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Bibliographic record and links to related information available from the Library of Congress catalogue. Note: Content data is generated by the machine based on pre-publication provided by the publisher. Content may vary from the printed book or be incomplete or contain other codes. CHAPTER 1: Semiconductor Diodes 1.1 Introduction 1.2 Semiconductor Speedometer 5.5 6.2 Construction and characteristicsJFETS 6.3 Transfer features 6.4 Specification data sheets (JFETs) 6.5 Instrumentation 6.6 Important reports 6.7 Deple-Type MOSFET 6.8 Enhancement-Type MOSFET 6.9 Frequency amplifier 8.10 Configuration 10.5 Control system 17.2 Reset 16.3 16.4 reabsorption devices and electronic devices. (1) Recognition Our sincere appreciation must be extended to instructors who used the text and sent comments, corrections and suggestions. We also want to thank Rex David-son, Director of Production at Prentice Hall, for keeping together the many detailed as-pects of production. Our sincere thanks to Dave Garza, Senior Editor and Linda Ludewig, Editor, at Prentice Hall for their editorial support of the Seventh Edition of this text. We want to thank those who have shared their suggestions and their evasions of this text for its many different values. The comments of these individu-als allowed us to present Electronic Devices and Circuit Theory in this seventh edition: Ernest Lee Abbott Napa College, Napa, CA Phillip D. Anderson Muskegon Community College, Muskegon,Al Anthony EG&G VACTEC Inc. A. Duane Bailey Southern Alberta Institute of Technology, Calgary, Alberta, CANADA Joe Baker University of Southern California, Los Angeles, CA Jerrold Barrosse Penn StateâOgontz Ambrose Barry University of North CarolinaâCharlotte Arthur Birch Hartford State Technical College, Hartford, CT Scott Bisland SEMATECH, Austin, TXuke Edward Bloch The Perkin-Elmer Corporation Gary C. Bocksch Charles S. 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Jean Youns ITT Technical Institute, Troy, Mi Charles E. Yunghans Washington E. Yunghans Western University, Bellingham, WA Ulrich E. Zeisler Salt Lake Community College, Salt Lake City, UT (3) PN Chapter 1 Semiconductor diodes 1.1 Introduction It is now that about 50 years since the first transistor was introduced the first transistor on 23 December 1947. For those of us who have experienced the change from the tubes of the glass envelope to the era of the solid state, it still seems a few years ago. The first edition of this text contained heavy pipe coverage, with subsequent editions involving the important decision as to how much pipe coverage should be and how much semiconductor devices should be. It doesn't seem valid anymore to mention tubes or compare the advantages of one over the other ... we are firmly in the era of the solid state. The miniaturisation it has entailed leaves us to wonder about its limitations. Com-freed systems now appear on wafers thousands of times smaller than the single elector of previous networks. New designs and surfaces of weekly systems. The engineer comes increasingly limited in his knowledge of the wide range of advances – it is quite difficult to keep up with changes in an area of research or development. We have also reached a point where the main purpose of the Con-Tainer is simply to provide some means to manage the device or system and to provide a mechanism for attacking the rest of the network. Miniaturization seems to be limited by three factors (each of which will be addressed in this text): the quality of the semiconductor material itself, the technique of network design and the limitations of production and processing equipment. 1.2 Ideal diode The first electronic device to be introduced is called the diode. It is the simplest devices of semiconductors, but it plays a very vital role in electronic systems, with characteristics of characteristic that correspond closely to those of a simple switch. It will appear in a range of app-plications, extending from simple to complex. In addition to details of its construction and characteristics, the very important data and graphs to be found on the specification sheets will also be covered to ensure an understanding of the thermology used and to demonstrate the wealth of information generally available to manufacturers. The ideal term will be used frequently in this text as new devices are introduced. It refers to any device or system that has ideal features – perfect in any way. It provides a basis for comparison and reveals where improvements can be made. The ideal diode is a two-terminal device with symbol and features shown in Figg. 1.1a and B, respectively. 1 (4) 2 Chapter 1 semiconductors P N Ideally, a diode will conduct current in the direction defined by the arrow in the symbol and acts as an open circuit to any attempt to establish current the management of the opposite site. Basically: the characteristics of an ideal diode are those of a switch that can lead the current in one direction. In the description of the elements to be followed, it is essential that the various symbols of the letters, the polarity of tension and the current directions are defined. If the polarity of the applied voltage is consistent with that shown in FIG. 1.1a, the portion of the characteristic that is considered in Fig. 1.1b is right of the vertical axis. If a reverse voltage is applied, the characteristics on the left are relevant. If the current through the diode has the direction indicated in Fig. 1.1a, the part of the characteristics to consider is above the horizontal axis, while a reverse in the direction would require the use of the characteristics below the axis. For most of the Charac-thertistic device appearing in this book, the ordered axis (or â€ œyâ€ Asse) will be the current axis, while the Ascissa (or â€ œX Asse) will be the axis voltage. One of the important parameters for the diode is the resistance to the point or reunite of the operation. If we consider the rere-gion conduction defined by the direction of the ID and polarity of VDIN Fig. 1.1a (upright panel of Fig. 1.1b), we will find that the value of the resistance forward, RF, as defined by the Ohm law is RF V if f 0 (circuit) in which VFIS voltage forward through the diode and IFIS current forward through the diode. The ideal diode, therefore, is a short circuit for the conduction region. Consider the potential region negatively applied (third quadrant) by FIG. 1.1b, RR V IR R (open circuit) where VR is reversed through the diode and IR is the reverse current in the diode. The ideal diode, therefore, is an open circuit in the region of non-involvement. In review, the conditions set out in FIG. 1.2 are applicable. 5,20 or any inverse potential-Bias 0 MA 0 V 2, 3, MA, ... DV A + DV + â DI 0 DIDV = 0 (limited by the circuit) Open circuit short circuit (a) (b) DI In general, it is relatively simple to determine whether a diode is in the conduction region or not counterfeiting Simply by noticing the direction of the current ID (5) 3 PN The resulting current has the opposite direction, as shown in Fig. 1.3b, the equivalent of the open circuit is appropriate. 1.3 Semiconductor Materials Figure 1.3 a) Conduction and (B) Non-Agricultural States of the ideal diode as determined by the direction of the conventional current established by the network. D i = 0 (B) D I D ID ID (A) As mentioned above, the primary purpose of this section is to introduce the acteristic characteristics of an ideal device for comparison with the charcharcharacteristic characteristics of the varietytrade. As we proceed through the next sections, keep in mind the following questions: How close will the endurance be forward or â"¨ â"¨ a practical practitioner's endurance Compare with the desired level 0? Is the resistance of reverse shapes great enough to allow open-circuit continuation? 1.3 Semicle materials The label semiconductor provides a hint of its characteristics. The semi-is normally applied to a range of intermediate levels between two limits. The conductive term is applied to any material that will support a generous charge flow when a limited magnitude voltage source is applied through its terminals. An insulator is a material that offers a very low level of conductivity under pressure from an applied voltage source. A semiconductor, therefore, is a material that has a level of conductivity somewhere between the extremes of an isolator and a conductor. Inversely connected to the conductivity of a material it is its resistance to the load of charge, or current. That, higher is the level of conductivity, lower is the level of resistance. In the tables, the term resistance (, Greek letter RE) is often used when comparing material resistance levels. In metric units, the resistance of a material is measured in -cm or -m. The-CM units derive from the replacement of the units for each quantity of Fig. 1.4 in the following equation (derived from the RL / A base resistance equation): R L A () C (m cm2) ‡ '-cm (1.1) In fact, if the area of fig. 1.4 is 1 cm2 and the length 1 cm, the magnitude of the resistance of the cube of Fig. 1.4 is equal to the size of the material resistance as shown below: RA L ((1 CMM 2)) OHMS This fact will be useful to remember how we compare the levels of resistances in the discussion-sions to follow. Table 1.1 there are typical resistance values for three large categories of materials. Although it can be familiar with the electrical properties of the copper and (6) 4 chapter 1 semiconductor diodes pn table 1.1 typical values of resistance semiconductor isolator 106-cm 50 -cm (germalum) 1012-cm (copper) 50103-cm (Silicon) (mica) Mica from your past studies, the characteristics of the semiconductor materials of Ger-Manium (GE) and silicon (Yes) can be relatively new. As you will find in the chapters to follow, they are certainly not the only two semiconductor materials. They are, as-Ever, the two materials that received the largest range of interest in the development-option of semiconductor devices. In recent years, moving has been constantly towards silicon and far from germanium, but germanium is still in a modest production. Note Table 1.1 The extreme range between the conductor and Mate-Rials insulating materials for the length of 1 cm (1-cm2area) of the material. Eighteen places separate the positioning of the decimal point for a number from the other. GE and you have re-collected the attention they have for a number of reasons. A very important consideration the fact that they can be manufactured at a very high level of purity. In fact, recent progress has reduced impurity levels in pure material to 1 part inBil-Leone (110.000.000.000.000). You could ask if these low levels of impurities are really NEC-Exario. Surely they are if you thought that adding a portion of impurities (of the correct type) per million in a wafer of silicone material can change that material from a relatively poor conductor to a good conductor of electricity. Of course, we take care of a new spectrum of levels of comparison when we deal with the semi-conductor medium. The ability to change the characteristics of the material significantly through this process, known as "Doping ", "€" is another reason why GE and SI have received such a wide attention. Additional reasons include the fact that their characteristic capping can be significantly modified through the application of heat or light - an im-port-port consideration in the development of thermoseed and light-sensitive devices. Some of GE's unique qualities and SI's noted above are due to their atomic structure. The atoms of both materials form a very precise model that is periodic in nature (i.e., it is repeated continuously). A complete pattern is called crystal and the periodic arrangement of atoms is a reticle. For GE and SI The crystal has the three-dimensional diamond structure of Fig. 1.5. Any material composed exclusively to the re-torment crystal structures of the same type is called a single crystal structure. For semiconductor materials of the practical application in the field of electronics, this feature of single crystal exists and, moreover, the periodic structure does not change significantly with the addition of impurities in the doping process. We now examine the structure of the atom itself and known as it could affect the electrical characteristics of the material. As you know, the atom consists of three basic particles: electron, proton and neutron. In atomic lat-tice, neutrons and protons form the nucleus, while electrons rotate around the nucleus in a fixed orbit. The BOHR models of the two most commonly used semi-conductors, the germanium and silicon, are shown in Fig. 1.6. As indicated by Fig. 1.6a, the Germanio Atom has 32 electrons in orbiting, while the silicon has 14 electrons in orbiting. In any case, there are 4 electrons in the outer shell (valence). The potential (ionization potential) required to remove one of these 4 valence electrons is lower than the required for any other electron in the structure. In a pure germanium or silicone crystal these 4 valence electrons are linked to 4 adjacent atoms, as shown in Fig. 1.7 for silicon. Both GE and SI are referred to as tetravalent atoms because each has four valence electrons. A bond of atoms, strengthened by the sharing of electrons, is called the bond of cova-lent. (7) 5 p n Although the covalent bond will involve a bondstrong between valence electrons and their parent atom, it is still possible for valence electrons to absorb a kinetic energy sufficient from natural causes to break covalent covalentand take the state "free". The free term reveals that their movement is quite sensitive to the electrical fields applied as established by voltage sources or any potential difference. These natural causes include effects such as light energy in the form of photons and thermal energy from the surrounding medium. At room temperature there are about 1.51010 free carriers in a cubic centimeter of intrinsic silicon material. Intrinsic materials are those semiconductors that have been carefully refined to reduce impurities to a very low level, essential as pure that can be made available through modern technology. The free electrons in the material due to only natural causes are indicated as intrinsic vectors. At the same temperature, the intrinsic material of the germanium will have about 2.51013 free vectors per cubic centimeter. The ratio of the number of carriers in germanium to silicon is greater than 103 and indi-cate than the germanium is a better conductor at room temperature. This may be true, but both are still considered poor conductors in the intrinsic state. Note in Table 1.1 that the resistance also differs from a ratio of about 10001, with the silicon that has the largest value. This should be the case, of course, since resistance and conductivity are inversely related. An increase in temperature of a semiconductor can cause a substantial increase in the number of free electrons in the material. As the temperature rises from absolute zero (0 K), an increasing number of emission electrons absorbs sufficient thermal energy to break the covalent bond and contribute to the number of free vectors as described above. This increased number of carriers will increase the conductivity index and will result in a lower resistance level. Semiconductor materials such as Ge and Si that show a reduction of resistance with temperature increase are called having a negative temperature coefficient. You will probably remember that the resistance of most conductors will increase with the temperature. This is due to the fact that the number of carriers in a conductor will be 1.3 Semiconductor Materials Figure 1.6 Atomic structure: (a) German; (b) silicon. (8) not significantly increase with temperature, but their vibration pattern on a relatively fixed position will make it increasingly difficult for electrons to pass through. An increase in temperature therefore involves an increase in the level of resistance and a coefficient of temperature pos-itive. 1.4 LEVELS ENERGY In the isolated atomic structure there are discrete (individual) energy levels associated with each orbiting electron, as shown in Fig. 1.8a. Each material, in fact, will have its own set of energy levels eligible for electrons in its atomic structure. Further electron from the core, higherenergy state, and any electron that has left its parent atom has a higher energy state than any electron in the atomic structure. 6 Chapter 1 Semiconductor Semiconductor p n Figure 1.8 Energy levels: (a) discrete levels in isolated atomic structures; (b) conduction bands and valence of an isolator, semiconductor and conductor. Energy Energy Energy Energy E > 5 eVg Valence band Valence band Conduction band The bands overlap "Free" electrons to establish the conduction Valence electrons linked to the atomic structure E = 1.1 eV (Si) g E = 0.67 eV (Ge) g E = 1.41 eV (Ge) g V (GaAs) g Semiconductor isolator (b) Eg Valence band Conductor Energy gap Energy gap etc. Valance Level (outer shell) Second Level (next inner shell) Third Level (etc.) Energy nucleus (a) (9) ionization is the mechanism by which an electron can absorb enough energy to detach from the atomic structure and enter the conduction band. You will notice that the energy associated with each electron is measured in electronvolts (eV). The unit of measurement is appropriate, since WQV eV (1.2) is derived from the definition equation for the voltage VW/Q. The Q charge is the charge associated with a single electron. Replacing the charge of one electron and a potential difference of 1 volt in Eq (1.2) gives an energy level called 1 electron volt. Since energy is also measured in joules and the charge of an electron1,61 019coulomb, WQV (1.61 019C) (1 V) and 1 eV1.61 019J (1.3) At 0 K or absolute zero (273.15°C), all valence electrons of semiconductor materials are blocked in the Their outer shell of the atom with energy levels associated with the valence band of Fig. 1.8b. However, at room temperature (300 K, 25°C) a large number of valence electrons have acquired enough energy to leave the valence band, cross the energy gap defined by Egin Fig. 1.8b and enter the conduction band. For silicon Eg is 1.1 eV, for germanium 0.67 eV and for gallium arsenide 1.41 eV. The obviously lower Egfor germanium explains the greater number of vectors in this material than silicon at room temperature. Note for the insulator that the energy gap is typically 5 eV or more, which severely limits the number of electrons that can enter the conduction band at room temperature. The conductor has electrons in the conduction band even at 0 K. Obviously, then, at room temperature there are more than enough free vectors to support a strong charge flow, or current. We will find in Section 1.5 that if some impurities are added to the intrinsic materials of semiconductors, energetic states in the forbidden bands will occur which will cause a net reduction of Eg for both semiconductor materials Â" consequently, a higher carrying density in the conduction band at room temperature! 1.5 EXTRINSIC MATERIALS TYPE The characteristics of semiconductor materials can be significantly altered of some atoms of impurity in the relatively pure semiconductor material. These impurities, even if added to only one part in 10 million, can alter the band structure so that The electrical properties of the material. A semiconductor material that has undergone the doping process is called an extrinsic material. There are two extrinsic materials of immeasurable importance of device manufacturing semiconductor: type n and type p. Every will be described in detail in the following paragraphs. N-type material Both materials N- and P-type are formed by adding a fixed number of impurity atoms in a germanium or base silicon. TYPE N, will be created in addition to those impure elements that have five electron of value (pentavalent), for example a-timy, arsenic and phosphorus. The effect of these impurity elements is indicated in 7 1.5 Extrinseca MaterialsÃ ¢ N- and P-Type (10) Ã ¢ Antimony (SB) Impureness Yes AAA Ã ¢ Ã ¢ Ã Ã, Ã, Ã, Ã ¢ Ã , Ã, is, is YES YES YES YES SI SI fifth electron of antimonio value 8 Chapter 1 Semiconductor Diodes PN Figure 1.9 Antimony Impurities in type n. Fig. 1.9 (using antimony as impurity in a silicon base). Note that the four hatching bonds are still present. There is, however, a further fifth electron due to the impurity atom, which not associated with any particular covalent bond. This electron mineral re-produce, vaguely linked to its parent (antimony) atom, is relatively free to move within the NeOformato type N material. Since the impouritty atom inserted has given an electron relatively Ã ¢ â,¬ Å "free" to the structure: impurities spread with five electron valence are called donor atoms. It is important to realize that even if a large number of A free vectors ¢ have been established in type N material, it is still electrically neutral because ideally the number of protons positively in the nuclei is still equal to the number of free ¢ Ã ¢ and orbiting negative electrons in the structure. The effect of this dock process on its conductivity can be described by using the energy-band diagram of Fig. 1.10. It should be noted that a discrete level of energy (called donor) appears in the prohibited band with a significantly lower than material Intrinsic. These electrons Ã ¢ freeÃ ¢ Cause of adding SIT IM-purity at this level of energy and have less difficulty to absorb a sufficient measurement of thermal energy to Move into the conduction band at room temperature. The result is that at room temperature, there are a large number of vectors (electrons) in the level of conduction and the conductivity of the material increases significantly. At room temperature in an intrinsic material it is about a free electrons for every 1012 atoms (from 1 to 109 for GE). If our dosing level was 1 to 10 million (107), the ratio (1012/107105) indicates that the concentration of carriers has increased by a ratio of 100.0001. Figure 1.10 Impurity effect on the energy band structure. energy bandwidth of conduction valence bandEnergy level G E = 0.05 EV (SI), 0.01 EV (GE) (11) P-type Material The P-Type material is formed by doping a pure germanium or silicon crystal with impurity atoms with three electrons of Valence. The most used elements for this purpose are boron, gallium and indium. The effect of one of these elements, boron, on a silicon base is indicated in Figure 1.11. 9 1.5 External materials â € "N- and P-type P N Figure 1.11 Borone impurity in material type p. Note that there is now an insufficient number of electrons to complete the cova-Lent ties of the newly formed pattern. The resulting vacation is called a hole and is represented by a small circle or positive sign due to the absence of a negative charge. Since the resulting vacation will readily accept an electron â € œliberoâ €: the impure spread with three valence electrons are called acceptor atoms. The resulting P-Type material is electrically neutral, for the same reasons described for the N-Type material. Electron with respect to the hole flow The effect of the hole on the conduction is shown in Figure 1.12. If an electron of value requires enough kinetic energy to break its covalent bond and fill the void created by a hole, then a vacation, or a hole, will be created in the covalent bond that released the electron. There is therefore a transfer of holes to the left and electron to the right, as shown in Figure 1.12. The direction to use in this text is that of the conventional flow, which is indicated by the direction of the flow of the hole. (12) Majority and minority carriers in the intrinsic state, the number of free electrons in GE or was due only to those few electrons in the valence band that acquired enough energy from thermal or bright sources to break the covalent bond or At the very little impure that they could not be removed. The vacancies left behind in the covalent bonding structure represent our very limited offer of holes. In a type N material, the number of holes has not changed significantly from this intrinsic level. The net result, therefore, is that the number of electrons far exceeds the number of holes. For this reason: in a N-Type material (fig. 1.13a) the electron is called the majority vector and the hole the minority vector. For the P-type material the number of holes very exceeds the electronic number, as shown in Figure 1.13b. Therefore: in a material P-Type the hole is the majority vector and the electron is the minority vector. When the fifth electron of a donor atom leaves the atom parent, the remaining atom buys a positive net charge: hence the positive sign in the donor-ion representation. For similar reasons, the negative sign appears in the course of acceptance. The N- and P-Type materials represent the basic blocks of semiconductor devices. We will find in the next section that the of a single type n mater-ial with a type p mater-ial will be translated into a semiconductor element of considerable im portance in electronic systems. Chapter 1Diodes p n Figure 1.13 (a) n-type material; (B) p-type material. + + Â â â â â + â â â â â â â â â â â + Minority carrier p-type n-type ions Donor Majority carriers Accept ions Majority carriers + + + + + + + + + + + + + + â â â â + + + the semiconductor diode is formed simply by putting together these materials (constructed from the same base, Ge or Si), as shown in figure 1.14 using techniques to be described in chapter 20. At the moment the two materials are â congiungetiâ the electrons and holes in the junction region will join, with consequent lack of carriers in the region near the junction. This region of positive and negative ions discovered is called the re-gion of exhaustion due to the depletion of carriers in this re-gion. Since the diode device is a two-stroke, the application of a voltage across its terminals leaves three possibilities: no bias (VD0 V), forward bias (VD 0 V), and reverse bias (V VD0) . Each is a condition that will result in a response that the (13) No Applied Bias (VD0 V) Under no-bias (no applied voltage) conditions, any minority carrier (holes) in the n-type material that can be found at 'interior of the depletion region will pass directly into the p-type material. Closer the minority carrier is at the junction, the greater is the attraction for the layer of negative ions and less opposition from the positive ions in the n-type material depletion region. For the purposes of future discussions we assume that all of the minority carriers n-type material that find them in the depletion region because of their random motion will pass directly into the p-type material. The similar discussion can be applied to the minority carriers (electrons) of the p-type material. The carrier flow was shown in Figure 1.14 for carriers to mi-nority of each material. The majority carriers (electrons) of the n-type material must exceed the at-tractive forces of the positive ions in the layer of n-type material and the shield of negative ions in the p-type material to migrate in the zone beyond the re- gion of p-type material exhaustion. However, the number of majority carriers is so great in the n-type material that invariably there will be a small number of majority carriers with sufficient kinetic energy to pass through the depletion region in the ma-terial p-type. Again, the same type of discussion can be applied to the majority carriers (holes) of the p-type material. The resulting stream due to the majority carriers is also shown in Figure 1.14. A thorough examination of Fig. 1:14 will reveal that the relative magnitude of the flow vectors are such that the net flow in both directions is zero. This cancellation of carriers has been shown by crossed lines. The length of the vector that represents the hole It has been established longer than for the flow of electrons to demonstrate that the mag-finity of each should not be the same for deletion and that the levels of drugging for each material can cause an unequal load of holes and electrons. in synthesis-mary, therefore: in the absence of an applied polarization voltage, the net flow of charge in any direction of a semiconductor diode is zero. 11 1.6 semiconductor diode p n (14) the symbol for a diode is repeated in fig. 1.15 with the associated n- and p-type regions. Note that the arrow is associated with the p-type component and the bar with the type n. region as indicated, for vd0 v, the current in each direction is 0 but. reverse polarization condition (vd0 v) if an external potential of v volt is applied through the joint such that the POS-itive terminal is connected to type n material and the negative terminal is connected to the type p material as shown in Fig. 1.16, the number of positive ions discovered in the area of emptying type n material will increase due to the large number of a free voltage electron taken to the positive potential of the applied material. for similar reasons, the number of negative ions discovered will increase in type p material. The net effect, therefore, is an enlargement of the emptying region. This widening of the emptiness region will establish too large barrier one for major carriers to be overcome, reducing the majority to zero career flow as shown in Fig. 1.16. 12 chapter 1 semiconductor diodes figure 1,17 reverse polarization conditions for a semiconductor diode. figure 1.15 conditions No-polarization for a semiconductor diode. the number of minority carriers, however, that are entering the depletion region will not change, causing minority carriers of the same magnitude indicated in Fig. 1.14 without applied tension. the current that exists in conditions of reverse polarization is called the current sat-URATA opposite and is represented by is. the reverse saturation current is rarely more than a few microamps except for high voltage devices. In fact, in recent years its level is typically in the range na for silicon devices and in the low range microampere for germanium. the term saturation comes from the fact that it reaches the maximum level quickly and does not vary significantly with the increase of the reverse polarization potential, as shown by the characteristics of fig diode. 1.19 per vd0 v. the reverse-polarized conditions are represented in fig. 1.17 for the diode and junction symbol pn. note, in particular, that the iside direction against the arrow of the symbol. It should also be noted that the negative potential is linked to the p-type material and the positive potential of type n Materialã the difference of letters underlined for eachreveals a condition of reverse polarization. Forward-Bias condition (vd 0 v) To forward-polarization or â ona condition is established applying positive potential to p type material and negativeto the n-type material as shown in Figure 1.18. For future reference, therefore: A semiconductor diode is advanced when the p-type and p os-itive and n-type and negative association was established. (15)13 p n The application of a potential VD of lips forward "pressure" electrons in n-type material and holes in p-type material to recombine with ions near the border and reduce the width of exhaustion region as shown in figure 1.18. The re-surrecting flow of electron minor wagons from p-type material to ma-terial n-type (and holes from mama-terial n-type to mama-terial p-type) has not changed in magnitude (because the conduction level is mainly controlled by the limited num-ber of impurities in the material), but the reduction of the width of the depletion flow has brought a reduced electron As the applied bias increases by magnitude the exhaustion region continues to decrease in width until an electron flood can pass through the joint, re-1.6 Semiconductor Diode Figure 1.18 Avanti-biased p-n joint. Figure 1.19 Characteristics of silicon semiconductor diode. 10 12 14 15 16 18 19 20 1 2 4 7 8 9 0.3 0.5 0.7 1 –10 –20 –30 –40 ID (mA) (V) D V D V - + defined polarity and direction for the graph region of the lips forward (V > 0 V, I > 0 mA) D I D VD I s I - 0.2 uA - 0.3 uA - 0,4 uA μ 0 Note that the vertical scale of Fig. 1.19 is measured in brakes (although some semiconductor diodes will have a mea-insured vertical scale in ampere) and the horizontal scale in the lip region forward has a maximum of 1 V. Typically, then, the tension through a forward-faded diode will be less than 1 V. Also note, how quickly the current rises beyond the knee of the curve. It can be demonstrated through the use of solid state physics that the general activity of carbonization of a semiconductor diode can be defined by the following equation for the regions forward and reverse: IDIs(and kVD/TK1) (1.4) where the saturation current Isreverse k11,600/ with 1 for Ge and 2 for Si for relatively low current levels (1 diode or below the SiK component). IDIse kVD/TK Is For positive values of VD the first term ofabove will grow very quickly and overwhelm the effect of the second term. The result is that for positive values of VD, ID will be positive and grow as function you x which appears in Fig. 1.20. At VD0 V, Eq. (1.4) becomes IDI (e 0 1) Ã¤ (11) 0 mA as ap-pearing in Figure 1.19. For negative values of VD the first term will descend rapidly from being-low is, resulting in ID Is, which is simply the horizontal line of Fig. 1.19. The breakdown of the features of VD0 V is simply due to the dramatic change in scale from mA to A. Note in Fig. 1.19 that the available commercial unit has features that are shifted to the right by a few tenths of volts. This is due to the internal "body" resis-tance and external resis-tance "contact" of a diode. Each contributes to an additional voltage at the same current level, determined by Ohm's law (VIR). Over time, as production methods improve, this difference will diminish and the effective character approaches those of Eq. (1.4). It is important to note the scale change for the vertical and horizontal axes. For positive ID values the scale is in milliamps and the current scale under the axis is in microamperes (or perhaps nanoamperes). For VDthe scale for positive values is in tenths of volts and for negative values the scale is in tens of volts. Initially, Eq. (1.4) appears a bit complex and may develop an unjustified fear that will be applied to all diode applications to follow. Fortunately, however, a number of approximations will be made in a later section which denies the need to apply Eq. (1.4) and provide a solution with a minimum of mathematical difficulties. Before leaving the lip object forward, the conditions for conduction (the âœonâ state) are repeated in Figure 1.21 with the required biasing polarity polarity and the resulting direction of the flow of most of the vector. Note in particular that the direction of conduction corresponds to the arrow in the symbol (as revealed for the ideal diode). Zener Region Although the scale of Fig. 1.19 is in tens of volts in the negative region, there is a point where the application of too negative voltage will result in an acute change 14 Chapter 1 Semiconductor Diode Figure 1.20 Plot of former (17) 15 1.6 Semiconductor Diode pn Figure 1.22 Region Zener. in the characteristics, as shown in Figure 1.22. The current rises at a very fast rate in a direction opposite to that of the positive voltage region. The reverse-bias poten-tial that results in this dramatic change in features is called the Zener poten-tial and is given the symbol VZ. As the voltage across the diode increases in the region of the inverse forms, the velocity of the minority vectors responsible for the inverse saturation current Iswill also increases. In the end, their velocity and associated kinetic energy (WK12mv 2) will be to release additional carriers through collisions with otherwise stable atomic structures . That is, un'ionizzazione un'ionizzazione will result in which valence electrons absorb sufficient energy to leave the parent atom. These additional supports can therefore help the ionization process to the point where a high avalanche current is established and the determined avalanche break region. The avalanche region (VZ) can be brought closer to the vertical axis by increasing drug levels in p- and type n. However, such as VZdecreases at very low levels, for example 5 V, another mechanism, called Zener distribution, will contribute to the sudden change in the feature. It occurs because there is a strong electric field in the region of the junction that can interrupt the bond forces within the atom and â€ œGenerate ... Although the Zener breaking mechanism is a significant contrib-utor only at lower levels of VZ, this sudden change in the characteristic at any level is called region and diodes employ this unique portion of the characteristic of a p-n junction are called Zener diodier. They are described in detail in Section 1.14. The Zener region of the semiconductor diode described must be avoided if the acceptable re-response of a system should not be completely altered by the sudden change of characters-stics in this reverse-voltage region. The maximum reverse polarization potential that can be applied before entering the Zener region is called the reverse voltage peak (indicated simply as the PIV rating) or the reverse voltage peak (indicated with PRV rating). If an application requires a greater PIV than that of a single unit, a num-ber of diodes of the same characteristics can be connected in series. The diodes are also connected in parallel to increase the current transport capacity. Silicon respect germanium (18) of direct tension-polarization necessary to reach the oscillation zone upwards. It is typically the size order of 0.7V per silicon diodes available on the market and 0.3 V for diodes to the germanium when rounded to the nearest tenths. The higher silicon offset is mainly due to the factor in Eq. (1.4). This factor plays a role in de-termining the shape of the curve only at very low current levels. Once the curve begins its vertical rise, the factor drops to 1 (the continuous value for the germanium). This is demonstrated by the similarities in the curves when the offset potential is achieved. The potential for this increase is commonly referred to as offset, threshold, or potential cooking. Often, the first letter of a term describing a particular quan-tity is used in the notation for that quanquan-tity. However, to ensure a minimum of con-fusion with other terms, such as output voltage (Vo) and direct voltage (VF), the VThas no-tion are adopted for this book, by the word âBrowse: VT0.7 (si) VT0.3 (Ge) Obviously, the more the oscillation upward is the vertical axis , plus a complement device. However, other characteristics of silicon with respect to germanium still make the choice in the majority of the available units. The temperature can have a marked effect on the characteristics of a silicon semiconductor diode as witnessed by a typical silicon diode in Figure 1.24. It has been found experimentally that: The saturation current Iswill just about double in magnitude for each increase in temperature of 10 ° C. 16 Chapter 1 Semiconductor Diodes p n (19) 17 1.7 Levels of resistance p n Figure 1.24 Variation in diode characteristics with temperature variation. It is not uncommon for a diode of germanium with a Isin order of 1 or 2 A at 25 ° C to obtain a current of 100 mA A0.1 loss at a temperature of 100 ° C. Current levels of this magnitude in the region of reverse towers definitely would put into question our open-circuit condition in the desired region of the torches. Typical values of Isfor silicon are much lower than those of germanium for the power levels and similar current, as shown in Figure 1.23. The result is that even at elevated temperatures levels of silicon diodes Isfor do not reach the same high levels obtained for germanium, a very im-carrier reason that silicon devices enjoy a significantly more high level of development and use in design. Basically, the equivalent of an open circuit in the inverse region forms is better achieved at any temperature compared to the silicon with germanium. The increasing levels of temperature Iswith represent lower levels of tresh-old voltage, as shown in Figure 1.24. Just increase the level of Isin Eq. (1.4) and note the previous increase of the diode current. Of course, the level of TKanche will increase in the same equation, but the level of increase of Iswill sovrapotenzierÃ change per-centage smaller in TK. Since © the temperature increases the features forward are becoming more and more "ideal", but we will find when we review the sheets of specifications that the temperatures beyond the normal operating range may have an ef-fect very deleterious effect on the maximum power and current levels of the diode. In the region of the shapes of the reverse breakdown voltage increases with the temperature, but it should be noted the undesirable increase of the saturation current. 1.7 LEVELS OF RISISTENZA (20) or static DC Resistance The application of a dc voltage to a circuit containing a semiconductor diode re-sulterÃ in an operating point on the characteristic curve that will not change with time. The resistance of the diode to the operating point can be simply found by finding the corresponding levels of VDand IDAS shown in Figure 1.25 or by applying the following equation: V RD ID D (1.5) The dc resistance levels at the knee and below will be greater than the levels resistance obtained for the vertical section of an increase of the characteristics. The lev-els of resistance in the region will reverse lips high enough. Since © ohmmeters typically employ a relatively constant-current source, the determined resistance will be at the preset current level (typically , a few milliamps) . 18 Chapter 1 Semiconductor Diodes p n Figure 1-25 Determination Determination dc resistance of a diode at a partico-lar operating point. In general, therefore, the lower the current through a greater diode is the dc resistance level. Determine the dc resistance level for the diode of Fig. 1.26 a (a) ID2 mA (b) ID20 mA (c) VD 10 V Solution (a) A ID2 mA, VD0.5 V (from the curve) and RD V ID D 2 0 m 5 VA 250 EXAMPLE 1.1 (21) 19 pn Figure 1.28 Determination of AC resistance in a Q-point. A straight line traced tangent to the curve through the Q-point as shown in Fig. 1.28 will define a particular variation of tension and current that can be used to discourage ac mine or dynamic resistance for this region of the characteristics of the diodes. An ef-fort should be made to maintain the voltage and current change as small as possible and equid instant from both sides of the Q-point. In the equation form, RD V I d where it means a change in finite quantity. (1.6) is the slope, the lower the value of the Vdfor the same change of Idand less resistance. The AC resistance in the vertical-increasing feature is therefore very small, while the AC resistance is much higher than low current levels. In general, therefore, the lower Q-point of operation (lower current or lower voltage) is the higher AC resistance (B) At ID20 mA, VD0.8 V (from the curve) and RD V ID D 2 0 .8 m VA 40 (c) At VD 10 V, ID is 1 A (from the curve) and RD V ID D 1 10 VA 10 M clearly support some of the previous considerations on the level of a CA or dynamic resistance It is obvious from eq. 1.5 and 1.1 Example that the DC resistance of a diode is independent of the shape of the characteristic in the region surrounding the inter-est point. If a sineicide is applied instead of DC input, the situation will change completely. The variable input moves the instantaneous operating point up and down a region of features and thus defines a specific change in current and voltage, as illustrated in Fig. 1.27. Without applied variable signal, the operating point would be the Q-point contained in Fig. 1.27 determined by the applied cc levels. The Q-point des-ignaziano comes from the word quiescent, meaning a stop or unvarying.â Figure 1.27 Definition of dynamic resistance or ac. (22) p n Solution (a) For ID2 mA; the tangent line in ID2 mA was designed as shown in figure and a 2 mA oscillation above and below the specified diode current was chosen. To ID4 mA, VD0.76 V, ea ID0 mA, VD0.65 V. The resulting current and voltage variations are Id4 MA0 mA4 and Vd0.76 V0.65 V0.11 V and AC resistance: rd V Id d 0 4 .1 m 1 AV 27.5 (b) For ID25 mA, the tangent line in ID25 mA was designed as shown on the fig ure and an oscillation of 5 mA above and under the specified diode current was cho-sen. At ID30 mA, VD0.8 V, and ID20 mA, VD0.78 V. The switch-out result andare ID30 MA20 MA10 mA and Vd0.8 V0.78 V0.02 V and AC resistance is rd V Id d 1 0 .0 m 2 VA 2 For characteristics1.29: (a) Determine the AC resistance to id2 but. (b) Determine the AC resistance to id25 but. (c) Compare the results of the parties (a) and (b) to the DC resistances to each current level. 20 Chapter 1 Semiconductor Diodes Example 1.2 Figure 1.29 Example 1.2V (V) of (MA) ID 0 5 10 15 20 25 30 2 4 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 Ã, â € Ã Ã, â € ™ , Ã € VD (23) 21 1.7 Resistance levels PN (C) for ID2 MA, VD0.7 V and RD V ID D 2 0. M 7 VA 350 which far exceeds RDOF 27.5. For id25 ma, vd0.79 v and rd v id d 2 0 5 .7 m 9 goes 31.62 which far exceeds rdof 2. We have graphically found dynamic resistance, but there is a basic definition in differential calculation which states: the derivative of a function at a point is equal to the slope of the tangent line drawn at that point. The equation (1.6), as defined by Fig. 1.28, is therefore essentially the search for the drift of the function at point Q of operation. If we find the derivitalize of the general equation (1.4) for the semiconductor diode with respect to the prejudice applied and thus reversing the result, we will have an equation for dynamic or AC fitting in that region. That is, taking the derivative of EQ. (1.4) As regards the AP-PLESS prejudice will result in DV D D D D (ID) D V [is (and KVD / TK1)] and D D V ID D T K K (IDIS) After some basic maneuvers of the differential calculation. In general, IDIS in the vertical section of the characteristics and DD V ID DT KK ID ID REPLACEMENT 1 for GE and YES in the Vertical-Rise section of the characteristics, we obtain K 11, 600 11, 1 600 11.600 and in the temperature room, TKTC273 Â ° 25 Â ° 25 Â ° 273 Â ° 298 Â ° so that TKK 11 2, 9 6 8 00 38.93 and DD V ID D 38.93ID leafing through the result to define a resistance ratio (RV / I) DÃ DD V ID D 0. I 0 D 26 or RD (24) 22 Chapter 1 Semiconductor diodes PN The meaning of EQ. (1.7) It must be clearly understood. It implies that dynamic resistance can be found simply by replacing the quious value of the curved diode in the equation. It is not necessary to have available features or to worry about splashing the tangent lines as defined by EQ. (1.6). It is important to keep in mind, however, the EQ. (1.7) It is accurate only for IDIN values of the vertical section of the curve. For minor values of ID, 2 (silicon) and the value of RD OB-TAINED must be multiplied by a factor of 2. for small idbelow values the knee of the curve, EQ. (1.7) becomes inappropriate. All determined resistance levels have so far been defined by the JUNC-TON PN and do not include the resistance of the semiconductor material itself (called body resistance) and the resistance introduced by the connection between the semiconduc-Tor material and the external metallic conducsemondalmondum -tor (called contact resistance). These international resistance levels can be included in EQ. (1.7) Adding Denotated by RBAS that appears in EQ. (1.8). RD resistance, therefore, includes the defined defined dynamic re-systances Eq. 1.7 and RB of re-sistency just introduced. rd 26 ID mV rB ohms (1.8) The rBcan factor varies from typically 0.1 for high-power devices to 2 for some low-power, general-use diodes. For example 1.2 ac resistance to 25 mA was calculated to be 2 . Using Eq. (1.7), we rd 26 ID mV 2 5 6 mV A 1.04 The difference of about 1 could be treated as a rB contribution. For example, 1.2 ac resistance to 2 mA was calculated to be 27.5 . Using Eq. (1.7) but multiplying by a factor of 2 for this region (in the knee of the bend 2), rd2 26 ID mV 22 2 6 m A V 2(13)26 The difference of 1.5 could be treated as the contribution due rB. Actually, determine rdto a high degree of accuracy from a characteristic curve using Eq. (1.6) is a difficult process at best and the results must be treated with a salt grain. At low diode current levels the rB factor is normally small enough compared to rdto allows to ignore its impact on the ac diode resistance. In high current lev-els the level of rBmay approaches that of rd, but since there will frequently be other resistive elements of a much larger size in series with the diode that we will assume in this book that the ac resistance is determined exclusively by rdand the im-pact of rB will be ignored if not otherwise noticed. The technological improvements of the years of review suggest that the rB level will continue to decrease in magnitude and eventually will become a factor that can certainly be ignored compared to rd. The above discussion focused exclusively on the lip region ahead. In the torque region it is assumed that the change of current along the line Is is nil from 0 V to the Zener region and the consequent ac resistance with Eq. (1.6) is sufficiently high to allow the approximation of the open circuit. Average resistance AC (25)deter-23 1.7 Levels of resistance p n under a straight line between the two intersections established by the max-imum values and minmax-imum input voltage. In the form of equation (Note Fig. 1.30), rav V Id d pt. to pt. (1.9) For the situation indicated by Figure 1.30, Id17 mA2 mA15 mA and Vd0.725 V0.65 V0.075 V with rav V Id d 0 1 . 5 07 m 5 A V 5 If the ac resistance (rd) was determined at ID2 mA its value would be more than 5, and if determined at 17 mA it would be less. Between ac resistance would be the transition from high value to 2 mA to less than 17 mA. The equation (1.9) defined a value that is considered the average of the ac values from 2 to 17 mA. The fact that a resistance level can be used for a wide range of features will prove quite useful in defining equivalent circuits for a diode in a later section. As with dc and ac resistance levels, the lower the current level used to determine the higher average strength is theresistance . Table 1.2 has been developed to strengthen the important conclusions of the last pages and to emphasize the differences between the various pages . pages. Resistance levels. As previously indicated, the content of this section constitutes the base for a series of resistance calculations to be carried out in the sections and in the following chapters. Figure 1.30 Determination of the average AC resistance between the indicated limits. D (V) VI (MA) ID 0 5 10 15 20 0.1 0.2 0.3 0.4 0.4 0.6 0.7 0.8 0.9 1 (26) 24 Chapter 1 Semiconductor Diodes PN Table 1.2 Resistance Levels Equation Design Type Special Characteristics D determination DC or Static Rd V ID D defined as a point on the AC or RD V ID 26 MV characteristics defined by a dynamic tangent line to the Q-Point Media AC RAV V ID D PT. to pt. Defined by a straight line between the operating limits 1.8 Equivalent diode circuits An equivalent circuit is a combination of properly chosen elements to make the most of the actual terminal characteristics of a device, system or other in a particular operating area. In other words, once the equivalent circuit is defined, the symbol of the device can be removed from a scheme and the equivalent circuit can be inserted in its place without seriously altering the actual behavior of the system. The result is often a network that can be resolved using traditional circuit analysis techniques. Linear Equivalent Circuit PieceWise (27) Re-25 1.8 Equivalent Circuit Dioding P N Solt in the open circuit status of the device. Because a silicon semiconductor diode reaches the conduction status only when VD reaches 0.7 V with a forward polarization (as shown in fig. 1.31), a VT battery opposite the direction of conduction must appear in the equivalent circuit as shown In fig. 1.32. The battery simply specifies that the voltage through the device must be greater than the battery threshold voltage before it is possible to establish the conduction through the device in the direction dictated by the ideal diode. Once the conductivity is established, the diode resistance will be the specified value of RAV. Keep in mind, however, that the VT in the equivalent circuit is not an independent voltage source. If a voltmeter is placed on an isolated diode on the summit of a laboratory bench, no reading of 0.7 V is obtained. The battery simply represents the or-zontal displacement of the characteristics that must be exceeded to establish the conduction. The approximate level of the RAVCAN is generally determined starting from a specified operating point on the specification tab (to be discussed in section 1.9). For example, for a semiconductor silicon diode, if IF10 MA (forward forward for the diode) to VD0.8 V, we know that for silicon it is necessary to move 0.7 V before the characteristics increase and RAV V ID PT. to pt. 1 0 0 0 .8 m v A 0 0 .7 m V A 1 0 0 0 .1 m V A 10 As obtained for FIG 1.30. Equivalent circuit For most applications, the resistance RAV is small enough to be ignored with respect to the other elements of the network. The removal of RAV by equivalent figure 1,32 components of the linear equivalent circuit at times. D V D I + Â «VT RAV 0.7 V 10 Â« Â| D V Ideal diode + Â «Â» Â «Â» I (28) 26 Chapter 1 Semiconductor The Diodes p n circuit is the same which implies that the characteristics of the diode appear as shown in Figure 1.33. In fact, this approximation is often used in semiconductor analysis, as shown in Chapter 2. The reduced equivalent circir-cuit appears in the same number. It is stated that an advanced silicon diode in an electronic system under dc conditions has a decrease of 0.7 V through it in the conduction state at any level of diode current (in nominal values, of course). Ideal equivalent circuit Now that the ravhas has been removed from the equivalent circuit, we take a step forward and we establish that a level of 0.7-V can often be ignored compared to the applied voltage level. In this case the equivalent circuit will be reduced to that of an ideal diode as shown in Figure 1.34 with its characteristics. In chapter 2 we will see that this approximation is often done without a serious loss of accuracy. In industry a popular replacement for the phrase "diodo equivalent circuit" is the diode model - a model by definition is a representation of an existing device, object, system, and so on. In fact, this replacement terminology will be used almost exclusively in the chapters to follow. Figure 1.34 Diode ideal and its characteristics. Summary table For clarity, the diode models used for the range of parameters and applications of the circuit are provided in Table 1.3 with their linear features. Each of them will be examined in more detail in Chapter 2. There are always exceptions to the general rule, but it is quite safe to say that the simplified equivalent model will be exploited more frequently in the analysis of electronic systems, while the ideal diode is often applied in the analysis of power systems where larger voltages meet. Figure 1.33 Simplified equivalent circuit for silicon semiconductor diode. – Ω D V D I 0 V = 0.7 VT av r = 0 D I + VD Ideal Diode (29)27 1.9 Diode Specifications Sheets p n 1.9 DIODE SPECIFICATIONS The data relating to the specific semiconductor devices are normally provided by the manufacturer in one of the two forms. Most frequently, it is a very short description limited to perhaps a page. Otherwise, it is a thorough examination of the features using graphs, artworks, tables, and so on. In both cases, there are specific data pieces that must be included for proper use of the device. They include: 1. VF forward voltage (to a specified current and temperature) 2. The maximum current forward IF (at specified temperature) 3. The reverse saturation current IR (at a specified voltage and temperature) 4. The reverse voltage rating [PIV or PRV or V(BR), where BR comes from the term "breakdown" (at specified temperature)] 5. Themaximum power dissipation at a particular temperature 6. capacity levels (as defined in section 1.10) 7. Reverse recovery time trr (as defined in section 1.11) 8. operationRange Depending on the type of diode in consideration, additional data can also be provided, such as frequency range, noise level, switching time, thermal lev-lev-els and point repeat values. For the question in mind, the meaning of data will usually be self-inflection. If the maximum power or valuation of the dissipation is also provided, it is intended to be equal to the following product: PDMaxVDID (1.10) where IDAD View the diode current and voltage in a particular operating point. Table 1.3 Diodo equivalent circuits (models) Type Conditions Model Features Linear model at strokes Simplified model RNETworkrav Device ideal RNETWorkrav (30) 28 Chapter 1 Semiconductor Diodes PN If we apply the simplified model for a particular application (a common requirement), we can replace VDVT0.7 V for a silicon diode in EQ. (1.10) and de-termines the consequent dissipation of the power for comparison with the maximum power. That is, pdazzepato ID (0,7 V) (1.11) (31) 29 1.9 sheets of specific diodes P N An exact copy of the data provided for a high voltage/low loss diode appears in figgs 1.35 and 1.36. This example would represent the expanded list of data and features. The term straightener is applied to a diode when used frequently in a grinding process to be described in Chapter 2. Page 2 In this section the approximate model is used to study a series of series diodes configurations with DC inputs. The content will establish a foundation in diode analysis that will take over the sections and chapters to follow. The procedure described may, in fact, be applied to networks with any number of diodes in a variety of configurations. For each configuration, the status of each diode must be determined first. What diodes are â€ œOnÂ € and are â€ œoffâ€? Once determined, the appropriate equivalent as defined in Section 2.3 can be replaced and the remaining parameters of the specified network. In general, a diode is in the state â€ œOdo if the current established by the applied sources is such that its direction corresponds to that of the arrow in the diode symbol and VD0.7 V for silicon and VD0.3 V for the germanium. For each configuration, mentally replace the diodes with resistive elements and note the resulting current direction established by the applied tensions (â€ œpressura "). If the resulting direction is a â€ œMatchâ€ with the arrow in the diode symbol, you will experience the driver through the diode and the device is in the state â€ œon ". The above description is, of course, quota on the offer having a voltage greater than the voltage â€ œTurno-on "(VT) of each diode. If a diode is in the state â€ ", one can place a drop from 0.7-V through the element, or the network can be redesigned with the vtoquivalent circuit asTable 2.1. In time the preference will probably simply be to include drop from 0.7-V through each â€ "diodo and draw a line through each diode in theor state opened. Initially, however, the replacement method will be used to ensure that appropriate voltage and current levels are determined. The series circuit of fig. 2.10 Described in detail in point 2.2 will be used to demonstrate the approach described in the previous points. The state of the diode is determined first of all by mentally replacing the diode with a resistive element, as shown in Fig. 2.11. The resulting direction of I coincides with the arrow in the symbol of the diode, and since EVT the diode is in the state Â «ON.Â» The network is then redesigned as indicated in fig. 2.12 With the corresponding model for the polarized silica-shaped icon diode forward. Note that VDIS polarity is the same that it would result if the diode is actually a resistive element. The resulting voltage and current levels are the following: VDVT (2.4) VRevt (2.5) IDIR V R (2.6) 59 Series 2.4 Diodes configurations with DC inputs Figure 2.9 (a) Approximate notation of the model; (b) Ideal notation of diodes. Figure 2.10 Set of diodes configuration. Figure 2.11 Determination of the diode status of Fig. 2.10. R i + Â «and VR + Â« Fig. 2.12 Replacing the equivalent model for the diode Â «a» of Fig. 2.10. In Fig. 2.13 The diode of Fig. 2.10 was inverted. By mentally replacing the diode with a resistive element, as illustrated in figure 2.14, it turns out that the resulting current direction does not correspond to the arrow in the diode symbol. The diode is located in the state «Offâ», which gives rise to the equivalent circuit of Fig. 2.15. Due to the open circuit, the curtain of the diode is 0 A and the voltage through the resistance R is the following: VRIRRIDR (0 A) R0 V The fact that VR0 V will establish and volts through the open circuit, as defined From the tension law of Kirchhoff. Always keep in mind that in any case the Kirchhoff voltage law must be respected! For the configuration of diodes in series of Fig. 2.16, determine VD, VR and ID. Solution Because the applied voltage establishes a current clockwise that corresponds to the arrow of the symbol and the diode is in the state Â «OnÂ», VD0.7 V VRevD8 V0.7 V7.3 V IDIR VR 2 7 .2 .3 K V 3.32 But repeat the example 2.6 with the inverted diode. Solution By removing the diode, we find that the direction of I is opposed to the arrow in the symbol of the diode and the equivalent of the diode is the open circuit regardless of the model used. The result is the network of fig. 2.17, where ID0 due to the open circuit. From Vrirr, VR (0) R0 V. Applying the Kirchhoff voltage law around the closed circuit are obtained evdvr0 and Vdevre0E8 V 60 Chapter 2 Diodes' applications Example 2.6 Example 2.7 Figure 2.13 Reversal of the diode of Fig. 2.10. Figure 2.14 Determination of the diode status of Fig. 2.13. Figure 2.15 Replacing the equivalent model for the diode «Offâ» of Figure 2.13. 2.16 Circuit for Example 2.6. Figure 2.17 Determination of Unknown Quantities for Example 2.7. + "Â" R= 0 A A 0 to 8 ver 2.2kÂ ¢ "| vr + Ã ¢ â,¬" i vd and 10 v 5 v +10 ve = Ã ¢ â,¬ "5 v Ã ¢ â,¬" 5 ve = + 10 ve 61 2.4 Series Diodes configurations with DC inputs Example 2.8 Figure 2.18 Source notation. Figure 2.19 Diodes circuit series 2.8. In particular, note in Example 2.7 High voltage through the diode even if it is a state Ã ¢ â,¬ Å "offÃ ¢ â,¬. The current is zero, but the voltage is significant. For the review, keep in mind the following for the analysis to be followed: 1. An open circuit can have any tension through its terminals, but the current is modified 0 A. 2. A short circuit has a 0-V Drop through its terminals, but the current is limited only by the surrounding network. In the next example the notation of figure 2.18 will be used for the applied voltage. It is a common sector notation and one with which the reader should become very familiar. This notation and other defined voltage levels are processed further in Chapter 4. For the diode configuration series of fig. 2.19, determine VD, VR and ID. Solution Although the "Pressure", establish a current with the same direction as the arrow symbol, the applied voltage level is insufficient to transform the silicon diode Ã ¢ â,¬ Å "ON.Ã,Â» the point of operation On the characteristics it is shown in fig. 2.20, establishing the equivalent of the open circuit as appropriate approximation. The resulting voltage and the current levels are therefore the following: ID0 A VRIRRIDR (0 A) 1.2 K 0 V and VDE0.5 against Figure 2.20 Operating point with E0.5 V. Determine VOAND IDPOR OF THE CIRCUIT OF THE SERIES FIG . 2.21. 62 Chapter 2 Example of applications Diodes 2.9 Page 3 4.1 Introduction The analysis or design of a transistor amplifier requires knowledge of both the DC and AC response. Too often it is assumed that the transistor is a magical device that can lift the level of the AC input applied without the assistance of an external energy source. In reality, the improved output AC power level is the result of an energy transfer from applied DC supplies. The analysis or design of any electronic amplifier therefore has two components: the DC portion and the AC portion. Fortunately, the overlap theorem is applicable and the survey on the DC conditions can be totally separated from the AC response. However, it is necessary to keep in mind that during the design or the synthesis phase the choice of parameters for DC levels will affect the response BC and vice versa. The DC level of a transistor is controlled by a number of factors, including the range of possible operating points on the characteristics of the device. In section 4.2 We will specify the range for the BJT amplifier. Once the desired DC and voltage levels have been defined, it is necessary to build a network that will establish the desired operating point - a number of these networks analyzed in this chapter. Each design will also determine the stability of the system, i.e. how sensitive it is to the temperature systemTopic to be investigated in a later section of this chapter. Although various networks are analyzed in this chapter, there is a similarity between the analysis of each configuration due to the recurring use of the following important basic relationships for a transistor: VBE0.7 V (4.1) ie (1) IBIC (4.2) ICIB (4.3) In fact, once the analysis of the first networks is clearly understood, the path to the solution of the networks to follow beginnings to become quite obvious. In most cases the ibis basic current the first quantity to be determined. Once the IB is known, EQS reports. (4.1) Through (4.3) can be applied to find the quantities of Re-Maining interest. The similarities in the analysis will be immediately obvi-ous while progressing through the chapter. The equations for hibare as well as similar for a number of configurations that an equation can be derived from another simply from dropping or adding a term or two. The primary function of this chapter is to develop a level of familiarity with the BJT transistor that would allow a DC analysis of any sistem that could use the BJT amplifier. 4.2 Spooked policy The term biasing that appears in the title of this chapter is an all-inclusive term for the application of DC voltages to establish a fixed level of current and voltage. For the transistor amplifiers the resulting DC current and the voltage establish a point of operation on the characteristics that define the region that will be used for the amplification of the applied signal. Since the point of operation is a fixed point on the characteristics, it is also called the quious point (abbreviated Q-Point). By definition, quiescent means quiet, still, inactive. Figure 4.1 shows a characteristic general output device with four indicated operating points. The biasing circuit can be designed to set the OPERATION device in one of these points or others within the active region. The maximum mouse calipers are indicated on the characteristics of Fig. 4.1 from a horizontal line for the Max-Imum current ICMAXE collector a vertical line at the maximum VCEMAX voltage-to-emitter. The maximum power limit is defined by the PCMAX curve in the same figure. At the lower end of the stairs are the region of Cutoff, defined by IB 0, and the saturation region, defined by VCEVcesat. The BJT device could be biased to operate outside these maximum limits, but the result of this operation would be or considerable shortening of the duration of the device or destruction of the device. Confining ourselves in the active region, many different operating areas can be selected. The chosen Q-Point often depends on the expected use of the circuit. However, we can consider some differences between 144 Chapter 4 DC Figure 4.1 Various operating points within the operating limits of a transistor. 5 IC max Saturation IC (mA) VCE 0 5 10 15 20 25 10 15 80Î¼A 60Î¼A 50Î¼A 40Î¼A 30Î¼A 20Î¼A 10Î¼A Cutoff VCE max VCE sat B B C PC max 70Ã,Î¼a 20 (v) to 0Ã,îa ib = various points shown in fig. 4.1 To present some basic notions on the point of operation and then on the polarization circuit. If no bias is used, the device would initially be completely switched off, with a point q a aÃ ¢ â¡ââ ââtio is a zero current through the device (and a zero voltage through it). Because it is necessary to distort a device so that it can respond to the entire range of an input signal, the point A would not be suitable. For point B, if a signal is applied to the circuit, the device varier in current and voltage from the operating point, allowing the device to react (and possibly amplify) to both positive and negative excursions of the input signal. If the input signal is chosen correctly, the voltage and current of the device will vary, but not enough to push the device to the cutoff or saturation. The C point would allow some positive and negative variations of the output signal, but the peak peak value would be limited by the proximity of VCE0V / IC0 but. The operation in point C raises even some concerns for non-linearity introduced by the fact that the spacing between the IB curves is changing quickly to this region. In general, it is preferable to operate where the device gain is quite constant (or linear) to make sure that the amplification on all the oscillation of the input signal is the same. Point B is a larger and therefore more linear operating spacing region, as shown in Figure 4.1. The D point sets the device's operating point near the maximum voltage and power level. The oscillation of the output voltage in the positive direction is therefore limited if you do not want to exceed the maximum voltage. The point B seems therefore the best operating point in terms of linear earnings and greater voltage and current possible. This is generally the desired condition for small signal amplifiers (chapter 8), but not necessarily for power amplifiers, which will be examined in chapter 16. In this discussion, we will focus mainly on the polarization of the transistor for amplification operations of a small signal. Another very important distortion factor must be considered. After selecting and prevented the BJT at the desired operating point, the temperature effect must also be taken into account. The temperature causes the device's parameter changing as the transistor current gain (AC) and transistor dispersion current (ICEO). Higher temperatures determine an increase in dispersion currents in the device, thus modifying the operating condition set by the polarization network. As a result, the design of the network must also guarantee a certain stability of the so that temperature changes are translated into minimal changes at the point of operation. This maintenance of the operating point can be specified by a stability factor, S, which indicates the degree of change of the operating point due to a temperature change. A highly stable circuit is desirable, and the stability of some basic polarization circuits will be compared. For the BJT to be part ofits linear or active operating region must be true: 1. The base-emitter junction must be forward-shaped (most positive p-region voltage), with a consequent forward-shaped tension of about 0.6 to 0.7 V. 2. The base-collector joint must be inverted (n-region plus positive), with the reverse voltage-bias is any value within the maximum limits of the device. [Note that for forward bias the voltage through the p-n junction is p-positive, while for the reverse bias it is opposite (reverse) with n-positive. This emphasis on the first letter should provide a means to help memorize the required voltage polarity.] The operation in the cut, saturation and linear regions of the BJT characteristic is provided as follows: 1. Linear operation-region: Base-emitter biased junction forward Base-inverted collector biased 145 C2 C VCC IC VCE VBE IB RB B C1 RC + â output signal ac input signal E C + â 2. Operation Cutting Region: Base-Emitter Biased Reverse 3. Functioning of the saturation region: Base-emitter biased biased Base-collector biased 4.3 FIXED-BIAS CIRCUIT The fixed form circuit in Fig. 4.2 provides a relatively simple and simple analysis of the input to transistor bias analysis. Even if the network uses an npn transistor, the equations and calculations apply equally well to a pnp con- figuration transistor simply by changing all current directions and voltage polarity. The indications for the rental of the cur- Fig. 4.2 are the actual current indications, and voltages are permitted by the standard double-subscription notation. For dc analysis the network can be isolated from the indicated ac levels by replacing the capacitors with an open circuit equivalent. In addition, the VCC supply can be separated into two supplies (for analysis purposes only) as shown in Figure 4.3 to allow a separation of the input and output circuits. It also reduces the connection between the two to the IB base current. Separation is certainly valid, as you can see in Figure 4.3 that VCCis connects directly to RBand RCjust as in Fig. 4.2. 146 Chapter 4 Page BJTs 4 Electronic devices are intrinsically sensitive to very high frequencies. Most of the ca-pacitive shunt effects can be ignored at lower frequencies because the XC 1/2f C reactivity is very large (equivalent to open circuit). This, however, cannot be ignored at very high frequencies. XC will become small enough due to the high value of f to introduce a low reactivity path âshortingâ. In the p-n semiconductor diode, there are two capacitive effects to consider. Both types of abilities are present in the forward and reverse regions, but one thus surpasses the other in every region we consider the effects of only one in every region. In the region of inverse forms the ability to transition- or depletion-region (CT), while in the region of forward forms we have the capacity to spread (CD) or storage. Remember thatThe basic equation for the capacity of a parallel plate capacitor is defined by CA / D, where it is the permission of the dielectric (insulator) between the area plates to separate from a distance d. In the polarization reversal region there is a purification region (without vectors) that essentially behaves as an isolator between the opposite charge layers. Since the amplitude of depletion (d) will increase with the increase of the potential of Reverse-Bias, the resulting transition capacity will decrease, as shown in fig. 1.37. The fact that the ability depends on the potential of reverse polarization applied to be applied in numerous electronic systems. In fact, in chapter 20 a diode will be introduced whose functioning depends entirely on this phenomenon. Although the effect described above also manifests in the polarization region forward, it is obscured by a capacity effect that depends directly on the speed with which the charge is injected into the regions immediately outside the exhaustion region. The result is that an increase in current levels will translate into an increase in diffusion capacity levels. However, higher current levels translate into a reduction in associated resistance levels (to be demonstrated soon), and the consequent time constant (RC), which is very important in high-speed applications, does not become excessive. Figure 1.37 Transition and diffusion capacity compared to the polarization applied for a silicon diode. 0 0.25 0.5 5 10 15 20 25 (v) C 5 10 15 Allarization forward (c) Reverse CD polarization (c) CT (PF) 32 Chapter 1 Semiconductor diodes PN The capacitive effects described above are: represented by a condenser parallel to the Ideal diode, as shown in fig. 1.38. For low or medium frequency applications (except for the power area), however, the condenser is normally included in the diode symbol. 1.11 Reverse Recovery time There are some data that are normally provided in the devices specifications of the diodes provided by the producers. One of these quantities not yet considered is the time of reverse recovery, indicated by TRR. In the polarization state forward it was previously demonstrated that there is a large number of electrons coming from type N material that progress through type P material and a large number of holes in the N-type conduction requirement. Electrons in type P and the holes passing through type N material create a large number of minority vectors in each material. If the applied voltage should be reversed in order to establish a situation of reverse-bias, ideally we would like to see the diode instantly change from the conduction state to that of nonconduzione. However, due to the high number of minority carriers in each material, the diode current is reversed as shown figure 1.39 and remains at this level measurable for the period ts (storage time) necessary for minor carriers to return to their majority carrier status in the opposite material. Basically, the diode will remain inShort circuit status with a current Irverse determined by the network parameters. In the end, when this storage phase has passed, the current will reduce level to that associated with the state of non-contaduction. This second worse than time is indicated by TT (transition interval). The reverse recovery time is the sum of these two intervals: TRRTSTT. Of course, it is an important consideration in high speed switching applications. The most available moving diodes on the market have a Trrin the range of some nanoseconds at 1 s. The units are available, however, with a TRR of a few hundred picoseconds (1012). Figure 1.38 Including the effect of transition or diffusion capacity on the semiconductor diode. Figure 1.39 Definition of reverse recovery time. D I Next Retromisca The status change (on off) required on t = tt t1 desired answer 1 t t tt rr t 1.12 semiconductor diode notation The most frequently used notation for semiconductor diodes is supplied in fig. 1.40. For most diodes any marking as a point or a band, as shown in Fig. 1.40, appears at the end of the cathode. The terminological anode and the cathode is a carryover from the notation of the vacuum tube. The anode refers to the upper or positive potential and the cathode refers to the lower or negative terminal. This combination of bias levels will translate into a bias forward or Ã ¢ â,¬ Ã ¢ â,¬ Ã ¢ â,¬ "Conditions for the diode. A number of semiconductor diodes available on the market appear in fig. 1.41. Some details of the actual construction of devices such as those that appear in Fig. 1.41 are supplied in chapters 12 and 20. 33 1.13 Diodes test PN 1.13 Diodes test The conditions of a semiconductor diode can be determined quickly using (1) a digital meter Display (DDM) With a diode control function, (2) the OHMMETRE section of a multimeter or (3) a curve trace. Page 5 The characteristics of the D1N4148 diode used in the above analysis will now be used using some Maneuvers a little more sophisticated than those previously used. First of all, the network in Fig. 2.129 is built using the procedures described 100 Chapter 2 Diodes applications Figure 2.127 The Figusti 2.126 circuit filled With 101 2.13 Pspice Windows Figure 2.128 Output files for Windows PSPice analysis of the circuit 2.127. Figure 2,129 network to contain the features of the D1N4148 diode. on. Note, however, the VD that appears above the diode D1. A point in the network (which represents the anode voltage on the ground to the diode) has been identified as a particular voltage by double-clicking on the wire above the device and typing VD in the attribute value set as a label. The resulting voltage VDIS, in this case, the voltage across the diode. the analysis installation is chosen by clicking on the analysis setting icon (in the left upper edge of the schematic with the horizontal blue bar and the two small squares and rectangles) or using the sequence analysis installation. Within the Analy-Sis-Setup Analy-Sis-Setup dialog boxDC Sweep is activated (the only one necessary for this ex-reculation), followed by a click of the Sweep DC rectangle. The dia- Sweep DC registry box will appear with various surveys. In this case, it is intended to sweep the source voltage from 0 to 10 V in increments of 0.01 V, so that the offset Var. Type is voltage, the scanning type will be linear, the mail name, and the initial value 0 V, the final value 10V, and the increment 0.01V. Then, with an OK followed by a closure of the 102 Chapter 2 of Applications Figure 2.130 Features of the D1N4148 diode. Since the plot we want is ID versus VD, we need to change the horizontal VD (x axis). This is achieved by selecting Trama and then X-Axis Settings to get dialog Settings on the X-Axis dialog. Next, we click on Axis variable and select V (Vd) from the sale. After OK, we return to the dialog box to set the horizontal scale. Choose Defined by the user, then enter 0V to 1V as this is the field of interest for Vd with a linear scale. Choose OK and it is found that the horizontal axis is now V (Vd) with range of 0 ÷ 1.0 V. The vertical axis must now be set IDby first choice Trace (or the Trace icon, which is the red waveform with two sharp spikes and a set of axes) and then add to get additional Tracks. By choosing I (D1) and clicking OK will involve the plot of Fig. 2.130. In this case, the resulting graph extends between 0 and 10 mA. The range can be reduced or expanded simply by going to Case Y Setting and defining the field of interest. In the previous analysis, the voltage to the heads of the diode was 0,64 V, corresponding to a current of about 2 mA on the chart (rename the solution of 2,07 mA for the current). If the resulting current had been closer to 6.5 mA, the voltage to the heads of the diode would have been about 0.7 V and the SPICE solution closer to the handwritten ap-profile. If Ishad was set 3.5E-15A and all other parameters removed from the diode card, the curve would have moved to the right and a 0,7 V and 2,07 mA crossing would have gotten. Set analysis, we are ready to get the solution. The analysis to be performed will get a complete solution for the network for each E value from 0 to 10 V with increments of 0.01-V. In other words, the network will be analyzed 1000 times and the resulting data stored for the plot you want to get. The analysis is performed by the Analysis-Run Probe sequence, followed by an immediate appearance of the Mi- croSim probe chart showing only a horizontal axis of the source voltage and running between 0 and 10 V. § 2.2 Load-Line Analysis 1. (a) Using the features of Fig. 2.131b, determine ID, VD, and VRfor the circuit of Fig. 2.131a. (B) Repeat the point (a) using the approximate pattern for the diode and compare the results. (C) Repeat the part (a) using the ideal model forDiode and compares the results. 103 Problems Problems 2. (a) Using the characteristics of Fig. 2.131B, determine Idand VDFor circuit of Fig. 2.132. (B) Repeat the â €