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TUNNEL DIODLARDA TUNNEL TOKINING ANALITIK IFODASINI HOSIL QILISH

Annotatsiya. *Ushbu ishda tunnel diodlarda kuzatiladigan tunnel tokning fizik tabiati va uning matematik ifodasi Esaki nazariyasi asosida tadqiq qilindi. Tunnel tok zichligining integral formulasi energetik sathlar zichligi va Fermi-Dirak taqsimot funksiyalarini hisobga olgan holda tahlil etildi hamda analitik soddalashtirish amalga oshirildi. Natijada tunnel tokning kuchlanishga bog'liqligini ifodalovchi soddalashtirilgan matematik model hosil qilindi. Olingan natijalar tunnel diodlarning volt-amper xarakteristikasini nazariy jihatdan tavsiflash va manfiy differensial qarshilik hodisasini izohlashda muhim ahamiyatga ega.*

Kalit so'zlar*: tunnel diod, Esaki nazariyasi, manfiy differensial qarshilik, Fermi-Dirak taqsimoti, holatlar zichligi, kvant tunnellanish, tunnel o'tish, analitik model, p–n o'tish, tunnellanish ehtimoli.*

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АНАЛИТИЧЕСКОЕ ВЫВЕДЕНИЕ ВЫРАЖЕНИЯ ДЛЯ ТУННЕЛЬНОГО ТОКА В ТУННЕЛЬНЫХ ДИОДАХ

Аннотация. *В работе исследована физическая природа туннельного тока в туннельных диодах и получено его математическое выражение на основе теории Эсаки. Проанализирована интегральная формула плотности туннельного тока с учетом плотности энергетических состояний и*

функции распределения Ферми-Дирака, после чего выполнено ее аналитическое упрощение. В результате получена упрощенная математическая модель зависимости туннельного тока от напряжения. Полученные результаты имеют значение для теоретического описания вольт-амперной характеристики туннельных диодов и объяснения области отрицательного дифференциального сопротивления.

***Ключевые слова**: туннельный диод, теория Эсаки, отрицательное дифференциальное сопротивление, распределение Ферми-Дирака, плотность состояний, квантовое туннелирование, туннельный переход, аналитическая модель, p–n-переход, вероятность туннелирования.*

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DERIVATION OF AN ANALYTICAL EXPRESSION FOR TUNNEL CURRENT IN TUNNEL DIODES

***Annotation.** This work investigates the physical nature of tunnel current in tunnel diodes and derives its mathematical expression based on Esaki theory. The integral expression for tunnel current density is analyzed by taking into account the density of energy states and the Fermi-Dirac distribution function, followed by an analytical simplification. As a result, a simplified mathematical model describing the dependence of tunnel current on voltage is obtained. The results are important for the theoretical description of the current–voltage characteristics of tunnel diodes and for explaining the negative differential resistance region.*

***Keywords**: tunnel diode, Esaki theory, negative differential resistance, Fermi–Dirac distribution, density of states, quantum tunneling, tunnel transition, analytical model, p–n junction, tunneling probability.*

Kirish. Yarimo‘tkazgichli elektronika va nanoelektronika sohasida kvant-mexanik hodisalarga asoslangan asboblarning volt-amper xarakteristikalari (VAX) tarkibiy qismlarini o‘rganish dolzarb masalalardan biri bo‘lib kelmoqda. Xususan, kuchli legirlangan p-n o‘tishli tuzilmalarda elektronlarning potensial baryer orqali sizib o‘tishi, ya’ni, tunnel effekti ilk bor L.Esaki tomonidan kashf etilgan va ushbu hodisa asosida ishlovchi tunnel diodining fundamental ishlash prinsiplari bayon qilingan [1].

Mavzuga oid adabiyotlarning tahlili. Keyinchalik, tor p-n o‘tishlarida tunnel jarayonlarining asbob xarakteristikalariga hamda uning parametrlariga ta’siri L.Esaki va Y.Miyahara tomonidan tajribaviy zanjirlarda kengroq tahlil etildi [2]. E.O.Kane tunnel diodlaridagi to‘g‘ri va teskari tok zichliklarining energetik zonalar shakli, sathlar zichligi va elektronlarning energetik taqsimot funksiyalariga (Fermi–Dirak taqsimotiga) bog‘liqligining matematik va kvant-mexanik modelini ishlab chiqdi [3]. Ushbu nazariy modelni amaliyotda qo‘llash, kremniy va germaniy asosidagi tunnel diodlarining konstruksiyalarini loyihalash hamda ularning VAX xususiyatlarini eksperimental tekshirish ishlari J.A.Lesk va N.Holonyak tomonidan amalga oshirildi [4]. Bilvosita (indirect) tunnel o‘tishlarda fononlarning ishtiroki va ushbu jarayonning to‘g‘ri tok integrallariga ta’siri R.N.Hall tomonidan o‘rganildi [5]. Tunnel diodining o‘ziga xos xususiyati bo‘lgan salbiy differensial qarshilik sohasini, VAXning egrilik darajasini hamda cho‘qqi (peak) va vodiy (valley) toklari nisbatini aniqlash mexanizmlari J.Karlovsky tadqiqotlarida yoritildi [6]. Real xarakteristikalarda rekombinatsiya jarayonlari mavjudligi va oltin hamda boshqa aralashmalar bilan legirlashning toklar shakllanishiga ta’siri S.T.Sah tomonidan nazariy asoslandi [7]. VAXning minimum (vodiy) nuqtasida kuzatiladigan va ideal integral modeldan chetlashuvchi ortiqcha tok (excess current) tabiati A.G Chynoweth, W.L. Feldmann va R.A.Logan tomonidan tadqiq etildi [8]. GaAs asosidagi tunnel diodlarning VAX xususiyatlari va vaqt o‘tishi bilan degradatsiyasi R.M.Minton va R.Gmelin ishlarida tahlil qilindi [9]. Tunnel diodlarni yuqori chastotali generatorlar va osillatorlar zanjirlariga integratsiya qilish hamda ularning ekvivalent sxemalarini yaratish J.J.Meyer va G.J.Wheeler tomonidan o‘rganildi [10]. Esaki integral tenglamalarini analitik yechish bilan bir qatorda, ularni kompyuter modellashtirish orqali VAX ni sonli hisoblash usullari T.A. Demassa va D.P.Knott tomonidan taklif etildi [11]. Tunnel o‘tish vaqti va zaryad tashuvchilarning kvant tabiati masalalari D.K.Roy tomonidan qayta ko‘rib chiqildi [12]. Shu bilan birga, ushbu tadqiqotda Tsu–Esaki integral tenglamasini analitik va sonli yondashuvlar asosida yechish hamda turli geterostruktura parametrlari va legirlash konsentratsiyalarini hisobga oluvchi tunnel tok zichligi modelini olishga e’tibor qaratiladi.

Tadqiqot metodologiyasi. Tadqiqotda tunnel tokini ifodalash uchun Tsu-Esaki modeli asos qilib olindi. Tunnel tokining shakllanishi n-yarimo‘tkazgichning o‘tkazuvchanlik zonasidagi to‘lgan energetik sathlar, p-yarimo‘tkazgichning valentlik zonasidagi bo‘sh o‘rinlar, ularning Fermi-Dirak taqsimoti va p–n

o‘tishdagi potensial to‘siqning shaffofligi bilan bog‘landi. Avval to‘g‘ri va teskari tunnel toklarining integral ifodalari ko‘rib chiqildi, so‘ng ular orasidagi farq orqali to‘liq tunnel toki yozildi. Keyingi bosqichda holatlar zichligi uchun 3D erkin elektron gaz modeli qo‘llanib, integral ifoda analitik soddalashtirildi va tunnel tokning kuchlanishga bog‘liqligini ifodalovchi yakuniy model olindi. Hisoblash natijalari kuchli legirlangan GaAs tunnel diodi uchun I–V xarakteristika ko‘rinishida tasvirlandi.

Tahlil va natijalar. Tsu-Esaki modelida tunnel tokini eksperiment o‘tkazmagan holda oldindan baholash uchun integral ifoda yechildi. Tunnel dioddan o‘tayotgan to‘g‘ri tunnel toki n-yarimo‘tkazgichning o‘tkazuvchanlik zonasidagi elektronlar bilan to‘lgan energetik sathlar zichligiga va p-yarimo‘tkazgichning valentlik zonasidagi elektronlar bilan to‘lmagan, berilgan energiyaga ega bo‘lgan bo‘sh o‘rinlar zichligiga proporsionaldir. Teskari tok esa p-yarimo‘tkazgichning valentlik zonasidagi to‘ldirilgan energetik sathlar bilan shunday energiyaga ega bo‘lgan n-yarimo‘tkazgichning o‘tkazuvchanlik zonasidagi bo‘sh o‘rinlarga proporsional. Bundan tashqari, p–n o‘tishdan o‘tayotgan tunnel tok potensial baryerning shaffofligiga ham bog‘liqdir.

Aytilganlarni hisobga olgan holda to‘g‘ri tok Esaki nazariyasiga asosan integral ko‘rinishda ifodalanadi. Keyin teskari tok aniqlanadi va p–n o‘tishdagi to‘liq tunnel toki to‘g‘ri va teskari toklarning ayirmasi sifatida olinadi. Keyingi analitik almashtirishlar orqali (4)-ifodaga kelinadi. Mazkur ifoda asosida kuchli legirlangan GaAs tunnel diodining I–V xarakteristikasi hisoblandi.

Aytilganlarni hisobga olgan holda to‘g‘ri tok Esaki nazariyasiga asosan, quyidagi ko‘rinishni qabul qiladi:

$$J_{p\to n}A\int_{\varepsilon_n}^{\varepsilon_p} f_p(\varepsilon)\rho_p(\varepsilon)L(1-f_n(\varepsilon))\rho_n(\varepsilon)d\varepsilon \quad (1)$$

Teskari tok esa:

$$J_{n\to p}A\int_{\varepsilon_n}^{\varepsilon_p} f_n(\varepsilon)\rho_n(\varepsilon)L(1-f_p(\varepsilon))\rho_p(\varepsilon)d\varepsilon \quad (2)$$

p-n o‘tishdagi to‘liq tunnel toki *(1)* va *(2)* larning ayirmasiga teng bo‘ladi

$$J=A\int_{\varepsilon_n}^{\varepsilon_p} L\rho_n(\varepsilon)\rho_p(\varepsilon)\left(f_n(\varepsilon)-f_p(\varepsilon)\right)d\varepsilon \quad (3)$$

$$\varepsilon_n=0,\qquad \varepsilon_p=eV_K-E_g-eV,\qquad f_n(\varepsilon)=\frac{1}{e^{\frac{E-\mu_n}{KT}}+1}$$

$$f_p(\varepsilon)=\frac{1}{e^{\frac{\varepsilon+\mu_p-eV_K+E_g+eV}{KT}}+1},\qquad \rho_n(\varepsilon)=C\sqrt{\varepsilon},\quad \rho_p(\varepsilon)=C'\sqrt{eV_K-E_g-eV-\varepsilon}$$

Ifodalarni qo‘yib, integralni hisoblaymiz:

$$J=A\int_0^{eV_K-E_g-eV} L\ C\sqrt{\varepsilon}\ C'\sqrt{eV_K-E_g-eV-\varepsilon}\left(\frac{1}{e^{\frac{E-\mu_n}{KT}}+1}-\frac{1}{e^{\frac{\varepsilon+\mu_p-eV_K+E_g+eV}{KT}}+1}\right)$$

$$ALCC'\int_0^{eV_K-E_g-eV}\sqrt{\varepsilon\left(eV_K-E_g-eV-\varepsilon\right)}\left(\frac{1}{e^{\frac{E-\mu_n}{KT}}+1}-\frac{1}{e^{\frac{\varepsilon+\mu_p-eV_K+E_g+eV}{KT}}+1}\right)$$

ε ning o‘rtacha arifmetik qiymati $\varepsilon=\frac{1}{2}(eV_K-E_g-eV)$ ni qo‘yib, ildizni integral belgisi ostidan chiqarib yuboramiz:

$$J=ALCC'\frac{eV_K-E_g-eV}{2}\int_0^{eV_K-E_g-eV}\left(\frac{1}{e^{\frac{E-\mu_n}{KT}}+1}-\frac{1}{e^{\frac{\varepsilon+\mu_p-eV_K+E_g+eV}{KT}}+1}\right)d\varepsilon$$

$eV_K-E_g=\mu_n+\mu_p$ dan foydanalamiz: $\mu_p-eV_K+E_g=-\mu_n$

integralni hisoblash uchun $\int\frac{1}{e^x}dx=ln\frac{e^x}{e^x+1}$ dan foydalanamiz:

$$J=ALCC'\frac{eV_K-E_g-eV}{2}KT\left(ln\frac{e^{\frac{\varepsilon-\mu_n}{KT}}}{e^{\frac{\varepsilon-\mu_n}{KT}}+1}-ln\frac{e^{\frac{\varepsilon-\mu_n+eV}{KT}}}{e^{\frac{\varepsilon-\mu_n+eV}{KT}}}\right)\Big|_0^{eV_K-E_g-eV}=$$

$$=ALCC'\frac{eV_K-E_g-eV}{2}KT\left[\left(ln\frac{e^{\frac{\mu_p-eV}{KT}}}{e^{\frac{\mu_p-eV}{KT}}+1}-ln\frac{e^{\frac{\mu_p}{KT}}}{e^{\frac{\mu_p}{KT}}+1}\right)-\left(ln\frac{e^{-\frac{\mu_n}{KT}}}{e^{-\frac{\mu_n}{KT}}+1}-ln\frac{e^{\frac{-\mu_n+eV}{KT}}}{e^{\frac{-\mu_n+eV}{KT}}+1}\right)\right]=$$

$ALCC'KT=A'$ deb belgilab olamiz:

$$= \frac{A'}{2}(\mu_n + \mu_p - eV) ln \left(\frac{\left(e^{\frac{\mu_p}{KT}} + 1\right)\left(e^{-\frac{\mu_n}{KT}} + 1\right)}{\left(e^{\frac{\mu_p - eV}{KT}} + 1\right)\left(e^{\frac{eV - \mu_n}{KT}} + 1\right)} \right)$$

Agar, $f_p(\varepsilon)=\frac{1}{e^{\frac{\varepsilon+\mu_p-eV_K+E_g+eV}{KT}}+1}$ va

$J=J_{n\to p} - J_{p\to n}$ larni shu ko‘rinishda olsak, tunnel tok

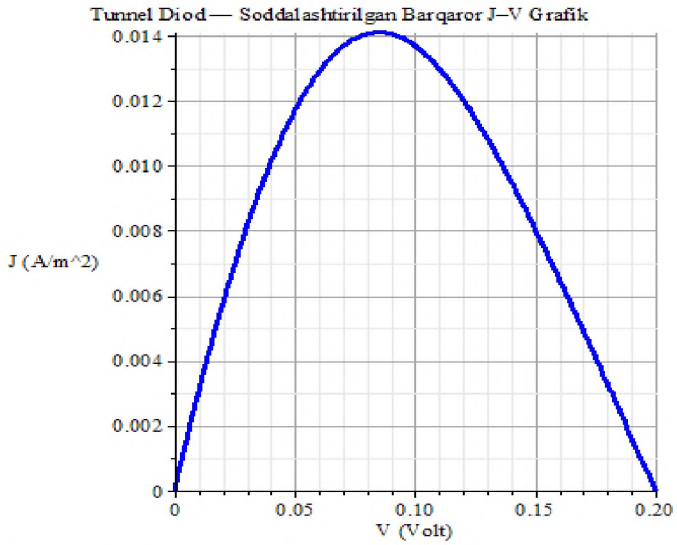
$$J = \frac{A'}{2}(\mu_n + \mu_p - eV) ln \left(\frac{\left(e^{\frac{\mu_p}{KT}}+1\right)\left(e^{-\frac{\mu_n}{KT}}+1\right)}{\left(e^{\frac{\mu_p - eV}{KT}}+1\right)\left(e^{\frac{eV - \mu_n}{KT}}+1\right)} \right) \quad (4)$$

shu natijaga kelamiz.

μ_n va μ_p lar aynan qanday asosli tunnel diod uchun Fermi energiyasi

$$\mu_n = \frac{\hbar^2}{2m_n^*}(3\pi^2 N_D)^{\frac{2}{3}} \; ; \quad \mu_p = \frac{\hbar^2}{2m_p^*}(3\pi^2 N_A)^{\frac{2}{3}} \quad (5)$$

Bu formulalar erkin elektron gaz modeli va 3D holatlar zichligidan olinadi. Franz-Keldysh effekti optik yutilish hodisasi bilan bevosita bog‘liq bo‘lib, yutilgan yorug‘lik energiyasining bir qismi tunnel diod-



ning kristall panjarasidagi elektronlarga uzatiladi. Kuchli legirlangan GaAs tunnel diodlarining tunnel tokini hisoblash uchun yuqoridagi (4) ifodadan foydalanamiz va quyidagi 2-rasmdagi grafikni hosil qilamiz.

2-rasm. AsGa asosli tunnel tokining I–V xarakteristikasi.

Xulosa. Ushbu ishda istalgan geteroo‘tishli tunnel diodlarining volt-amper harakteristikasi keltirilgan bo‘lib, Tsu-Esaki modeli hamda ushbu modelning integral yechimi olingan. Kuchli legirlangan GaAs tunnel diodlarining tunnel tokini hisoblash ishlari amaliy tajribalardagi ishlar bilan mos ravishda qiymatlar hisobga olingan.

Foydalanilgan adabiyotlar ro‘yxati:№

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KONSOL STERJENNING EGILISHGA BIKIRLIGINI ERKIN TEBRANISHLAR VA NAZARIY MODEL ASOSIDA ANIQLASH

Annotatsiya. *Ushbu maqolada bir uchi qistirib mahkamlangan, ikkinchi uchi erkin (konsol) sterjenning egilishga bikirligini ikkita usul yordamida aniqlash masalasi ko‘rib chiqilgan. Sterjenning erkin so‘nuvchi ko‘ndalang tebranish jarayonini eksperimental qayd etish va uning grafigidan foydalanib chastota tavsiflarini ajratib olish orqali Eyler–Bernulli dinamik tenglamasi va konsol balkaning chegaraviy shartlaridan kelib chiqadigan xarakteristik (chastota) tenglama asosida tebranish davri, chastotasi, logarifmik dekrement hamda so‘nish koeffitsiyenti hisoblangan va EIning sonli qiymati topilgan. Olingan natijalar asosida taqqoslash ishlari bajarilgan.*

Kalit so‘zlar: *Eyler-Bernulli tenglamasi, konsol balka, chastota, egilish bikirligi (EI), logarifmik dekrement.*

ОПРЕДЕЛЕНИЕ ИЗГИБНОЙ ЖЁСТКОСТИ КОНСОЛЬНОГО СТЕРЖНЯ НА ОСНОВЕ СВОБОДНЫХ КОЛЕБАНИЙ И ТЕОРЕТИЧЕСКОЙ МОДЕЛИ

Аннотация. *В данной статье рассматривается задача определения изгибной жёсткости стержня, один конец которого жёстко защемлён, а другой свободен (консольного стержня), двумя методами. Путём экспериментальной регистрации процесса свободных затухающих поперечных колебаний стержня и извлечения частотных характеристик по его графику, на основе динамического уравнения Эйлера–Бернулли и характеристического (частотного) уравнения, вытекающего из граничных условий консольной балки, были рассчитаны период, частота колебаний, логарифмический декремент и коэффициент затухания, а также найдено численное значение EI. На основе полученных результатов выполнены сравнительные работы.*

Ключевые слова: *уравнение Эйлера–Бернулли, консольная балка, частота, изгибающий момент (EI), логарифмический декремент.*

DETERMINATION OF THE FLEXURAL RIGIDITY OF A CANTILEVER BEAM BASED ON FREE VIBRATIONS AND A THEORETICAL MODEL

Annotation. *This article examines the problem of determining the flexural rigidity of a rod–specifically a cantilever rod fixed at one end and free at the other–using two methods. By experimentally recording the process of free damped transverse oscillations and extracting frequency characteristics from the resulting plot, the oscillation period and frequency, logarithmic decrement, and damping coefficient were calculated, and the numerical value of flexural rigidity (EI) was determined; these calculations were based on the dynamic Euler-Bernoulli equation and the characteristic (frequency) equation derived from the cantilever beam's boundary conditions. A comparative analysis was conducted based on the obtained results.*

Keywords: *Euler–Bernoulli equation, cantilever beam, frequency, bending stiffness (EI), logarithmic decrement.*

Kirish. Konstruksiya elementlarining egilishga bikirligi *EI* sterjen, balka va boshqa elementlarning statik va dinamik harakatlarini baholashda asosiy mexanik xarakteristikalardan biri hisoblanadi [1]. *EI* ni aniqlashning ikki asosiy yo‘li mavjud: statik usul (ma’lum yuklama ostida egilishni o‘lchash) va dinamik usul (erkin yoki majburiy tebranish chastotasidan foydalanish) [2]. Dinamik usulning afzalligi shundaki, bunda sterjenning bikirligini tez va bir necha marta qayta aniqlash imkonini beradi [3].