

# The Semiconductor Diode

## 1. Introduction

The semiconductor diode (Fig.1) is an electronic component with two terminals, made from semiconductor materials (germanium, silicon, gallium arsenide, selenium), which permits the unidirectional flow of the electric current through it.

The history of the semiconductor diode starts with the discovery of the unilateral conduction across a contact between a metal and a galena (PbS), in 1874, by Karl Ferdinand Braun (Nobel prize). Later, in 1894, Jagadish Chandra Bose used a crystal (made from PbS) to receive radio waves. In 1930's the first point-contact diodes (crystal diodes) were developed at Bell Telephone Labs, to be used in military equipment ten years later (during World War II).

In 1938, the german physicist Walter Schottky created a theory that explained the rectifying behavior of a metal-semiconductor contact as dependent on a barrier layer at the surface of contact between the two materials. The diodes manufactured on the basis of this invention were named Schottky barrier diodes.

In the 1940, Russel Ohl (Bell Labs) discovered the silicon pn junction, and in 1950, William Shockley (Bell Labs) noticed the Zener effect (named after Clarence Melvin Zener who first described the property concerning the breakdown of electrical insulator in 1934) in early semiconductor diodes.

After the war, in 1946, Sylvania Electric Products factory from US, started the mass production of 1N34 crystal germanium diode (we will simulate it during this lab). Then, in 1950's, several European and US manufacturers began the mass production of silicon rectifiers (based on Mr. Ohl discover), and of the Zener diodes (we are going to simulate some, too).

Today, most types of diodes are based on the pn junction and they are made of silicon.

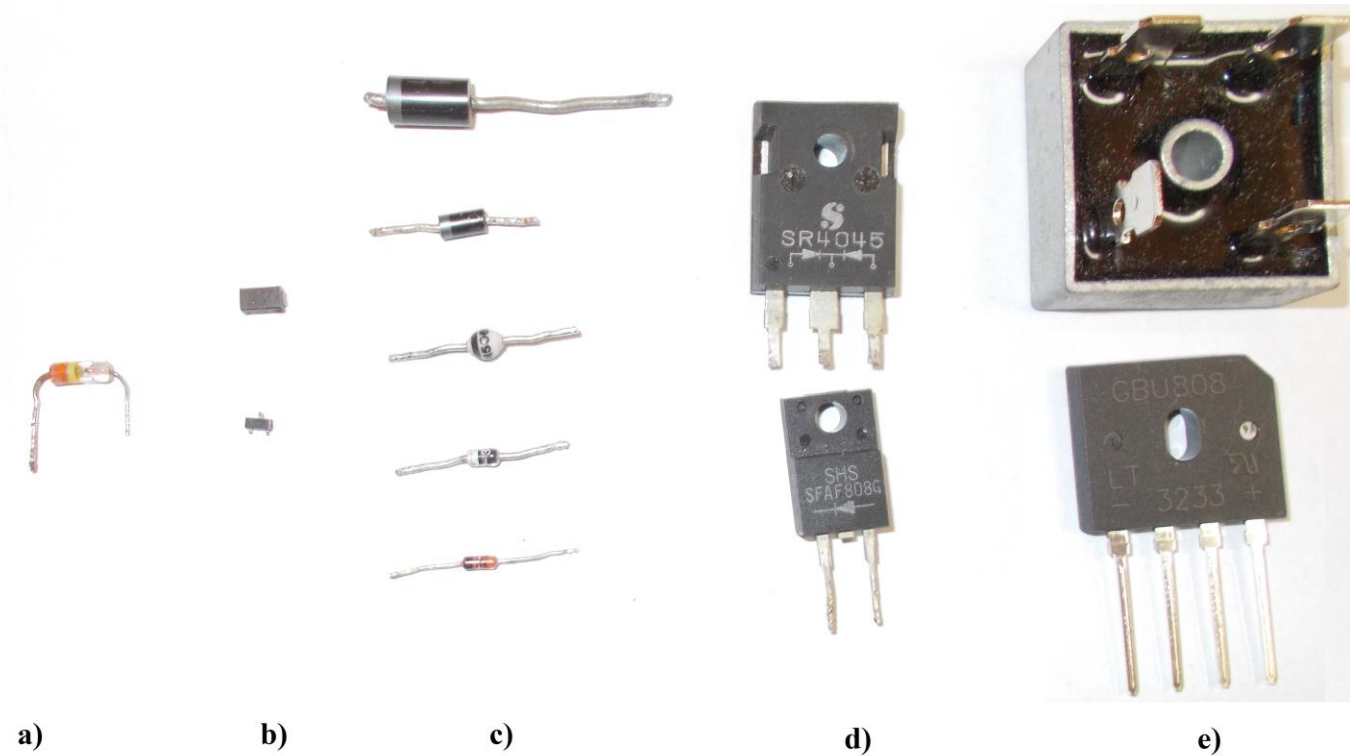


Fig.1. Several types of diodes: a) germanium point-contact diode (manufactured by IPRS Băneasa -RO); b) SMD silicon diodes; c) low power silicon diodes (pn junction and Schottky barrier); d) Medium power silicon diodes; e) silicon bridge rectifiers (pn junction)

## 2. The diode brief theory

This component (Fig.2) has two terminals: the anode (A) and the cathode (K). The case is made from glass (low power diodes), plastic (low and medium power diodes) and metal-glass, metal-plastic or metal-resin (high power diodes). For low and medium power diodes, the cathode is marked with one (silicon diodes) or more (some crystal germanium diodes) colored bands.

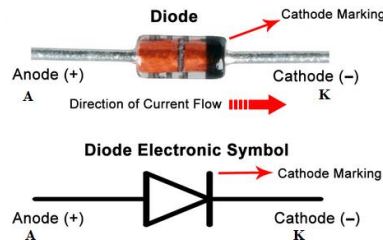


Fig.2. A typical low power silicon diode in a glass case

When the diode is DC(direct current) biased, it has a current-voltage characteristic similar to Fig.3. Two modes of operation are possible:

- Forward bias: when the voltage applied between the anode and the cathode is positive ( $V_{AK}>0$ );
- Reverse bias: when the voltage applied between the anode and the cathode is negative ( $V_{AK}<0$ );

In forward bias (quadrant I) the I-V characteristic may be approximated by the exponential law:

$$I_A = I_0 \cdot \left[ \exp\left(\frac{q \cdot V_A}{m \cdot k \cdot T}\right) - 1 \right] \quad (1)$$

Where:

$I_A$  is the anode current;

$I_0$  is the reverse saturation current caused by diffusion of minority carriers from the neutral regions to the depletion region (leakage current);

$V_A$  is the potential between the anode and the cathode (the dropout voltage);

$m$  is the ideality term ( $m \in [1; 2]$ );

$V_{th} = \frac{k \cdot T}{q}$  (26mV at room temperature, 298K) is the thermal voltage.

In this regime, the diode may be considered a closed switch (if the dropout voltage may be neglected).

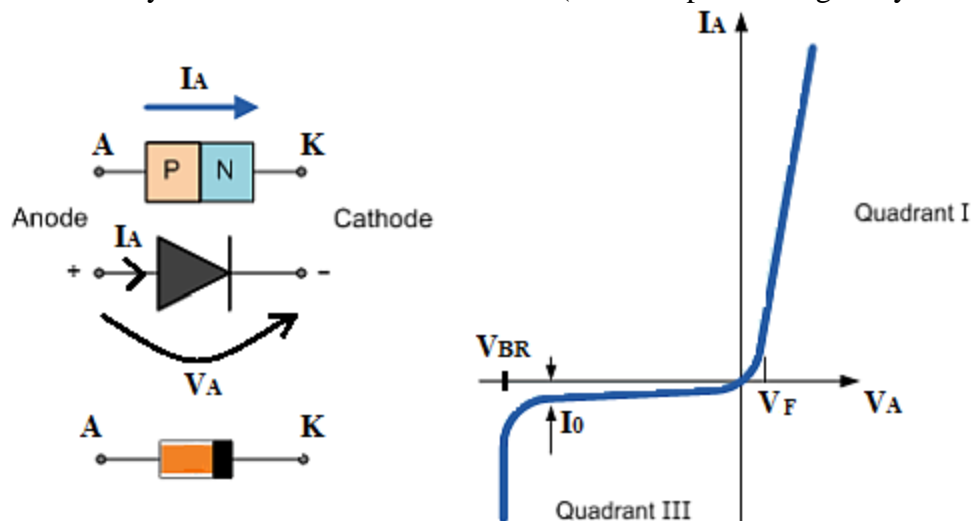


Fig.3.The I-V characteristic for a diode

In the reverse bias (quadrant III), there are two operating modes:

- The blocking region: where the reverse current is very small – approximately  $I_0$  (named also the leakage current). In this regime, the diode may be considered as an open switch (if the saturation current may be neglected).
- The breakdown region where the reverse current through the diode strongly increases, and the reverse voltage is almost constant ( $V_{BR}$ , or  $V_Z$  for Zener diodes). In this regime, the diode is used as a voltage regulator or a voltage reference.

The operating mode of the diode may involve the use of this device powered by both direct current (DC) and alternating current (AC) (Fig.4).

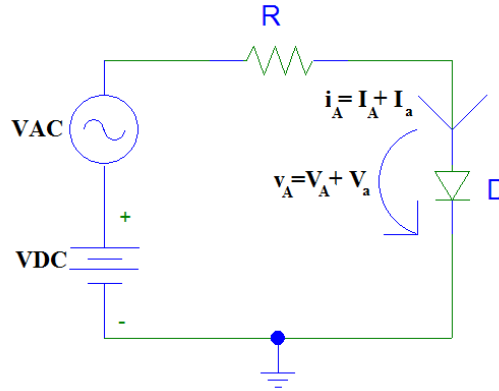


Fig.4.The diode biased from DC and AC sources

The current through the circuit may be calculated if the values of the supply voltage (VDC) and the forward voltage ( $V_A$ ) on the diode are measured by using a voltmeter:

$$I_A = \frac{V_{DC} - V_A}{R} \quad (2)$$

In some applications, the AC signal applied to device has low amplitudes. It is stated that the diode works at small signal when the AC voltage on the diode ( $V_a$ ) does not exceed the thermal voltage,  $V_{th}$ :

$$V_{th} = \frac{k \cdot T}{q} \quad (3)$$

$$V_a \ll V_{th} \quad (4)$$

In this state (small signal AC amplitude on the device), the diode has an AC equivalent circuit, depending on the polarity of the DC voltage which is applied at the same time on its terminals:

- If the diode is in forward bias in DC, the AC equivalent circuit is the dynamic resistance (a resistor) connected in parallel with the diffusion capacitance (a capacitor) (Fig.5):

$$R_d = \frac{m \cdot k \cdot T}{q \cdot I_A} \quad (5)$$

$$C_d = \frac{\tau_0}{2 \cdot R_d} \quad (6)$$

,where  $\tau_0$  is the common lifetime of excess holes and electrons in the semiconductor.

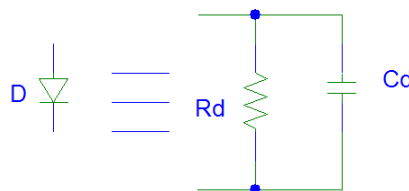


Fig.5.The AC equivalent circuit in forward bias (small signal)

The dynamic resistance ( $R_d$ ) should not be confused with static resistance (DC resistance) in forward bias:

$$R_f = \frac{V_A}{I_A} \quad (7)$$

If the applied signal (the AC source) has a low frequency (below 1KHz), the influence of the diffusion capacitance ( $C_d$ ) is small and it may be neglected. The equivalent circuit is presented in Fig.6.

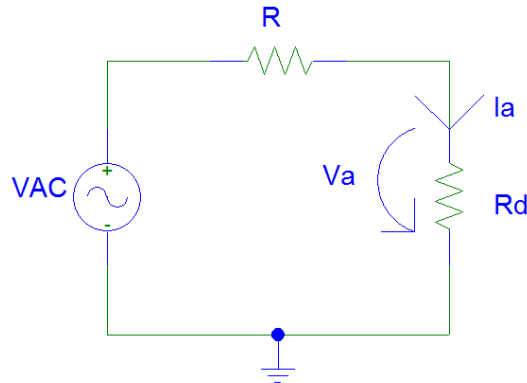


Fig.6.The AC equivalent circuit of Fig.4 in forward bias (small signal) and low frequency

The AC current amplitude through the diode is:

$$I_a = \frac{V_{AC}}{R + R_d} \quad (8)$$

The AC voltage amplitude through the diode becomes:

$$V_a = R_d \cdot I_a = \frac{R_d}{R + R_d} \cdot V_{AC} \quad (9)$$

From Eq.9, the dynamic resistance of the diode may be calculated if the dropout voltages are measured with an AC millivolt meter:

$$R_d = \frac{V_a}{V_{AC} - V_a} \cdot R \quad (10)$$

- If the diode is in reverse bias in DC, the AC equivalent circuit is the barrier capacitance (a capacitor) (Fig.7):

$$C_b = \frac{\epsilon \cdot A_J}{l} \quad (11)$$

, where:

- $\epsilon$  is the electrical permittivity of the semiconductor;
- $A_J$  is the cross-sectional area of the junction;
- $l$  is the total width of the space charge region inside the junction ( $l = l_p + l_n$ ).

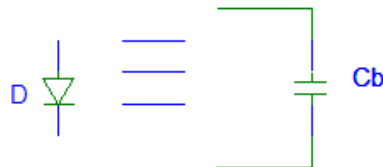


Fig.7.The AC equivalent circuit in reverse bias (small signal)

When a high amplitude AC signal is applied to the diode terminals, the current-voltage characteristic of the device can be strongly nonlinear. In such situations, the diode can be used to rectify the alternating current. Usually, diodes with a high breakdown voltage in reverse bias and a very low dropout voltage in forward bias are chosen for this type of application.

### 3. Laboratory exercises

#### 3.1 The static (DC) characteristic of the diode

##### 3.1.1 Germanium diode

Since the *Student* version of *PSpice* does not contain a germanium part in its libraries, we will create a model for the germanium point-contact diode 1N34 by using the *Pspice Model Editor Student* application (modeled.exe). (Fig.8). A second option is to copy the files generated by the *Model Editor* following the instructions in *Annex 2*.

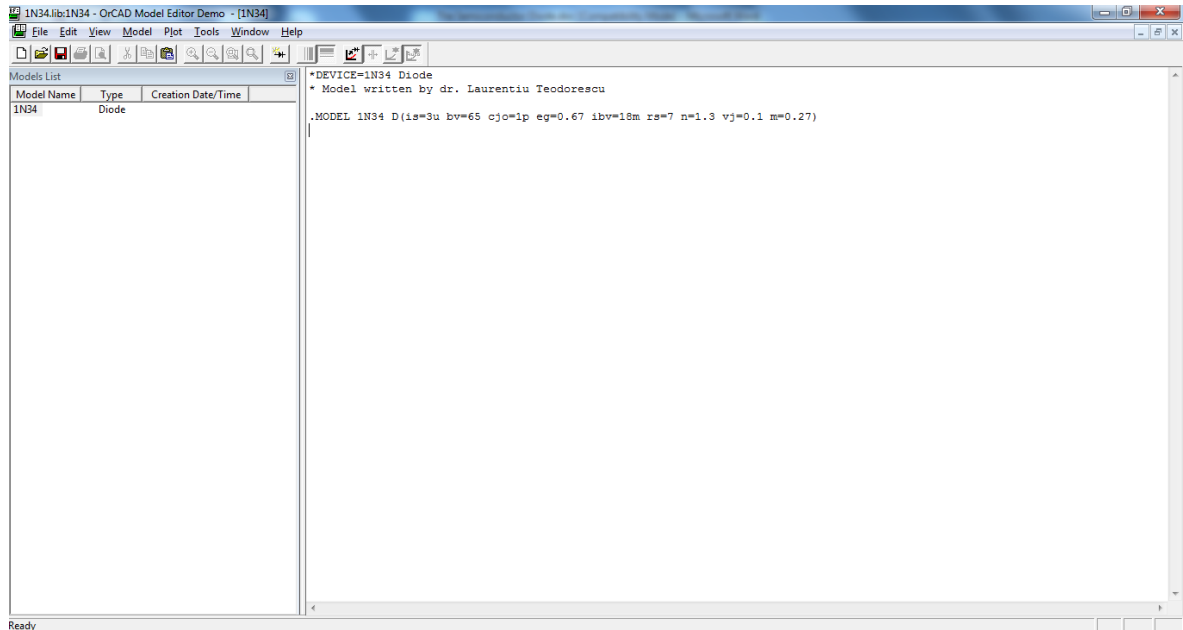


Fig.8.Creating the model for 1N34 germanium diode by using the *Model Editor*

The model is built by performing several steps:

1. *Model->New...->write 1N34*
2. *View->Model Text*
3. *write in the right window:*

\**DEVICE=1N34 Diode*

\**Model written by dr. Laurentiu Teodorescu*

*.MODEL 1N34 D(is=3u bv=65 cjo=1p eg=0.67 ibv=18m rs=7 n=1.3 vj=0.1 m=0.27)*

4. *Save and close.*

The symbol (1N34.slb) and the library (1N34.lib) should be automatically generated in the *UserLib* folder. Next step is to draw the circuit presented in Fig.9 by using the *PSpice Schematics* editor. The power source is a DC voltage source. D1 is the 1N34 germanium point-contact diode.

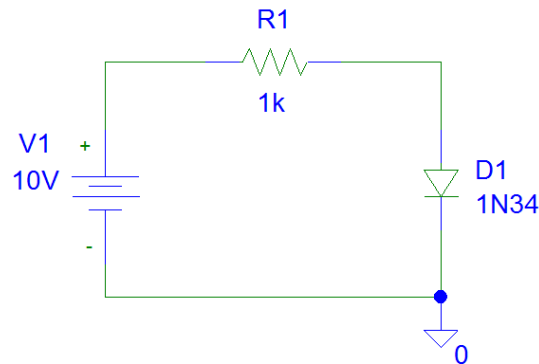


Fig.9. Biasing a germanium crystal diode from a DC voltage source

The simulation will be a DC sweep type (linear) in forward bias: V1 supplies the circuit with a DC voltage that will vary between 0 and 10V by using a step (increment) of 0.01V.(Fig.10). The simulation results in *Pspice A/D Demo* are made by measuring the current according to the voltage at the terminals, so the dropout voltage will be set on the X axis: *Plot->Axis Settings...->X Axis -> Axis Variable -> VI(D1)*. The results are named in *Table 1*.

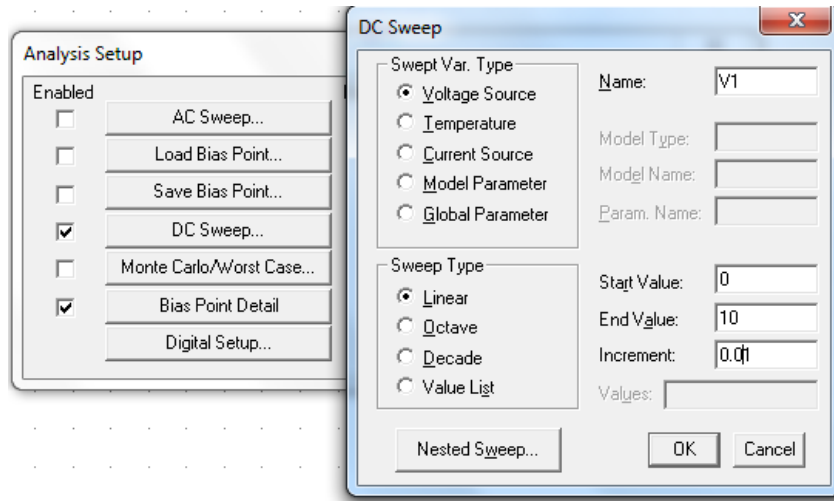


Fig.10. Sweep type settings for the DC voltage source (V1)

Then, the diode is mounted in reverse bias by changing the polarity of V1 (starting from -110V to 0V, with an increment 0.1V). R1 value should be changed to 1M $\Omega$  (Fig.11). The dropout voltage in will be set on the X axis: *Plot->Axis Settings...->X Axis -> Axis Variable -> VI(D1)*.

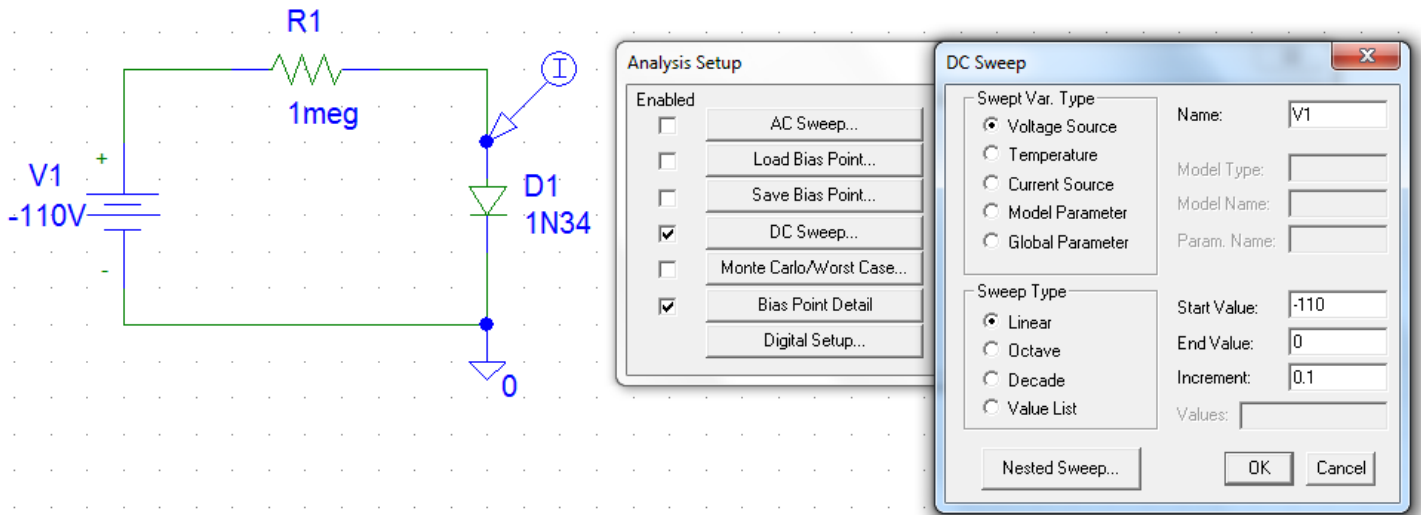


Fig.11. The schematic and the configuration for reverse bias (1N34)

The results should be depicted in *Table 1*.

Table 1 - DC bias for the 1N34 germanium diode (point-contact)

Diode	Dropout voltage ( $V_A$ , V)	Anode current ( $I_A$ , mA)
D1 – germanium (1N34)	-64.844	
	-64.840	
	-64.832	
	-64.827	
	-64.820	
	-64.811	
	-64.797	
	-64.765	
	-64.681	
	-60	
	-50	
	-40	
	-20	
	-10	
	0	
	0.025	
	0.05	
	0.06	
	0.07	
	0.08	
	0.09	
	0.1	
	0.15	
	0.2	
	0.25	
0.3		
0.34		

### 3.1.2 Silicon diode

Replace D1 (1N34) with D2 (1N4148) in the schematic (the diode 1N4148 may be found in the *eval.slb* library) (Fig.12) and repeat the simulation. The dropout voltage will be set on the X axis: *Plot->Axis Settings...->X Axis -> Axis Variable -> V1(D2)*.

The results should be collected in *Table 2*.

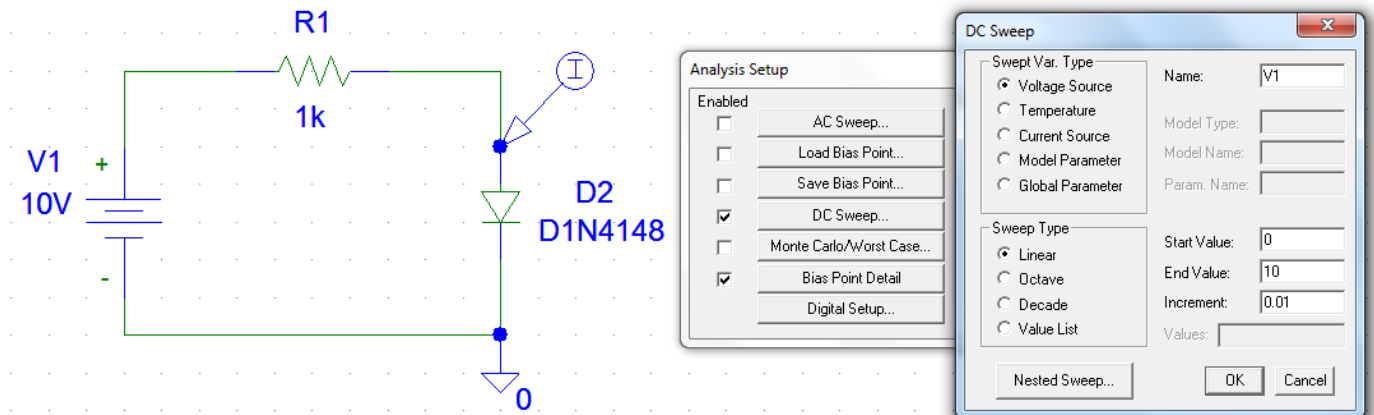


Fig.12.The schematic and the configuration for forward bias (1N4148)

Then, the silicon diode will be connected in reverse bias (Fig.13). Run the simulation again and write the current values in the required points of interest in *Table 2*. The dropout voltage will be set on the X axis: *Plot->Axis Settings...->X Axis -> Axis Variable -> VI(D2)*.

*Table 2 - DC bias for the 1N4148 silicon diode (pn junction)*

Diode	Dropout voltage ( $V_A$ , V)	Anode current ( $I_A$ , mA)
D2 – silicon (1N4148)	-99.941	
	-99.938	
	-99.935	
	-99.931	
	-99.927	
	-99.923	
	-99.917	
	-99.909	
	-99.899	
	-99.881	
	-99.875	
	-99.867	
	-99.855	
	-99.818	
	-90	
	-80	
	-70	
	-60	
	-50	
	-40	
	-30	
	-20	
	-10	
	0	
	0.05	
	0.1	
	0.15	
	0.2	
	0.25	
	0.3	
	0.35	
	0.4	
	0.45	
0.5		
0.55		
0.6		
0.65		
0.7		
0.718		



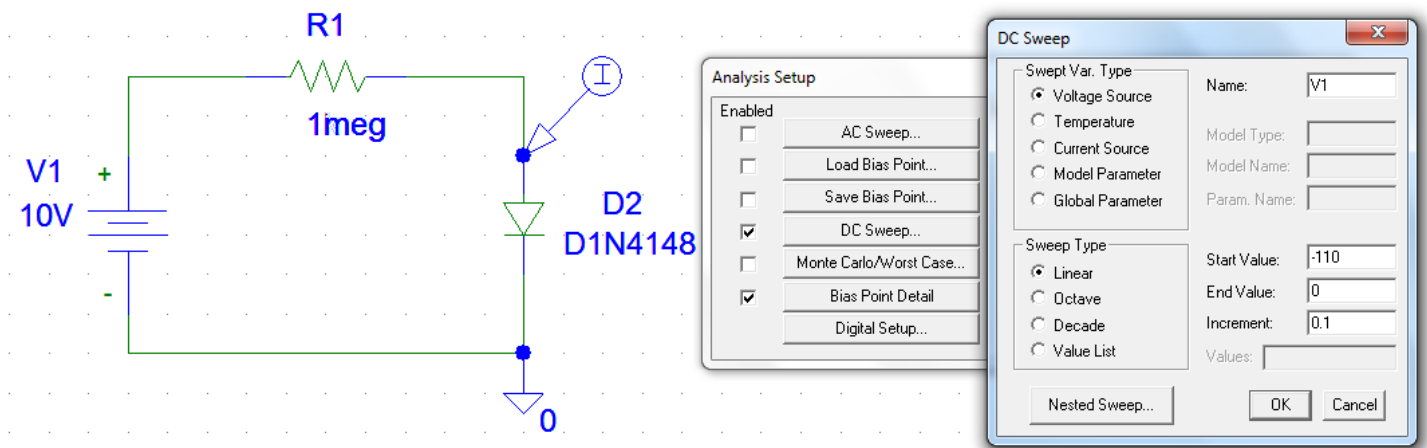


Fig.13.The schematic and the configuration for reverse bias (1N4148)

**Exercises**

1. Do the calculus for the DC current through the diode ( $I_A$ ) by using Eq.2 (measure V1 and  $V_A$ , then calculate  $I_A$ ).
2. Draw the I-V characteristics of the germanium and silicon diodes on the same graph by using a piece of graph paper.
3. Compare the dropout voltage in forward bias for the germanium and silicon diodes at the same current on the graph paper. Explain the results.
4. Mount a silicon diode (1N4148) in series with the germanium diode (1N34) from Fig. 9 and run the simulation again. What is the difference between the DC voltages ( $V_{A1}$ ,  $V_{A2}$ ) in forward bias on these devices?
5. Mount a silicon diode (1N4148) in parallel with the germanium diode (1N34) from Fig. 9 and run the simulation again. What is the difference between the DC anode currents ( $I_{A1}$ ,  $I_{A2}$ ) through these devices?

*3.2 The dynamic resistance of the diode*

Draw the schematic from Fig.14. V2 is a sine-wave voltage source used for time domain analysis of the circuit, with the following parameters: VOFF=0; FREQ=1k; TD=0; DF=0; PHASE=0; VAMPL=600mV.

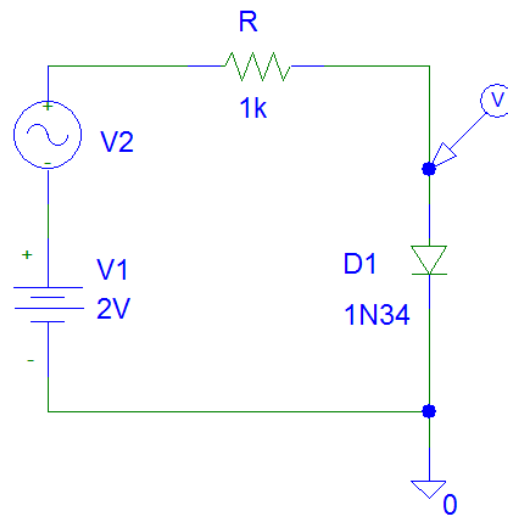


Fig.14.The AC circuit for the germanium diode 1N34 (forward bias)

The AC voltage,  $V_a$  (RMS value), on the diode D1 may be calculated by selecting *Trace->Add Trace....->* and by writing in the Trace Expression field:  $(MAX(V(D1:1))- MIN(V(D1:1)))/(2*SQRT(2))$  (Fig.15). In the same manner you can calculate the RMS  $V_{AC}$  voltage:

*Trace->Add Trace....->* , then select:  $(MAX(V1(V2))- MIN(V1(V2)))/(2*SQRT(2))$ .

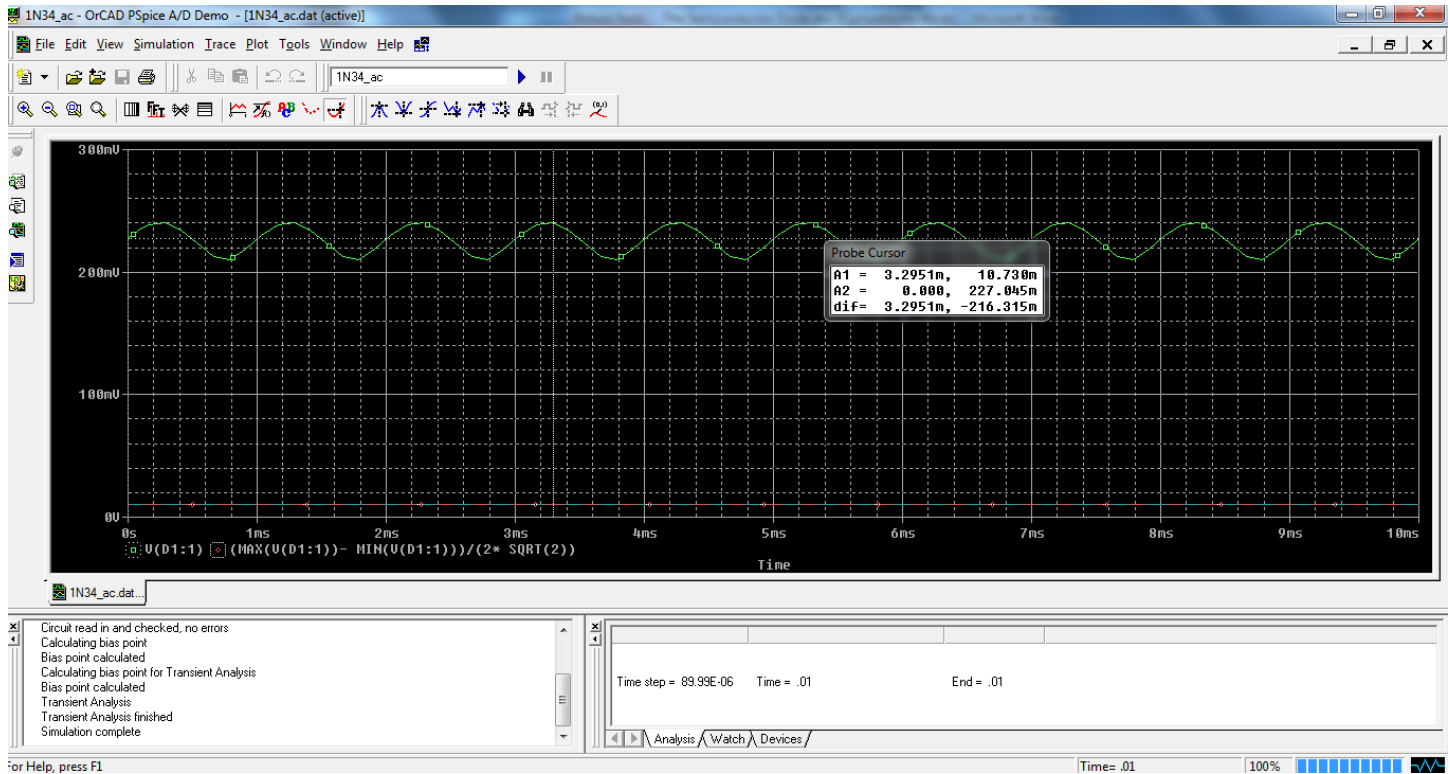


Fig.15.The AC analysis in forward bias for the germanium diode (1N34)

Change the DC supply voltage (Table 3) and repeat the simulation. Replace the germanium diode 1N34 by 1N4148 silicon diode and do the simulations again. Calculate the dynamic resistance by using the Eq. 10.

Table 3 – The dynamic resistance

Diode	DC supply voltage ( $V_{DC}$ )	Forward voltage ( $V_A$ , V)	Anode current ( $I_A$ , mA)	AC voltage of voltage source ( $V_{AC}$ , mV RMS)	AC voltage on the diode ( $V_a$ , mV RMS)	Dynamic resistance ( $\Omega$ )
1N34 (germanium)	2	0.227	1.773	414.04	10.73	
	4					
	6					
	8					
	10					
1N4148(silicon)	2					
	4					
	6					
	8					
	10					

**Exercise**

1. Calculate  $m_1$  and  $m_2$  for D1 and D2 by using the Eq. 5.

### 3.3 The Zener diode

Draw the circuit from Fig.16. This is a parametric voltage regulator based on the 1N750 Zener diode. The diode is in the reverse bias.

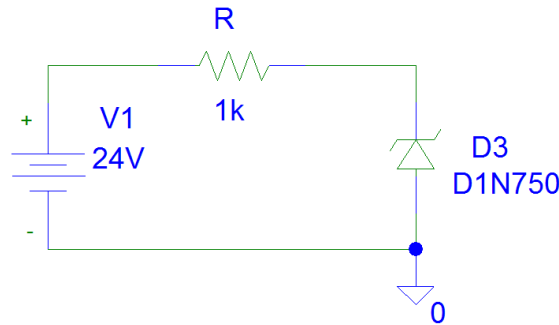


Fig.16.The parametric voltage regulator with the Zener diode

The current through the diode ( $-I_A = I_Z$ ) may be calculated by using the Kirchhoff equation:

$$-I_A = \frac{V_{DC} - (-V_A)}{R} \quad (12)$$

, where  $V_{DC}$  is the supply voltage (from V1) and  $-V_A (V_Z)$  is the reverse voltage on the Zener diode.

The simulation will be of a DC sweep type, with the supply voltage varying from 0 to 30V with a step of 0.1V. Write the results in *Table 4*.

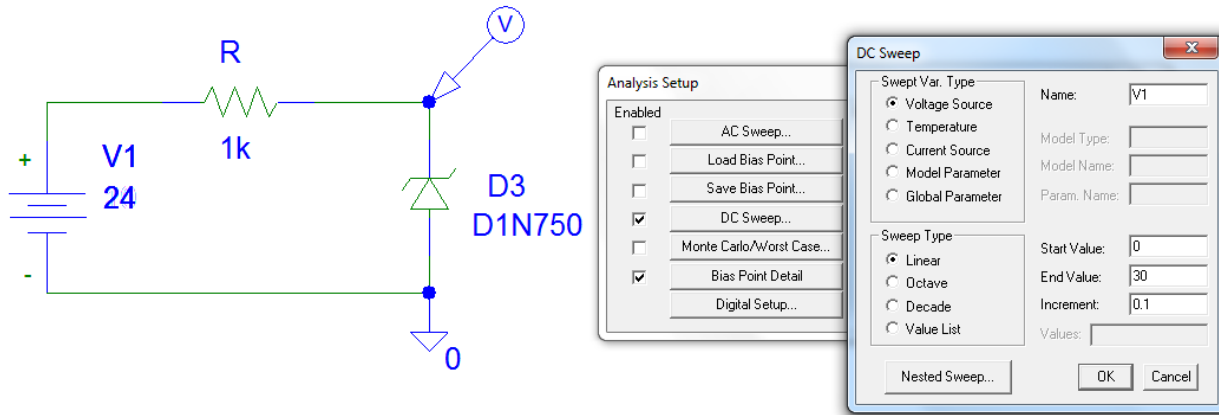


Fig.16.The parametric voltage regulator with the Zener diode

Table 4

Diode	$V_{DC}(V_1, V)$	$-V_A(V_Z, V)$	$-I_A(I_Z, V)$
D3-1N750	0		
	1		
	2		
	3		
	4		
	5		
	6		
	7		
	10		
	15		
	20		
	25		
30			

## Annex 1

Table 1

Po s.	Component type	Value	Library
1.	R (resistor)	<p>Numerical value is taken from the laboratory platform.</p> <ul style="list-style-type: none"> <li>- Mili-ohms if <i>m</i> is written after the numerical value</li> <li>- Ohms if nothing is written after the numerical value</li> <li>- Kilo-ohms if <i>k</i> is written immediately after the numerical value</li> <li>- Mega-ohms if <i>meg</i> is written immediately after the numerical value</li> </ul>	Analog.slb
2.	D1 (germanium point contact diode)	1N34	Custom design
3.	D2 (silicon pn junction, fast switching)	1N4148	Eval.slb
3.	D3 (silicon pn junction, Zener)	1N750	Eval.slb
4.	VSIN (used to function as a signal generator, sine-wave voltage source for time domain analysis)	<ul style="list-style-type: none"> <li>- <b>DC</b>: the DC component of the sine wave</li> <li>- <b>AC</b>: the AC value of the sine wave.</li> <li>- <b>VOFF</b>: the DC offset value (set to zero if you need a pure sinusoid).</li> <li>- <b>VAMPL</b>: the undamped amplitude of the sinusoid; i.e., the peak value measured from zero if there were no DC offset value.</li> <li>- <b>FREQ</b>: the frequency in Hz of the sinusoid.</li> <li>- <b>TD</b>: the time delay in seconds (set to zero for the normal sinusoid).</li> <li>- <b>DF</b>: damping factor (set to zero for the normal sinusoid).</li> <li>- <b>PHASE</b>: phase advance in degrees (set to 90 if you need a cosine wave form).</li> </ul> <p>Note: the normal usage of this source type is to set <b>VOFF</b>, <b>TD</b> and <b>DF</b> to zero as this will give you a 'nice' sine wave.</p>	Source.slb
5.	VDC (simple DC voltage source)	<ul style="list-style-type: none"> <li>- Value in volts.</li> </ul>	Source.slb
6.	GND_ANALOG	<ul style="list-style-type: none"> <li>- Ground (node potential is 0 volts).</li> <li>- It is <b>mandatory</b> to be used in any PSpice schematic!</li> </ul>	Port.slb

## **Annex 2**

### **Instructions for installing Spice libraries to simulate the germanium diode 1N34.**

1. The files “1N34.lib” and “1N34.slb” should be copied in the folder where the Spice libraries are installed. For example, if the default settings are used, the path is: “C:\Program Files\OrCAD\_Demo\PSpice\Library”

2. In the *Schematics* editor will be added the paths to the libraries:

- A. Analysis-Library and include files...-Browse...-C:\Program Files\OrCAD\_Demo\PSpice\Library\1N34.lib –Open-Add Library\*-OK
- B. Options-Editor Configuration-Library Settings...-Browse...-C:\Program Files\OrCAD\_Demo\PSpice\Library\1N34.slb-Open-Add\*-OK-OK

### **Bibliography**

1. Cadence Design Systems, PSpice User’s guide, Second Edition, 31 May 2000, Portland, Oregon, USA