

## Insulating Foams for Microelectronics

Since the invention of the integrated circuit (IC) in 1958, chip designers have enhanced processing speeds by squeezing more and more transistors onto microchips. They have accomplished this by shrinking transistors, by shrinking the distance between them, and by increasing the number of layers in a chip. These improvements have reduced the time it takes for electrical signals to travel within integrated circuits by reducing the length of the connecting lines between transistors. Further development of more densely integrated semiconductor circuits depends critically on the availability of effective electrical insulators.

### COMPOSITE PERFORMANCE SCORE

(Based on a four star rating.)

No Stars

### The Challenge of Improving Electrical Insulation

The electrical and material properties and its geometric shape determine an insulator's effectiveness. An insulating material must have a minimum geometric size, depending on its properties, to provide the desired electrical insulation. As integrated circuits shrink, the room avail-

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able for the material insulating the wires is reduced, and if insulation is inadequate, the current that carries signals on the chip "leaks," causing signal confusion or "cross-talk." This lowers the reliability of the logic, memory, or processing functions being executed by the integrated circuit.

A group of researchers at IBM recognized that progress toward more densely integrated circuits would be impeded by the material properties of the current industry standard for insulation, silicon dioxide. There are a number of materials with dielectric constants ( $k$ )—a measure of the ease with which electrons pass through a material—lower than that of silicon dioxide. The ideal insulator, in terms of its impermeability to electron flow and fields, is a vacuum. Air (e.g., air pockets in foam) is an excellent

alternative: by creating pores filled with air in a material, its dielectric constant can be decreased. Thus, the researchers sought to figure out how to control the process of creating pores in a material (controlled porosity), with the goal of developing a method of providing new insulating materials to successive generations of IC devices.

### Research too Uncertain for Company Funding

At the time IBM researchers submitted the proposal, few internal resources were available for hardware development due to a shift in priorities in favor of software development. In addition, IBM management considered the development of controlled porosity into a commercially viable practice to be too uncertain a prospect to justify the level of internal support necessary to mount the required research program.

At the time, company resources addressing electrical interconnection problems were focused on a research effort to substitute copper for aluminum in the fabrication of chip wires. IBM management believed that substituting copper for aluminum in the fabrication of wires might circumvent the need for improved insulators, copper being a much better conductor than aluminum. Some believed that the substitution of copper would allow for increases in signal speed sufficient to eliminate the need for the increased levels of integration that would make a new type of insulator necessary.

These factors combined to make the company unwilling to proceed with the research on controlled porosity without assistance. The researchers submitted their

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proposal in ATP's 1992 General Competition and received an award. The ATP award reduced the risk of the research to a level that IBM management was willing to provide the necessary internal support to pursue the research.

The ATP awarded IBM \$1.8 million for a three-year, \$5.8 million project to research and develop alternative methods for producing insulating foams using organic polymers. These foams were to make use of the insulation quality of air by creating tiny, nanometer-scale air pockets in a polymeric structure. IBM researchers aimed to develop organic polymer nanofoams with dielectric constants (k) as low as 2.0, almost twice as good as that of silicon dioxide, with its dielectric constant of 3.9.

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### **The Project Team**

The project was led by researchers at IBM's Almaden Research Center in San Jose, California, and facilities in East Fishkill, New York. Some of the work was subcontracted to researchers at Virginia Polytechnic Institute, Exflur Research, and Sandia National Laboratories. The composition of this team reflected an effort by IBM to harness the expertise of these institutions and to expose expert chemists to the specific needs of the microelectronics industry.

### **Researchers Pursue Three Parallel Research Efforts**

Research on low-k dielectric foams was guided by a number of requirements. First, to be usable as insulators, foams must be produced with a specific horizontal and vertical thickness. Second, they must be structurally rigid to withstand the stresses of fabrication. Third, they must be able to withstand the high temperatures used in the

deposition of metal wiring in the fabrication of integrated circuits. Aluminum wiring is deposited at temperatures of more than 450° C.

The researchers pursued three different approaches to the development of low-k dielectric foams for insulation of microelectronics devices. One approach investigated closed-cell molecular foams. These foams incorporated a cage-like molecular structure inside a polymer, forming tiny pores in which the polymer would encapsulate air or other gaseous molecules. Given the lack of data on this technology, however, there was concern as to whether molecular foams with dielectric constants of less than two could be achieved while still meeting the other requirements for microelectronic applications. Researchers anticipated this approach might need to be combined with one of the other two processes.

The second approach to constructing polymer foams built on a method called induced phase separation, which had been developed by Sandia National Laboratories. The researchers sought to determine whether this process could produce extremely thin, heat-resistant foam structures suitable for microelectronic applications.

The third approach investigated the block copolymer method, considered the most promising by IBM. This approach combined two different polymers with different chemical and physical properties to create a structure that would provide the desired performance as an insulator while withstanding the heat employed in the process of fabricating aluminum circuitry.

### **Achievements**

The first approach, which examined closed-cell molecular foams, was abandoned early in the project. The process did not produce foams that had low enough dielectric constants and that were uniform in their insulating properties.

The researchers carried out extensive experimentation with the second approach, which used induced phase separation. This technique developed extremely good electrical insulating foams, some of which had dielectric

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*Using the block copolymer method, IBM and its colleagues generated foams with the desired thermal characteristics, as well as foams with the desired electrical insulation, but could not produce foam that had both qualities at the desired levels.*

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## PROJECT HIGHLIGHTS

### PROJECT:

To develop a method for creating insulators for integrated circuits by controlling porosity, with the goal of enabling multiple generations of ever faster and more densely integrated circuits.

**Duration:** 3/01/93 – 2/28/96

**ATP Number:** 92-01-0103

### FUNDING (in thousands):

ATP	\$1,602	29%
Company	3,940	71%
Total	\$5,542	

### ACCOMPLISHMENTS:

Research on low-k dielectric foams demonstrated the potential feasibility of polymer foams as insulators. Critical requirements and unpromising approaches were identified. Researchers pursued three approaches in the attempt to create effective foam insulators, and achieved the following: presented the new technology at several professional conferences;

- identified two methods, involving molecular foams and induced phase separation, as technically infeasible;
- found that one of the methods, involving block copolymers, offers promise for creating foam insulators suitable for microelectronics use;
- published results in technical journal articles in the field of microelectronics, including “Templating Nanoporosity in Thin-Film Dielectric Insulators,” *Advanced Materials* 1998; and “Nanoporous Polyimides,” *Advances in Polymer Science* 1999, which laid out the state of the art in the development of block copolymers and the processes used to create nanofoams; and
- stimulated further research on insulators for microelectronics.

### COMMERCIALIZATION STATUS:

IBM has continued its efforts to develop block copolymers for use as insulators. Much work, however, remains to develop a viable process for incorporating block-copolymer foams into microprocessors, and commercialization has not yet been achieved.

### OUTLOOK:

The progress achieved by the ATP project, in combination with favorable market developments, has spurred additional industry efforts to develop insulating foams, and IBM’s research results are guiding much of this effort. One initiative is a new ATP-funded joint venture project led by Dow Chemical Company and involving IBM, which aims to develop block copolymers from which to create nano-foam insulators with dielectric constants as low as 1.5. The participation of Dow, a major material supplier, may signal the creation of a base of suppliers capable of providing high-performance insulators for microelectronics. Thus, the outlook is positive for the more recent efforts that have grown out of this project, but not for this project directly.

**Composite Performance Score:** No Stars

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constants lower than two. The pores in these foams, however, were too large. It was not possible to use them in an insulating layer thin enough for an integrated circuit of the required density. Because the size of the air pockets could not be sufficiently reduced, the team chose not to pursue this approach further.

Using the block copolymer method, IBM and its colleagues generated foams with the desired thermal characteristics, as well as foams with the desired electrical insulation, but could not produce foam that had both qualities at the desired levels. The researchers did develop significantly better microelectronic insulators, but these insulators would only be usable in the future if copper

wiring were to be substituted for aluminum, so that fabrication temperatures could be kept below 400° C.

### Post-Project Developments

Toward the end of the ATP project, IBM’s other work on the substitution of copper for aluminum indicated that the move to copper alone would not be enough to speed up integrated circuits as much as desired. New insulating materials would, after all, be necessary to meet performance needs. Thus, work on block copolymers continued at IBM.

Since the end of the ATP project, IBM has made considerable progress in the development of improved block copolymer foams, but much work remains in the development of a viable process for incorporating these materials into the fabrication of microprocessors. Indeed, low dielectric constant insulators ( $k < 2.5$ ), including polymer foams, have yet to be fully developed or incorporated into integrated circuits. Separately, however, IBM’s first series of integrated circuits with copper wiring (CMOS 7S) have

been developed, lowering IC processing temperatures and increasing the possibility of lower-k polymer dielectrics being used in future circuits.

In the meantime, IBM also undertook R&D on non-porous, lower-k dielectric materials that may serve in place of silicon dioxide. For instance, IBM researchers initiated a study of “toughened organosilicates,” which have dielectric constants in the range of 2.6–3.0.

### **ATP-supported Research Stimulates Industry-Wide R&D Efforts**

Greater understanding of low-k dielectric polymer foams resulting from ATP-funded work at IBM has opened a new window for the study of porous dielectrics (including but not limited to polymer foams) as alternative insulators. At the same time, market conditions have become more favorable. The push toward network computing has also focused attention on the need to develop advanced materials for the high-end microprocessors required for network server functions.

As a result, many U.S. corporations, including Lucent Technologies, Texas Instruments, Motorola, Dow Corning, BF Goodrich, Allied Signal, Dow, Dow Chemical, and Du Pont, as well as IBM, are now reviving research into low-k dielectric materials. A number of key strategic alliances (Allied Signal–Nanopore, IBM–Siemens–Toshiba, and IBM–Apple–Motorola) have been formed to pursue R&D in advanced devices and materials. Low-k dielectric materials research has also been stimulated through industry consortia such as SEMATECH.<sup>1</sup> Consequently, U.S. corporations remain major global players in the development of new low-k dielectric materials for on-chip applications.

The results of IBM’s earlier research were substantial enough to attract the interest of a major materials supplier, Dow Chemical Company. Dow formed a joint venture involving IBM’s Almaden Research Center and Yorktown Heights facilities, applied to the ATP, and, in October 1998, was awarded ATP funding. The new project aims to identify and develop polymers to produce nanofoams with a dielectric constant as low as 1.5, and integrate them in common IC fabrication. If the Dow-IBM partnership proves successful, it could help establish a U.S. supplier base for high-performance insulating materials. ATP support in developing new ways to produce insulators for new generations of high-performance microelectronics has helped to secure an important technical option for the industry. It represents one of the efforts underway to sustain progress in integrated circuit technology and increase U.S. producers’ share of the global microelectronics market.

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<sup>1</sup> Companies and alliances cited are listed in ATP Final Report, “Low Dielectric Polymers for Microelectronic Applications,” No. 70NANB3H1365, February 12, 1997, p. 68.