# SEMICONDUCTORS AND SEMIMETALS

## VOLUME 7

## Applications and Devices

## Part A

# SEMICONDUCTORS AND SEMIMETALS

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COLUMBUS, OHIO

VOLUME 7

Applications and Devices

Part A

1971

*ACADEMIC PRESS New York and London*

ACADEMIC PRESS, INC.
111 Fifth Avenue, New York, New York 10003

*United Kingdom Edition published by*
ACADEMIC PRESS, INC. (LONDON) LTD.
Berkeley Square House, London W1X 6BA

LIBRARY OF CONGRESS CATALOG CARD NUMBER: 65-26048

PRINTED IN THE UNITED STATES OF AMERICA

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# Preface

The extensive research that has been devoted to the physics of semiconductors and semimetals has been very effective in increasing our understanding of the physics of solids in general. This progress was made possible by significant advances in material preparation techniques. The availability of a large number of semiconductors with a wide variety of different and often unique properties enabled the investigators not only to discover new phenomena but to select optimum materials for definitive experimental and theoretical work.

In a field growing at such a rapid rate, a sequence of books which provide an integrated treatment of the experimental techniques and theoretical developments is a necessity. The books must contain not only the essence of the published literature, but also a considerable amount of new material. The highly specialized nature of each topic makes it imperative that each chapter be written by an authority. For this reason the editors have obtained contributions from a number of such specialists to provide each volume with the required detail and completeness. Much of the information presented relates to basic contributions in the solid state field which will be of permanent value. While this sequence of volumes is primarily a reference work covering related major topics, certain chapters will also be useful in graduate study. In addition, a number of the articles concerned with applications of specific phenomena will be of value to workers in various specialized areas of device development.

Because of the important contributions which have resulted from studies of the III–V compounds, the first few volumes of this series have been devoted to the physics of these materials: Volume 1 reviews key features of the III–V compounds, with special emphasis on band structure, magnetic field phenomena, and plasma effects. Volume 2 emphasizes physical properties, thermal phenomena, magnetic resonances, and photoelectric effects, as well as radiative recombination and stimulated emission. Volume 3 is concerned with optical properties, including lattice effects, intrinsic absorption, free carrier phenomena, and photoelectronic effects. Volume 4 includes thermodynamic properties, phase diagrams, diffusion, hardness, and phenomena in solid solutions as well as the effects of strong electric fields, hydrostatic pressure, nuclear irradiation, and nonuniformity of impurity distributions on the electrical and other properties of III–V compounds. Volume 5, which is devoted to infrared detectors, is the first of a number of volumes to deal specifically with applications of semiconductor properties. Volume 6 is concerned with injection phenomena in solids, including current injection and filament formation, double injection, internal photo-emission, and photoconductor–metal contacts. The present volume is issued in two parts, 7A and 7B, and is concerned with semiconductor devices, including those utilizing bulk negative resistance phenomena as well as effects due to barriers and junctions.

Subsequent volumes of *Semiconductors and Semimetals* will include further work on infrared detectors and a variety of fundamental phenomena such as lattice dynamics, galvanomagnetic effects, luminescence, nonlinear optical phenomena, and electro-, thermo-, piezo-, and magnetooptical effects.

The editors are indebted to the many contributors and their employers who made this series possible. They wish to express their appreciation to the Bell and Howell Company and the Battelle Memorial Institute for providing the facilities and the environment necessary for such an endeavor. Thanks are also due to the U.S. Air Force Offices of Scientific Research and Aerospace Research and the U.S. Navy Office of Naval Research and the Corona Laboratories, whose support has enabled the editors to study many features of compound semiconductors. The assistance of Crystal Phillips, Martha Karl, and Inez Wheldon in handling the numerous details concerning the manuscripts and proofs is gratefully acknowledged. Finally, the editors wish to thank their wives for their patience and understanding.

R. K. WILLARDSON
ALBERT C. BEER

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# SEMICONDUCTORS AND SEMIMETALS

VOLUME 7

Applications and Devices

Part A

Bulk Negative Resistance Devices

# CHAPTER 1

# Applications Utilizing Bulk Negative Resistance

*John A. Copeland*
*Stephen Knight*



## I. Introduction

At the present time, a completely new class of electronic devices is being developed on the basis of the bulk negative resistance that appears in *n*-type GaAs and other compound semiconductors. The purpose of this chapter is to discuss bulk negative resistance with emphasis on the basic physical phenomena, the ways in which it can be utilized, the practical considerations for device design, and some device fabrication techniques which have been recently developed. The last section summarizes present achievements and discusses future promise and some general physical limitations.

The reason that material and device technology for GaAs devices and investigation of other materials and types of bulk negative resistance are being widely pursued is that there is promise that a variety of electronic devices and integrated circuits can be made with greater capability than is presently possible. This improvement will be in terms of speed for logic, digital, and functional devices and in terms of power and frequency for rf power generators.

The concept of a negative-resistance effect in bulk semiconductors was proposed in 1954 by Shockley[1] for minority carriers and in 1959 by Böer[2] for majority carriers if the mobility should decrease with increasing electric field $E$ faster than $E^{-1}$. Both men realized that the space-charge growth resulting from a bulk negative resistivity would dominate the electrical behavior of devices. In 1961, the work of Ridley and Watkins[3] and also Hilsum[4] showed that there was a mechanism for majority-carrier negative resistance, intervalley scattering, which will be discussed in the next section. This effect was first observed by Gunn in 1963.[5]

## II. Band-Structure Models

The bulk negative resistance that appears in $n$-type GaAs and InP (III–V compounds) as well as CdTe and ZnSe (II–VI compounds) is due to the two distinct types of valleys or $k$-space minima in the conduction band.[6] This mechanism, known as the transferred-electron effect, the two-valley effect, or the Ridley–Watkins–Hilsum effect, will be the subject of most of this part. There have been other possible mechanisms suggested which have not yet been experimentally identified.[7] Negative resistance has been observed[8] in $n$-type Ge which is possibly due to the elliptical symmetry of the six [111] valleys or to the transferred-electron effect.[9]

Closely related phenomena to the effects caused by bulk negative resistivity are piezoelectric amplification and high-field domain formation in GaAs, CdS, and other compound semiconductors[10] and high-field domain formation due to traps.[11] The basic mechanisms for these phenomena are not

[1] W. Shockley, *Bell Syst. Tech. J.* **33**, 799 (1954).

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[11] K. W. Böer, *Z. Phys.* **155**, 170, 184 (1959); K. W. Böer and J. J. Ward, *Solid State Commun.* **5**, 467 (1967).

directly related to bulk negative resistance. The high-field domains due to these other mechanisms may be used for device applications similar to some that are discussed later.

The conduction-band structure of GaAs along the [100] direction of $k$-space is shown by the top curve of Fig. 1. The electron velocity $v_g$ associated with location of the electron in $k$-space is proportional to the derivative of the energy $\mathscr{E}$ with respect to wave number $k$,

$$v_g = \frac{1}{\hbar}\frac{d\mathscr{E}}{dk} \tag{1}$$

and is shown by the middle curve in Fig. 1.

To find the average drift velocity as a function of electric field, it is necessary to know how the conduction electrons are distributed in $k$-space as a function of electric field. Possible distribution functions are represented by the bottom curve of Fig. 1. Finding the exact distribution function is a complex problem, since solving the Boltzmann transport equation involves a detailed knowledge of several types of electron–lattice scattering interactions.

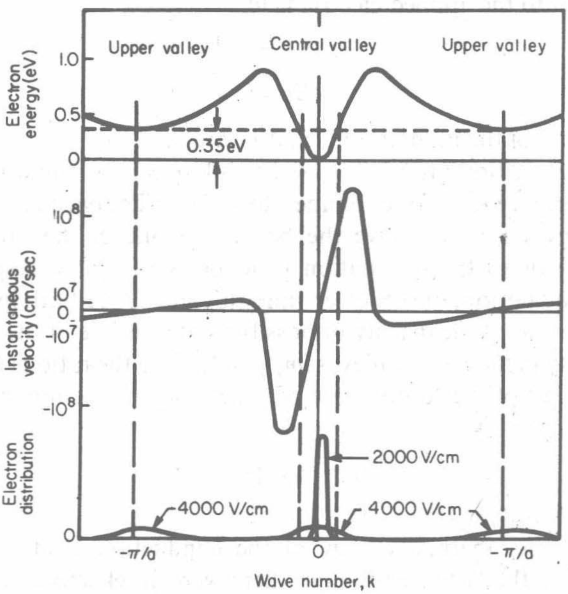


FIG. 1. The upper curve shows the energy of conduction-band electrons versus wave number $k$. The two minima are commonly referred to as the upper and central valleys. The middle curve shows the velocity $h^{-1}\ d\mathscr{E}/dk$ versus $k$, and the lower curve illustrates the behavior of the electron distribution function for electric field as electric field is increased from 2000 to 4000 V/cm.

1. Mean-Length Model

To illustrate the most important features of the two-valley effect, a simple model, similar to the one originally used by Ridley and Watkins[3] and by Hilsum,[4] will be presented. Afterwards, the effect of improvements on the approximations will be discussed, and references will be made to more detailed treatments. The initial model assumes the following:

1. The conduction band consists of two types of valleys which are parabolic so that

$$\mathscr{E}_1(k) = (\hbar^2/2m_1^*)\mathbf{k}^2 \tag{2}$$

$$\mathscr{E}_2(k) = \mathscr{E}_g + (\hbar^2/2m_2^*)(\mathbf{k} - \mathbf{k}_2)^2. \tag{3}$$

The intervalley energy gap $\mathscr{E}_g$ is about 0.35 eV for GaAs. For simplicity, it is assumed that there is one lower valley and a set of $N$ higher-energy valleys. The lower valley is located at the center of the first Brillouin zone. The other valleys are centered about a set of points $\mathbf{k}_2$ which are symmetrically related. The extension to other cases is straightforward, but complicates the notation.

2. The average drift velocity of electrons in each of the valleys is assumed proportional to the applied electric field,

$$v_1(E) = \mu_1 E, \tag{4}$$

$$v_2(E) = \mu_2 E, \tag{5}$$

but the values of the mobilities $\mu_1$ and $\mu_2$ are unequal.

3. The occupation probability of the valleys can be found in terms of an electron thermal energy $\mathsf{T}_e$ (or temperature $T_e$).[11a] The occupation probability of an energy state $\Delta E$ above the bottom of one of the upper valleys is $\exp(-\mathscr{E}_g/\mathsf{T}_e)$ times the occupation probability of the corresponding state $\Delta E$ above the bottom of the lower valley ($\mathscr{E}_g$ and $\mathsf{T}_e$ are both in electron-volt units). The ratio of the density of possible states in one of the upper valleys to the density in the lower valley is $(m_2^*/m_1^*)^{1.5}$, so the ratio of the number of electrons in all of the second type of valleys, $n_2$, to the number in the first valley $n_1$ is given by

$$n_2/n_1 = Z \exp(-\mathscr{E}_g/\mathsf{T}_e), \tag{6}$$

where $Z$ is $N(m_2^*/m_1^*)^{1.5}$.

4. The excess thermal energy of the conduction electrons $\mathsf{T}_e - \mathsf{T}_0$ is transferred to the lattice as though there were an effective free path $\lambda$. The

[11a] To avoid confusion, the electron thermal energy in electron volts is designated by $\mathsf{T}_e$, the energy (temperature) in degrees Kelvin is designated by $T_e$. Thus, $\mathsf{T}_e \equiv k_B T_e$, where $k_B$ is Boltzmann's constant.