Разбалловка

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ISPhO2026

Русский

Σ 0.0
Сумма баллов

A1 0.50 Total electric charge near the junction must be equal to zero. Using this fact, write an equation connecting widths of depletion layers d_n, d_p and impurities concentrations N_a, N_d.

1	The expression for the volume charge density $\rho = \pm q_e N_{a,d}$ ($+$ for holes, $-$ for electrons) is used.	0.20	
2	The correct answer is obtained: $N_a d_p = N_d d_n$.	0.30	

A2 0.50 Show that the following equation holds for electric field

$$\frac{dE_x}{dx} = \frac{\rho}{\varepsilon_0 \varepsilon},$$

where ρ – volume charge density in the corresponding point.

1	Gauss's law is used (either for a small volume between the planes at x and $x + \Delta x$, or in the differential form).	0.50	

A3 1.00 Find the electric field $E_x(x)$ as a function of x. Assume that far from junction the field is equal to 0. Express the answer in terms of N_a, N_d, d_n, d_p, ε, ε_0 and q_e.

1	The expression $\rho = \pm q_e N_{a,d}$ is used.	0.10	
2	It is used that $E_x(x) = \int \frac{dE_x}{dx} \mathrm{d}x$ up to a constant of integration.	0.20	
3	The correct dependence $E_x(x) = 0$ for $x \in (-\infty; -d_p) \cup (d_n; +\infty)$ is obtained.	0.20	
4	The correct dependence $E_x(x) = -\frac{q_e N_a (x + d_p)}{\varepsilon_0 \varepsilon}$ for $x \in [-d_p, 0]$ is obtained.	0.25	
5	The obtained dependence $E_x(x)$ for $x \in [-d_p, 0]$ differs from the correct one by a constant shift in x and/or by a numerical scaling factor.	0.15	
6	The correct dependence $E_x(x) = \frac{q_e N_d (x - d_n)}{\varepsilon_0 \varepsilon}$ for $x \in (0, d_n]$ is obtained.	0.25	
7	The obtained dependence $E_x(x)$ for $x \in (0, d_n]$ differs from the correct one by a constant shift in x and/or by a numerical scaling factor.	0.15	

A4 1.00 Find the electrostatic potential $\varphi(x)$ as a function of x. Assume that $\varphi(0) = 0$. Express the answer in terms of N_a, N_d, d_n, d_p, ε, ε_0 and q_e. Determine the potential difference at large distance to the junction $\Delta\varphi = \varphi(x = +\infty) - \varphi(x = -\infty)$.

1 The relation $\varphi'(x) = -E_x(x)$ is used.	0.20	
2 For each of the intervals: $\{x < -d_p\}$, $\{-d_p \le x < 0\}$, $\{0 \le x < d_n\}$, and $\{x \ge d_n\}$, the obtained dependence $\varphi(x)$ differs from the correct one by an additive constant and/or by a numerical scaling factor (0.1 points for each interval).	4 × 0.10	0
3 The correct dependence $\varphi(x)$ is obtained for all x: $$\varphi(x) = \begin{cases} -\frac{q_e N_a d_p^2}{2\varepsilon_0\varepsilon}, & x < -d_p, \\ \frac{q_e N_a (x^2 + 2d_p x)}{2\varepsilon_0\varepsilon}, & x \in [-d_p, 0), \\ \frac{q_e N_d (2d_n x - x^2)}{2\varepsilon_0\varepsilon}, & x \in [0, d_n), \\ \frac{q_e N_d d_n^2}{2\varepsilon_0\varepsilon}, & x \ge d_n. \end{cases}$$	0.20	
4 The correct expression for the potential difference is obtained: $\Delta\varphi = \frac{q_e(N_a d_p^2 + N_d d_n^2)}{2\varepsilon\varepsilon_0}$.	0.20	

A5 0.50 Draw a qualitative plot of the potential $\varphi(x)$ as function of x.

1 The plot passes through the point with coordinates $(0, 0)$.	0.10	
2 The plot exhibits a strictly monotonic increase over the range $-d_p \le x \le d_n$.	0.20	
3 The plot has a zero slope over the range $x \ge d_n$.	0.10	
4 The plot has a zero slope over the range $x \le -d_p$.	0.10	

A6 1.00 Actually, the potential difference is determined by the material properties and the temperature. Knowing the potential difference, one can calculate depletion layers widths. Express the widths d_n, d_p in terms of $\Delta\varphi$, N_a, N_d, ε, ε_0 and q_e. Calculate their numerical values for $\Delta\varphi = 0.8\ \mathrm{V}$.

1 The relation $N_a d_p = N_d d_n$ from part A1 is used.	0.20	
2 The correct answer is obtained: $d_p = \sqrt{\frac{2\varepsilon\varepsilon_0 \Delta\varphi N_d}{q_e N_a (N_a + N_d)}}$.	0.20	
3 The correct numerical value is computed: $d_p \approx 58.7\ \mathrm{nm}$.	0.20	
4 The correct answer is obtained: $d_n = \sqrt{\frac{2\varepsilon\varepsilon_0 \Delta\varphi N_a}{q_e N_d (N_a + N_d)}}$.	0.20	
5 The correct numerical value is computed: $d_n \approx 117.5\ \mathrm{nm}$.	0.20	

A7 0.50 Determine the maximum value of the electric field in the junction $E_{\max}$. Express the answer in terms of $\Delta\varphi$, N_a, N_d, ε, ε_0 and q_e. Calculate its numerical value for $\Delta\varphi = 0.8\ \mathrm{V}$.

1 It is noted or used that $\lvert E_x(x)\rvert$ attains its maximum value at $x = 0$.	0.10	
2 The correct answer is obtained: $E_{\max} = \sqrt{\frac{2q_e \Delta\varphi N_a N_d}{\varepsilon\varepsilon_0 (N_a + N_d)}}$.	0.20	
3 The correct numerical value is computed: $E_{\max} \approx 9.08 \cdot 10^6\ \mathrm{V/m}$.	0.20	

B1 0.50 Let n_{10} denote the concentration of electrons in p-type semiconductor without external voltage. Similarly let p_{10} denote the concentration of holes in n-type semiconductor without external voltage. Determine electron concentration n_1 in p-type semiconductor and hole concentration p_1 in n-type semiconductor after the voltage V is applied. Consider region outside of depletion layers, where electric field is zero. Express the answers in terms of p_{10}, n_{10}, V, T, k and q_e.

1 The correct answer is obtained: $n_1 = n_{10} \cdot \exp\left(\frac{q_e V}{kT}\right)$.	0.25	

2 The correct answer is obtained: $p_1 = p_{10} \cdot \exp\left(\frac{q_e V}{kT}\right)$.	0.25	

B2 1.00 Consider the volume between the planes with coordinates x and $x + \Delta x$ (Fig. 3). Write down the condition that the holes concentration in this volume does not change. Take into account the holes flux through the two planes and holes recombination. In the limit $\Delta x \to 0$ obtain a differential equation for the concentration deviation from equilibrium value $\Delta p = p_1 - p_{10}$ as a function of x. The answer may also include D_p and τ_p.

1 The rate of change in the number of holes within the volume under consideration due to recombination is determined or otherwise taken into account.	0.10	
2 The rate of change in the number of holes within the volume under consideration due to diffusion through the plane is determined or otherwise taken into account (0.1 points for each of the two planes).	2 × 0.10	0
3 The condition of a constant particle concentration within the considered volume is written correctly.	0.30	
4 The differential equation $\frac{d^2 \Delta p}{dx^2} = \frac{\Delta p}{\tau_p D_p}$ is obtained. 5 The correct equation is obtained, but its expression includes either p_1 or p_{10}.	0.40 0.30	

B3 0.60 Find the distance L_p, over which the deviation of holes concentration from equilibrium decreases by e times. Express the answer in terms of D_p, τ_p. Compute numerical value for $D_p = 1.0 \cdot 10^{-3}\ \mathrm{m}^2/\mathrm{s}$, $\tau_p = 5.0 \cdot 10^{-7}\ \mathrm{s}$.

1 The solution of the differential equation from part B2 is found in the form $\Delta p = a \exp\left(-\frac{x}{\sqrt{\tau_p D_p}}\right) + b \exp\left(\frac{x}{\sqrt{\tau_p D_p}}\right)$.	0.20	
2 It is shown or used that $b = 0$.	0.10	
3 The correct answer is obtained: $L_p = \sqrt{\tau_p D_p}$.	0.20	
4 The correct numerical value is computed: $L_p \approx 2.24 \cdot 10^{-5}\ \mathrm{m}$.	0.10	

B4 0.80 Determine the hole concentration $p_1(x)$ in region $x > d_n$ as a function of coordinate (in n-type semiconductor outside of the depletion layer). Express the answer in terms of p_{10}, V, T, L_p, d_n, k and q_e.

1 The general form of the dependence $p_1(x) = p_{10} + a \exp\left(-\frac{x}{L_p}\right)$ for $x > d_n$ is obtained.	0.10	
2 To find $p_1(d_n)$, the result of part B1 is used.	0.20	
3 The relation $\frac{p_1(d_n)}{N_a} = \exp\left(\frac{q_e V}{kT}\right) \frac{p_{10}}{N_a}$ or an equivalent one is obtained.	0.20	
4 The correct answer is obtained: $p_1(x) = p_{10} + p_{10}\left(\exp\left(\frac{q_e V}{kT}\right) - 1\right) \exp\left(-\frac{x - d_n}{L_p}\right)$. 5 The answer differs from the correct one by a shift of d_n in x.	0.30 0.20	

B5 0.80 Determine the density of hole diffusion current j_p at the boundary of depletion layer $x = d_n$. Express the answer in terms of p_{10}, V, L_p, D_p, T, k and q_e.

1 The relation $J_p = -D_p \frac{dp_1}{dx}$ is used.	0.20	
2 The derivative of the dependence $p_1(x)$ from part B4 is correctly found.	0.20	
3 The relation $j_p = q_e J_p$ is used.	0.20	

4	The correct answer is obtained: $$j_p = \frac{q_e D_p p_{10}}{L_p}\left(\exp\left(\frac{q_e V}{kT}\right) - 1\right).$$	0.20	

B6 0.80 The junction cross section area is A. Derive the expression for the total current I through the junction as a function of applied voltage V, semiconductor parameters N_a, N_d, τ_p, τ_n, D_p, D_n, n_i and constants k, q_e.

1	The expression for j_n is obtained by replacing D_p with D_n, and L_p with L_n.	0.20	
2	It is used that $j = j_p + j_n$.	0.20	
3	It is used that $I = jA$.	0.20	
4	The correct answer is obtained: $$I = q_e A n_i^2 \left(\exp\left(\frac{q_e V}{kT}\right) - 1\right)\left(\frac{1}{N_d}\sqrt{\frac{D_p}{\tau_p}} + \frac{1}{N_a}\sqrt{\frac{D_n}{\tau_n}}\right).$$	0.20	

B7 0.30 Draw a qualitative plot of the relation $I(V)$, obtained in previous task.

1	The plot is strictly monotonically increasing.	0.10	
2	The plot is strictly convex downward.	0.10	
3	The plot approaches a horizontal asymptote as as $x \to -\infty$.	0.10	

B8 0.20 Calculate the numerical values of the saturation current I_∞ at large negative voltage, and the value of current I_1 for $V = 0.7\ \mathrm{V}$.

1	The correct numerical value is computed: $I_\infty = 5.77 \cdot 10^{-16}\ \mathrm{A}$.	0.10	
2	The correct numerical value is computed: $I_1 = 3.23 \cdot 10^{-4}\ \mathrm{A}$.	0.10	