Electronic Circuits

Handbook for Design and Applications

U. Tietze
Ch. Schenk

2nd edition

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Ulrich Tietze • Christoph Schenk • Eberhard Gamm

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Preface

The purpose of this book is to help the reader to understand off-the-shelf circuits and to enable him to design his or her own circuitry. The book is written for students, practicing engineers and scientists. It covers all major aspects of analog and digital circuit design. The book is a translation of the current 12th edition of the German bestseller *Halbleiter-Schaltungstechnik*.

Part I describes semiconductor devices and their behavior with respect to the models used in circuit simulation. This part introduces all major aspects of transistor level design (IC-design). Basic circuits are analyzed in five steps: large-signal transfer characteristic, small-signal response, frequency response and bandwidth, noise and distortion. Digital circuits are covered starting with the internal circuitry of gates and flip-flops up to the construction of combinatorial and sequential logic systems with PLDs and FPGAs. Design examples and a short form guide for the digital synthesis tool *ispLever* are included on the CD enclosed.

Part II is dedicated to board level design. The main chapters of this part describe the use of operational amplifiers for signal conditioning including signal amplification, filtering and AD-conversion. Further chapters cover power amplifiers, power supplies and other important functional blocks of analog systems. The chapters are self-contained with a minimum of cross-reference. This allows the advanced reader to familiarize himself quickly with the various areas of applications. Each chapter offers a detailed overview of various solutions to a given requirement. In order to enable the reader to proceed quickly from an idea to a working circuit, we discuss only those solutions we have tested thoroughly by simulation. Many of these simulation examples are included on the CD enclosed.

Part III describes circuits for analog and digital communication over wireless channels. The first chapter is dedicated to transmission channels, scattering parameters and analog and digital modulations. Further chapters treat the architecture of transmitters and receivers, the high frequency behavior of components, circuits for impedance matching, high frequency amplifiers and mixers for frequency conversion.

To support analog circuit design, design examples and a short-form guide for the well known circuit simulator *PSpice* are included on the CD. This package contains libraries with examples of scalable transistors for IC-like design. The library also supports S-parameter and loop-gain simulations. An HTML-based index allows comfortable navigation throughout the simulations.

Our homepage *www.tietze-schenk.com* offers updates, supplements and design examples. We encourage you to use our email-address *mail@tietze-schenk.com* for feedback and comments.

We would like to thank Dr. Merkle at Springer Heidelberg for the administration, Gerhard Büsching for the translation and Danny Lewis at PTP-Berlin for the assembly of this book. In particular we like to thank Dr. Eberhard Gamm for the contribution of the first four chapters of circuit design fundamentals in part I and the chapters of communications in part III. We have added him as a young innovative author.

Erlangen, July 2007 U. Tietze, Ch. Schenk, E. Gamm

Overview

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Part I

Device Models and Basic Circuits

Chapter 1: Diode

The diode is a semiconductor component with two connections, which are called the *anode* (A) and the *cathode* (K). Distinction has to be made between discrete diodes, which are intended for installation on printed circuit boards and are contained in an individual case, and integrated diodes, which are produced together with other semiconductor components on a common semiconductor carrier (*substrate*). Integrated diodes have a third connection resulting from the common carrier. It is called the *substrate* (S); it is of minor importance for electrical functions.

Construction: Diodes consist of a pn or a metal-n junction and are called pn or Schottky diodes, respectively. Figure 1.1 shows the graphic symbol and the construction of a diode. In pn diodes the p and the n regions usually consist of silicon. Some discrete diode types still use germanium and thus have a lower forward voltage, but they are considered obsolete. In Schottky diodes the p region is replaced by a metal region. This type also has a low forward voltage and is therefore used to replace germanium pn diodes.

In practice the term *diode* is used for the silicon pn diode; all other types are identified by supplements. Since the same graphic symbol is used for all types of diodes with the exception of some special diodes the various types of discrete diodes can be distinguished only by means of the type number printed on the component or the specifications in the data sheet.

Operating modes: A diode can be operated in the *forward, reverse* or *breakthrough mode*. In the following Section these operating regions are described in more detail.

Diodes that are used predominantly for the purpose of rectifying alternating voltages are called *rectifier diodes*; they operate alternately in the forward and reverse region. Diodes designed for the operation in the breakthrough region are called *Zener diodes* and are used for voltage stabilization. The *variable capacitance diodes* are another important type. They are operated in the reverse region and, due to the particularly strong response of the junction capacitance to voltage variations, are used for tuning the frequency in resonant circuits. In addition, there is a multitude of special diodes which are not covered here in detail.

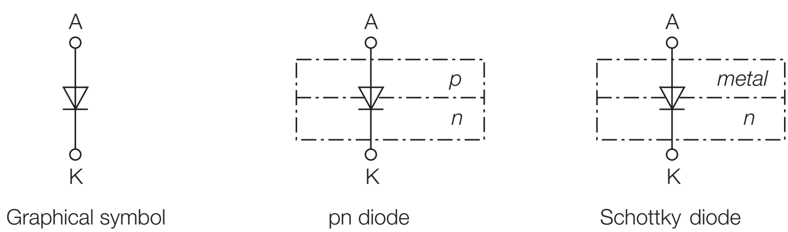


Fig. 1.1. Graphical symbol and diode construction

1.1 Performance of the Diode

The performance of a diode is described most clearly by its characteristic curve. This shows the relation between current and voltage where all parameters are *static* which means that they do not change over time or only very slowly. In addition, formulas that describe the diode performance sufficiently accurately are required for mathematical calculations. In most cases simple equations can be used. In addition, there is a model that correctly reflects the *dynamic performance* when the diode is driven with sinusoidal or pulse-shaped signals. This model is described in Sect. 1.3 and knowledge of it is not essential to understand the fundamentals. The following Sections focus primarily on the performance of silicon pn diodes.

1.1.1 Characteristic Curve

Connecting a silicon pn diode to a voltage $V_D = V_{AK}$ and measuring the current I_D in a positive sense from A to K results in the characteristic curve shown in Fig. 1.2. It should be noted that the positive voltage range has been enhanced considerably for reasons of clarity. For $V_D > 0\,\mathrm{V}$ the diode operates in the forward mode, i.e. in the *conducting state*. In this region the current rises exponentially with an increasing voltage. When $V_D > 0.4\,\mathrm{V}$, a considerable current flows. If $-V_{BR} < V_D < 0\,\mathrm{V}$ the diode is in the reverse-biased state and only a negligible current flows. This region is called the *reverse region*. The *breakthrough voltage* V_{BR} depends on the diode and for rectifier diodes amounts to $V_{BR} = 50 \ldots 1000\,\mathrm{V}$. If $V_D < -V_{BR}$, the diode breaks through and a current flows again. Only Zener diodes are operated permanently in this *breakthrough region*; with all other diodes current flow with negative voltages is not desirable. With germanium and Schottky diodes a considerable current flows in the forward region even for $V_D > 0.2\,\mathrm{V}$, and the breakthrough voltage V_{BR} is $10 \ldots 200\,\mathrm{V}$.

In the forward region the voltage for typical currents remains almost constant due to the pronounced rise of the characteristic curve. This voltage is called the *forward voltage* V_F

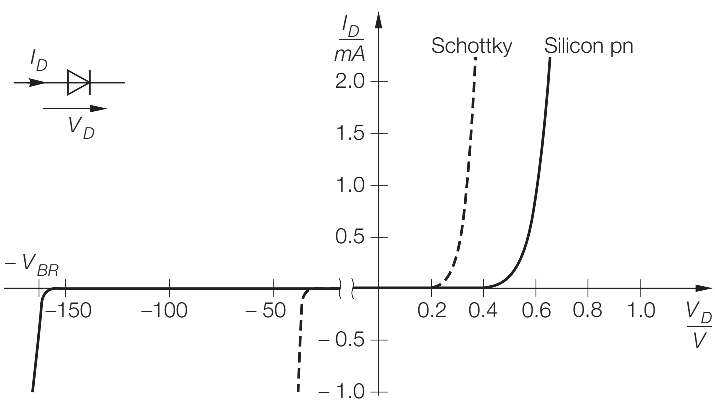


Fig. 1.2. Current-voltage characteristic of a small-signal diode

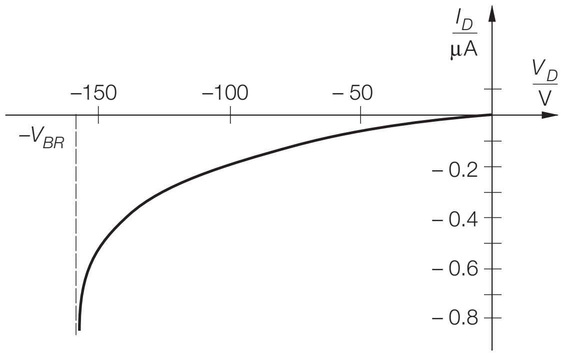


Fig. 1.3. Characteristic curve of a small-signal diode in the reverse region

and for both germanium and Schottky diodes lies at $V_{F,Ge} \approx V_{F,Schottky} \approx 0.3 \ldots 0.4\,\text{V}$ and for silicon pn diodes at $V_{F,Si} \approx 0.6 \ldots 0.7\,\text{V}$. With currents in the ampere range as used in power diodes the voltage may be significantly higher since in addition to the *internal* forward voltage a considerable voltage drop occurs across the spreading and connection resistances of the diode: $V_F = V_{F,i} + I_D R_B$. In the borderline case of $I_D \to \infty$ the diode acts like a very low resistance with $R_B \approx 0.01 \ldots 10\,\Omega$.

Figure 1.3 shows the enlarged reverse region. The *reverse current* $I_R = -I_D$ is very small with a low reverse voltage $V_R = -V_D$ and increases slowly when the voltage approaches the breakthrough voltage while it shoots up suddenly at the onset of the breakthrough.

1.1.2 Description by Equations

Plotting the characteristic curve for the region $V_D > 0$ in a semilogarithmic form results approximately in a straight line (see Fig. 1.4); this means that there is an exponential relation between I_D and V_D due to ln $I_D \sim V_D$. The calculation on the basis of semiconductor physics leads to [1.1]:

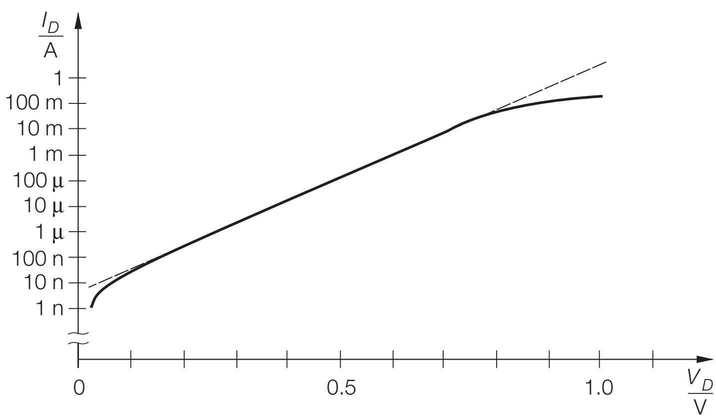


Fig. 1.4. Semilogarithmic representation of the characteristic curve for $V_D > 0$

$$I_D(V_D) = I_S \left(e^{\frac{V_D}{V_T}} - 1 \right) \qquad \text{for } V_D \geq 0$$

For the correct description of a real diode a correction factor is required which enables the slope of the straight line in the semilogarithmic representation to be adapted [1.1]:

$$\boxed{I_D = I_S \left(e^{\frac{V_D}{nV_T}} - 1 \right)} \tag{1.1}$$

Here, $I_S \approx 10^{-12} \ldots 10^{-6}$ A is the *reverse saturation current*, $n \approx 1 \ldots 2$ is the *emission coefficient* and $V_T = kT/q \approx 26\,\text{mV}$ is the *temperature voltage* at room temperature.

Even though (1.1) actually applies only to $V_D \geq 0$ it is sometimes used for $V_D < 0$. For $V_D \ll -nV_T$ this results in a constant current $I_D = -I_S$ which is generally much smaller than the current that is actually flowing. Therefore, only the qualitative statement that a small negative current flows in the reverse region is correct. The shape of the current curve as shown in Fig. 1.3 can only be described with the help of additional equations (see Sect. 1.3).

$V_D \gg nV_T \approx 26 \ldots 52\,\text{mV}$ applies to the forward region and the approximation

$$I_D = I_S \, e^{\frac{V_D}{nV_T}} \tag{1.2}$$

can be used. Then the voltage is:

$$V_D = nV_T \ln \frac{I_D}{I_S} = nV_T \ln 10 \cdot \log \frac{I_D}{I_S} \approx 60 \ldots 120\,\text{mV} \cdot \log \frac{I_D}{I_S}$$

This means that the voltage increases by $60 \ldots 120\,\text{mV}$ when the current rises by a factor of 10. With high currents the voltage drop $I_D R_B$ at the spreading resistance R_B must be taken into account, which occurs in addition to the voltage at the pn junction:

$$V_D = nV_T \ln \frac{I_D}{I_S} + I_D R_B$$

In this case it cannot be described in the form $I_D = I_D(V_D)$.

For simple calculations the diode can be regarded as a switch that is opened in the reverse region and is closed in the forward region. Given the assumption that the voltage is approximately constant in the forward region and that no current flows in the reverse region, the diode can be replaced by an ideal voltage-controlled switch and a voltage source with the forward voltage V_F (see Fig. 1.5a). Figure 1.5b shows the characteristic curve of this equivalent circuit which consists of two straight lines:

$$\begin{aligned} I_D &= 0 && \text{for } V_D < V_F && \rightarrow \text{switch open (a)} \\ V_D &= V_F && \text{for } I_D > 0 && \rightarrow \text{switch closed (b)} \end{aligned}$$

When the additional spreading resistance R_B is taken into consideration, we have:

$$I_D = \begin{cases} 0 & \text{for } V_D < V_F \quad \rightarrow \text{switch open (a)} \\ \dfrac{V_D - V_F}{R_B} & \text{for } V_D \geq V_F \quad \rightarrow \text{switch closed (b)} \end{cases}$$

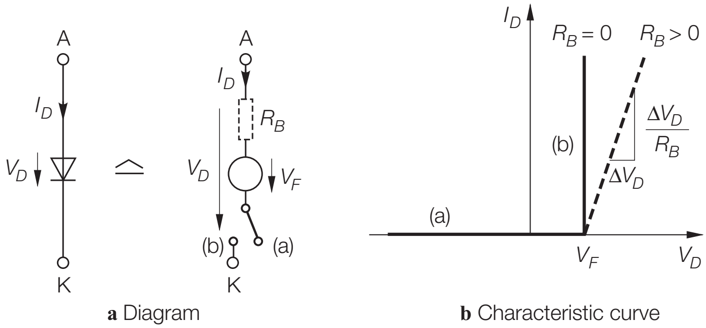


Fig. 1.5. Simple equivalent circuit diagram for a diode without (-) and with (- -) spreading resistance

The voltage V_F is $V_F \approx 0.6\,\text{V}$ for silicon pn diodes and $V_F \approx 0.3\,\text{V}$ for Schottky diodes. The corresponding circuit diagram and characteristic curve are shown in Fig. 1.5 as dashed lines. Different cases must be distinguished for both variations, that is, it is necessary to calculate with the switch open *and* closed and to determine the situation in which there is no contradiction. The advantage is that either case leads to linear equations which are easy to solve. In contrast, when using the e function according to (1.1), it is necessary to cope with an implicit nonlinear equation that can only be solved numerically.

Example: Figure 1.6 shows a diode in a bridge circuit. To calculate the voltages V_1 and V_2 and the diode voltage $V_D = V_1 - V_2$ it is assumed that the diode is in the reverse state, that is, $V_D < V_F = 0.6\,\text{V}$ and the switch in the equivalent circuit is open. In this case, V_1 and V_2 can be determined by the voltage divider formula $V_1 = V_b R_2/(R_1 + R_2) = 3.75\,\text{V}$ and $\text{V}_2 = V_b R_4/(R_3 + R_4) = 2.5\,\text{V}$. This results in $V_D = 1.25\,\text{V}$, which does not comply with the assumption. Consequently the diode is conductive and the switch in the equivalent circuit is closed; this leads to $V_D = V_F = 0.6\,\text{V}$ and $I_D > 0$. From the nodal equations

$$\frac{V_1}{R_2} + I_D = \frac{V_b - V_1}{R_1} \quad , \quad \frac{V_2}{R_4} = I_D + \frac{V_b - V_2}{R_3}$$

it is possible to eliminate the unknown elements I_D and V_1 by adding the equations and inserting $V_1 = V_2 + V_F$; this leads to:

$$V_2 \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} \right) = V_b \left(\frac{1}{R_1} + \frac{1}{R_3} \right) - V_F \left(\frac{1}{R_1} + \frac{1}{R_2} \right)$$

This results in $V_2 = 2.76\,\text{V}$, $V_1 = V_2 + V_F = 3.36\,\text{V}$ and in $I_D = 0.52\,\text{mA}$ by substitution in one of the nodal equations. The initial condition $I_D > 0$ has been fulfilled, that is, there is no contradiction and the solution has been found.

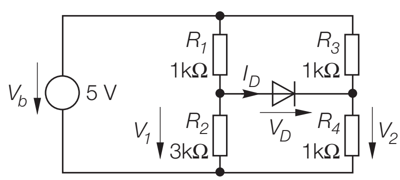


Fig. 1.6. Example for the demonstration of the use of the equivalent circuit of Fig. 1.5

1.1.3 Switching Performance

In many applications the diodes operate alternately in the forward mode and in the reverse mode, for example when rectifying alternating currents. The transition does not follow the static characteristic curve as the parasitic capacitance of the diode stores a charge that builds up in the forward state and is discharged in the reverse state. Figure 1.7 shows a circuit for determining the *switching performance* with an ohmic load ($L = 0$) or an ohmic-inductive load ($L > 0$). Applying a square wave produces the transitions shown in Fig. 1.8.

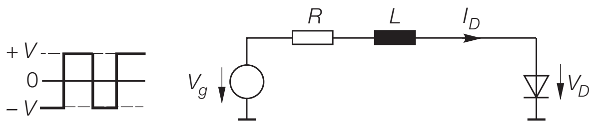


Fig. 1.7. Circuit for determining the switching performance

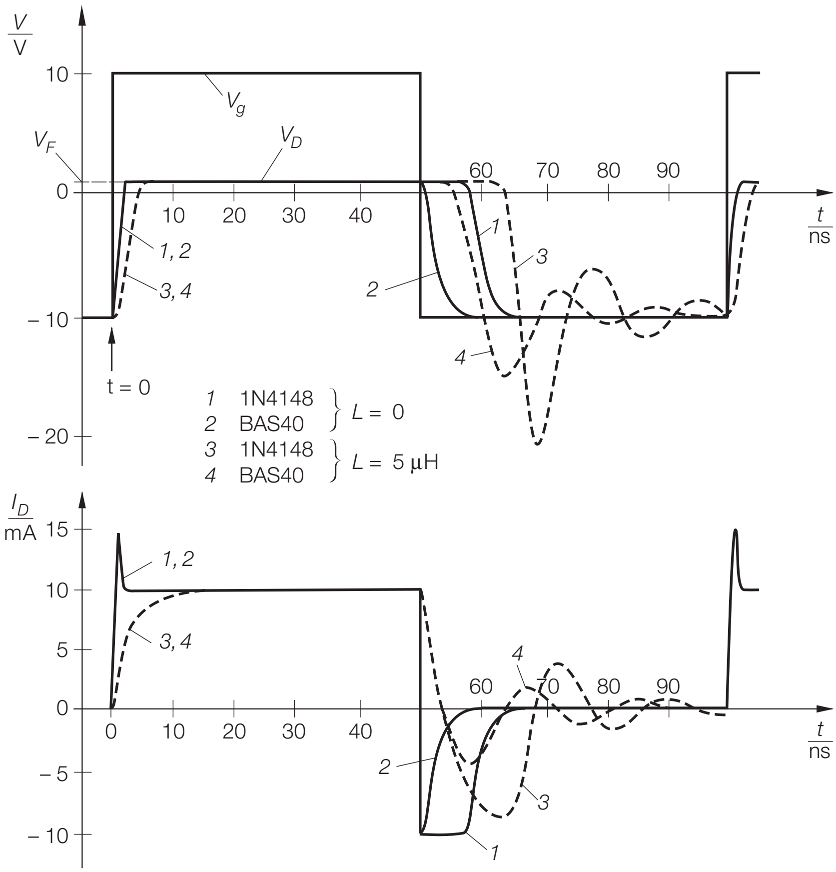
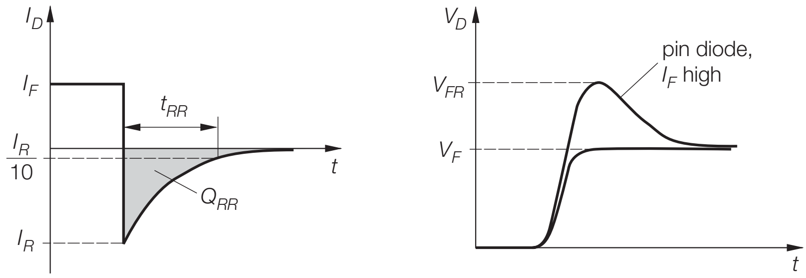


Fig. 1.8. Switching performance of the silicon diode 1N4148 and the Schottky diode BAS40 in the measuring circuit of Fig. 1.7 with $V = 10\,\mathrm{V}$, $f = 10\,\mathrm{MHz}$, $R = 1\,\mathrm{k\Omega}$ and $L = 0$ or $L = 5\,\mu\mathrm{H}$



a Switching off

b Switching on

Fig. 1.9. Illustration of switching performance

Switching performance with ohmic load: With an ohmic load ($L = 0$) a current peak caused by the charge built up in the capacitance of the diode occurs when the circuit is activated. The voltage rises during this current peak from the previously existing reverse voltage to the forward voltage V_F which terminates the switch-on process. In pin diodes[1] higher currents may cause a voltage overshoot (see Fig. 1.9b) as these diodes initially have a higher spreading resistance R_B at the switch-on point. Subsequently the voltage declines to the static value in accordance with the decrease of R_B. When switching off there is a current in the opposite direction until the capacitance is discharged; then the current returns to zero and the voltage drops to the reverse voltage. Since the capacitance of Schottky diodes is much lower than that of silicon diodes of the same size, their turn-off time is significantly shorter (see Fig. 1.8). Therefore, Schottky diodes are preferred for rectifier diodes in switched power supplies with high cycle rates ($f > 20\,\text{kHz}$), while the lower priced silicon diodes are used in rectifiers for the mains voltage ($f = 50\,\text{Hz}$). When the frequency becomes so high that the capacitance discharge process is not completed before the next conducting state starts, the rectification no longer takes place.

Switching performance with ohmic-inductive load: With an ohmic-inductive load ($L > 0$) the transition to the conductive state takes longer since the increase in current is limited by the inductivity; no current peaks occur. While the voltage rises relatively fast to the forward voltage, the current increases with the time constant $T = L/R$ of the load. During switch-off the current first decreases with the time constant of the load until the diode cuts off. Then, the load and the capacitance of the diode form a series resonant circuit, and the current and the voltage perform damped oscillations. As shown in Fig. 1.8 high reverse voltages may arise which are much higher than the static reverse voltage and consequently require a high diode breakthrough voltage.

Figure 1.9 shows the typical data for *reverse recovery (RR)* and *forward recovery (FR)*. The *reverse recovery time* t_{RR} is the period measured from the moment at which the current passes through zero until the moment at which the reverse current drops to 10 %[2] of its maximum value I_R. Typical values range from $t_{RR} < 100\,\text{ps}$ for fast Schottky diodes to $t_{RR} = 1 \ldots 20\,\text{ns}$ for small-signal silicon diodes or $t_{RR} > 1\,\mu\text{s}$ for rectifier diodes. The *reverse recovery charge* Q_{RR} transported during the capacitance discharge corresponds to

[1] pin diodes have a nondoped (*intrinsic*) or slightly doped layer between the p and n layers in order to achieve a higher breakthrough voltage.

[2] With rectifier diodes the measurement is sometimes taken at 25 %.

the area below the x axis (see Fig. 1.9a). Both parameters depend on the previously flowing forward current I_F and the cutoff speed; therefore the data sheets show either information on the measuring conditions or the measuring circuit. An approximation is $Q_{RR} \sim I_F$ and $Q_{RR} \sim |I_R| t_{RR}$ [1.2]; this means that in a first approximation the reverse recovery time is proportional to the ratio of the forward and reverse current: $t_{RR} \sim I_F/|I_R|$. However, this approximation only applies to $|I_R| < 3 \ldots 5 \cdot I_F$, in other words, t_{RR} can not be reduced endlessly. In pin diodes featuring a high breakdown voltage, the high cutoff speed may even cause the breakdown to occur far below the static breakdown voltage V_{BR} if the reverse voltage at the diode increases sharply before the weakly doped i-layer is free of charge carriers. With the transition to the forward state the *forward recovery voltage* V_{FR} occurs, which also depends on the actual switching conditions [1.3]; data sheets quote a maximum value for V_{FR}, typically $V_{FR} = 1 \ldots 2.5\,\mathrm{V}$.

1.1.4 Small-Signal Response

The performance of the diode when controlled by *small* signals around an operating point characterized by $V_{D,A}$ and $I_{D,A}$ is called the *small-signal response*. In this case, the nonlinear characteristic given in (1.1) can be replaced by a tangent to the operating point; with the small-signal parameters

$$i_D = I_D - I_{D,A} \quad , \quad v_D = V_D - V_{D,A}$$

one arrives at:

$$i_D = \left. \frac{dI_D}{dV_D} \right|_A v_D = \frac{1}{r_D} \, v_D$$

From this the *differential resistance* r_D of the diode is derived:

$$\boxed{r_D = \left. \frac{dV_D}{dI_D} \right|_A = \frac{nV_T}{I_{D,A} + I_S} \overset{I_{D,A} \gg I_S}{\approx} \frac{nV_T}{I_{D,A}}} \tag{1.3}$$

Thus, the equivalent small-signal circuit for the diode consists of a resistance with the value r_D; with large currents r_D becomes very small and an additional spreading resistance R_B must be introduced (see Fig. 1.10).

The equivalent circuit shown in Fig. 1.10 is only suitable for calculating the small-signal response at low frequencies ($0 \ldots 10\,\mathrm{kHz}$); therefore, it is called the *DC small-signal equivalent circuit*. For higher frequencies it is necessary to use the AC small-signal equivalent circuit given in Sect. 1.3.3.

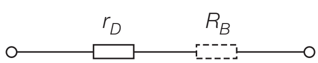


Fig. 1.10. Small-signal equivalent circuit of a diode