MATERIALS AND PROCESSING: CORE COMPETENCIES AND STRATEGIC RESOURCES

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The mix of products manufactured by AT&T and other companies engaged in information movement and management (IM&M) markets is changing rapidly. Brought about by market demand, the changes offer increased functionality at decreasing prices. These product benefits result from intense efforts to develop new concepts and materials, as well as new ways to process the materials. All companies that derive revenue from manufactured products are subject to market demand, but only those able to marshal adequate materials and processing resources will remain competitive.

Introduction

Research and development activities in materials and processing underlie all manufacturing efforts at AT&T. These core competencies include the synthesis of new materials and the associated characterization and understanding of the underlying science in terms of phenomena evident in, and exhibited by, the new materials. Also included among the core competencies is the ability to transform (process) known or new materials into practical forms that can be turned into marketable products. (Software production is the only manufacturing activity that does not rely on materials and associated processing technologies.) In 1989, AT&T's revenues from manufactured products in which materials and processing played a central role amounted to ten billion dollars.

For AT&T's manufacturing to remain competitive in fields where it is already competitive, and to regain competitiveness where it has fallen behind, the core competencies of materials and processing need to be nurtured. They represent a strategic resource that is crucially important, not only to maintain the current product line, but also to create new product families (see Figure 1).

This issue of the *AT&T Technical Journal* identifies some of the underlying themes in the areas of materials and processing. It tries to provide a better understanding of the way future products might derive proprietary benefits from AT&T's competence in those fields.

The overview article by Laudise, McCall, and Nagel presents a cogent account of the critical role of materials and processing in a manufacturing environment.

From Art to Science

During the past hundred years, the creation and transformation of materials has undergone a revolutionary change: from an art ("Heat, beat, and hope," as one of our colleagues put it) into a science where, more often than not, it is possible to predict, estimate, and engineer the properties of a new material by knowing its fundamental structure. Yet, the continual drive to increase the capability of materials places ongoing demands on fundamental understanding.

Manufactured products such as silicon integrated circuits, photonic devices, lasers and detectors, optical fibers, printed wiring boards, and hybrid integrated circuits, serve as the foundation for most of the subsystems and systems marketed by AT&T. The company's ability to manufacture these and other products, instead of buying them from suppliers, gives it a proprietary advantage. Product feature differentiation, reduced product cycle time, and often lower costs—all of them essential in a highly competitive market— result from this advantage. However, it is rarely recognized that, just as the capabilities of subsystems and systems are limited by their components, the capabilities of components can be no better than the materials and processes used in their fabrication. Subsequent papers in this issue identify materials and process capabilities and limitations for a number of different generic technologies.

Silicon Predominates in ICs

Silicon continues to be the principal material for digital and analog integrated circuits (ICs). The main thrust in silicon IC technology is toward ever-decreasing feature dimensions and a corresponding exponential increase in the number of components (transistors) per chip (see Figure 2 in the paper by Reichmanis and Thompson, this issue). To have acceptable yields during manufacture,

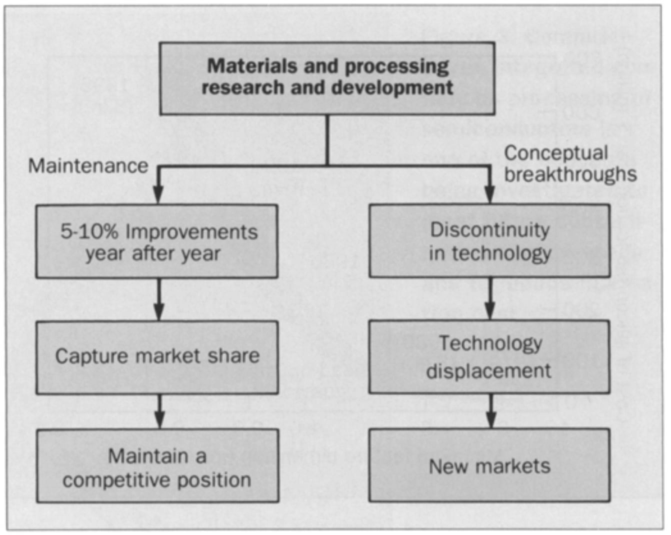

Figure 1. Competence in materials and processing permits a company continually to improve existing products. At the same time, it enables the company to leap-frog competition by introducing novel technologies.

defects, either present in the starting material or introduced while the material is being processed, must be less than one per wafer per masking step. Such a tight requirement has forced discoveries and inventions about the growth of bulk silicon material, the growth of epitaxial layers, lithographic patterning with feature-sizes below 1 micrometer (μm), feature-size control below 0.08 μm, plasma processing, etching, metal bonding, and encapsulation.

Along with increases in circuit density and complexity has come a tremendous explosion in the cost of silicon fabrication lines (see Figure 2). At this rate, required capital investments will far exceed the capabilities of all but a few large silicon fabricators by the end of this decade. Finding a way around this dilemma is coupled with the need to control particulate contamination in processing at sizes well below today's acceptable minimum feature size. Various concepts, such as controlled

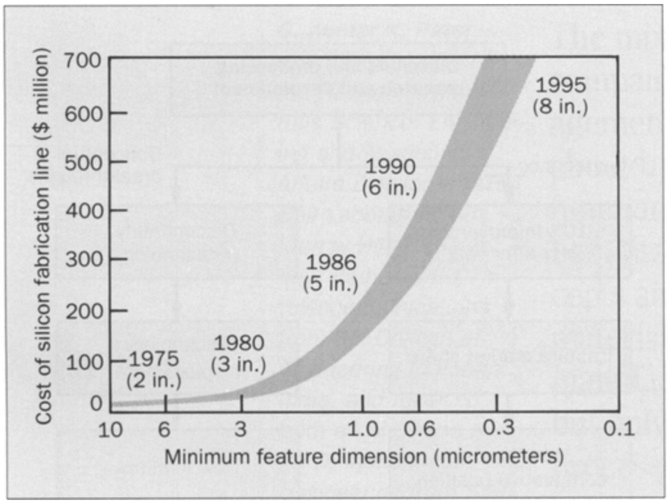

Figure 2. The projected fabrication-line cost associated with continually reduced feature size and larger silicon wafer diameters could exceed the capabilities of all but a few well-capitalized companies.

environment integrated semiconductor processing (see Figure 3), could provide the needed new directions.

The Drive to Miniaturize Further

Silicon technology requires high-resolution lithographic resists for masks as well as for exposure on silicon. For the former, the need for electron-beam (e-beam) resists is well established. For the latter, resists face the resolution limitation forced by the wavelength of light used to expose the wafer. Diffraction effects limit available resolution to dimensions comparable to the wavelength of the radiation. With silicon technology being driven toward the use of shorter and shorter wavelengths, current development of deep ultraviolet (UV) resists should be adequate for 0.25 μm design rule technology. Smaller features, however, will require X-ray resists with characteristics appropriate for high-yield manufacturing of ICs with sub-0.25 μm design criteria.

The initial use of X-rays may involve contact printing (1:1), reminiscent of the early days of optical lithography in IC fabrication. The long-term goal is to migrate to projection printing with X-rays. This concept is revolutionary in the X-ray region, where the "optical" elements required to focus the radiation would necessitate the development of mirrors capable of high reflectivity at these short wavelengths. This by itself is a formidable materials and processing challenge. Yet another revolutionary direction is the use of projection e-beam lithography to fabricate ICs with minimum feature widths below 0.25 μm.

Two papers—Benson, Kimerling and Panousis' about silicon processing, and Reichmanis and Thompson's about lithographic materials— describe the accomplishments and future directions of silicon IC materials and processing.

Interconnection Technologies

With individual integrated circuits becoming ever more complex and capable, the need has developed for novel interconnection technologies between them to enable high-speed transfer of information at low heat dissipation. Going beyond traditional printed wiring boards (PWBs) and hybrid integrated circuits (HICs), a new interconnection technique called the multichip module (MCM) is becoming important. At present, it is being used only in certain critical applications. The technologies used for this technique offer flexibility far beyond those available to current PWBs. They rely on well-proven many-micrometer linewidth photolithography, with either silicon or ceramics as the substrate. The ability to mount unencapsulated ICs on MCMs allows a significant cost reduction.

Just as PWBs, and now MCMs, have become vehicles for the use of ICs in systems, the need for a similar vehicle to interconnect optical components will become increasingly important. Unlike silicon ICs that are based on a single material, optical devices are often made of incompatible materials. Hybrid integration of optical components may be the first cost-effective direction to explore. Silicon optical bench technology has enormous

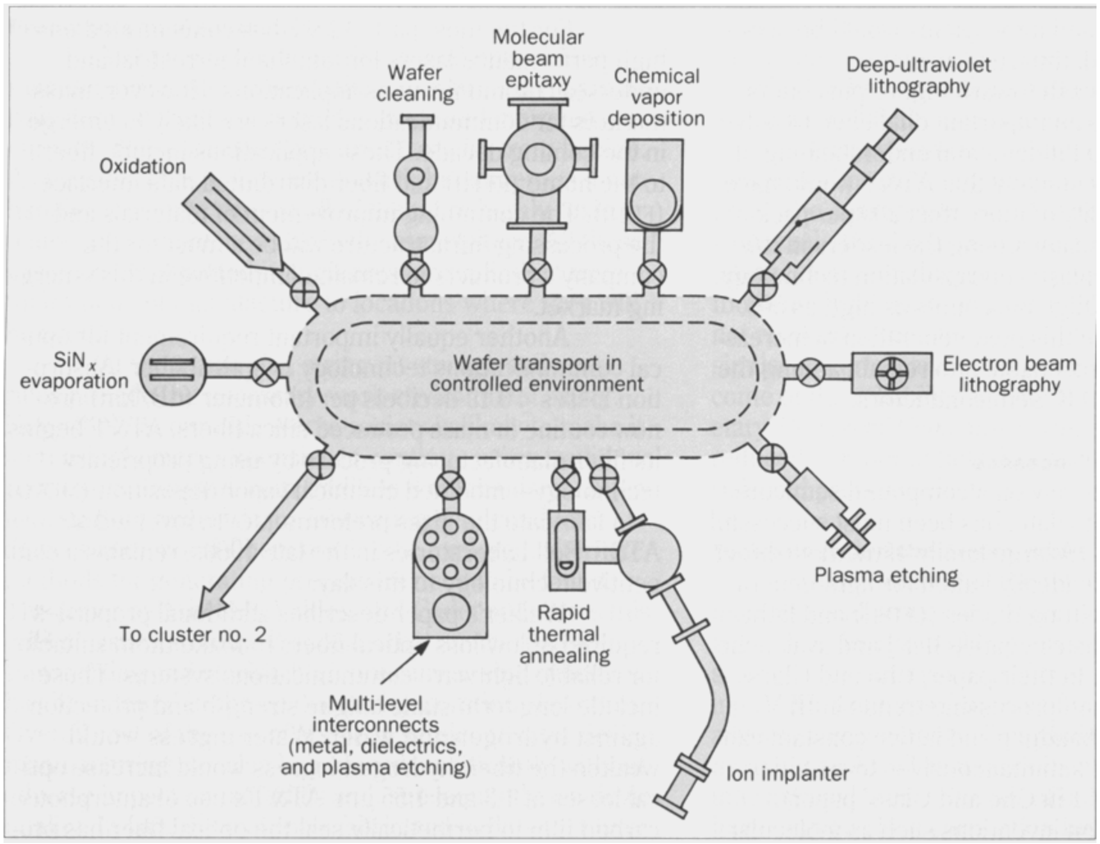

Figure 3. Computer-driven integrated continuous processing of semiconductors is one of the concepts being investigated to meet future contamination control needs and to reduce fabrication cost.

potential for providing such a mechanism. Using molded plastics to fabricate optical interconnect components is likely to be the low-cost direction for many applications. The paper by Blonder, Gottscho, and Tai describes the role of new materials and processing technologies in future electronic and optical interconnect technologies.

Integrated Circuit Packaging

In spite of the future directions in electronics interconnection technology that demand use of unpackaged IC chips, encapsulation of ICs in sturdy and reliable packages will continue to be important. Plastics and ceramics are the primary materials used for packaging. Ceramics generally represent the top range of packaging technology in terms of their capabilities and cost. Plastic packaging, on the other hand, is beginning to acquire some of the important reliability features of ceramic packages at a fraction of their cost. For many years, plastic packaging had been an empirical art. Lando and Manzione, in their article, describe how the disciplines of chemistry, mechanics, and rheology have provided scientific underpinnings to this technology, making it highly reliable at high yields. Because packaging is the final "added value" step in the IC manufacturing process, compromised reliability and lower yields would be economically prohibitive and, thus, unacceptable.

The continuing push toward higher pin-counts for IC packages provides an important challenge to polymer scientists. Without a fundamental understanding of polymeric materials, it is unlikely that AT&T would have today's pin-count capability of more than 200 per package, positioning the company among the leaders in this high input-output (I/O) plastic encapsulation technology. The future points to package pin-counts as high as 500. AT&T's ability to provide this next generation of increasingly complex devices will enable it to remain among the few top manufacturers of IC semiconductors.

Photonic Materials and Processes

Photonic devices rely on a compound semiconductor technology that, to date, has been most successful using the III-V materials. A large family of them — direct bandgap materials — are ideally suited for light generation (lasers and light emitting diodes [LEDs]) and light detectors (positive-intrinsic-negative [PIN] and avalanche photodetectors [APDs]). In their paper, Cho and Glass describe the materials and processing trends in III-V semiconductors whose bandgap and lattice constant can be tailored—though not simultaneously— to specific applications (see Figure 1 in Cho and Glass' paper). Novel thin-film fabrication inventions such as molecular beam epitaxy (MBE) by Cho and Arthur in the late 1960s revolutionized the field and have created a new concept: bandgap engineering. With MBE, we can create semiconductors with properties that do not exist in naturally occurring materials. This, in turn, permits us to make devices with properties heretofore not possible. Because MBE can grow thin films with unprecedented thickness control down to the single molecular level, uniformity across the entire wafer, and reproducibility from wafer to wafer, it has recently become the workhorse for the mass production of lasers such as those used in compact disk (CD) players.

For the most part, AT&T has concentrated on high performance lasers for long-haul terrestrial and undersea communications applications. However, mass markets for communications lasers are likely to emerge in the coming decade. These applications include fiber to the home (FTTH) and fiber distributed data interface (FDDI). The continuing improvement of materials and the processing infrastructure will be a must for the company's products to remain competitive in this emerging market.

Another equally important requirement for optical communications technology is optical fiber. Absorption losses $\leq$ 0.19 decibels per kilometer (dB/km) are now routine in mass-produced silica fibers. AT&T begins its fiber manufacturing process by using proprietary technology—modified chemical vapor deposition (MCVD) —to fabricate the glass preforms. MCVD, invented at AT&T Bell Laboratories in the late 1960s, remains a competitive technology to this day.

Walker's paper describes additional properties required of low-loss optical fibers to make them suitable for reliable lightwave communications systems. These include long-term static fatigue strength and protection against hydrogen and water. Water ingress would weaken the fiber; hydrogen ingress would increase optical losses at 1.3 and 1.55 μm. AT&T's use of amorphous carbon film to hermetically seal the optical fiber has provided an important differentiating characteristic for our fibers in the marketplace.

Although the desirable optical and mechanical properties of optical fibers are derived from silica, they must be protected from mechanical abuse with appropriate polymer coatings. Walker's paper emphasizes the importance of these coatings for providing long-term reliability and minimizing microbend losses while the fibers are being cabled. Future trends focus on cost reduction and the development of high-temperature-resistant coatings that would be required for the large-scale deployment of optical fibers in FTTH applications.

Precursors to Manufacturing

Most semiconductor device and optical fiber manufacturing relies on volatile, ultrapure starting materials derived from a variety of organic and inorganic precursors. These gaseous precursors are far from benign. As a matter of fact, they are downright dangerous if not handled properly. Almost all of them are highly toxic; many ignite spontaneously in the atmosphere. All these gases are transported in high pressure cylinders from their points of manufacture to locations where they will be used.

At the usage site, stringent storage and usage rules provide the necessary work-environment safety. Nevertheless, our risk-averse society is likely to make it increasingly more expensive to continue using traditional precursors obtained from traditional mechanisms. Alternate starting materials for fabricating semiconductor devices and optical fibers need to be explored; alternate methods for generating precursors need to be found. The paper by Mitchell, Valdes, and Cadet addresses this critical issue carefully. It appears that an alternative to transporting and storing high pressure arsine cylinders has been found in the on-demand generation algorithm. Overall cost of the use of arsine in semiconductor device manufacturing can also be reduced significantly without adverse impact on materials and, subsequently, on device quality. In fact, the materials fabricated to date that have used on-demand arsine technology are better. This idea should be applicable to other precursors, too. It should be possible for the semiconductor manufacturing industry in the United States to prosper, at the same time responding to legitimate societal concerns regarding the safe use of toxic precursors.

Reliability Based on Correct Procedures

Tremendous progress has been made in the fundamental understanding of materials and processes. Because these two core competencies are extremely complex by their very nature, implementation of materials science and processing in the manufacturing environment depends on correct procedures. That is why, despite the best intentions and the most profound understanding, reliability needs to be addressed continually.

Detailed understanding of field failures provides design and process engineers with important guidance about the appropriate use of materials. In their paper, Comizzoli, Landwehr and Sinclair describe recent advances in providing prescriptive directions from failure mode analysis (FMA) to assure that future designs will not encounter the types of problems experienced with similar materials and processing in the past. A useful outcome of the reliability activity is the creation of a proprietary *Designers' Companion*, which should lead to a reduced number of field failures associated with materials and process selections.

Technology and the Environment

Consideration of the interrelationship between materials and processing and environmental issues has become an increasingly important activity in materials science. For example, significant effort is spent in designing AT&T products that must function unimpaired in adverse environments. This ability takes on special meaning as AT&T increases its marketing efforts in the international arena. Studies of indoor air contamination have found a close correlation between outdoor pollution and indoor contaminants, regardless of the quality of air filtration systems. The paper by Graedel and Guth shows that outdoor pollution levels in many foreign cities can be considerably higher than those in the United States. Therefore, selecting materials and processes for products that could be used anywhere in the world requires special care.

An associated issue is the environmental impact of products after they have been discarded by consumers. As we move toward the next century, all manufacturers will be affected by increased social pressure to design products that place minimal stress on the environment. The cradle-to-grave design of products emphasizes:

- Materials that can be reclaimed easily after they have served their useful purpose, or
- Materials that disintegrate without polluting after they are no longer needed, or
- In those rare circumstances when discarded materials do not disintegrate benignly, the materials are biostable, i.e., they remain stable for a long time without leaching toxic substances.

The most cogent example of AT&T's commitment to environmentally benign processing is the decision to eliminate all chlorofluorocarbon (CFC) emissions from its manufacturing operations by 1994, substantially ahead of the goals set by the 1987 *Montreal Protocol on Substances that Deplete the Ozone Layer.* Ratified by 59 nations to date, the protocol calls for a 50 percent reduction from 1986 rates of CFC consumption by July 1, 1998. The search for and use of alternate materials and processing is likely to pay off handsomely, not only in the public's acceptance of manufacturing industries, but also in reduced overall costs.

Conclusion

While this collection of articles provides specific examples of current advances in materials and processing at AT&T, systems already deployed have long benefited from the company's past materials expertise. Two such nationally recognized examples are the low-loss optical fibers and TAT-8, the first transatlantic optical fiber telecommunications cable. These AT&T developments received the American Society of Materials' prestigious Engineering Materials Achievement Award in 1983 and 1990, respectively. Success in the marketplace for AT&T's manufactured products, as well as similar recognition of excellence in the future, will depend crucially on our ability to preserve and build on the company's core competencies in materials and processing by maintaining the necessary breadth and depth in these disciplines.

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