ТЕМПЕРАТУРНАЯ ЗАВИСИМОСТЬ ОСЦИЛЛЯЦИИ ПОПЕРЕЧНОГО МАГНИТОСОПРОТИВЛЕНИЯ В ОБЪЕМНЫХ УЗКОЗОННЫХ ПОЛУПРОВОДНИКАХ

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Аннотация: *В этой статье применена температурная зависимость колебаний поперечного магнитосопротивления узкозонных полупроводников. Новый метод расчета осцилляции поперечного магнитосопротивления* $\rho_{zz}^{3d}(E,B,T)$ *в объемных полупроводниках зависит от ширины зоны* $E_g^{3d}(T)$ *объемного узкозонного полупроводника. С помощью метода Варшни объяснен существенный вертикальный сдвиг осцилляций температурно-зависимых* $\rho_{zz}^{3d}(E,B,T)$ *объемных узкозонных полупроводников.*
Ключевые слова: *полупроводник, магнитное поле, магнитосопротивление, осцилляция, квантовая яма.*

HAJMIY TOR SOHALI YARIMO'TKAZGICHLARDA KO'NDALANG MAGNITOQARSHILIK OSSILLYATSIYALARINING HARORATGA BOG'LIQLIGI

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Annotatsiya: *Ushbu maqolada hajmiy tor sohali yarimo'tkazgichlarning ko'ndalang magnitoqarshilik ossillyatsiyalarining haroratga bog'liqligi tadbiq etilgan. Hajmiy yarimo'tkazgichlarda ko'ndalang magnitoqarshilik ossillyatsiyalari* $\rho_{zz}^{3d}(E,B,T)$ *ni hajmiy tor sohali yarimo'tkazgichning ta`qiqlangan soha kengligi* $E_g^{3d}(T)$ *ga bog'liqligini hisoblashning yangi usuli taklif etilgan. Hajmiy tor sohali yarimo'tkazgichlarning* $\rho_{zz}^{3d}(E,B,T)$ *ni haroratga bog'liqligida ossillyatsiyalarning vertikal bo'ylab jiddiy siljishi Varshni metodi yordamida tushuntirilgan.*
Kalit so'zlar: *yarimo'tkazgich, magnit maydon, magnitoqarshilik, ossillyatsiya, kvant o'ra.*

TEMPERATURE DEPENDENCE OF TRANSVERSE MAGNETORESISTANCE OSCILLATION IN BULK NARROW-BAND SEMICONDUCTORS

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Abstract: *In this article, the temperature dependence of transverse magnetoresistance oscillations of narrow-band semiconductors is applied. A new method for calculating transverse magnetoresistance oscillations* $\rho_{zz}^{3d}(E,B,T)$ *in volume semiconductors depends on the gap width* $E_g^{3d}(T)$ *of a volume narrow-band semiconductor. A significant vertical shift of oscillations in temperature-dependent* $\rho_{zz}^{3d}(E,B,T)$ *of volume narrow band semiconductors is explained using Varshni's method.*
Keywords: *semiconductor, magnetic field, magnetoresistance, oscillation, quantum well.*

Kvantlovchi magnit maydon ta`siridagi kvant magnit effektlari yordamida asosiy fizik kattaliklar: ko'ndalang magnitoqarshilik, magnit singdiruvchanlik, termoelektr EYUK va boshqa kinetik hodisalarni aniqlashga imkon beradi. Jumladan, ko'ndalang magnitoqarshilik va magnit singdiruvchanlik ossillyatsiyalari hajmiy yarim o’tkazgichli tuzilmalardagi erkin zaryad tashuvchilarning energiya spektrlari haqida qimmatli ma`lumotlarni beradi. Kvantlovchi magnit maydonda ko’ndalang magnitoqarshilik quyidagi ifoda yordamida aniqlanadi[1]:

$$\rho_{zz}^{3d}(E,B) = \frac{1}{\sigma_{zz}^{3d}(E,B)} = \left[-\frac{(2m)^{\frac{1}{2}} e^2}{\pi^2 \hbar^3} \hbar\omega_c \int_{\hbar\omega_c/2}^{\infty} \sum_{N_L} \left[E - \left(N_L^{3d} + \frac{1}{2} \right) \hbar\omega_c \right]^{1/2} \tau_{N_L}^{3d}(E) \frac{\partial f_0^{3d}(E)}{\partial E} dE \right]^{-1} \quad (1)$$

Bu yerda, N_L^{3d} – ruxsat etilgan sohadagi diskret Landau sathlari soni, ω_c -magnit maydonining siklotron chastotasi, $\tau_{N_L}^{3d}(E)$ - hajmiy yarimo’tkazgichlarda erkin elektronlarning impuls bo’yicha relaksasiya vaqti. *E* – kvantlovchi magnit maydondagi erkin elektron energiyasi. $\frac{\partial f_0^{3d}(E)}{\partial E}$ hajmiy yarimo’tkazgichlar uchun Fermi-Dirak taqsimot funksiyasining energiya bo’yicha olingan hosilasi. Ushbu formuladan ko’rinib turibdiki, effektiv massa energiya bo’yicha o’zgarmaydi, ya`ni bu ifoda faqat kvadratik dispersiya qonuni uchun amal qiladi. Lekin, shunday yarimo’tkazgichlar mavjudki, o’tkazuvchanlik sohasining tubi va valent sohasining shiftida joylashgan erkin zaryad tashuvchilarning effektiv massasi energiya bo’yicha kuchli o’zgaradi($m^*(E_n^{3d})$ va $m^*(E_p^{3d})$).

Bu holat ko’proq ta`qiqlangan sohasi kichikroq bo’lgan, ya`ni tor sohali yarimo’tkazgichlarda kuzatiladi[1-8].

Agar dispersiya qonuni kvadratik bo’lmasa, unda zaryad tashuvchilarning effektiv massasi energiyaga kuchli bog’liq bo’ladi($m^{¿}(E)$). [2-4].

So’nggi 10-15 yillarda hajmiy tor sohali yarimo’tkazgichli tuzilmalarda ko’ndalang magnitoqarshilik va magnit singdiruvchanlik ossillyatsiyalarini ($\rho_{zz}^{3d}(E,B)$ va $\chi_{zz}^{3d}(E,B)$) aniqlash bo’yicha bir qator tajriba natijalari olingan[9-12]. Bunda $\rho_{zz}^{3d}(E,B)$ va $\chi_{zz}^{3d}(E,B)$ o’zgarmas past haroratlarda kuzatilgan, lekin haroratning ortish dinamikasi bo’yicha, $\rho_{zz}^{3d}(E,B,T)$ ni nazariyasi ko’rilmagan.

Mavjud ilmiy adabiyotlardan ma`lumki, kuchli magnit maydondagi erkin elektronlarning energiyasi quyidagi ifoda bilan aniqlanadi [1]:

$$E_{N\pm}^{3d} = -\frac{E_g^{3d}}{2} + \frac{1}{2}\sqrt{(E_g^{3d})^2 + 4E_g^{3d}\left[\left(N + \frac{1}{2}\right)\hbar\omega_c + \frac{\hbar^2 k_z^2}{2m_n}\right]} \quad (2)$$

Bu ifoda hajmiy yarimo’tkazgichlar uchun o’rinli bo’lib, $\pm\frac{1}{2} g_0 \mu B$ spinning hadi hisobga olinmagan. E_N^{3d} - nokvadratik dispersiya qonuni uchun hajmiy yarimo’tkazgichlarning o’tkazuv-chanlik sohasidagi erkin elektron energiyasi. E_g^{3d} - uch o’lchovli tor sohali yarimo’tkazgichning ta`qiqlangan soha kengligi.

Bu yerda E_N - parabolik bo’lmagan dispersiya qonuniga ega kvantlovchi magnit maydondagi o’tkazuvchanlik zonasining elektron energiyalari. E_g - tor zonali yarim o’tkazgichlarning ta`qiqlangan zona kengligi.

(2) ifodadan k_z^{3d} ni aniqlab, uni differensiallaymiz:

$$dk_z^{3d} = \frac{\sqrt{2m}}{\hbar} \frac{\frac{2E_N}{E_g} + 1}{2\sqrt{\frac{E_N^2}{E_g} + E_N - \left(N + \frac{1}{2}\right)\hbar\omega_c}} \quad (3)$$

U holda, (3) ifodadan foydalanib, hajmiy yarimo’tkazgichlarda ko’ndalang magnitoqarshilik ossillyatsiyalari quyidagi formula orqali hisoblanadi:

$$\rho_{zz}^{3d} = \left[-\frac{(2m)^{\frac{1}{2}} e^2}{\pi^2 \hbar^3} \hbar\omega_c \int_{\hbar\omega_c/2}^{\infty} \sum_N \left(\frac{2E_N^{3d}}{E_g^{3d}} + 1 \right) \left[\frac{E_N^2}{E_g^{3d}} + E_N^{3d} - \left(N_L^{3d} + \frac{1}{2} \right) \hbar\omega_c \right]^{1/2} \tau_N^{3d}(E) \frac{\partial f_0^{3d}(E)}{\partial E} dE \right]^{-1} \quad (4)$$

Ushbu formuladan ma`lum bo’ldiki, $E_g^{3d} \to \infty$, ya`ni, material hajmiy keng sohali yarimo’tkazgichga aylansa, $\frac{2E_N}{E_g} \to 0$ va $\frac{E_N^2}{E_g} \to 0$ bo’ladi, bunda (4) ifoda (1) ga aylanadi. Bu esa oldingi qonuniyat bajarilayotganidan dalolat beradi.

Ma`lumki, erkin elektronlarning sochilish mexanizmida relaksasiya vaqtini aniqlashning bir qator turlari mavjud(optik, akustik va boshqalar). Biroq, ularning umumiy formulasi $\tau^{3d} = \tau_0^{3d} E^r$ - relaksasiya vaqtini aniqlash ifodasidan topiladi. Bunda, darajaning qiymati *r* ga qarab tarqalish mexanizmi o’zgaradi: $r = -\frac{1}{2}$ - akustik tebranish, $r = \frac{3}{2}$ - ionli tebranish [13].

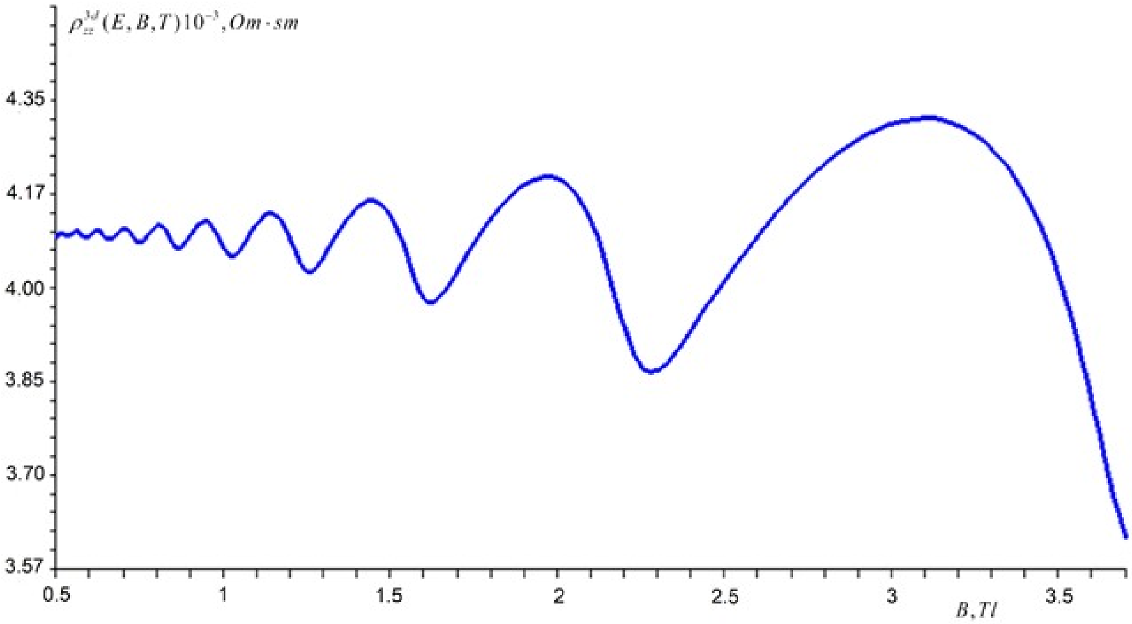
(4) formuladan foydalanib, nokvadratik dispersiya qonuni uchun tor sohali hajmiy yarimo’tkazgichlarda $\rho_{zz}^{3d}(E, B, T)$ ni turli haroratlarda tahlil qilaylik. Ushbu formula tahlilida amaliy matematik dasturlar (Maple) orqali grafik usuldan foydalanamiz. 1-rasmda hajmiy tor sohali *InSb* yarimo’tkazgich uchun $\rho_{zz}^{3d}(E, B, T)$ ni kvantlovchi magnit maydon induksiyasi *B* ga bog’liqligi grafigi keltirilgan. Bunda kvant ossillyatsiya jarayoni 0.5 Tl dan boshlangan va harorat T = 4 K da nazariy hisoblangan. *InSb* uchun ta`qiqlangan soha kengligi T = 0 K da $E_n^{3d} = 0.234\, eV$ [14] deb olingan. Magnit maydon induksiyasi qiymati B = 0.5÷3.5 Tl oraliqda diskret Landau sathlari soni $N_L^{3d} = 9$ ga teng bo’lishi aniqlangan. 1-rasmdagi grafikdan ko’rinib turibdiki, kvantlovchi magnit maydon induksiyasi ortishi bilan ko’ndalang magnitoqarshilik ossillyatsiyalarining amplitudalari balandligi ko’tarilishi kuzatilmoqda. Bu esa, albatta olingan (4) formulani kvant ossillyatsiya qonuniyatlari bajarilayotganligidan dalolat bermoqda.

Hajmiy yarimo’tkazgichlarda $\rho_{zz}^{3d}(E, B, T)$ ni $E_g^{3d}(T)$ ga bog’liqligini hisoblash

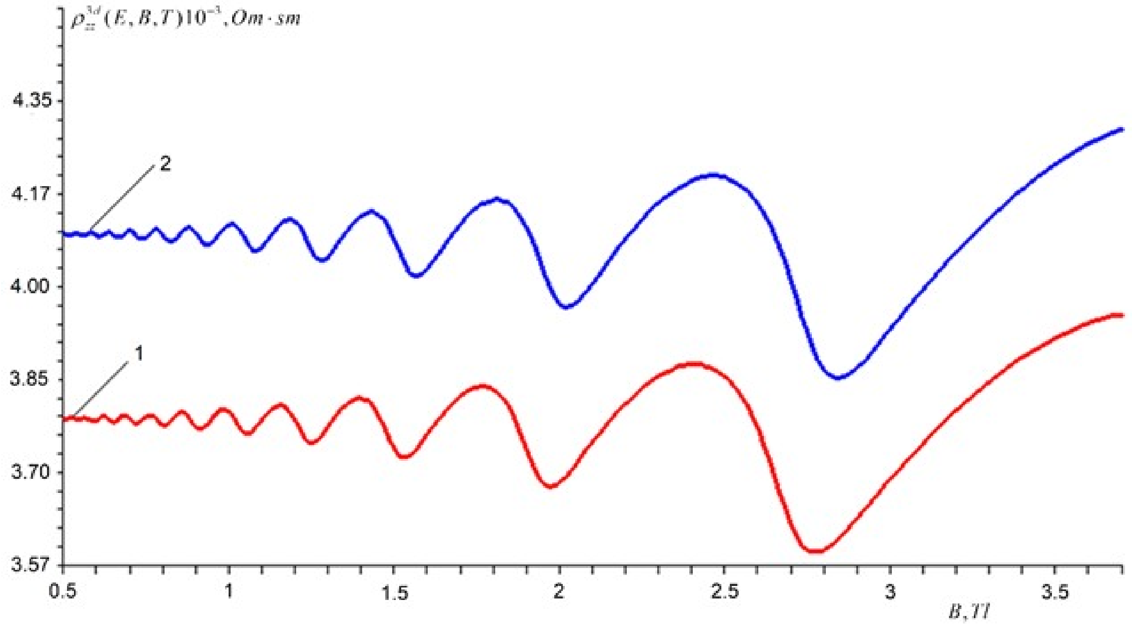
Hajmiy yarimo’tkazgichli materiallar uchun olingan (4) ifodadan ko’rinib turibdiki, $\rho_{zz}^{3d}(E, B, T)$ ossillyatsiyalari nafaqat haroratga, balki yarimo’tkazgichning ta`qiqlangan soha kengligiga ham bog’liq bo’lmoqda. Buni tahlil qilish uchun ikki xil tor sohali hajmiy yarimo’tkazgichlarda $\rho_{zz}^{3d}(E, B, T)$ ni hisoblaylik. 2-rasmda hajmiy yarimo’tkazgichlardagi ta’qiqlangan soha kengligini $\rho_{zz}^{3d}(E, B, T)$ ga bog’liqligi grafiklari ko’rsatilgan. 2-rasmda T = 4 K haroratda *InSb* (E_g = 0.234 eV [14]) va *InAs* (E_g=0.414 eV [14]) hajmiy yarimo’tkazgichlar uchun $\rho_{zz}^{3d}(E_g, B, T)$ ossillyatsiyalari keltirilgan. Bu ruxsat etilgan sohadagi ossillyatsiyalari soni 12 ga teng bo’lib, bu diskret Landau sathlari sonini anglatadi. Ushbu grafiklar (4) formula bo’yicha hisoblangan. Rasmdagi grafikdan ko’rinib turibdiki, hajmiy yarimo’tkazgichlarni ta’qiqlangan soha kengligini ortishi bilan $\rho_{zz}^{3d}(E_g, B, T)$ ossillyatsiyalari OY o’qiga nisbatan yuqoriga qarab siljishini kuzatish mumkin.

Xususan, sonli hisoblarga qarasak, *InSb* uchun B = 0.5 Tl, T = 4 K da $\rho_{zz}^{3d} \approx 3.76 \times 10^{-3}\ Om \cdot sm$ ga teng bo’lsa, *InAs* hajmiy yarimo’tkazgich uchun xuddi shu magnit maydon induksiyasi va haroratda ko’ndalang magnitoqarshilik ossillyatsiyasi qiymati $\rho_{zz}^{3d} \approx 4.06 \times 10^{-3}\ Om \cdot sm$ ga teng bo’ladi. Ushbu sonli usullar yordamida keltirilgan hisoblashlarni boshqa magnit maydon induksiyalarini qiymatlarida ham bajarish mumkin. Bunda $E_{g1}^{3d} > E_{g2}^{3d}$ bo'lsa, $\rho_{zz}^{3d}(E_{g1}, B, T) > \rho_{zz}^{3d}(E_{g2}, B, T)$ kelib chiqadi. Bundan xulosa qilish mumkinki, hajmiy tor sohali yarimo'tkazgichlarning ta'qiqlangan soha kengligi yordamida ko'ndalang magnitoqarshilik ossillyatsiyalarini boshqarishga imkon bermoqda. Bu esa, [15] ishda keltirilgan tajriba natijalarini, ya'ni harorat va ta'qiqlangan soha kengligini ortishi bilan $\rho_{zz}^{3d}(E_g, B, T)$ ni yuqoriga qarab harakatlanishi sababini tushuntira oladi. Biroq, mavjud adabiyotlarda keltirilgan (1) ifodadan ko'rinib turibdiki, kvadratik dispersiya qonuniga muvofiq, $\rho_{zz}^{3d}(B, T)$ ta'qiqlangan soha kengligiga bog'liq emas.

Endi hajmiy yarimo'tkazgichlarda ko'ndalang magnitoqarshilik ossillyatsiyalari $\rho_{zz}^{3d}(E, B)$ ni haroratga bog'liqligini ko'rib chiqaylik. Yuqorida keltirilgan 1 va 2-rasmlarda o'zgarmas past harorat T = 4 K da $\rho_{zz}^{3d}(E_g, B)$ hisoblangan. Bunda *kT ≈ 0.345* meV, bu esa albatta $\hbar\omega_c$ ga nisbatan juda kichik, ya'ni $\hbar\omega_c >> kT$.



1-rasm. *InSb* da T = 4 K da $\rho_{zz}^{3d}(E, B, T)$ ossillyatsiyalari.



2-rasm. Hajmiy yarimo'tkazgichlardagi ta'qiqlangan soha kengligini $\rho_{zz}^{3d}(E,B,T)$ ga bog'liqligi. Bunda *T* = 4 K. 1 – *InAs*, 2 –*InSb*.

Kvantlovchi magnit maydon qonuniga ko'ra, ushbu shart bajarilganda o'tkazuvchanlik sohasini diskret Landau sathlari keskin paydo bo'ladi. Har bir sathlarning cho'qqilari eng yuqori qiymatga ega bo'ladi. Bunda termik yuvilish juda zaif hisoblanadi. [16-21] ishlarda termik kengayish(yuvilish) qonuniyatini o'rganish maqsadida statistik funksiyalar – delta funksiyalardan (Lorens, Gauss, $\frac{\partial f_0}{\partial E}$, *GN* taqsimot funksiyalari) foydalanilgan.

$$\int_{-\infty}^{\infty}\delta(x,\gamma)dx = 1 \quad (5)$$

(5) shartni qanoatlantiruvchi, γ-parametrga bog'liq bo'lgan va "qo'ng'iroq" shaklidagi $\delta(x,\gamma)$ funksiya, $\lim_{\gamma\to 0}\delta(x,\gamma)\to\delta(x)$ ga aylanadi:

$$\delta(x) = \begin{cases} 0, & x \neq 0 \\ \infty, & x = 0 \end{cases} \quad (2.6)$$

Bunda,

$$\int_{-\infty}^{\infty}\delta(x)dx = 1 \quad (2.7)$$

Masalan, $\lim_{x\to 0}\frac{\sin x}{x}\to\infty$.

Yuqoridagi (5), (6) va (7) shartlarni qanoatlantiruvchi statistik funksiyalardan biri Fermi-Dirak taqsimot funksiyasidan energiya bo'yicha olingan hosila:

$$\lim_{T\to 0}\frac{\partial f_0}{dE}\to\delta(E,\mu) \quad (8)$$

Bundan, [22-26] ishlardan, (5) ÷ (8) shartlardan hamda hajmiy tor sohali yarimo'tkazgichlar uchun $\rho_{zz}^{3d}(E_g,B)$ ossillyatsiyalarini hisoblashda olingan (4) formulalardan ko'rinib turibdiki, $\rho_{zz}^{3d}(E_g,B)$ ni haroratga bog'liqligini, ya'ni $\rho_{zz}^{3d}(E_g,B,T)$ ni $\frac{\partial f_0(E,\mu,T)}{\partial E}$ orqali hisoblash mumkin.

Kvantlovchi magnit maydondagi diskret sathlarni termik yuvilishi hisobiga ushbu energetik sathlar silliqlanishiga olib keladi. Haroratning ko’tarilishi bilan $\rho_{zz}^{3d}(E_g,B,T)$ ossillyatsiya amplitudalari sekin pasaya boshlaydi. $kT \approx \hbar\omega_c$ shart bajarilganda, $\rho_{zz}^{3d}(E_g,B,T)$ ossillyatsiyalari yo’qoladi. $kT >> \hbar\omega_c$ da esa ko'ndalang magnitoqarshilik ossillyatsiyalari yo’qolib, uzluksiz energetik spektrga aylanadi.

[6, 27-33] ishlarda hajmiy yarimo’tkazgichlarning ta’qiqlangan soha kengligini haroratga bog’liqligi mukammal o’rganilgan. Jumladan, [27-28] ishlarda $GN(E,T)$ taqsimot funksiyasini ruxsat etilgan sohalarga qo’llash natijasida $E_g^{3d}(T)$ ni kelib chiqishini nazariy tahlili keltirilgan. Bunda, $GN(E,T)$ funksiyani qatorga yoyish orqali harorat ortishi bilan holatlar zichligining dumi ta’qiqlangan soha kengligiga kirib borishi kuzatilgan. Bundan tashqari [13-14, 34] ishlarda $E_g^{3d}(T)$ ni Varshnining empirik formulasi yoki Feynni analitik ifodasi va boshqa $E_g^{3d}(T)$ munosabatlar orqali nazariy va tajribaviy jihatdan muhokama qilingan. Masalan, Varshnining empirik formulasi quyidagi ko'rinishga ega [14, 34]:

$$E_g^{3d}(T) = E_g^{3d}(0) - \frac{\alpha_1 T^2}{\alpha_2 + T} \tag{9}$$

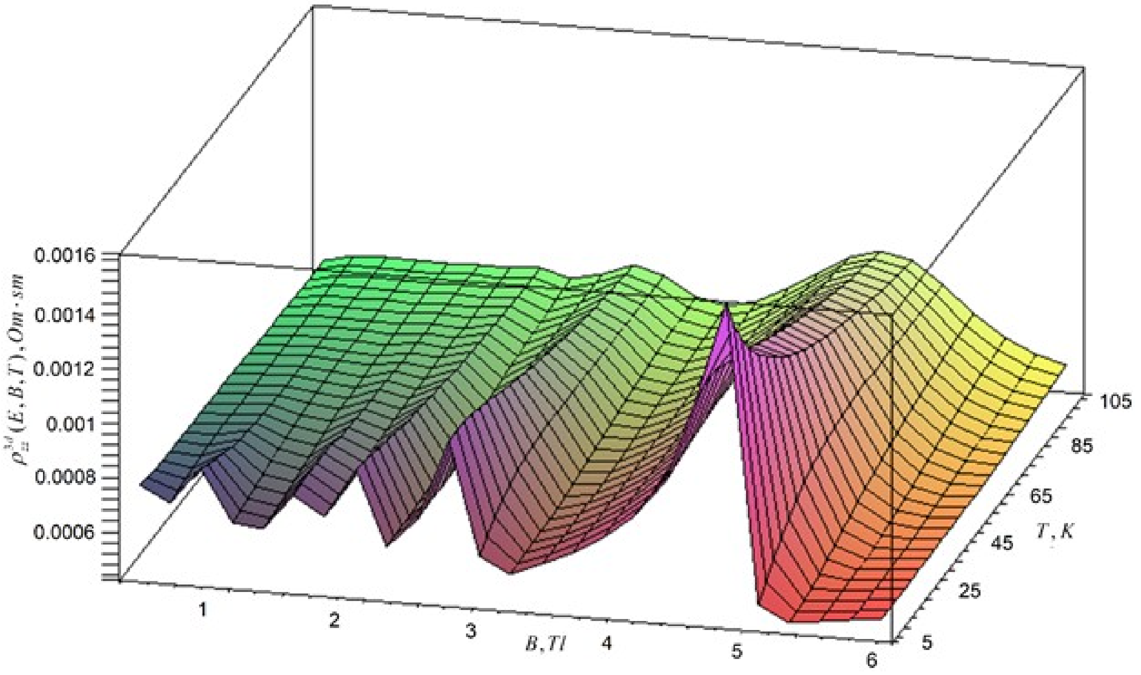
Bunda, α_1 va α_2 - hajmiy yarimo’tkazgichlarni termik – empirik parametrlari.

U holda, (5) ÷ (8) shartlar va (9) ifodalardan foydalanib, ko'ndalang magnitoqarshilik ossillyatsiyalari $\rho_g^{3d}(E_g^{3d}(T),B,T)$ ni quyidagicha aniqlanadi:

$$\rho_{zz}^{3d}(E_g(T),B,T) = \left(-\frac{(2m)^{\frac{1}{2}}e^2}{\pi^2\hbar^3}\right)\hbar\omega_c \cdot \left[\int_{\hbar\omega_c/2}^{\infty}\sum_{N_L}\tau_0 E' \left(\frac{2E_N}{E_g^{3d}(0) - \frac{\alpha_1 T^2}{\alpha_2 + T}} + 1\right)\left[\frac{E_N^2}{E_g^{3d}(0) - \frac{\alpha_1 T^2}{\alpha_2 + T}} + E_N - \left(N_L + \frac{1}{2}\right)\hbar\omega_c\right]^{1/2} \frac{\partial f_0(E,\mu,T)}{\partial E}dE\right]^{-1} \tag{10}$$

Yangi keltirib chiqarilgan (10) analitik ifoda $\rho_g^{3d}(E,B,T)$ ni $E_g^{3d}(T)$ orqali aniqlash formulasi, ya’ni $\rho_{zz}^{3d}(E_g^{3d}(T),B,T)$ - hajmiy tor sohali ko'ndalang magnitoqarshilik ossillyatsiyalari deyiladi. Endi, ushbu taklif qilinayotgan (10) analitik ifoda orqali turli haroratlarda $\rho_{zz}^{3d}(E_g^{3d}(T),B,T)$ ossillyatsiyalarini grafik tahlil qilaylik.

3-rasmda *n-*$Bi_2Te_{2.85}Se_{0.15}$ tor sohali hajmiy yarimo’tkazgich uchun uch o’lchamli $\rho_{zz}^{3d}(E_g^{3d}(T),B,T)$ ko'ndalang magnitoqarshilik ossillyatsiyalari kiritilgan. Bunda, *n-*$Bi_2Te_{2.85}Se_{0.15}$ uchun $E_g^{3d}(0) = 0.18\,eV$ [35] ga teng bo’lib, magnit maydon induksiyasi qiymati 0.5 Tl dan 6 Tl gacha, harorat esa 5 K dan 105 K gacha o’zgarmoqda. Ushbu 3D grafikdan ko’rinib turibdiki, harorat T = 5 K da $\rho_{zz}^{3d}(E_g^{3d}(T),B,T)$ ossillyatsiya amplitudalari keskin ko’rinmoqda. Hatto, kichik magnit maydonlarda (B = 1 Tl) ham ossillyatsiya cho’qqilari yaqqol kuzatilmoqda. Harorat sekin ko’tarilgan sari (T = 10 K, 15 K, 25 K) $\rho_{zz}^{3d}(E_g^{3d}(T),B,T)$ ossillyatsiya cho’qqilari pasaya boshlamoqda, magnit maydon induksiyasi qiymat B = 0.5 Tl ÷ 1.5 Tl oraliqda bu cho’qqilar yo’qolmoqda. Harorat 105 K da esa $\frac{\partial f_0(E,\mu,T)}{\partial E}$ delta funksiyani termik yuvilish hisobiga B = 0.5 Tl ÷ 4 Tl oraliqda $\rho_{zz}^{3d}(E_g^{3d}(T),B,T)$ ossillyatsiyalari uzluksiz energetik spektrga aylanmoqda, ya’ni bunda magnit maydon ta’siri ko’rinmayapti. Xulosa qilib shuni aytish mumkinki, keng sohali hajmiy yarimo'tkazgichlarda $\rho_{zz}^{3d}(E,B,T)$ ossillyatsiyalarini hisoblash uchun (1) formula bo'yicha, tor sohali hajmiy yarimo'tkazgichlarda esa, biz taklif qilayotgan (10) analitik ifodalardan foydalanish tavsiya etiladi.



3-rasm. ***n-$Bi_2Te_{2.85}Se_{0.15}$*** **tor sohali hajmiy yarimo'tkazgich uchun** $\rho_{zz}^{3d}(E_g^{3d}(T),B,T)$ **ossillyatsiyalarining uch o'lchamli ko'rinishi**

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