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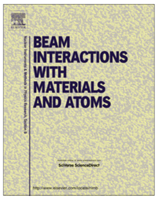

Gamma-radiation-induced dielectric relaxation characteristics of layered crystals of phlogopite mica

Navjeet Kaur[a], Mohan Singh[a,*], Lakhwant Singh[a], A.M. Awasthi[b], Jitender Kumar[b]

[a] Department of Physics, Guru Nanak Dev University, Amritsar, Punjab 143005, India
[b] Thermodynamics Laboratory, UGC-DAE Consortium for Scientific Research, Indore 452001, India

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ABSTRACT

In the present investigation, the influence of gamma irradiation on the dielectric relaxation characteristics of phlogopite mica was studied over the frequency range of 0.1 Hz–10 MHz and in the temperature range of 593–813 K by measuring the dielectric permittivity, electric modulus and conductivity. By comparing the dielectric spectra obtained for pristine and irradiated samples, it was observed that gamma irradiation significantly enhances the dielectric constants (ε' and ε'') of phlogopite mica because of the production of defects and lattice disorder by the gamma irradiation. The values of the activation energy for pristine and irradiated mica (determined from the electric modulus and the conductivity) were found to be substantially similar, suggesting that the same types of charge carriers are involved in the relaxation mechanism. The experimentally measured electric modulus and conductivity data could be well interpreted by the Havriliak–Negami dielectric relaxation function. The scaling of the electric-modulus spectra of both pristine and irradiated mica results in a master curve, which indicates that the relaxation mechanism is independent of temperature. Cole–Cole plots were also employed to analyze the non-Debye relaxation mechanism. This research will boost the reader's interest concerning the emerging contributions of irradiation and materials such as mica in electrical engineering.

1. Introduction

Modern technology has focused our interest in enhancing the performance of various devices in electrical engineering. Considerable resources have been invested in both experimental and theoretical research, but the possibility of employing materials available in nature and exploring their potential for cutting-edge applications in technology has been largely neglected. Among several natural materials that could be considered for this purpose, micaceous minerals are very stable, sensitive and abundant materials in their most advantageous forms, and they stand out over others because of their tremendous prospects for fruitful applications [1–7]. Dielectric measurements have proven to be a crucial tool in the study of relaxation behavior. A complete understanding of the dielectric relaxation of micaceous minerals is important from the standpoint of applications. Dielectric relaxation spectroscopy of annealed phlogopite mica at various temperatures has also been studied by the present authors [2]. We are currently focusing on the different routes through which the material can provide more beneficial and high-quality results. In the present research article, a study of the gamma-radiation-induced dielectric relaxation characteristics of the phlogopite mica is presented. The interaction of ionizing radiation, especially γ radiation, with matter is very significant [1,3–5,8]. Ionizing radiation leads to the production of defects as a result of various processes involved during the interaction, e.g., atomic displacements can be caused by momentum and energy transfer to electrons or by the rearrangement of atoms. These irradiation-induced effects and defects can stimulate significant improvement in the dielectric properties of the material. The present investigation was conducted to understand the effects of ionizing radiation (γ radiation) on the dielectric relaxation spectroscopy of phlogopite mica over a range of temperature (593–813 K) and frequency (0.1 Hz–10 MHz). To the best of our knowledge, this is the first attempt that has been made to study the influence of gamma irradiation on the dielectric properties of phlogopite mica over a wide range of frequency and temperature.

2. Experimental details

In the present research, sheets of phlogopite mica ($\approx$200 μm thick) supplied by Shree GR Exports Private Limited, Kolkata, India, were used. These phlogopite-mica sheets were irradiated with gamma rays (doses ranged from 5 kGy to 100 kGy) using a ^{60}Co gamma source at room temperature that was acquired from the

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* Corresponding author. Mobile: +91 99144 90280.
E-mail address: mohansinghphysics@gmail.com (M. Singh).

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Inter University Accelerator Centre (IUAC), New Delhi, India. The dose rate in the gamma chamber at the time of irradiation was ~7.88 kGy/h. The dielectric constant (ε') and dielectric loss (ε'') for the gamma-irradiated samples were measured in the frequency range of 0.1 Hz–10 MHz at room temperature. The variation of these two parameters (ε' and ε'') as a function of frequency for samples subjected to various gamma doses is depicted in Figs. 1 and 2, respectively. It was observed that the dielectric constant (ε') and the dielectric loss (ε'') increase with increasing gamma dose and exhibit maxima for the phlogopite mica that was irradiated with a 25 kGy gamma dose. The 25 kGy gamma-irradiated sample was therefore identified as the one that should prove to be most informative for a deeper understanding of the gamma-irradiation-induced dielectric relaxation characteristics of phlogopite mica. The dielectric relaxation characterization of pristine and 25 kGy gamma-dose-irradiated phlogopite mica was executed in the frequency range off 0.1 Hz–10 MHz and over the temperature range of 593–813 K. All the dielectric measurements were performed using a NOVO-CONTROL (Alpha-A) high-performance frequency analyzer installed at the UGC-DAE Consortium for Scientific Research, Indore, India. The phlogopite sample was mounted in a sample holder between two parallel electrodes, forming a mica capacitor. To minimize noise disturbance, proper shielding of the sample holder was implemented. The theoretical curve fitting of the measured conductivity and electric-modulus data was performed using the Havriliak–Negami dielectric relaxation formulation superimposed with a conductivity term, as given below [9]:

$$\varepsilon^*(\omega) = \varepsilon' - i\varepsilon'' = -i\left(\frac{\sigma_{dc}}{\varepsilon_0\omega}\right)^n + \left\{\frac{\Delta\varepsilon}{\left[1+(i\omega\tau)^\alpha\right]^\beta} + \varepsilon_\infty\right\} \quad (1)$$

where ε_0 is the vacuum permittivity, τ is the characteristic relaxation time, and ε_∞ represents the value of ε' at infinite frequency. $\Delta\varepsilon$, which is known as the relaxation strength, gives the difference between ε' at zero and infinite frequency (ε_∞). $\Delta\varepsilon$ is proportional to the area under the maximum value or the relaxation peak of ε''. α and β are the symmetry- and asymmetry-dependent broadening parameters, respectively. The parameter α is related to depicts the broadness of the spectrum and determines the slope of the low-frequency side of the relaxation in the dielectric loss ε''. The parameter β is related to the asymmetry of the spectra, and the value of $-\alpha\beta$ determines the slope of the high-frequency side of the ε'' relaxation curve. The value of both parameters α and β are constrained to lie between 0 and 1.

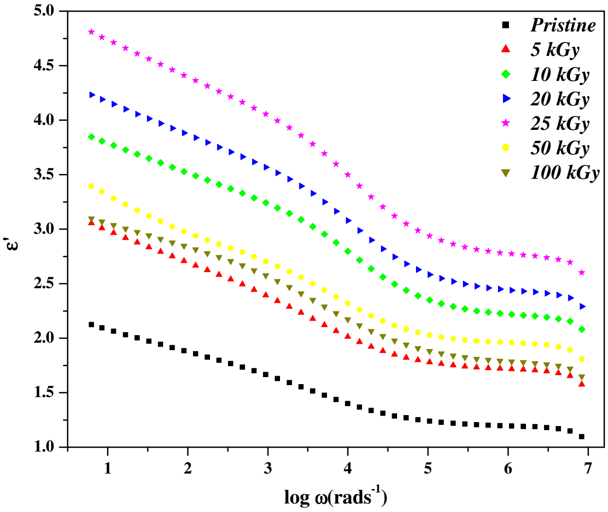

Fig. 1. Frequency dependence of the dielectric constant (ε') of phlogopite mica subjected to various gamma-ray doses.

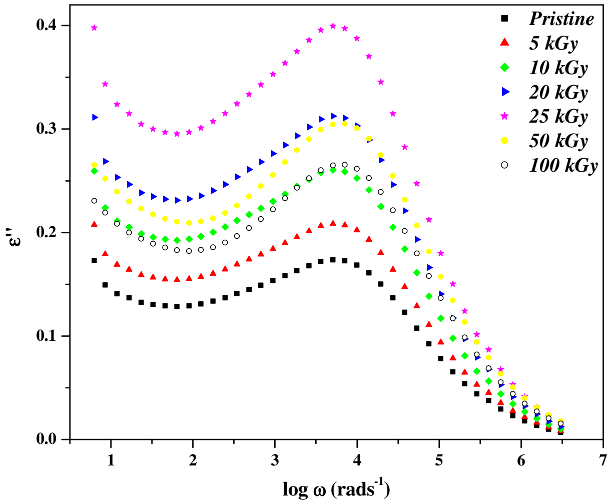

Fig. 2. Frequency dependence of the dielectric loss (ε'') of phlogopite mica subjected to various gamma-ray doses.

3. Results and discussion

Dielectric relaxation spectroscopy was used to study the influence of an applied electric field on pristine and gamma-irradiated phlogopite mica. The frequency- and temperature-dependent behavior of the dielectric permittivity ($\varepsilon^* = \varepsilon' - i\varepsilon''$) demonstrates the response of the phlogopite to the applied field by providing information regarding the properties of the material. The dielectric permittivity (ε^*) develops from the space-charge polarization originating within the dielectric material. The real part (ε') represents the polarizability, and the imaginary part (ε'') represents the energy losses attributable to the polarization and ionic conduction. Each polarization mechanism dominates at a certain characteristic relaxation frequency.

The frequency response (0.1 Hz–10 MHz) of the dielectric constant (ε') and dielectric loss (ε'') of phlogopite mica before and after gamma irradiation (5–100 kGy) at room temperature is presented in Figs. 1 and 2, respectively. These results demonstrate that the dielectric constant (ε') and dielectric loss (ε'') increase with increasing gamma dose up to 25 kGy and then decrease for higher gamma doses. The increase in the dielectric constant (ε') and dielectric loss (ε'') with the increase in the accumulated gamma dose up to 25 kGy may be attributable to the disturbance in the material structure caused by the production of atomic displacements and various lattice defects. As the gamma dose increases up to 25 kGy, more ions are activated with lattice disorders, and their interactions and migration through the material increase the space-charge polarization and thereby increase the dielectric constant (ε') and dielectric loss (ε''). Above 25 kGy, as the gamma dose increases, the dielectric constant and dielectric loss decrease because of the rearrangement of atoms and primary defects in the material. This means that at higher gamma doses, redistribution of the incident energy occurs, and stable defects are formed that suppress the migration of carriers and the polarization effect, which in turn decreases the dielectric constant and dielectric loss. It is also observed that ε' decreases as the frequency increases because the dipoles can no longer comply with the field at high frequencies. A similar trend is observed for the dielectric loss (ε'') for varying frequencies and gamma doses (Fig. 2). The increase in the dielectric constant of mica near 25 kGy is a characteristic feature of