MAX PLANCK SOCIETY

Press Release

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Technological Breakthrough in Silicon Photonics

Max Planck scientist introduces a new method for the manufacture of silicon nanocrystals for optoelectronics and storage technology

A technique for tailormaking silicon nanocrystals on 4-inch wafers has been developed and submitted for patent (German patent number: DE 101 04 193 A 1) by Dr. Margit Zacharias and colleagues of the Max Planck Institute of Microstructure Physics, Halle(Saale), Germany. Following a standard procedure in silicon technology, a thermally unstable silicon compound in the form of an ultra-thin layer (only two to five nanometers) is first deposited on a substrate. A subsequent thermal treatment leads to a phase separation in this layer, in which silicon clusters and nanocrystals form depending on the temperature; these clusters and crystals are embedded in a matrix of thermally stable silicon dioxide. The size of the nanocrystals is controlled via the thickness of the deposited layer. This process makes possible the cost-effective manufacture of high-density arrays of silicon clusters or nanocrystals (Solid State Phenomena 94 (3003) 95 - 104). Both Motorola and STMicroelectronics have recently announced breakthroughs based on silicon nanocrystal technology--Motorola with the first 4-megabit memory, and STMicroelectronics with light-emitting diodes (LED).

Silicon, one of the base elements of our planet, is the foundation of the modern information society. Modern electronics would be unthinkable without the development of silicon transistors; such transistors are made possible only by the outstanding characteristics and stability of silicon and its oxides. However, the increasing miniaturization of microelectronics, the demands of optoelectronics, and the development of optical data transmission also show the limits of silicon technology: silicon is an indirect semiconductor and, as such, has a very inefficient light emission at room temperature. Thus, the structures most used in optoelectronics are based on the III-V elements such as gallium arsenide or indium phosphide, or corresponding combinations and are not compatible with silicon.

Structures in nanometer range provide a viable solution due to the fact that silicon manifests different characteristics on the nanoscale. In a range of very few nanometers, the movement of electrons and electron vacancies in silicon is narrowly restricted, and so-called "quantum-confinement" effects appear which enlarge the band gap of silicon and shift the light emission into visible range. The possible advantages of this effect have spurred over ten years of intensive research worldwide in the field of silicon nanocrystals. The methods of manufacture are diverse, but controlling the size of the nanocrystals has remained problematic. For technological utilization it is required that the density, size, and position of the nanocrystals be controlled independently. This has not been possible with the prevailing techniques such as the manufacture of

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porous silicon, ion implantation, and the manufacture of thick SiOx films.

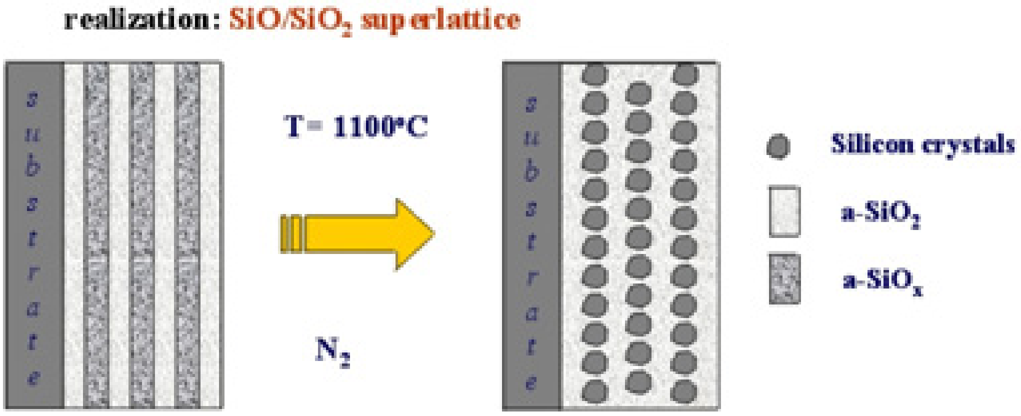

Fig. 1: *Phase separation and production of silicon nanocrystals in a matrix of siliconoxide through tempering of amorphous SiO/SiO2-superlattices at 1100 °C (2012°F).*

Image: Max Planck Institute of Microstructure Physics

Researchers at the Max Planck Institute for Microstructure Physics have recently developed a means of controlling the size of silicon nanocrystals and custom manufacturing these crystals on 4-inch wafers. The new technique is based on a combination of multi-layer structures with layer thicknesses of very few nanometers and varying band gaps, so-called "superlattices" (see Figure 1), and a phase separation in the ultra-thin layers. The superlattice structure of amorphous silicon oxide layers ($SiOx/SiO_2$) is manufactured using a currently standard technique. The Max-Planck researchers employed a novel but simple variation of this technique by evaporating the silicon oxide either in a vacuum or in a oxygen-containing atmosphere (see Figure 1). The resulting amorphous SiO/SiO_2-superlattice structure was then tempered in a nitrogen-containing atmosphere at 1100°C (2012°F). Through the thus thermally-activated phase separation, the SiO in the ultra thin sublayers transformed into pure silicon nanocrystals and into amorphous SiO_2, whereby the nanocrystals were automatically surrounded with an approriate barrier material (see Figure 2).

The size of the crystals within the range in question - from two to five nanometers - can be determined by the thickness of the layer. The distance between the crystals can be adjusted by varying the thickness of the SiO_2 barrier layers and the oxygen content of the SiOx-layers. A higher oxygen content would automatically lead to a higher proportion of the amorphous SiO_2 after the phase separation and thereby to a larger distance between the silicon nanocrystals within the sublayer. The luminescence of the silicon increases with the number of crystals, and the quantum efficiency of small crystals is higher than that of the larger; therefore, primarily very small crystals in high density are required for the highest possible luminenscence intensity. When the nanocrystal structures are implanted with erbium ions, a very effective energy transfer occurs from the nanocrystals to the Er^{3+}-ions, and the luminescence shifts into a technologically useful range of 1.54 micrometers. This particular wavelength is of great technological importance due to the fact that the fiber optic cable employed in optical data transmission exhibits a transmission maximum at 1.54 micrometers. Additionally, erbium-doped glass fiber is used as an amplifier for the optical data transmission.

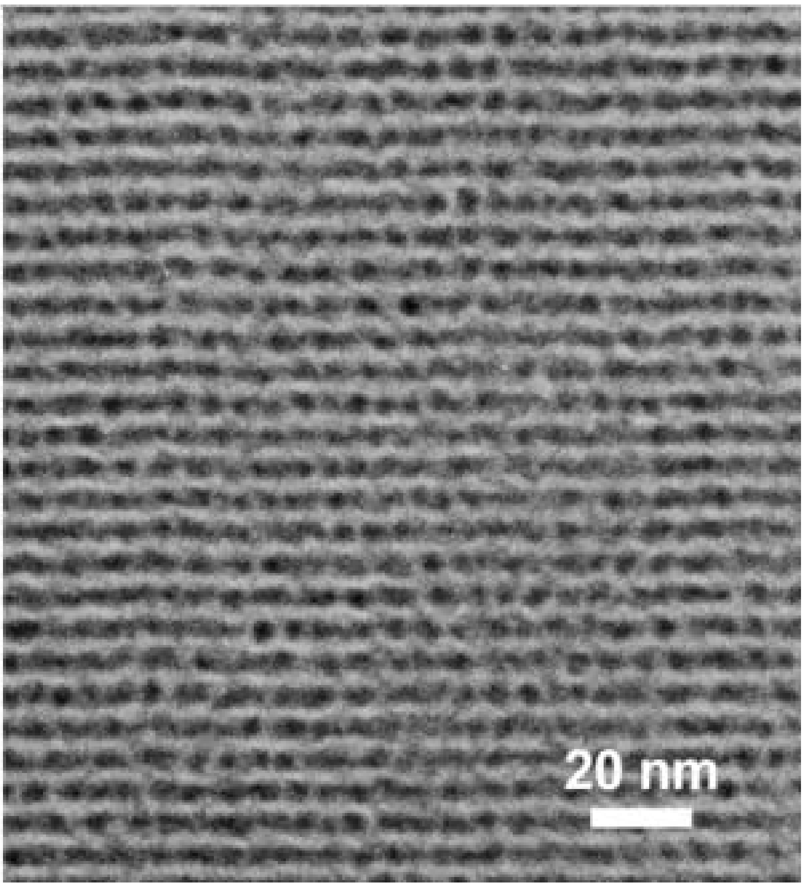

Fig. 2: *Electron microscope image of a thin-layer film after tempering.*

Image: Max Planck Institute of Microstructure Physics

In autumn of 2002 STMicroelectronics introduced a light-emitting diode based on nanocrystalline silicon which operates at 1.54 micrometers with a efficiency factor of 10 percent. This technology still relies on the standard technique of ion implantation which produces and randomly distributes silicon crystals in thick $Si0_2$ layers. This efficiency factor could be exceeded by using the new technique to produce structures containing a dense matrix of crystals only 2 nanometers in size. Memory circuitry is a further area of application of silicon nanocrystals in oxide matrices. Thus, Motorola recently introduced the first 4-megabit memory, which utilizes the electrical charge storage capabilities of silicon nanocrystals.

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Original work:

M. Zacharias
Dichte Anordnung von Si Nanokristallen
Patent DE 10104193 A 1

M. ZACHARIAS, L.X. YI, J. HEITMANN, R. SCHOLZ, M. REICHE, U. GÖSELE
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Solid State Phenomena 94 (2003) 95-105

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Mat. Res. Soc. Symp. Proc. Vol. 737 (2003) 271

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