ELECTRONIC DEVICES

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C2 - Diodes. DR circuits.
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Contents

- Physical structure. Symbol.
- Current-voltage characteristic
- Operating regions
- Operating (quiescent) point
- Parameters of the diode
- Constant voltage drop model
- Analysis of two-port DR networks
Physical structure – *pn* junction

![Diode symbol](image)

**Anode (A)**

**Cathode (K)**

**Circuit symbol**

**Directions for current and voltage**

The arrow in the diode’s symbol indicates the direction of the forward current flow.
The current flowing through the diode is controlled by the voltage drop across the diode itself – **nonlinear** semiconductor device.

**Diode equation – William Shockley (Bell Labs, 1950)**

\[
i_D = I_S (e^{nV_T} - 1)
\]

- \(I_S\) - saturation current (~ nA - pA)
- \(n=2\) discrete diodes
- \(n=1\) integrated diodes

**Thermal voltage**

\[
V_T = \frac{KT}{q}
\]

- \(K\) - Boltzmann’s constant
- \(q\) - elementary charge (electric charge carried by a single electron)
- \(T\) - absolute temperature measured in K

\[
V_T = 25 \text{mV} \ @ \ 20^\circ \text{C}
\]
Exponential model of the diode (valid in forward and reverse regions)

\[ i_D = I_S (e^{nVT} - 1) \]

\[ i_D \approx I_S e^{nVT} \]

Threshold voltage
\[ V_{Th} \approx 0.6V \]

Mind the scale for the Y-axis!
Numerical illustration

\(D\) is a rectifier diode, 1N400x with \(I_s = 14\) nA, \(n = 2\)

Assuming a voltage drop across the diode

\[v_D = 0.7\,\text{V}\]

the current through the diode results as:

\[i_D = 14 \cdot 10^{-9} \left(e^{2.25} - 1\right) = 16.8\,\text{mA}\]
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\[ i_D = I_S \left( e^{nV_T} - 1 \right) \]

**Operating regions**

Forward bias \( v_D > 0V \)

Reverse bias \( v_D < 0V \)

\( V_{Th} \approx 0.6 \, V \)

\( \{ \)

- (off) \( v_D < V_{Th}; \quad i_D = 0 \)
- (on) \( v_D > V_{Th}; \quad i_D > 0 \)
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\[ Q(V_D; I_D) \]

Operating (quiescent) point

Illustration for 1N400x with \( I_S = 14 \text{ nA}, \ n = 2 \)

\begin{align*}
Q1(0.3V; 0mA) \\
Q2(0.7V; 14.5mA) \\
Q3(0.78V; 70.8mA)
\end{align*}
Operating (quiescent) point

Temperature dependence

\[ i_D \approx I_S e^{nV_T} \]

\( I_S, V_T \) - depend directly on the temperature.

At a constant current, the voltage across the diode decreases by \( \sim 2 \text{ mV} \) for every \( 1^\circ \text{C} \) increase in temperature.

\[ TC = -2 \frac{\text{mV}}{^\circ \text{C}} \quad \text{negative temperature coefficient} \]

\[ v_D(T_2) = v_D(T_1) + TC \cdot (T_2 - T_1) \bigg|_{I_D = \text{cst}} \]

At a constant voltage across the diode, the current increases with the temperature.
The parameters of the diode are defined (and computed) in the operating (quiescent) point, $Q(V_D, I_D)$

- Static parameters – defined in static regime (dc)
  - static resistance $r_D$

- Dynamic parameters – defined in variable regime (ac)
  - *a.k.a.* small signal parameters
    - dynamic (small signal resistance) $r_d$
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Parameters of the diode

Static parameters

\[ r_D = \frac{V_D}{I_D} \]  
\[ g_D = \frac{1}{r_D} = \frac{I_D}{V_D} \]

Example:

\( Q_1(0.65\,\text{V}; 5.4\,\text{mA}) \)
\[ r_{D1} = \frac{0.65}{5.4} = 120\,\Omega \]

\( Q_2(0.7\,\text{V}; 14.5\,\text{mA}) \)
\[ r_{D2} = \frac{0.7}{14.5} = 48.3\,\Omega \]

\( Q_3(0.78\,\text{V}; 70.8\,\text{mA}) \)
\[ r_{D3} = \frac{0.78}{70.8} = 11\,\Omega \]

As the current increases, the diode goes in deeper conduction and its static resistance decreases.
Dynamic (small signal) parameters
A small ac signal is superimposed on the dc quantities

\[ v_D(t) = V_D + v_d(t) \]
\[ i_D(t) = I_D + i_d(t) \]

Dynamic (small signal) resistance:

\[ r_d = \frac{v_d}{i_d} \bigg|_Q \quad \text{or} \quad r_d = \frac{\delta v_D}{\delta i_D} \bigg|_Q \]

Small signal approximation:
linear region around Q

\[ r_d = \frac{nV_T}{I_D} \]
 Parameters of the diode

Interpretation of $r_D$ and $r_d$

D modelling in the OP

**OPTIONAL**
Example

a) Draw the dc equivalent circuit.

b) Assuming Q(0.64V; 4.7mA), what is the value of the static resistance?

c) Draw the small-signal equivalent circuit.

d) What is the value of the small-signal resistance in Q?
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Constant voltage drop model

\[ v_D < 0.7 \text{ V} \]

\[ D - \text{(off)} \]

\[ v_D > 0.7 \text{ V} \]

\[ D - \text{(on)} \]

\[ \begin{cases} v_D < 0.7 \text{ V} \\ i_D = 0 \end{cases} \]

\[ \begin{cases} v_D = 0.7 \text{ V} \\ i_D > 0 \end{cases} \]
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Analysis of two-port DR networks

- Circuit with a dc voltage source and a resistor

![Circuit with a dc voltage source and a resistor](image)

Diode equation: \( I_D = I_S e^{n V_T} \)

KVL: \( V_I = I_D R + V_D \)

\[\begin{align*}
\text{Diode equation:} & \quad I_D = I_S e^{n V_T} \\
\text{KVL:} & \quad V_I = I_D R + V_D
\end{align*}\]

Two solving methods:

1. Graphical method
2. Numerical method (successive approximation)

Compute \( Q(V_D, I_D) \)

Transcendental equation

\[ V_I - V_D = R I_S e^{n V_T} \]

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Analysis of two-port DR networks

Graphical method

Diode equation:

\[ I_D = I_S e^{nV_T} \]

KVL (load line equation):

\[ V_I = I_D R + V_D \]
Graphical method

Effect of $R$ on the quiescent point, $Q$

![Graphical representation of the effect of $R$ on the quiescent point $Q$. The diagram shows the quiescent point $Q$ for $R$ and $Q_1$ for $R_1 > R$.](image)
Numerical method - simplified

Assume the voltage drop across the diode \( V_D = 0.7 \, V \) and compute the current \( I_D \) using the load line equation

\[
V_D = 0.7V \\
I_D = \frac{V_I - V_D}{R}
\]
Example

What is the operating (quiescent) point $Q$ of the diode $D$?

$V_D > 0.6V \quad D - \text{(on)}$

Assume $V_D = 0.7V$ across the conducting diode

$I_D = \frac{V_I - V_D}{R} \quad I_D = \frac{9 - 0.7}{0.5} = 16.6mA$

$Q(0.7V, 16.6mA)$
Numerical method - iterative

1. Consider an initial value of diode voltage, eg. $V_D^{(0)} = 0.7$ V and compute current $I_D^{(0)}$ using the load line equation

   \[(V_D^{(0)}, I_D^{(0)}) - \text{initial solution}\]

2. Using $I_D^{(0)}$, compute voltage $V_D^{(1)}$ from diode equation, then current $I_D^{(1)}$ from the load line equation

   \[(V_D^{(1)}, I_D^{(1)}) - \text{solution after first iteration}\]

Repeat step 2 if more accurate values are required.

For quick, first order analysis of the circuit, the initial solution is considered!
V_i = 3 V, \ R = 0.5 \ K\Omega, \\
D is 1N400x, \ I_S = 14 \ nA, \ n = 2.

What is the operating (quiescent) point Q of diode D?

Quick, first order analysis:

\[ V_D > 0.6V \quad \text{D – (on)} \]

Assume \( V_D = 0.7 \ \text{V} \) across the conducting diode

\[
I_D = \frac{V_I - V_D}{R} \quad I_D = \frac{3 - 0.7}{0.5} = 4.6\text{mA} \quad Q(0.7\text{V}, 4.6\text{mA})
\]
Example

**Detailed analysis**

\[ I_D = \frac{V_I - V_D}{R} \quad I_D = I_S e^{nVT} \quad V_D = nV_T \ln \left( \frac{I_D}{I_S} \right) \]

Step 1

\[ V_D^{(0)} = 0.7V \quad I_D^{(0)} = \frac{3 - 0.7}{0.5} = 4.6mA \]

Step 2

\[ V_D^{(1)} = nV_T \cdot \ln \left( \frac{I_D^{(0)}}{I_S} \right) = 2 \cdot 0.025 \cdot \ln \left( \frac{4.6mA}{14nA} \right) = 0.635V \]

\[ I_D^{(1)} = \frac{V_I - V_D^{(1)}}{R} = \frac{3 - 0.635}{0.5} = 4.73mA \]

Step 3

\[ V_D^{(2)} = nV_T \cdot \ln \left( \frac{I_D^{(1)}}{I_S} \right) = 2 \cdot 0.025 \cdot \ln \left( \frac{4.73mA}{14nA} \right) = 0.637V \]

\[ I_D^{(2)} = \frac{V_I - V_D^{(2)}}{R} = \frac{3 - 0.637}{0.5} = 4.726mA \]

\[ Q(0.637V; 4.726mA) \]
Summary

Our first encounter with the diode revealed details regarding:

- Physical structure. Symbol.
- Current-voltage characteristic
- Operating regions
- Operating (quiescent) point
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Next week: DR switching circuits.