phosphorous ions (phosphorous atoms with one or more electrons temporarily removed) in the near-surface region of the solid silicon crystal.

In a vacuum chamber, phosphorous ions were accelerated in an electrostatic field to the desired energy (speed) and then made to impinge on the surface of the silicon crystal. The ions would strike the surface, collide with or scatter among the electrons and nuclei of the silicon atoms, and eventually come to rest in the surface layers of the solid in a predictable way with known depth and density distributions.

Unfortunately, a major problem with this approach was that the ion implantation process caused heavy damage, wreaking havoc with the otherwise orderly lattice structure of the silicon crystal. It is estimated that, with typical ion concentrations required by commercial applications, *every* atom within the affected solid was physically displaced at least several times.

As a result, there were many lattice defects, vacancies, and clumps of unconnected atoms, known as interstitial excesses. Most of the implanted dopants were not electrically activated, because they did not occupy key positions known as substitutional sites, in what remained of the crystal's lattice structure. For most applications it was necessary to repair the damage, at least partially, and activate the implanted atoms electrically.

Conventionally, this was done by heating the doped solid in a furnace-type oven at high temperatures for 30 minutes or more. But this thermal annealing process was often accompanied by undesirable and unpredictable consequences such as incomplete repair, random precipitation of dopants in the near-surface regions, excess migration of dopants out of the desired region, degradation of other electrical properties, and warping or decomposition of the underlying substrate materials.

In search of a better means of repair, Basic Energy Sciences researchers pursued a report by Soviet scientists concerning the use of lasers to deposit energy on the surfaces of solids in amounts sufficient to cause temporary melting. Guided by this work and the success of related pilot projects, funded in part by the Department of Energy's Exploratory R&D program, the researchers set out to investigate the phenomenon of laser annealing, particularly as it might be compared to conventional thermal annealing, and undertook a wide variety of experimental and theoretical studies.

Specifically, these researchers characterized the effects of various forms of lasers and their illuminating radiations, as to appropriate wavelengths, energy densities, beam diameters, and pulse durations. It was found during these studies, for example, that most samples of ion implanted silicon could be fully repaired by a single pulse from a ruby laser of approximately 50 one-billionths of a second.

Energy densities were optimized, so that the amount of energy deposited in the near-surface region was sufficient to ensure annealing, but below the thresholds for vaporization and subsurface damage. Wavelengths (i.e., energies) of the laser's light were matched to the excitation energies of the electrons in the sample's atoms, insuring minimum reflection and transmission and maximum energy absorption of the laser's energy by the surface material.

Experiments were conducted on a range of implanted ion densities (10^{14} to 10^{17} ions per square centimeter) covering the full range of interest for semiconductor device fabrication. The experiments tested ions of boron, phosphorous, arsenic, and antimony—the more important dopants for semiconductor devices in single-crystal silicon.

A full battery of instruments were used to characterize the "before" and "after" properties of the laser annealed samples. All results pointed to complete repair. After annealing, for example, highly magnified pictures of thin sections of samples made by transmission electron microscopy, showed no holes, stacking faults, or dislocations. Electron diffraction patterns showed that crystal and lattice structures had returned to normal. Diagnostic techniques, such as Rutherford ion-backscattering and ion-channeling, showed that the atoms had realigned themselves in orderly rows and columns.

More fundamentally, Basic Energy Sciences researchers characterized the phenomena which took place *during* transition. The melting front traveled from the surface to its end-depth and back again, a round-trip distance of 40 one-millionths of an inch. The sample solidified at an average speed of about 270 centimeters per second. They determined that the bulk of the near-surface material would remain in a molten state on the order of a few