



(RESEARCH ARTICLE)



PHENOMENOLOGICAL STUDY OF THE DIFFUSION COEFFICIENT OF A SERIES VERTICAL JUNCTION SILICON SOLAR CELL

Mountaga BOIRO *, Mamadou Yacine BA, Dibor FAYE, Mamadou Bamba SENE, and Amadou DIAO

Laboratoire de Semi-conducteurs et d'Energie Solaire, Département de Physique, Faculté des Sciences et Techniques, Université Cheikh Anta DIOP, Dakar, Sénégal.

* Corresponding Author

ORCID Details

Mountaga BOIRO: <https://orcid.org/0009-0001-9742-2220>

Mamadou Yacine BA: <https://orcid.org/0009-0006-2423-2713>

Dibor FAYE: <https://orcid.org/0009-0000-2905-4406>

Mamadou Bamba SENE: <https://orcid.org/0009-0002-8193-9169>

Amadou DIAO: <https://orcid.org/0000-0002-7658-6293>

World Journal of Advanced Research and Reviews, 2026, 32(01), 1068–1073

Publication history: Received on 09 September 2026; revised on 15 October 2026; accepted on 17 October 2026

Article DOI: <https://doi.org/10.30574/wjarr.2026.32.1.2653>

Copyright © 2026 Author(s) retain the copyright of this article. This article is published under the terms of the Creative Commons Attribution License 4.0

ABSTRACT

Within the framework of phenomenological studies, this research highlights the Bode and Nikyste diagrams of the diffusion coefficient as a function of the resonance frequency and the cutoff frequency. We determined the expression of the complex diffusion coefficient D_n^* as a function of the excitation frequency and the magnetic field. Since the diffusion coefficient is a recombination parameter that models the cell's ability to diffuse carriers within the material, we identified three behaviors of the solar cell resistive, inductive, and capacitive during the diffusion process

Keywords: Bode's diagram, Nyquist's diagram, Cut-off frequency, Resonance frequency, Magnetic field, Photovoltaic cell, Vertical series junction.

1 INTRODUCTION

Indeed, against a global backdrop of rising consumption—linked in particular to rapid population growth—reserves are becoming increasingly scarce. It is estimated that global reserves will be depleted by around 2030 if consumption is not radically altered, and by 2100 at the latest if efforts are made to address both production and consumption [1].

These constraints can be summarized as “socioeconomic and ecological constraints” [2]. Among these solutions, electricity generation using solar cells has been the focus of significant research attention, as it appears to be one of the possible solutions to the environmental problem [3]. It is a clean energy source [4] that does not emit CO₂ into the atmosphere, so its environmental impact is minimal. Photovoltaic (PV) systems, made from semiconductor materials, convert photons into electricity. This is how an electric current is generated when the circuit is closed to an external load [3, 5]. Photovoltaic energy offers new possibilities for access to energy thanks to its ease of implementation. Since

the first solar cell was presented by Bell Labs in 1954 [6,7]. The solar cell market is dominated by the use of silicon due to the low cost and easy availability of this semiconductor. However, laboratory data show that the efficiency of silicon photovoltaic solar cells is currently around 26% [8,9]. Due to its greater resistance to radiation and its applications in the space sector, p-type bulk silicon was the first type of solar cell to be studied and produced [10,11]. Several factors affect the efficiency of solar cells. In an effort to improve the conversion efficiency of photovoltaic modules, research has been conducted on bifacial solar cells [12–13], monofacial solar cells [3, 14–15], and vertical-junction solar cells [16–17]. This research can be conducted under steady-state conditions [17], transient conditions [18–19], and dynamic frequency-domain conditions [20]. The purpose of this article is to compare the phenomenological behavior of a series vertical-junction silicon solar cell and a bifacial solar cell under a magnetic field.

2 MATHEMATICAL MODELING OF THE PROBLEM

A monocrystalline silicon cell consists of a single crystal. It has a uniform appearance and is bluish-gray or black in color. There are also cells composed of several assembled crystals, known as microcrystalline silicon (grains smaller than 1 μm), polycrystalline (grains smaller than 1 mm), or multicrystalline (grains smaller than 10 cm). These can be recognized—if the grains are thick enough—because they form a mosaic of twinning planes [21].

The vertical-junction solar cell is designed such that the incident light rays are parallel to the junction plane. Shown here are an n+-p-p+ series vertical-junction solar cell [10] and a single cell from a series vertical-junction solar cell under a magnetic field.

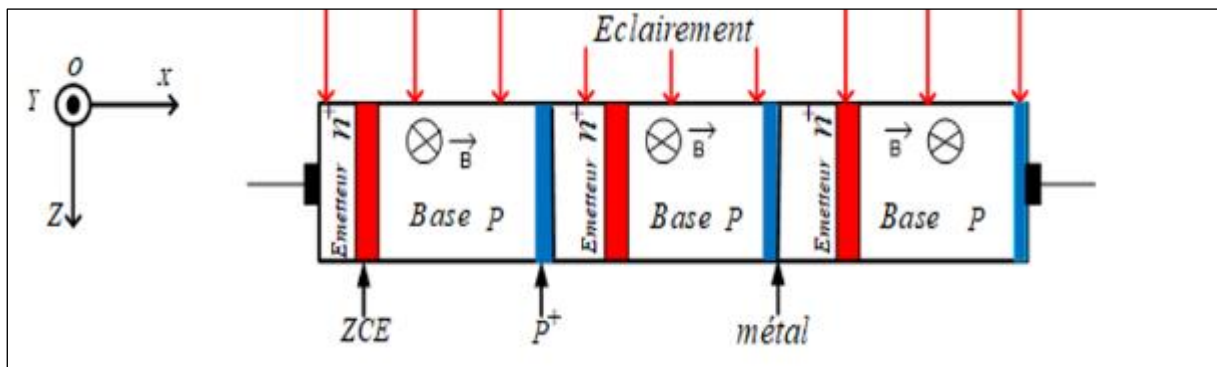


Figure 1: Series Vertical-Junction Photovoltaic Cell

When the photovoltaic cell is illuminated, the photogenerated minority carriers in the base are governed by the continuity equation in the dynamic frequency domain [22]:

$$D^* \cdot \frac{\partial^2 \delta(x,z,t)}{\partial x^2} - \frac{\delta(x,z,t)}{\tau} = -G(z,t) + \frac{\partial \delta(x,z,t)}{\partial t} \quad (1)$$

Where x and z are the spatial variables, along the (ox) and (oy) axes, respectively.

D^* is the complex electron diffusion coefficient as a function of the magnetic field and the modulation frequency; t is time; τ is the average lifetime of minority carriers in the base;

$\delta(x,z,t)$ is the density of minority carriers in the base; and $G(z,t)$ is the overall generation rate of minority carriers.

$$\delta(x,z,t) = \delta(x,z) \cdot e^{i\omega t} \quad (2)$$

Where $e^{i\omega t}$ is the temporal component, $g(z)$ and $\delta(x,z)$ are the spatial components of the doping rate and the minority carrier density, respectively. The expression for the generation rate $g(z)$ is given by:

$$g(z) = \alpha \phi (1 - R) \times e^{-\alpha z} \quad (3)$$

Let ϕ be the flux of incident monochromatic photons; α be the monochromatic absorption coefficient of the material, and R be the monochromatic reflectance coefficient of the material. Substituting equations (3) and (2) into equation (II-1) yields:

$$\frac{\partial^2 \delta(x,z,\lambda,\omega,B)}{\partial x^2} - \frac{\delta(x,z,\lambda,\omega,B)}{L^2(\omega,B)} = -\frac{g(z)}{D(\omega,B)} \quad (4)$$

$L^*=L(\omega, B)$ represents the complex diffusion length. It depends on the excitation frequency and the magnetic field.

We define:

$$L^2(\omega, B) = \tau \cdot D(\omega, B) \quad (5)$$

A general solution to equation (II-5) is:

$$\delta(x, z, \lambda, \omega, B) = K_1 \cdot e^{\frac{x}{L(\omega, B)}} + K_2 \cdot e^{-\frac{x}{L(\omega, B)}} + \frac{L^2(\omega, B)}{D(\omega, B)} \cdot \phi \cdot \alpha \cdot (1 - R) e^{-\alpha \cdot z} \quad (6)$$

Where the coefficients K_1 and K_2 are determined by the boundary conditions.

at the emitter-base junction ($x = 0$):

$$D(\omega, B) \cdot \frac{\partial \delta(x, z, \lambda, \omega, B)}{\partial x} \Big|_{x=0} = S_f \cdot \delta(x, z, \lambda, \omega, B) \Big|_{x=0} \quad (7)$$

in the middle of the base at $x = H/2$:

$$\frac{\partial \delta(x, z, \lambda, \omega, B)}{\partial x} \Big|_{x=\frac{H}{2}} = 0 \quad (8)$$

Let H be the thickness of the base of the photovoltaic cell along the (ox) axis; let S_f be the recombination rate at the junction.

Results and Discussion

Bode's Diagram

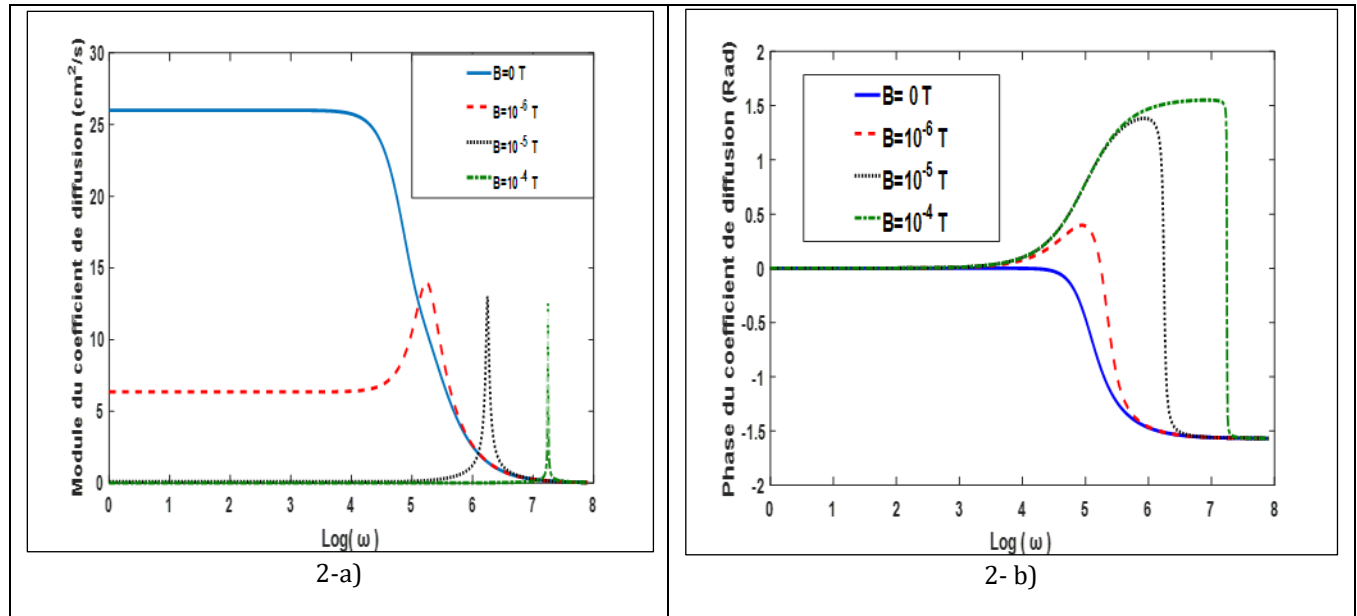


Figure 2: The Bode plot The diffusion coefficient 2-a) is virtually independent of frequency when the magnetic field is zero. When a magnetic field is applied, resonance peaks appear. The diffusion coefficient models the ability of minority carriers to diffuse within the material. In practice, as the excitation frequency and the magnetic field increase, the magnitude of the diffusion coefficient decreases. The phase 2-b) can be zero, positive, or negative. This reflects resistive, inductive, and capacitive phenomena.

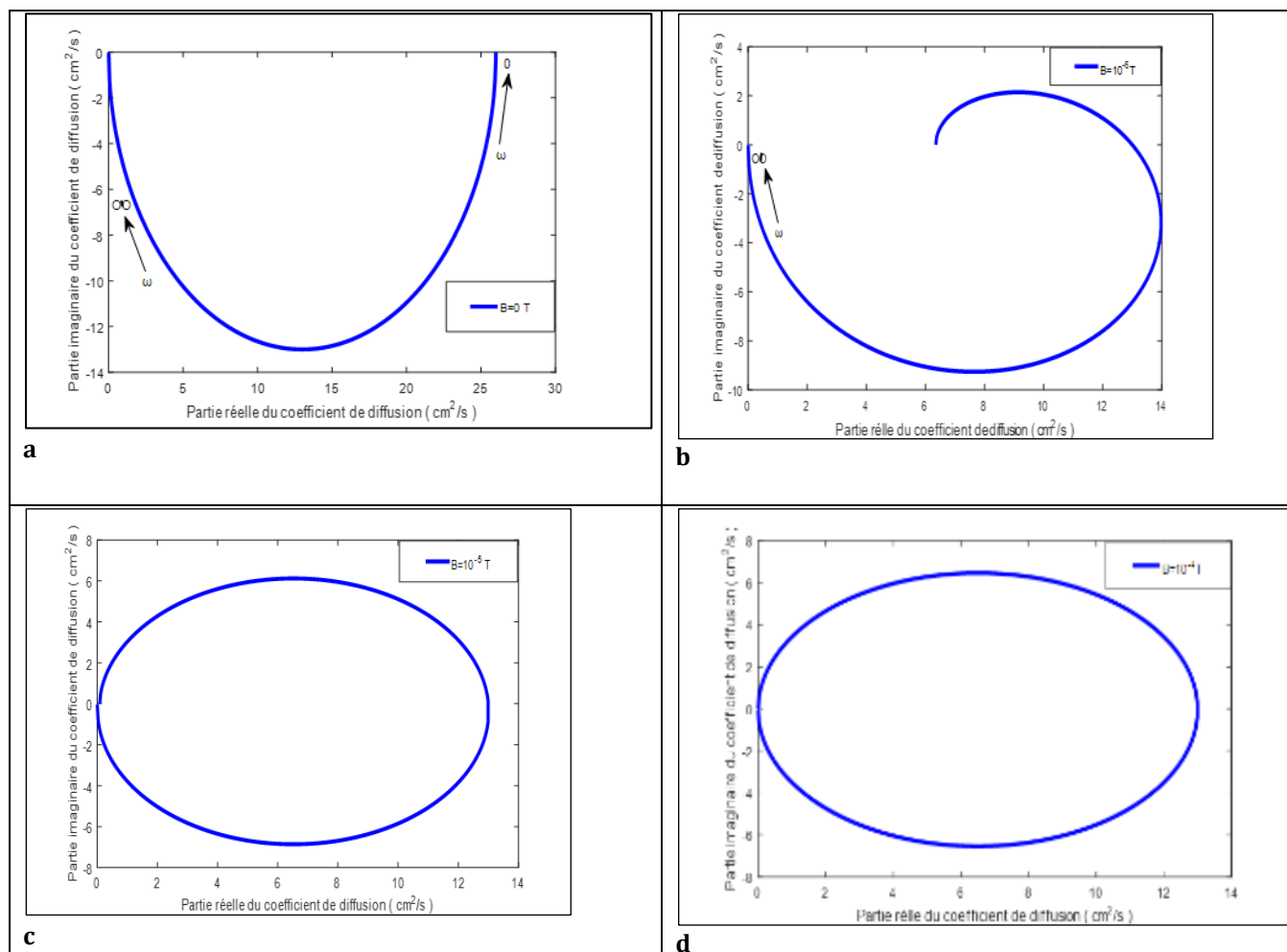


Figure 3: Phase of the diffusion coefficient as a function of the logarithm of frequency for different values of the magnetic field

The Nyquist diagram is a representation of the imaginary part as a function of the real part of the diffusion coefficient.

When the magnetic field is zero (Figure 3a), we have a semicircular diagram. The phase is practically zero. As the frequency approaches 0, the imaginary part of the diffusion coefficient is zero, and the real part of the diffusion coefficient is equal to its short-circuit value: this is the resistive effect. Conversely, as the frequency approaches infinity, both the real and imaginary parts are zero, and capacitive and inductive phenomena become apparent. Indeed, in the high-frequency range, with a consistently strong magnetic field, resonance peaks occur. Thus, carrier diffusion diminishes as these two quantities become significant.

Curves (c) and (d) are circles, which means that the inductive and capacitive effects of the diffusion coefficient cancel each other out. The negative and positive parts of the phase are confirmed by the Nyquist plot.

3 CONCLUSION

The diffusion coefficient is a recombination parameter that has a significant influence on conversion efficiency. The performance of a photovoltaic cell is limited by the recombination of photogenerated carriers at the surface and in the bulk before they cross the potential barrier. This study allowed us to identify three main phases: a zero phase with the cutoff frequency as the upper limit; a positive phase between the cutoff frequency and the resonance frequency; and a positive phase with the resonance frequency as the lower limit.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Acknowledgments

We would like to acknowledge the Solar Energy and Semi-conductors Laboratory of the Faculty of Sciences and Techniques of the Cheikh Anta Diop University/Dakar-Senegal for supporting this work.

Disclosure of conflict of interest

The authors declare no conflicts of interest regarding the publication of this paper.

REFERENCES

- [1] K. Kassmi, M. Hamdaoui and F. Olivié (2007) "Design and modelling of a photovoltaic system dapted by an analog MPPT control" *Revue des Energies Renouvelables*, Vol.10(4) pp : 451 – 462
- [2] Sene, M., Boiro, M. , Faye, A. , Diao, A. and Mbow, C. (2022) "Effects of the Nature of Boundaries Conditions and Their Truncation Errors on the Distribution of Minority Carriers in Silicon Solar Cell." *Journal of Modern Physics*, vol. 13(3) pp: 315-322. doi: 10.4236/jmp.2022.133022.
- [3] F. Dincer and M. Meral, (2010) "Critical Factors that Affecting Efficiency of Solar Cells," *Smart Grid and Renewable Energy*, Vol. 1(1), pp. 47-50. doi: 10.4236/sgre.2010.11007.
- [4] W. A. El-basit, A. M. A. El-maksood and F. A. E. S. Soliman, (2013) "Mathematical Model for Photovoltaic Cells", vol.23, pp:13-28
- [5] Fthenakis, V. M., & Kim, H. C. (2011) "Photovoltaics : Life-cycle analyses. *Solar Energy*" vol. 85(8), pp:1609–1628. doi : 10.1016/j.solener.2009.10.002
- [6] Michaud, J.G. (2005) *La fabuleuse histoire de l'énergie solaire*. INCA Productions, Californie, E-U
- [7] Ouedraogo, A., Bazyomo, S.D.Y.B., Ouedraogo, S., Razakou, A; Bathiebo, D.J. (2018) " Improvement of the Silicon Solar Cell Performance by Integration of an Electric Field Source in the Solar Cell or Solar Module System", *Smart Grid and Renewable Energy*, vol 9, pp: 285-298. Doi : 10.4236/sgre.2018.912018.
- [8] Green, A.M., Yoshihiro, H., Hishikawa, Y., Warta, W., Ewan, D.D., Dean, H.L., Jochen, H.E. et Anita, W.Y.H. (2017) *Solar Cell Efficiency Tables (Version 50)*. *Progrès dans le domaine du photovoltaïque : Research and Applications*, vol 25, pp : 668-676. <https://doi.org/10.1002/pip.2909>
- [9] Green, A.M., Yoshihiro, H., Hishikawa, Y., Warta, W., Ewan, D.D., Dean, H.L., Jochen, H.E. et Anita, W.Y.H. (2018) "Solar Cell Efficiency Tables (Version 51). *Progrès dans le domaine du photovoltaïque*" *Research and Applications*, vol26, pp :3-2 <https://doi.org/10.1002/pip.2978>
- [10] Pasquinelli, M. , Simon, J. , Rouzo, J. , Flory, F. and Escoubas, L. (2017) "Normalized Area Solar Cell and Potential Applications" *Journal of Applied Mathematics and Physics*, vol5, pp:1106-1112. doi: 10.4236/jamp.2017.55097.
- [11] Cotter, J.E., Guo, J.H., Cousins, P.J., Abbott, M.D., Chen, F.W. and Fisher, K.C. (2006) "P-Type versus N-Type Silicon Wafers: Prospects for High-Efficiency Commercial Silicon Solar Cells" *IEEE Transactions on Electron Devices*, vol53, pp:1893-1901. <https://doi.org/10.1109/TED.2006.878026>
- [12] Diao, A. , Wade, M. , Thiame, M. and Sissoko, G. (2017) "Bifacial Silicon Solar Cell Steady Photoconductivity under Constant Magnetic Field and Junction Recombination Velocity Effects" *Journal of Modern Physics*, vol8, pp:2200-2208. doi: 10.4236/jmp.2017.814135
- [13] Zerbo, I. , Zoungrana, M. , Sourabié, I. , Ouedraogo, A. , Zouma, B. and Bathiebo, D. (2016) "External Magnetic Field Effect on Bifacial Silicon Solar Cell's Electrical Parameters" *Energy and Power Engineering*, vol 8, pp:146-151. doi: 10.4236/epe.2016.83013.
- [14] Ba, M. , Thiam, N. , Thiame, M. , Traore, Y. , Diop, M. , Ba, M. , Sarr, C. , Wade, M. and Sissoko, G. (2019) " Base Thickness Optimization of a (n+-p-p+) Silicon Solar Cell in Static Mode under Irradiation of Charged Particles" *Journal of Electromagnetic Analysis and Applications*, vol11, pp:173-185. doi: 10.4236/jemaa.2019.1110012
- [15] Samoura, A, Sakho, O , Faye, O. and Beye, A. (2017) "Base Doping Effects on the Efficiency of Vertical Parallel Junction Solar Cells". *Open Journal of Applied Sciences*, vol7, pp: 282-290. Doi: 10.4236/ojapps.2017.76023.
- [16] Gora Diop, hamet yoro ba, ndeye thiam, youssou traoré, Babou Dione, mamour Amadou ba, Pape Diop, Masse Samba DIOP, Oulimata MBALLO and Grégoire SISSOKO (2019) "Base thickness Optimization of a vertical series junction silicon solar cell under magnetic field by the concept of back surface recombination velocity of minority carrier" *ARPJ Journal of Engineering and Applied Sciences* vol.14(23) pp: 1-8

- [17] Moussa Ibra Ngom, Marcel Sitor Diouf, Amary Thiam, Mohamed bderrahim Ould El Moujtaba and Grégoire Sissoko “Influence of Magnetic Field on the Capacitance of a Vertical Junction Parallel Solar Cell in Static Regime, Under Multispectral Illumination” *Int. J. Pure Appl. Sci. Technol.*, vol 31(2) (2015), pp: 65-75
- [18] Sy, K.M., Diene, A., Tamba, S., Diouf, M.S., Diatta, I., Dieye, M., Traore, Y., & Sissoko, G. (2016). “ Effect of temperature on transient decay induced by charge removal of a silicon solar cell under constant illumination.” *Journal of Scientific and Engineering Research*, vol 3(6), pp: 433-445.
- [19] E. H. Ndiaye, G. Sahin, M. Dieng, A. Thiam, H. L. Diallo, M. Ndiaye, G. Sissoko (2015) “Study of the intrinsic recombination velocity at the junction of silicon solar cell under frequency modulation and radiation”, *Journal of Applied Mathematics and Physics*, vol 3, pp:1522-1535 <http://dx.doi.org/10.4236/jamp.2015.311177>
- [20] H. L. Diallo, M. Wade, I. Ly, M. Ndiaye, B. Dieng, O.H. Lemrabott, A.S. Maïga and G. Sissoko, (2015) “1D Modeling of a Bifacial Silicon Solar Cell under Frequency Modulation, Monochromatic Illumination: Determination of the Equivalent Electrical Circuit Related to the Surface Recombination Velocity”, *Research Journal of Applied Sciences, Engineering and Technology* vol 4, pp:1672-1676
- [21] Thomas Mambrini. Thèse de doctorat “Caractérisation de panneaux solaires photovoltaïques en conditions réelles d’implantation et en fonction des différentes technologies”. Météorologie. Université Paris Sud - Paris XI, 2014. Français. pp.47-75
- [22] W.V. Roosbroeck, (1953) “The transport of added current carriers in a homogeneous semiconductor”, *Phys. Rev*, vol.91(2), pp:282-289 <https://doi.org/10.1103/PhysRev.91.282>