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This Week's Citation Classic™

Chang L L, Esaki L, Howard W E, Ludeke R & Schul G. Structures grown by molecular beam epitaxy. *J. Vac. Sci. Technol.* **10**:655-62, 1973.
[IBM Thomas J. Watson Research Center, Yorktown Heights, NY]

The process of molecular beam epitaxy is described in terms of its applications to compound semiconductors. The emphasis is on the superlattice structure made of alternating layers of GaAs and GaAlAs. We report the growth technique, the structural characterization, and the observation of electron transport via quantum states. [The *SCI*® indicates that this paper has been cited in over 95 publications since 1973.]

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"Refreshed from a one-year sabbatical leave at the Massachusetts Institute of Technology, I returned in 1969 to the IBM Thomas J. Watson Research Center which I had joined six years earlier. At the time, the idea of a semiconductor superlattice was just conceived. It was to be made with periodic, ultrathin layers of two semiconductors. If the period was narrowed to the range shorter than the electron mean free path, energy would be quantized and the associated electron system would belong to the quantum regime. Amid skepticism, we set out to prove that textbook exercises in quantum mechanics could be demonstrated in the laboratory. L. Esaki was the group leader and the principal architect of the ideas.

"We fully recognized the challenge to fabricate a series of layers, each approximately 100 Å thick and with a degree of smoothness on the scale of atomic dimensions. The first problem we had to face was to select the semiconductor materials and the process for their epitaxial deposition. After a few false starts, we decided on GaAs-GaAlAs because of favorable lattice and energy considerations, and chose molecular beam epitaxy, a process which had just come to the scene at the time and which appeared to satisfy the stringent requirements of the superlattice.

"With little experience in ultrahigh vacuum techniques, we designed and assembled our first molecular beam epitaxial system. It had a number of undesirable features and quite often broke down. I recall that at times when the system was on a working streak, we had to operate it continuously day and night in order to produce as many samples as possible. We struggled but persisted, and eventually succeeded in making the superlattice structure, characterizing metallurgically the formation of the periodic layers and demonstrating electronically the creation of the quantum states through their effect on transport properties.

"We continued to work in the field which was spreading rather rapidly. The technique of molecular beam epitaxy gradually matured and was applied to a variety of semiconductors.[1] Superlattices and related quantum-well heterostructures involving different materials and configurations were fabricated.[2] They exhibited unusual physical properties which were pursued earnestly at many laboratories both for studies in physics and material science and for device applications in electronics. The impact of our paper and, thus, the reason for its frequent citation, I believe, lies primarily in its opening up this new field with the demonstration that man-made structures on such a fine atomic scale can be achieved. I am pleased to learn that our original work was identified as a *Citation Classic*™. In writing this commentary, I would like to commend my coauthors for their important contributions to this work."

1. **Chang L L.** Molecular beam epitaxy. (Keller S P, ed.) *Handbook on semiconductions.* Amsterdam: North-Holland, 1980. Vol. 3. p. 563-97.
2. ------------. A review of recent advances in semiconductor superlattices. *J. Vac. Sci. Technol. B* 1:120-5, 1983.

