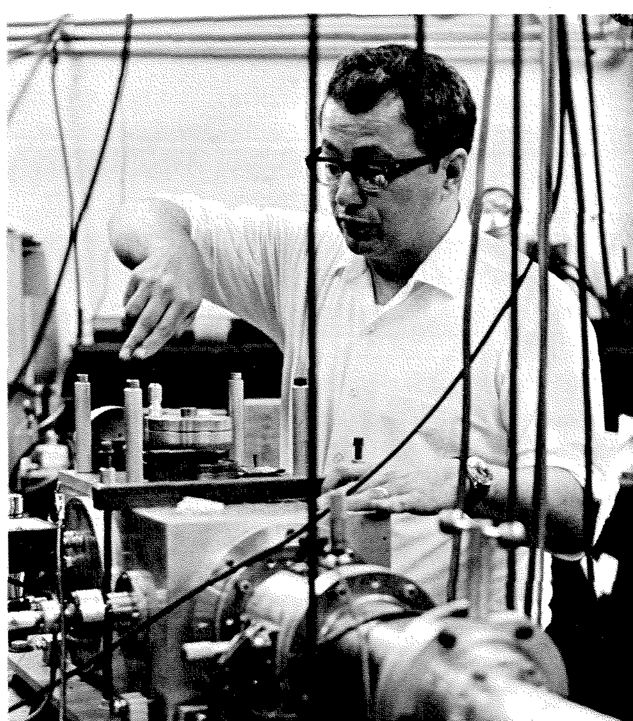
Accelerators, Channeling, and Solid State Physics

by James W. Mayer

The activities of the Kellogg Laboratory are not entirely devoted to nuclear and atomic physics. Nuclear particles are extremely useful as probes to determine the properties of solids. These particles provide a simple and direct means of determining the composition of surface layers, the number and location of impurity atoms in crystalline materials, and the amount of disorder in a single crystal. Of course, using million-electron-volt (MeV) protons or helium ions produced in a two-story-high Van de Graaff accelerator to analyze a paper-thin region in a crystal might seem somewhat extreme. However, this information is relevant in many practical applications such as transistors, whose characteristics are entirely determined by the properties of the first few microns of material. Our work is based on the recent discovery that the interactions of energetic charged particles depend strongly on the alignment of the incident beam of particles with the crystal lattice. Under the right conditions the crystal atoms, even though they are held in place by only 10-electron-volt binding energy, can steer MeV charged particles along the "channels" in the crystal lattice structure.

In one sense channeling phenomena are like skipping a stone on water. If the stone approaches the water at a small enough angle, it will skip nicely. Similarly, if a fast-moving, positively charged particle, say a 1 MeV helium ion, is incident at a small angle to a close-packed atomic plane, it can be reflected by a succession of gentle collisions without making a violent impact with any of the lattice atoms. Since hundreds of lattice atoms in the plane may participate in steering the incident helium ion, one may visualize the plane of atoms as a sheet of charge rather than a set of individual scattering centers. On this basis the MeV ion can be considered as being reflected by a potential barrier. As long as the incident angle is small enough (one or two degrees for MeV particles) so that the component of the particle velocity normal to the plane is less than that needed to penetrate the potential barrier, the particle can easily be steered or channeled. At larger incident angles, the particle can easily penetrate through the planes. After all, when skipping stones, a flat trajectory is required for best results.

In a single crystal, steering can also be achieved by rows of atoms. In this case the rows can be treated as a "string of charge," a concept introduced by Jens



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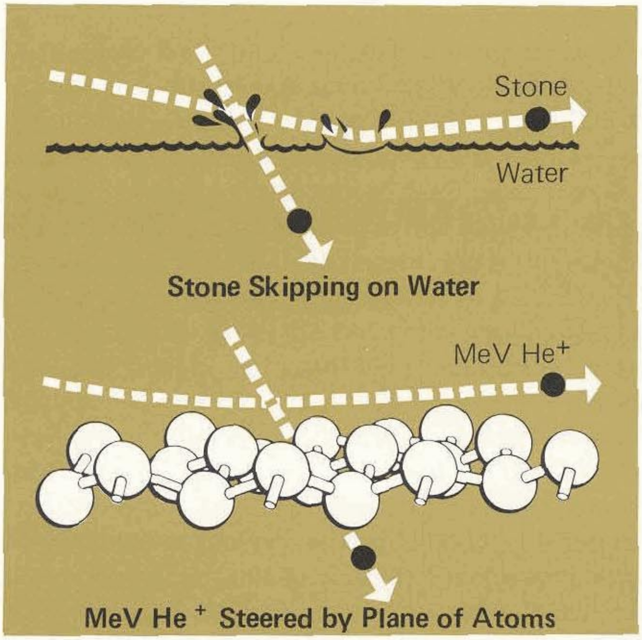


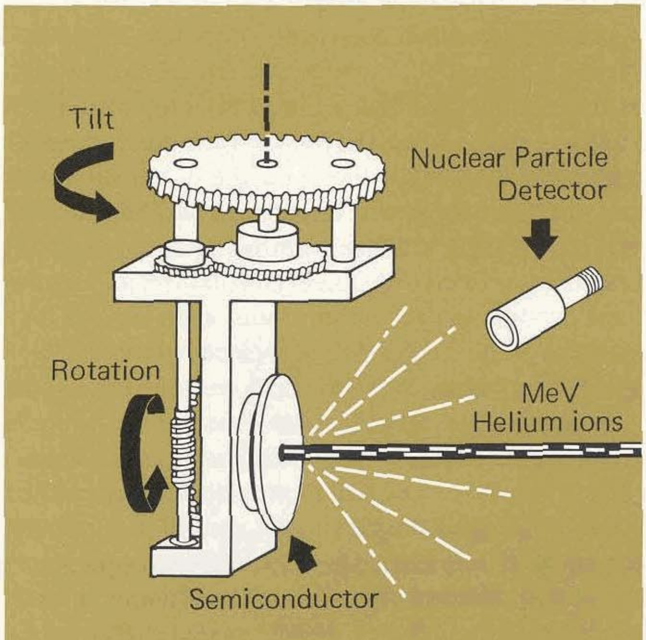
Skipping a stone on water is analogous to steering fast-moving particles (e.g. million-electron-volt helium ions) by planes of atoms. The steering is accomplished by a series of gentle pushes given to the ion by each of the many atoms it passes over.

Lindhard at Aarhus University in Denmark. In his elegant and simple theory, channeling is described as a classical steering process arising from the Coulomb repulsion between the screened nuclear charges of the projectile and lattice atoms. In measurements both at Caltech and the Chalk River Nuclear Laboratories in Canada, we have found that the approximation of strings and planes of charge describes very well the dependence of the steering process on both the characteristics of the incident ion and the lattice. We are particularly interested in the steering aspects of semiconductor lattice structures in order to use channeling effect techniques as a tool to investigate these materials.

Since the collisions during channeling are gentle ones rather than the normal violent collisions, channeling can influence particle ranges and particle energy loss, yields of nuclear reactions, in fact almost all the standard charged particle interactions studied in nuclear laboratories. Different aspects of these effects have been demonstrated at many laboratories over a wide range of particles (protons to xenon ions), energies (10 keV to 50 MeV), and crystals (diamond to tungsten). The effects are so large, one or two orders of magnitude in some instances, that it is hard to realize why channeling remained undiscovered until less than six years ago. To demonstrate the effect, one needs only a parallel beam of particles and a single crystal target.

The use of channeling techniques to determine the position of foreign atoms in a host lattice is based on the fact that the well-channeled particles do not approach closely to the atoms on lattice sites. In fact, the distance of closest approach is of the order of 0.1 to 0.2 angstroms for helium ions in the 1 MeV energy range. These distances of approach are orders of magnitude larger than those required for close impact processes such as nuclear reactions or backscattering (i.e., when the incident particle can interact strongly enough with one lattice atom to be scattered backwards through an angle from 120 to 180 degrees). In fact, the distances of approach are sufficiently large to exclude interactions with the inner shell electrons which for a nonchanneled beam give rise to the production of x-rays.

Measurement of the yield of any of these "close impact" processes provides a very sensitive means of determining the influence of channeling effects. A typical experimental setup in the Kellogg Laboratory

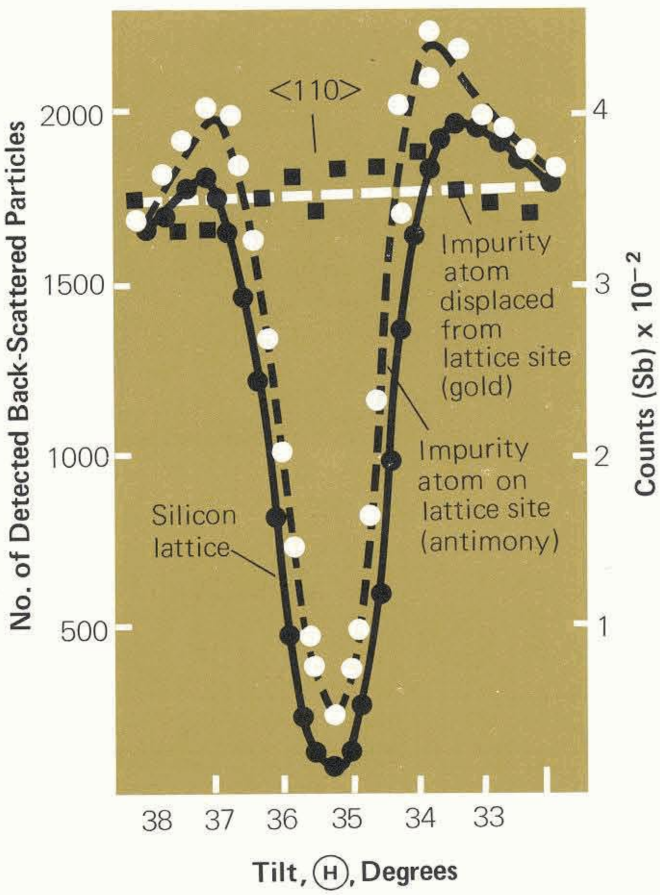


Schematic view of an experimental setup for determination of the lattice location of impurity atoms in a semiconductor. When the incident beam of helium ions strikes the sample, a small fraction are scattered back into the detector. The number and energy of these backscattered particles are measured as a function of sample tilt and rotation.

is to mount a single crystal of silicon on a goniometer so that the crystal can be tilted and rotated with respect to the incident beam of strongly collimated MeV particles. A nuclear particle detector is used to determine the number and energy distribution of backscattered particles. As the crystal is tilted in such a way that a crystallographic axis (a "string" direction) is aligned with the beam, a 10- to 100-fold decrease in the number or yield of backscattered particles is observed.

So far we have not considered how one can detect the presence of a small percentage of foreign atoms in a host crystal. This is a crucial point in semiconductor technology, where the properties of silicon transistors, for example, are determined largely by the presence of much less than one atomic percent of impurity atoms. It is the "doping" action of these atoms which determines to a large extent electrical behavior of the semiconductor. Fortunately, in channeling-effect measurements, there are several methods by means of which the interaction of the incident beam with dopant or impurity atoms gives rise to a signal that can be clearly distinguished from the more numerous interactions with the lattice atoms. For light dopant atoms such as lithium or boron, there are specific nuclear reactions that provide a clearly identifiable "signal." In other cases, the characteristic x-rays from the dopant atoms have an energy spectrum distinct enough that they can be distinguished from the x-ray emission from the host atoms. A particularly simple case arises when the mass of the impurity atom is heavier than that of the lattice atoms, such as antimony atoms in silicon. In this case the helium ion loses less energy scattering backwards off the heavy antimony atom than off the silicon lattice atoms. Energy analysis of the backscattered particles is sufficient to identify the scattering from the impurity atoms. Typical sensitivity levels achieved in these measurement techniques 10^{-1} to 10^{-2} atomic percent of dopant atoms to host lattice atoms.

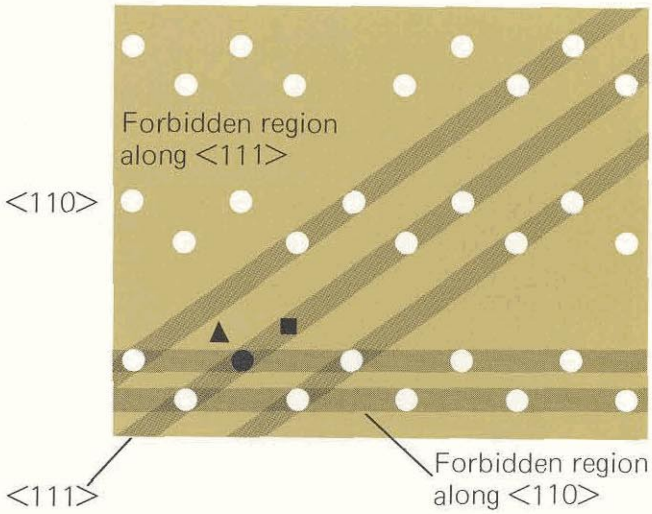
In atom location studies one can treat the crystal as being composed of "allowed" and "forbidden" regions; that is, a well-channeled particle moving along an axial direction is "forbidden" to interact closely with atoms located inside a cylinder of about 0.2 angstroms radius stretched along the row of atoms. On the other hand, the beam can interact with atoms that are displaced from the rows by more than 0.2 angstroms. For example, in a silicon crystal containing impurity atoms on lattice sites, the yield of scattering interactions with impurity atoms will show nearly the



This curve shows how the lattice location of impurity atoms can be determined by analysis of the interaction of MeV helium ions with the silicon host crystal and the impurities. As the sample is tilted so that the <110> crystallographic axis is aligned with the incident ion beam, a channeling condition, the number of backscattering interactions with the silicon lattice atoms decreases by a factor of 30. If the impurity atoms (antimony) are on lattice sites (substitutional location), there will be a similar decrease in the number of interactions. On the other hand, if the impurities (gold) are not on lattice sites, interaction with these atoms does not show orientation effects.

same orientation dependence as the yield from the silicon lattice itself. If the impurity atoms are displaced from a lattice site, the scattering interactions with these atoms will not show such orientation effects.

The diamond lattice of typical semiconductors such as silicon or gallium arsenide provides unique possibilities to study the lattice location of impurity atoms because of the existence of well-defined interstitial sites. These interstitial sites are positions along certain lattice rows that can be occupied by an impurity atom without taking the place of a host lattice



○ — Silicon Lattice Atoms

	Direction Effect <111>	<110>	Impurity
●	yes	yes	substitutional
■	yes	no	"regular" interstitial
▲	no	no	off lattice site

The diamond lattice typical of semiconductors, such as silicon, provides a simple case for determining the lattice location of impurity atoms. Well-channeled energetic ions do not penetrate into the lattice rows (forbidden regions) and cannot interact with impurity atoms contained within these regions. Consequently, one may determine the lattice location of the impurities from directional effects in the yield of backscattered particles.

atom. (The latter is a substitutional position.) Along one set of rows the atoms are spaced evenly. But along another set of rows the atoms are spaced in groups of two. It is along this direction that the regular well-defined interstitial sites are located. If one then tilts the crystal so that the incident beam is swept through a lattice axis, in one case interstitial sites are in the "forbidden" region, and in the other case the interstitial sites are in the "allowed" region. Consequently, by measuring the scattering yield along the two directions, one can determine whether the impurity atoms are on regular interstitial sites or substitutional sites, or whether they are displaced by more than 0.1 to 0.2 angstroms from either of these two well-defined sites.

Channeling-effect measurements have been applied systematically to solid state problems only in the past three years. One of the first major applications was the analysis of lattice disorder and atom location in semiconductors which had been implanted with dopant elements. That is, we use one type of heavy-ion accelerator to introduce (implant) the impurity atoms at keV energies and another accelerator to analyze the implanted structure by using lighter particles (protons, helium ions, carbon ions) at MeV energies. This work was started by a group at Chalk River Nuclear Laboratories and continues as a collaboration between Chalk River, Caltech, and the Research Institute for Physics in Stockholm.

As a result of channeling investigations, we have found that implanted impurity atoms can be on substitutional lattice sites in concentrations orders of magnitude above those found in thermal diffusion studies. Also there are certain classes of elements which are located on both substitutional and the regular interstitial sites. We have observed the motion of these elements from substitutional to interstitial and then to precipitation sites. In measurements carried out in collaboration with the Hughes Research Laboratories, we have found that the electrical characteristics of the dopant atoms are strongly dependent on their lattice position. As an example, a column III element, thallium, which captures an extra electron when substitutional (an acceptor), gives up one of its electrons (becomes a donor) when on interstitial sites.

We started our investigations with implantation in semiconductors because this technique offers some unique advantages in fabrication of semiconductor devices. From a more general viewpoint, the solid state aspects of ion implantation are particularly broad because of the range of physical properties that are sensitive to the presence of foreign atoms in solids. The mechanical, electrical, optical, magnetic, and superconducting properties of a solid are affected and indeed may be dominated by the properties of implanted layers. Implantation makes it possible to obtain impurity concentrations and distributions which are of particular interest and which are otherwise unobtainable.

The application of channeling effects is not restricted, of course, to semiconductors or implantation. Studies of diffusion in metals, radiation damage effects, oxidation, corrosion, and others are possible. It only depends on the ingenuity of the investigator to choose the right conditions so that meaningful data can be obtained.