

Correlation morphological analysis of secondary phase inclusions in $\text{Ge}_{1-x-y}\text{Sn}_x\text{Mn}_y\text{Te}$

V. E. Slynko¹, V.I. Ivanov¹, O.A. Sydor¹, V.M. Vodopyanov¹, L. Kilanski², S. Piotrowska²

¹Chernivtsi Branch of Frantsevych Institute for Problems of Materials Science, NASU, 5 Iryny Vilde St., Chernivtsi, 58001, Ukraine

²Institute of Physics, Polish Academy of Sciences, Aleja Lotnikow 32/46, PL-02668 Warsaw, Poland
e-mail: slynko.vasily@gmail.com

Introduction. The interpretation of magnetic phenomena in IV-VI diluted magnetic semiconductors (DMS) often rests on the assumption of host-lattice perfect homogeneity. However, thermodynamic instabilities during synthesis can lead to phase separation, creating a micro-composite structure. This work proposes a method to identify and quantify these "hidden" secondary phase inclusions in $\text{Ge}_{1-x}\text{Sn}_{x+z}\text{Mn}_y\text{Te}$ to ensure the correct interpretation of low-temperature magnetic responses, particularly $\chi_{ac}(T)$. The samples were cut from ingots grown by the vertical Bridgman with Sn or Mn overload.

Methodology. We developed a Correlation Morphological Analysis (CMA) based on a dataset of 160+ high-resolution SEM images (1280×960 px). By correlating grayscale contrast with localized micro-XRF (EDS) data, we reconstructed the volumetric distribution of secondary phases using Delesse's principle ($\Phi \approx A_{inc}/A_{total}$), which is statistically valid for randomly oriented inclusions [1]. Here Φ – volumetric fraction of the secondary phase inclusions; A_{inc} – total area of inclusions measured on the SEM micrographs; A_{total} – total analyzed area of the sample surface.

Table. Volumetric and compositional parameters of micro-inclusions in $\text{Ge}_{1-x}\text{Sn}_{x+z}\text{Mn}_y\text{Te}$

Ingot	Solid solution	Total x/y/z	Dominant incl. phase	Te (at. %)	Size (μm)	Vol. (%)
1292	$\text{Ge}_{1-x}\text{Sn}_{x+z}\text{Mn}_y\text{Te}$	0.2/0.05/0.01	MeTe_2 + Eutectic Te	65.0÷75.0	1÷10	5÷7
1293	$\text{Ge}_{1-x}\text{Sn}_{x+z}\text{Mn}_y\text{Te}$	0.2/0.05/0.03	MeTe_2 (AFM clusters)	≈ 64.0	2÷8	3÷4
1294	$\text{Ge}_{1-x}\text{Sn}_{x+z}\text{Mn}_y\text{Te}$	0.2/0.05/0.05	MeTe_2 + V_{Ge} -zones	56.0÷66.0	3÷10	4÷5
1295	$\text{Ge}_{1-x}\text{Sn}_x\text{Mn}_y\text{Te}$	0.2/0.03/0	MeTe_2 (high Mn content)	≈ 65.5	2÷12	4÷6

Results. Three types of structural anomalies were identified across the $\text{Ge}_{1-x-y}\text{Sn}_x\text{Mn}_y\text{Te}$ sample series (1292–1295) obtained from ingots grown by the vertical Bridgman method:

1. Stoichiometric ditellurides $(\text{Ge},\text{Sn},\text{Mn})\text{Te}_2$ (Te≈65%). These result from cationic sublattice degradation – a localized expulsion of Mn and Sn from the NaCl-type lattice to minimize Gibbs free energy $G = H - T \times S$ (where H – enthalpy, T – absolute temperature, S – entropy).

2. Te-rich eutectic enclaves (Te≈75%). These represent residues of the melt (eutectic point ≈375 °C [2]), forming non-magnetic "ballast" in interdendritic spaces. According to the Ge–Te phase diagram, the eutectic point corresponds to a composition of ≈85 at. % Te and 15 at. % Ge.

3. Defective matrix (Te≈56÷62%) saturated with cation vacancies (V_{Ge}).

Conclusions. The identified micro-inclusions (3–7% vol.) act as a static antiferromagnetic background without altering the fundamental magnetic behavior of the DMS matrix. Identifying this composite nature is a prerequisite for "virtual purification" (deconvolution) of the magnetic signal. This approach effectively eliminates secondary "ballast" effects, thereby enabling a more rigorous validation of advanced dynamic cluster model (0D–3D) in $\text{Ge}_{1-x-y}\text{Sn}_x\text{Mn}_y\text{Te}$ systems [3].

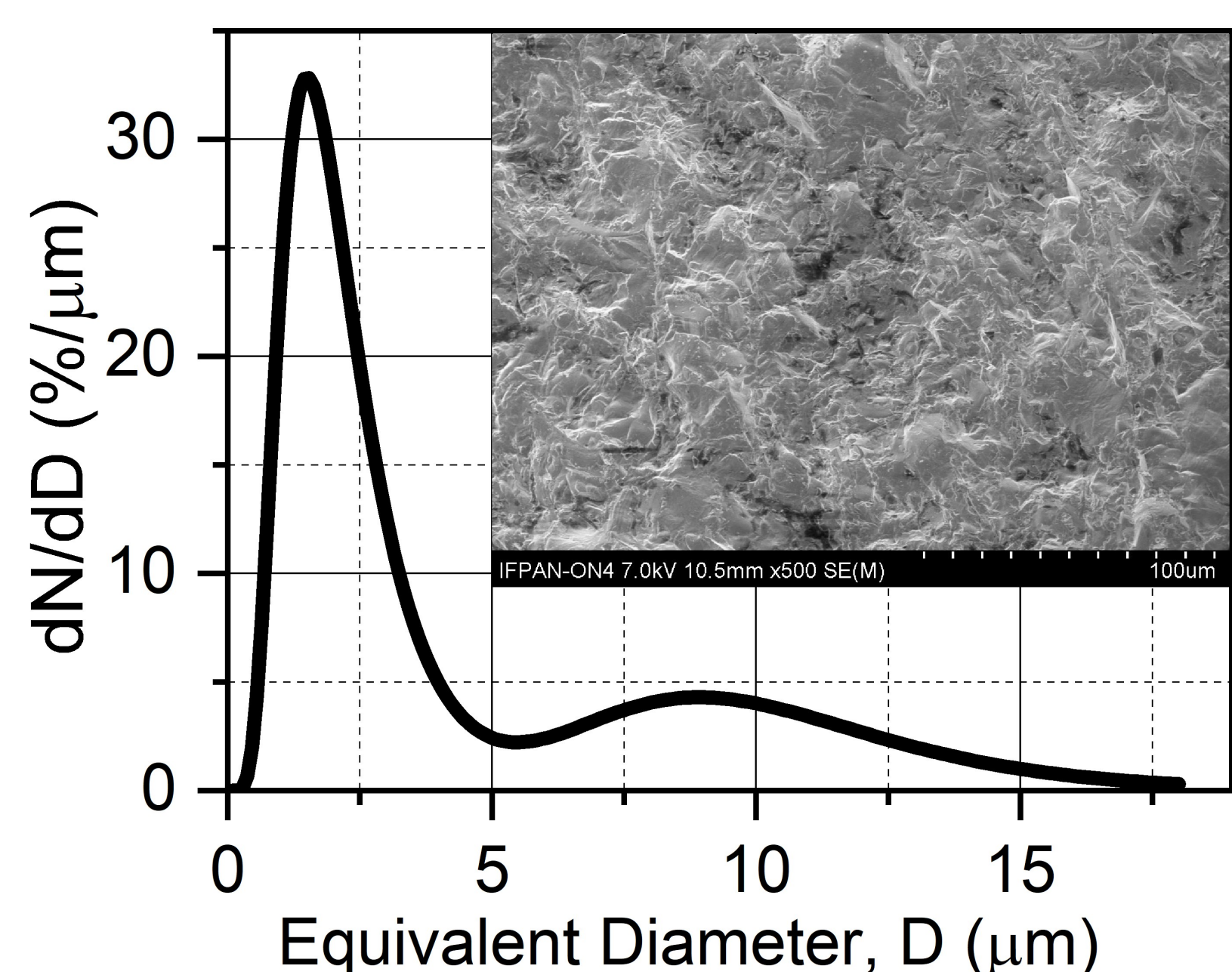


Fig. Particle size distribution profile (dN/dD) as a function of equivalent diameter for secondary phase microinclusions in the $\text{Ge}_{1-x-y}\text{Sn}_x\text{Mn}_y\text{Te}$ crystal (sample 1292/2).

References

- [1] E. E. Underwood, Quantitative stereology for microstructural analysis, in: Microstructural analysis, Springer, pp. 35–66 (1970). https://doi.org/10.1007/978-1-4615-8693-7_3
- [2] H. Okamoto, Ge-Te (Germanium-Tellurium), J. Phase Equilib. 21, 496 (2000). <https://doi.org/10.1361/105497100770339789>
- [3] V. Slynko et al., Dynamic cluster magnetic subsystems in diluted magnetic semiconductor $\text{Ge}_{1-x-y}\text{Sn}_x\text{Mn}_y\text{Te}$, Fiz. Nizk. Temp. 52, 290 (2026) [Low Temp. Phys. 52, 290 (2026)]. <https://doi.org/10.1063/10.0042378>