IRSTI 29.19.31; 29.19.23 https://doi.org/10.26577/RCPh2025954

Adem Akkuş
Gaziosmanpaşa University, Tokat, Turkey
*e-mail: ademakkus76@yahoo.com

AN ANALYTICAL EVALUATION OF SEMICONDUCTOR RESISTANCE CHANGES IN WEAK MAGNETIC FIELDS

Variations in electrical resistance under the influence of magnetic fields play a crucial role in numerous technological applications, including hard disk drives and microcircuit sensors. In this study, the change in the electrical resistance of a semiconductor exposed to a weak magnetic field is examined within a generalized theoretical framework. The analysis is carried out by formulating the system using single-parameter Fermi–Dirac distribution functions. All calculations use the analytical expression of these functions proposed by the author. A comparison between the analytical results and those obtained through numerical methods demonstrates a high degree of agreement, confirming the reliability and accuracy of the proposed formulation. The analytically derived results are presented in tabular form to enhance clarity and facilitate direct comparison. This approach not only provides a simplified analytical treatment of magnetoresistance effects in semiconductors, but also enables the modeling of material behavior under variable external conditions. Therefore, the formulation developed in this work is expected to contribute to the theoretical design of semiconductor devices, particularly in applications requiring precise control of electronic transport properties under magnetic influence.

Keywords: magnetic field, semiconductors, resistivity, Fermi-Dirac distribution functions, chemical potential.

Адем Аққұс
Газиосманпаша университеті, Токат, Түркия
*e-mail: ademakkus76@yahoo.com

Жартылай өткізгіштердің кедергісінің әлсіз магнит өрістеріндегі өзгерістерін аналитикалық бағалау

Электрлік кедергінің магниттік өрістер әсерінен өзгеруі қатты дискілер мен микросхема сенсорлары сияқты көптеген технологиялық қолданбаларда маңызды рөл атқарады. Бұл ұсынылған зерттеуде әлсіз магниттік өріске ұшыраған шала өткізгіштің электрлік кедергісінің өзгерісі жалпыланған теориялық негізде қарастырылады. Талдау бір параметрлі Ферми–Дирак таралу функцияларын қолдану арқылы жүргізілді. Барлық есептеулерде автордың ұсынған функциялардың аналитикалық өрнегі пайдаланылды. Аналитикалық нәтижелер мен сандық әдістер арқылы алынған нәтижелерді салыстыру жоғары деңгейдегі сәйкестікті көрсетті, яғни, бұл ұсынылған тәсілдің сенімділігі мен дәлдігін дәлелдейді. Алынған аналитикалық нәтижелер анықтылықты арттыру және тікелей салыстыруды жеңілдету үшін кестелік түрде берілген. Бұл тәсіл жартылай өткізгіштердегі магниткедергі әсерлерін аналитикалық түрде қарастыруды жеңілдетіп қана қоймай, сонымен қатар сыртқы шарттар өзгергенде материалдың мінез-құлқын модельдеуге мүмкіндік береді. Сондықтан, осы жұмыста ұсынылған формулалар магнит өрісі әсеріндегі электрондық тасымалдау қасиеттерін дәл бақылауды қажет ететін қолданбалар үшін жартылай өткізгіш құрылғыларды теориялық жобалауға маңызды үлес қоса алады.

Түйін сөздер: магнит өрісі, жартылай өткізгіштер, электрлік кедергі, Ферми–Дирак таралу функциялары, химиялық потенциал.

Адем Аккуш
Университет Газиосманпаша, Токат, Турция
*e-mail: ademakkus76@yahoo.com

Аналитическая оценка изменений сопротивления полупроводников в слабых магнитных полях

Изменения электрического сопротивления под воздействием магнитных полей играют важную роль во многих технологических приложениях, включая жёсткие диски и микросхемные датчики. В данном исследовании рассматривается изменение электрического сопротивления полупроводника, подвергнутого воздействию слабого магнитного поля, в рамках обобщённой теоретической модели. Анализ проводится с использованием однопараметрических функций распределения Ферми–Дирака. Во всех вычислениях используется аналитическое выражение этих функций, предложенное автором. Сравнение между аналитическими результатами и результатами, полученными численными методами, демонстрирует высокий уровень согласия, что подтверждает достоверность и точность предложенной формулировки. Полученные аналитические результаты представлены в табличной форме для повышения наглядности и облегчения прямого сравнения. Данный подход не только упрощает аналитическое описание эффектов магнетосопротивления в полупроводниках, но и позволяет моделировать поведение материала при изменяющихся внешних условиях. Следовательно, разработанная в данной работе модель может способствовать теоретическому проектированию полупроводниковых устройств, особенно в приложениях, требующих точного контроля электронного транспорта под воздействием магнитных полей.

Ключевые слова: магнитное поле, полупроводники, электросопротивление, функции распределения Ферми–Дирака, химический потенциал.

Introduction

Organic semiconductors are widely used as important functional materials in many areas of electrical and electronic technology [1–6]. These materials possess unique electronic properties and functionalities that can be tailored through chemical synthesis to meet specific requirements. Additionally, they are expected to provide electronic applications that are more cost-effective, lighter, and mechanically flexible than current inorganic-based technologies. However, there is still much to learn about the properties of these materials, which can behave differently depending on external factors such as magnetic field, temperature, film thickness, and others [7–14].

One such external factor is the change in electrical resistance of materials under magnetic fields, a phenomenon known as magnetoresistance. Magnetoresistance is widely used in commercial applications, such as computer hard disks and on-chip sensors.

In organic semiconductors, magnetoresistance, referred to as organic magnetoresistance (OMAR) is characterized by changes in electrical resistance upon application of a magnetic field. This effect is typically explained by mechanisms such as spin-dependent processes and hyperfine interactions and plays a significant role in the development of organic spintronic devices [15-20].

In this study, the change in the resistance of semiconductors exposed to an external magnetic field is calculated using an analytical approach based on Fermi–Dirac distribution functions. An analytical formula expressing this behavior has been derived within the framework of kinetic theory using one-dimensional Fermi functions.

The proposed theoretical approach may contribute to guiding future experimental studies in the right direction.

Methods

Analytical formula for calculating semiconductor resistance in a weak magnetic field

Using kinetic theory of transport phenomena, the analytical formula for the change in the resistance of semiconductors under the influence of a weak magnetic field can be expressed as follows [2–4]:

$$\rho(H,\eta)=\rho(0)\left[1+\left(\frac{uH}{c}\right)^2 A_2(\eta)\right] \tag{1}$$

Here, μ is the chemical potential, B is the magnetic field, χ represents the magnetic susceptibility, and $\rho(0)$ is the resistivity in the absence of a magnetic field. The function $A_2(\eta)$ is defined as follows:

$$\begin{aligned}A_2(\eta)=\frac{(F_{3/2}(\eta))^2}{(F_{r+1}(\eta))^4}&[F_{r+1}(\eta)F_{3r+1}(\eta)\\&-(F_{2r+1/2}(\eta))^2\end{aligned} \tag{2}$$

Here, $F_\alpha(\eta)$ is the Fermi function, defined as follows:

$$F_\alpha(\eta)=\int_0^\infty \frac{e^{x-\eta}x^\alpha}{e^{x-\eta}+1}dx\,, \tag{3}$$

Here, η is the variable $-\infty<\eta<\infty$ varies within a certain interval, and α is the parameter can take arbitrary integer or non-integer values. In cases involving charge carriers scattered by acoustic phonons or by ions, the constant r typically takes the values $r=0$, $r=2$, respectively. In the study [21], authors have provided the following analytical formulas for the precise calculation of the one-parameter Fermi function:

$$\begin{aligned}F_\alpha(\eta)=&\frac{\eta^{\alpha+1}}{\alpha+1}+\lim_{N\to\infty}\sum_{i=1}^{N} f_i(-1)K_i(\alpha,\eta)\\&+\lim_{N'\to\infty}\sum_{j=0}^{N'} f_j(-1)e^{\eta(1+j)}\\&\times\frac{\Gamma(\alpha+1,\eta(j+1))}{(j+1)^{\alpha+1}}\quad \text{for}\quad 0<\eta<\infty\end{aligned} \tag{4}$$

and

$$\begin{aligned}F_\alpha(\eta)=&\lim_{L\to\infty}\sum_{i=0}^{L} f_i(-1)e^{-|\eta|(i+1)}\\&\times\frac{\Gamma(\alpha+1)}{(i+1)^{\alpha+1}}\quad \text{for}\quad -\infty<\eta\le 0\end{aligned}\,. \tag{5}$$

where the function $K_i(\alpha,\eta)$ is calculated according to the following formula:

$$K_i(\alpha,\eta)=\begin{cases}\sum_{j=0}^{\alpha}(-1)^j f_j(\alpha)\eta^{\alpha-j}\\ \times\frac{\gamma(j+1,i\eta)}{i^{j+1}}\ \text{for integer}\ \alpha>0\\ \lim_{M\to\infty}\sum_{j=0}^{M}(-1)^j f_j(\alpha)\eta^{\alpha-j}\\ \times\frac{\gamma(j+1,i\eta)}{i^{j+1}}\ \text{for noninteger}\ \alpha\end{cases} \tag{6}$$

In Eqs. (4), (5), and (6), the indices $N, L, M\ ve\ N'$ are the upper bounds of the sums. special functions $\Gamma(\alpha)$, $\Gamma(\alpha,x)\ ve\ \gamma(\alpha,x)$ are complete and incomplete Gamma functions and are written as follows [22-24]:

$$\Gamma(\alpha)=\int_0^\infty t^{\alpha-1}e^{-t}dt \tag{7}$$

$$\gamma(\alpha,x)=\int_0^x t^{\alpha-1}e^{-t}dt \tag{8}$$

$$\Gamma(\alpha,x)=\int_x^\infty t^{\alpha-1}e^{-t}dt \tag{9}$$

Calculation results and discussion

The change in the electrical resistance of semiconductors under weak magnetic fields has been calculated using Equation (1) for various values of the η relevant parameters. A computational algorithm based on Equation (1) was developed using the Mathematica 10 programming language. The calculations were carried out for silicon (Si) as the semiconductor material, considering the hole mobility $u = 45.10^{-3} m^2 / V.s$, intrinsic resistivity $\rho(0) = 25\,\Omega.m$, and the applied magnetic field $H = 0.05\,Tl$. Our analytical results, alongside those obtained from numerical integration methods, are presented in Table 1. As can be seen from the table, there is a good agreement between the analytical calculations and the numerical results, confirming the accuracy and reliability of the proposed analytical approach. Furthermore, the results indicate that the derived analytical expression is general and remains valid for arbitrary values of the physical parameters.

Table 1. Comparative results for the electrical resistance of the semiconductor under the weak magnetic field

η	Eq. (1)	Numerical calculation results
-5.0	3.99905770701113E-09	3.99905770701113E-09
-0.3	3.999057707013538E-09	3.999057707013555E-09
-0.7	3.999057707012535E-09	3.999057707012535E-09
-1.6	3.999057707011747E-09	3.999057707011747E-09
-4.8	3.999057707010885E-09	3.99905770708621E-09
-8.8	3.999057707010217E-09	3.999057707010211E-09
1.0	3.999057707016095E-09	3.999057707016061E-09
2.6	3.999057707031013E-09	3.99905770702209E-09
16.8	3.999057707180921E-09	3.99905770710575E-09

Conclusion

This general applicability highlights the advantage of the analytical formulation in modeling the magnetoresistive behavior of semiconductors under weak magnetic fields. It offers a useful theoretical framework that can complement experimental investigations and support the design of magneto-sensitive semiconductor devices.

References

1 A.B. Pippard, Magnetoresistance in Metals, (Cambridge Press, Cambridge, UK, 1989).

2 B.M. Askerov, Kinetic effects in semiconductor, (Leningrad, , Russia, 1970). (in Rus.).

3 B.M. Askerov, Electron transport in semiconductor, (Word Scientific, Singapore, 1985).

4 W. Jones, & H. N. Norman, Theoretical Solid State Physics, (Dover, London, UK, 1985).

5 J. M. Ziman, Electrons and phonons: The theory of transport phenomena in solids, (Clarendon Press, Oxford, 1960).

6 O.S. Gryazanov, Tables for the calculation of kinetic coefficients in semiconductors, (Nauka, Leningrad, Russia, 1971).

7 F.J. Blatt, Theory of Mobility of Electrons in Solids, Solid State Phys. **4**, 199–366 (1957). https://doi.org/10.1016/S0081-1947(08)60155-1

8 R. Saffert, J. Schapawalow, G. Landwehr, E. Gmelin, Nernst-Ettingshausen and Seebeck Effect of Pure and Electron-Irradiated Tellurium at Low Temperatures, Phys. Stat. Sol. B**.** **61,** 509–519 (1974). https://doi.org/10.1002/pssb.2220610216

9 X. Liu, X. C. Xie, Spin Nernst effect in the absence of a magnetic field, Solid State Commun. **150**, 471–474 (2010). https://doi.org/10.1016/j.ssc.2009.12.017

10 V. V. Shchennikov, S. V. Ovsyannikov, Thermoelectric power, magnetoresistance of lead chalcogenides in the region of phase transitions under pressure, Solid State Commun. **126**, 373–378 (2003). https://doi.org/10.1016/S0038-1098(03)00210-2

11 P. Drude, Zur Elektronentheorie der Metalle, Ann. Phys. **306**, 566-613 (1900). https://doi.org/10.1002/andp.19003060312

12 U.I. Erkaboev, R. G. Rakhimov, J. I. Mirzaev, N. A. Sayidov, The influence of external factors on quantum magnetic effects in electronic semiconductor structures, Int. J. Innov. Technol. Explor. Eng. **9**, 1557-1563 (2000). htts://doi.org/10.35940/ijitee.E2613.039520

13 R.W. Series, & D.T.J. Hurle, The use of magnetic fields in semiconductor crystal growth, J. Cryst. Growth. **113,** 305-328 (1991). https://doi.org/10.1016/0022-0248(91)90036-5

14 C. Frank-Rotsch, N. Dropka, F. M. Kießling, P. Rudolph, Semiconductor crystal growth under the influence of magnetic fields Cryst. Res. Technol. **55**, 1900115 (2020). https://doi.org/10.1002/crat.201900115

15 P. A. Bobbert, T. D. Nguyen, F. W. A. Van Oost, V. B. Koopmans, M. Wohlgenannt, Bipolaron mechanism for organic magnetoresistance, Phys. Rev. Lett. **99**, 216801 (2007). https://doi.org/10.1103/PhysRevLett.99.216801

16 W. Wagemans, P. Janssen, A. J. Schellekens, F. L. Bloom, P. A. Bobbert, B. Koopmans, The many faces of organic magnetoresistance, In Spin. **1**, 93-108 (2011). https://doi.org/10.1142/S2010324711000082

17 U. Niedermeier, M. Vieth, R. Pätzold, W. Sarfert, H.Von Seggern, Enhancement of organic magnetoresistance by electrical conditioning, App. Phys. Lett. **92**, 193309 (2008). https://doi.org/10.1063/1.2924765

18 V. N. Prigodin, J. D. Bergeson, D. M. Lincoln, A. J. Epstein, Anomalous room temperature magnetoresistance in organic semiconductors, Synth. Met. **156,** 757-761 (2006). https://doi.org/10.1016/j.synthmet.2006.04.010

19 F. L.Bloom, W. Wagemans, B. Koopmans, Temperature dependent sign change of the organic magnetoresistance effect, J. Appl. Phys. **103**, 07F320 (2008). https://doi.org/10.1063/1.2839317

20 J. Ren, Y. Zhang, S. Xie, Charge current polarization and magnetoresistance in ferromagnetic/organic semiconductor/ferromagnetic devices, Org. Electro. **9**, 1017-1021 (2008). https://doi.org/10.1016/j.orgel.2008.07.008

21 I. I. Guseinov, B. A. Mamedov, Unified treatment for accurate and fast evaluation of the Fermi Dirac functions, Chin. Phys. B. **19**, 050501 (2010). https://doi.org/10.1088/1674-1056/19/5/050501

22 I. S. Gradshteyn, I. M. Ryzhik, Tables of Integrals, Sums, Series and Products, (4th ed., Academic Press, New York, 1980).

23 I. I. Guseinov, B. A.Mamedov, M. Kara, M. Orbay, On the computation of molecular auxiliary functions A_n and B_n, Pramana J. Phys. **56**, 691-696 (2001). https://doi.org/10.1007/s12043-001-0093-x

24 E. Çopuroğlu, Theoretical estimation of entropy of solids by using integer and non-integer n-dimensional Debye functions. Physica A: Statistical Mechanics and its Applications, **593**, 126915 (2002). https://doi.org/10.1016/j.physa.2022.126915

Мақала тарихы:
Түсті – 02.06.2025
Түзетілген түрде түсті – 20.12.2025
Қабылданды – 20.12.2025

Article history:
Received 02 June 2025
Received in revised form 20 December 2025
Accepted 20 December 2025

Автор туралы мәлімет:

Адем Аққұс – PhD, физика кафедрасы, Газиосманпаша университеті, Токат, Түркия, e-mail: ademakkus76@yahoo.com

Information about authors

Adem Akkuş – PhD, Department of Physics, Gaziosmanpaşa University, Tokat, Turkiye, e-mail: ademakkus76@yahoo.com