Micro- and nanoelectronics. Condensed matter physics

Микро- и наноэлектроника. Физика конденсированного состояния

UDC 537.632
https://doi.org/10.32362/2500-316X-2025-13-3-122-128
EDN IJRLMF

RESEARCH ARTICLE

Features of the magnetorefractive effect in Co–Si nanocomposites

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• **Submitted:** 14.11.2024 • **Revised:** 03.02.2025 • **Accepted:** 20.03.2025

Abstract
Objectives. The work set out to study the spectra of the magnetorefractive effect (MRE) in the cobalt–silicon (Co–Si) nanocomposite, taking into account the contribution of the size effect (SE), and to compare the results obtained by varying the parameters of the SE. The presented approaches to investigating the magnetooptical properties of nanocomposites, which are relevant for the practical application of nondestructive testing methods, have the potential to significantly increase the efficiency of their use in various fields, including spintronics and optics.
Methods. Computer modeling approaches based on the Bruggeman approximation are used to model the examined structure as a medium with effective properties.
Results. MRE spectra obtained within the framework of the modeling fell within the range of 0.5–3.5 eV. The modeling was carried out for MRE both with and without taking into account the semiclassical size effect. The resultant modeling of the spectral dependencies of the MRE is based on the example of a Co–Si nanocomposite at different cobalt particle sizes and form factors. The influence of size effects on the form of the MRE spectra is confirmed. The reliability of the methods is confirmed by a comparison of the obtained results with empirical data. The value of the obtained results consists in the good agreement of all the calculated parameters of the discussed nanocomposite and the form of the spectral dependencies of the MRE with the results of various experiments.
Conclusions. The confirmation that both the size and form factor of granules have a significant impact on the appearance of the MRE spectra raises the prospect of developing promising nanocomposite properties at particular particle sizes. The presented results highlight the possibility of optimizing the material characteristics to improve sensitivity in magnetic sensors and noncontact devices for studying nanostructures.

Keywords: nanocomposites, effective medium theory, magnetorefractive effect, ferromagnetic, size effects

For citation: Yurasov A.N., Kulgunina R., Yashin M.M., Simdyanova M.A. Features of the magnetorefractive effect in Co–Si nanocomposites. *Russian Technological Journal.* 2025;13(3):122–128. https://doi.org/10.32362/2500-316X-2025-13-3-122-128, https://www.elibrary.ru/IJRLMF

Financial disclosure: The authors have no financial or proprietary interest in any material or method mentioned.

The authors declare no conflicts of interest.

НАУЧНАЯ СТАТЬЯ

Особенности магниторефрактивного эффекта в нанокомпозитах Co–Si

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• **Поступила:** 14.11.2024 • **Доработана:** 03.02.2025 • **Принята к опубликованию:** 20.03.2025

Резюме
Цели. Целью работы является исследование спектров магниторефрактивного эффекта (МРЭ) в нанокомпозитах «кобальт–кремний» (Co–Si) с учетом вклада размерного эффекта, а также сравнение полученных результатов при изменении параметров размерного эффекта. Данное исследование является важным для практического применения бесконтактных методов, т.к. оно направлено на расширение их возможностей и создание новых подходов к неразрушающему контролю и исследованию магнитооптических свойств нанокомпозитов, что может значительно повысить эффективность их использования в различных областях, включая спинтронику и оптику.
Методы. Применялось компьютерное моделирование в рамках перспективного метода эффективной среды – приближения Бруггемана, согласно которому исследуемая структура заменяется средой с эффективными свойствами.
Результаты. В рамках моделирования получены спектры МРЭ в диапазоне 0.5–3.5 эВ. При этом моделирование проводилось для МРЭ без учета и с учетом квазиклассического размерного эффекта. Конечным результатом стало моделирование спектральных зависимостей МРЭ на примере нанокомпозита Co–Si при различных значениях размера частиц и форм-фактора кобальта. Показано влияние размерных эффектов на вид спектров МРЭ. Достоверность методик хорошо подтверждается сравнением полученных результатов с эмпирическими данными, а ценность полученных результатов обусловлена тем, что все рассчитанные параметры обсуждаемого нанокомпозита и форма спектральных зависимостей МРЭ хорошо согласуются с результатами различных экспериментов.
Выводы. В рамках моделирования показано, что учет размеров и форм-фактора гранул оказывает значительное влияние на вид спектров МРЭ, демонстрируя перспективные свойства нанокомпозита при определенных размерах частиц. Представленные результаты подчеркивают возможность оптимизации характеристик материала для улучшения чувствительности в магнитных сенсорах и устройствах бесконтактного исследования наноструктур.

Ключевые слова: нанокомпозиты, теория эффективной среды, магниторефрактивный эффект, ферромагнетик, размерные эффекты

Для цитирования: Юрасов А.Н., Кулгунина Р., Яшин М.М., Симдянова М.А. Особенности магниторефрактивного эффекта в нанокомпозитах Co–Si. *Russian Technological Journal*. 2025;13(3):122–128. https://doi.org/10.32362/2500-316X-2025-13-3-122-128, https://www.elibrary.ru/IJRLMF

Прозрачность финансовой деятельности: Авторы не имеют финансовой заинтересованности в представленных материалах или методах.

Авторы заявляют об отсутствии конфликта интересов.

INTRODUCTION

Investigating the magnetorefractive effect (MRE) in cobalt–silicon (Co–Si) nanocomposites is an important factor in the development of advanced magnetic and optical devices. Understanding the contribution of the size effect to this phenomenon is crucial for elucidating the magnetic and optical properties of nanomaterials, thus expanding the possibilities for various kinds of noncontact research [1–3].

Significant changes in the physicochemical properties of nanocomposites as the result of decreased grain size can include significant improvements in MRE functionality. In this connection, Co–Si nanocomposites are of particular interest due to their unique magneto-optical properties. A deeper understanding of the mechanisms governing the interaction between the light and the magnetic field in such systems can be achieved by modeling the MRE taking into account the size effect [4, 5].

Thus, taking into account the possible significant enhancement of practically important effects such as magnetoresistance, quantum Hall effects, MRE and many others, investigation of the properties of promising nanostructures represents an urgent task [6]. Co–Si nanocomposite materials provide an interesting example of a nanostructure; by modeling the observed optical and magneto-optical effects represents a useful noncontact and nondestructive approach to estimating characteristic parameters of the studied samples [7, 8].

MATHEMATICAL MODEL AND CALCULATION METHODS

In the paper, a mathematical model based on the effective medium theory is developed to analyze the MRE in composite materials containing cobalt nanoparticles in a silicon matrix. The main purpose of the calculation is to investigate the influence of the size effect and particle form factor on the MRE spectra.

The magnetorefractive effect describes the effect of the magnetic field on the complex refractive index of the nanocomposite, which is expressed by the change in the dielectric permittivity ε under the magnetic field [9]. In this study, the effective medium approximation (EMA) using the Bruggeman model is chosen to calculate the effective permittivity ε^{EMA} using the Co–Si nanocomposite as an example. The volume fraction of metallic particles (Co) in this structure is $X = 0.5$.

The calculation is carried out for particles with diameters ranging from 2 to 8 nm with different values of the form factor L in order to study the effect of varying the particle size and shape on the MRE spectra.

The magnetorefractive effect is calculated as the change in the reflection coefficient R of the nanocomposite [10]:

$$\frac{\Delta R}{R} = -(1-R)\left(\frac{\Delta\rho}{\rho}k^2\left[\frac{3n^2-k^2-1}{(n^2+k^2)((1-n)^2+k^2)}\right]\right), \quad (1)$$

where $\frac{\Delta\rho}{\rho}$ is the magnetoresistance; k, n are the extinction and refraction coefficients, respectively.

The key parameters of the model are the diagonal and non-diagonal complex components of the dielectric permittivity tensor (DPT):

$$\gamma = \gamma_1 - i\gamma_2,\ \varepsilon = \varepsilon_{01} - i\varepsilon_{02}, \quad (2)$$

where ε_{01} and γ_1 are the real parts of the diagonal and non-diagonal DPT components; ε_{02} and γ_2 are the imaginary parts of the DPT components, respectively.

These parameters depend on quasi-classical size effects, which are considered in the paper as a contribution of particle shape and size as captured by the MRE spectral dependence.

The size effect is accounted for by additive terms in the diagonal and non-diagonal components of the DPT based on the Drude–Lorentz model. The dielectric permittivity and the absorption coefficient of the particles are calculated with respect to the free path time τ and the concentration of the particles. The effective medium theory [11] is optimal for describing the spectral dependencies of nanostructures and nanocomposites in particular. The effective medium is described by Bruggeman's equation, which takes into account the contribution of the magnetic component of the material, the volume concentration of cobalt, and the shape of the nanoparticles:

$$X\frac{\varepsilon_1-\varepsilon^{EMA}}{\varepsilon^{EMA}+L(\varepsilon_1-\varepsilon^{EMA})} + (1-X)\frac{\varepsilon_0-\varepsilon^{EMA}}{\varepsilon^{EMA}+L(\varepsilon_0-\varepsilon^{EMA})} = 0, \quad (3)$$

where ε_0 and ε_1 are the dielectric permittivities of the medium components, while L is the form factor of the medium particles.

The size effects are taken into account by varying the particle form factors L and by additives in the diagonal and non-diagonal DPT components of the nanocomposite ferromagnetic component. This is related to electron scattering on the granule surfaces. Finally, given the size effect contribution to the DPT, the DPT complex components ε_{mod} and γ_{mod} are expressed as follows, according to the Drude–Lorentz model [11, 12]:

$$\varepsilon_{\text{mod}} = \varepsilon_{\text{Co}} + \frac{\omega_p^2}{\omega(\omega + i/\tau_{\text{bulk}})} - \frac{\omega_p^2}{\omega(\omega + i/\tau_{\text{gr}})},$$
$$\gamma_{\text{mod}} = \gamma_{\text{Co}} + \frac{4\pi\sigma_{xy}^{\text{bulk}}/\tau_{\text{bulk}}^2}{\omega(\omega + i/\tau_{\text{bulk}})^2} - \frac{4\pi\sigma_{xy}^{\text{gr}}/\tau_{\text{gr}}^2}{\omega(\omega + i/\tau_{\text{gr}})^2}, \quad (4)$$

where ε_{Co} and γ_{Co} are the diagonal and non-diagonal components of the ferromagnetic DPT (here cobalt); ω_p is the plasma frequency; ω is the electromagnetic wave frequency; $\sigma_{xy}^{\text{bulk}} = 4\pi M_s R_{\text{bulk}} / \rho_{\text{bulk}}^2$; $\sigma_{xy}^{\text{gr}} = 4\pi M_s R_{\text{gr}} / \rho_{\text{gr}}^2$; M_s is the saturation magnetization of the ferromagnet; R_{bulk} and R_{gr} are the extraordinary Hall effect coefficients of the bulk and granules, respectively; ρ_{bulk} and ρ_{gr} are the specific resistances of the bulk and granules, respectively; τ_{bulk}, τ_{gr} are the electron mean free times in the bulk and granules, respectively.

The size effect is evident in both the extraordinary Hall effect parameter and the resistivity:

$$R_{\text{gr}} = R_{\text{bulk}} + 0.2R\frac{l}{r_0}\left(1 + \frac{l}{r_0}\right), \quad (5)$$

$$\rho_{\text{gr}} = \rho_{\text{bulk}}\left(1 + \frac{l}{r_0}\right), \quad (6)$$

where R is the value of the extraordinary Hall effect parameter of the surface material of the granules, r_0 is the particle size of the nanocomposite, and l is the electron mean free path.

MODELING RESULTS

After obtaining the values of the MRE parameter ($\Delta R/R$) ignoring the size effect by equations (1)–(3) within the framework of the promising method of the effective medium–Bruggeman approximation, the influence of the quasi-classical size effect on the spectra at different particle shape L (form factor) and cobalt particle diameter d is analyzed. A nanocomposite with cobalt volume fraction $X = 0.5$ is selected as the sample. This choice is determined by the proximity to the percolation threshold, which can significantly modify and amplify the physical effects.

As shown in Fig. 1, the most significant change in MRE observed in the nearest infrared (IR) region of the spectrum taking the size effect and particle diameter d = 2 nm into account is due to intra-band transitions. According to Fig. 2, the size effect contribution becomes noticeable only from 4 nm granule size.

In Fig. 3, the quasi-classical size effect is considered for different particle form factors. The highest effect enhancement corresponds to L = 0.2. The obtained order of magnitude results, which are in good agreement with the known experimental data for nanocomposites (e.g. [3, 4]), show a general trend of MRE enhancement with decreasing particle size and form factor.

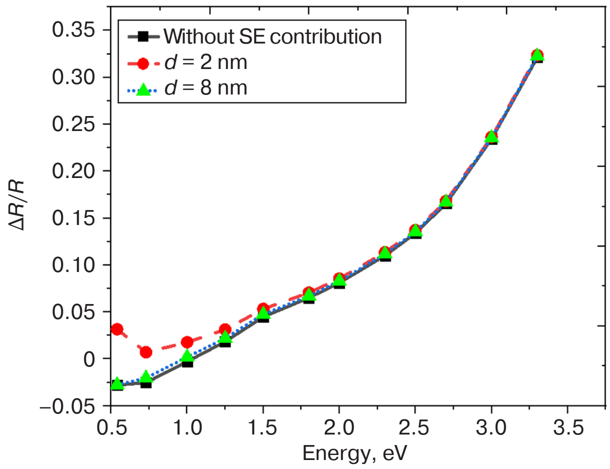

Fig. 1. MRE as a function of the incident electromagnetic wave energy without (solid line) and with the contribution of the size effect for Co particle sizes of d = 2 nm (dots) and d = 8 (dashed line) nm

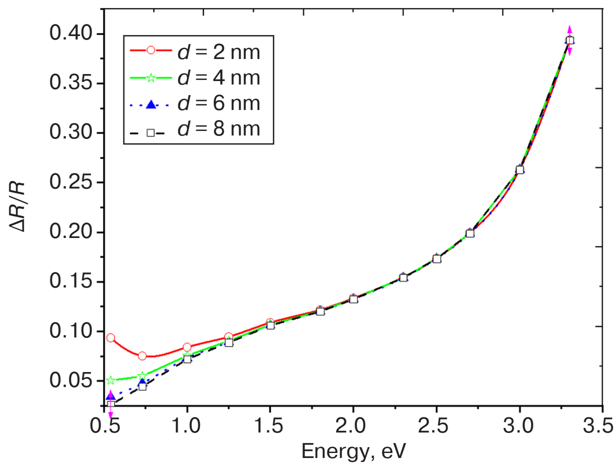

Fig. 2. MRE as a function of the incident electromagnetic wave energy considering the size effect contribution for the Co–Si nanocomposite at different particle diameters d = 2, 4, 6, and 8 nm

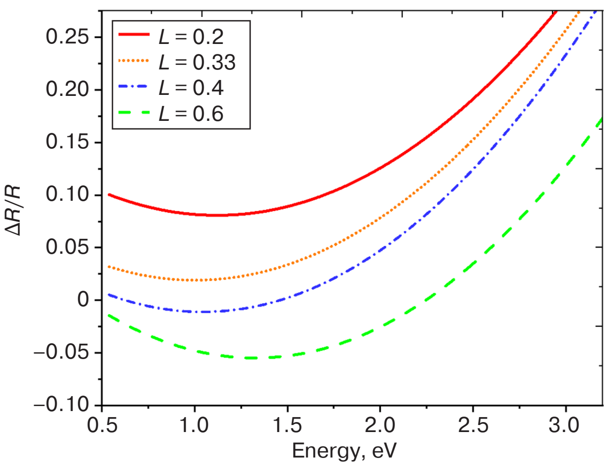

Fig. 3. MRE as a function of the incident electromagnetic wave energy considering the size effect contribution for the Co–Si nanocomposite at $L = 0.2$, 0.33, 0.4, and 0.6

The results open the prospect for a wide range of promising applications of nanocomposites in modern electronics based on the optical, magneto-optical, galvanomagnetic and other effects observed in the discussed nanostructures [13–15].

CONCLUSIONS

Model MRE spectra are obtained on the example of Co–Si nanocomposites taking the contribution of the size effect into account. In addition to the quasi-classical size effect, the results confirm the importance of considering the particle form factor contribution to the MRE spectral dependencies. All results are within the order of magnitude consistent with known data for similar nanostructures.

The results can be used to extend the possibilities of noncontact research methods and develop highly sensitive sensors and memory systems based on a wide range of nanostructures, such as the Co–Si nanocomposite.

ACKNOWLEDGMENTS

The study was supported by the "RTU MIREA Accelerator" program.

Authors' contributions

A.N. Yurasov—computer simulation, discussion of results, writing and editing the text of the article.

R. Kulgunina—literature review, computer simulation, discussion of results, writing the text of the article.

M.M. Yashin—model development, computer simulation, discussion of results, writing the text of the article.

M.A. Simdyanova—literature review, computer simulation, discussion of results, writing the text of the article.

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Translated from Russian into English by K. Nazarov
Edited for English language and spelling by Thomas A. Beavitt

MIREA – Russian Technological University.
78, Vernadskogo pr., Moscow, 119454 Russian Federation.
Publication date May 30, 2025.
Not for sale.

МИРЭА – Российский технологический университет.
119454, РФ, г. Москва, пр-т Вернадского, д. 78.
Дата опубликования 30.05.2025 г.
Не для продажи.