Ion Implantation

At a time when many scientists are concerned about securing funds to support their research, those working on ion implantation may be in a fortunate position. Not only is their research of interest in purely scientific terms, but it is beginning to show considerable promise for industrial applications. In the ion implantation technique, beams of ions are accelerated to energies in the range of about 10 kev to 1 Mev and are directed into solid targets in order to modify their properties. One obvious application is in the fabrication of transistors, and earlier this year Hughes Aircraft Corporation marketed the first transistors produced with ion implantation.

The transistors' important characteristics arise from low concentrations of specific impurity atoms in the crystal lattices of semiconducting materials such as silicon and germanium. The impurity atoms, or dopants, are usually from those columns of the chemical periodic table which flank the column for silicon and germanium. Semiconductors are usually doped by a diffusion method in high-temperature furnaces. However, ion implantation doping can be better controlled, and it may be of use in fabricating a wider range of semiconductor devices. As well as altering the electrical properties of semiconductors, ion implantation has definite industrial potential for improving the current-carrying capabilities of type II superconductors and for modifying the optical properties of phosphors and electroluminescent materials. It is also possible that implanted ions can change other properties of solids such as magnetism, mechanical hardness, and optical transmission.

International Interest

These practical attributes of ion-beam technology have been a main topic of discussion at recent scientific conferences and in scientific advisory committees both in the United States and in Great Britain. These groups also examined the important problems now open to investigation by beams of accelerated ions.

The original purpose of an American panel, convened by William Fowler, California Institute of Technology, under the auspices of the National Academy of Sciences, was to investigate and publicize new uses of low energy particle accelerators (less than 5 Mev). Since most nuclear physics research now deals with higher energies, Fowler and his colleagues were hoping to breathe new life into these old accelerators. Ion implantation was one of their major recommendations as a field worthy of study. Their other recommendations for the low energy accelerators include studies of atomic structure by the beam foil technique and studies of nuclear reactions revelant to astronomy.

The Ion Implantation Panel of Britain's Science Research Council issued a report in February which called for further development. The panel, whose chairman was G. Dearneley, of the Atomic Energy Research Establishment (AERE) at Harwell, noted the rapid expansion of ion implantation research throughout the world. The major centers of activity in the United States are M.I.T., Stanford, Bell Telephone Laboratories, Hughes Aircraft, and Ion Physics Corporation. In Britain, the universities of Sussex, Surrey, and Salford, the government laboratories at Harwell and at the Services Electronics and Research Laboratory (SERL), Baldock, plus several firms devote sizable efforts to research and development. Two firms in Japan, Hitachi and Toshiba, have received large government grants to develop ion implanted semiconductor devices. The other major centers include Chalk River Laboratory, Canada; the Centre d'Etude Nucléaire, Grenoble, France; and Aarhus University, Denmark. There are also active groups at Caltech, Sandia Corporation, IBM, and North American Rockwell.

Scientists from most of these institutions congregated in May for the International Conference on Ion Implantation held at North American Rockwell's Science Center in Thousand Oaks, California. There was also a large and enthusiastic European conference on ion implantation in England in September at the University of Reading. The United States and Canada were well represented at this European meeting which was sponsored by the Institute of Physics and the Physical Society with the Institute of Electrical Engineers.

At the Reading conference, J. Beale of Mullard Research Laboratory, Surrey, commented on the present state of ion implantation technology for semiconductor doping. He feels that now there is no barrier preventing its exploitation for commercial use. It is impressive that an expert in this field is willing to state publicly that neither technical nor economic factors are inhibiting the practical application of ion implantation. Representatives from Lintott Engineering Ltd., Horsham, even provided a practical demonstration of Beale's pronouncement. At the conference, they set up an ion implantation machine which produced milliampere beams of dopant ions. But the most amazing aspect is that they assembled the apparatus in only a few hours.

The recent upsurge of interest in ion implantation results from, among other things, (i) the demands of semiconductor technology for control of impurities at depth and concentrations accessible to ions accelerated to modest energies; (ii) the gradual increase in understanding of radiation damage in semiconductor materials; and (iii) the continued development of ion sources, charged-particle beam handling, and accelerator design—all of which accompanied the interdisciplinary interest in the interaction of energetic ions with single-crystal solids. William Shockley, who shared the 1956 Nobel prize as coinventor of the transistor, foresaw the value of ion implantation for the doping of semiconductors when in 1954 he filed a far-reaching patent. Although it was not known at the time, the early attempts at doping crystals were spoiled by the radiation damage produced by the fast ions impinging on the crystal lattice.

Radiation Damage

The first practical device was made in 1962 by T. Alväger and N. J. Hansen, Argonne National Laboratory, who fabricated a nuclear particle detector by implanting 10-kev phosphorus ions into silicon. Although it did not work very well, the two physicists managed to overcome the problem of radiation damage by annealing the detector at 600°C after the implantation.

When fast ions penetrate into the crystal lattice, they disrupt the orderly array of the atoms in the crystals. When the implanted device is used in an electrical circuit, these defects trap the conduction electrons and holes and generally degrade desirable characteristics. The high-temperature annealing heals many of these defects. The reordering of the lattice also assists, in some cases, in locating the implanted impurity ions on substitutional positions in the lattice where they provide the desired electrical activity. Since the basic interactions of accelerated ions with solids are very complex, there had been few detailed studies. Consequently, little was known about the exact mechanisms that cause the radiation damage and those that heal it. The commercial prospects of ion implantation have stimulated considerable research on this problem over the past 8 years.

"Channeling"

The discovery of "channeling" in crystals played an important role in the increasing interest in the development of ion implantation techniques. Prior to 1963 most solid state physicists believed that ions would penetrate crystalline material and amorphous material in a similar manner. However, J. A. Davies and his colleagues at Chalk River found ions that penetrated to unexpectedly large depths in crystals. At the same time, M. T. Robinson and O. S. Oen of Oak Ridge National Laboratory, during a computer calculation of the trajectories of copper ions within a simulated copper lattice, observed that some of the ions had extraordinarily large ranges. These ions found their way down "open" channels in the cubic lattice. Since all crystal lattices possess a high degree of symmetry, at certain orientations the atoms on the lattice sites are lined up in rows and planes between which are open channels. When fast ions enter parallel to these channels or at an angle that is smaller than a characteristic critical angle, the ions penetrate much further than they do when entering from "random" directions. The theoretical explanation for channeling was later developed by J. Lindhard and his collaborators at Aarhus University, Denmark. They emphasized that the effectiveness of channeling does not depend on the transparency of the open channels but on the high probability for small-angle scattering between the ions and atoms

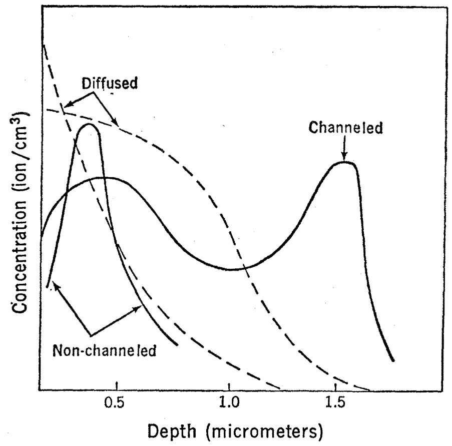

Fig. 1. Typical distributions of dopants within silicon. Only those impurities introduced by channeled implantation display a well-defined boundary.

in the crystal lattice. Thus, the correlations between successive collisions force the ions to ricochet down the channels. Figure 1 shows some typical distributions of dopants which were implanted by diffusion and by ion beams. The phenomenon of channeling, which is being studied extensively in a number of laboratories around the world, has provided an extremely useful technique for measuring both the radiation damage and the lattice location of impurity ions implanted into solids. However, it is important to note that our understanding of the energy transfer processes that occur during collisions within solids is still far from adequate.

By doping semiconductors with radio-

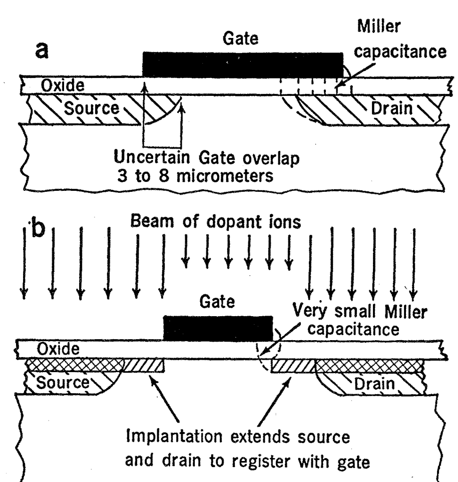

Fig. 2. Cross sections showing the three elements in MOSFET's. (a) In the conventional type, parasitic capacitance is introduced by the gate overlap. (b) Ion implantation reduces this capacitance and improves the frequency response of the transistor. [Courtesy of G. Dearneley and J. H. Freeman, AERE, Harwell]

active isotopes such as phosphorus-32, it is possible to study the spatial distribution of the impurity atoms within the lattice. Thin slices are sequentially removed from the front face of the semiconductor, and the radioactivity, which remains after each cut, is measured. Using this radioactive tracer method to map impurity densities, researchers have been able to compare the density distributions for impurities implanted by diffusion with those implanted by ion beams—both channeled and unchanneled (see Fig. 1). Chemical diffusion is a thermodynamic equilibrium process, and the density distribution is limited by the solubility of the foreign species within its crystalline host. Higher densities of impurities can be achieved with ion implantation since it is not restricted by this thermal equilibrium. However, if the concentration of ions is too high, they may precipitate into clusters that may adversely affect the semiconductor's physical properties.

Use of Rutherford Backscattering

Ion bombardment can even be used to determine the location of impurity atoms within a lattice. These techniques were pioneered by a group at Chalk River. They rely on Rutherford backscattering of alpha particles (helium ions) from the doped crystal and are able to distinguish between impurity atoms occupying substitutional positions (regular lattice sites) from those occupying interstitial positions between the lattice rows or planes. If the doped crystal is aligned so that the beam of alpha particles is channeled, an interstitial impurity has a higher probability of backscattering the alphas than a substitutional impurity does. In this orientation of the crystal, the substitutional impurity atoms are effectively shielded from the alphas by the regular rows of the lattice. An alpha beam impinging on the crystal from a random direction cannot distinguish between interstitial and substitutional impurities. Thus, by measuring the difference between the backscattering alpha spectra for the crystal in both channeling and random orientation, it is possible to determine the relative number of impurity atoms on the lattice sites. The electrical activity of dopant ions in transistors depends on their being substitutional. Thus the Rutherford scattering technique provides a means of studying this important property as it varies with the details of ion implantation and annealing procedures.

Rutherford backscattering is applicable to cases in which the impurity atoms are heavier than the atoms of the crystal. In this situation, alpha particles scattered from the impurities can be distinguished from the much larger number of alpha particles scattered from the host lattice. This results from the fact that alpha particles scattered from heavy atoms retain more of their energy than when they are scattered from light atoms. If the impurity is lighter than the lattice atoms, its signal is overwhelmed by the "low-energy tail" of alphas scattered from the host atoms. Variations on the Rutherford backscatter technique can overcome this problem. Rather than look for backscattered alphas, research groups have transmuted the impurity nuclei by bombarding the crystal with protons, and then measuring the particles emitted from the nuclear reactions, such as alphas, to distinguish the impurity from the host lattice. Several experimental groups have used this method successfully to determine the locations of boron implanted in silicon. Another variant was developed by J. A. Cairns and R. S. Nelson at AERE, Harwell. They used low energy heavy ions to induce characteristic x-rays from the dopants. Again, they compared the yields when the crystal was aligned for channeling and when it was unaligned.

The Rutherford backscatter technique can also be used to estimate the amount of radiation damage within a crystal. Since the crystal defects disrupt the channeling effects, the spectra of the backscattered alpha particles observed for heavily damaged crystals show no differences between the channeled and the "random" directions. Not only have these studies aided researchers in determining the best temperature for healing the defects, but they have also shown that interstitial dopant ions migrate to lattice sites during annealing. In some applications, the crystalline specimen is bombarded while hot in order to anneal the defects as they occur. For silicon, about 450°C is usually adequate. However, for full electrical activity, it is often necessary to anneal at 800° to 900°C. Since these temperatures are lower than the 1000°C or more required to diffuse impurities, the implanted distribution retains its sharp boundary within the crystal. About 650°C is necessary to heal silicon after bombardments at ambient temperature.

Ion implantation is attractive as a possible way of doping compound semiconductors such as gallium arsenide and cadmium sulfide. These materials are difficult and sometimes impossible to dope by diffusion since they develop harmful defects at high temperatures. Yet they are materials of great importance, particularly for electroluminescent devices. Implantation results in materials of this kind are relatively few, but it is clear that the effects of damage produced by the implantation are extremely important. How to effectively anneal these semiconductors and still not thermally degrade them is a problem that is now being studied with very cautious optimism.

MOSFET Sandwich

At Hughes Aircraft Corporation, in Newport Beach, California, R. W. Bower and his associates have developed a commercial method for fabricating field effect transistors consisting of metal, oxide, and semiconductor (MOSFET) for which both ion implantation and diffusion are used. There are three important elements in MOSFET's—the source, the drain, and the gate. During conventional production, the source and the drain are diffused into the semiconductor through openings etched in an oxide mask. The metal gate is then deposited through a second mask (Fig. 2a). Because of misalignment of the two masks, and because the source and drain diffuse sideway, the gate overlaps them by several micrometers. This overlap gives rise to parasitic capacitance, called Miller capacitance, which limits the high-frequency performance of the transistor. This undesirable characteristic can be overcome by fabricating the MOSFET with gaps between the elements, and by then implanting additional dopant ions to more exactly align the source and drain with the gate (Fig. 2b). There is very little sideway motion of the implanted ions. Hughes has marketed a 64-bit dynamic shift register capable of operating at frequencies greater than 20 Mhz as compared with a previous high of about 10 Mhz.

Since the MOSFET's must be produced in ultraclean high vacuums, the semiconductor silicon wafers must be reloaded after each bombardment. The Hughes facility can handle about six wafers at a time. At AERE, Jim Stephen and J. H. Freeman in collaboration with John Shannon, of the Mullard Research Laboratory, have developed an apparatus capable of handling several hundred 2-inch (5-cm) silicon wafers for the manufacture of MOSFET's with beams of boron ions. Susuma Namba at Osaka University is working on a technique for increasing the depth of the implanted region. He first diffuses boron into silicon by conventional techniques and then bombards the specimen with protons in order to create vacancies deeper in the lattice. A further diffusion extends the doped region. Hitachi Limited is supporting Namba's research.

Improved high-frequency performance is but one virtue of the ion-beam doping process. Scientists at the Mostek Corporation in Massachusetts, by utilizing the controllability of this new process, have manufactured MOSFET metal-oxide-semiconductor devices with low threshold voltage (1 to 2 volts). This allows for lower power dissipation and better stability. Everything else being equal, a lower threshold voltage diminishes the probability that the transistor will turn on at random (parasitic turn on). Furthermore, Mostek has manufactured ion-implanted integrated circuits which incorporate two types of transistors (enhancement mode and depletion mode). This combination, which cannot be fabricated by diffusion methods, improves switching speeds by factors of 2 or 3 and has the extra advantage that fewer power supplies are needed.

Prospects

In addition to the many devices that have been and will be built, ion implantation has a manyfold role in science and technology. For example, implanted radioactive ions can be used to measure the wear on moving parts of machinery. Previously, an entire component of the machine was activated, and the amount of wear was measured by monitoring the radiation in the lubricating field. Ion implantation of radioactive nuclides avoids the use of large quantities of activity, but it still provided the same information. At the other end of the spectrum, implanted radioactive ions can be used to measure the magnetic fields within crystals, or, if the magnitude of the crystal field is already known, certain properties of the radioactive nucleus can be measured. The information is obtained from measurements of the angular correlation of gamma rays emitted by the nucleus as it precesses within the field of the host lattice.—GERALD L. WICK