

# The Superlattice Story with the Esaki Tunnel Diode

Leo Esaki

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Chairman, The Science & Technology Promotion Foundation of Ibaraki

## Report Documentation Page

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# Participants in the Quantum Revolution

Lamb  
1955

Bloch  
1952

Wigner  
1963

Rabi  
1944

Ting  
1976

Kantorovic  
1975

## 1979 Cockchafer Speech at Lindau

»Maikäfer-Rede« 1979,  
vlnr, vorne: I. Giaever, L. Esaki,  
J. Schwinger, P. Dirac,  
hinten: W. Lamb, F. Bloch,  
A. Kastler, E. Wigner, I. Rabi,  
S. Ting u. L. Kantorovic  
1979 cockchafer speech:  
(from the left, front row)  
I. Giaever, L. Esaki, J. Schwinger,  
P. Dirac; (behind) W. Lamb,  
F. Bloch, A. Kastler, E. Wigner,  
I. Rabi, S. Ting, L. Kantorovic



Giaever  
1973

Esaki  
1973

Schwinger  
1965

Dirac  
1933

from Science at First Hand – 50 years of the Meetings of Nobel Laureates in Lindau on Lake Constance

# QUANTUM PRINCIPLES INTO PRACTICE

Quantum Tunneling –

The Esaki Diode, Double-Barrier Resonant Tunnel Diodes, etc.

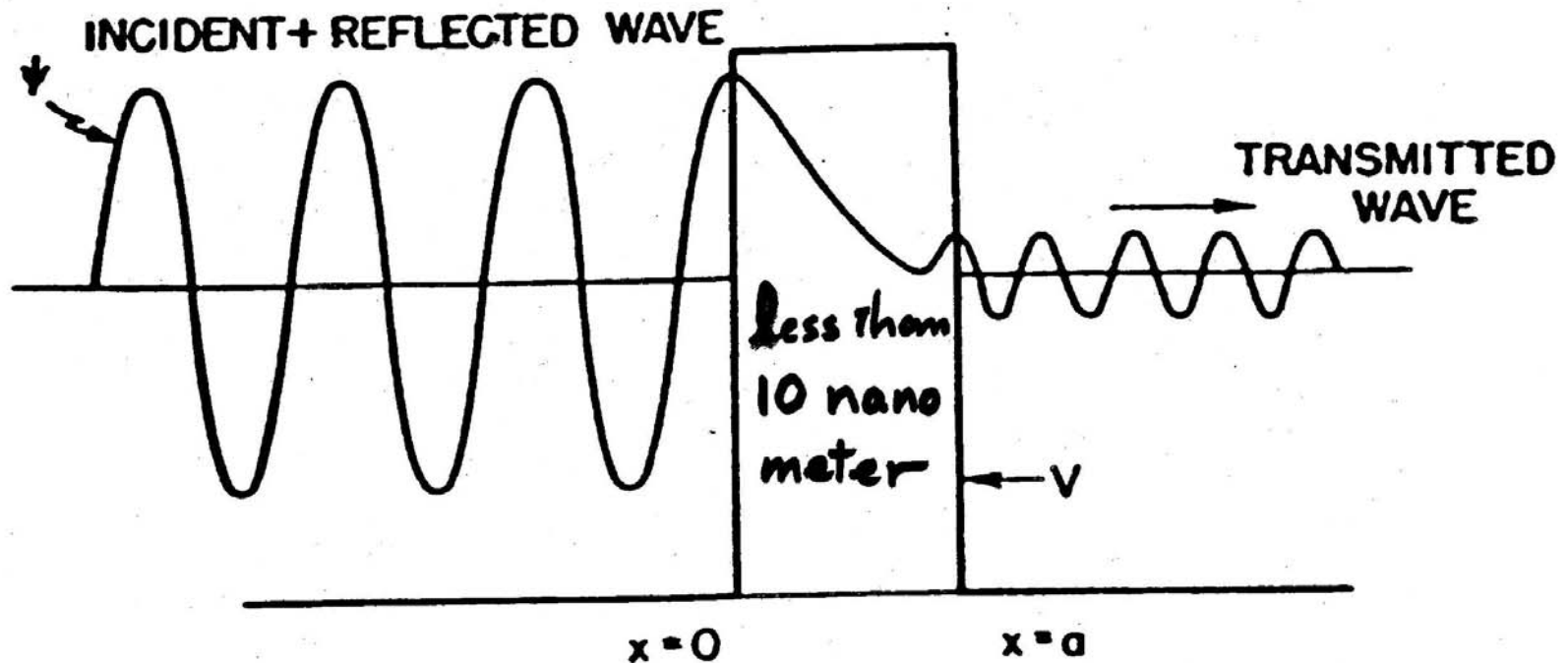
Quantum Nano-structures □

Man-made Superlattices, Wires, Dots, etc.

Quantum Informatics □

Quantum Teleportation, Quantum Computers, etc.

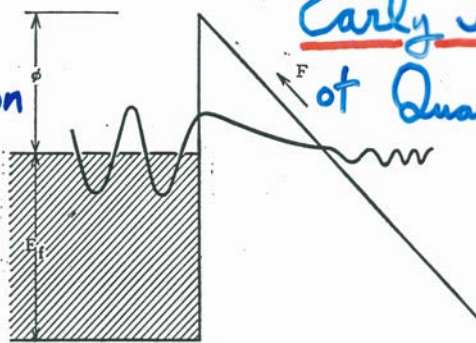
# Electron Tunneling



Quantum-Mechanical Effect

Fowler & Nordheim : 1928

- Field Emission
- Early Triumphs  
of Quantum Theory.



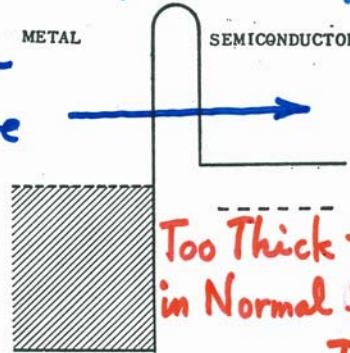
$$J = AF^2 \exp(-4(2m)^{1/2} \phi^{3/2} / 3\hbar F)$$

Fig. 1 Fowler-Nordheim tunneling.

Wilson, Frankel & Joffe, Nordheim : 1932

- Quantum Theory of Rectification :

- Zener Diode



Creative  
Failures,

Too Thick to Tunnel  
in Normal Semiconductor  
Diodes

$$J = J_s (\exp(\frac{eV}{kT}) - 1)$$

Fig. 2 Early model of metal-semiconductor rectifiers.

## Zener Effect

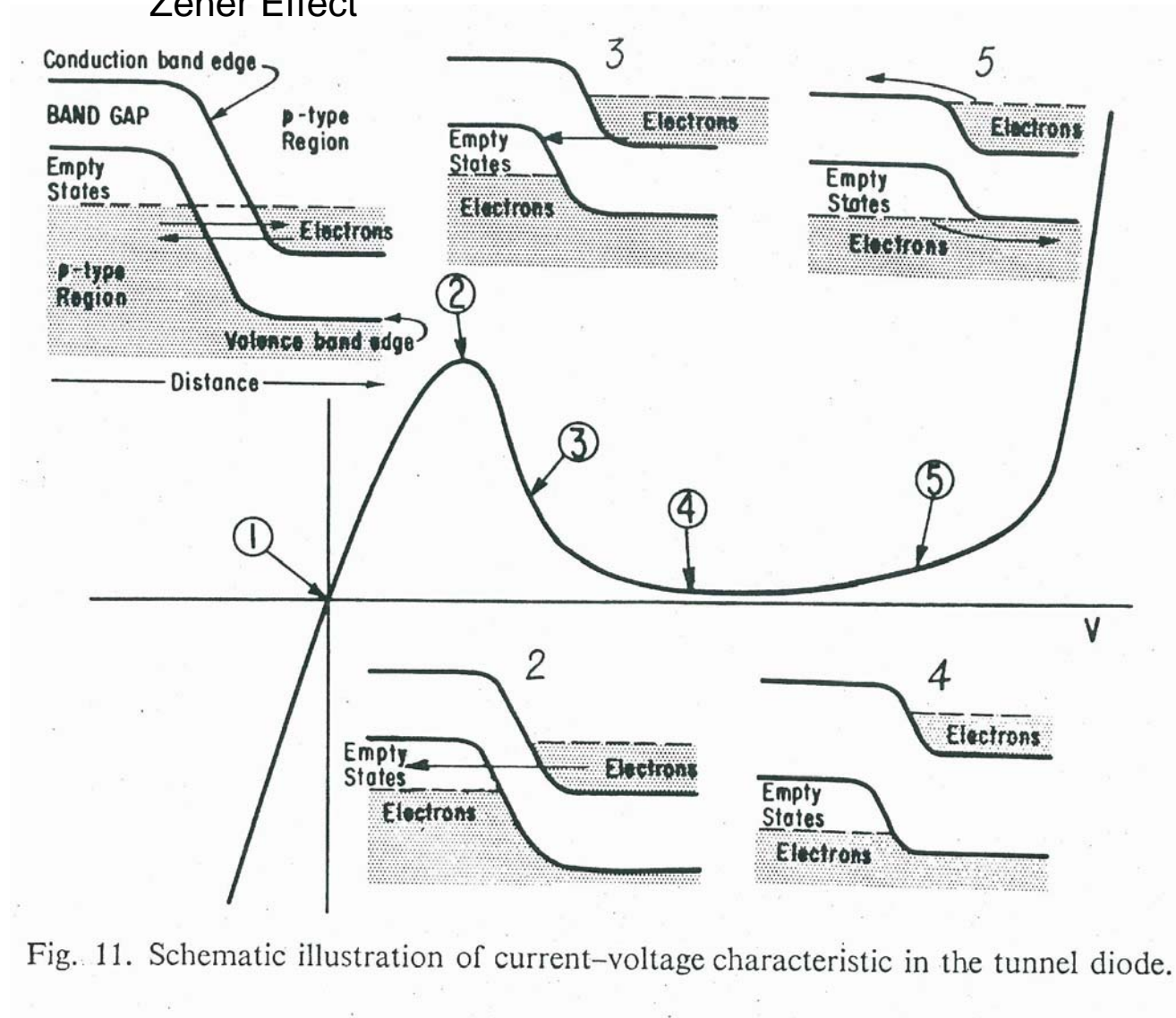


Fig. 11. Schematic illustration of current-voltage characteristic in the tunnel diode.

□□□□ Tunnel Diode 1957

## New Phenomenon in Narrow Germanium *p-n* Junctions

LEO ESAKI

*Tokyo Tsushin Kogyo, Limited, Shinagawa, Tokyo, Japan*

(Received October 11, 1957)

IN the course of studying the internal field emission in very narrow germanium *p-n* junctions, we have found an anomalous current-voltage characteristic in the forward direction, as illustrated in Fig. 1. In this *p-n* junction, which was fabricated by alloying techniques, the acceptor concentration in the *p*-type side and the donor concentration in the *n*-type side are, respectively,  $1.6 \times 10^{19} \text{ cm}^{-3}$  and approximately  $10^{19} \text{ cm}^{-3}$ . The maximum of the curve was observed at  $0.035 \pm 0.005$  volt in every specimen. It was ascertained that the specimens were reproducibly produced and showed a general behavior relatively independent of temperature. In the range over 0.3 volt in the forward direction, the current-voltage curve could be fitted almost quantitatively by the well-known relation:

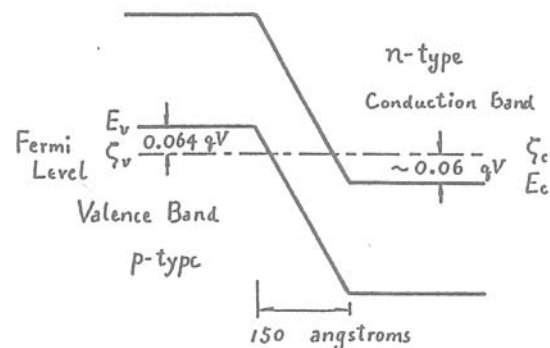
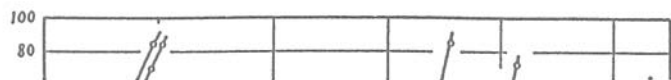


FIG. 2. Energy diagram of the *p-n* junction at 300°K and no bias voltage.

$I = I_s [\exp(qV/kT) - 1]$ . This junction diode is more conductive in the reverse direction than in the forward direction. In this respect it agrees with the rectification direction predicted by Wilson, Frenkel, and Joffe, and Nordheim 25 years ago.<sup>1</sup>



W. Brattain (55 yrs) visited Leo Esaki (32 yrs) at Sony in 1957

International Union of Pure and Applied Physics

**Solid State Physics**  
in Electronics and Telecommunications

Proceedings of an International Conference  
held in Brussels, June 2-7, 1958

# Crystals, Electronics, and Man's Conquest of Nature

W. SHOCKLEY

*Shockley Semiconductor Laboratory of Beckman Instruments, Inc.*

## Introduction

It is particularly appropriate that solid state physics and its applications to electronics should be the subject of an international symposium at the Brussels World's Fair. The Exposition is dedicated to showing man's progress in molding his environment to his liking, and electronics is one of his most powerful new tools in this endeavor. Furthermore, an important symbol of the Fair is the atomic arrangement of a crystal, and crystals are the subject-matter of solid state physics.

The most beautiful demonstration of the Zener effect so far achieved is presented at this symposium by L. Esaki of Tokyo. Esaki has studied  $p$ - $n$  junctions which are very heavily doped on both sides, so that there is a built-in field of the order of  $5 \times 10^5$  volt/cm. Under these conditions, current flows by the Zener mechanism even at zero voltage. Esaki finds that as forward bias is increased across the junction, this possibility of direct tunneling disappears and, as a consequence, he observes a predictable negative resistance region. The Zener effect is also dealt with from a theoretical point of view at this meeting by G. H. Wannier of Bell Telephone Laboratories.



W. Shockley (48 yrs), Leo Esaki (33 yrs) in 1958



1847

ALEXANDER  
GRAHAM  
BELL

1947

LEAVE THE BEATEN  
TRACK OCCASIONALLY  
AND DIVE INTO THE  
WOODS. YOU WILL BE  
CERTAIN TO FIND  
SOMETHING THAT  
YOU HAVE NEVER  
SEEN BEFORE

## **Examples in 1-D Mathematical Physics:**

**Resonant Electron Tunneling (1930s)**

**Kronig-Penney Bands (1931)**

**Tamm Surface States (1932)**

**Zener Band-to-Band Tunneling (1934) \***

**Stark Ladders including Bloch Oscillations(1940s)\***

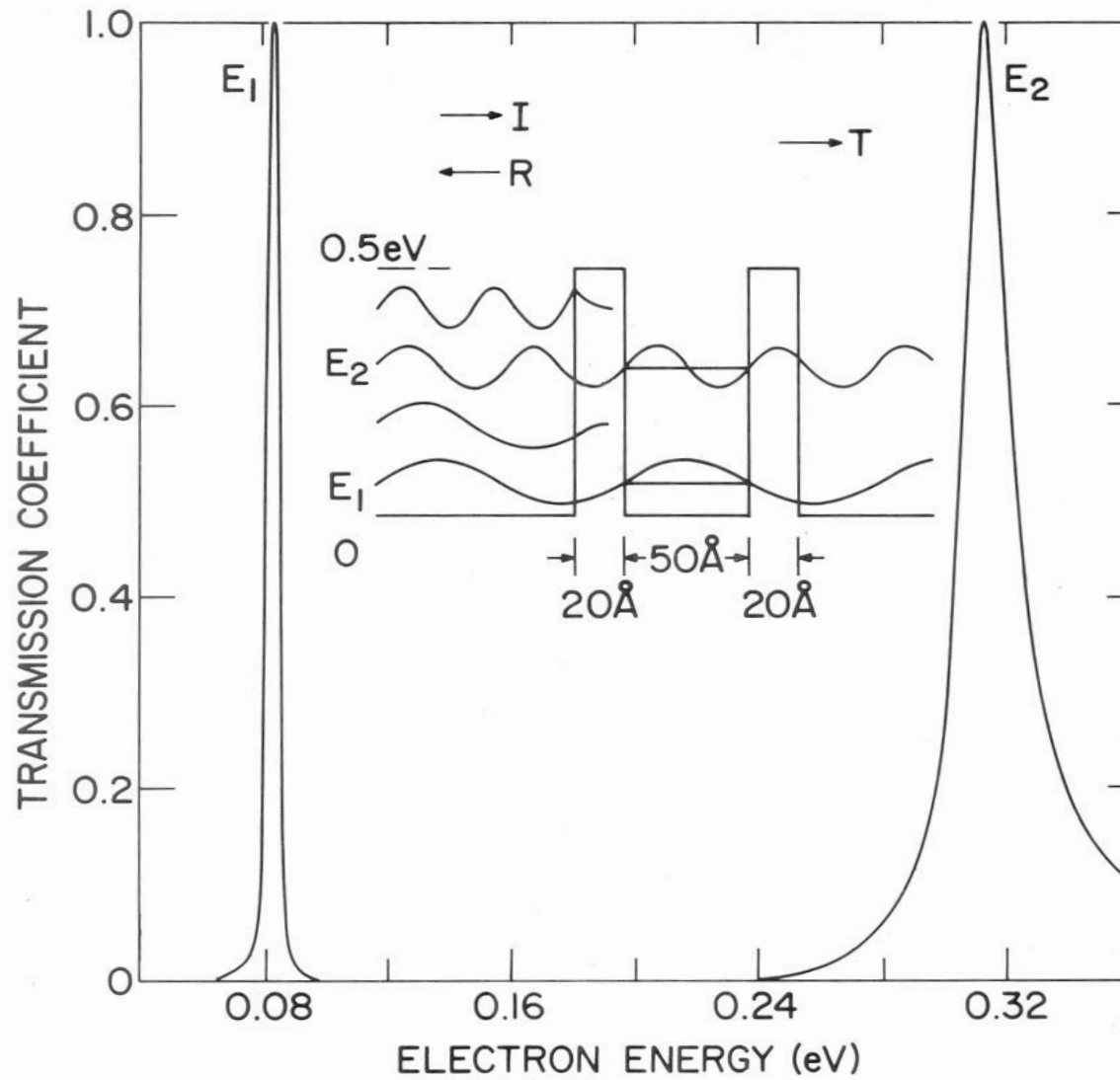
**Those which had remained textbook exercises,  
could for the first time, be practiced in a  
laboratory:**

## **Do-It-Yourself Quantum Mechanics with MBE**

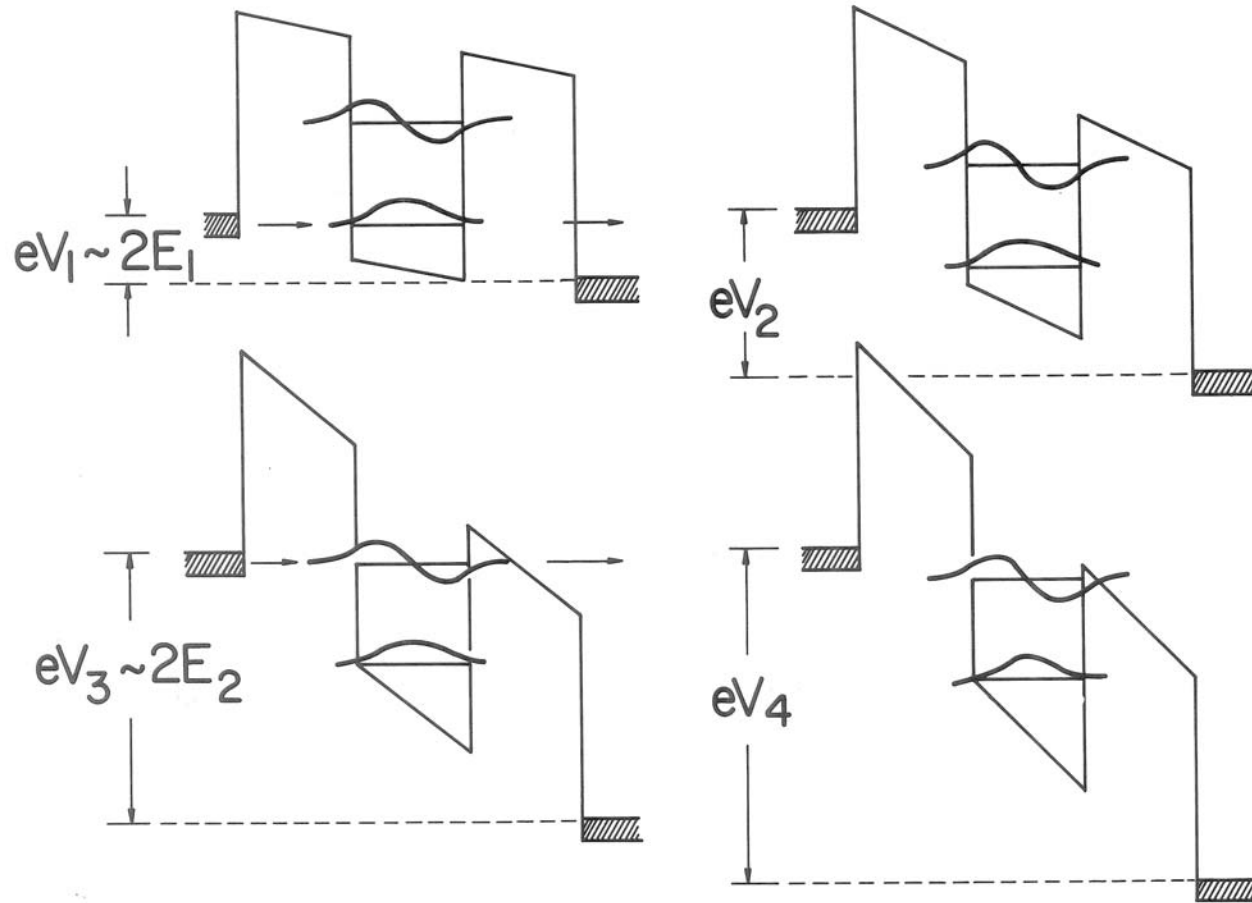
**This approach makes a “gedanken-experiment” a  
reality and offers a new degree of freedom in  
semiconductor research.**

**\* not observable at ordinary circumstances**

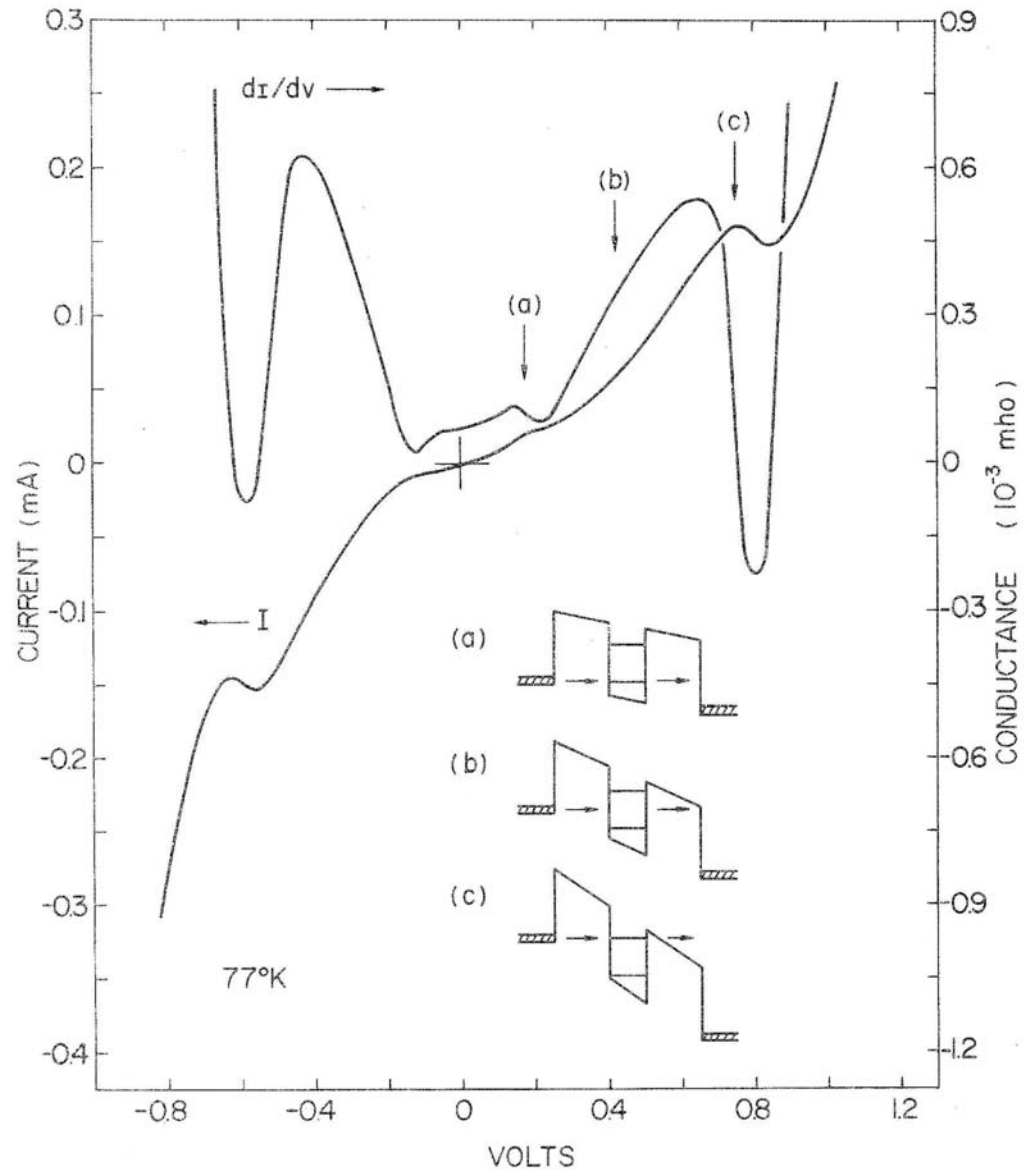
# Resonant Tunneling



Total Energy and Transverse Momentum  
Should be conserved.

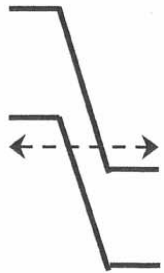


# Chang, Esaki and Tsu (1974)



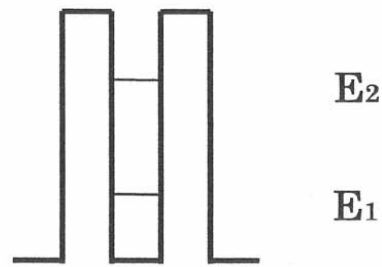
**1957**

**bipolar**



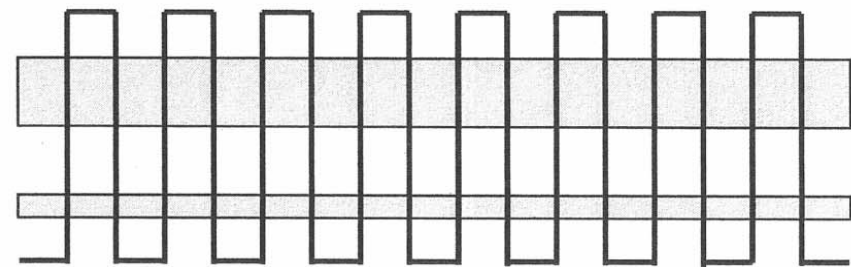
**Esaki  
Tunnel  
Diode**

**unipolar**



**Double Barrier  
Resonant Tunnel  
Diode**

**1969**



**Superlattice  
Low-dimensional Quantum Structure**

**From left to right, the Esaki diode,  
a resonant tunnel diode and a superlattice.**

IEEE

SOLID STATE DEVICE RESEARCH CONFERENCE

Rochester, New York

June 23-26, 1969

Session 4 □ Junction and Other Devices

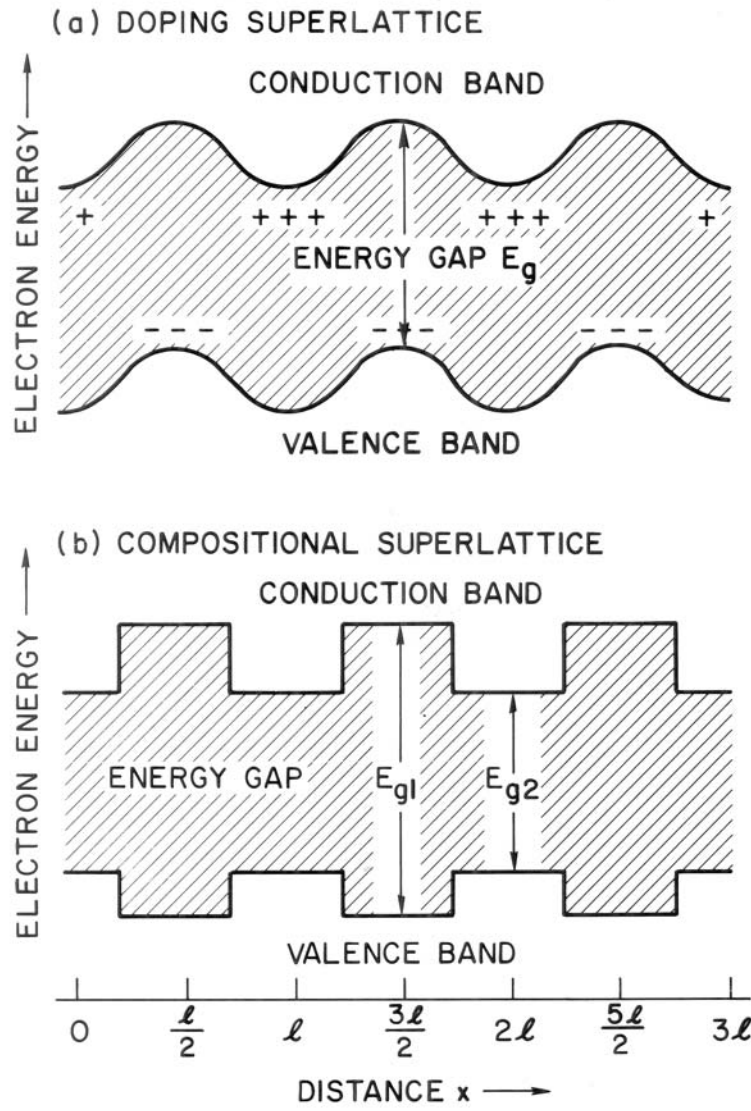
Morning Session

Tuesday, June 24, 1969

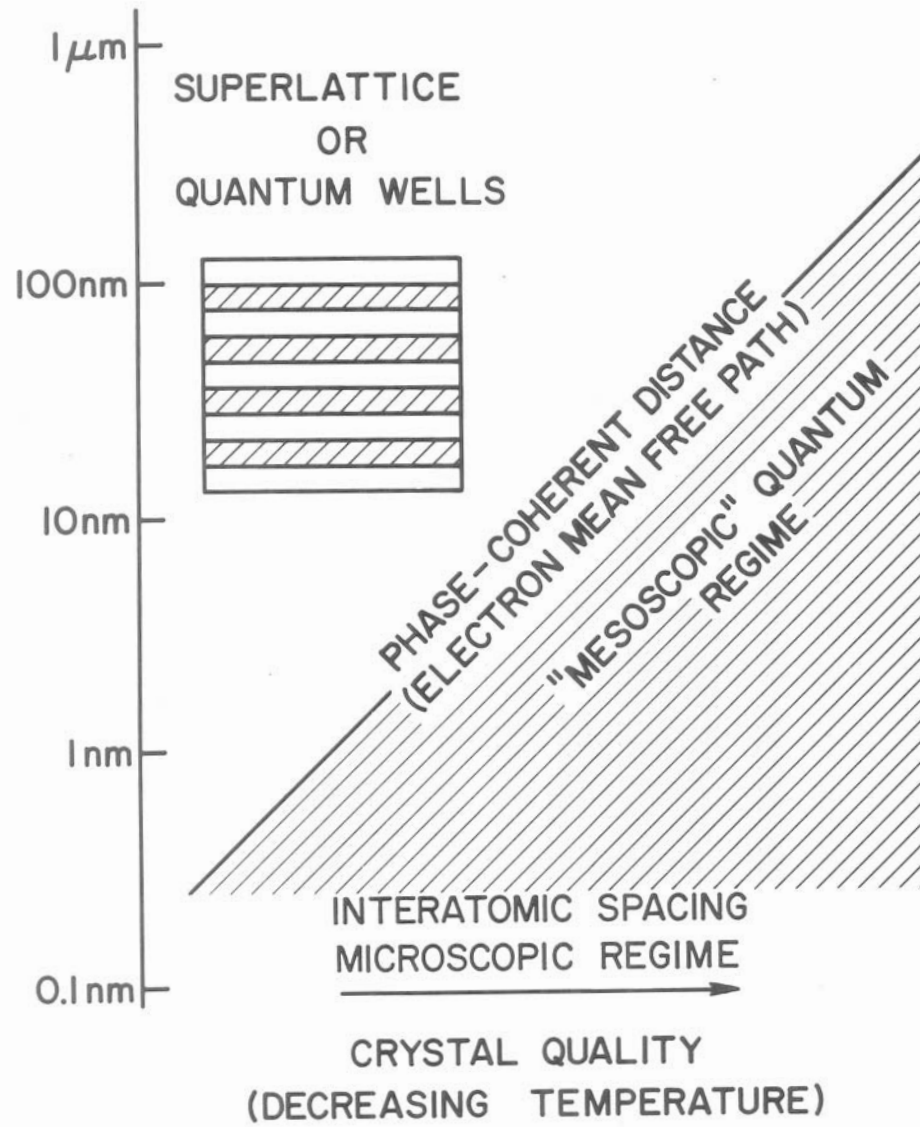
Chairman: L. Esaki  
IBM Watson Research Center

Organizer: R. Stratton  
Texas Instruments Inc.

- |    |  |   |
|----|--|---|
| 1. | The Schottky Barrier Cold Cathode  | C.A. Stolte, J. Vilms, and R.J. Archer<br>Hewlett-Packard Laboratories              |
| 2. | Physical Model for Burst Noise In Semiconductor Devices  | S.T. Hsu and R.J. Whittier<br>Fairchild Semiconductor                               |
| 3. | Ultra-High Speed Power Thyristor Turn-On by Laser Triggering   | J.S. Roberts<br>Westinghouse Research Laboratories                                  |
| 4. | Field Dependence of Space Charge and Switching Effects in Semiconductors Having High Trap Density of Amorphous Structure | R.H. Krambeck, P.T. Penousis, and W.C. Johnson<br>Bell Telephone Laboratories, Inc. |
| 5. | A Thin Film Inductance Using Thermal Filaments   | C.N. Berglund and R.H. Walden<br>Bell Telephone Laboratories, Inc.                  |
| 6. | A Superconducting Tunneling Diode  | W.C. Scott<br>Texas Instruments Incorporated  |
| 7. | Superlattice and Negative Conductivity in Semiconductors   | L. Esaki and R. Tsu<br>IBM Watson Research Center                                   |



MACROSCOPIC REGIME



## Electric Quantization

(Wannier-Stark ladder—Bloch Oscillation)

$$E_n = E_0 + n\hbar\omega_B \quad : \quad n = \pm 1, \pm 2, \pm 3, \dots$$
$$\hbar\omega_B = eEd > \frac{\hbar}{\tau}$$

The effect is hardly observable in ordinary crystals. But, because of the large lattice constants of superlattices, the condition could be fulfilled with reasonable field strengths,  $E \leq 10^4$  V/cm.

## Magnetic Quantization

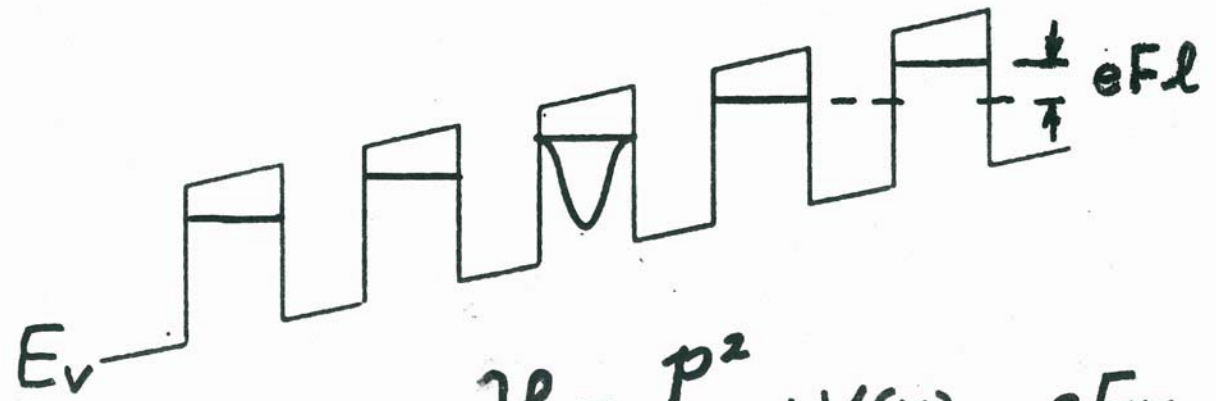
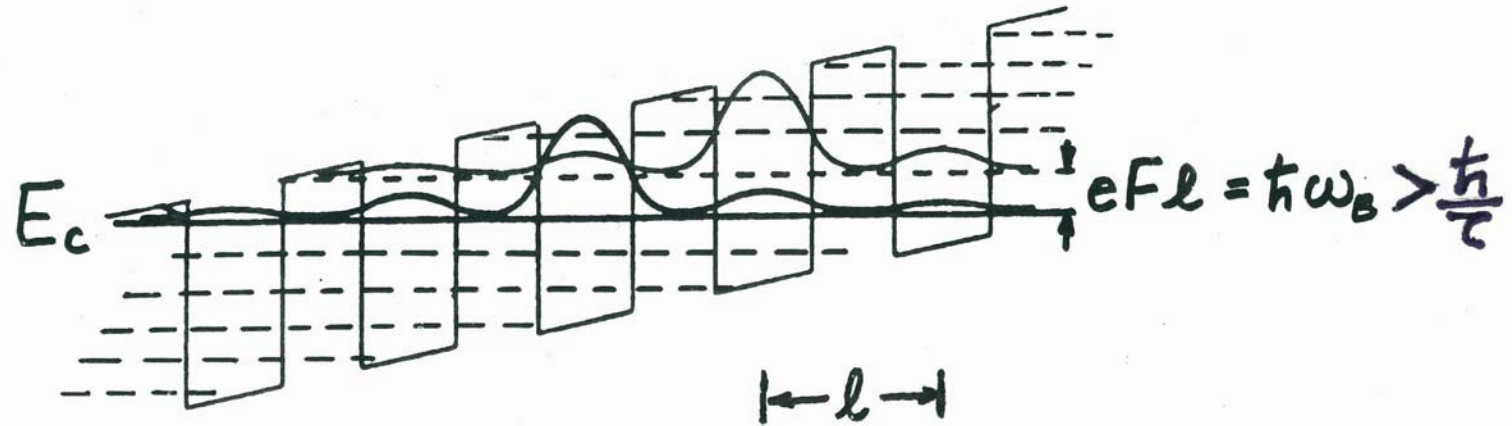
(Landau levels)

$$E_n = \left(n + \frac{1}{2}\right)\hbar\omega_c + \frac{\hbar^2 k_2^2}{2m} \quad : \quad n = 0, 1, 2, \dots$$
$$\omega_c = \left(\frac{|e|\hbar}{m}\right)B > \frac{1}{\tau}$$

# STARK LADDERS

$$\psi(x) \quad E$$

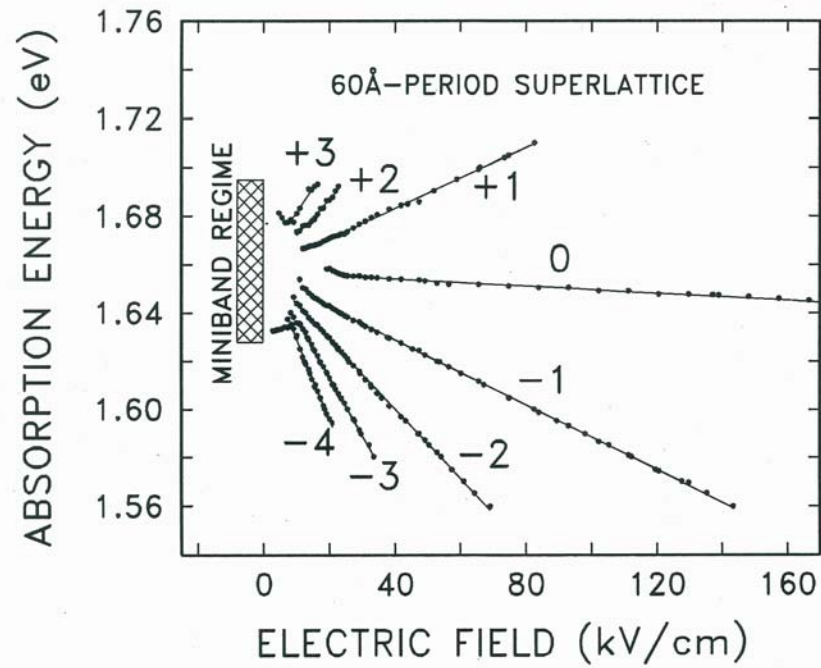
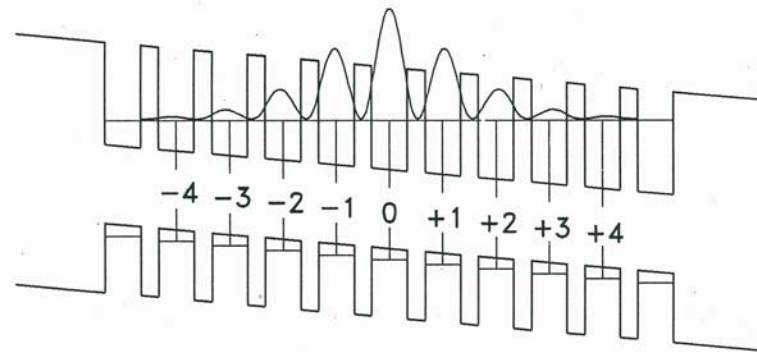
$$\psi(x-nl) \quad E - neFl$$

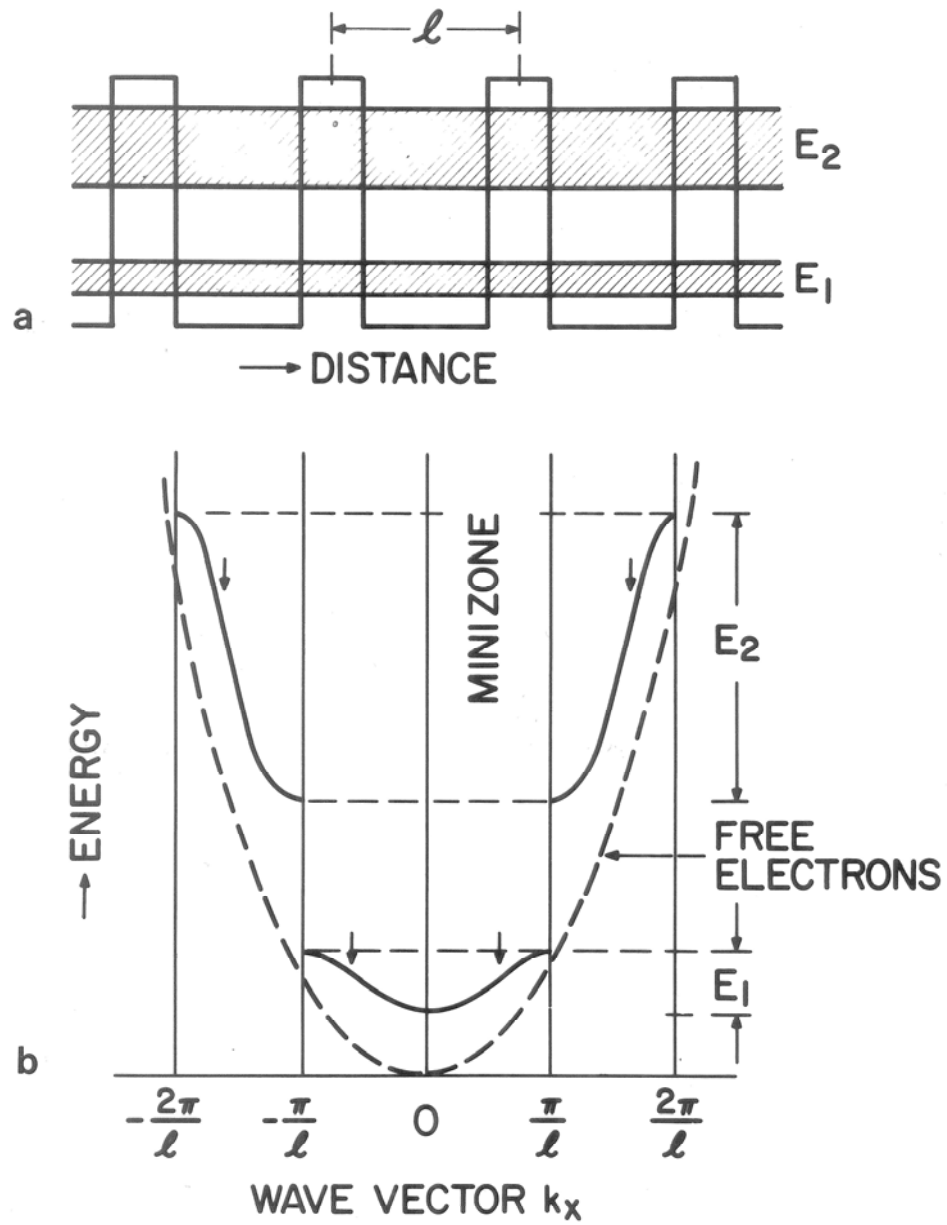


$$\mathcal{H} = \frac{p^2}{2m} + V(r) - \underline{eFr}$$

# Mendez, Agullo-Rueda and Hong (1988)

COHERENCE AND LOCALIZATION IN SUPERLATTICES





## The Equation of Electron Motion (Path Integration Method)

$$\hbar \frac{\partial k_z}{\partial t} = eF, \quad v_z = \frac{1}{\hbar} \frac{\partial E}{\partial k_z}$$

$$\frac{dv_z}{dt} = \frac{eF}{\hbar^2} \left( \frac{\partial^2 E}{\partial k_z^2} \right), \quad E = \frac{E_1}{2} (1 - \cos k_z \ell)$$

$$v_d = \int_0^{\infty} \exp(-t/\tau) dv_z$$

$$= \frac{eF}{\hbar^2} \int_0^{\infty} \left( \frac{\partial^2 E_z}{\partial k_z^2} \right) \exp(-t/\tau) dt$$

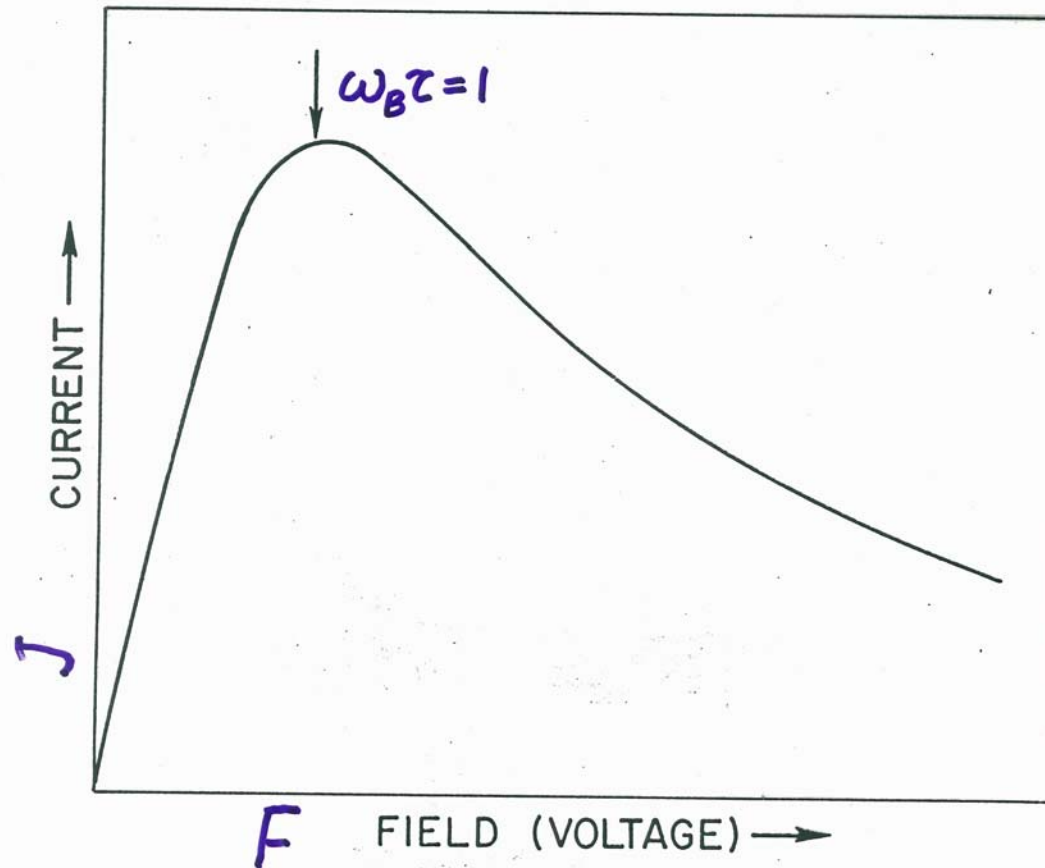
$$J = nev_d = \frac{enF\tau}{m^*} \left( \frac{1}{1 + \left( \frac{eF\tau\ell}{\hbar} \right)^2} \right)$$

$$J = \frac{\hbar n}{m^* l} \omega_B \tau \left( \frac{1}{1 + (\omega_B \tau)^2} \right)$$

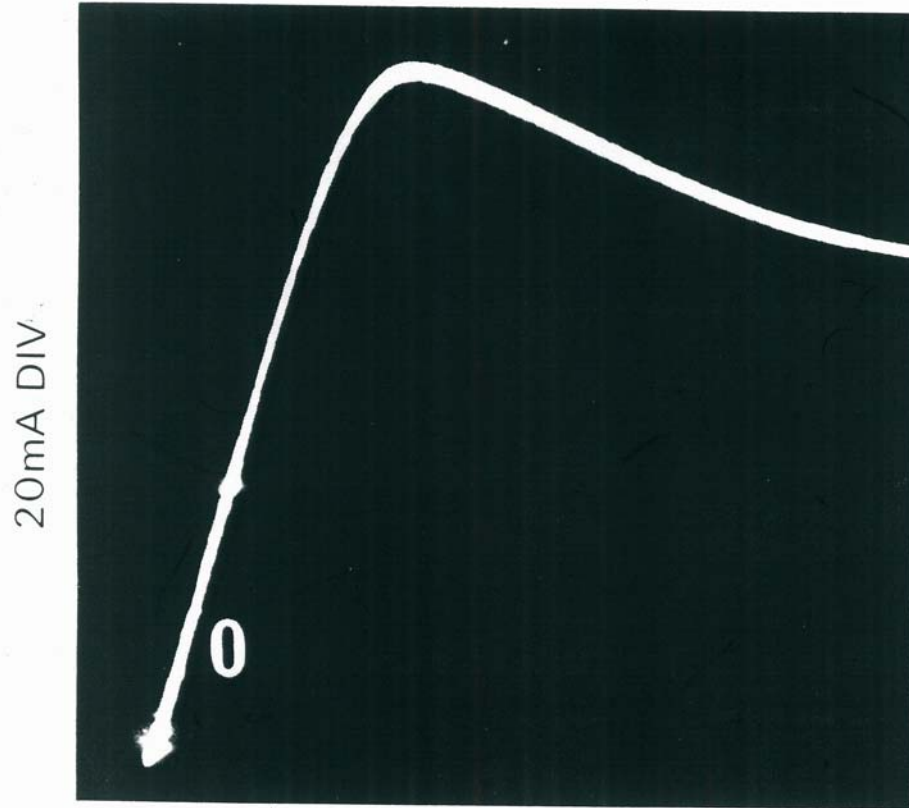
$$\omega_B = eFl/\hbar$$

$\omega_B \tau > 1$  for Negative Resistance

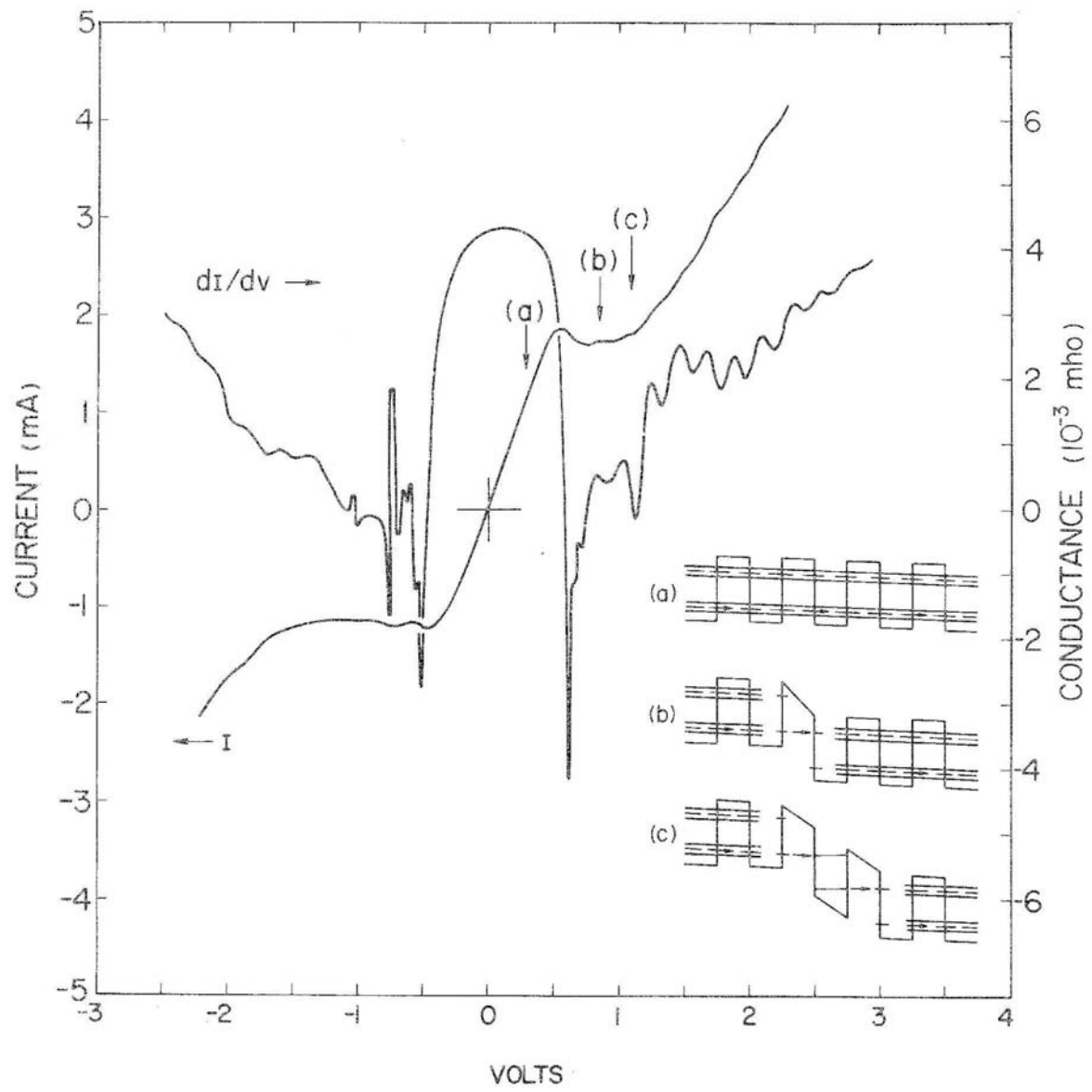
$\omega_B \tau > 2\pi$  for Bloch Oscillations



Esaki, Chang, Howard and Rideout (1972)



IV DIV  
Current-voltage Trace  
for a MBE-grown GaAs-GaAlAs  
Superlattice of 70 Å period.



**Observation of Esaki-Tsu Negative Differential Velocity in GaAs/AlAs Superlattices**

A. Sibille, J. F. Palmier, and H. Wang

*Laboratoire de Bagneux, Centre National d'Etudes des Télécommunications, 196 Avenue Henri Ravera, 92220 Bagneux, France*

F. Mollot

*Centre National de la Recherche Scientifique, L2M, 196 Avenue Henri Ravera, 92220 Bagneux, France*

(Received 10 July 1989)

The perpendicular peak velocity and critical field have been measured in a series of GaAs/AlAs superlattices as a function of the miniband width and miniband position relative to the AlAs  $X$  confined levels. The data cannot be explained by the electric-field localization mechanism [R. Tsu and G. Döhler, *Phys. Rev. B* **12**, 680 (1975)] in the range of superlattice parameters investigated, but are qualitatively understood in terms of electron acceleration within the miniband [L. Esaki and R. Tsu, *IBM J. Res. Develop.* **14**, 61 (1970)].

PACS numbers: 73.20.Dx, 72.20.Ht, 73.40.Gk

## POSSIBILITY OF THE AMPLIFICATION OF ELECTROMAGNETIC WAVES IN A SEMICONDUCTOR WITH A SUPERLATTICE

R. F. Kazarinov and R. A. Suris

A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR, Leningrad  
Translated from *Fizika i Tekhnika Poluprovodnikov*, Vol. 5, No. 4,  
pp. 797-800, April, 1971  
Original article submitted January 5, 1971

The possibility of the appearance of a negative differential resistance in semiconductors whose conduction (or valence) band is split into several subbands (minibands) has been considered in [1-3] in the case of a potential whose period is greater than that of the crystal lattice. This negative resistance is due to the Bragg reflections experienced by an electron accelerated in an external electric field. This mechanism is realized if

$$\frac{\hbar}{\tau} < eaF \ll I_0.$$

in a plane perpendicular to the period is fixed:

$$E_n^{(\alpha)}(p_{\perp}) = E^{(\alpha)} - eaFn + \frac{p_{\perp}^2}{2m}.$$

Here,  $n$  is an integer and  $E^{(\alpha)}$  is the average energy of the  $\alpha$ -th band. The wave function of an electron is centered on a superlattice site  $n$  and extends over several sites along the direction of the field  $F$ . The number of these sites is of the order of  $I_{\alpha}/eaF$ , where  $I_{\alpha}$  is the width of the  $\alpha$ -th miniband. If  $eaF > I_{\alpha}$ , an electron of the  $\alpha$ -th band is localized within one well. Under these con-

## High-Power Infrared (8-Micrometer Wavelength) Superlattice Lasers

Gaetano Scamarcio,\* Federico Capasso,† Carlo Sirtori,‡  
Jerome Faist, Albert L. Hutchinson, Deborah L. Sivco,  
Alfred Y. Cho

A quantum-cascade long-wavelength infrared laser based on superlattice active regions has been demonstrated. In this source, electrons injected by tunneling emit photons corresponding to the energy gap (minigap) between two superlattice conduction bands (minibands). A distinctive design feature is the high oscillator strength of the optical transition. Pulsed operation at a wavelength of about 8 micrometers with peak powers ranging from  $\sim 0.80$  watt at 80 kelvin to 0.2 watt at 200 kelvin has been demonstrated in a superlattice with 1-nanometer-thick AlInAs barriers and 4.3-nanometer-thick GaInAs quantum wells grown by molecular beam epitaxy. These results demonstrate the potential of strongly coupled superlattices as infrared laser materials for high-power sources in which the wavelength can be tailored by design.

Semiconductor superlattices consist of a periodic stack of nanometer-thick layers of two materials (quantum wells and barriers) (1). The period  $d$  of this artificial crystal is typically much larger ( $\sim 5$  nm) than the lattice constant of the bulk crystalline constituents ( $\sim 0.5$  nm). This superimposed po-

electrically pumped Bloch oscillator remains elusive.

We report a coherent infrared (IR) source based on strongly coupled superlattices that demonstrates the potential of these materials for lasers in the technologically important mid-IR spectrum. Laser ac-



## OBSERVATION OF BLOCH OSCILLATIONS IN A SEMICONDUCTOR SUPERLATTICE

Karl Leo, Peter Haring Bolivar, Frank Brüggemann, and Ralf Schwedler

Institut für Halbleitertechnik, RWTH Aachen,  
Sommerfeldstrasse 24, W-5100 Aachen, Germany

Klaus Köhler

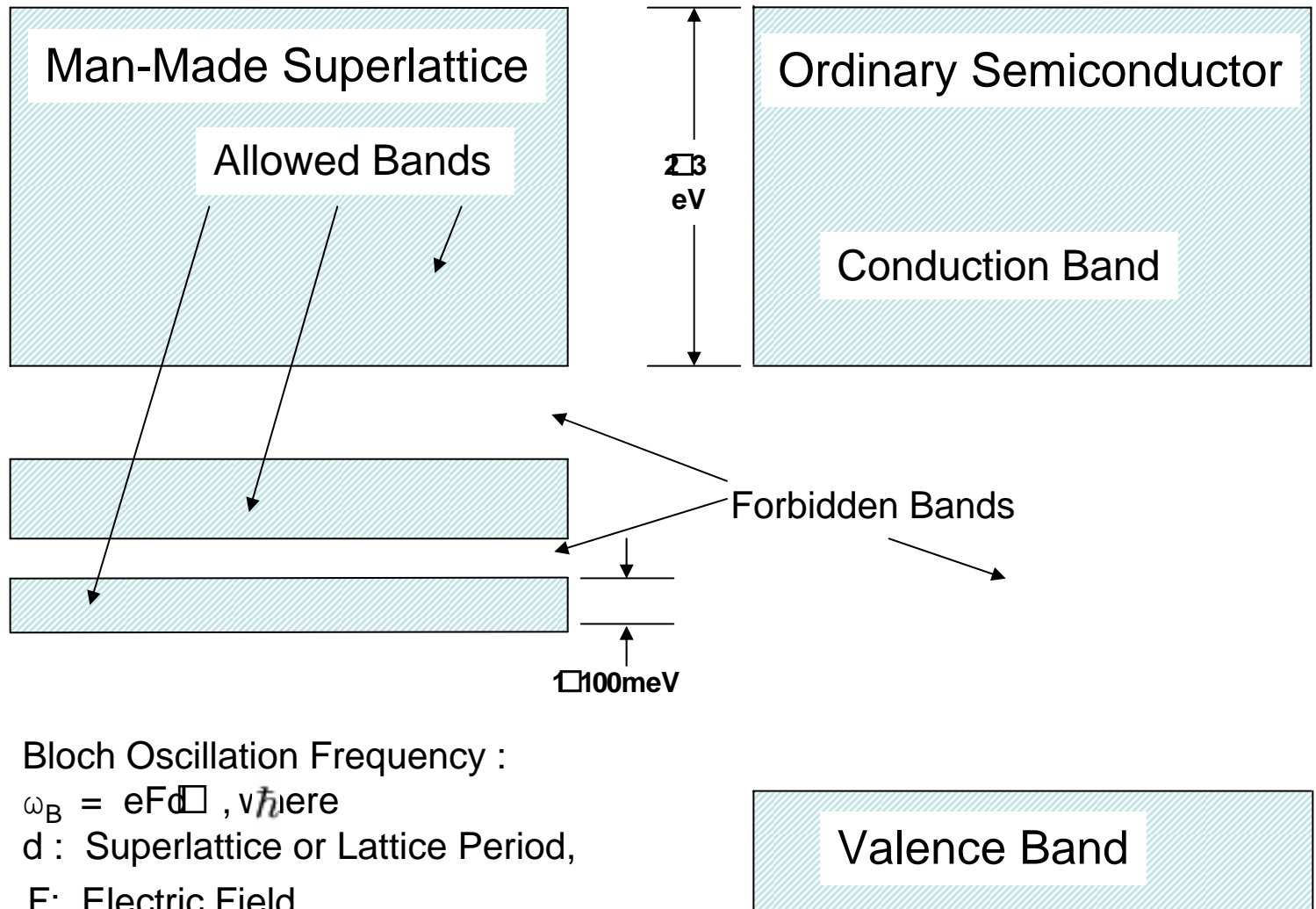
Fraunhofer-Institut für angewandte Festkörperphysik,  
Tullastrasse 72, W-7800 Freiburg, Germany

Received 29 September 1992 by G. Güntherodt

**We report unambiguous experimental evidence for electron Bloch oscillations: The transient four-wave mixing signal of a biased semiconductor superlattice shows a periodic modulation with a time constant expected from Bloch oscillation theory. The oscillation frequency can be tuned over 400% with the applied electric field. The electron performs up to four oscillation cycles before the coherence is lost.**

## Historical Events of Bloch Oscillations

- **Felix Bloch**, Z. Physik 52, 555 (1928) “Über die Quantenmechanik der Elektronen in Kristallgittern”  
The quantum theory of electrons in crystal lattice, implicating Bloch oscillations.
- **Clarence Zener**, Proc. R. Soc. London, Ser. A145, 523 (1934) “A Theory of the Electrical Breakdown of Solid Dielectrics”  
The theoretical treatment of Zener tunneling and Bloch oscillations.
- **Leo Esaki and Ray Tsu**, IBM J. Res. Dev. 14, 61 (1970) “Superlattice and Negative Conductivity in Semiconductors”  
The first proposal of a semiconductor superlattice with novel properties such as a negative resistance or Bloch oscillations.
- **Karl Leo et.al.**, Solid State Communications 84, 943 (1992) “Observation of Bloch Oscillations in a Semiconductor Superlattice”  
The first experimental confirmation of Bloch oscillations.

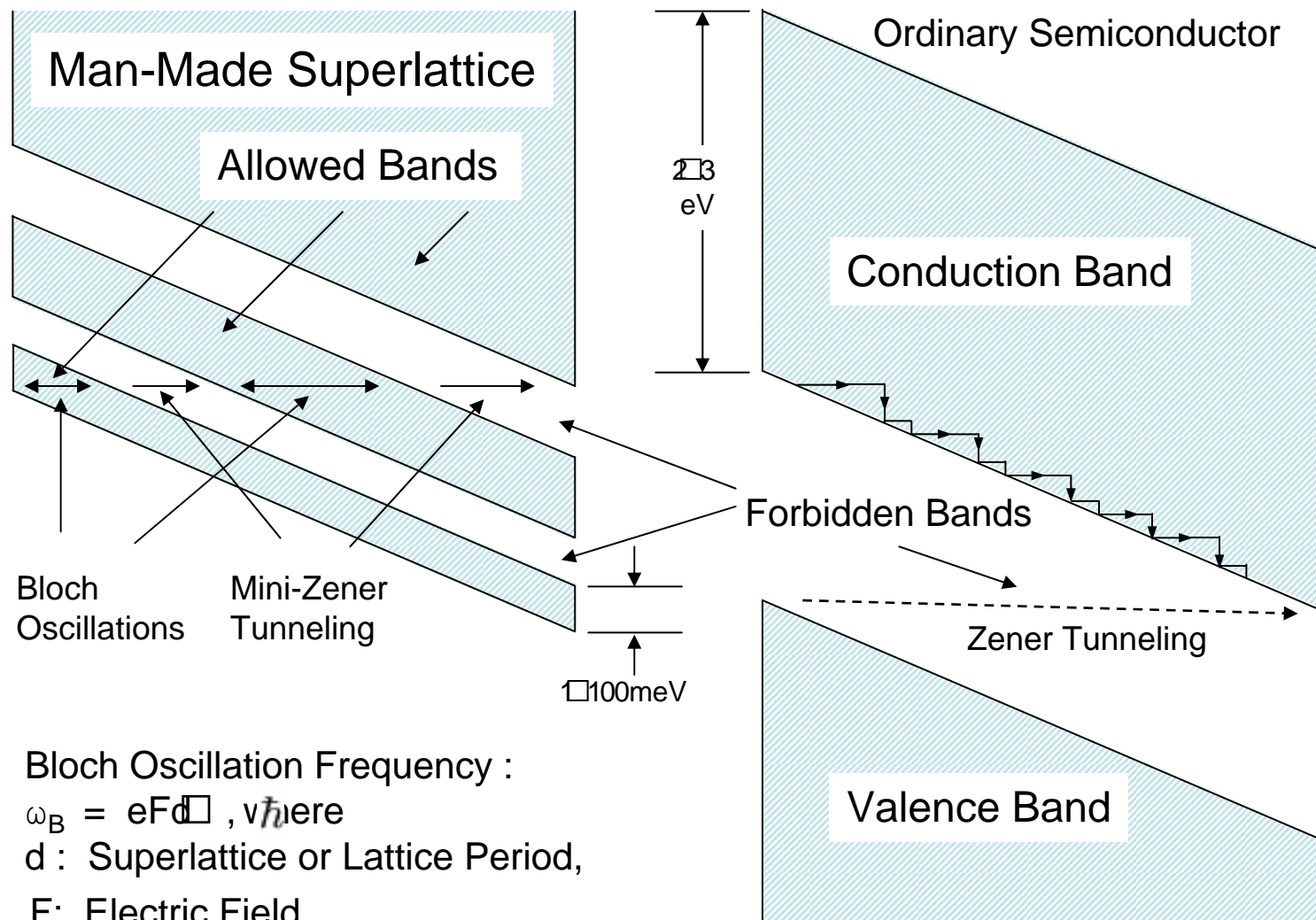


Bloch Oscillation Frequency :

$$\omega_B = eFd / \hbar, \text{ where}$$

d : Superlattice or Lattice Period,

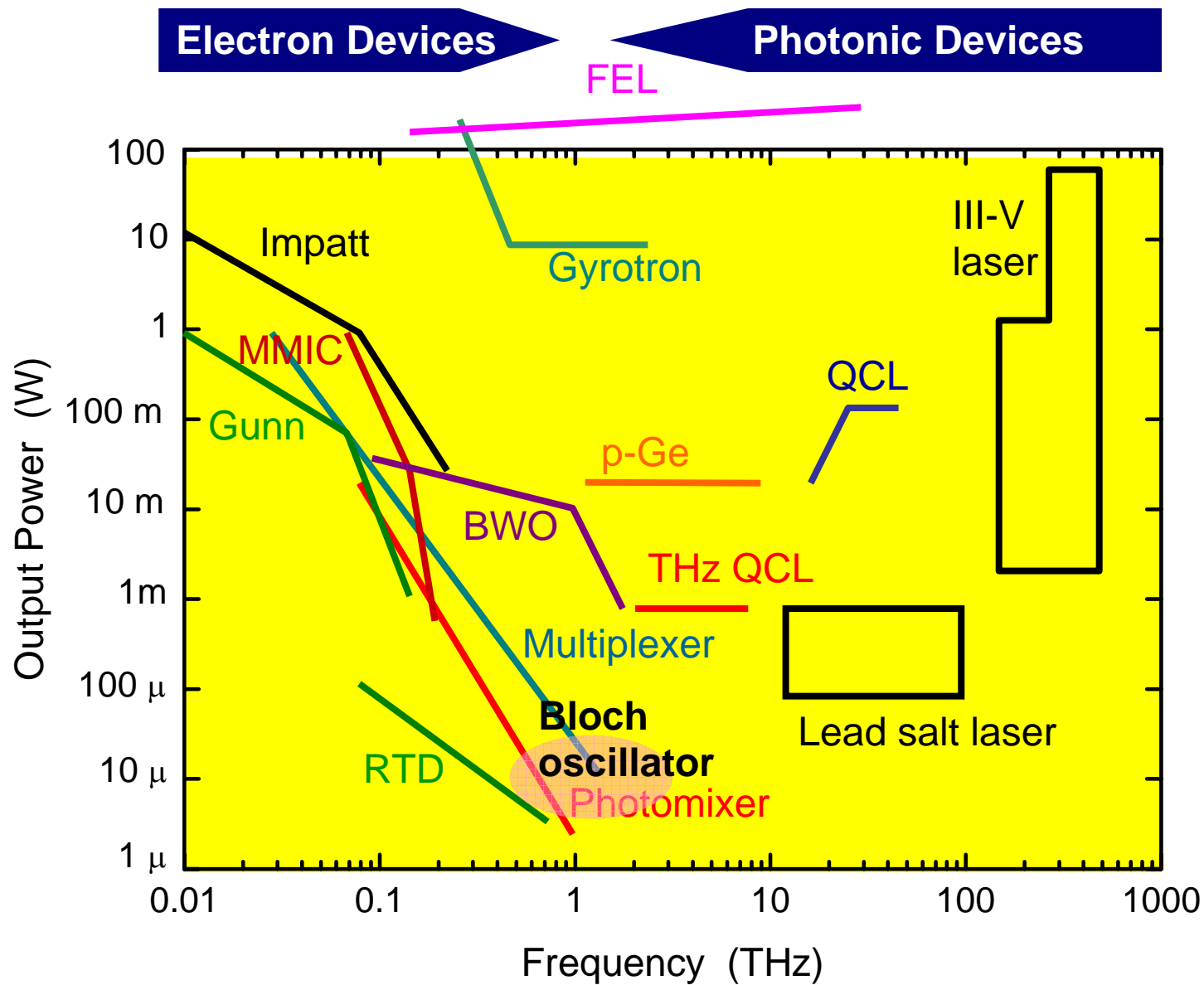
F: Electric Field



Bloch oscillation in semiconductor superlattices is the macroscopic quantum effect similar to the Josephson effect observed in weakly coupled superconductors. In both cases, if a DC electric field is applied to the system, an AC field is generated.

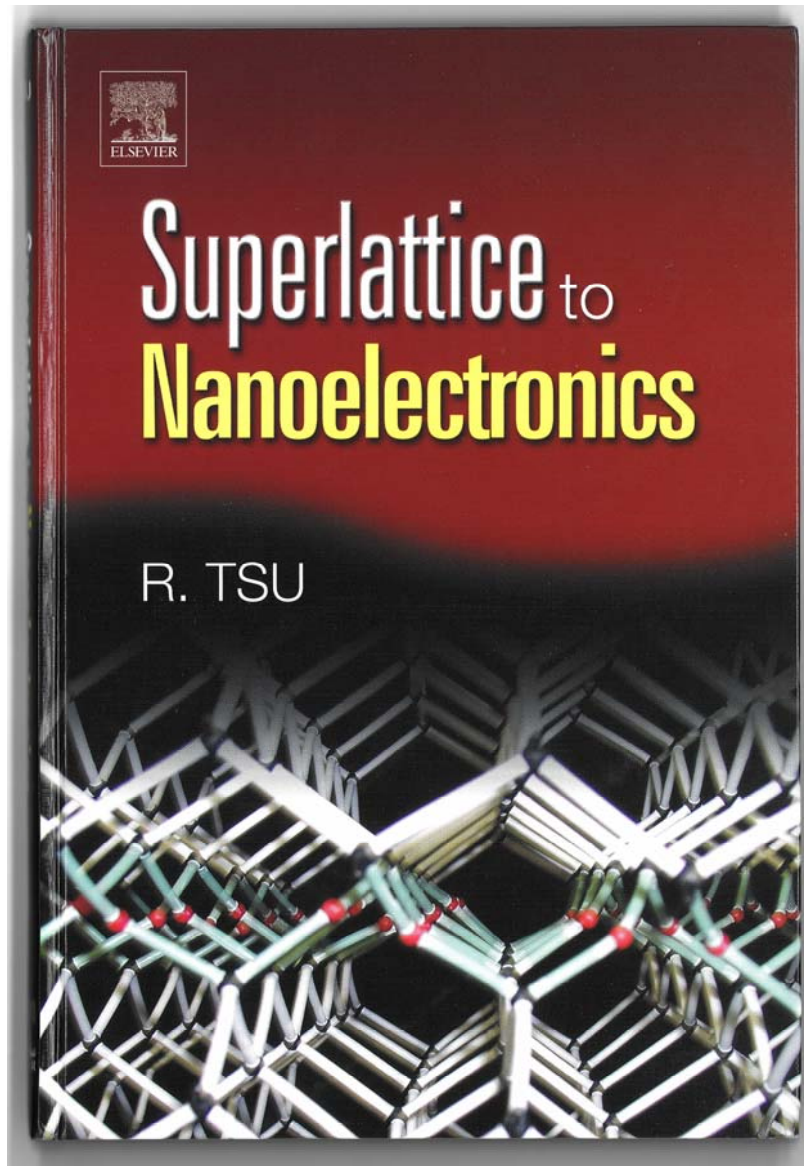
In Bloch oscillation, the frequency  $\nu_B$  is given by  $eFd/h = Fd/2\Phi_0$  where  $F$  is the uniform electric field strength,  $d$  is the superlattice constant,  $h$  denotes Planck's constant and  $\Phi_0$  is the unit of the flux quantum, whereas in the Josephson effect, the frequency  $\nu_J$  is given by  $2eV/h = V/\Phi_0$  where  $V$  is an applied voltage.

# Technology Gap in the THz Range





Raphael Tsu and Leo Esaki (right) in 1975



Ray Tsu, who was involved in the very early stage of the development of man-made superlattices, recently wrote a book entitled “Superlattice to Nanoelectronics”, where he stated

*“ Frankly, without Esaki’s experience and forcefulness, I would have given up ”*

indicating tough environment, and also mentioned what I said to him on one occasion,

*“ Experts are not always right ”*

## Referee's comments, rejecting for publication in Physical Review

In summary, then, **the paper is highly speculative and presents little material not already known and understood.** While one should not arbitrarily dismiss speculative papers per se, in a case such as the present where an experimental test of the speculation is close at hand I believe one should incorporate the material of the paper into one which reports the performance of the device so constructed. The paper as it now stand has the flavor of a publication whose principal purpose is to establish priority of an interesting idea. **Such arguments can be settled by reference to internal laboratory reports, and already overcrowded journals should not be burdened with these matters.**

L. Esaki

R. Tsu

## **Superlattice and Negative Differential Conductivity in Semiconductors\***

**Abstract:** We consider a one-dimensional periodic potential, or "superlattice," in monocrystalline semiconductors formed by a periodic variation of alloy composition or of impurity density introduced during epitaxial growth. If the period of a superlattice, of the order of  $100\text{\AA}$ , is shorter than the electron mean free path, a series of narrow allowed and forbidden bands is expected due to the subdivision of the Brillouin zone into a series of minizones. If the scattering time of electrons meets a threshold condition, the combined effect of the narrow energy band and the narrow wave-vector zone makes it possible for electrons to be excited with moderate electric fields to an energy and momentum beyond an inflection point in the  $E-k$  relation; this results in a negative differential conductance in the direction of the superlattice. 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.

## **This Week's Citation Classic®**

CC/NUMBER 28  
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**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 *SCI*® indicates that this paper has been cited in over 405 publications.]

**Leo Esaki**  
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May 13, 1987

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.

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 Semicon-

Esaki and his coworkers' pioneering research on superlattices and quantum wells in the 1970s and 1980s triggered a wide spectrum of experimental and theoretical investigations resulting in not only the observation of a number of intriguing new phenomena such as

differential negative resistance,

high electron mobilities,

large excitonic binding energies,

large Stark shifts,

distinct Wannier-Stark ladders and Bloch oscillations,

but also the emergence of a new class of transport and optoelectronic devices such as

high electron-mobility transistors (HEMT),

high-speed resonant tunnel diodes,

high-performance injection lasers with quantum wells,

high-power cascade superlattice lasers.

## ARO CASE STUDIES

*This case study is one of a series summarizing research activities sponsored under the ARO contract research program. The principal motivation is to document examples of the long term commitment of the U.S. Army to science and technology. Analysis of the events surrounding research accomplishments also provides valuable "lessons learned" concerning the management of long term investments characteristic of research. Descriptions of program initiatives are also presented in this series to stimulate innovative R&D approaches and to support technology transfer.*

*The Army Research Office and its predecessor organizations have sponsored research for more than forty years. The results of this investment have materialized in several high profile Army capabilities, for example the application of lasers in the precision guidance of munitions. Although the returns are large, the research investment requires a long term perspective. Furthermore, the details of the connection between the technological success stories and the antecedent research are frequently obscured in time. This brochure and other descriptions are designed to document a technical "audit trail" of the Army investments in science and technology.*

*ARO is the point organization for the Army's research, development, and acquisition process. Its mission is to bridge the gap between the national scientific talent and Army technological needs. This task is carried out by a cadre of staff scientists and engineers with significant experience in advanced research and the use of an extensive network of the country's best scientific and engineering talent. A major function of the ARO staff is to translate new scientific opportunities which may be exploited for Army use and to define Army needs in technology to the at-large research community.*

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# The Superlattice Story

*The superlattice concept proposed under Army sponsored research triggered a revolution in solid state physics. Since the announcement by Leo Esaki and Raphael Tsu in 1970, thousands of scientific papers by laboratories throughout the world have been published. By the end of 1996 more than 465 patents have been awarded on topics relating to the application of microelectronic or optoelectronic devices, and techniques for producing superlattice materials.*

*The field is parallel to the evolution of the design and engineering of chemicals, electronics, and structures to produce large scale, macro level effects. In this case, the origins are traceable to the singular contributions of the very small team sponsored by the U.S. Army Research Office in the late 1960s at IBM's central research facility located in Yorktown Heights, New York.*

## Perspectives

It may seem difficult to believe, but there was a time when solid state physics was based on a model of an infinitely extending periodic lattice of atomic sites, far removed from a terminating surface or any interruption in the crystalline periodicity. In a 1969 proposal to the Army Research Office based on an IBM Yorktown Heights Research Note, Esaki and Tsu suggested the upset of this normally desirable periodicity by varying either impurity concentrations, alloy compositions, or both during the epitaxial growth of the crystal. Their proposal indicated that such structures "should show entirely new properties not seen in the host crystal ... this means that we now are able to produce a man-made, new group of semiconductor materials."

Excerpts from the Superlattice Story prepared by US Army Research Office in 1997

The superlattice concept proposed (in February, 1969) under Army sponsored research triggered **a revolution in solid state physics** .... ..

The impact of Esaki's research has been profound. The superlattice concept precipitated more than **10,000 publications** and is directly involved in some **465 patents** in the U.S. alone, by the end of 1996.... .. The superlattice may be regarded as the trunk of a genealogical tree of quantum effect devices,... .. The characteristic dimensions of superlattice devices certainly served **as the precursor of today's "smaller and smaller" nanotechnology emphasis.**

A list of “five don’ts” which anyone with an interest in realizing his or her creative potential should follow. Who knows, it may even help you win a Nobel Prize.

**Rule number one:** Don’t allow yourself to be trapped by your past experiences. If you allow yourself to get caught up in social conventions or circumstances, you will not notice the opportunity for a dramatic leap forward when it presents itself. Looking back at the history of the Nobel Prize, you will notice that most of the laureates have received the Nobel Prize for work they had done during their thirties. In my case, I was 32 years old when I developed the “Esaki tunnel diode.” The point that I am trying to make is that younger people are able to look at things with a clearer vision, one that is not clouded by social conventions and past history.

**Rule number two:** Don't allow yourself to become overly attached to any authority in your field – the great professor perhaps. By becoming closely involved with the great professor, you risk losing sight of yourself and forfeiting the free spirit of youth. Although the great professor may be awarded the Nobel Prize, it is unlikely that his subordinates will ever receive it.

**Rule number three:** Don't hold on to what you don't need. The information-oriented society facilitates easy access to an enormous amount of information. The brain can be compared to a personal computer with an energy consumption of about 25 watts. In terms of memory capacity or computing speed, the human brain has not really changed much since ancient times. Therefore, we must constantly be inputting and deleting information, and we should save only the truly vital and relevant information. As the president of a university, I have the opportunity to meet with many people and to exchange meishi (name card) with them. I try to discard the name cards as soon as possible, so that I always leave maximum memory space open. I'm kidding, of course.

**Rule number four:** Don't avoid confrontation. I myself became embroiled in some trouble with the company I was working for many years ago. At times, it is necessary to put yourself first and to defend your own position. My point is that fighting is sometimes unavoidable for the sake of self-defense.

**Rule number five:** Don't forget your spirit of childhood curiosity. It is the vital component for imagination.

Having listed the five rules, let me say that they do not constitute the sufficient conditions for success. They are merely suggested guidelines. Good Luck!



