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Low Temperature Luminescence Behavior of Trace Cr and Fe Impurities in Gd₃Ga₅O₁₂ Single Crystals

This article examines the influence of unintentional Cr³⁺ and Fe³⁺ impurity ions on the luminescent properties of Gd₃Ga₅O₁₂ (GGG) single crystals. The characteristic features of the spectra excited by high-energy synchrotron radiation in the temperature range of 10–300 K are analyzed. It is shown that at 10 K the luminescence is dominated by a narrow-band emission of Cr³⁺ ions arising from the spin-forbidden ²E→⁴A₂ transition, which indicates weak electron–phonon coupling and high crystalline homogeneity. It is revealed that with increasing temperature the intensity of this transition decreases significantly, while a broadband luminescence emerges, associated with the spin-allowed ⁴T₂→⁴A₂ transition and the contribution of Fe³⁺ ion emission. The temperature evolution of the spectra is shown to result from thermal redistribution of the Cr³⁺ excited-state populations, interlevel state mixing, and partial removal of the spin-forbidden nature of Fe³⁺ transitions due to lattice vibrations. Based on the study, conclusions are drawn regarding the role of impurity centers in energy transfer and nonradiative relaxation processes. The results are of interest both for fundamental photonics and for the development of efficient luminescent materials and optical devices designed to operate over a wide temperature range.

Keywords: gadolinium gallium garnet (GGG), synchrotron radiation, Cr³⁺ ions, Fe³⁺ ions, luminescence, excitation spectra, temperature dependence, energy transfer, electron–phonon coupling, nonradiative relaxation, impurity centers, optical properties

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Introduction

Garnet crystals are widely used in laser technologies, optical sensors, and other photonic applications due to their unique luminescent properties [1–10]. Similar studies of luminescent materials with varying compositions have been reported, for example, for YAGG phosphors with different Al/Ga ratios, demonstrating how modification of crystal composition affects spectral and luminescent characteristics [11]. Chromium and iron are typical impurities that penetrate the lattice at various stages of synthesis. Even small amounts of Cr³⁺ or Fe³⁺ can significantly affect the spectroscopic and luminescent characteristics of the material, as confirmed by similar temperature-dependent luminescence studies in other garnet systems [12]. In GGG, Cr³⁺ exhibit a rich spectroscopic behavior determined by their 3d³ configuration in an octahedral field [13]. At the same time, the luminescent properties of Cr³⁺ are sensitive to a number of factors: temperature, concentration, local environment, and the presence of other impurities. In GGG, Cr³⁺ substitutes for Gd³⁺ in octahedral sites, forming characteristic spectra with sharp (²E→⁴A₂) and broad (⁴T₂→⁴A₂) bands [14]. The authors of [14] demonstrated a sharp decrease in intensity upon heating (by 90–99 % at 300 K) due to the increased probability of nonradiative relaxations.

When Fe³⁺ and rare-earth ions are simultaneously present in the GGG structure, excitation transfer becomes possible, which can be enhanced with increasing temperature, thereby influencing the selectivity and luminescent properties [15]. In [16], it was shown that the spectral position of the deep-red emission band of Fe³⁺ can be modified by adjusting the crystal field strength (CFS). Moreover, it was demonstrated that the thermal response of Fe³⁺ luminescence can be significantly improved by incorporating Cr³⁺ ions, thus enabling thermally activated nonradiative energy transfer Fe³⁺ → Cr³⁺. The authors of [16] showed that reducing

the CFS has a favorable effect on the performance of contactless temperature sensing in Fe^{3+} -based luminescent thermometers.

The study of the temperature dependence of the luminescence spectra of these materials is of crucial importance for understanding their optical characteristics and optimizing their applications. The aim of this work was to quantitatively separate and compare the contributions of unintentional impurity luminescence centers Cr^{3+} and Fe^{3+} to the integral luminescence of a $\text{Gd}_3\text{Ga}_5\text{O}_{12}$ single crystal under VUV excitation (160–250 nm) at temperatures of 10–300 K, as well as to determine the mechanisms of thermally controlled redistribution of impurity ion level populations and the energy transfer channels from the host lattice to the impurities.

Methods

The $\text{Gd}_3\text{Ga}_5\text{O}_{12}$ single crystals were grown by the Czochralski method using an iridium crucible. A mixture of argon (98 %) and oxygen (2 %) was used as the growth atmosphere. High-purity oxides Gd_2O_3 and Ga_2O_3 (99.99 wt. %) served as the starting materials. It should also be noted that GGG crystals contain a certain amount (10^{-3} – 10^{-4} wt.%) of uncontrolled impurity ions, which is practically difficult to avoid. The samples were prepared in the form of flat plates 0.48 mm thick, oriented in the (111) plane with polished surfaces.

The luminescence studies were carried out using synchrotron radiation at the Superlumi/P66 beamline of the PETRA III synchrotron facility at DESY in Hamburg. This setup has proven to be highly effective for investigating luminescence processes excited in the VUV region [17–21].

The synchrotron radiation provided high-intensity, tunable excitation in the required spectral range, which was selected using a 2-meter monochromator with a spectral resolution of 0.4 nm. This ensured precise excitation of luminescent states in the single crystals. The emitted luminescence from the single crystals was detected using an ANDOR Kymera monochromator, which provided a spectral resolution of 0.2 nm, allowing for accurate detection of luminescence peaks. For sensitive detection over a wide spectral range, a Newton 920 CCD camera (Oxford Instruments, UK) was employed, while photon counting was performed using a Hamamatsu R6358 photomultiplier tube (Hamamatsu Photonics, Japan), particularly effective in the ultraviolet range.

Experiments were conducted at a temperature of 10 K using a helium-cooled cryostat to minimize thermal noise and nonradiative losses. The excitation spectra were corrected against the sodium salicylate signal, ensuring the acquisition of accurate and reliable data across the entire spectral range.

Results and Discussion

The excitation spectra of $\text{Gd}_3\text{Ga}_5\text{O}_{12}$ crystals measured at room temperature for emission wavelengths of 780, 754, and 694 nm (Fig. 1) exhibit characteristic features indicating the influence of unintentional Cr^{3+} and Fe^{3+} impurity ions in the crystal. For the 694 nm luminescence band, starting from approximately 5.5 eV, a sharp increase is observed in the excitation spectrum along with a relatively broad and smooth structure. This energy corresponds to the excitonic transition ($E_g = 5.66$ eV) [22], which is also associated with the excitation of unintentional impurity centers, primarily Cr^{3+} ions, through exciton migration.

In the region around 5 eV, when detecting at 754 nm and 780 nm, an additional peak is clearly visible, which can be unambiguously attributed to the presence of Fe^{3+} ions — a typical unintentional impurity often found in gallium garnets grown under standard conditions.

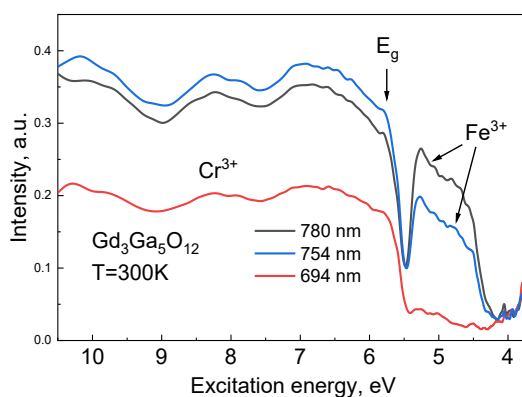


Figure 1. Excitation spectra of the $\text{Gd}_3\text{Ga}_5\text{O}_{12}$ crystal measured at $T = 300$ K. $\lambda_{\text{reg}} = 780$ nm, $\lambda_{\text{reg}} = 754$ nm, and $\lambda_{\text{reg}} = 694$ nm

Analysis of the excitation spectra reveals a pronounced influence of Cr^{3+} and Fe^{3+} impurity ions, which manifest themselves as broad excitation bands in the 6–9 eV region and as a distinct peak around 5 eV, respectively. These impurities form additional levels within the band gap, facilitating uncontrolled energy trapping and affecting the luminescence characteristics.

The luminescence spectra of the GGG crystal excited by synchrotron radiation were studied at different temperatures. The emission spectra in the temperature range 300–10 K consist of a broad band spanning 650–870 nm (Fig. 2), which arises from the combined emission of two types of unintentional impurity centers. The component with a maximum around 730 nm is unambiguously associated with the ${}^4\text{T}_2 \rightarrow {}^4\text{A}_2$ transition of Cr^{3+} ions, whereas the band peaking at ≈ 775 nm is attributed to Fe^{3+} luminescence [23, 24]. To confirm this, luminescence spectra were recorded at 210 K under excitation at wavelengths $\lambda = 160$ nm and $\lambda = 250$ nm. In Figure 3, the band with a maximum at 775 nm is clearly distinguished, confirming the contribution of Fe^{3+} .

The temperature evolution of the luminescence spectra excited by high-energy quanta of 7.75 eV (160 nm) unambiguously reflects the different behavior of the two unintentional impurity centers — Cr^{3+} and Fe^{3+} . At temperatures below 210 K, the characteristic R-lines of Cr^{3+} begin to appear. At 10 K, the spectrum is characterized by structured lines in the 690–710 nm range, corresponding to the spin-forbidden ${}^2\text{E} \rightarrow {}^4\text{A}_2$ transition. As the temperature increases up to 300 K, the narrow structure is suppressed, and a broad symmetric luminescence band of 650–870 nm develops. This is associated with the dominance of the spin-allowed ${}^4\text{T}_2 \rightarrow {}^4\text{A}_2$ transition of Cr^{3+} ions and enhanced Fe^{3+} emission, indicating stronger thermal mixing of states and an increased contribution of electron–phonon interaction at higher temperatures.

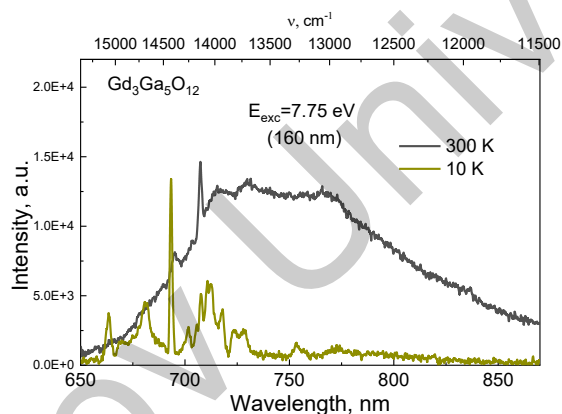


Figure 2. Temperature-dependent luminescence spectra of the GGG crystal

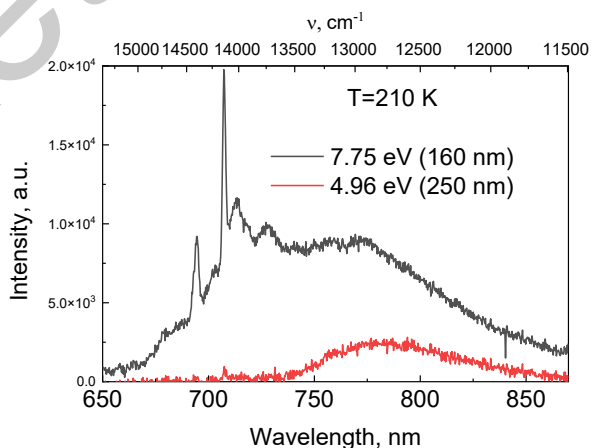


Figure 3. Luminescence spectra of GGG under 160 nm and 250 nm excitation

The experimental results can be explained as follows. Cr^{3+} ions in GGG are characterized by energy levels typical for d^3 ions: ${}^4\text{A}_2$, ${}^2\text{E}$, and ${}^4\text{T}_2$. Under excitation with 160 nm radiation in the VUV region, elec-

tronic excitations in the crystal matrix are captured by Cr^{3+} and Fe^{3+} impurity ions. Relaxation of Cr^{3+} occurs via two dominant channels: the narrow-band ${}^2\text{E} \rightarrow {}^4\text{A}_2$ and the broadband ${}^4\text{T}_2 \rightarrow {}^4\text{A}_2$. Their relative contribution depends on temperature and crystal parameters [25].

Subsequent energy transfer processes occur through phonon-assisted mechanisms and interlevel relaxation, leading to population of the excited states ${}^2\text{E}$ and ${}^4\text{T}_2$. At 10 K, the spectrum is characterized by structured lines in the 690–710 nm range, corresponding to the spin-forbidden ${}^2\text{E} \rightarrow {}^4\text{A}_2$ transition of Cr^{3+} ions occupying octahedral sites of the garnet lattice. The observed linewidth of the R-lines is only a few cm^{-1} , indicating high crystalline homogeneity of the material and weak electron–phonon coupling at low temperature. At cryogenic temperatures, relaxation predominantly terminates at ${}^2\text{E}$, resulting in emission with a characteristic narrow spectral structure. Increasing temperature promotes a larger contribution from transitions through ${}^4\text{T}_2$, since thermal lattice expansion reduces the energy gap ΔE between the ${}^2\text{E}$ and ${}^4\text{T}_2$ levels and enhances their mixing.

In the excitation spectrum of luminescence monitored at 780 nm, a clear band with a maximum at ~ 5 eV (250 nm) is observed (Fig. 1). However, photons of this energy cannot directly produce emission at 750–780 nm; instead, the energy can be absorbed by defect centers and subsequently transferred to Fe^{3+} ions. Emission at 780 nm was excited only by the 250 nm excitation band, which may be related to charge-transfer transitions involving Fe^{3+} ions at different sites. The increase in luminescence intensity with rising temperature can be explained as follows. The ${}^4\text{T}_1 \rightarrow {}^6\text{A}_1$ transition in Fe^{3+} ions is spin-forbidden, since $\Delta S \neq 0$. The broad emission band in the 740–820 nm region has been shown in [26] to correspond to this internal transition of Fe^{3+} . The enhancement of intensity with increasing temperature is explained by the standard mechanism of vibrational and spin-orbit mixing, which grows with the amplitude of lattice vibrations and local symmetry distortions. As temperature increases, these vibrations become stronger, disrupting the local symmetry of Fe^{3+} ions. As a result, the efficiency of orbital mixing increases, leading to an enhanced quantum yield of the Fe^{3+} band. An additional contribution arises from competition with trap states: higher temperatures promote thermal ionization of defects, making Fe^{3+} a more effective acceptor of migrating excitonic energy.

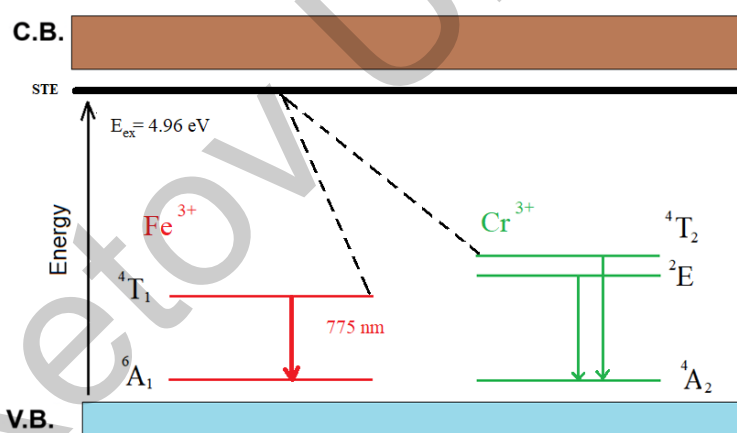


Figure 3. Cr^{3+} and Fe^{3+} centers schematic energy-level diagram in single crystal GGG

Conclusion

The luminescence spectra of unintentional Cr^{3+} and Fe^{3+} impurity ions in GGG under excitation by high-energy synchrotron radiation at 160 nm exhibit a pronounced and systematic temperature evolution. At cryogenic temperatures (~ 10 K), luminescence is dominated by narrow-band emission associated with the ${}^2\text{E} \rightarrow {}^4\text{A}_2$ transition of Cr^{3+} ions, characterized by high spectral resolution. With increasing temperature up to 300 K, a transition to broadband luminescence is observed, governed by the spin-allowed ${}^4\text{T}_2 \rightarrow {}^4\text{A}_2$ transition, accompanied by spectral broadening and faster dynamics. These changes are explained by mechanisms of energy transfer from defect centers, thermal redistribution of level populations, and enhanced electron–phonon coupling. The results are important both for understanding fundamental processes in luminescent materials and for the development of highly efficient optical devices operating under varying temperature conditions.

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References

- Jovanić, B., Bettinelli, M., Radenković, B., Despotović-Zrakić, M., & Bogdanović, Z. (2012). Optical spectroscopy of nano-crystalline $\text{Gd}_3\text{Ga}_5\text{O}_{12}$ doped with Eu^{3+} and high pressures. *Materials Chemistry and Physics*, 132(2-3), 273–277. DOI: 10.1016/j.matchemphys.2011.11.037
- Elzbiaciak-Piecka, K., Sójka, M., Tian, F., Li, J., Zych, E., & Marciniak, L. (2023). The comparison of the thermometric performance of optical ceramics, microcrystals and nanocrystals of Cr^{3+} -doped $\text{Gd}_3\text{Ga}_5\text{O}_{12}$ garnets. *Journal of Alloys and Compounds*, 963, 171284. DOI: 10.1016/j.jallcom.2023.171284
- Wollesen, L., Douissard, P.A., Pauwels, K., Baillard, A., Loiko, P., & Brasse, G. ... (2025). Microstructured growth by liquid phase epitaxy of scintillating $\text{Gd}_3\text{Ga}_5\text{O}_{12}$ (GGG) doped with Eu^{3+} . *Journal of Alloys and Compounds*, 1010, 177267. DOI: 10.1016/j.jallcom.2024.177267
- Kamińska, A., Brik, M.G., Boulon, G., Karbowski, M., & Suchocki, A. (2010). Spectroscopy of gadolinium gallium garnet crystals doped with Yb^{3+} revisited. *Journal of Physics: Condensed Matter*, 22(25), 255501. DOI: 10.1088/0953-8984/22/25/255501
- Bartosiewicz, K., Markovskiy, A., Horai, T., Szymanski, D., Kurosawa, S., Yamaji, A., Yoshikawa, A., & Zorenko, Y. (2022). A study of Mg^{2+} ions effect on atoms segregation, defects formation, luminescence and scintillation properties in Ce^{3+} doped $\text{Gd}_3\text{Al}_2\text{Ga}_3\text{O}_{12}$ single crystals. *Journal of Alloys and Compounds*, 905, 164154. DOI: 10.1016/j.jallcom.2022.164154
- Kamińska, A., Duzynska, A., Berkowski, M., Trushkin, S., & Suchocki, A. (2012). Pressure-induced luminescence of cerium-doped gadolinium gallium garnet crystal. *Physical Review B*, 85(15), 155111. DOI: 10.1103/PhysRevB.85.155111
- Buryi, M., Gaston-Bellegarde, A.M., Pejchal, J., Levchenko, F., Remeš, Z., Ridzoňová, K., Babin, V., & Chertopalov, S. (2023). The role of Er^{3+} content in the luminescence properties of $\text{Y}_3\text{Al}_5\text{O}_{12}$ single crystals: Incorporation into the lattice and defect state creation. *Crystals*, 13(4), 562. DOI: 10.3390/cryst13040562
- Mironova-Ulmane, N., Popov, A.I., Antuzevics, A., Kriek, G., Elsts, E., Vasil'chenko, E., Sildos, I., Puust, L., Ubizskii, S.B., & Sugak, D. ... (2020). EPR and optical spectroscopy of neutron-irradiated $\text{Gd}_3\text{Ga}_5\text{O}_{12}$ single crystals. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 480, 22–26. DOI: 10.1016/j.nimb.2020.05.027
- Mironova-Ulmane, N., Sildos, I., Vasil'chenko, E., Chikvaidze, G., Skvortsova, V., Kareiva, A., Muñoz-Santiuste, J.E., Pareja, R., Elsts, E., & Popov, A.I. (2018). Optical absorption and Raman studies of neutron-irradiated $\text{Gd}_3\text{Ga}_5\text{O}_{12}$ single crystals. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 435, 306–312. DOI: 10.1016/j.nimb.2018.01.041
- Karipbayev, Z.T., Kumarbekov, K., Manika, I., Dauletbekova, A., Kozlovskiy, A.L., Sugak, D., Ubizskii, S.B., Akilbekov, A., Suchikova, Y., & Popov, A.I. (2022). Optical, structural, and mechanical properties of $\text{Gd}_3\text{Ga}_5\text{O}_{12}$ single crystals irradiated with $^{84}\text{Kr}^+$ ions. *Physica Status Solidi (B)*, 259(9), 2100415. DOI: 10.1002/pssb.202100415
- Tulegenova, A.T., Nogaibekova, G.Zh., Saidzimov, I.A., Vilchinskaya, S.S., & Markhabayeva, A.A. (2024). Spectral Characteristics of Photoluminescence Synthesized in the Field of Radiation YAGG Phosphors with Different Al/Ga Ratio. *Bulletin of the University of Karaganda — Physics*, 4, 114–122. DOI: 10.31489/2024PH4/114-122
- Aralbayeva, G.M., Manika, I., Karipbayev, Zh., Suchikova, Y., Kovachov, S., Sugak, D., & Popov, A.I. (2023). Micromechanical Properties of $\text{Gd}_3\text{Ga}_5\text{O}_{12}$ Crystals Irradiated with Swift Heavy Ions. *Journal of Nano- and Electronic Physics*, 15(5), 05020. DOI: 10.21272/jnep.15(5).05020
- Orucu, H., Ozen, G., Collins, J., & Di Bartolo, B. (2009). Temperature dependence of the luminescence spectra of garnet crystals doped with chromium ions. *Optical Materials*, 31(7), 1065–1070. DOI: 10.1016/j.optmat.2007.12.016
- Lupei, V., Elejalde, M. J., Brenier, A., & Boulon, G. (1994). Spectroscopic properties of Fe^{3+} in GGG and the effect of co-doping with rare-earth ions. *Journal de Physique IV*, 4(C4), 303–306. DOI: 10.1051/jp4:1994478
- Kniec, K., Ledwa, K. A., Maciejewska, K., & Marciniak, L. (2020). Intentional modification of the optical spectral response and relative sensitivity of luminescent thermometers based on Fe^{3+} , Cr^{3+} , Nd^{3+} co-doped garnet nanocrystals by crystal field strength optimization. *Materials Chemistry Frontiers*, 4(6), 1697–1705. DOI: 10.1039/D0QM00097C
- Omelkov, S.I., Chernenko, K., Ekström, J.C., Jurgilaitis, A., Khadiev, A., Kivimäki, A., & Kirm, M. (2022). Recent advances in time-resolved luminescence spectroscopy at MAX IV and PETRA III storage rings. *Journal of Physics: Conference Series*, 2380, 012135. DOI: 10.1088/1742-6596/2380/1/012135
- Kalinko, A., Kotlov, A., Kuzmin, A., Pankratov, V., Popov, A. I., & Shirmane, L. (2011). Electronic excitations in ZnWO_4 and $\text{Zn}_x\text{Ni}_{1-x}\text{WO}_4$ ($x = 0.1-0.9$) using VUV synchrotron radiation. *Central European Journal of Physics*, 9(2), 432–437. DOI: 10.2478/s11534-010-0128-1
- Pankratov, V., Popov, A. I., Kotlov, A., & Feldmann, C. (2011). Luminescence of nano- and macrosized $\text{LaPO}_4:\text{Ce}$, Tb excited by synchrotron radiation. *Optical Materials*, 33(7), 1102–1105. DOI: 10.1016/j.optmat.2010.12.041

- 19 Zhunusbekov, A.M., Karipbayev, Z.T., Tolegenova, A., Kumarbekov, K.K., Nurmoldin, E.E., Baizhumanov, M.M., Kotlov, A., & Popov, A.I. (2024). Comparative VUV synchrotron excitation study of YAG:Eu and YAG:Cr ceramics. *Crystals*, 14(5), 897. DOI: 10.3390/cryst14050897
- 20 Zhunusbekov, A.M., Strelkova, A.V., Karipbayev, Z.T., Kumarbekov, K.K., Akilbekov, A., Kassymkhanova, R.N., Kassymzhanov, M.T., Smortsova, Y., & Popov, A.I. (2025). Luminescence investigation of BaMgF₄ ceramics under VUV synchrotron excitation. *Crystals*, 15(2), 127. DOI: 10.3390/cryst15020127
- 21 Ghimire, K., Haneef, H.F., Collins, R. W., & Podraza, N.J. (2015). Optical properties of single-crystal Gd₃Ga₅O₁₂ from the infrared to ultraviolet. *Physica Status Solidi (B)*, 252(9), 2191–2198. DOI: 10.1002/pssb.201552115
- 22 Orucu, H., Ozen, G., Collins, J., & Di Bartolo, B. (2011). Spectroscopy of chromium doped garnets in a wide temperature range. *MRS Proceedings*, 1053, EE04-01. DOI: 10.1557/PROC-1053-EE04-01
- 23 Varney, C.R., Reda, S.M., Mackay, D.T., Rowe, M.C., & Selim, F.A. (2011). Strong visible and near-infrared luminescence in undoped YAG single crystals. *AIP Advances*, 1(4), 042170. DOI: 10.1063/1.3671646
- 24 Gluchowski, P. & Chaika, M. (2024). Crystal-field strength variations and energy transfer in Cr³⁺-doped GGG transparent nanoceramics. *The Journal of Physical Chemistry C*, 128(23), 9641–9651. DOI:10.1021/acs.jpcc.4c01658
- 25 Somakumar, A.K., Bulyk, L.-I., Tsiumra, V., Barzowska, J., Xiong, P., Lysak, A., Zhdachevskyy, Y., & Suchocki, A. (2023). High-Pressure Near-Infrared Luminescence Studies of Fe³⁺-Activated LiGaO₂. *Inorganic Chemistry*, 62(31), 12434–12444. DOI: 10.1021/acs.inorgchem.3c01627
- 26 Müller, R., Mangold, M., Bauer, S., Huber, F., Herr, U., & Thonke, K. (2022). Zeeman spectroscopy of the internal transition ⁴T₁ → ⁶A₁ of Fe³⁺ ions in ZnO. *Journal of Applied Physics*, 132(6), 065702. DOI:10.1063/5.0098499

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Gd₃Ga₅O₁₂ монокристалдарындағы Cr және Fe қоспаларының төмен температуралы люминесценциялық қасиеттері

Мақалада Gd₃Ga₅O₁₂ (GGG) монокристалдарының люминесценциялық қасиеттеріне Cr³⁺ және Fe³⁺ иондарының еріксіз қоспаларының әсері қарастырылды. 10–300 К температура диапазонында жоғары энергиялы синхротрондық сәулелену мен қоздырылған спектрлердің сипаттық ерекшеліктері талданды. 10 К температурада люминесценция негізінен Cr³⁺ иондарының спинге тыйым салынған ²E → ⁴A₂ ауысуынан туындайтын сызықты сәулелену мен анықталатыны көрсетілді, бұл электрон-фонондық байланысының әлсіздігін және кристалдың жоғары біртектілігін көрсетеді. Температура артқан сайын бұл ауысудың интенсивтілігі айтарлықтай төмендеп, кеңжолақты люминесценция пайда болады. Ол спинге рұқсат етілген ⁴T₂ → ⁴A₂ ауысуымен және Fe³⁺ иондарының сәулеленуімен байланысты. Спектрлердің температуралық эволюциясы Cr³⁺ иондарының қозған күйлерінің жылулық қайта бөлінуімен, деңгей аралық күйлердің араласуы мен және тор тербелістерінің әсерінен Fe³⁺ ауысуларының спиндік тыйымының ішінара жойылуымен түсіндіріледі. Зерттеу негізінде энергияны тасымалдау және сәулеленбейтін релаксация процестеріндегі қоспа орталықтарының ролі туралы қорытындылар жасалды. Нәтижелер іргелі фотоника үшін де, кең температура диапазонында жұмыс істейтін тиімді люминесценттік материалдар мен оптикалық құрылғыларды әзірлеу үшін де маңызды.

Кілт сөздер: гадолиний галлий гранаты (GGG), синхротрондық сәулелену, Cr³⁺ иондары, Fe³⁺ иондары, люминесценция, қозуспектрлері, температураға тәуелділік, энергия тасымалдау, электрон-фонондық байланыс, сәулеленбейтін релаксация, қоспаорталықтары, оптикалық қасиеттер

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Низкотемпературное поведение люминесценции примесей Cr и Fe в монокристаллах Gd₃Ga₅O₁₂

В данной статье рассматривается влияние непреднамеренных ионов-примесей Cr³⁺ и Fe³⁺ на люминесцентные свойства монокристаллов Gd₃Ga₅O₁₂ (GGG). Проанализированы характерные особенности спектров, возбужденных высокоэнергетическим синхротронным излучением в температурном диапазоне 10–300 К. Показано, что при 10 К люминесценция определяется узкополосным излучением ионов Cr³⁺, обусловленным спин-запрещенным переходом ²E → ⁴A₂, что свидетельствует о слабой электрон-фононной связи и высокой однородности кристалла. Выявлено, что с повышением температуры интенсивность данного перехода существенно снижается, тогда как проявляется широкополосная люминесценция, связанная со спин-разрешенным переходом ⁴T₂ → ⁴A₂ и вкладом излучения ионов Fe³⁺. Доказано, что температурная эволюция спектров обусловлена тепловым перераспределением

населённости уровней Cr^{3+} , межуровневым смешением состояний, а также частичным снятием спинового запрета переходов Fe^{3+} за счёт колебаний решётки. На основе проведённых исследований сформулированы выводы о роли центров-примесей в процессах переноса энергии и безызлучательной релаксации. Полученные результаты представляют интерес как для фундаментальной фотоники, так и для разработки эффективных люминесцентных материалов и оптических устройств, функционирующих в широком температурном диапазоне.

Ключевые слова: гадолиний-галлиевый гранат (GGG), синхротронное излучение, ионы Cr^{3+} , ионы Fe^{3+} , люминесценция, спектры возбуждения, температурная зависимость, перенос энергии, электрон-фононное взаимодействие, безызлучательная релаксация, центры-примеси, оптические свойства

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