



THEORETICAL MODELING OF THE COMBINED EFFECTS OF LIGHT AND MECHANICAL DEFORMATION ON THE CURRENT–VOLTAGE CHARACTERISTICS OF p–n JUNCTION DIODES

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Abstract. The influence of external physical factors on the electrical characteristics of semiconductor devices is an important problem in modern semiconductor physics, optoelectronics, sensor technology, and microelectronics. This study investigates the effects of illumination and mechanical deformation on the current–voltage (I – V) characteristics of a p–n junction diode using theoretical analysis and mathematical modeling. The physical mechanisms of carrier generation, recombination, drift and diffusion transport, deformation-induced modification of energy bands, carrier mobility, and saturation current are considered. Particular attention is given to the separate and combined effects of optical radiation and mechanical strain. A modified Shockley model incorporating deformation-dependent saturation current is developed. For small deformation, the saturation current is represented as a function of strain, while the photocurrent is considered dependent on light intensity, deformation, and time. On this basis, a generalized mathematical model of the form $I = I(V, t, \Phi, \epsilon)$ is proposed. The model makes it possible to describe both static and dynamic changes in the current–voltage characteristics under simultaneous optical and mechanical influences. The theoretical analysis demonstrates that illumination primarily changes the photocurrent and shifts the I –

Keywords: p–n junction diode, current–voltage characteristic, illumination, mechanical deformation, photocurrent, Shockley model, carrier mobility, saturation current, semiconductor sensor, mathematical modeling.

Annotatsiya. Mazkur maqolada p–n o‘tishli diodning volt-ampere xarakteristikasiga yorug‘lik va mexanik deformatsiyaning alohida hamda birgalikdagi ta‘hiri nazariy jihatdan tadqiq etiladi. Yorug‘lik ta‘sirida fotogeneratsiya, elektron-kovak juftlarining hosil bo‘lishi, rekombinatsiya va fototok shakllanish jarayonlari tahlil qilinadi. Mexanik deformatsiyaning kristall panjara parametrlari, energetik zonalar, taqiqlangan zona kengligi, zaryad tashuvchilar harakatchanligi, drift va diffuziya toklariga ta‘hiri ko‘rib chiqiladi. Deformatsiya ta‘sirida to‘yinish tokining o‘zgarishini hisobga oluvchi modifikatsiyalangan Shockley modeli taklif etiladi. Yorug‘lik intensivligi, deformatsiya va vaqt omillarini birgalikda hisobga oluvchi umumlashgan $I = I(V, t, \Phi, \epsilon)$ modeli ishlab chiqiladi. Nazariy tahlil natijalari yorug‘likning asosan fototokni o‘zgartirishi va volt-ampere xarakteristikasini manfiy toklar sohasi tomon

siljitishini, deformatsiya esa energetik zonalar, tashuvchilar harakatchanligi va to‘yinish toki orqali xarakteristikaning qiyaligi va amplitudasiga ta’sir qilishini ko‘rsatadi.

Kalit so‘zlar: p–n o‘tishli diod, volt-amper xarakteristika, yorug‘lik, mexanik deformatsiya, fototok, Shockley modeli, zaryad tashuvchilar harakatchanligi, to‘yinish toki, yarimo‘tkazgichli sensor, matematik modellashtirish.

INTRODUCTION

Semiconductor p–n junctions constitute one of the fundamental elements of modern electronic, optoelectronic and sensing systems. Their rectifying properties and sensitivity to external physical factors make them suitable for a wide range of applications, including photodiodes, solar cells, optical receivers, semiconductor sensors, switching elements and automated control systems. The electrical behavior of a p–n junction is determined by charge-carrier generation, recombination, drift and diffusion processes. Consequently, any external factor capable of modifying carrier concentration, mobility or energy-band parameters may lead to measurable changes in the current–voltage characteristic.

The classical theory of p–n junctions was developed by W. Shockley and subsequently extended through systematic studies of semiconductor-device physics. The Shockley equation provides a fundamental description of the current–voltage behavior of an ideal diode and establishes a relationship between the applied voltage, saturation current, temperature and charge-carrier transport. Later developments in semiconductor physics demonstrated that the parameters entering this relationship may vary under optical, thermal, electrical and mechanical influences.

Illumination is particularly important because photons with sufficient energy can generate electron–hole pairs in a semiconductor. The additional carriers contribute to the current flowing through the junction and produce a photocurrent. The physical principles of photogeneration, recombination, quasi-Fermi-level splitting and photovoltaic response form the basis of photodiodes and solar cells. Under illumination, the current–voltage characteristic of a p–n junction therefore differs from the characteristic obtained under dark conditions.

Mechanical deformation represents another important external factor. Strain modifies the crystal lattice and may consequently affect the energy-band structure, bandgap, effective masses, carrier mobility and diffusion parameters. Such effects have become particularly important in strain-engineered semiconductor devices and flexible electronics. Studies of strained silicon have shown that mechanical deformation can be employed to control carrier transport and improve the performance of semiconductor devices. The importance of studying these effects simultaneously is related to the fact that practical semiconductor devices frequently operate under several external influences at the same time. Photovoltaic devices, optical sensors, flexible electronics and semiconductor structures used in aerospace or industrial environments may experience optical radiation and mechanical loading simultaneously. Therefore, considering only one external factor may not adequately describe the behavior of a real device.

2. MATERIALS AND METHODS

2.1. Physical model of the p–n junction. When p-type and n-type semiconductor regions are brought into contact, electrons from the n-region diffuse toward the p-region, while holes from the p-region diffuse toward the n-region. As a result, a depletion region containing ionized donor and acceptor centers is formed near the interface. The redistribution of charge produces an internal electric field and a potential barrier that oppose further diffusion of the majority carriers. The current through the junction is determined by two fundamental transport mechanisms: drift and diffusion. Drift current is associated with the movement of charge carriers under the action of an electric field, whereas diffusion current arises from gradients in carrier concentration. The total current may therefore be represented schematically as $J = J_{dr} + J_{dif}$. For electrons and holes, the drift-current densities can be expressed as $J_n = q\mu_n nE$, $J_p = q\mu_p pE$, where q is the elementary charge, μ_n and μ_p are the electron and hole mobilities, n and p are the carrier concentrations, and E is the electric field. The diffusion contribution depends on concentration gradients and diffusion coefficients. According to the Einstein relationship, $D_n = (kT/q)\mu_n$, $D_p = (kT/q)\mu_p$, where D_n and D_p are the electron and hole diffusion coefficients, k is the Boltzmann constant and T is absolute temperature. These relationships are important for the present model because mechanical deformation may modify both μ and D .

2.2. Shockley model.

The saturation current depends on semiconductor parameters and charge-carrier transport. In a simplified form it can be associated with diffusion coefficients, diffusion lengths and doping concentrations:

$I_s \propto qA n_i^2 \left(\frac{D_n}{L_n N_A} + \frac{D_p}{L_p N_D} \right)$, where A is the junction area, n_i is the intrinsic carrier concentration, L_n and L_p are diffusion lengths, and N_A and N_D are acceptor and donor concentrations.

Thus, any external influence that modifies n_i , D_n , D_p , L_n , L_p , or the energy-band structure can indirectly modify the saturation current.

2.3. Optical generation and photocurrent. When a semiconductor absorbs photons with sufficient energy, electron–hole pairs are generated. The generation rate can be represented in simplified form as $G = \alpha\Phi$, where α is the optical absorption coefficient and Φ is the incident photon flux or a quantity proportional to illumination intensity. The generated carriers undergo transport and recombination. If the excess carrier concentration is denoted by Δn , its time-dependent behavior can be represented by $\frac{d\Delta n}{dt} = G - \frac{\Delta n}{\tau}$, where τ is the effective carrier lifetime. For constant illumination and an initially equilibrium semiconductor, the solution has the form $\Delta n(t) = G\tau(1 - e^{-(t/\tau)})$.

Consequently, the photocurrent can be expressed in a corresponding dynamic form:

$I_{ph}(t) = I_{ph,\infty} (1 - e^{-(t/\tau)})$. This relationship explains why the electrical response of an illuminated p–n junction can be time-dependent immediately after the light is applied.

The current under illumination can therefore be represented generally as

$I = I_s [\exp(\frac{qV}{nkT}) - 1] - I_{ph}$. $I = I_s [\exp(\frac{qV}{nkT}) - 1] - I_{ph}$. The sign convention reflects the fact that photocurrent shifts the diode characteristic toward the negative-current region, as demonstrated by the theoretical modeling presented in the dissertation.

3. RESULTS

3.1. Deformation-dependent Shockley model. The theoretical analysis demonstrates that the saturation current cannot always be regarded as a constant when mechanical deformation is present. Because deformation changes both the energy-band structure and transport parameters, the saturation current becomes a function of strain: $I_s = I_s(\varepsilon)$. The Shockley equation can consequently be modified as $I(V, \varepsilon) = I_s(\varepsilon) [\exp(\frac{qV}{nkT}) - 1]$. $I(V, \varepsilon) = I_s(\varepsilon) [\exp(\frac{qV}{nkT}) - 1]$. For small deformation, the dissertation proposes the approximation $I_s(\varepsilon) = I_{s0}(1 + \gamma\varepsilon)$ where I_{s0} is the saturation current in the undeformed state and γ represents the deformation sensitivity of the saturation current.

The resulting relationship becomes $I(V, \varepsilon) = I_{s0}(1 + \gamma\varepsilon) [\exp(\frac{qV}{nkT}) - 1]$. $I(V, \varepsilon) = I_{s0}(1 + \gamma\varepsilon) [\exp(\frac{qV}{nkT}) - 1]$. This form provides a relatively simple way of evaluating the influence of strain on the current–voltage characteristic and can also be adapted to experimental data. The theoretical analysis in the dissertation indicates that tensile deformation and compressive deformation may produce different changes in the saturation current. In the adopted model, increasing tensile deformation is associated with an increase in saturation current and consequently with an increase in the total diode current, whereas compressive deformation produces the opposite tendency under the assumed parameter conditions.

3.2. Influence of deformation on drift and diffusion currents. The influence of deformation becomes particularly apparent when the current is analyzed in terms of its transport components. For drift current, $J_{dr} = q\mu nE$. If $\mu(\varepsilon) = \mu_0(1 + \beta\varepsilon)$, then, under a first-order approximation, $J_{dr}(\varepsilon) = J_{dr0}(1 + \beta\varepsilon)$. Consequently, an increase in carrier mobility produces an increase in the drift-current contribution. The diffusion coefficient changes simultaneously: $D(\varepsilon) = (kT/q)\mu(\varepsilon)$. Therefore, diffusion current also becomes deformation-dependent.

The dissertation emphasizes that the effect is not restricted to mobility. Because deformation can modify the bandgap, $E_g = E_g(\varepsilon)$

the intrinsic carrier concentration changes as well. This produces an additional contribution to the deformation dependence of the transport current.

The combined effect can therefore be represented by $J = J_{dr}(\varepsilon) + J_{dif}(\varepsilon)$

Under illumination, the generated carrier concentration is additionally time-dependent. The generalized transport relationship consequently becomes

$$J = J(t, \Phi, \varepsilon)$$

4. DISCUSSION

The theoretical results demonstrate that a p–n junction diode should be regarded as a multiparameter physical system rather than as a device whose current depends exclusively on applied voltage. The classical Shockley model remains a fundamental starting point because it establishes the relationship between voltage and current under equilibrium or near-equilibrium conditions. However, when external influences are introduced, several of its parameters

become functions of those external variables. Under illumination, the dominant additional process is photogeneration. The incident radiation produces electron–hole pairs and changes the carrier populations. The resulting photocurrent modifies the I–V characteristic. This mechanism is fundamental to photodiodes and solar cells and has been extensively discussed in semiconductor optoelectronics. Mechanical deformation acts through a different physical pathway. Strain modifies the crystal lattice and therefore affects the electronic band structure and transport properties. Research on strain engineering has demonstrated the possibility of controlling carrier mobility through mechanical modification of semiconductor structures.[8–11] The dissertation extends this concept to the p–n junction I–V characteristic by introducing strain dependence into the saturation current.

One of the important theoretical implications is that the saturation current should be treated as a dynamic physical parameter rather than a strictly fixed constant when external mechanical loading is significant. In the proposed model,

$I_s = I_s(E_g, \mu, \epsilon)$ meaning that the saturation current depends on bandgap-related effects and carrier-transport parameters. The resulting generalized equation $I = I(V, t, \Phi, \epsilon)$ provides a framework for describing a diode under simultaneous electrical, optical and mechanical conditions.

The model also helps distinguish static and dynamic regimes. In the static case,

$\partial I / \partial t = 0$ and the characteristic can be described by fixed values of illumination and deformation. In the dynamic case, both $\Phi = \Phi(t)$ and/or $\epsilon = \epsilon(t)$ may vary with time.

The latter situation is particularly important for sensors. A deformation-sensitive photodiode, for example, can simultaneously provide information about optical intensity and mechanical loading. The theoretical model may consequently be useful for developing multifunctional sensing systems.

5. CONCLUSION

The theoretical influence of illumination and mechanical deformation on the current–voltage characteristics of p–n junction diodes has been analyzed.

The analysis demonstrates that illumination changes the electrical response primarily through photogeneration, recombination and photocurrent formation. The photocurrent is time-dependent during the transition from the dark state to the illuminated steady state and causes a shift of the I–V characteristic toward the negative-current region.

Mechanical deformation affects the p–n junction through changes in the crystal lattice, energy-band structure, bandgap, carrier mobility, diffusion coefficients and intrinsic carrier concentration. These changes lead to deformation dependence of the saturation current and consequently modify the amplitude and slope of the current–voltage characteristic.

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