O‘ZBEKISTON RESPUBLIKASI

OLIY TA’LIM, FAN VA INNOVATSIYALAR VAZIRLIGI

FARG‘ONA DAVLAT UNIVERSITETI

FarDU. ILMIY XABARLAR

1995-yildan nashr etiladi
Yilda 6 marta chiqadi

5-2025
ANIQ FANLAR

НАУЧНЫЙ ВЕСТНИК. ФерГУ

Издаётся с 1995 года
Выходит 6 раз в год

MUNDARIJA

FIZIKA-TEXNIKA

FarDU. Ilmiy xabarlar – Scientific journal of the Fergana State University

Volume 31 Issue 5, 2025-yil DOI: 10.56292/SJFSU/vol31_iss5/a162

UO'K: 621.381.3

DIODNING VOLT–AMPER XARAKTERISTIKASI

ВОЛЬТ–АМПЕРНАЯ ХАРАКТЕРИСТИКА ДИОДА

CURRENT–VOLTAGE CHARACTERISTIC OF THE DIODE

Mamatova Mahliyo Adhamovna[1]
[1]Doctor of Philosophy (PhD) in Physics and Mathematics, Fergana State University

Yusupova Mahliyo Shavkatjon qizi[2]
[2]Master's Degree in Physics, Fergana State University

Annotatsiya

Maqolada yarimo'tkazgich diodlarning volt–amper xarakteristikasi chuqur tahlil qilingan. Diffuziya tenglamalari va tegishli chegaraviy shartlardan foydalanib, yupqa va qalin baza qatlamlari uchun zaryad tashuvchilar konsentratsiyasi hamda tok zichliklarining analitik ifodalari hosil qilindi. Tadqiqotda termik tokning roli alohida ko'rib chiqildi. U xususiy tashuvchilar konsentratsiyasiga kuchli bog'liq bo'lib, kremniy va germaniy diodlari orasida sezilarli farq qiladi. Natijada ushbu diodlarning to'g'ri o'tkazish kuchlanishlari orasidagi farq odatda 0,3–0,4 V ni tashkil etishi isbotlandi va bu jarayonning fizik mexanizmlari tushuntirildi. Shuningdek, emitter va bazaning xususiy qarshiliklari orqali ifodalangan injeksiya koeffitsienti kiritilib, tok o'tish jarayonining yanada aniq tavsifi berildi. Olingan natijalar diodlarning ishlashini chuqurroq tushunishga yordam beradi va ularning elektronika amaliyotidagi samaradorligini oshirish uchun mustahkam nazariy asos yaratadi.

Аннотация

В статье представлен всесторонний анализ вольт–амперной характеристики полупроводниковых диодов. С использованием уравнений диффузии и соответствующих граничных условий получены аналитические выражения для концентрации носителей и плотности токов как для тонкого, так и для толстого базового слоя. Особое внимание уделено термическому току, величина которого существенно зависит от собственной концентрации носителей и значительно различается у кремниевых и германиевых диодов. В исследовании показано смещение прямого напряжения примерно на 0,3–0,4 В между этими типами диодов и раскрыты соответствующие физические механизмы. Введение коэффициента инжекции через удельные сопротивления базы и эмиттера уточняет описание процессов проводимости. Полученные результаты способствуют более глубокому пониманию работы диодов и создают надежную теоретическую основу для оптимизации их характеристик в электронных приложениях.

Abstract

This article presents a comprehensive analysis of the current–voltage (I–V) characteristic of semiconductor diodes. Using diffusion equations and appropriate boundary conditions, analytical expressions for carrier concentrations and current densities are derived for both thin- and thick-base approximations. Special attention is given to the role of thermal current, which is highly dependent on intrinsic carrier concentration and differs significantly between silicon- and germanium-based diodes. The study highlights the forward voltage shift of approximately 0.3–0.4 V between these diode types and explains the underlying physical mechanisms. The introduction of the injection coefficient through specific resistances of the base and emitter further refines the description of current flow. The results contribute to a deeper understanding of diode operation and provide a solid theoretical foundation for optimizing their performance in electronic applications.

Kalit so'zlar: *yarimo'tkazgich diod, volt–amper xarakteristika, diffuziya, termik tok, injeksiya koeffitsienti*

Ключевые слова: *полупроводниковый диод, вольт–амперная характеристика, диффузия, термический ток, коэффициент инжекции*

Key words: *semiconductor diode, current–voltage characteristic, diffusion, thermal current, injection coefficient*

INTRODUCTION

The current–voltage (I–V) characteristic of a semiconductor diode represents one of the fundamental dependencies in solid-state electronics and serves as the basis for understanding the physical mechanisms governing charge transport across the p–n junction. The analysis of the diode's static volt–ampere characteristics not only provides insights into the distribution of charge carriers in the base and emitter regions but also forms the foundation for practical device modeling and design.

The formation of the I–V characteristic is directly related to the steady-state distribution of minority and majority carriers, which can be described through diffusion equations and corresponding boundary conditions. Depending on the thickness of the base layer, approximations such as thin-base or thick-base conditions are employed, resulting in simplified analytical solutions for the carrier concentration profiles. These solutions demonstrate that in real diodes the carrier distribution may be exponential or nearly linear, leading to distinct forms of current flow through the device.

In this work, the diode's current–voltage characteristic is systematically derived on the basis of diffusion theory, boundary conditions, and carrier injection analysis. Special attention is given to the differences between germanium- and silicon-based diodes, highlighting the influence of material parameters on thermal current, forward voltage shift, and overall device performance.

LITERATURE REVIEW AND METHODOLOGY

To determine the static current–voltage characteristic of a diode, it is necessary to calculate the stationary distribution of electrons in the base region. In addressing this problem, the general diffusion equation, which describes the steady-state distribution of electron concentration, is employed. By setting the time-dependent derivative of this equation equal to zero ($\frac{\partial \Delta n}{\partial t} = 0$), the following stationary form of the equation is obtained:

$$\frac{d^2\Delta n}{dx^2} - \frac{\Delta n}{L^2} = 0$$

The general solution of this equation is expressed in the form of a sum of exponentials:

$$\Delta n(x) = A_1 e^{\frac{x}{L}} + A_2 e^{-\frac{x}{L}}$$

Here, the coefficients A_1 and A_2 are determined from the boundary conditions. Denoting the base thickness by w, the following boundary condition is satisfied at the point $x = w$:

$$\Delta n(x = w) = 0$$

In the ohmic contact region, the concentration of charge carriers remains at the equilibrium value regardless of the concentration distribution in the base. The physical essence of this condition lies in the fact that, within the contact zone, the boundary value of the carrier concentration consistently maintains the equilibrium state.

To fully specify the boundary conditions, we now choose the coordinate $x = 0$. Taking into account the assumption described in Section 3 and the expression, the concentration value at the boundary—determined by the applied external voltage—can be written in the following form through $\Delta n(x = 0)$:

$$\Delta n(0) = n_0\left(e^{\frac{U}{\varphi t}} - 1\right).$$

Based on the boundary conditions, the values of the coefficients A_1 and A_2 are determined as follows:

$$A_1 = -\frac{\Delta n(0)}{2sh\left(\frac{w}{L}\right)} e^{-\frac{w}{L}}; \qquad A_1 = -\frac{\Delta n(0)}{2sh\left(\frac{w}{L}\right)} e^{\frac{w}{L}}$$

As a result, $\Delta n(x)$ takes the following form:

$$\Delta n(x) = n_0\left(e^{\frac{U}{\varphi t}} - 1\right)\frac{sh\left(\frac{w-x}{L}\right)}{sh\left(\frac{w}{L}\right)}$$

If the base layer has a sufficiently large thickness, i.e., the condition $w > (2 \div 3)L$ is satisfied, then for the purpose of simplifying the calculations, the base thickness may be assumed infinite ($w \to \infty$). Under this boundary condition, the coefficients A_1 and A_2 are simplified as follows:

$$A_1 = 0; A_2 = \Delta n(0)$$

As a result, the electron concentration in the base takes the following simplified exponential form:

$$\Delta n(x) = n_0\left(e^{\frac{U}{\varphi t}} - 1\right) e^{-\frac{w}{L}}$$

If the base is thin, i.e., the condition $w < 0.5L$ is satisfied, the hyperbolic sine functions in formula can be approximately simplified for small arguments as follows:

$$sh\left(\frac{w-x}{L}\right) \approx \frac{w-x}{L}; \quad sh\left(\frac{w}{L}\right) \approx \frac{w}{L}$$

In this case, due to the thinness of the base and the dominance of diffusion processes, the distribution of electrons becomes nearly linear. As a result, the electron concentration in the base takes the following linear form:

$$\Delta n(0) = n_0\left(e^{\frac{U}{\varphi t}} - 1\right) * \left(1 - \frac{x}{w}\right). \quad (1)$$

Such a distribution is characteristic of real diodes. Below, we derive the analytical relation describing the current–voltage characteristic of the diode. In the general case, the electric current consists of the sum of electron and hole flows, and the current density can be written in the following form:

$$j(x) = j_n(x) + j_p(x) \quad (2)$$

Here, $j_n(x)$ denotes the distribution of the electron current density in the base, while $j_p(x)$ represents the distribution of the hole current density in the emitter. By differentiating expression (2) with respect to the x -coordinate and substituting the result into expression, we obtain the following relation for the distribution of the electron current density in the base, $j_n(x)$:

$$j_n(x) = -\frac{qD_{пб}}{L_{пб}}\left(e^{\frac{U}{\varphi t}} - 1\right)\frac{ch\left(\frac{w_б - x}{L_{пб}}\right)}{sh\left(\frac{w_э}{L_{pэ}}\right)} \quad (3)$$

RESULTS AND DISCUSSION

To improve accuracy, the corresponding indices for the base layer and electrons have been introduced into the above expression. Based on the same approach, the following expression can be written for the hole current density in the emitter layer:

$$j_p(x) = -\frac{qD_{pэ}}{L_{pэ}}\left(e^{\frac{U}{\varphi t}} - 1\right)\frac{ch\left(\frac{w_э - x}{L_{пб}}\right)}{sh\left(\frac{w_э}{L_{pэ}}\right)} \quad (4)$$

Here, $L_{pэ}$ denotes the diffusion length of holes in the emitter, while the x -coordinate is measured inward from the boundary into the emitter. In expressions (4), by setting $x = 0$ and multiplying both sides by the surface area S, we then add the resulting currents $J_n(0)$ and $J_p(0)$. In this way, we obtain the current–voltage characteristic of an idealized diode:

$$J = J_0\left(e^{\frac{U}{\varphi t}} - 1\right). \quad (5)$$

Here

$$J_0 = \frac{qD_{пб}S}{L_{пб}th\left(\frac{w_б}{L_{пб}}\right)}n_{0б} + \frac{qD_{pэ}S}{L_{pэ}th\left(\frac{w_э}{L_{pэ}}\right)}p_{0б}$$

The current J_0 is also referred to as the "thermal current," since its magnitude strongly depends on temperature. In addition, this current is often termed the "saturation reverse current," because under reverse bias conditions (i.e., $|U| \gg \varphi_T$), the reverse current of the idealized diode is exactly equal to $-J_0$ and remains constant, independent of the applied voltage. The static current–voltage characteristic of the idealized diode is shown in Fig. 3.1.

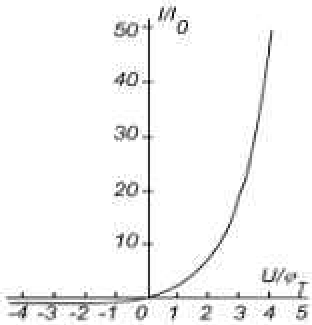

Fig. 1. Static current–voltage characteristic of the idealized diode.

We now introduce the concept of the injection coefficient. This parameter makes it possible to evaluate the relative contribution of the principal current component associated with electrons in the diode. It is defined as follows:

$$\gamma = \frac{J_n(0)}{J_p(0)+J_n(0)} = \frac{J_n(0)}{J(0)}. \quad (6)$$

For the purpose of simplifying subsequent analyses and ensuring convenience, the injection coefficient can be expressed in terms of the specific resistances of the emitter and the base. In this case, it takes the following form:

$$\gamma \approx 1 - \frac{\rho_э}{\rho_б} \quad (7)$$

For this purpose, it is necessary to apply expressions (6) at $x = 0$, subsequently transforming from diffusion coefficients to mobilities, from the concentrations of minority carriers to those of majority carriers, and then to specific resistances. As can be observed, in a unidirectional transition the electron current plays the dominant role. Therefore, the first term in equation (7) may be neglected, and the thermal current is expressed as follows:

$$J_0 = q\frac{DS}{Lth\left(\frac{w}{L}\right)}n_0 \quad (8)$$

In particular, when the base is thin, i.e., $w \ll L$ and $th\left(\frac{w}{L}\right) \approx \frac{w}{L}$, the following simplified expression can be obtained:

$$J_0 = q\frac{DS}{w}n_0\,. \quad (9)$$

If the base is "thick," i.e., $w \ll L$ and $th\left(\frac{w}{L}\right) \approx 1$, the thermal current takes the following form:

$$J_0 = q\frac{DS}{L}n_0 \quad (10)$$

Since the equilibrium concentration n_0 is proportional to n_i^2 (the square of the intrinsic carrier concentration), the value of n_i in silicon is significantly smaller compared to that in germanium. Therefore, the thermal current in silicon-based diodes is considerably lower than in germanium-based diodes. One of the key features of the characteristic (9) is its extremely steep (exponential) form in the forward direction. As a result, in semiconductor diodes, large forward currents—on the order of several amperes or higher—can be achieved at small voltages not exceeding 1 V. Due to the very steep slope of the forward branch, it is often more convenient to rewrite expression (9) in the following form:

$$U = \varphi_T \ln\left(\frac{J}{J_0} + 1\right) \quad (11)$$

It follows from this expression that the forward conduction voltages of silicon-based diodes are considerably higher than those of germanium-based diodes. This effect is associated with the fact that the thermal current in silicon diodes is several orders of magnitude smaller. As a result, the difference in forward conduction voltages between germanium- and silicon-based diodes is typically around 0.3–0.4 V. Therefore, when the current–voltage characteristics of both types of diodes are plotted on the same absolute scale along the current axis, their appearance (Fig. 1) differs significantly: the characteristic of a silicon-based diode appears "shifted" along the voltage axis by several tenths of a volt compared to that of a germanium-based diode.

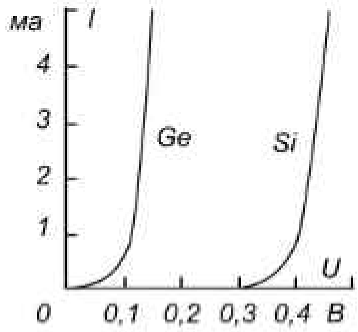

Fig. 2. Current–voltage characteristics of germanium- and silicon-based diodes.

CONCLUSION

The study of the current–voltage characteristic of semiconductor diodes provides a comprehensive understanding of the physical processes underlying carrier transport across the p–n junction. By employing diffusion equations and boundary conditions, analytical expressions for carrier concentrations and current densities were derived for both thin- and thick-base approximations. These results confirm that the carrier distribution in real diodes may exhibit exponential or nearly linear behavior, which directly affects the form of the I–V curve.

Furthermore, the introduction of the injection coefficient, expressed through the specific resistances of the base and emitter, allowed for a more accurate description of the relative contributions of electron and hole currents to the total conduction process. This approach strengthens the theoretical framework and aligns well with experimental observations.

In conclusion, the results emphasize that the diode's I–V characteristic is not only a fundamental descriptor of device behavior but also a sensitive indicator of material properties and design parameters. Understanding these relationships is essential for optimizing diode performance in modern electronic applications.

REFERENCES

1. Sze, S. M., & Ng, K. K. Physics of Semiconductor Devices. 3rd ed. Hoboken: Wiley-Interscience, 2007. – 815 p.
2. Streetman, B. G., & Banerjee, S. Solid State Electronic Devices. 7th ed. Pearson Education, 2016. – 602 p.
3. Neamen, D. A. Semiconductor Physics and Devices: Basic Principles. 5th ed. New York: McGraw-Hill, 2012. – 762 p.
4. Pierret, R. F. Semiconductor Device Fundamentals. Addison-Wesley Publishing Company, 1996. – 792 p.