

Esaki L & Tsu R. Superlattice and negative differential conductivity in semiconductors. *IBM J. Res. Develop.* 14:61-5, 1970.  
[IBM Thomas J. Watson Research Center, Yorktown Heights, NY]

We proposed "a semiconductor superlattice" of a one-dimensional periodic structure "engineered" with epitaxy of alternating ultrathin layers, and we predicted that, if the period of such a superlattice was shorter than the electron mean free path, the electron system would exhibit quantum mechanical effects. [The *SC7*<sup>®</sup> indicates that this paper has been cited in over 405 publications.]

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The superlattice idea occurred to us while examining the feasibility of structural formation of potential barriers and wells that were thin enough to exhibit resonant tunneling through them. We first considered, using advanced thin-film techniques, how to fabricate a simple double-barrier structure and then proceeded to fabricate a series of barriers—a superlattice. In analyzing the electron dynamics in such a structure, we predicted unusual transport properties including a negative resistance.

In general, if characteristic dimensions such as superlattice periods and well widths are reduced to less than the electron mean free path or the quantum-mechanical phase-coherent length, the entire electron system will enter a new "mesoscopic" quantum regime—between the microscopic and the macroscopic. Therefore, if our experimental attempt was successful, the elegance of one-dimensional quantum physics, which had remained a textbook exercise, could, for the first time, be practiced in a laboratory—"do-it-yourself quantum mechanics" would be possible. In the paper we said (without much confidence at that time), "The study of superlattices and observations of quantum mechanical effects on a new physical scale may provide a valuable area of investigation in the field of semiconductors."

The original version of the paper<sup>1</sup> was rejected for publication by *Physical Review* on the referee's unimaginative assertion that it was "too speculative" and involved "no new physics." However, this proposal was quickly accepted by the Army Research Office, which

continues to sponsor, in part, our investigations to this date.

We have now witnessed remarkable progress in the study of superlattices and quantum wells; throughout the world, research has been carried out in all aspects of physics, material science, and devices, and beneficial cross-fertilizations are prevalent. A variety of "engineered" structures exhibit extraordinary transport and optical properties; most of them do not exist in any "natural" crystal. Thus, this new degree of freedom offered to semiconductor research through material engineering has inspired many ingenious experiments, resulting in observations not only of predicted effects, but also of totally unknown phenomena. Activities in this new frontier of semiconductor physics, in turn, give immeasurable stimulus to applications, leading to unprecedented transport and optical devices.

The growth of papers on the subject for the last decade is indeed phenomenal. For example, the number and percentage of the total papers in this area presented at the International Conference on the Physics of Semiconductors, held every other year, have increased as shown in the accompanying table. In the last 10 years the literature has had an annual growth rate of nearly 70 percent.<sup>2</sup>

This paper, together with our early experiments, apparently helped open a new area of interdisciplinary investigations.

Table showing the growth of research in superlattices and quantum wells from 1972 to 1986. A=Year of conference. B=Location of conference. C=Number of papers on superlattices and quantum wells presented at conference. D=Percentage that C is of total papers presented at conference.

A	B	C	D
1972	Warsaw	1	<1
1974	Stuttgart	1	<1
1976	Rome	1	<1
1978	Edinburgh	4	1.3
1980	Kyoto	7	2.6
1982	Montpellier	23	7.7
1984	San Francisco	74	21.1
1986	Stockholm	140	28.8

1. Esaki L & Tsu R. Superlattice and negative differential conductivity in semiconductors. Yorktown Heights, NY: IBM, 1969. IBM Research Note RC-2418.
2. Esaki L. A bird's-eye view on the evolution of semiconductor superlattices and quantum wells. *IEEE J. Quantum Electron.* QE-22:1611-24, 1986.

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