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STATSIONAR VA VIRTUAL SATHLAR. ELEKTRONNING TUNNEL O'TISH HODISASI

Annotatsiya: *Ushbu ishda yarimo'tkazgichli geterotuzilmalar kvant o'rasini hosil bo'lishi va undagi energetik sathlar ko'rsatib o'tilgan. Elektronlarni energetik sathga mos energiya qiymatlarini sonli aniqlovchi ifodalar berilgan. Shuningdek, elektronlar oqimining, ularning potensial to'siqdan o'tish va qaytish koeffitsientlarini formulalari keltirilgan.*

Kalit so'zlar: *Kvant o'ra, potensial to'siq, statsionar sathlar, virtual sathlar, o'tish koeffitsienti, qaytish koeffitsienti*

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СТАЦИОНАРНЫЕ И ВИРТУАЛЬНЫЕ УРОВНИ. ЯВЛЕНИЕ ЭЛЕКТРОННОГО ТУННЕЛЬНОГО ПЕРЕХОДА

Аннотация: *В данной работе рассматривается формирование квантовых ям в полупроводниковых гетероструктурах и энергетических уровней в них. Приведены выражения для численного определения значений энергии, соответствующих электронным уровням. Кроме того, приведены формулы для электронного тока, а также коэффициента прохождения электронов через потенциальный барьер и соответствующих коэффициентов отражения.*

Ключевые слова: *Квантовая яме, потенциальный барьер, стационарные уровни, виртуальные уровни, коэффициент перехода, коэффициент возврата*

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STATIONARY AND VIRTUAL LEVELS. THE PHENOMENON OF ELECTRONIC TUNNELING

Annotation: *This paper presents the formation of quantum wells in semiconductor heterostructures and the energy levels within them. Expressions for the numerical determination of the energy values corresponding to electron levels are provided. In addition, formulas for the electron current, as well as the transmission of electrons through a potential barrier and the corresponding reflection coefficients, are given.*

Keywords: *quantum well, potential barrier, stationary levels, virtual levels, transmission coefficient, reflection coefficient.*

KIRISH

Bizga ma’lumki, bugungi kunda keng o‘rganilgan AlGaAs/GaAs geterotuzilma asosida yuqori harakatchanlikka ega bo‘lgan elektronli tranzistorlar yaratilgan. InAlAs/InGaAs geterotuzilmalarda esa ishchi chastotasi yanada yuqoriroq tranzistorlar yaratish mumkinligi ko‘rsatilgan [1-3]. Bunday geterotuzilmalarning xarakterli jihati shundaki, bunday tuzilmalarda elektronlarining effektiv massasi kichik bo‘ladi. Agar, InAlAs/InGaAs geterotuzilma ichiga yupqa InAs qatlami kiritilsa tranzistor ishchi xarakteristikasi yanada yaxshilanib, ishchi chastotasi 250-260 GHz gacha ortishi mumkin [4].

Yupqa InAs qatlami kiritilgan InAlAs/InGaAs geterotuzilma asosida rezonans-tunnel diodlar yaratish va ishchi xarakteristikalarini takomillashtirish mumkinligi [5-6] adabiyotlardan ma’lum. Bu yo‘nalishda hozirga qadar ko‘plab yutuqlarga erishilgan va ilmiy tadqiqotlar hozirgi kunda ham jadal davom etmoqda [7-8].

Elektronlar uchun potensial o’radagi energiya sathlarida *statsionar energiya sathlari* va *virtual energiya sathlari* kabi tushunchalar o’rinli. Elektronning bunday sathlari haqidagi ma’lumotlar [9-15] adabiyotlarda batafsil keltirilgan. Ushbu tushunchalarni quyida qisqacha keltirib o‘tamiz.

Tadqiqot metadologiyasi

Kristall o‘tkazuvchanlik zonasidagi elektron $m^{¿}$- effektiv massa bilan xarakterlanadi. Kvant o’rani tor zonali yarimo‘tkazgichning har ikki tomonidan keng zonali yarimo‘tkazgich (yoki dielektrik) ni kontaktka keltirib hosil qilish mumkin. Bunda, elektron uchun 1-rasmdagi kabi potensial o‘ra hosil bo‘lishi mumkin.

Kvant o‘rada elektron harakatini aniqlovchi harakat tenglamasi – Shredinger tenglamasi bo‘lib, uni quyidagicha yozish mumkin

$$-\frac{\hbar^2}{2m^{¿}}\frac{\partial^2\psi}{\partial x^2}+U(x)\psi=E\psi \qquad (1)$$

Har bir qatlam uchun potensial energiyani quyidagicha yozish mumkin:

$$U(x)=¿\left\{0, \qquad |x|<W/2¿¿¿¿\right. \qquad (2)$$

O‘ra ichida ruxsat etilgan sathlar $E<U_0$ ni topish uchun, 1-3 sohalarda (1) tenglama yechimini quyidagicha tasvirlash mumkin

$$\psi_1(x)=A_1e^{\beta x}, \quad \psi_3(x)=B_3e^{-\beta x}, \quad \psi_2(x)=A_2e^{iKx}+B_2e^{-iKx} \qquad (3)$$

Bu yerda, $K=\sqrt{2m^{¿}E}/\hbar$, $\beta=\sqrt{2m^{¿}(U_0-E)}/\hbar$ deb belgilandi. Soddalashtirish uchun, 1-rasmdagi barcha qatlamlar (materiallar) uchun effektiv massa teng deb olindi. (3) to‘lqin funksiyalar va ularning hosilalarini o‘ra chegarasi $x=\pm W/2$ da tenglik (tikish) shartidan quyidagi transendent tenglamaga kelamiz

$$\frac{K^2-\beta^2}{2K\beta}=ctg\left(KW\right) \tag{4}$$

Ushbu tenglamani sonli yechish orqali ruxsat etilgan energiya sathlarini topish mumkin. Xususiy holda, chekiz chuqur ($U_0=\infty$) o‘ra uchun

$$E_n=\frac{\hbar^2\pi^2n^2}{2m^{¿}W^2} \tag{5}$$

Energiyaning $E<U_0$ bo‘lgan diskret qiymatlari *statsionar sathlar* deyiladi. Bu holatlarda elektron o‘ra ichida muqarrar tura oladi, ya’ni bog‘langan holatlarda harakat - *finit* harakatdir.

Agar elektron energiyasi potensial to‘siq balandligidan katta bo‘lsa $E>U_0$, bog‘langan holatlar mavjud emas. Masalan, chapdan kelayotgan elektron o‘ra ustidan o‘tishi yoki qaytishi mumkin. Mikrozarralar to‘lqin xossasiga ham ega bo‘lgani sababli, xuddi yorug‘lik kabi ikki sirt chegarasidan o‘tishi va qaytishi mumkin. Shu sababli (1) tenglamada energiya berilgan (ma’lum) deb o‘tish va qaytish koeffitsiyentlarini (ehtimolini) hisoblash talab etiladi. U holda, 1-rasmdagi 1-2 sohalarda (1) tenglama yechimini quyidagicha, ya’ni tushuvchi va qaytuvchi to‘lqinlar ko‘rinishida tasvirlash mumkin

$$\psi_j(x)=A_je^{iK_jx}+B_je^{-iK_jx} \tag{6}$$

Bu yerda, $K_1=\sqrt{2m^{¿}\left(E-U_0\right)}/\hbar$, $K_2=\sqrt{2m^{¿}E}/\hbar$ deb belgilandi. 3- sohada esa, faqat o‘tgan to‘lqin bo‘ladi xolos

$$\psi_3(x)=A_3e^{iK_3x} \tag{7}$$

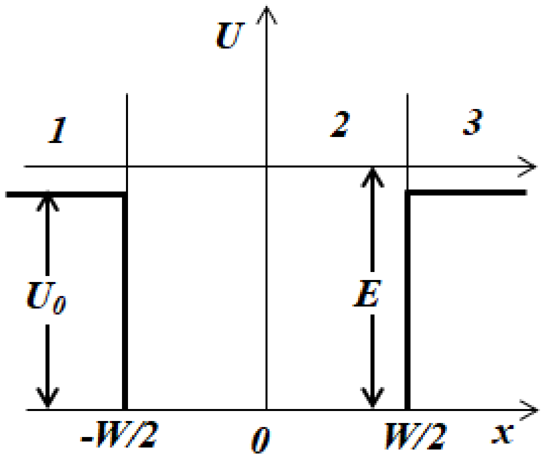
Bu yerda, $K_3 = \sqrt{2m^{¿}(E - U_0)}/\hbar$. Biror bir sohadagi elektron to‘lqinini oqimi quyidagicha topiladi

$$J = \frac{i\hbar}{2m^{¿}}\left(\Psi \frac{d\Psi^{¿}}{dx} - \Psi^{¿}\frac{d\Psi}{dx}\right) \tag{8}$$

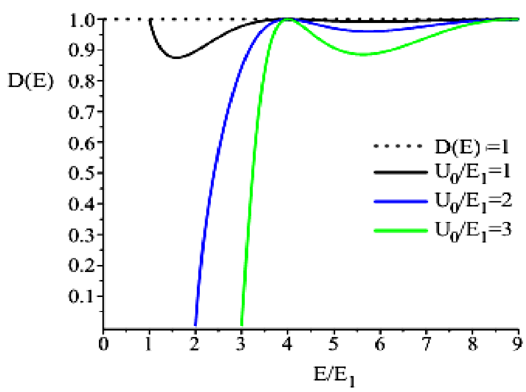
O‘tish koeffitsiyenti - o‘tgan to‘lqin oqimini tushgan to‘lqin oqimiga nisbatiga teng. (6-8) va chegaraviy shartlardan foydalansak quyidagi kelib chiqadi [9, 11]

$$D = \frac{J_3}{J_1} = \left[1 + \frac{U_0^2 \sin^2(K_2 W)}{4E(E - U_0)}\right]^{-1}, \quad E > U_0 \tag{9}$$

Ushbu formulani tahlil qilish maqsadida quyidagicha tasvirlaylik.



1-rasm. Kengligi W va chuqurligi U_0 bo‘lgan kvant o‘ra ko‘rinishi [11]



2-rasm. O‘tish koeffitsiyenti (10) ni energiyaga bog‘lanishi

$$D=\left[1+\frac{U_0^2\sin^2\left(\pi\sqrt{E/E_1}\right)}{4E\left(E-U_0\right)}\right]^{-1}, \quad E_1=\frac{\hbar^2\pi^2}{2m^{¿}W^2} \qquad (10)$$

2-rasmda o‘tish koeffitsiyenti (10) ni $U_0/E_1=1,2,3$ qiymatlardagi energiyaga bog‘lanishi grafigi keltirilgan.

2-rasmdan ko‘rinadiki, elektron energiyasi orta borsa o‘tish koeffitsiyenti ossillyatsiyalanar ekan. Energiyaning ma’lum qiymatlarida o‘tish ehtimoli muqarrar $D(E)=1$, boshqa qiymatlarda esa $D(E)<1$ - qaytish ehtimoli ham mavjud bo‘lar ekan. Energiyaning $D(E)=1$ shart bajariluvchi qiymatlari diskret bo‘lib, ular *rezonans energiya sathlari* deyiladi. Ushbu sathlarni (10) formuladan topish mumkin. Buning uchun $\sin^2\left(\pi\sqrt{E/E_1}\right)=0$ bo‘lishi kerak. Bu tenglama ildizlari

$$E_n=\frac{\hbar^2\pi^2n^2}{2m^{¿}W^2}, \quad E>U_0, \quad n=1,2,3\ldots \qquad (11)$$

Xulosa

O‘ra ustida harakatlanuvchi elektronda $E>U_0$ bo‘lgani uchun rezonans sathlarni ba’zan *virtual* yoki atom fizikasidagi kabi - *kvazistatsionar, metastabil sathlar* deb ham atashadi. Agar elektron kengligi W va balandligi U_0 bo‘lgan bitta potensial to‘siq ustida harakatlansa ham xuddi yuqoridagi kabi xususiyatlar kuzatiladi.

2-rasmdan ko‘rinadiki, ossillyatsiya amplitudasi kichik, maksimumlar atrofidagi piklar kengligi katta. Shu bois amalda bunday rezonanslarni kuzatish qiyin.

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