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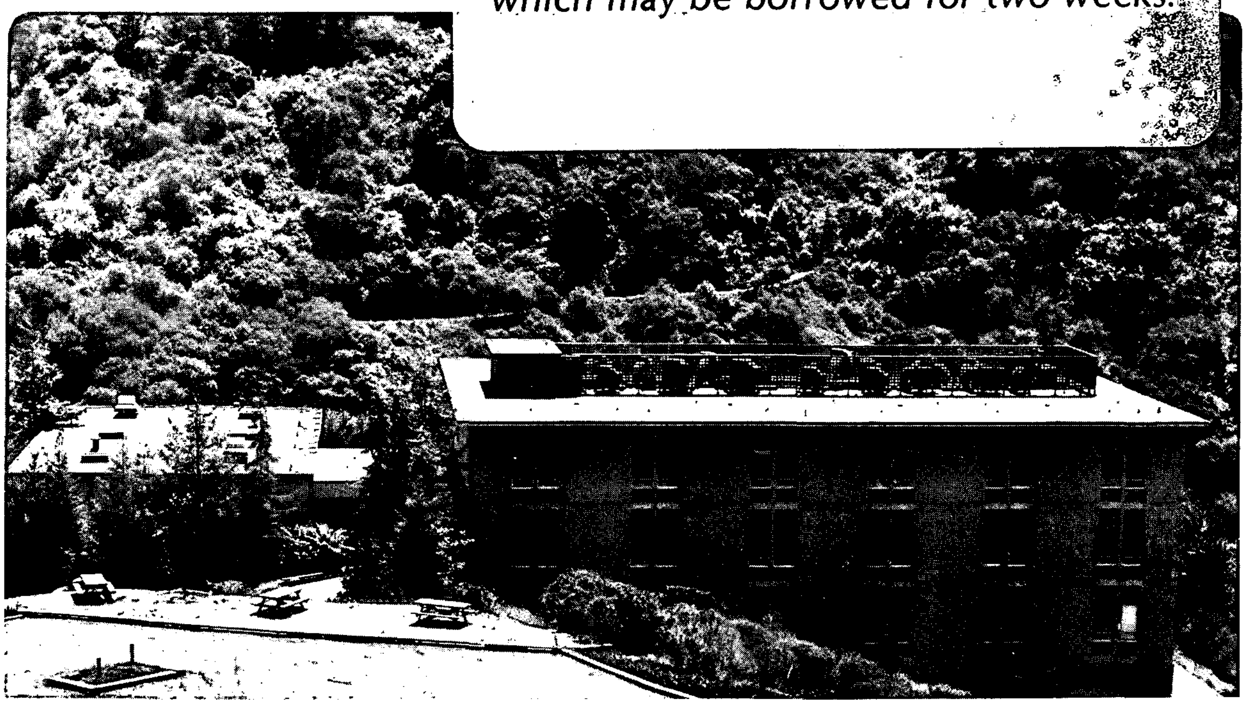

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ADVANCED MATERIALS SYSTEMS AS COMMERCIAL OPPORTUNITIES

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I'll start with a disclaimer. This lecture will not tell you how to become rich and famous by commercializing advanced materials. What I will try to do is provide some perspective about trends in this field as they relate to industrial opportunities.

One of the first points to be appreciated about materials is that while the number of interesting substances in the world is vast, the number of commercial materials is relatively small. Sometimes newly discovered substances become developed into materials, but this is rare because a large number of constraints must be satisfied before it can occur. The constraint that most often blocks commercialization is manufacturing cost, but there are many others including safety features, and the degree to which the profile of the physical properties of the new material matches the profiles required by specific applications. These profiles were quite simple many years ago, but they continually become more complex.

Historically, the property profiles of materials were determined by the primary producers (1). This started at the mines and their associated smelters; at the clay-pits and their potteries; at the forests and their lumber-mills; and so on. Whatever they produced is what the user had to work with. As methods for fabrication advanced the variety of shapes that could be manufactured increased, and the property profiles of products became increasingly determined by the methods used by fabricators to make semi-finished mill products. Later, the emphasis shifted to finished products that were differentiated by the material they were constructed from. That is, there were discrete metal components, ceramic components, plastic components, and so on.

The culmination of this period is represented by the advent of components made of polymeric structural materials. Polymers can be formed into complex shapes inexpensively, so the market for polymeric objects developed rapidly; even though raw polymers are relatively expensive and do not possess outstanding properties. This is quite different from the earlier case of the growth of the steel industry. The success of steel was based on inexpensive raw materials combined with outstanding engineering properties.

In the most recent several decades integration has been occurring (2). This has been shifting commercial opportunities to industries that use materials, and from those that produce them. It has also been increasing the demand for extensive profiles of properties, as contrasted with the relatively narrow profiles that were needed when materials formed clearly differentiated components of machines.

One consequence of the trend toward integration is that the functions of materials have become much more important than their places of origin; or the costs of their raw materials. In looking to the future, this trend will continue because it is here that materials technology will make the greatest advances, and it is here that the greatest fractional utility is added. For example, a pound of aluminum as ingot is worth roughly a dollar a pound. After conversion to a semi-finished structural shape it is worth perhaps five dollars per pound; but after conversion to a microconductor on a silicon chip it is worth about 500 million dollars per pound! Most of the value comes, of course, from the processing that integrates the aluminum into a system.

Another way to make this same point is to consider the elasticity of demand for materials. For commodity materials, price elasticity is high so large changes in consumption cause only small changes in price (3). But for materials that have been integrated into systems, price elasticity is relatively low, so small changes in consumption lead to substantial changes in price. Both cases only apply to "normal" that is, competitive markets. Since low elasticity helps to maintain gross margins, business operations in this arena will tend to prosper more than those dealing with commodities.

Still another indicator is relative price changes (4). By this I mean price changes relative to an average change of zero for the economy as a whole. Some relative changes are increases, and some are decreases, while the sum of all relative changes is zero. For many years (at least 25), the relative real prices of commodity materials have been decreasing. At the same time, the relative prices of materials in sophisticated integrated systems have been increasing. Thus materials in their commodity forms have been getting relatively less important commercially, while the opposite is true for their integrated forms.

What I have said so far has been a preamble to saying that commercial opportunities in the materials area lie principally in materials systems, and much less in components made from differentiated individual materials. I'll try to clarify the difference through some examples.

The phrase "material system" implies an operational function. Therefore, in considering where commercial opportunity lies, it is important to ask, "what functional areas are likely to grow most in the forseeable future ?"

A short list of technologies that are likely to show major growth in the is as follows:

1. Photonics
2. Robotics
3. Prosthetics

4. Astronautics
5. Nanoelectronics

I shall discuss some of the materials systems associated with these technologies with selected examples of the new materials that are involved.

1. Photonics (optics)

Electronics has been based on the large ratio of charge to mass for electrons which allows them to be manipulated efficiently. The particles of photonics, namely photons, have neither charge nor mass. Their lack of mass allows them to be manipulated at very high frequencies which is useful in communication systems. Their lack of charge allows them to be concentrated into very small volumes which is useful for fabricating materials.

There are two principal branches of photonics. One is optical communications (including data processing) in which advanced materials are needed to: generate, transmit, detect, analyze, focus, and display light. The other principal branch is materials processing in which advanced materials are needed to make powerful lasers together with systems for manipulating and controlling the beams of light they emit.

For example, outstanding advances have been made in the purification of materials so they can transmit light over long distances. In a few years this capability was improved by a factor of ten thousand compared with the best of previous glasses (Figure 1). The performance of pure glasses in terms of transparency is truly spectacular. (Figure 2).

There is not enough space here to describe the many other new materials that are involved with photonics, but I do want to describe a relatively simple device that illustrates how various functional materials can be integrated to perform a higher level function.

Figure 3 shows a battery-operated laser that emits a highly collimated beam of green light. It does this by means of the following chain of functional events: a battery provides electric current to drive a small array of GaAs lasers which emit light that excites an yttrium aluminum garnet rod that contains fluorescent neodynium ions. This rod lases emitting a beam of infra-red light. The infra-red beam then passes through a crystal of lithium niobate which converts it into a beam of green light. Thus the device consists of an integrated series of materials each of which performs a specific function.

2. Robotics

Although the inputs to robots are critically important, so are the outputs. For actuating the outputs nothing as versatile as biological muscle has been found thus far, but one acctuator design that is close is of interest (Figure 4). For its "muscles" it uses a "shape-memory" alloy. This is a metal that remembers its shape prior to a phase-transformation that is induced by temperature. In the case of this robot hand, the material there are actuating wires that are short above a certain temperature and long below the same temperature. These actuating wires are heated by electric currents to make the fingers bend and the wrist rotate. The result is a robotic system that is much more compact, and lighter, than those actuated by hydraulic cylinders or stepping motors.

3. Prosthetics

There is a powerful demand for improved prosthetic materials systems. It is generated by accidents, disease, violence, and by aging of the population. Perhaps the most commonly known system in this class is contact lenses. Dental prostheses are also well known.

Most non-biological materials irritate living tissues. Some mildly, some severely enough to induce carcinomas. One of the most benign and therefore potentially most useful is pure carbon. The biologically benign aspect of carbon has been known for millenia by people with tatoos. A hard form of it, known as "glassy-carbon" has been used for many years in artificial heart valve systems. But a disadvantage of glassy carbon is that it is quite brittle; also, it is extremely stiff which often makes it mechanically incompatible with biological tissues; including bone.

In recent years, considerable work has been done on the development of composites consisting of carbon fibers embedded in carbon matrices. These are called carbon-carbon composites. They are mainly intended for high temperature applications such as engines and rocket nose-cones, but they have considerable potential for prosthetics. For certain levels of porosity they can be both compliant and tough (non-brittle). These properties combined with their high level of bio-compatibility make these composites are highly desirable for prostheses.

4. Astronautics

This topic includes both the exploration and the exploitation of space. Both will require new power supplies; probably of the nuclear fusion variety. Implosions driven by ion-beams appear to have the best chance for success in realizing the necessary controlled fusion reactions. For building effective ion-acceleration systems, materials that can be quickly and easily magnetized are needed. Among many others, of course.

The speed with which a material can be magnetized depends on the mobility of the magnetic domain-walls within it. As these move they change the magnetization. A dramatic improvement in this property occurred in recent years with the advent of metallic glasses. These are made by cooling selected alloys very rapidly from the liquid state. As a result there is too little time for them to crystallize, so they retain the glassy structure of the liquid.

Because of the ease with which metallic glasses can be magnetized and demagnetized they have made it possible to build very efficient transformers that are being used in the distribution system for electric power (Figure 5). Such transformers have the potential to save large amounts of energy each year (up to 35 billion KWH per year).

In addition, these new materials have made it possible to design the huge magnetic switches that are one of the keys to the ion-accelerators needed for controlled thermonuclear reactors which in turn are needed for advances in astronautics. Switches that weigh a few tons and can switch terawatt-sized pulses of electric power have been built from metallic glasses. The pulses consist of as much as one million amperes at 2.5 million volts.

5. Nanoelectronics

We are all familiar with the profound effects that micro- electronic devices have had on our lives in recent decades. These devices have structural elements in them as small as one micrometer; that is, one millionth of a meter.

A new generation of even smaller devices is now being developed. They will be as small as one nanometer, or one billionth of a meter, which is the size of many individual molecules and much smaller than many biological molecules.

I shall describe just one example of electronics at the nanometer level. This is the use of a nano-engineered structure to increase the mobility of electrons in a semiconductor system. Figure 6 shows a structure that is layered at the nanometer level (5). Figure 7 is a schematic diagram of such a layered structure. This schematic diagram indicates that electrons, put into the material by the Al donors in the layers of GaAlAs, can lower their energies by moving into the pure GaAs layers.

Once they are in these pure layers, the electrons can move around without being scattered by Al-ions. Therefore their mobilities are much higher than in monolithic GaAlAs where they are subject to Al-ion scattering. The increase can be as much as a factor of one thousand. Figure 8 indicates the increases in electron mobility that have been achieved over several years through the use of these nanscopic artificial structures.

Machining can also be done on a very fine scale (6). This can be done through etching techniques that use ion-beams or photon beams, but it can also be done mechanically as illustrated in Figure 9. Here a tiny machining chip that looks like a spring is shown. The diameter of the spiral is about 0.5 micron and the chip thickness is about 20 nm., or 0.02 micron.

In closing let me emphasize once more that the trend in advanced materials is toward integration. Materials and their functions are combined to form materials systems. These systems are fabricated by being built up "organically". This is occurring both at large scales where composites are integrated into airframe structures, and at small scales where semiconductors, metals, and insulators are integrated into nanoelectronic systems.

Acknowledgment

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FIGURES

1. Dramatic reduction in the absorption of light in glass in recent history.

2. Comparison of the transmission of light through glasses.

3. Battery-operated laser system in which light that is generated by semiconductor diodes is used to pump a YAG:Nd laser whose red output is converted to green light by a lithium niobate crystal (courtesy Amoco Corporation).

4. Robotic hand actuated by shape-memory wires (courtesy Hitachi, Ltd.).

5. Improvement in the efficiencies of transformers with metallic glass cores over those with conventional silicon steel cores.

6. Portion of one hundred layer specimen in which 13 nm. oayers of InP alternate with 10 nm. layers of GaInAs alloy. Magnification is 600,000X. From reference (5).

7. Schematic drawing of layered material with accompanying sketch of energy level diagram for electrons in this structure.

8. Maximum electron mobilities in layered structures compared with uniform (non-layered) structure.

9. Photograph of nanoscopic machining chip shaved from aluminum fluoride. Magnification is 16,000X. Reference (6).

Figure 1

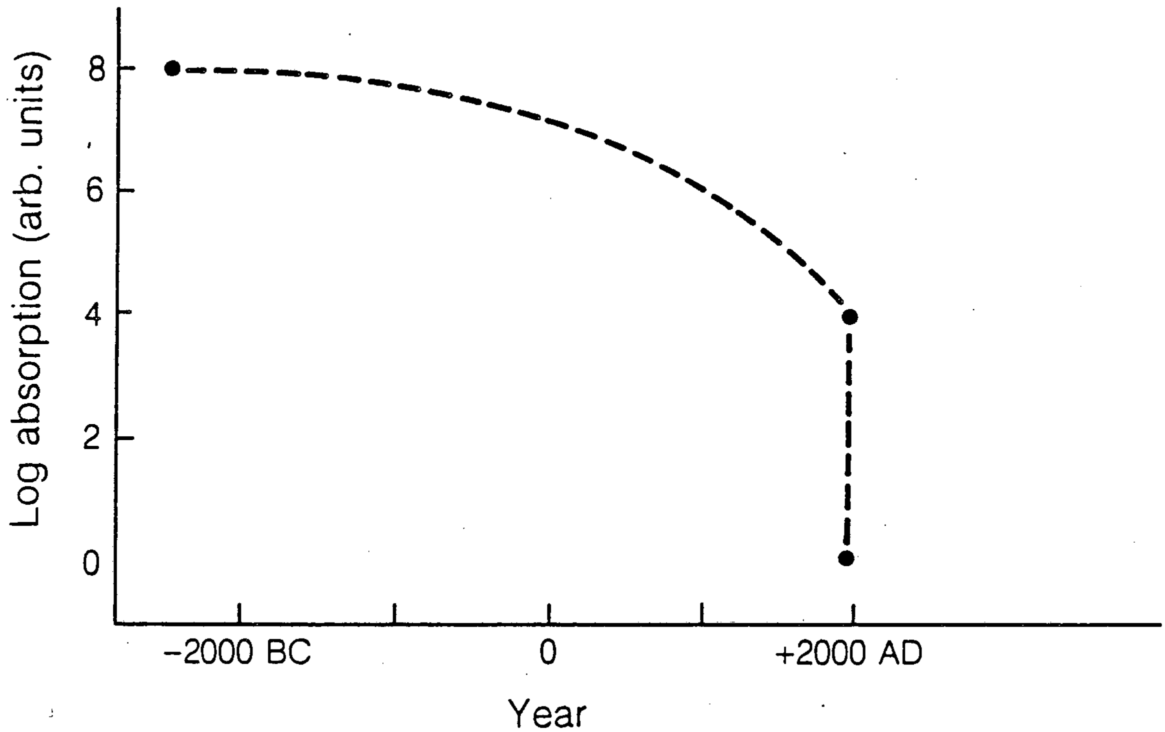

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Figure 2

Material	Transmission Distance (inches)
Window glass	0.2
Glass fiber	6×10^6

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Figure 3

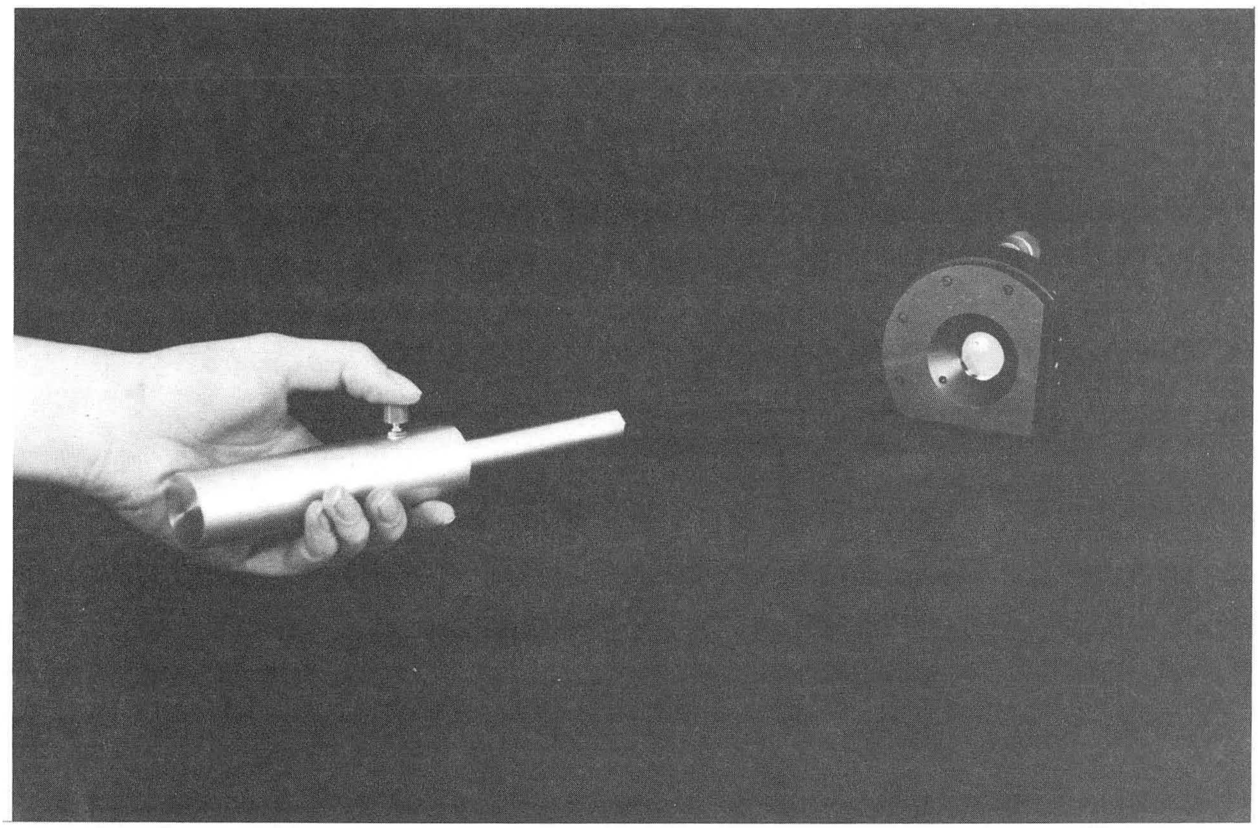

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Figure 4

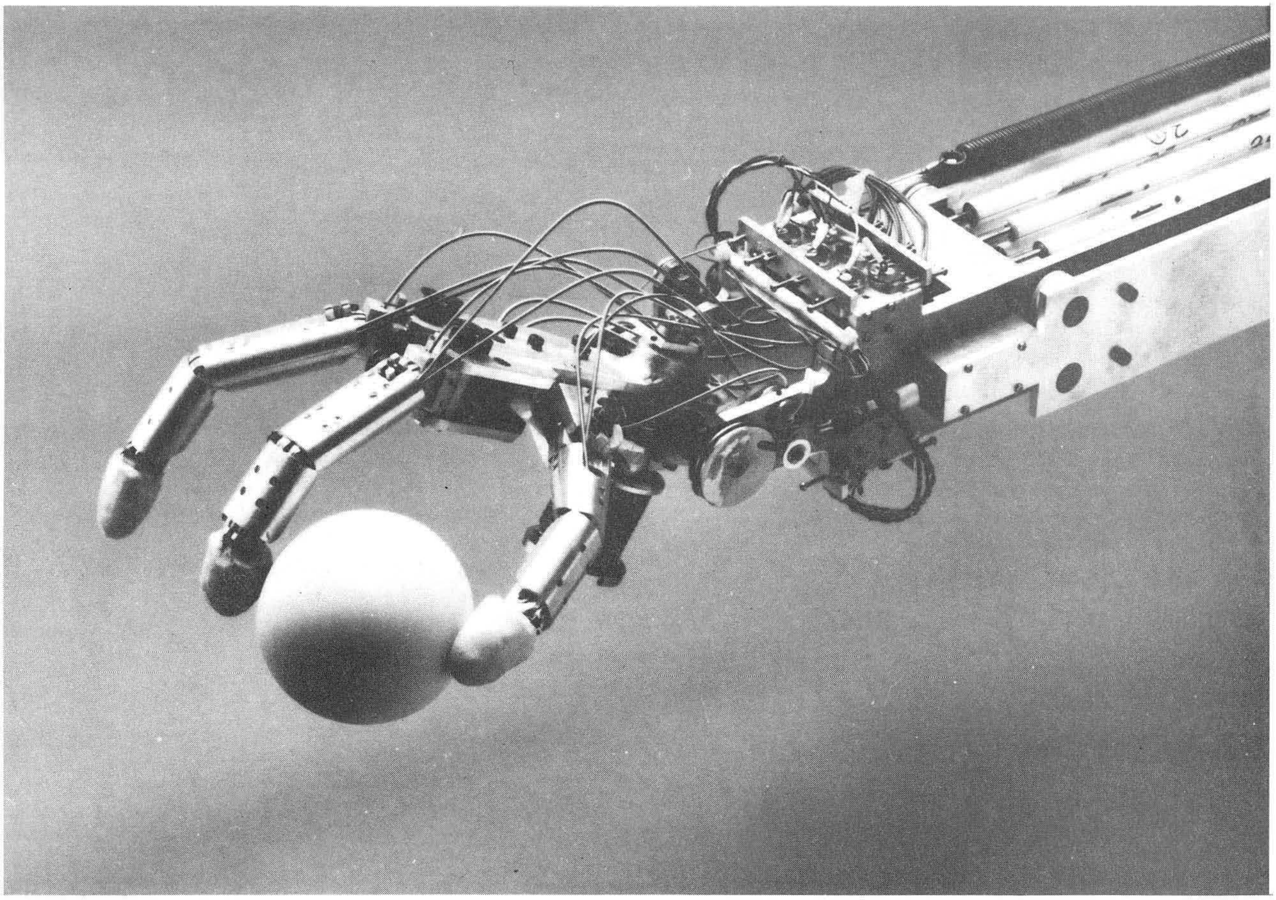

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Figure 5

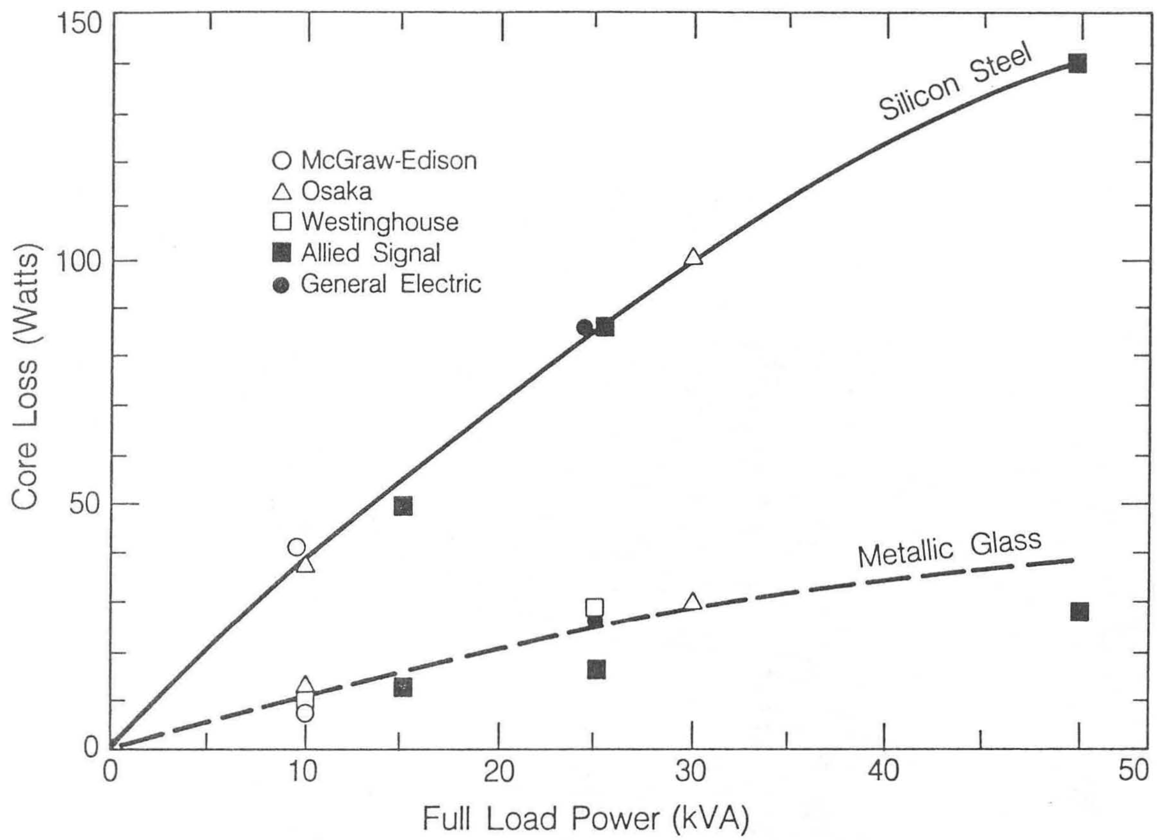

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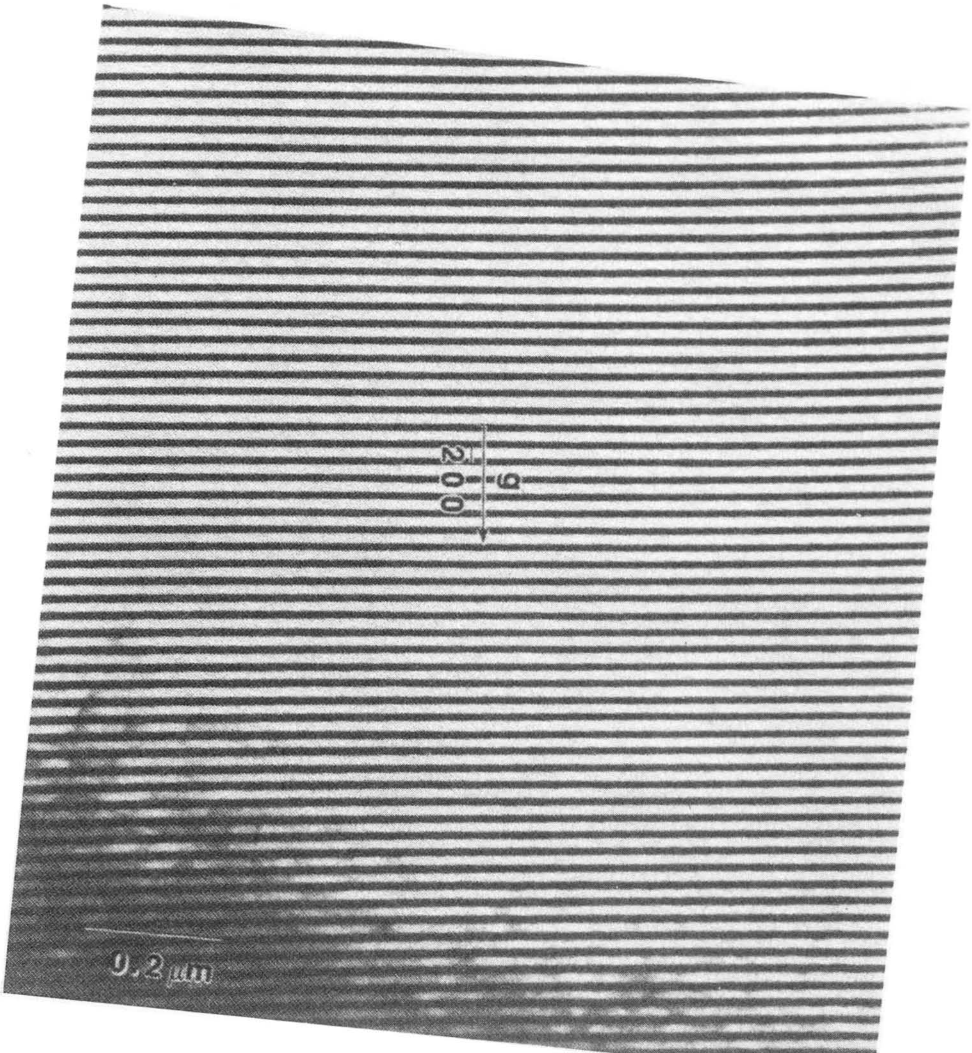
Figure 6



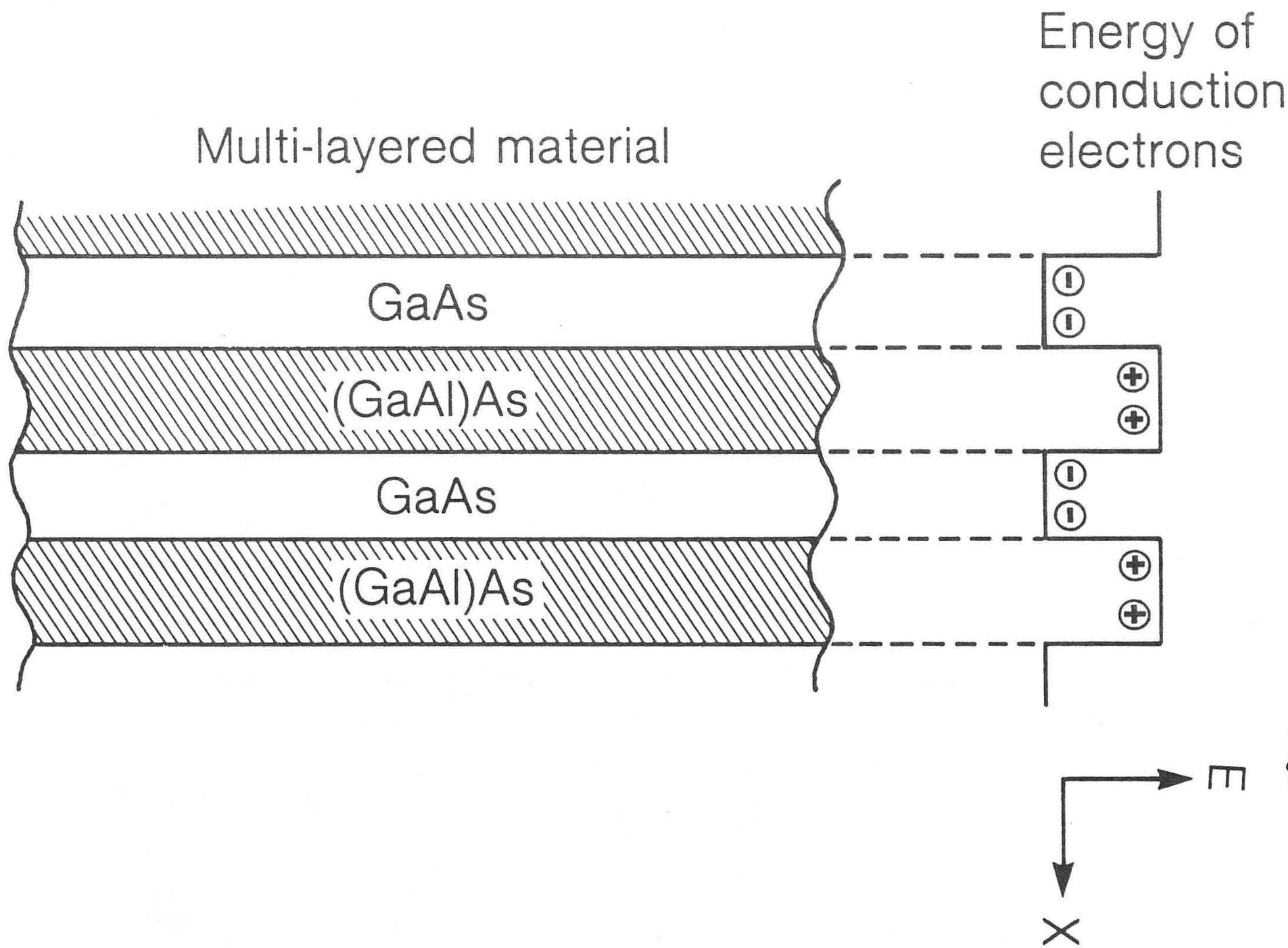


Figure 7

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Figure 8

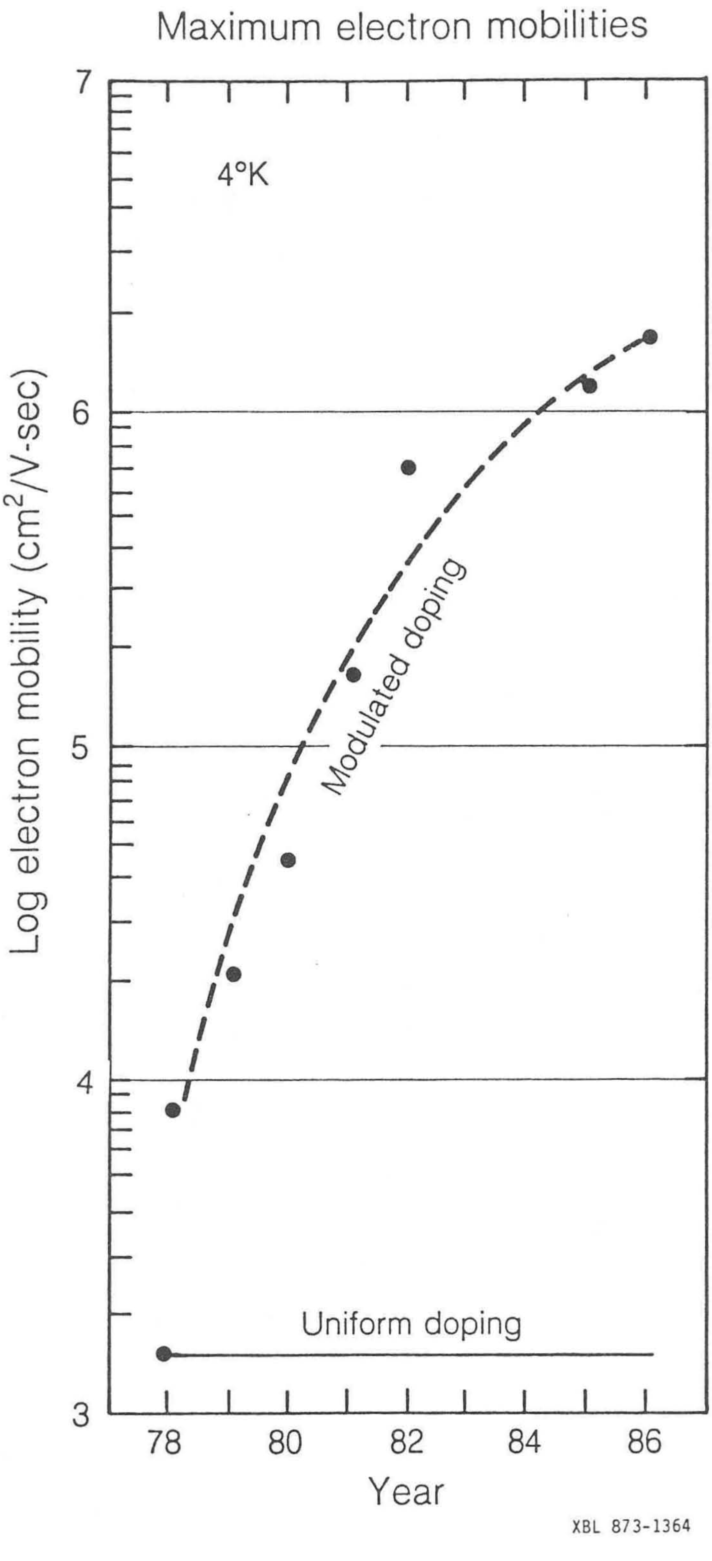

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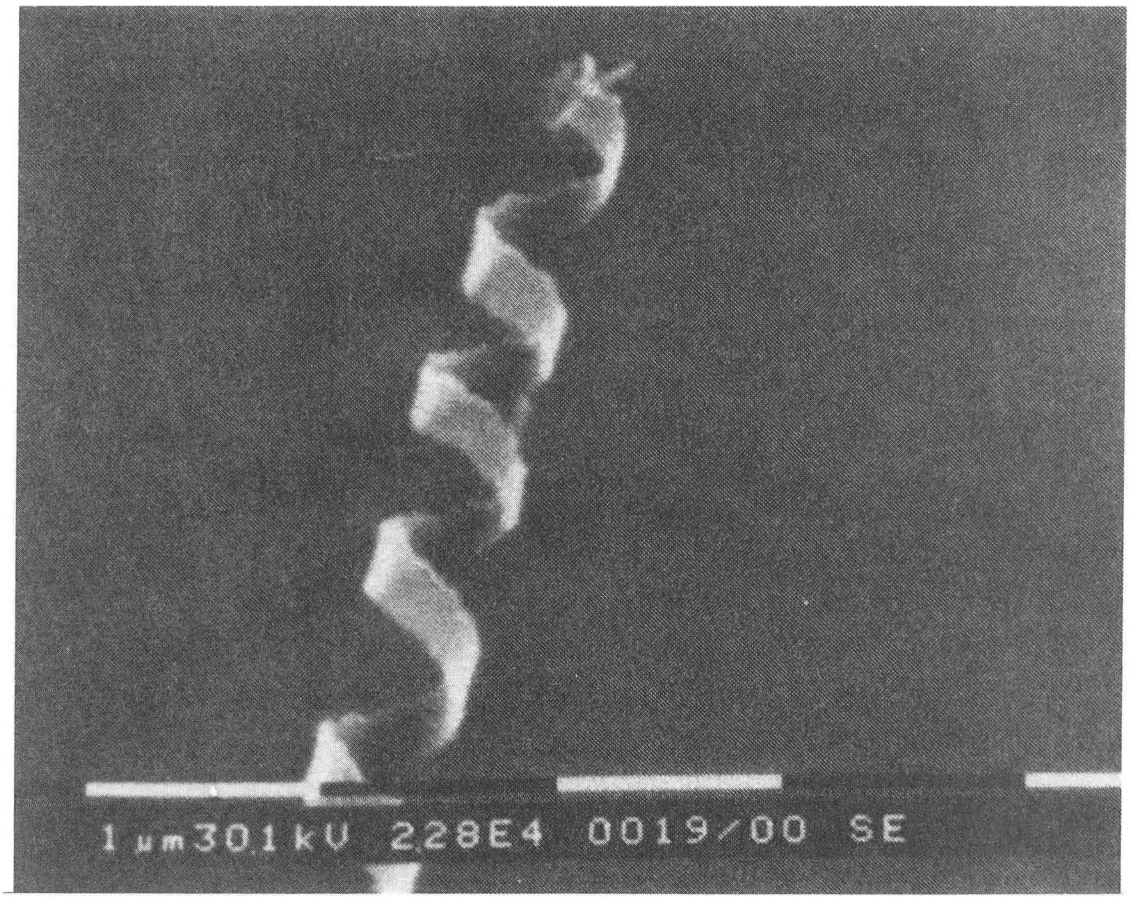
Figure 9



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