomers' constant hunger for more photons: the bigger the telescope's mirror, the larger its light-gathering power for the study of distant galaxies, and the clearer its view into our own galaxy's dusty star-forming regions. But instead of being cast as a single huge disk, in the traditional style of telescope-making, the Keck mirror will be built as a mosaic of 36 hexagonal segments, each only 1.9 meters across. These individual segments will be vastly easier to handle and transport. Once assembled inside the telescope, moreover, they will be vastly easier to control. Whereas a one-piece mirror would have sagged hopelessly under its own weight, the segments will be supported individually. At the same time, they will constantly be monitored and readjusted by a computer-controlled positioning system, which will keep the overall optical surface accurate to better than a micrometer no matter how the telescope tilts and turns.

The trick, of course, is to make the segments. Itek's work begins when the mirror blanks arrive in big wooden crates from the Schott glass works in Meinz, West Germany, where they are cast. Each $100,000 blank is a 2-meter-wide disk of Zero-Dur, a translucent ceramic that is essentially impervious to expansion or contraction with changing temperature. Forty-three are on order: 36 for the segments of the primary mirror, 6 spares, and 1 "just in case."

Once a blank has been removed from its crate and inspected, it goes into the polishing machine, where its upper surface will be ground to an accuracy measured in tenths of micrometers. Anything less perfect than that and the telescope's images will be fuzzy and degraded. The polishing itself is a standard process, albeit painstaking. (It typically takes 5 to 8 weeks.) What makes it such a challenge in this case is the fundamental fact of segmentation. As in any reflecting telescope, the Keck mirror as a whole will form a shallow, dish-like surface known as a paraboloid, which is the mathematical curve that allows it to reflect starlight to a sharp focus. But this means that the individual segments have to be pieces of a paraboloid—with surfaces that turn out to be subtle, asymmetric, and very difficult to achieve using standard polishing techniques.

The solution pioneered by the Keck development team is a method known as stress polishing. The first thing that the Itek technicians do when they place a new mirror blank in the polishing machine is to glue a series of levers around its outside edge. Next, they hang precisely calibrated weights on the levers, thus producing an infinitesimal warp in the disk. And then they proceed with the polishing. The advantage of all this is that now they have to produce only a very simple surface: a section of a sphere. Yet when the weights are removed, the mirror will snap back to form exactly the asymmetric surface desired.

The stress polishing technique has been tested extensively both in California and at Itek, and appears to work quite well. Unfortunately, however, polishing is not the whole story. Once the blank comes out of the machine and has had its optical precision verified in a multistory, laser-equiped test stand, another group of technicians stands ready to attack it with saws and drills. The edges are sliced off to convert the 2-meter disk into a 1.9-meter hexagon. Fifty-six mounting holes are sunk into the back surface, including one hole some 25 centimeters across right in the middle. And then the segment as a whole is mated to a complex structure known as a wiffletree, which will support it inside the telescope.

To no one's surprise, the newly mounted segment emerges from all this with a reflecting surface noticeably less perfect than when it started. That subtle, all-important asymmetry is just a little bit off. And for Smith and his team, the question all along has been what to do about it. Subjecting the segment to another round of polishing is out of the question: the polishing pad would overlap the edges of the hexagon and round them off, destroying the surface altogether. (This is why the segment was polished as a larger disk in the first place.)

At the same time, however, the best conventional alternative—grinding away the surface errors point by point with a diamond-tipped, computer-controlled cutting tool—has its own drawbacks. Unless one spends a very great deal of time getting the surface just right, the mirror is left with microscopic ripples having a spacing about the width of the tool itself. Indeed, this is exactly what is found on the first two Keck segments, which were done this way as part of the project's research and development effort. The problem is that CARA cannot afford to spend that kind of time, not with 36 segments and 6 spares to fabricate by next year. So going with this technique would mean ripply segments and a noticeably degraded performance.

Faced with that distasteful prospect, the CARA researchers have once again been forced to innovate. Their solution, known as the "warping harness," was not even tested and verified on a real mirror until August 1988. "And only then did we commit to production," says Smith.

The idea is to correct the errors by warping the segments again, this time permanently. To accomplish this, 30 small leaf springs are introduced into each segment's wiffletree support structure. These springs are then adjusted individually to give the segment just a few, finely calibrated pounds of stress. In the end the mirror surface bends by no more than a fraction of a micrometer. But it is enough to bring the surface back into tolerance.

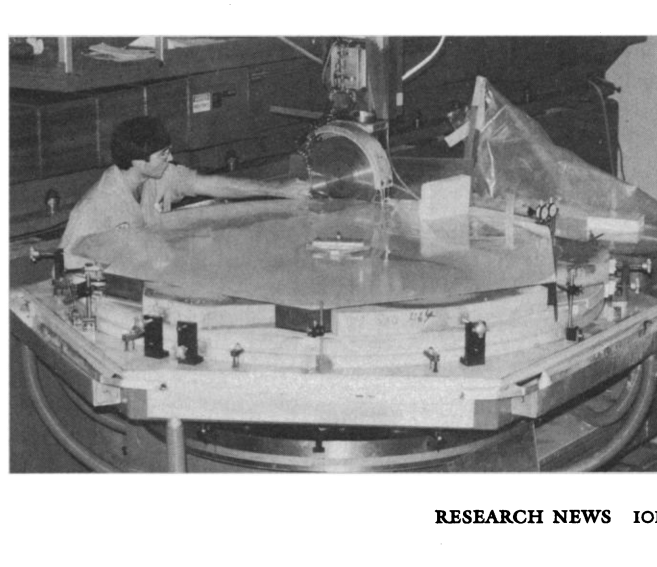
"No further polishing is needed," says Smith. Indeed, for that reason alone, the warping harness method turns out to be significantly cheaper than computer-controlled repolishing, quite aside from yielding a better product. Moreover, it will allow the segments to be precisely readjusted and matched with one another once they are installed in the telescope, something that would be very hard to do otherwise.

Itek is currently working on the fifth mirror segment, which is the first to go through the process since CARA gave its go-ahead for the warping harness approach. "We're not yet in full production mode," says Smith, "but we hope to be there within the next couple of months." The goal is to achieve a processing time of 8 weeks per mirror, he says. Because of the delay in getting to this point, however, CARA has recently contracted with a second optical firm, Tinsley Laboratories in Richmond, California, to stress polish about 20 of the segments. All other fabrication steps will still be performed at Itek.

Assuming that no further problems develop, says Smith, the telescope should start to come together in about a year. The observatory dome has already been completed on the summit of Mauna Kea. Construction for the headquarters building is well under way in the nearby town of Weimea. And the open, latticework telescope structure is undergoing final testing at its fabrication plant in Terragona, Spain. Once that testing is complete, the telescope structure will be disassembled and shipped to Hawaii, where it will be reconstructed in the dome by the end of the year.

"We expect to start installing mirrors by February 1990," says Smith. Testing of mirror alignment and computer positioning of the segments will begin shortly thereafter, as soon as the first nine mirrors are in place. ("Nine mirrors will give you the equivalent of a 5-meter telescope," notes Smith.) Sometime in the course of those tests the shutters of the dome will open and the abbreviated Keck Telescope will receive its first starlight. Almost immediately the astronomers will start inviting themselves in "just to test our instruments"—and doubtless to sneak in a little science on the side. Over the course of the next year or so, the mirror will steadily grow outward as new segments are added to the periphery. And in mid- to late-1991—"about the time the astronomers are ready to kick us out," says Smith—the full-scale telescope should be ready for routine observations.

■ M. MITCHELL WALDROP



Itek Optical Works

Optical work. *An Itek technician lops off the edges of a freshly polished mirror segment with a diamond-tipped saw.*