CREE RESEARCH, INC.

Processes for Growing Large, Single Silicon Carbide Crystals

Most computer chips today consist of tiny electrical and electronic components on a thin slice of silicon crystal. As many as five million discrete components can be placed on a piece of crystal less than two inches square. Silicon crystal chips, however, are quite sensitive to heat. Electricity passing through a chip's superthin connecting wires creates heat, just as it does in the heating element of a toaster. If too much heat builds up, the chip loses its functionality.

COMPOSITE PERFORMANCE SCORE

(Based on a four star rating.)

★ ★ ★ ★

Beating the Heat in Electronic Devices

This ATP project with Cree Research, a small company in North Carolina's Research Triangle Park, made significant progress in the development of an alternative raw material for making crystal slices — silicon carbide. This material belongs to a class of semiconductors having wide bandgap, which means they are relatively insensitive to increased temperatures. Silicon carbide's thermal conductivity is greater than that of copper, so it rapidly dissipates heat. It is impervious to most chemicals and highly resistant to radiation. Silicon carbide is extremely hard — it is used as grit in common sandpaper — indicating that devices made with the substance can operate under extreme pressure. It also possesses high field strength and high saturation drift velocity, characteristics suggesting that devices made of it can be smaller and more efficient than those made of silicon.

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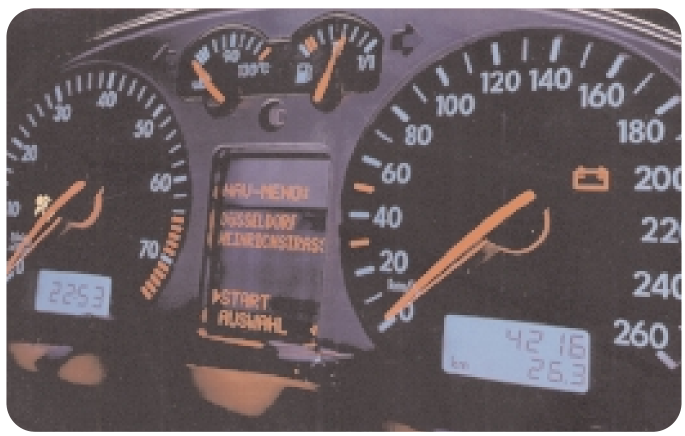
Cree and others have shown that, even at red-hot temperatures, silicon carbide devices maintain functionality. Some of them, in fact, have continued to operate at 650 degrees Celsius. The wide bandgap also allows silicon carbide devices to operate at shorter wavelengths, enabling



Cree's LED chips are used by Siemens A.G. for back lighting for this dashboard.

the creation of blue light-emitting diodes (LEDs) that could not be made from silicon. Moreover, full-color LED displays become possible with the existence of blue LEDs, as blue was a missing primary color.

Growing Large Crystals to Reduce Costs

Cree was founded in 1987 to commercialize silicon carbide and began by making LEDs on a silicon carbide substrate. Prior to its ATP project, Cree was already the world leader in silicon carbide technology and had been making one-inch-diameter silicon carbide crystals. But progress in the development of devices based on silicon carbide had been stymied by difficulties in growing large, high-quality single crystals, a bottleneck that led Cree to pursue more research.

PROJECT HIGHLIGHTS

PROJECT:
To substantially reduce the cost and improve the durability of light-emitting diodes (LEDs) and other electronic and optoelectronic devices by increasing the quality and size (to 2 inches or more) of silicon carbide (SiC) single crystals.

Duration: 6/15/1992 — 6/14/1994

ATP Number: 91-01-0256

FUNDING (in thousands):

ATP	$1,957	82%
Company	435	18%
Total	$2,392	

ACCOMPLISHMENTS:
Cree essentially met or exceeded all of the technical milestones. Successful development of the technology is indicated by the fact that the company:

- applied for one patent on technology related to the ATP project;
- presented several papers at professional conferences;
- raised $13.2 million via an initial public stock offering in February 1993;
- made high-quality, two-inch SiC wafers, greatly opening up the blue LED and SiC wafer markets;
- raised approximately $17.5 million in a private stock offering in September 1995;
- increased annual revenues from $3 million at the start of the ATP project in 1992 to $7.5 million at the end of the ATP award period in 1994;
- received $5.8 million from the Defense Advanced Research Projects Agency in May 1995 for further development of silicon carbide growth processes to support production of three-inch wafers;
- formed Real Color Displays, a wholly owned subsidiary, to exploit this technology for full-color LED displays;
- received a $6 million order in September 1996 from Siemens for blue LEDs; and
- supplied the SiC wafers for components in the SiC solid-state transmitter used by Westinghouse Electric to make the first U.S. commercial-scale high-definition TV (HDTV) broadcast in April 1996.

COMMERCIALIZATION STATUS:
The larger SiC wafers, made with the ATP-funded technology, are being used in the fabrication of blue LEDs sold to many industrial customers. The wafers are also being provided in limited quantities for development projects in government and industry research laboratories.

OUTLOOK:
The improved processing technology makes the outlook for the commercial use of SiC crystals highly promising. The cost of producing blue LEDs has already been reduced substantially, and the expected widespread commercial availability of larger diameter SiC wafers promises a new range of applications, including HDTV transmitters. Benefits in the form of lower costs and higher quality will accrue to industrial users of blue LEDs and SiC wafers, as well as to consumers who use devices containing these two Cree products.

Composite Performance Score: ★ ★ ★ ★

COMPANY:
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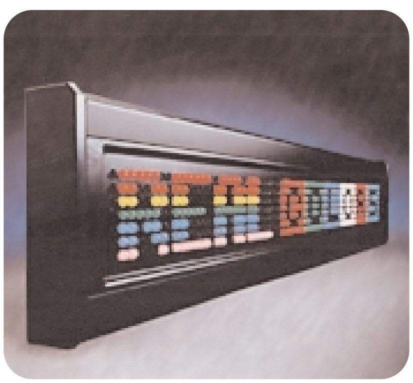
Number of Employees: 41 at project start, 210 at the end of 1997



The Real Color Display™, a moving sign which is capable of displaying the full range of colors, made possible by the use of blue LEDs.

During the ATP project, Cree advanced silicon carbide technology by developing methods to greatly reduce the amount of imperfections in crystals and to increase their size to two inches or greater in diameter. Larger diameter crystals result in lower production costs, which are crucial to opening markets for silicon carbide devices. The company also developed ways to significantly improve the doping (adding impurities to achieve desired properties) and epitaxial deposition (growing one crystal layer on another) processes for silicon carbide. Improving doping uniformity directly increases production yield and thus reduces costs.

Cree's success with the ATP project enables the fabrication of electronic devices that can operate at much higher temperatures and withstand high power levels. Silicon carbide components used in experimental high-definition television (HDTV) transmission, for instance, delivered more power, lasted longer and cost less to produce than conventional silicon-based components. Now equipment that was costly to manufacture (owing to the need for heat-dissipation systems) can be produced less expensively, and devices that were impractical to make with pure silicon can be made with silicon carbide.

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The low-cost blue light emitting diode (LED) produced with new silicon carbide crystal technology.

New Products: Blue LEDs and Silicon Carbide Wafers

The ATP project has been highly productive for Cree and the economy at large. The company has used the new technology to produce larger silicon carbide wafers to use in its fabrication process for blue LEDs. It is also offering the larger silicon carbide wafers for sale to other companies.

Cree is using the ATP-funded technology to reduce the cost of producing blue LEDs, and their sales have increased substantially. Production cost is primarily a function of the number of wafers processed. If wafer size can be increased dramatically, the cost per device will decrease dramatically because so many more devices can be made on a wafer. The silicon carbide wafer technology is also aimed at markets for other blue light-emitting optoelectronic devices, optical disk storage, microwave communications, and blue and ultraviolet laser diodes, as well as high-temperature, high-power, and high-frequency semiconductors.

Benefits for the Economy

Benefits from the new silicon carbide technology are already accruing to customers who have bought large volumes of blue LEDs or silicon carbide wafers to use in their own production. Performance measures (resistance, power output, sensitivity to light, operating temperature) for silicon carbide devices are frequently large, relative to available alternatives. Economic benefits from these performance improvements spill over to other producers involved in fabrication and assembly before a wafer-based product reaches the end user. The total of these incremental benefits is expected to be much larger than the profits Cree receives for selling the silicon carbide wafers.

Cree's private success has led to public benefit, which is expected to grow as the number of applications for larger silicon carbide wafers increases. Westinghouse, for example, used Cree's silicon carbide wafers in fabricating components for the transmitter it used in the first commercial-level HDTV broadcast in the United States, in 1996. Westinghouse said its transmitter can deliver three times more power, has longer life and costs less to produce than conventional silicon-based transmitters. Although the number of HDTV transmitters that will use silicon carbide wafers is unknown at this time, widespread use of this technology in HDTV broadcasting could produce large general economic benefits if it speeds commercialization of HDTV.

ATP Advantages

Cree reports it was attracted to the ATP as a funding source for the development of the bulk crystal and epitaxial growth technologies because the company could retain its process technology knowledge. The ATP award also helped Cree form alliances with research partners and speed the development work, enabling the company to get results about 18 months sooner than it would otherwise have been able to do. During the course of its two-year ATP project, Cree also grew significantly.

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Company officials say the success of the ATP-funded project was primarily responsible for a subsequent award of $5.8 million from the Defense Advanced Research Projects Agency (DARPA) to further develop silicon carbide growth processes to produce three-inch wafers. If wafer size can be increased to three inches, the cost per device will drop even further. This DARPA project got under way in May 1995.