Solar Power: Promising New Developments

Discussions of the uses of solar energy in the near future have tended to focus on the heating and cooling of buildings and not on the generation of electricity. The ultimate solar power device—photovoltaic cells that convert photons into electric energy—is often relegated, with nuclear fusion, to the next century. There are nonetheless ambitious plans afoot for near-term applications of photovoltaic solar cells. Japan is planning to operate a 1-megawatt solar power plant in the early 1980's; in the United States, according to H. R. Bleiden of the National Science Foundation, 5000 megawatts of solar cell capacity could be in use by 1990 (both numbers refer to peak power output in full sunlight). Lending new credibility to these forecasts and improving the prospects for early terrestrial use of solar cells are increasingly successful efforts to develop fabrication techniques that dramatically reduce the cost of these devices.

The most successful experiments so far are those being conducted by A. I. Mlavsky of Tyco Laboratories, Inc., Waltham, Massachusetts, and B. Chalmers of Harvard University. The Tyco-Harvard collaborators have grown continuous ribbons of crystalline silicon about 2.5 centimeters in width, 250 micrometers in thickness, and up to 2 meters in length (Fig. 1). The ribbons are of sufficient quality that they can be made into solar cells with efficiencies as high as 10 percent. The rate at which the ribbons are grown, about 2.5 centimeters per minute, and the suitability of the resulting crystal for the production of solar cells without further mechanical treatment both represent major advances over existing methods. Typically, in existing methods, a large cylindrical crystal of silicon is formed by pulling it very slowly from a crucible of molten material, thin wafers are sawed from the cylinder, and these are treated to produce solar cells—in all, an expensive, batch process that is wasteful of silicon (because wafers cannot be cut ideally thin) and not readily automated. In contrast, the ribbon growth method lends itself readily to streamlined processes for the production of solar cells at a very great reduction in cost.

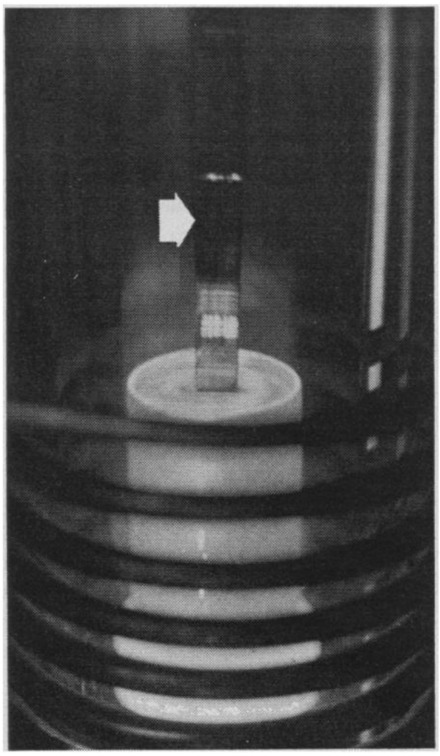

Fig. 1. A silicon crystal being formed in a continuous ribbon. The coils of the electric furnace hide the crucible of molten silicon and the die from which the crystal is drawn. [Source: Tyco Laboratories, Inc.]

Sapphire, then Silicon

The process used to grow the silicon ribbon was developed in the late 1960's by Tyco for growing sapphire (single-crystal aluminum oxide) and is now used commercially to produce sapphire tubes for sodium vapor lamps and other products. RCA and Kyoto Ceramic, Inc., of Japan have licensed the process from Tyco to grow sapphire ribbons as substrates for silicon-on-sapphire (SOS) integrated circuits. Silicon is a much more difficult material to work with than sapphire, however, in that temperatures must be controlled to within 1° or 2°C for the silicon to grow continuously (as opposed to within 20°C for sapphire filaments or tubes) and impurities are more critical.

In the process, known as edge-defined film-fed growth, molten silicon is drawn up through a specially designed die by capillary action (Fig. 2). A seed crystal of the preferred orientation is dipped into the molten silicon and then pulled away as crystal growth begins. The width of the resulting ribbon is determined by the meniscus of molten sodium between the die and the edge of the continually growing crystal. The real advantage of the method, according to Chalmers, is its inherent stability, in that the process automatically corrects for variations in the crucible temperature, in the height of the column of molten silicon, and in the speed of growth. If, for example, the temperature at the top of the die increases, bringing more heat to the crystal-liquid interface and slowing the growth rate, the interface retreats slightly to a new position, thus adjusting the temperature gradient and correcting the heat balance.

With sapphire, growth can be continued almost indefinitely by replenishing the molten material in the crucible, and as many as 25 filaments can be produced from a single crucible. Replenishment and multiple growth have not yet been demonstrated for silicon ribbons, but Mlavsky sees no great obstacle to their achievement, perhaps within a year. Really continuous growth of silicon crystals will not be possible, however, because of molten silicon's unfortunate propensity for dissolving everything it touches, including dies and crucibles. Indeed, impurities in the silicon ribbon, leached from the die during formation, have the effect of poisoning

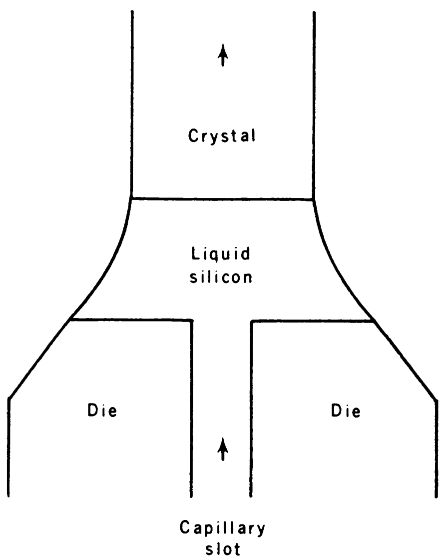

Fig. 2. Schematic of the edge-defined crystal growth process. The limiting factor in how fast the crystal can grow is the rate at which heat can be conducted away from the crystal-liquid interface into the growing ribbon. Below that limit, however, stable, steady-state conditions can be maintained despite minor variations in temperature or growth rate.

the resulting solar cells and greatly reducing their efficiency, a problem that was only recently resolved by making the die from extremely pure graphite. Silicon carbide and silica (silicon dioxide) have also been considered as die materials. Nonetheless, frequent replacement of dies and crucibles is an inherent part of the concept. Mlavsky hopes eventually to grow ribbons 5 centimeters wide and 125 micrometers thick for periods of at least 16 hours—a schedule that would yield ribbons about 50 meters long—but he believes that ribbons even half as long would prove economically feasible. The major uncertainty still to be resolved is how much the die will dissolve and whether impurities will accumulate to unacceptable levels within that period.

In theoretical studies closely tied to the experiments, Chalmers is modeling the crystal growth process to find optimum manufacturing conditions. There is a trade-off, for example, between the advantages of maintaining a high temperature gradient in the molten silicon and the desire to keep the temperature near the die as low as possible. Experimental problems include the development of heat shields to obtain the desired temperature distribution in and around the crucible and die and the development of equipment to pull a long ribbon of silicon.

Even if all the production problems of the edge-defined growth technique have not been resolved for silicon, the ribbons produced so far do represent a major breakthrough. They contain some grain boundaries and other crystal defects, but few enough that impurities have been a larger problem. To make solar cells, phosphorus is diffused into pieces of the ribbon (which is already doped with boron) to form a semiconductor junction, a grid of contacts to collect the current is deposited on the surface, and the silicon is coated with an antireflective material. Centralab, a major solar cell manufacturer located in El Monte, California, has made and tested cells from some of Tyco's ribbon, and they confirm the 10 percent efficiency obtained. "It's good silicon," says P. Iles of Centralab's research facility.

Iles believes that the availability of silicon ribbon will permit mechanization, if not automation, of the cell manufacturing process, although little has been done as yet. Several years ago, in fact, an ad hoc group of scientists from several industries and research laboratories with interests in silicon products studied the prospects for large-scale production of solar cells, starting with the at that time doubtful assumption that silicon ribbon yielding 10 percent efficient cells was available. They concluded that ribbon could be converted on a large scale to solar cell arrays for something like \$22 per kilogram. Assuming that the cost of making raw high-grade silicon can be reduced substantially (it now costs an extravagant \$66 per kilogram), Mlavsky estimates that solar panels might be sold at less than \$400 per kilowatt (peak power at full sunlight) of capacity, or roughly the equivalent of electric power produced conventionally with oil at \$11 per barrel.* Mass production, which these estimates assume, is still clearly some time away, because a large market for solar cells has yet to develop and because the shift from handcrafted production techniques analogous to those in a Swiss watch factory has only just begun.

Crystal growing techniques other than the edge-defined method are also being investigated, although most observers believe the Tyco process to be the best bet at present, because its feasibility is already established. Considerable effort is beginning to be expended on reducing the cost of solar cell production with existing methods. Most firms in the business are reducing prices for cells intended for terrestrial use and attempting to find new applications for their product (\$5 per watt in very large quantities was the lowest price cited to *Science*, and remote installations such as lookout towers operated by the Forest Service are currently a prime market). How rapidly new production techniques are brought into operation and how cheap solar cells will eventually be will depend a great deal on the amount of money invested in the effort, which now depends largely on the National Science Foundation's fledgling solar energy research program. But it seems inescapable that solar power in the form of photovoltaic cells could become a reality well before the end of the century.

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* A comparison with the cost of power delivered to the consumer is more favorable. A 2-kilowatt rooftop panel costing \$1000 and delivering an average of 10 kilowatt-hours per day would pay for itself in about 6 years at the electric rates prevalent in the Washington, D.C., area (about \$0.05 per kilowatt-hour).

Autoimmune Diseases in Animals: Useful Models for Immunology

Autoimmune diseases are associated with reactions of an organism's immune system to its own cells. The mechanism is believed to involve, among other things, a loss of tolerance for antigens of a specific tissue or organ such as the thyroid gland, the skeletal muscles, or the myelin sheath of the central nervous system. One approach to understanding this phenomenon is the study of an autoimmune disease that can be produced in animals—experimental allergic encephalomyelitis (EAE). Recent investigators have dealt with such questions as how self-tolerance is lost and how the components of the immune system interact.

Numerous theories to explain loss of self-tolerance have been advanced, but none of them have been experimentally established. Proponents of various theories differ as to whether autoimmunity is caused by the appearance of new mutant cells of the immune system which lack self-tolerance or whether it results from a defect in a control mechanism that normally maintains self-tolerance. In what may be the first step in deciding among these theories, S. Orgad and I. Cohen of the Weizmann Institute in Israel used the fact that the etiology of EAE is well described to design an experiment that provides evidence consistent with the theory that autoimmunity results from a defect in a control mechanism.

When an animal develops EAE, it undergoes a specific autoimmune response: namely, it produces sensitized T lymphocytes (thymus-derived cells of the immune system) that react to a component of the myelin sheath (the structure that insulates axons of the central nervous system). This component is commonly called myelin basic protein (BP). The reaction of T cells to BP results in a destruction of the myelin sheath, whereupon the animal becomes paralyzed and in most cases dies.

Orgad and Cohen sought to deter-