hundred nanoseconds (10^{-9} seconds) or, in total, about one-third of one-millionth of a second!

Solidification of the melted region took place so fast that the silicon atoms and the dopant atoms would settle into their proper lattice positions comfortably, but the solidification time was too short to allow any dopant atoms to agglomerate (by precipitation) or escape (by vaporization). By varying the duration of the laser pulse, other desired effects could be achieved.

Additionally, by using this knowledge the researchers were able to achieve dopant concentrations that exceeded by two orders of magnitude (100 times) those allowed by normal equilibrium chemistry, greatly enhancing electrical performance. Ion implantation, in combination with laser annealing, prevented atom precipitation and migration, leading to large excesses in atom concentrations above the solid solubility limits.

This supersaturated or metastable condition had never before been possible to achieve in standard metallurgical processes. Its achievement opened a whole new realm of materials exploration and industrial possibilities.

Finally, the researchers determined that ultra-rapid surface melting had other useful possibilities. They discovered that when dopant atoms were merely deposited as a thin film on the surface and then laser irradiated, they could be made to diffuse into the temporarily melted surface and then fast-frozen there during solidification. This new process avoided entirely the need for ion implantation in certain applications.

Altogether, the results of this work contributed significantly to the emergence of modern semiconductor manufacturing and near-surface materials processing techniques. For example, while lasers were originally chosen for their ability to deliver intense energy with precise control, it soon became apparent from the theoretical and experimental evidence that certain, more conventional sources of light and heat could be substituted for lasers to obtain annealing results which were acceptable for a number of commercial applications.

Guided by this evidence, industry found that arc lamps and high-intensity halogen lamps could provide annealing nearly comparable to that obtained with conventional furnaces but with greatly increased manufacturing production efficiency. The commercial process became known as rapid thermal annealing.

Annual sales of rapid thermal annealing equipment grew explosively, from near zero to more than $10 million in 5 years, and to nearly $100 million in 10 years. One leading semiconductor manufacturer set the early trend by using rapid thermal annealing to produce 10 million devices per week, with yearly sales valued at $15 million.

Semiconductor manufacturers entering markets for ultra-high density computer memory chips incorporated rapid thermal annealing in production lines to produce a new standard size, one-megabit memory device (one million "bytes" of memory). In producing such a device, rapid thermal annealing is used for many processing steps, including the annealing of ion implantation damage, promoting glass reflow to achieve flat surfaces, annealing polysilicon to achieve lower electrical resistance, and alloying metals to semiconductors to improve the performance of electrical contacts.

Basic Energy Sciences researchers continued to make contributions to follow-on applications. In the manufacture of very large scale integrated circuits, for example, certain chemicals are introduced as gases rather than liquids, in a process known as photochemical processing. By choosing the appropriate intensity and wavelength of laser light, one can achieve localized doping of the semiconductor, or localized etching of the surface. This process makes possible the direct writing of the many fine line features that one must achieve in very large scale integrated devices, while eliminating many of the costly masking steps required in conventional technologies.

Finally, as semiconductor devices become more sophisticated and densely packed, with as many as one million transistors positioned on a chip half the size of a postage stamp, the slightest interactions between various parts of the circuit become detrimental. To eliminate such "cross talk," manufacturers pursued another new technology stemming from laser annealing, called "silicon on insulator" technology.

Silicon on insulator technology involves a layered, three-dimensional design. Silicon is deposited on an insulating substrate. This is followed by selected laser melting and crystal formation. Because the active region of the device is physically separated by the insulation from underlying areas,