Category of Generation and Design of New Materials Creating Novel Functions

Reasons for Award: For the creation and realization of the concept of man-made superlattice crystals which lead to generation of new materials with useful applications

Dr. Leo Esaki proposed in 1969 the concept of semiconductor "superlattice," man-made single-crystal with a periodic one-dimensional structural modification. He predicted that a superlattice would exhibit peculiar properties such as negative differential conductivity because the density of states has a short-period modulation in the k-space. He proposed to realize a superlattice by modulating either alloy composition or impurity density during thin-film crystal growth. His efforts on molecular-beam epitaxy paid off in 1972 when he discovered a negative differential conductivity in a GaAlAs superlattice. He also predicted a resonant tunneling phenomenon between adjacent potential wells in a superlattice, and confirmed it experimentally in 1973.

Dr. Esaki's work on superlattice had a tremendous influence on other scientists. Firstly, he suggested the concept of modulation doping (overflow of conduction electrons or holes that originate from impurities in a wide-bandgap region into a narrow-bandgap region). The HEMT, a high-speed field effect transistor, was developed in 1980 based on this concept, and is now widely used in wireless telecommunications. Secondly, semiconductor lasers and photo-detectors with superlattice (or multiple-quantum-well as it is often called) structures were invented during the 1980's and are now very important components in optical communications. Thirdly, GMR (Giant Magneto-Resistance) was discovered in the late 1980's in a superlattice structure consisting of magnetic and non-magnetic metals and are being pursued as sensors for magnetic recording.

Dr. Esaki's conception of superlattice has thus led to the discovery of many interesting new properties — electrical, optical, and magnetic — and their useful applications, which makes him well deserve the 1998 Japan Prize in the category of "Generation and Design of New Materials Creating Novel Functions." Dr. Leo Esaki was awarded a Nobel Prize in Physics in 1973 for his discovery of tunneling in semiconductor p-n junctions. Superlattice is another great accomplishment he has made.

The Evolution of Semiconductor Superlattices

Leo Esaki

In 1969, research on artificially structured materials was initiated when Esaki and Tsu proposed the concept of an engineered semiconductor superlattice with a one-dimensional periodic potential, where the period of the order of 10 nanometers is substantially longer than the lattice constant of the host crystal but shorter than the electron mean free path or the electron phase-coherent length. This was, perhaps, the first proposal which advocated the engineering of a new semiconductor material by applying the principles of quantum theory in conjunction with the most advanced techniques of crystal growth. This could be considered to be modern alchemy for it is intended to transform "common" semiconductors into "super" semiconductors. Since this proposal offered a new degree of freedom in research, rather like making a "gedanken-experiment" a reality, many ingenious studies were inspired, resulting in the observation of intriguing phenomena.

Before arriving at the superlattice concept, we had explored the feasibility of double-barrier formation by thin-film epitaxy, which could exhibit resonant electron tunneling. Such resonant tunneling arises from the interaction of the de Broglie waves with two potential barriers analogous to the Fabry-Perot resonator in optics. The idea of the superlattice occurred to us as a natural extension of double-and multi-barrier structures. Fig. 1 illustrates schematically the evolutionary path, starting with the Esaki diode of a single potential barrier, then moving to the double-barrier resonant tunnel diode and finally reaching the superlattice.

The proposal and the subsequent pioneering experiments triggered a wide spectrum of experimental and theoretical investigations, opening up a new field in semiconductor research of great scientific and technical importance. The superlattices and quantum wells on the nanometer-scale served as the precursor of a variety of new nanostructures, such as quantum wires, quantum dots and single electron devices. Many different engineered structures now exist that exhibit extraordinary transport and optical properties that cannot be found in any natural crystals, including extremely high electron mobilities, large excitonic binding energies, differental negative resistance, appreciable Stark shifts, distinct Wannier-Stark ladders and Bloch oscillations. Activity at the new frontiers of semiconductor physics has in turn given immeasurable stimulus to the engineering of novel semiconductor devices. Thus, a new class of transport and optoelectronic devices has emerged, for example, a high electron-mobility transistor (HEMT) and a high-performance injection laser incorporating quantum wells.

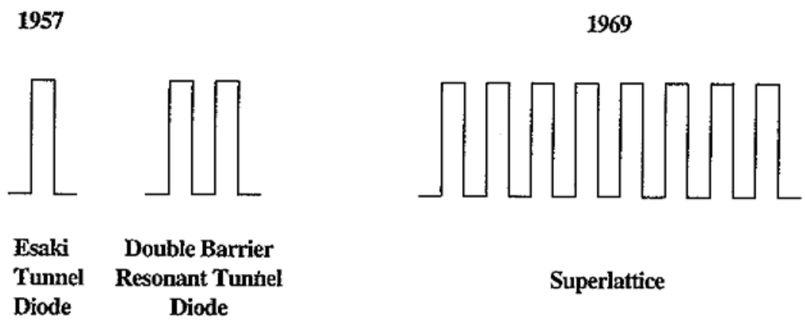

Fig.1 From left to right, the Esaki diode, the resonant tunnel diode and the superlattice.