

Interfaces, Quantum Wells, and Superlattices

Edited by
C. Richard Leavens and
Roger Taylor

NATO ASI Series

Series B: Physics Vol. 179

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C. Richard Leavens and
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National Research Council of Canada
Ottawa, Ontario, Canada



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Plenum Press

New York and London

Published in cooperation with NATO Scientific Affairs Division

Proceedings of a NATO Advanced Study Institute on
Interfaces, Quantum Wells, and Superlattices,
held August 16-29, 1987,
in Banff, Alberta, Canada

Library of Congress Cataloging in Publication Data

NATO Advanced Study Institute on Interfaces, Quantum Wells, and Superlattices
(1987: Banff, Alta.)

Interfaces, quantum wells, and superlattices / edited by C. Richard Leavens
and Roger Taylor.

p. cm.—(NATO ASI series B: Physics; v. 179)

"Proceedings of a NATO Advanced Study Institute on Interfaces, Quantum
Wells, and Superlattices, held August 16-29, 1987"—T.p. verso.

Bibliography: p.

Includes index.

ISBN 0-306-42983-7

1. Semiconductors—Surfaces—Congresses. 2. Quantum wells—Congresses.
3. Superlattices as materials—Congresses. I. Leavens, C. Richard. II. Taylor,
Roger. III. Title. IV. Series: NATO advanced science institutes series. Series B,
Physics; v. 179.

QC611.6.S9N384 1987

88-19476

537.6'22—dc19

CIP

© 1988 Plenum Press, New York
A Division of Plenum Publishing Corporation
233 Spring Street, New York, N.Y. 10013

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Interfaces, Quantum Wells, and Superlattices

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PREFACE

The NATO Advanced Study Institute on "Interfaces, Quantum Wells and Superlattices" was held from August 16th to 29th, 1987, in Banff, Alberta, Canada. This volume contains most of the lectures that were given at the Institute. A few of the lectures had already been presented at an earlier meeting and appear instead in the proceedings of the NATO Advanced Study Institute on "Physics and Applications of Quantum Wells and Superlattices" held in Erice from April 21st to May 1st earlier in the year and published by Plenum Press.

The study of semiconductor interfaces, quantum wells and superlattices has come to represent a substantial proportion of all work in condensed matter physics. In a sense the growth of interest in this area, which began to accelerate about 10 years ago and seems to be continuing, has been driven by technological developments. While the older generation of semiconductor devices was based on adjacent semiconductors with different properties (e.g. different doping levels) separated by interfaces, modern semiconductor devices tend to be based more and more on properties of the interfaces themselves. This has led, as an example, to the field of band-structure engineering. Improved understanding of the fundamental physics of these systems has aided technological developments and, in turn, technological developments have made available systems which exhibit novel and fascinating physical properties, such as the integer and fractional quantum Hall effects.

The purpose of this ASI was to help expand the group of scientists in NATO countries with expertise in the fundamental physics of semiconductors. Much of the expertise tends to be concentrated in a relatively small number of excellent institutions. By bringing together a very talented group of speakers we were able to provide a stimulating forum for discussion involving participants from thirteen countries and many different institutions.

The book contains 19 chapters with a mix of both experimental and theoretical topics. Chapter 1 serves as an introduction and chapter 2 then reviews the subject of Molecular Beam Epitaxy without which many of the most interesting systems, currently being studied, would not be possible. Chapter 3 discusses the calculation of electronic states in heterostructures whilst chapter 4 focuses on the experimental determination of sub-band energies. The next eight chapters discuss electronic and optical properties of systems with reduced dimensionality and quantum well or superlattice structure. These are followed by a chapter on resonant tunneling and one on polaron effects in heterostructures. Chapters 15-18 focus on high magnetic fields and the Quantum Hall Effect. Finally, chapter 19 contains a comprehensive review of the theory of Fibonacci superlattices.

We would like to thank all of the speakers for the considerable effort that they put into producing high calibre lectures. This was reflected in the fact that there was unvarying high attendance at all lectures despite the lure of fine weather and beautiful surroundings. Our chief regret concerns the fact that R. B. Laughlin's outstanding contribution to the ASI both through his lectures and his comments are not reflected in these published proceedings. Time constraints made it impossible for him to produce a manuscript before the publication deadline.

We would like to give special thanks to our co-organizers, A. H. MacDonald and E. W. Fenton, who both helped with the original NATO submission and provided much assistance and encouragement. Allan MacDonald also organized the lecture program and produced two excellent lectures. Meanwhile, Ed Fenton contributed heavily to all aspects of the organization of the ASI as well as helping out with the proofreading of several manuscripts. We would also like to thank P. J. Stiles and F. Stern for their advice and comments concerning the selection of speakers for the ASI. We are grateful to Marg Coll for her professional expertise in organizing registration, general information, sightseeing tours and the many other details necessary for a successful meeting. Finally we would particularly like to thank Kim Burke for handling all the secretarial duties, interfacing with the Banff Centre, keeping the organizers organized, handling the information desk during the second week of the ASI and retyping most of the manuscripts to the publisher's specifications.

Roger Taylor
C. Richard Leavens

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WHY INTERFACES, QUANTUM WELLS AND SUPERLATTICES? SOME COMMENTS

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INTRODUCTION

One of the key threads that run through the study of the systems in this summer school is our attempt to do something different rather than find out if Schroedinger's equation describes the physics involved. We are reasonably sure of that. What we are trying to put together is the simplest description of the real situation so that we may see which aspect of the physics dominates the problem. From an historical point of view, Bloch's theorem made life simpler in that we could conceive of many problems with many fewer variables to keep track of. But alas, the real world is not a combination of the effective mass theory and a simple one dimensional potential.

Where does all the interest in two-dimensional systems come from? Is it just because the dimensionality is different or is there something due to the dimensionality that has made these more interesting systems to study? Perhaps a little of both. The latter case is certainly the most logical. Here, in these systems, one is able to obtain extremely narrow and well defined energy levels. This results in our being able to test these systems on an exceedingly fine grained energy scale. In addition, one is able in many (but not all) of these systems to vary the electron (or hole) density over a wide range in a single sample.

To obtain high densities of carriers in 3D semiconductor systems, one has a few options. One can raise the temperature and thermally excite them. By doing so one can vary the density by varying the temperature. This results in two kinds of carriers and more scattering for higher temperatures due to the presence of phonons. A similar approach would be to shine light on the semiconductor. This would again result in two kinds of carriers but fewer phonons. Problems with non-uniform absorption of light are hard to escape. The last technique would be to dope the crystal with donors or acceptors. At least this would result in a single type of carrier. However there are major disadvantages, primary among these is the fact that the carriers exist in the same space as the bare coulomb centers. The compensating charge, equal in charge and number density severely limits the mobility.

What about two dimensional systems? It is obvious that the first step is to have the carriers be in a different region of space than the compensating charge. The easiest way to envisage such a system is in terms of the parallel plates of a capacitor. If we assume that when this capacitor is charged, it is the electrons induced on the surface of one of the plates that is of interest, it is obvious that the compensating positive charge is on the other plate. The separation of this positive charge from the electrons can be as large as we like. For a given surface charge density the only limitation is the voltage applied. The scattering from this compensating charge is negligible. We will see later that in the case of certain heterostructures the separation distance cannot be so large for a given density.

Here we see in the interest from the electronic properties point of view why two dimensional systems are so attractive. First we can increase the lifetimes of a single carrier system and then we can in addition vary the density of these carriers just by varying the voltage across a capacitor. It is important not only from the point of view of this workshop but in general to consider the effects that interfaces, quantum wells and superlattices have on properties other than the electronic ones. Where else do these systems modify properties? Without trying to be complete let us consider a few, although not necessarily in the chronological order that they were first studied.

Interfaces occur naturally in nature. A simple case is that of bicrystals, where in solidification a crystal grew with planar arrangements of atoms at the interface common to both crystal segments. The capacitor interfaces of the conducting plates and the insulator are vital to the electronics industry. The phonon spectra of structures with interfaces is no longer the same in all regions of space. Specific phonons exist localized to the interface. The crystal structure is different on either side of the interface. Optical properties are not everywhere the same. It is perhaps better to think then in terms of properties characteristic of the bulk materials on either side of the interface and then those that are modified by the presence of the interface.

Quantum wells exist in nature as well, at the interface of Te bicrystals for example. Another case is a fascinating material, SiC. This material has many stacking orders of the fundamental tetrahedra. Some have long periods. For anyone interested in superlattices, one should study this material. It is easy to grow the material with stacking faults. Such a system with a reverse change in stacking is a quantum well. These can be seen with an electron microscope. There would be phonons that were characteristic of the quantum well. The optical properties as well as Raman spectra would be altered.

Although not the only case in nature, the superlattices in SiC are worth talking about. Stacking orders that run from two to hundreds have been reported. The symmetry of the lattice ranges from cubic to hexagonal to rhombohedral. The basic cubic phonon bands have gaps at the k -values that are appropriate for the different stackings and are Raman active. The bandgap varies from about 2.2eV to 3.3eV. Further, the first convincing demonstration of an artificial superlattice was done by looking at the modification of x-ray scattering.

We attempt here to give examples of some of the systems that underlie the quantum wells that are the basis of the interesting electronic properties. In one sense this is a primer for an excellent review article by Ando, Fowler and Stern(AFS)¹. In the mid sixties a conference series called Electronic Properties of Two Dimensional Systems started

and meets every other year. The proceedings are published in book form and in Surface Science². For a good grounding in many of the points alluded to here, consult any standard condensed matter physics textbook such as Ashcroft and Mermin³. The number of other conferences and sessions in larger conferences that cover these subjects abound.

In order to end up with a separation of the compensating charge and the carriers of interest, one always constructs at least one interface between the material of interest and the barrier that keeps the two kinds of charge away from each other. Historically, the metal-oxide-semiconductor (MOS) capacitive-like structure is the best example. We will go over it in detail, but first we should generalize the structure. From it all quantum wells are easy to categorize. It is then not a quantum leap to the superlattice.

Firstly, the O in MOS does not have to be an oxide, but any material that acts in the tests in question as an insulator. Hence we can have nitrides or other native insulators grown on the semiconductor or even deposited or pushed against the semiconductor. Further we can deposit non-native insulators or even push things like thin mylar films against the semiconductor. We have successfully even used air and vacuum. With this kind of approach, anything goes..... even another semiconductor with a larger bandgap. This latter approach is an exciting one because of the current abilities worldwide to grow one semiconductor on another epitaxially in a controllable fashion.

Secondly, the compensating charge does not have to be easily varied, but if it can, much more can be learned about the system. The basis of much of the modern electronics revolution is based on a structure called a MOSFET, where the FET stands for field effect transistor. It works in a manner where the application of a voltage across the structure affects the conductivity of the material at the interface, in the quantum well. Another structure in wide use is the MNOSFET. It differs from the MOSFET in that the insulator has two different kinds of materials, an oxide and a nitride layer. The interface between the two contains many states where one can rather easily vary the charge density. One can put the compensating charge at the interface. In doing so it is possible to change the conductivity in the quantum well from zero with no voltage applied across the structure to conducting with no voltage applied simply by putting compensating charge in the insulating region.

The heterostructure, which was the first major breakthrough after the MOS structure for producing quantum wells of interest, is very similar to the MNOS structure. In this case the compensating charge is located on impurity states in the bulk of the semiconductor that is acting as the insulator as far away as possible from the interface with a compromise between the density one would want and a smooth lateral potential environment. Heterostructures are also made in structures that have a metal plate (gate) on the other side of the insulator and hence can also have a variation in the density as can the MOSFET.

It is easy to see how one can make a superlattice out of heterostructures. All we have to do is to take the heterostructure of material A (which acts as the insulator) and material B (which is the quantum well region) and make a periodic array. From the middle of material A to the middle of material B is just a heterostructure (as is the mirror image).

This look into what constitutes a superlattice is very general. One class that is very interesting is where A is doped and B is not and they are different compounds. This is the usual case for the heterostructure studied most, (Ga,Al)As:GaAs. The second kind are called nipi

structures. Here both A and B are the same host material but the doping is n in one and p in the other. The 'i's in nipi are for the insulating regions where there are no carriers as in a pn junction. The latest type of superlattice is somewhat of a misnomer as it is made of amorphous materials. It can be made as a compositional variation or doping variation or both.

There is another type of classification scheme for superlattices that has to do with how the valence and conduction bands in materials A and B line up at the interface. If the narrow gap semiconductor has its conduction band (valence band) lower (higher) than that of the insulator then the quantum well for the electrons (holes) is in the narrow gap material. As you can see, if the levels line up differently the quantum well for the electrons could be in B and that for the holes in A (or vice versa). A third possibility is that both the conduction and valence bands in one of the materials lie below the valence band of the other material. This results, under some conditions, in a semi-metal interface even without doping.

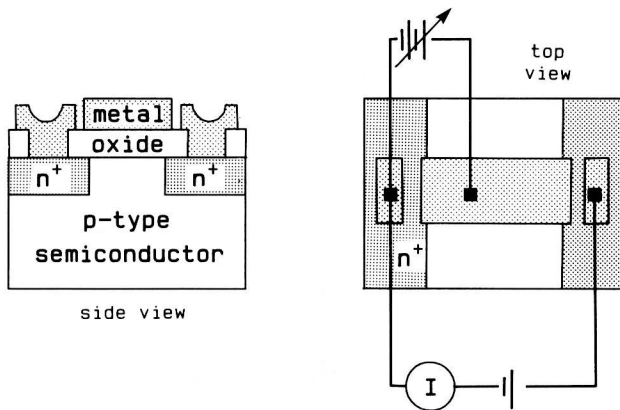


Fig. 1. Side and top views of a MOSFET.

THE PHYSICAL SYSTEMS

We discuss the physical layout of the different systems focusing on the MOSFET. It is the oldest system of interest and from its configuration we can easily extrapolate to the other systems. In Fig. 1 we show a side view and top view of a MOSFET. Because the density of carriers is directly proportional to the electric field normal to the surface and we apply a voltage not a field we should have a uniformly thick insulator. Secondly, we would like the interface to be a place where the potential is as smooth as possible. We would wish that there was no random potential variation along the surface. This requires that the surface be atomically smooth. Further there should not be compositional variation along the surface at and near the interface. All these comments hold for the other forms of quantum wells and superlattices.

We now describe a subset of structures for which we can vary the density. Our main interest in these systems is when they are at low temperatures. For this purpose let us consider them at $T=0K$ unless noted otherwise. The n^+ regions have been doped heavily enough that although the mobility is low, they are conducting at low temperatures while the bulk of the p-type semiconductor that we use as our example is not. When the upper electrode, usually called the gate, is positive relative to the n^+ regions we have a net positive areal charge density on the gate and the equivalent density of electrons at the interface of the semiconductor. These electrons are the inversion layer. They are often referred to as a two-dimensional electron gas (2DEG). A simple circuit and response are illustrated in Fig. 2.

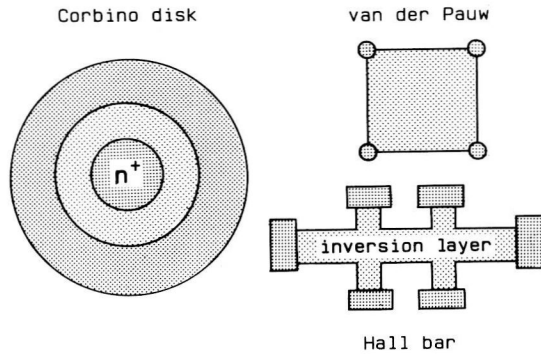


Fig. 2. Simple circuit and response diagrams.

Simple DC measurements as well as low frequency measurements are made utilizing three main structures when the dimensions along the well are defined and contacts are made to the perimeters. The two structures most often used with three dimensional samples are the van der Pauw structure and the Hall Bar. However the earliest successful work in Si MOSFETs utilized the Corbino disk structure. This structure has the advantage that the two-dimensional region 2D is entirely enclosed on the surface of the semiconductor so no possibility exists for surface leakage between the n^+ regions. The disadvantage with this structure is that it is a two terminal structure where the voltage drop is measured where the current enters and leaves the sample. In addition with only two probes, one cannot measure sufficient to determine both components of the magneto-conductivity tensor. All three structures are illustrated in Fig. 3. The standard Hall bar is the ideal structure to use, except for the possible leakage along the surface. One is able to measure longitudinal and transverse voltage drops and can determine both components of the magneto-conductivity and -resistivity tensors. It is a structure which is basically a resistance structure being long and thin while the Corbino disk is a conductance structure, being short and wide. The van der Pauw structure is simple and convenient to use. Surface leakage may be a problem; certainly geometry is. The analysis uses functional relationships that may lead to more uncertainties. Yet with a structure with four contacts one can obtain the full magneto-conductivity tensor.

Simple measurement considerations for the beginning researcher may help. Often one is plagued with high resistance contacts. It need not bother the latter two structures providing the current source has sufficient output voltage and the voltage measuring circuit has an impedance higher than the total resistance of the sample and contacts.

Methods of measurement are simple enough that simple instructional laboratories routinely carry out these measurements. Basically one can use either DC or AC techniques. Two simplistic approaches are constant current and constant voltage techniques. The constant current technique uses a constant current passed through a known resistor in series with the sample. One measures the voltage drop across both and then one has the ratio of the resistances. One uses this with the Hall bar and van der Pauw structures, basically resistive structures. For the constant voltage case, one has a resistor whose resistance is low compared to that of the sample in series with the sample. A constant voltage is applied to this series and the voltage drop across the resistor is measured. This voltage is proportional to the conductance of the sample and is usually good for the Corbino structure.

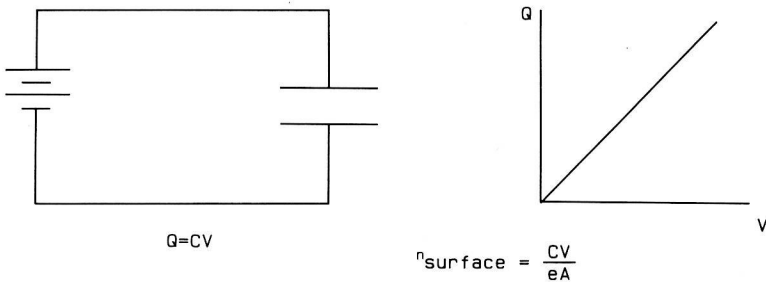


Fig. 3. Structures commonly used for simple DC and low frequency transport measurements.

All of the structures discussed above require the technology of making reasonably good conducting contacts to the carriers at the interface. In trying out new physical systems prepared by new techniques one often wishes to get on with the measurements without having to do any more than necessary. Contacts are usually problems. A scheme that has worked very well is the capacitively coupled one. It is illustrated in Fig. 4. In this situation one has no ohmic contacts to the inversion layer and relies on having low impedance "contacts" by virtue of the large area of the pads on the end and working at high enough frequencies for this to be the case. The high resistive gate material is chosen so that under some conditions one can "charge" this capacitor but also when the measurements are made, this resistance is much larger than that of the inversion layer below. This concept can be used for Corbino, van der Pauw and Hall bar sample structures. For the cases of superlattices, it is not as easy because of the shielding of each successive quantum well by the ones above it.

Recalling that we are idealizing the system that we want to study, we assume that it has a one-dimensional potential and treat it with simplistic approximations. We assume that the effective mass treatment applies in all three directions, that the dispersion is parabolic, that the electron has a spin but that the spin splitting may be added near the end of the discussions, that there is no spin-orbit interaction and that a semiclassical approach reveals all the essential physics. One recognizes that this is rarely the case but that adding specifics for individual problems is not difficult but perhaps tedious. Indeed the study of valence bands with their inherently more complicated band structure has been revealing of the complexity that the real world holds for us.

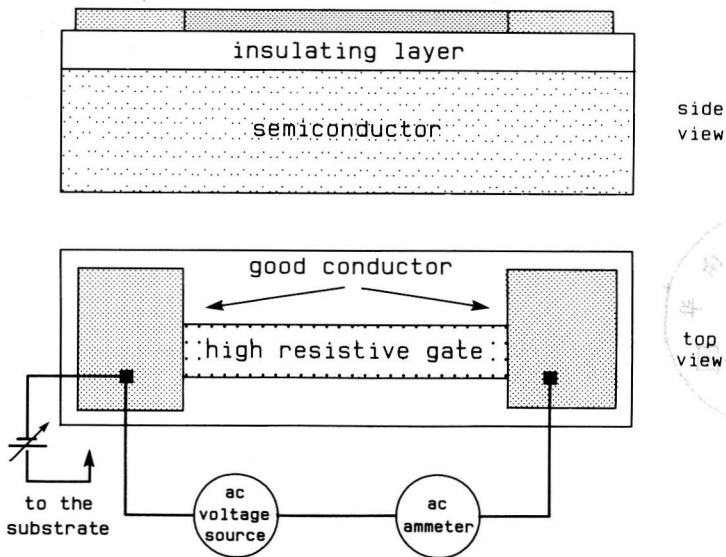


Fig. 4. Capacitively coupled scheme for making good conducting contacts to the carriers in the inversion layer.

The electric field perpendicular to the surface will be terminated on charges. These charges can be fixed, either unwanted fixed charge states or those from purposeful doping, as well as the mobile charges of interest. This is true in all systems. We must find the potential from a solution of the one dimensional Poisson equation

$$d^2\phi(z)/dz^2 = 4\pi\rho(z)/K_{sc} \quad (1)$$

where $\phi(z)$ vanishes in the bulk for the cases of a single quantum well (complete screening of the compensating charge). For the case of the MOSFET the charge is made up of depletion charge n_d (as the bulk minority carriers are being depleted) and mobile charge n_s . For the MOSFET and the heterostructure where one has a metal plate^s for the compensating charge one can define the mobile charge density as

$$n_s = C(V_g - V_t)/eA \quad (2)$$

where C/A is the capacitance per unit area, V_g is the gate voltage relative to the inversion layer, V_t is a threshold voltage and depends on oxide charge, thickness, workfunction differences and other things as well. Fig. 5 gives an example of a MOS structure with a gate voltage applied. We plot energy versus distance perpendicular to the surface. We have added a voltage difference between the inversion layer and the substrate of the semiconductor (the backside). It is used to indicate the cases where the potential past the two dimensional layer is not zero.

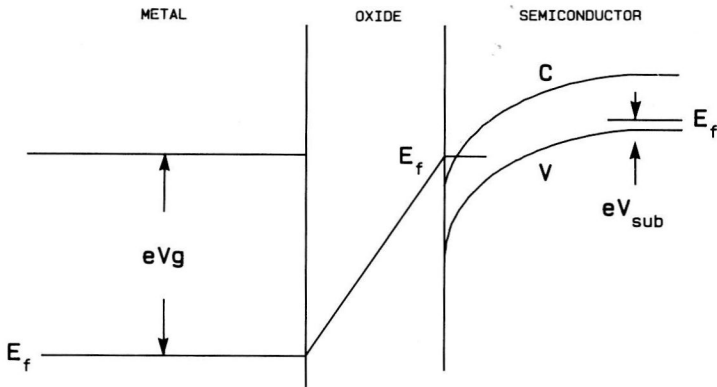


Fig. 5. Energy diagram for a MOS structure with an applied gate voltage.

To solve Poisson's equation, we must know the charge density. To know that we must know the wave functions. Quantum mechanical effects play a significant role at room temperature and the dominant one at the low temperatures of interest. It is easy to see that this is the case from the consideration of energies. The localization energies of the carriers in the quantum well are 10-100 meV. kT at room temperature is about 25 meV. The two degrees of freedom parallel to the surface have free dispersion. Appropriately we must solve an equation in the direction perpendicular to the surface, z , for the envelope of the wave function such as

$$(\hbar^2/2m_z)(d^2\Psi(z)/dz^2) + [E_i - V(z)]\Psi(z) = 0 \quad (3)$$

The energy levels are given as

$$E(k_x, k_y) = E_i + (\hbar^2/2m_z)(k_x^2 + k_y^2) \quad (4)$$

where the E_i are the energies of the localized motion.

It is obvious that we have made a significant change in the problem. If we are in a situation where the separation of the levels E_i are significantly larger than all the other energies in the problem, the carriers will act as if they are free in only two dimensions. In a sense we now have two dimensional bands. Fig. 6 illustrates the energy levels and some typical values for the Si case.