353 – Semiconductor diode

Acquired core competencies:

1. You familiarize yourself with nonlinear characteristic curves and identify the various operating ranges based on the characteristic curve shapes.
2. You use abstracted $I(U)$ characteristic curves to intuitively understand the $U(t)$ behavior of simple circuits under AC voltages.
3. You verify the validity of physical models or mathematical derivations by quantitatively testing the assumptions made.

1 Tasks

1. Measure the $I(U)$ characteristic curves of a rectifier diode and a Zener diode (both Si).
2. Investigate the rectifying effect of a Si rectifier diode.
3. Smooth the output voltage of a rectifier circuit by means of a capacitor, and analyze the residual ripple for different load currents.

2 Fundamentals

Keywords: AC voltage, RMS value, rectification, diode, Zener diode, capacitor, smoothing

2.1 Semiconductor diode

Semiconductor diodes are electrical components with a nonlinear $I(U)$ characteristic curve. The electrical behavior of semiconductor diodes is caused by a p-n junction. The bulk materials are usually silicon or germanium. For $U > U_S$, current flows (forward direction); for $U < U_S$, almost no current flows (reverse direction), see the characteristic curve in Fig. 1. The threshold voltage U_S is determined by drawing a tangent to the forward conduction region. Its point of intersection with the voltage axis at $I = 0$ corresponds to the threshold voltage.

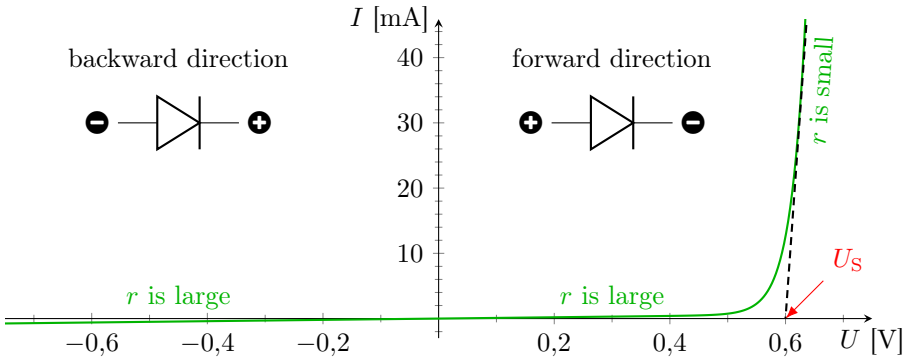


Figure 1: Typical diode characteristic curve (schematic). Forward direction: The point where the linear extrapolation (dashed line) of the steeply rising characteristic curve intersects the voltage axis yields the threshold voltage U_S. Reverse direction: A current flows here as well, albeit a very small one (depicted in exaggerated proportions).

The reverse voltage U_S of a diode depends on the bulk semiconductor material used and is typically 0,6 V… 0,7 V for Si (see Fig. 1) or 0,2 V… 0,3 V for Ge. In addition, the limiting values specified in the data sheets are important for practical applications. If the maximum allowable forward current is exceeded, the diode will be thermally damaged, a series resistor is therefore absolutely necessary! Exceeding the maximum allowable reverse voltage leads to carrier breakdown and, consequently, to an avalanche-like increase in current, which also causes irreversible damage. The differential internal resistance (i.e., the inverse slope of the $I(U)$ characteristic curve)

$$r = \frac{\mathrm{d}U}{\mathrm{d}I} \approx \frac{\Delta U}{\Delta I} \tag{1}$$

of a *hypothetical, ideal* diode is 0 in the forward bias region and ∞ in the reverse bias region. For *real* diodes, these extreme values are not reached; nevertheless, the differential internal resistance r is a highly nonlinear function of voltage, as shown by the $I(U)$ characteristic curve in Fig. 1. As a result, although the current does not change abruptly (but rather continuously) when U_S is exceeded, it does rise quite steeply, and hence r becomes small at $U > U_S$.

2.2 Rectification

There are two vital applications for rectifiers: (1) **Mains rectification** = Generating a DC voltage to supply a device from the AC mains voltage. The key factors here are efficiency and the residual ripple of the DC voltage. (2) **Signal rectification** = Recovery (demodulation) of low-frequency information (i.e., signal) from a high-frequency, modulated carrier wave. It is important to minimize distortion as much as possible; efficiency is of secondary importance.

Figure 2 illustrates the principle of half-wave rectification using a diode circuit. A pulsating DC voltage $U(t)$ drops across the resistor R, since the diode's polarity is in forward direction only when the positive half-wave of the input AC voltage is applied to the diode's anode. Hence, a current flows, resulting in a voltage drop across the resistor. During the negative half-cycle, the diode is in the reverse-biased state; no current flows, and consequently, there is no voltage drop across the resistor. Since the finite threshold voltage U_S drops across the diode during the forward-biased phase, the current flow time (t_1) and the cutoff time (t_2) are not equal.

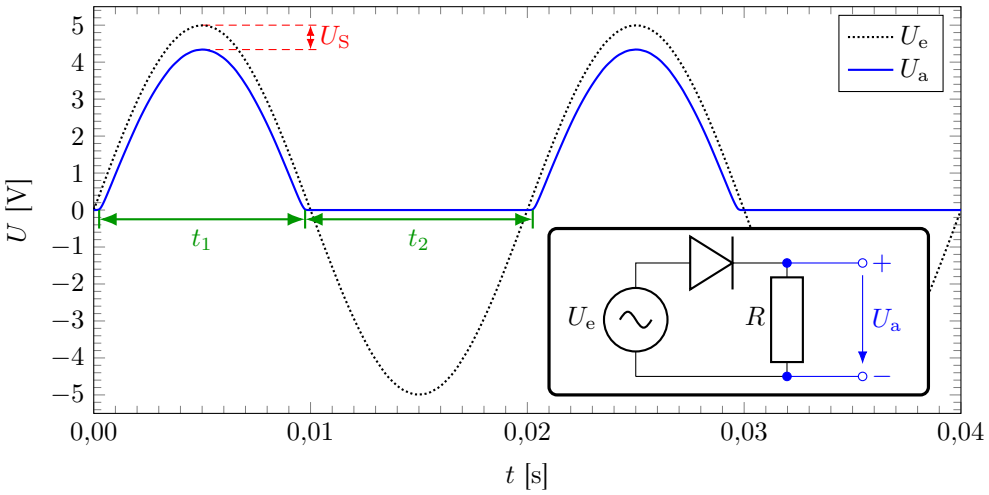


Figure 2: Half-wave rectification using a diode. Period time: $T = t_1 + t_2$, where $t_2 > t_1$.

☞ Circuits with **full-wave rectification** allow both the positive and the negative half-waves to be used. As you prepare for the experiment in advance, read up on the working principle of the **Graetz diode bridge circuit** (also known as a two-pulse bridge circuit – B2), for example here (EN) or here (DE).

2.3 Smoothing

The goal of mains rectification is not to produce a pulsating voltage, but rather a DC voltage with as little residual ripple as possible. By connecting a storage element (capacitor) in parallel with the output of the rectifier circuit, it is possible to significantly reduce the ripple. Figure 3 shows a circuit for smoothing a pulsating DC voltage.

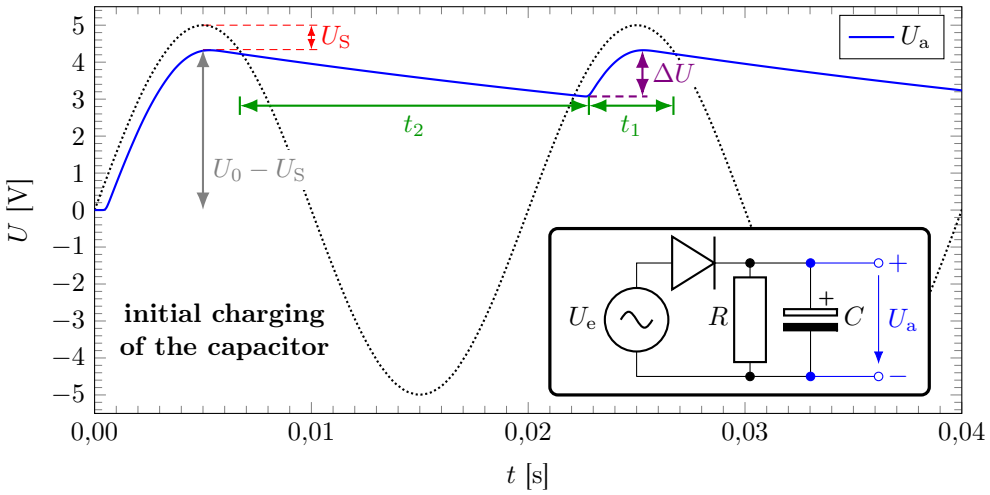


Figure 3: Half-wave rectification using a diode, followed by smoothing using a capacitor (here: electrolytic capacitor) to produce a constant DC voltage from a pulsating DC voltage. ΔU is the residual ripple of the output voltage.

During the time t_1, the anode of the diode is at a higher potential than the cathode. As a result, a current flows through the diode, charging the capacitor C almost up to $U_0 - U_S$. During the time interval t_2, the diode is in the reverse-biased state, and the capacitor C discharges through the resistor R. To obtain an estimate for ΔU, one can assume that the discharge current of the capacitor is

$$I = C \cdot \frac{\mathrm{d}U}{\mathrm{d}t} \tag{2}$$

This gives $\Delta U \approx \Delta t \cdot (I/C)$. Under the **assumption** that the discharge time constant can be expressed as $\tau = RC \gg T$, one can, **for simplicity**, carry out the calculation using a constant discharge current $I = (U_0 - U_S)/R$. In practice, the current flow time is $t_1 \ll T$, compare Fig. 3. Consequently, the discharge time can be approximated as $\Delta t \approx T = 1/f$. In summary, this gives the following equation for the residual ripple of the output voltage:

$$\Delta U \approx \frac{I}{C \cdot f} = \frac{U_0 - U_S}{R \cdot C \cdot f} = \frac{U_0 - U_S}{\tau \cdot f} \tag{3}$$

3 Experimental procedure

1. Use the LabVIEW programme “Kennlinie.vi” to automatically record the $I(U)$ characteristic curves of a rectifier diode and a Zener diode (both Si), by means of the setup shown in Fig. 4. Plot the characteristic curves graphically and mark the characteristic parameters (threshold voltage U_S and Zener voltage U_Z) in the graph.

2. Set up a half-wave rectifier as shown in Fig. 5, initially without a capacitor. Display the input and output voltages simultaneously on the Hameg HM1508 dual-channel oscilloscope in “DUAL” mode. Use a sinusoidal input voltage with an amplitude of 3 V and a frequency of 50 Hz. Use $R = 10\,\mathrm{k\Omega}$ here. Save the measurement data from the oscilloscope and plot the two curves in the same graph. Indicate the current flow time t_1, the cutoff time t_2, and the threshold voltage U_S in this graph.

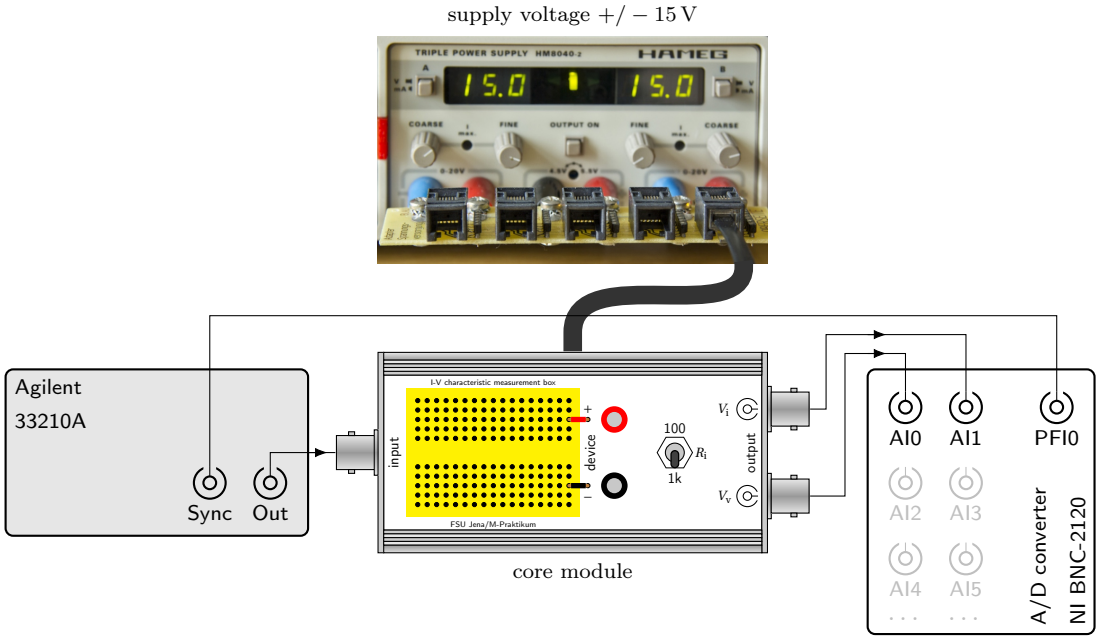


Figure 4: Configuration of the connections at the characteristic curve measurement station. The output of the Agilent 33210A function generator is connected to the input of the core module. Its outputs are in turn connected to the highlighted inputs of the NI BNC-2120 A/D converter (V_v to AI0, V_i to AI1, both set to GS). The generator's Sync output is connected to the trigger input (PFI0) of the A/D converter. The series resistor R_i is already built into the core module and can be selected via a toggle switch (100 Ω or 1 kΩ). The device under test is connected directly to the red and black sockets on the core module. The ground at the outputs V_i and V_v is *not* connected to the input ground. You should therefore only connect the core module to the devices shown in this flowchart.

3. Try to display and measure the reverse current I_S of the Si rectifier diode on the oscilloscope. Also try to measure the reverse current at $U = -24\,V_{DC}$ (use a separate circuit with a series resistor of 1 kΩ!). What value is given for I_S in the data sheet?

4. Now repeat task 2 using a capacitor. Determine the residual ripple of the output voltage for capacitances of $C = 4{,}7\,\mu F$ and $47\,\mu F$, and for resistances of $R = 1\,k\Omega$ and $10\,k\Omega$ (i.e., 4 different combinations). Save all the waveforms from the oscilloscope for your report. Compare the measured residual ripple in each case with the ΔU calculated using equation (3) and discuss the results. 👉 Measure **both resistors and both capacitors** on the separate Philips PM 6303 RCL meter and use these values for your calculations. The mode "RCL Auto" must not be used to measure electrolytic capacitors (*Elkos*)!

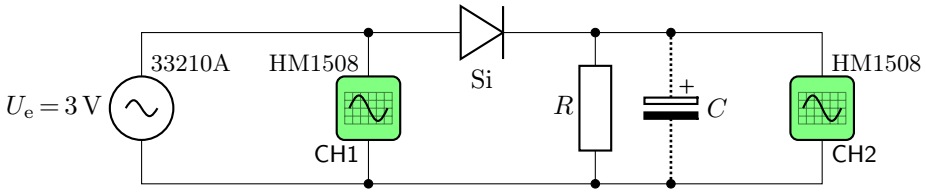


Figure 5: Half-wave rectification with optional smoothing using an electrolytic capacitor. For channel CH2, try AC coupling as well and adjust the gain so that you can measure the residual ripple as accurately as possible.