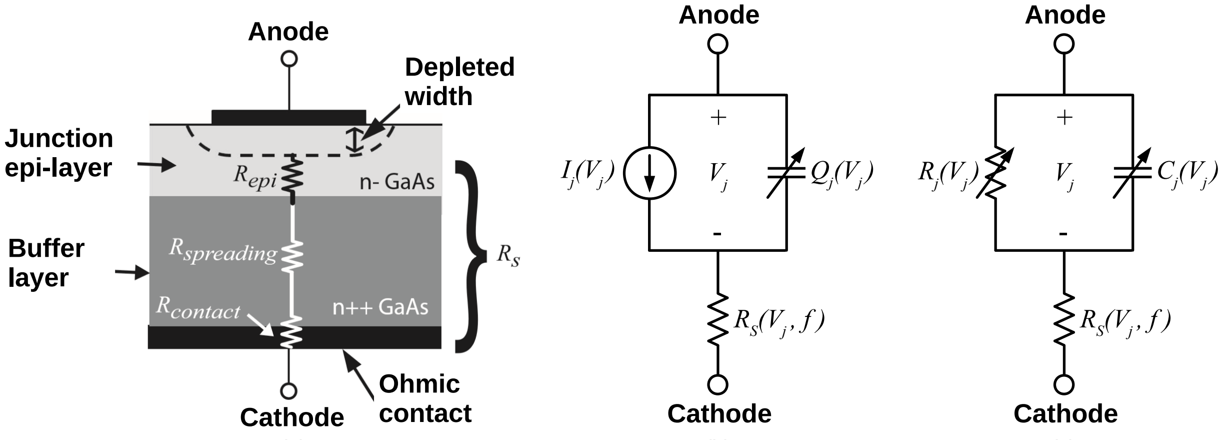
PRACTICUM III
Fundamental Basics of Modern Technologies
Practical #4
Temperature Dependence of a Metal-Semiconductor Junction's Transport Properties

1 Introduction

The steady progress of terahertz applications [1] stimulates the implementation of new and development of existing technologies for both radiation sources and receivers. At the moment, several basic technologies can be employed for the heterodyne detection of a terahertz radiation. Thus, the superconductor-insulator-superconductor (SIS) mixer is extremely efficient at frequencies below 1.4 THz [2], the superconducting hot electron bolometric (HEB) mixer can be used above that frequency and has no competitors in the sensitivity within the 'super-THz' range (i.e. 3–6 THz) [3], and the input frequency bandwidth of the planar Schottky diode (PSD) mixer is limited by ∼3 THz from the upper side [4]. In contrast to the superconducting technologies of the SIS and HEB mixers, the latter technology is based on semiconductors and is mainly associated with the use of layered GaAs-based structures, which do not imply usage of bulky and expensive cryogenic equipment to achieve decent sensitivity of a mixer. The lack of need to cool the PSD down to helium temperatures makes it quite attractive for practical applications. Moreover, the technology of planar diodes, unlike whisker contacted diode technology, allows to strictly control parameters of the devices being fabricated and enables easy way of integrating them with complex high-frequency circuits. But despite numerous advantages, the planar technology has certain drawbacks associated with appearance of a series resistance and shunt capacitance in the diode's intrinsic circuitry.



(a) (b) (c)

Figure 1: (a) Layered structure of the inner part of the PSD sample. (b-c) The lumped element models of the inner part of the PSD sample. Here R_s is the series resistance, I_j is the junction voltage dependent current, Q_j is the junction voltage dependent charge, R_j is the junction voltage dependent resistance, C_j the junction voltage dependent capacitance.

2 Experimental setup and device under study

Chip of the PSD sample is installed into a holder equipped with a banana cable attached to the cathode and anode leads. The holder is also equipped with a silicon temperature sensor. The temperature dependent resistance (figure 2) of the latter can be used as a readout parameter to monitor operating temperature of the sample. The PSD layered structure and its equivalent RC-circuitry are provided in figure 1(a) and figure 1(b-c), respectively. Detailed information on the sample properties required for the evaluation of its transport characteristics is summarized in figure 3.

3 Measurement and data processing

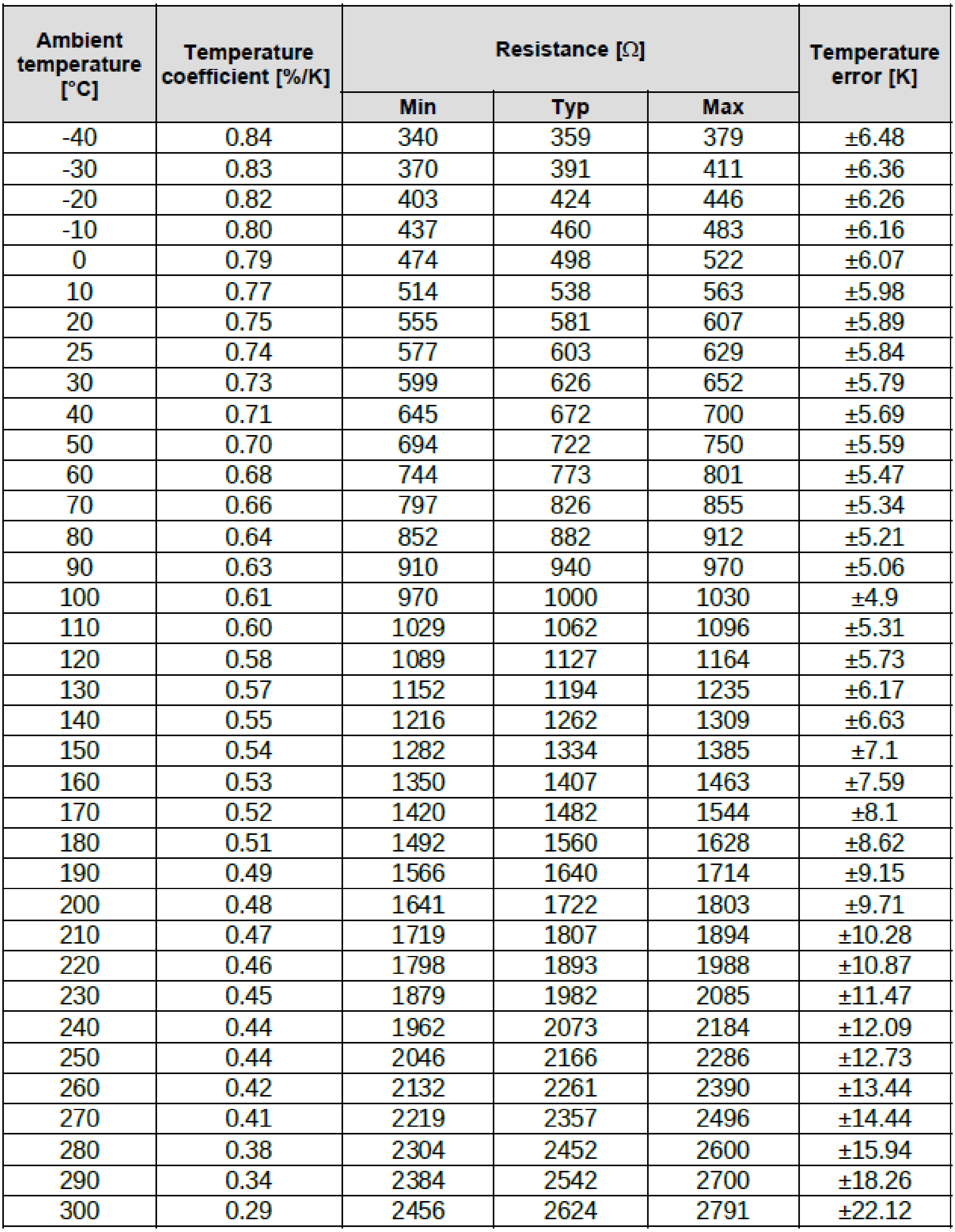
3.1 DC characterization

In order to evaluate basic DC parameters of the PSD samples, one can employ a standard analysis of the current-voltage (IV) characteristics. It is known that forward branch of the IV characteristics of the Schottky diode starting from the $V_d > 3\,k\,T/q$ and up to the end of the low voltage range, i.e. where drop of the bias voltage on the series resistance (R_s) is negligible compared to that of on the space charge region (figure 1), in the semi-log scale should obey a linear dependence law, and it can be expressed by an 'ideal IV curve'

$$ln(I_{id}(V_d)) = a\,V_d + b. \tag{1}$$

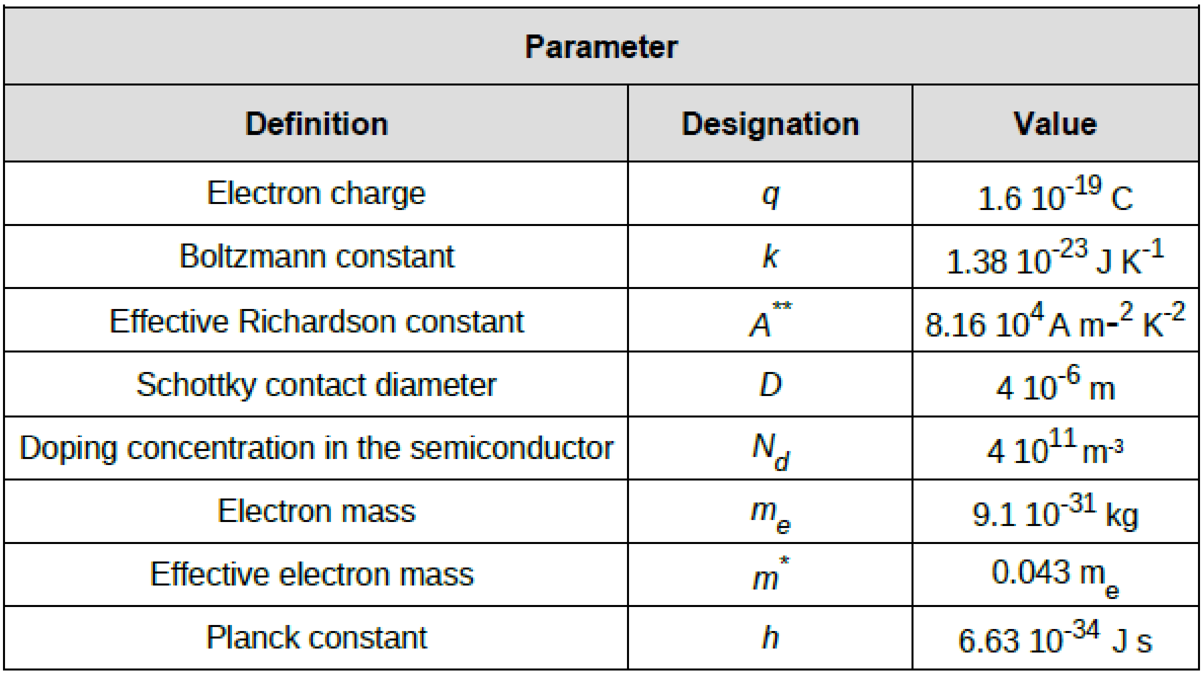
Hereinabove V_d is the DC voltage applied to the diode, q is the electron charge, k is the Boltzmann constant and T is the diode's physical temperature.

At the same time based on the thermionic-field emission model [5] the



Ambient temperature [°C]	Temperature coefficient [%/K]	Resistance [Ω]			Temperature error [K]
		Min	Typ	Max	
-40	0.84	340	359	379	±6.48
-30	0.83	370	391	411	±6.36
-20	0.82	403	424	446	±6.26
-10	0.80	437	460	483	±6.16
0	0.79	474	498	522	±6.07
10	0.77	514	538	563	±5.98
20	0.75	555	581	607	±5.89
25	0.74	577	603	629	±5.84
30	0.73	599	626	652	±5.79
40	0.71	645	672	700	±5.69
50	0.70	694	722	750	±5.59
60	0.68	744	773	801	±5.47
70	0.66	797	826	855	±5.34
80	0.64	852	882	912	±5.21
90	0.63	910	940	970	±5.06
100	0.61	970	1000	1030	±4.9
110	0.60	1029	1062	1096	±5.31
120	0.58	1089	1127	1164	±5.73
130	0.57	1152	1194	1235	±6.17
140	0.55	1216	1262	1309	±6.63
150	0.54	1282	1334	1385	±7.1
160	0.53	1350	1407	1463	±7.59
170	0.52	1420	1482	1544	±8.1
180	0.51	1492	1560	1628	±8.62
190	0.49	1566	1640	1714	±9.15
200	0.48	1641	1722	1803	±9.71
210	0.47	1719	1807	1894	±10.28
220	0.46	1798	1893	1988	±10.87
230	0.45	1879	1982	2085	±11.47
240	0.44	1962	2073	2184	±12.09
250	0.44	2046	2166	2286	±12.73
260	0.42	2132	2261	2390	±13.44
270	0.41	2219	2357	2496	±14.44
280	0.38	2304	2452	2600	±15.94
290	0.34	2384	2542	2700	±18.26
300	0.29	2456	2624	2791	±22.12

Figure 2: The temperature dependent resistance of the silicon temperature sensor installed into the sample holder.



Parameter		
Definition	**Designation**	**Value**
Electron charge	q	$1.6\ 10^{-19}$ C
Boltzmann constant	k	$1.38\ 10^{-23}$ J K^{-1}
Effective Richardson constant	A^{**}	$8.16\ 10^{4}$ A m-^{2} K^{-2}
Schottky contact diameter	D	$4\ 10^{-6}$ m
Doping concentration in the semiconductor	N_d	$4\ 10^{11}$ m^{-3}
Electron mass	m_e	$9.1\ 10^{-31}$ kg
Effective electron mass	m^*	0.043 m_e
Planck constant	h	$6.63\ 10^{-34}$ J s

Figure 3: The temperature dependent resistance of the silicon temperature sensor installed into the sample holder.

transport current within the low bias voltage range can be calculated as

$$I_{id}(V_d) \approx I_s\, exp\left(\frac{q\, V_d}{\eta\, k\, T}\right). \tag{2}$$

Thus, based on the measurement of the diode's IV curve its ideality factor and saturation current can be calculated as $\eta = q\,(a\,k\,T)^{-1}$ and $I_s = exp(b)$, respectively. The latter value is further used to calculate the zero bias current barrier height (Φ_{b0})

$$\Phi_{b0} = k\,T/q \cdot ln(A^{**} A\, T^2/I_s), \tag{3}$$

where A^{**} is the effective Richardson constant, A is the area of the Schottky contact. To account for natural lowering of the barrier height, an addend presented by the image force correction ($\Delta\Phi_{bi}$) to equation 3 can be introduced. $\Delta\Phi_{bi}$ is calculated to be ~40 meV for the n-type contacts employed [6, 7].

Making use of the η and Φ_{b0} values previously obtained, one can calculate the flat band barrier height (Φ_{bf}) of the Schottky contact as

$$\Phi_{bf} = \eta\,\Phi_{b0} - k\,T(\eta - 1)/q \cdot ln(N_c/N_d), \tag{4}$$

where N_d is the doping concentration in the semiconductor and N_c is the effective density of states in the conduction band of semiconductor employed. During the calculations we account for the temperature dependence of the latter parameter as $N_c = 2\,(2\pi m^*\, kT/h^2)^{1.5}$, where m^* is the effective electron mass and h is the Planck constant.

Beyond the low voltage range, where drop of the bias voltage on R_s can no longer be neglected, deviation of the experimental IV curve from the ideal shape can be used to calculate the series resistance value. Redistribution of voltages between the space charge region and series resistance within the PSD's layered structure can be expressed via 'real IV curve'

$$I_{re}(V_f) = I_s \left[exp \left(\frac{q \, V_j(V_f)}{\eta \, k \, T} \right) - 1 \right], \tag{5}$$

where $V_j(V_f) = V_f \, (1 - R_s / R_f(V_f))$. Here V_f is the voltage applied to the whole diode structure, V_j is the voltage incident to the space charge region and R_f is the total resistance of the diode (index 'f' denotes forward branch of the IV curve). Using R_s as a parameter to best fit the $I_{re}(V)$ function to the experimental outcome by the method of least squares, one can evaluate its actual value.

3.2 Properties of the Schottky barrier

Assuming the Gaussian distribution of the Schottky barrier height, one can define the Φ_{b0} value as [8]

$$\Phi_{b0} = \Phi_m - \sigma_s^2 \, q \, (2kT)^{-1}, \tag{6}$$

where Φ_m is the mean barrier height, which can be measured by the capacitance-voltage (CV) method, σ_s is the standard deviation of the barrier height distribution. The latter parameter is temperature dependent, namely, $\sigma_s^2(T) = \sigma_s^2(0) + \alpha_\sigma T$ [9]. In addition, it is generally stated that the flat band barrier height is basically the same as the barrier height obtained through the CV method [10, 11]. As a result, equation 6 takes the form

$$\Phi_{bf} - \Phi_{b0} = \sigma_s^2(0) \, q \, (2kT)^{-1} + \alpha_\sigma \, q \, (2k)^{-1}. \tag{7}$$

Thus, homogeneity of the Schottky barrier can be verified through comparing the Φ_{bf} and Φ_{b0} values, whose difference inversely depends on temperature. As one can notice, the slope and intercept of this linear function can be employed to define values of the standard deviation at zero temperature ($\sigma_s(0)$) and the temperature coefficient (α_σ).

3.3 Task 1

3.3.1 Measure positive branch of IV characteristics of a Schottky diode in the bias voltage range of 0 – 0.75 V with a step of 0.05 V. Please make sure that the diode's bias current does not exceed 10 mA during the measurement.

3.3.2 Repeat the measurement described hereinabove for operating temperatures of the Schottky diode of 30, 40 and 50°C.

Note: Measurement of a single IV characteristics should take not longer than 2-3 minutes, and the temperature increase rate should not exceed 1°C per minute. To achieve the latter, hotplate should be warmed up at the temperature of interest for a few minutes and further turned off during the bias voltage sweep. The temperature itself is to be measured by Si sensor as an average of the values acquired before and after the IV characteristics measurement.

3.3.3 Plot the family of IV characteristics measured at various operating temperatures of the Schottky diode in semilogarithmic scale (on a single canvas).

3.3.4 Check with a teaching fellow to complete Task 1 and to get clearance for implementing Task 2.

3.4 Task 2

3.4.1 With the aid of equations presented in section 3.1, extract values of $\eta, I_s, \Phi_{b0}, \Phi_{bf}$ from the family of temperature dependent IV characteristics. Template of the table required to present the calculations outcome is provided below.

Note: To fit experimental data, you can employ either linear regression or least square method in case of using equations 1 and 2, respectively. Choice of the software (e.g. spreadsheet, computer algebra system etc.) is up to you. Good agreement between the experimental data and the fits should be observed at mild voltages (figure 4).

3.4.2 Plot the temperature dependencies $\eta(T), \Phi_{bf}(T), \Phi_{bf}(T^{-1}) - \Phi_{b0}(T^{-1})$.

3.4.3 Using the latter dependence and with the aid of equations presented in section 3.2, evaluate mean and standard deviation of the Schottky barrier values along the metal-semiconductor interface.

Table 1: **Template of the table required to present the calculations outcome**

IV characteristics #	T [°C]	η	I_s [A]	R_s [Ω]	Φ_{b0} [eV]	Φ_{bf} [eV]
1	ambient					
2	30					
3	40					
4	50					

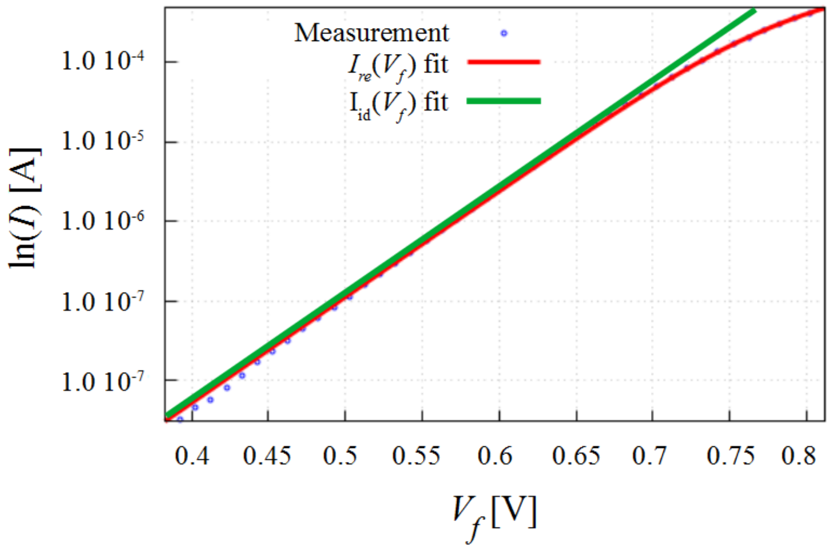


Figure 4: Example of an experimental IV characteristics of a Schottky diode along with the 'ideal' and 'real' fits.

4 Preceding Discussion Questions

1. What equipment is required to measure IV characteristics of a sample at certain temperature?
2. What is a positive branch of a diode's IV characteristics?
3. What is the maximum bias current of a Schottky diode allowed in the Lab experiments?
4. How can one measure temperature of a device under study with the aid of a Si thermometer?
5. What is the most efficient way to achieve temperature stability of a hotplate with no need to use an active feedback loop for temperature stabilization?
6. What is a laboratory autotransformer?
7. How can one convert a hotplate with discrete number of temperature regimes to a finely tunable one?
8. Please propose an experimental setup to implement the Lab tasks and provide its sketch.
9. What parameters of a Schottky diode's structure are required to evaluate values of $\eta, I_s, \Phi_{b0}, \Phi_{bf}$?
10. What should happen to a Schottky diode's transport current value, if its operating temperature is elevated and voltage applied to the diode is kept constant?

5 Defending Discussion Questions

1. What is a Schottky contact?
2. What is a difference in behavior of positive branch of a Schottky diode's IV characteristics compared to that of a p-n junction?
3. Why can one not observe perfect agreement between a Schottky diode's IV characteristics experimentally acquired and the $I_{id}(V_d)$ fit within the entire bias voltage range of 0 – 0.75 V?
4. Why can one not observe perfect agreement between a Schottky diode's IV characteristics experimentally acquired and the $I_{re}(V_f)$ fit within the entire bias voltage range of 0 – 0.75 V?
5. What happens to the saturation current value of a Schottky diode, if area of the Schottky contact is reduced by a factor of 10?
6. What happens to the zero bias current barrier height value of a Schottky diode, if area of the Schottky contact is reduced by a factor of 10?
7. What can be stated about quality of the metal/semiconductor interface in case of pronounced temperature dependence $\Phi_{bf}(T)$?
8. With the aid of a Schottky-Mott theory, evaluate value of a potential barrier arising at the Ti/GaAs interface.
9. What are the drawbacks of a planar Schottky diode technology?
10. What are the application areas of the Schottky diode based devices?

References

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