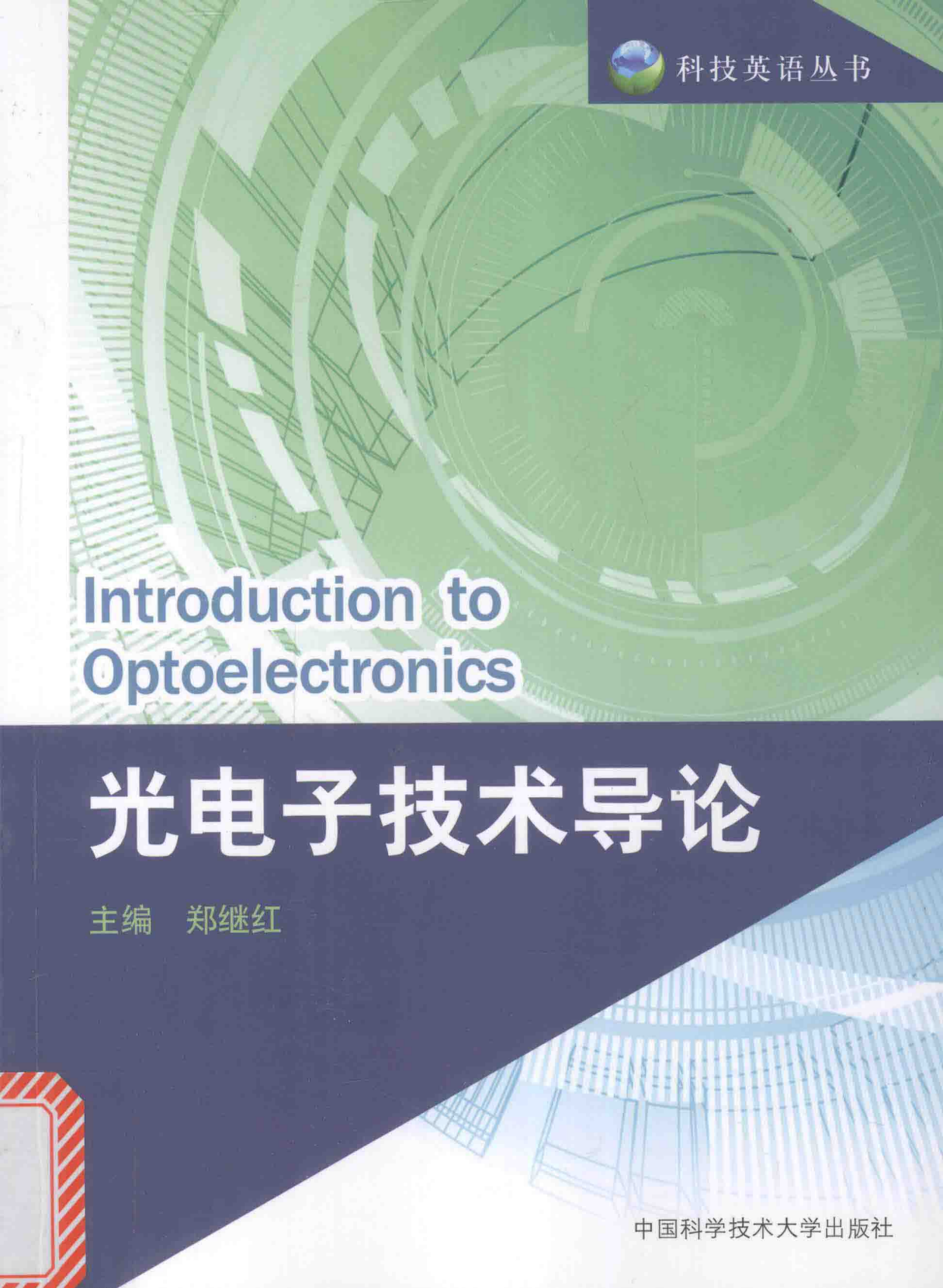
科技英语丛书
Introduction to
Optoelectronics
光电子技术导论
主编　郑继红
中国科学技术大学出版社

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Introduction to Optoelectronics

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内 容 简 介

光电子技术是光学和电子技术相结合而产生的新技术，涉及光电信息技术的方方面面，是未来信息产业发展的核心。本书第一章介绍了光电信息技术所涉及的半导体、光学及电学方面的基础知识；第二章介绍了几种基本的电光信息转换器件，包括发光二极管(LED)、半导体激光器(LD)、液晶显示(LCD)和有机发光二极管(OLED)；第三章介绍了光电信息转换器件，包括光电倍增管(PMT)、光敏二极管(PD)、光敏电阻(PR)、太阳能电池(Solar Cell)、电荷耦合器件(CCD)等常用光电子器件；在介绍了上述器件的工作原理、类型、特点、应用及发展等基础上，第四章着重介绍了现代光电信息技术的应用，包括激光全息技术、3D立体显示技术、光刻技术以及运用光电器件及相关技术实现光电探测的设计实现方法，例如光盘存储系统、自然光自动采集照明系统、红外安全光帘的光电系统设计等。

本书可作为高等院校及科研院所光电信息、电子信息、计算机、应用物理以及科技英语翻译等专业本科生基础光电子技术的全英或者双语教材，也可作为研究生及留学生的选用教材，还可作为上述领域的科研技术人员的学习或参考用书。

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Preface
前　言

21世纪是信息产业飞速发展的时代。光电信息技术更是信息时代发展的关键和核心。

由光子技术和微电子技术的结合、交叉和渗透而诞生了现代光电子技术。现代光电子技术的涵盖面特别广泛，围绕着信息的产生、传输、处理和接收过程以及光-电、电-光相互转换过程，诞生了各种光电电光器件，如发光二极管、半导体激光器、光电倍增管、光敏二极管、太阳能电池，以及各种光电子技术，如光纤通信技术、节能照明技术、液晶显示技术、立体显示技术、光刻技术等，这些器件和技术又显著地推动了人类社会生产的进步，同时也极大地提高和改善了人类的生活质量。

光电信息技术所涉及的学科知识广泛，包括光学、电学和半导体等相关基础知识，同时它又是新材料、光子、电子、计算机等前沿学科间相互渗透、相互作用而形成的高新技术学科。作为普通高等院校光电、电子、测控、计算机等相关专业的在校学生，应当在大学学习期间打好基础，掌握基本光电子器件的基本原理、性质特点以及应用发展等知识点，同时还应当具备运用所学的光电技术初步解决实际生产生活中问题的能力。同时，要培养学生对未来光电子技术发展的求知愿望，让学生了解日新月异的科技发展年代里出现的光电子技术热点和创新点。

但是，仅仅掌握光电信息技术的基础知识还是不够的。目前，随着国际化教育的深入发展，来华留学的学生数量和出国留学的学生数量都在逐年增加，如何让学生在学习专业知识的同时，获得良好的英语表达能力也显得非常重要。然而，在推行实施双语或者全英课程教学的过程中，我们常感到缺乏一本适合大学生使用的英文版光电子技术教材，既重视光电基础知识，又注重各种基本光电器件的介绍，同时还涵盖如何运用光电器件构建光电探测系统等内容。为此，我们着手编写了这本英文教材。

本书的内容体系沿袭了上海理工大学光电信息与计算机工程学院为光电信息专业的学生教学所编撰的《光电信息技术》教材。编写时，采用了全英文写作，在

《光电信息技术》这本较成熟教材的基础上，从国外相关书籍和互联网上搜集并更新了很多有益的英文资料，新增了一些当前光电领域热点技术的介绍，例如立体显示技术、激光全息技术、光刻技术等；同时还提供了学院教师在科研工作中设计的光电信息探测系统的教学实例。为了便于学生自学，本书中还特意增加了中英文专业词汇生词对照表。

本书的编撰得到了上海理工大学研究生创新教材建设的支持，由上海理工大学郑继红老师主编，杨永才、贾宏志和侯文玫等几位老师参编。光电学院的部分研究生也参与了资料的搜集和整理工作，为书稿的最终完成做了很多细致的工作，特别是博士研究生王康妮同学，以及硕士研究生王青青、王雅楠、李道萍、高正、陈铁阳等同学，在此一并向他们表示感谢。

由于时间仓促，书中难免存在疏漏之处，恳请广大读者批评指正，以便进一步修订改善。

编　者

2014 年 10 月

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Chapter 1
Physical Basis of Optoelectronic Information Technology

The development of the transistor and the ***integrated circuit*** (***IC***) has led to many remarkable capabilities. The IC permeates almost every facet of our daily lives, including such things as the compact disk player, the fax machine, laser scanners at the grocery store, and the cellular telephone. The semiconductor electronics field continues to be a fast-changing one. Moreover, optics is a field of science which is particularly lucid, logical, challenging, and beautiful. This chapter introduces basics of semiconductor, like energy bands, doping, and so on. Fundamentals of optics, like reflection, and refraction and basics of circuits are also introduced.

1.1 Theoretical Basis of *Semiconductor*

This section gives a brief introduction to semiconductors. Semiconductors play a vital role in optics both as sources and as detectors of light. The ***light-emitting diode*** (LED) and ***laser diode*** (LD) are widely used as the various forms of ***photodiode*** detector. ***Electrons*** and ***holes*** are carriers of electrical current in semiconductors and they are separated by an ***energy gap***. ***Photons*** are the smallest energy packets of light waves and their interaction with electrons is the key physical mechanism in optoelectronic devices.

1.1.1 Energy Bands and Electrical Conduction

A semiconductor is a material which has electrical conductivity to a degree between that of a metal (such as copper) and that of an ***insulator*** (such as glass). Semiconductors are the foundation of modern electronics, including ***transistors***, ***solar cells***, light-emitting diodes, ***quantum dots***, and digital and analog integrated circuits.

A semiconductor may have a number of unique properties, one of which is the ability to change conductivity by the addition of impurities ("***doping***") or by the interaction with another phenomenon, such as an electric field or light; this ability makes a semiconductor very useful for constructing a device that can amplify, switch, or convert an energy input. The modern understanding of the properties of a semiconductor relies on quantum physics to explain the movement of electrons inside a lattice of atoms.

Semiconductors are defined by their unique electric conductive behavior, somewhere between that of a metal and an insulator. The differences between these materials can be understood in terms of the quantum states for electrons, each of which may contain zero or one electron (by the ***Pauli exclusion principle***). These states are associated with the electronic band structure of the material. Electrical conductivity arises due to the presence of electrons in states that are delocalized (extending through the material), however, in order to transport electrons, a state must be partially filled, and it contains an electron only part of the time. If the state is always occupied with an electron, then it is inert, blocking the passage of other electrons via that state. The energies of these quantum states are critical, since a state is partially filled only if its energy is near to the ***Fermi level***.

High conductivity in a material comes from it, having many partially filled states and much state delocalization. Metals are good electrical conductors and have many partially filled states with energies near their Fermi level. Insulators, by contrast, have few partially filled states, their Fermi levels sit within band gaps with few energy states to occupy. Importantly, an insulator can be made to conduct by increasing its temperature: heating provides energy to promote some electrons across the band gap, inducing partially filled states in both the band of states beneath the band gap (***valence band***) and the band of states above the band gap (***conduction band***). An (***intrinsic***) ***semiconductor*** has a band gap which is smaller than that of an insulator, and at room temperature significant numbers of electrons can be excited to cross the band gap.

A ***pure semiconductor*** is not very useful, as it is neither a very good insulator nor a very good conductor. However, one important feature of the semiconductor (and some insulators, known as semi-insulators) is that their conductivity can be increased and controlled by doping with impurities and gating with electric fields. By doping and gating, either the conduction or valence band are moved much closer to the Fermi level, and the number of partially filled states are greatly increased.

Some semiconductor materials which have wider-band gap are sometimes referred to as semi-insulators. When undoped, these have electrical conductivity nearer to that of electrical insulators; when doped, they are useful as semiconductors. Semi-insulators find niche applications in micro-electronics, such as substrates for high electron mobility transistor (HEMT). An example of a common semi-insulator is gallium arsenide. Some materials, such as titanium dioxide, can even be used as insulating materials for some applications, while being treated as wide-gap semiconductors for other applications.

1.1.2 Charge Carriers (Electrons and Holes)

The partial filling of the states at the bottom of the conduction band can be understood as adding electrons to that band. The electrons do not stay indefinitely (due to the natural thermal recombination), but they can move around for some time. The actual concentration of electrons is typically very dilute, and so (unlike in metals) it is possible to think of the electrons in the conduction band of a semiconductor as a sort of classical ideal gas, where the electrons fly around freely without being subject to the Pauli exclusion principle. In most semiconductors, the conduction bands have a parabolic dispersion relation, and so these electrons

respond to forces (electric field, magnetic field, etc.) much like they would in a vacuum, though with a different effective mass. Because the electrons behave like an ideal gas, one may also think about conduction in very simplistic terms such as the Drude model, and introduce concepts such as electron mobility.

For partial filling at the top of the valence band, it is helpful to introduce the concept of an electron hole. Although the electrons in the valence band are always moving around, a completely full valence band is inert, not conducting any current. If an electron is taken out of the valence band, then the trajectory that the electron would normally have taken is now missing its charge. For the purposes of electric current, this combination of the full valence band, minus the electron, can be converted into a picture of a completely empty band which contains a positively charged particle that moves in the same way as the electron. Combined with the negative effective mass of the electrons at the top of the valence band, we arrive at a picture of a positively charged particle that responds to electric and magnetic fields just as a normal positively charged particle would do in vacuum, again with some positive effective mass. This particle is called a hole, and the collection of holes in the valence can again be understood in simple classical terms (as with the electrons in the conduction band).

1.1.3 Carrier Generation and Recombination

When ionizing radiation strikes a semiconductor, it may excite an electron out of its ***energy level*** and consequently leave a hole. This process is known as ***electron-hole pair*** generation. Electron-hole pairs are constantly generated from thermal energy as well, in the absence of any external energy source.

Electron-hole pairs are also apt to recombine. Conservation of energy demands that these recombination events, in which an electron loses an amount of energy larger than the band gap, be accompanied by the emission of thermal energy (in the form of phonons) or radiation (in the form of photons).

In some states, the generation and recombination of electron-hole pairs are in equipoise. The number of electron-hole pairs in the steady state at a given temperature is determined by quantum statistical mechanics. The precise quantum mechanical mechanisms of generation and recombination are governed by conservation of energy and conservation of momentum.

As the probability that electrons and holes meet together is proportional to the product of their amounts, the product is in steady state nearly constant at a given

temperature, providing that there is no significant electric field (which might "flush" carriers of both types, or move them from neighbour regions containing more of them to meet together) or externally driven pair generation. The product is a function of the temperature, as the probability of getting enough thermal energy to produce a pair increases with temperature, being approximately $\exp(-E_G/kT)$, where k is Boltzmann's constant, T is absolute temperature and E_G is band gap.

The probability of meeting is increased by carrier traps—impurities or dislocations which can trap an electron or hole and hold it until a pair is completed. Such carrier traps are sometimes purposely added to reduce the time needed to reach the steady state.

1.1.4 Doping[①]

By introducing small amounts of impurities into an otherwise-pure crystal, it is possible to obtain a semiconductor in which the concentration of carriers of one ***polarity*** is much in excess of the other type. Such semiconductors are referred to as extrinsic semiconductors vis-à-vis the intrinsic case of a pure and perfect crystal. For example, by adding pentavalent impurities, such are arsenic, which have a valence one more than Si, we can obtain a semiconductor in which the electron concentration is much larger than the hole concentration. In this case, we will have an ***n-type semiconductor***. If we add trivalent impurities, such as boron, which have a valence of one less than four, we then have an excess of holes over electrons — a ***p-type semiconductor***.

An arsenic (As) atom has five valence electrons whereas Si has four. When the Si crystal is doped with small amounts of As, each As atom substitutes for one Si atom and is surrounded by four Si atoms. When an As atom bonds with four Si atoms, it has one electron left unbounded. This fifth electron cannot find a bond to go into so it is left orbiting around the As atom, which looks like an As^+, as illustrated in Fig. 1-1(a). The As^+ ionic center, with an electron e^- orbiting it, resembles a hydrogen atom in a silicon environment. We can easily calculate how much energy is required to free this electron away from the As site, thereby

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① Kasap S O. Optoelectronics and Photonics: Principles & Practices [M]. 2nd ed. New Jersey: Prentice Hall, Inc., 2012: 203 - 205.

ionizing the As ***impurity*** by using our knowledge on the ionization of a hydrogen atom (removing the electron from the H-atom). This energy turns out to be a few hundredths of an electron volt, that is, ~ 0.05 eV, which is comparable to the thermal energy at room temperature ($\sim k_B T = 0.025$ eV). Thus, the fifth valence electron can be readily freed by thermal vibrations of the Si lattice. The electron will then be "free" in the semiconductor, or in other words, it will be in the CB. The energy required to excite the electron to the CB is therefore ~ 0.05 eV. The addition of As atoms introduces localized electronic states at the As sites because the fifth electron has a localized wave function, of the hydrogenic type, around As^+. The energy of these states, E_d, is ~ 0.05 eV below E_c because this is how much energy is required to take the electron away into the CB. Thermal excitation by lattice vibrations at room temperature is sufficient to ionize the As atom, that is, excite the electron from E_d into CB. This process creates free electrons; however, the As^+ ions remain immobile as shown in the energy band diagram of an n-type semiconductor in Fig. 1-1(b).

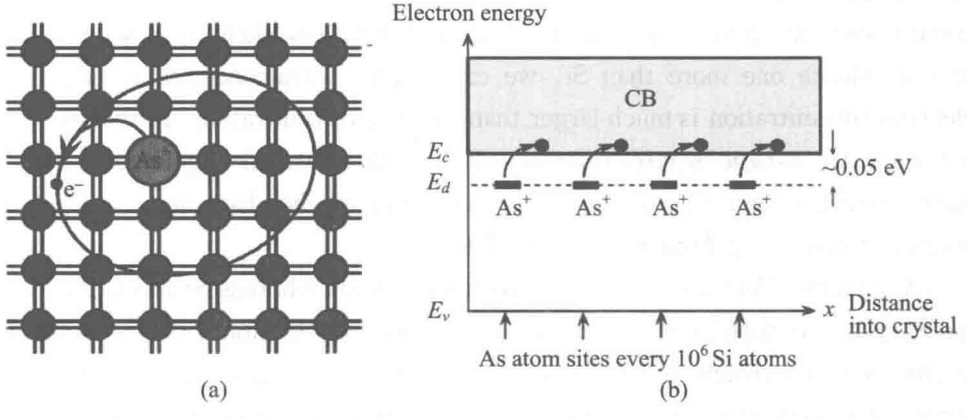

Fig. 1-1 Si crystal is doped with small amounts of As

(a) The four valence electrons of As allow it to bond just like Si but the fifth electron is left orbiting the As site. The energy required to release to free fifth-electron into the CB is very small. (b) Energy band diagram for an n-type Si doped with 1 ppm As. There are donor energy levels just below E_c around As^+ sites.

We should, by similar arguments to the above, anticipate that doping a Si crystal with a trivalent atom (valence of 3) such as B (boron) will result in a p-type Si that has an excess of holes in the crystal. Consider doping Si with small

amounts of B as shown in Fig. 1-2(a). Because B has only three valence electrons, when it shares them with four neighboring Si atoms one of the bonds has a missing electron which is of course a "hole". A nearby electron can tunnel into this hole and displace the hole further away from the B atom. As the hole moves away it gets attracted by the negative charge left behind on the B atom. The binding energy of this hole to the B^- ion (a B atom that has accepted an electron) can be calculated using the hydrogenic atom analogy just like in the n-type Si case. This binding energy also turns out to by very small, ~ 0.05 eV, so that at room temperature the thermal vibrations of the lattice can free the hole away from the B^- site, A free hole, we recall, exists in the VB. The escape of the hole from the B^- site involves the B atom accepting an electron from a neighboring Si-Si bond (from the VB) which effectively results in the hole being displaced away, and its eventual escape to freedom in the VB. The B atom introduced into the Si crystal therefore acts as an electron acceptor impurity. The electron accepted by the B atom comes from a nearby bond. On the energy band diagram, an electron leaves the VB and gets accepted by a B atom which becomes negatively charged. This process leaves a hole in the VB which is free to wander away illustrated in Fig. 1-2(b).

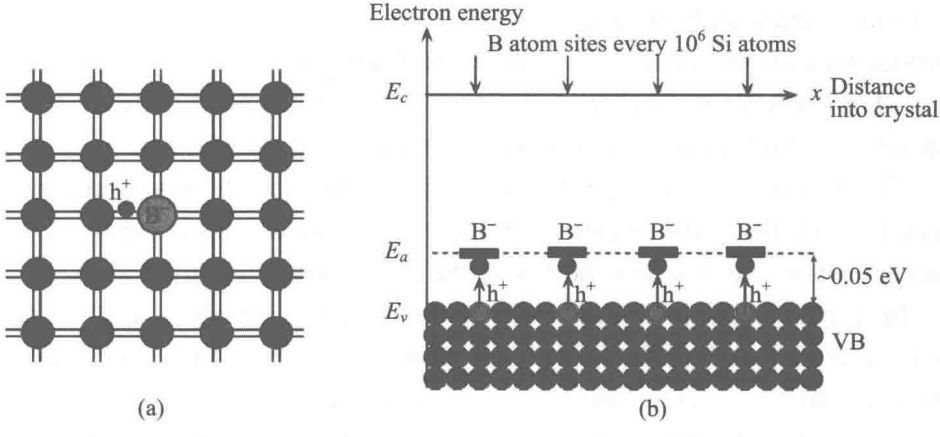

Fig. 1-2 Si crystal is doped with small amounts of B

(a) Boron doped Si crystal. B has only three valence electrons. When it substitutes for a Si atom one of its bonds has an electron missing and therefore a hole. (b) Energy band diagram for a p-type Si doped with 1 ppm B. There are acceptor energy levels just above E_v around B^- sites. These acceptor levels accept electrons from the VB and therefore create holes in the VB.

1.1.5 *P-N Junction*

A p-n junction, as shown in Fig. 1-3, is a boundary or interface between two types of semiconductor material, p-type and n-type, inside a single crystal of semiconductor. It is created by doping, for example by ion implantation, diffusion of ***dopants***, or by epitaxy (growing a layer of crystal doped with one type of dopant on top of a layer of crystal doped with another type of dopant). If two separate pieces of material were used, this would introduce a grain boundary between the semiconductors that severely inhibits its utility by scattering the electrons and holes.

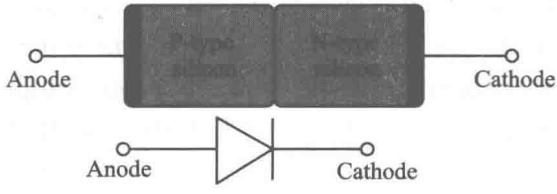

Fig. 1-3 A p-n junction

The circuit symbol is shown: the triangle corresponds to the p side.

P-n junctions are elementary "building blocks" of most semiconductor electronic devices such as diodes, transistors, solar cells, LEDs, and integrated circuits; they are the active sites where the electronic action of the device takes place. For example, a common type of transistor, the bipolar junction transistor, consists of two p-n junctions in series, in the form n-p-n or p-n-p.

The discovery of the p-n junction is usually attributed to American physicist Russell Ohl of Bell Laboratories. A Schottky junction is a special case of a p-n junction, where metal serves the role of the p-type semiconductor.

In a p-n junction, without an external applied voltage, an equilibrium condition is reached in which a potential difference is formed across the junction. This potential difference is called built-in potential V_{bi}.

After joining p-type and n-type semiconductors, electrons from the n region near the p-n interface tend to diffuse into the p region. As electrons diffuse, they leave positively charged ions (donors) in the n region. Likewise, holes from the p-type region near the p-n interface begin to diffuse into the n-type region, leaving fixed ions (acceptors) with negative charge. The regions nearby the p-n interfaces lose their neutrality and become charged, forming the ***space charge region*** or

depletion layer (see Fig. 1-4).

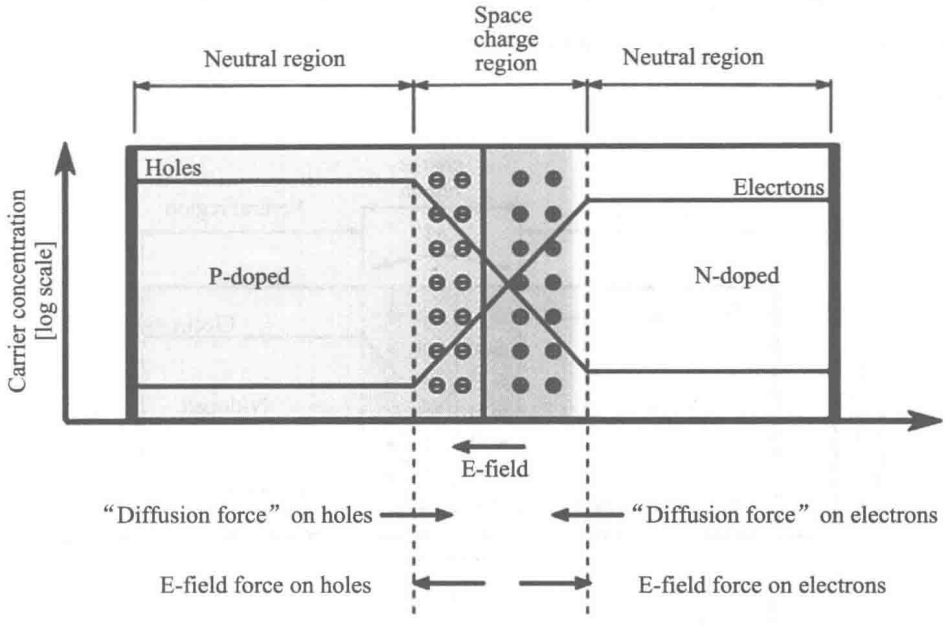

Fig. 1-4 A p-n junction in thermal equilibrium with zero-bias voltage applied (Eldon D E, Frederick C R, 2004)

Electron and hole concentration are reported with blue and red lines, respectively. Gray regions are charge-neutral. Light-red zone is positively charged. Light-blue zone is negatively charged. The electric field is shown on the bottom, the electrostatic force on electrons and holes and the direction in which the diffusion tends to move electrons and holes.

The electric field created by the space charge region opposes the diffusion process for both electrons and holes. There are two concurrent phenomena: the diffusion process that tends to generate more space charge, and the electric field generated by the space charge that tends to counteract the diffusion. The carrier concentration profile at equilibrium is shown in Fig. 1-4 with blue and red lines. Also shown are the two counterbalancing phenomena that establish equilibrium.

The space charge region is a zone with a net charge provided by the fixed ions (donors or acceptors) that have been left uncovered by majority carrier diffusion. When equilibrium is reached, the charge density is approximated by the displayed step function. In fact, the region is completely depleted of majority carriers (leaving a charge density equal to the net doping level), and the edge between the space

charge region and the neutral region is quite sharp [see Fig. 1-5, $Q(x)$ graph]. The space charge region has the same magnitude of charge on both sides of the p-n interfaces, thus it extends farther on the less doped side (the n side in Fig. 1-4 and Fig. 1-5).

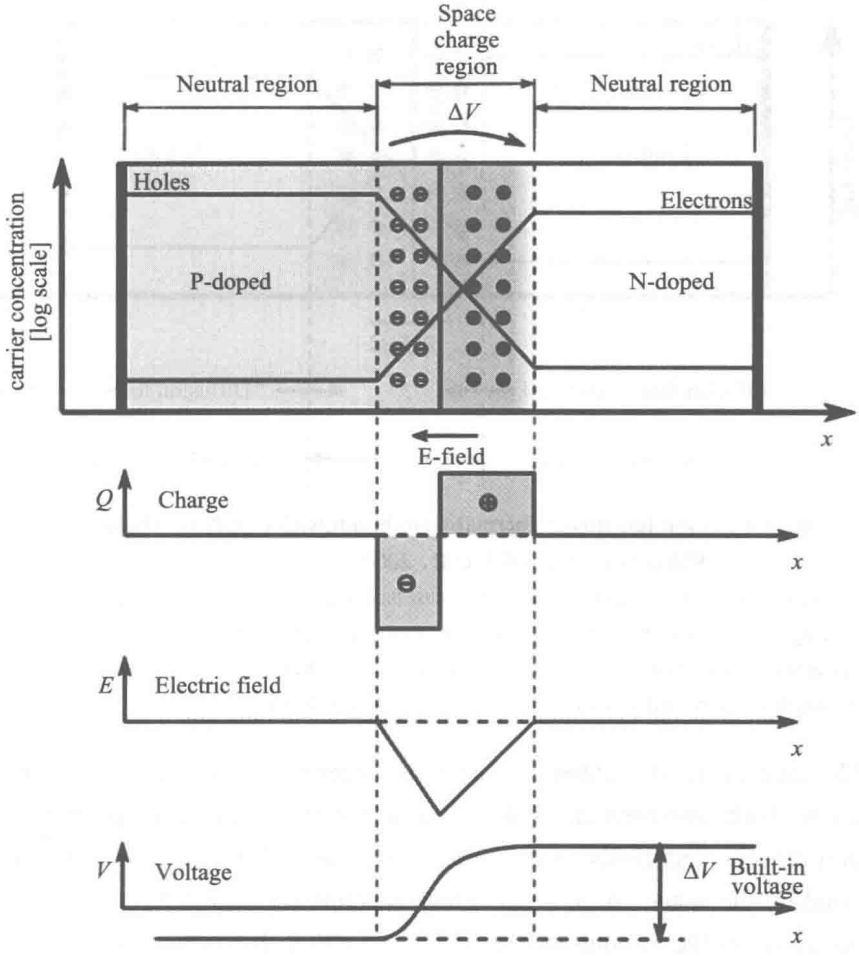

Fig. 1-5 A p-n junction in thermal equilibrium with zero-bias voltage applied

Under the junction, plots for the charge density, the electric field, and the voltage are reported.

In forward bias, as shown in Fig. 1-6, the p-type is connected with the positive terminal and the n-type is connected with the negative terminal. With a battery connected this way, the holes in the p-type region and the electrons in the n-type region are pushed towards the junction. This reduces the width of the