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YARIMO'TKAZGICHLARDA ZARYAD TASHUVCHILAR KONSENTRATSIYASINING TUNNEL EHTIMOLLIGIGA BOG'LIQLIGI.

Annotatsiya

Ushbu maqolada yarimo‘tkazgichlarda zaryad tashuvchilar konsentratsiyasi va haroratning tunnel effektiga ta’siri o‘rganildi. Tadqiqot davomida tunnellanish ehtimolini aniqlash uchun Schredinger tenglamasi va Wentzel-Kramers-Brilyon yaqinlashuvi asosida nazariy hisob-kitoblar olib borildi. Shuningdek, aralashma darajasi va haroratning Fermi sathi hamda tunnellanish jarayoniga qanday ta’sir ko‘rsatishi tahlil qilindi. Olingan natijalar shuni ko‘rsatadiki, aralashma miqdorining oshishi elektronlarning tunnellanish ehtimolini sezilarli darajada oshiradi. Ushbu natijalar nanoelektronika va tunnel diodlari kabi ilg‘or yarimo‘tkazgich texnologiyalarining rivojlanishi uchun muhim ilmiy asos bo‘lib xizmat qiladi.

Kalit so‘zlar: Yarimo‘tkazgich, zaryad tashuvchilar konsentratsiyasi, tunnel effekti, aralashma, harorat, Fermi sathi, kvant tunnellanishi, Schredinger tenglamasi, WKB yaqinlashuvi, nanoelektronika, tunnel diodi, kvant nuqtalar.

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ЗАВИСИМОСТЬ ЭФФЕКТА ТУННЕЛИРОВАНИЯ ОТ КОНЦЕНТРАЦИИ НОСИТЕЛЕЙ ЗАРЯДА И ТЕМПЕРАТУРЫ В ПОЛУПРОВОДНИКАХ

Аннотация

В данной статье изучается влияние концентрации носителей заряда и температуры на эффект туннелирования в полупроводниках. Теоретические расчёты проводились на основе уравнения Шрёдингера и приближения ВКБ для определения вероятности туннелирования. Кроме того, проанализировано влияние уровня легирования и температуры на уровень Ферми и процесс туннелирования. Полученные результаты показывают, что увеличение концентрации легирования значительно повышает вероятность туннелирования электронов. Эти выводы являются важной научной основой для развития передовых полупроводниковых технологий, таких как наноэлектроника и туннельные диоды.

Ключевые слова: Полупроводник, концентрация носителей заряда, эффект туннелирования, температура, уровень Ферми, квантовое туннелирование, уравнение Шрёдингера, приближение ВКБ, наноэлектроника, туннельный диод, квантовые точки.

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DEPENDENCE OF THE TUNNELING EFFECT ON CHARGE CARRIER CONCENTRATION AND TEMPERATURE IN SEMICONDUCTORS

Annotation

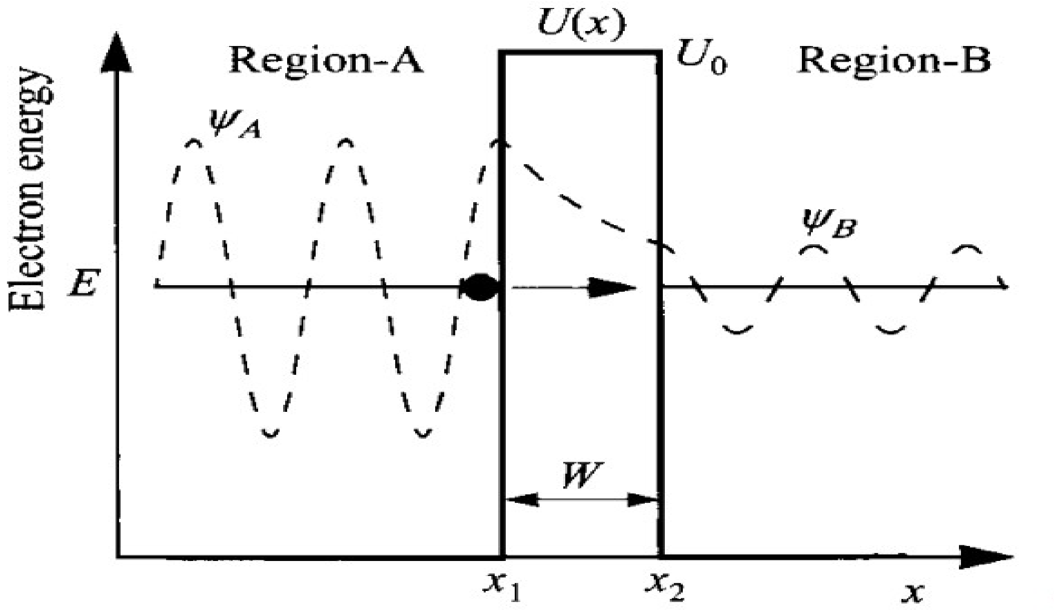
This paper examines the influence of charge carrier concentration and temperature on the tunneling effect in semiconductors. Theoretical calculations were performed using the Schrödinger equation and the WKB approximation to determine the tunneling probability. Additionally, the impact of doping levels and temperature on the Fermi level and tunneling process was analyzed. The results indicate that an increase in doping concentration significantly enhances the tunneling probability of electrons. These findings serve as an important scientific foundation for the development of advanced semiconductor technologies such as nanoelectronics and tunnel diodes.

Keywords: Semiconductor, charge carrier concentration, tunneling effect, temperature, Fermi level, quantum tunneling, Schrödinger equation, WKB approximation, nanoelectronics, tunnel diode, quantum dots.

KIRISH

Tunnel effekti – bu kvant mexanikasining fundamental hodisasi bo‘lib, unda elektronlar klassik fizika qonunlariga zid ravishda potensial to‘siqdan ma’lum ehtimollik bilan o‘tishlari mumkin. Bu hodisa elektronning to‘lqin xususiyatiga, ya’ni uning kvant mexanik holatiga bog‘liqdir va u yarimo‘tkazgichlarda, ayniqsa, nanostrukturalarda keng qo‘llaniladi[1]. Tunnel effekti zamonaviy elektronika, kvant nuqtalar, tunnel diodlari va boshqa ilg‘or qurilmalarning ishlash tamoyillarida muhim rol o‘ynaydi. Klassik nazariyada, agar elektron energiyasi potensial to‘siq balandligidan past bo‘lsa, u to‘siqdan o‘tishi imkonsiz bo‘ladi[3]. Ammo kvant mexanikasi, ayniqsa, Shredinger tenglamasi orqali ifodalanadigan to‘lqin tabiatli xarakteri tufayli, elektronlar potensial to‘siqni “kesib o‘tish” o‘rniga uning ichidan tunnellanishi mumkin. Shu jarayonni chuqurroq tushunish uchun quyidagi Shredinger tenglamasi keltiriladi: [1–4]

$$\frac{d^2\psi}{d x^2}+\frac{2 m^{¿}}{\hbar^2}\left(E-U\left(x\right)\right)\psi=0\left(1\right)$$



1-rasm. Elektronning to'lqin funksiyasi tunneli effekti asosida potensial to'siqni kesib o'tishi [1]

Eksperimental tadqiqotlar shuni ko‘rsatadiki, yarimo‘tkazgich materiallariga turli aralashmalar kiritilganda yoki tashqi omillar ta’sirida zaryad tashuvchilar konsentratsiyasi o‘zgarishi mumkin. Bu esa tunnel ehtimolligiga ta’sir ko‘rsatadi. Masalan**,** Sze (1981) tomonidan olib borilgan eksperimental tadqiqotlarda aralashmali yarimo‘tkazgichlarda zaryad tashuvchilar sonining ortishi tunnellanish ehtimolini oshirishini ko‘rsatgan. Durgesh Laxman Tiwari va K. Sivasankaran (2019) esa zaryad tashuvchilar konsentratsiyasining o‘zgarishi nanoelektronika qurilmalarining samaradorligiga qanday ta’sir qilishini o‘rgangan va yuqori konsentratsiyali materiallarda tunnellanish ehtimoli oshishini tasdiqlagan. Shuningdek, Langhua Hu va Duan Chen (2015) tomonidan nano-transistorlar ustida olib borilgan tadqiqotlarda, harorat va aralashma darajasi oshgani sari tunnellanish jarayoni sezilarli darajada kuchayishi aniqlangan. Ushbu tadqiqot natijalari bizning nazariy hisob-kitoblarimizni tasdiqlaydi.

TADQIQOT METODOLOGIYASI

Potensial to’siqning balandligi U, kengligi W bo’lgan hol uchun to’lqin funksiyasining umumiy ko’rinishi $\psi=e^{\pm ikx}$,bu yerda $k=\sqrt{2m¿(U(x)-E)}/\hbar$ ga teng.

Ushbu ifoda orqali, agar elektron energiyasi E potensial to‘siq balandligidan kichik bo‘lsa, k haqiqiy bo‘ladi va elektronning to‘lqin funksiyasi potensial to‘siq hududida eksponensial tarzda kamayishi kuzatiladi [2, 4]. Natijada, tunnellanish ehtimolligi elektronning to‘siq orqali “teshib o‘tishi” jarayoni sifatida namoyon bo‘ladi hamda to’lqin funksiyasining yechimi hamda tunnel ehtimolligi quyidagi (2) tenglik orqali hisoblanadi.[2]

$$T_t = ¿ \qquad (2)$$

Murakkabroq shakldagi potensial to’siqlar uchun, agar potensial U(x) tez o'zgarmasa, Schredinger tenglamasini Wentzel-Kramers-Brillouin yaqinlashuvi yordamida soddalashtirish mumkin. To'lqin funksiyasining yechimi $e^{\int ik(x)dx}$ bo'ladi va tunnellanish ehtimolini quyidagicha hisoblash mumkin:

$$T \approx e^{-2\int_{x_1}^{x_2} k(x)dx} \qquad (3)$$

$$k = \frac{\sqrt{2m¿(U(x)-E)}}{\hbar}$$

m — elektron massasi, U(x) — potensial to‘siq balandligi, E — elektron energiyasi, $\hbar$ — Plank doimiysi.

Wentzel-Kramers-Brilyon model orqali, har bir nuqtada elektronning tunnellanish ehtimoli hisobga olinadi va natijada umumiy tunnellanish ehtimolligi (3) tenglama yordamida aniqlanadi [6, 14]. Agar ushbu integralni hisoblab chiqilsa, quyidagi soddalashtirilgan formula hosil bo‘ladi:

$$T \approx e^{[-2kW]} = e^{\frac{\sqrt{2m¿(U(x)-E)}}{\hbar}W} \qquad (4)$$

Yuqoridagi ifodadan ko’rinib turibdiki, tunnellanish ehtimolligi elektronning energiyasiga, potensial to’siq balandligi va kengligiga hamda modda turiga bog’liq ekan.[1] Biroq, yuqorida keltirilgan ishlarda aralashmali yarimo’tkazgichlardagi zaryad tashuvchilar konsentratsiyasining tunnel effektiga bog’liqligi yetarli darajada o’rganilmagan.

Ishning maqsadi, aralashmali yarimo’tkazgichlardagi zaryad tashuvchilar konsentratsiyasining tunnel effektiga bog’liqligini o’rganishdan iborat

TAHLIL VA NATIJALAR

Yarimo’tkazgichlarda zaryad tashuvchilar konsentratsiyasi tunnel effektiga bog’liqligi.

Sof yarimo’tkazgichlarda zaryad tashuvchilar konsentratsiyasi, kiritmali yarimo’tkazgichlarga nisbatan ancha kichik bo’lganligi sababli, tunnellanish ehtimoli ham past bo’ladi. Shuning uchun, biz faqatgina, aralashmali yarimo’tkazgichlarda zaryad tashuvchilar konsentratsiyasining o’zgarishi, tunnel effektiga qanday bog’langanligini ko’rib chiqamiz. Tunnellanish jarayonida yarimo’tkazgichlardagi zaryad tashuvchilar konsentratsiyasi tunellash effektiga sezilarli ta’sir ko‘rsatadi. Aralashma konsentratsiyasi oshgani sari Fermi energiyasi ko‘tariladi, bu esa elektronlarning energiya taqsimotini kengaytiradi, natijada tunnellanish ehtimoli oshadi [4, 7, 8]. Tunnel hodisasi zaryad tashuvchilarning miqdori va ularning energiya taqsimoti bilan bevosita bog‘liq. Yarimo‘tkazgichli materiallarga turli aralashmalar kiritilganda yoki tashqi omillar ta’sirida zaryad tashuvchilar konsentratsiyasi o‘zgarishi mumkin. Bu esa tunnel ehtimolligiga ta’sir ko‘rsatadi va biz tunnellanish ehtimoli T_t va zaryad tashuvchilar konsentratsiyasi N_A yoki N_D o‘rtasidagi bog‘liqlikni quyida matematik ifoda orqali topamiz [3].

Yarimo’tkazgichlardagi elektronlarning konsentratsiyasi:

$$n = 2\left(\frac{2\pi m_n^{¿} kT}{h^2}\right)^{\frac{3}{2}} * e^{\frac{E-E_c}{kT}} \qquad (5)$$

n-tipli yarimo’tkazgichlarda zaryad tashuvchilar to’liq ionlashgan bo’lsa $n \approx N_D$ ga teng bo’ladi va (5) ifoda quyidagi ko’rinishni oladi.

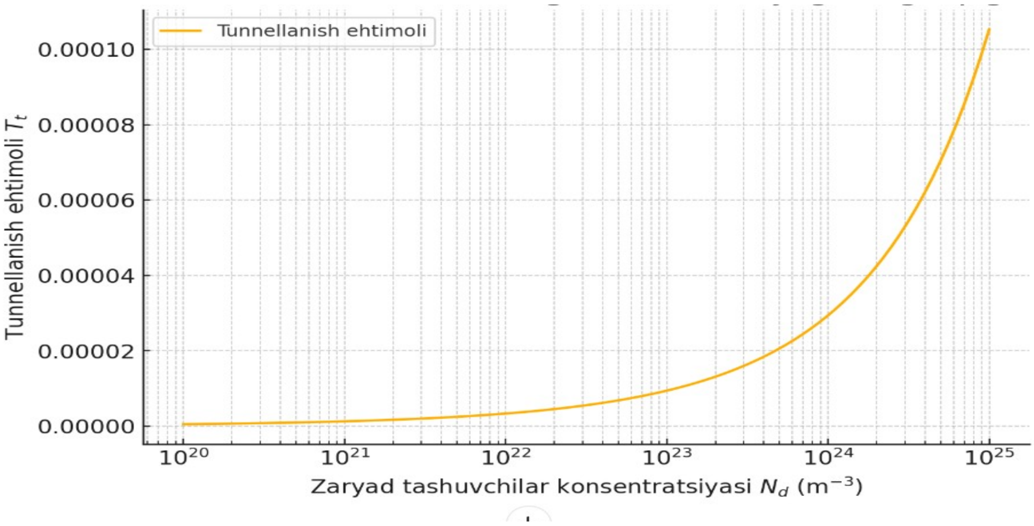
$$N_D = A * e^{\frac{E-E_c}{kT}} \qquad (6)$$

Bu yerda A=$2\left(\frac{2\pi m_n^{¿} kT}{h^2}\right)^{\frac{3}{2}}$ $N_D - ¿$donorlar konsentratsiyasi, E – Fermi energiyasi, $E_c - ¿$o’tkazuvchanlik zonasiga mos keluvchi energiya. (6) ifodadan ko’rinib turibdiki, zaryad tashuvchilar konsentratsiyasi Fermi sathiga bevosita bog’liq va n-tipli yarimo‘tkazgich uchun Fermi energiyasini quyidagi ifoda orqali aniqlanadi:

$$E = E_C + kT\left(\frac{N_D}{A}\right) \qquad (7)$$

(7) ifodani (4) ga olib borib qo’yish natijasida, (8) tenglikka ega bo’lamiz va ular o’rtasidagi bog’liqlikni quyida grafik orqali ifodalaymiz.

$$T \approx e^{\frac{\sqrt{2m^{¿}\left(U(x) - E_C + kT\left(\frac{N_D}{A}\right)\right)}}{\hbar} * W} \qquad (8)$$



2-rasm. Zaryad tashuvchilar konsentratsiyasining tunnel effektiga bog’liqlik grafigi.

2-rasmdan ko’rinib turibdiki, aynimagan yarimo’tkazgichlarda tunnellanish deyarli kuzatilmaydi. Aynigan yarimo’tkazgichlarda esa zaryad tashuvchilar sonining ortishi tunnellanish ehtimolini oshishiga sabab bo’ladi. Ushbu bog‘liqliklar nazariy modellarga qo‘shimcha ravishda eksperimental va nazariy tadqiqotlar orqali ham tasdiqlangan [7, 11, 16]. Shu sababli, yarimo’tkazgichlarda tunnellanish ehtimoli nafaqat aralashma konsentratsiyasi, balki harorat va elektr maydon kuchi kabi omillar bilan ham o‘zaro bog‘liqdir [8, 14, 16].

XULOSA

Tunnel effektining zaryad tashuvchilar konsentratsiyasiga bog‘liqligi tahlil qilindi va natijalarga ko‘ra, aralashmali yarimo‘tkazgichlarda aralashma konsentratsiyasi oshishi bilan Fermi sathi yuqorilab, tunnellanish ehtimoli ortishi aniqlandi. Sof yarimo‘tkazgichlarda zaryad tashuvchilar soni kam bo‘lgani sababli tunnel hodisasi deyarli kuzatilmaydi, ammo aralashma miqdori oshganda elektronlar energiyasi ortib, potensial to‘siq orqali o‘tish ehtimoli sezilarli darajada oshadi. Ushbu bog‘liqlik amaliy jihatdan tunnel diodlari, kvant nuqtalar va nanoelektronika kabi ilg‘or texnologiyalarning samaradorligini oshirish uchun muhim ahamiyat kasb etadi. Tunnel effektining konsentratsiyaga bog‘liqligini chuqur o‘rganish orqali yarimo‘tkazgich qurilmalarining ishlash tamoyillarini yanada yaxshilash mumkin.

FOYDALANILGAN ADABIYOTLAR

1. Sze, S. M. (1981). *Physics of Semiconductor Devices*. Wiley.
2. Feynman, R. (1965). *The Feynman Lectures on Physics*, Vol. III. Addison-Wesley.
3. Rasulov, E. & Begimqulov, U. (2009). *Kvant fizikasi*. Toshkent: Fan va texnalogiya.
4. Durgesh Laxman Tiwari, K. Sivasankaran. *Impact of carrier concentration and bandgap on the performance of double gate GNR-FET.* Superlattices and Microstructures Volume 130, June 2019, Pages 38-49 https://doi.org/10.1016/j.spmi.2019.04.019
5. Langhua Hu, Duan Chen, *Impact of geometric, thermal and tunneling effects on nano-transistors*. Journal of Computational Physics.Volume 290, 1 June 2015, Pages 169-187 https://doi.org/10.1016/j.jcp.2015.02.044
6. Javier García-Fernández, María Hernando, *Characterization of Tunneled Wide Band Gap Mixed Conductors: The* Na_2O*-*Ga_2O_3*-*TiO_2 *System. Nanomaterials* 2023, *13*(14), 2054;
7. Palepu. Shweta Patel. *Investigation of the dielectrically modulated electron hole bilayer tunnel field effect transistor for biomolecule detections.* Current Applied Physics. Volume 47, March 2023, Pages 60-71 https://doi.org/10.1016/j.cap.2023.01.001
8. Gulyamov G., Dadamirzaev M. G., Kosimova M. O. COMPARISON OF PARAMETERS OF TWO-DIMENSIONAL (2D) AND THREE-DIMENSIONAL (3D) PN-JUNCTION DIODES //Romanian Journal of Physics. – 2023. – T. 68. – C. 603.

9. Dadamirzaev, M., Kosimova, M., Maxmudov, A., & Tursunov, M. (2023). LIGHT POWER FACTOR ON THE CHARACTERISTICS OF TWO-DIMENSIONAL PN DIODES. *И ПРИКЛАДНЫЕ ПРОБЛЕМЫ СОВРЕМЕННОЙ ФИЗИКИ FUNDAMENTAL AND APPLIED PROBLEMS OF MODERN PHYSICS*, 27.
10. Gómez Viloria, M., Ben-Abdallah, P. & Messina, R. *Electronic Heat Tunneling between Two Metals beyond the WKB Approximation*. Physical Review B 108, Published 13 November, 2023.
11. Dadamirzaev, M. G., Kosimova, M. O., Boydedayev, S. R., & Makhmudov, A. S. (2024). COMPARISON OF 2D AND 3D PN JUNCTION DIFFERENTIAL CONDUCTANCE AND DIFFUSION CAPACITANCE1. *European Journal OF Physics*, *2*, 372-379.
12. Gulyamov, G., Erkaboev, U. I., Majidova, G. N., Qosimova, M. O., & Davlatov, A. B. (2015). New Method of Determining the Landau Levels in Narrow-Gap Semiconductors. *Open Journal of Applied Sciences*, *5*(12), 771-775.
13. Dadamirzayev, M. G., & Kosimova, M. O. (2018). The effect of the variation of the electric field of the UHF waves on the CVC of the asymmetric pn-junction. *ISJ Theoretical & Applied Science*, *10 (66)*, 401-405.
14. Gulyamov, G., Dadamirzaev, G., Dadamirzayev, M., & Kosimova, M. (2020). The influence of the microwave field on the characteristics of the pn junction. *Euroasian Journal of Semiconductors Science and Engineering*, *2*(4), 7
15. Gulyamov, G., Dadamirzaev, G., Dadamirzayev, M., & Kosimova, M. (2020). The influence of the microwave field on the characteristics of the pn junction. *Euroasian Journal of Semiconductors Science and Engineering*, *2*(4), 7.
16. Shkop, A. D. *Thermoelectric Effects in Tunneling of Spin-Polarized Electrons in a Molecular Transistor*. Condensed Matter > Mesoscale and

Nanoscale Physics. (2022, July 9). https://doi.org/10.48550/arXiv.2207.04234

17. Dadamirzaev, M. G., Kosimova, M. O., Boydedayev, S. R., & Makhmudov, A. S. (2024). Comparison of 2D and 3D pn Junction Differential Conductance and Diffusion Capacitance. East European Journal of Physics, (2), 372-379.
18. Taghinejad, M., Fathipour, M. & Niknejad, A. M. (2022). *The Effects of Source Doping Concentration and Doping Gradient on the ON-State Current of Si Nanowire TFETs*. *Journal of Computational Electronics, 21*.