# Refined 0D–3D dynamic cluster model of magnetic susceptibility in $Ge_{1-x-y}Sn_xMn_yTe$: the role of secondary phase microinclusions

**V. E. Slynko[1], M.V. Tovarnitskii[1], A.V. Zaslonkin[1], V.V. Netyaga[1], L. Kilanski[2], S. Piotrowska[2]**

*[1]Chernivtsi Branch of Frantsevych Institute for Problems of Materials Science, NASU, 5 Iryny Vilde St., Chernivtsi, 58001, Ukraine*
*[2]Institute of Physics, Polish Academy of Sciences, Aleja Lotnikow 32/46, PL-02668 Warsaw, Poland*
*e-mail: slynko.vasily@gmail.com*

The complex nature of the magnetic response in diluted magnetic semiconductors (DMS) $Ge_{1-x-y}Sn_xMn_yTe$, particularly the anomalous double-peaked temperature dependence of the dynamic magnetic susceptibility $\chi_{ac}(T)$, has been previously described within the framework of a dynamic 0D–3D cluster magnetic subsystem model [1]. While the initial theoretical approach successfully parameterized the macroscopic magnetic behavior, the microscopic mechanism driving the inter-cluster interactions requires refinement to avoid overestimating the role of bulk thermal lattice vibrations.

Recent comprehensive micro-XRF mapping of DMS $Ge_{1-x-y}Sn_xMn_yTe$ crystals (specifically, samples from ingot 1292, Figs. 1-2) has revealed the physical origin of these magnetic anomalies. The data unambiguously demonstrate the presence of structural micro-inhomogeneities. Instead of an idealized homogeneous matrix, the material contains localized microregions with pronounced deviations from stoichiometry, primarily characterized by an enriched tellurium content (reaching 65.0–75.0 at.% Te, in stark contrast to the nominal ~50 at.% of the host lattice). These secondary phase microinclusions exhibit typical dimensions ranging from 5 to 15 µm and occupy a volumetric fraction of approximately 5–7%.

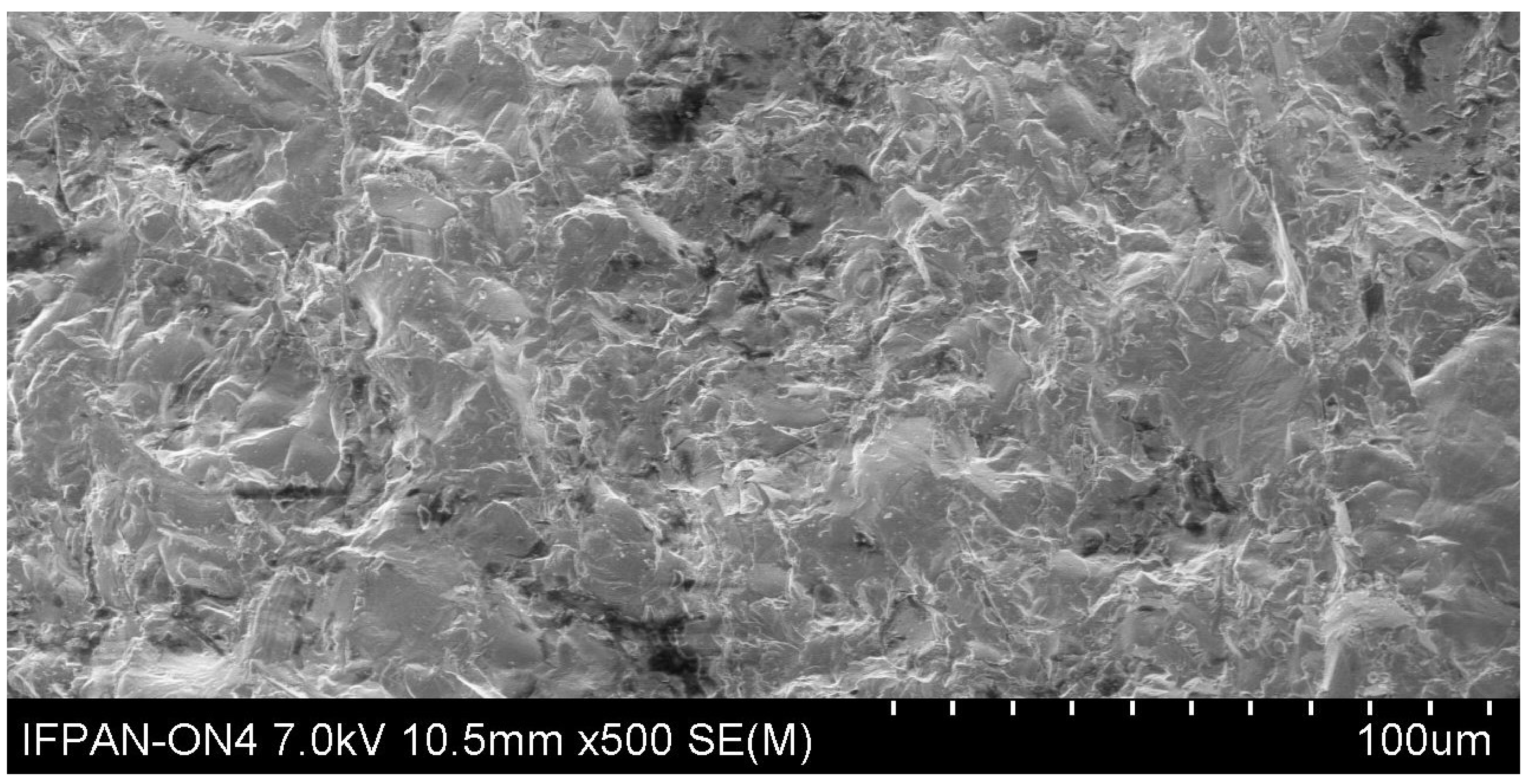


Fig. 1. Secondary phase microinclusions (enriched Te) in the 1292/2 $Ge_{1-x-y}Sn_xMn_yTe$ (× 500).

The formation of these Te-enriched microinclusions is an inevitable consequence of the crystal growth thermodynamics. Specifically, they arise due to compositional instabilities and segregation processes in the melt [2], which lead to microscopic fluctuations in the composition and density of *low-temperature eutectics* throughout the entire crystallization process. Therefore, absolute spatial homogeneity in these quaternary solid solutions is thermodynamically unattainable.

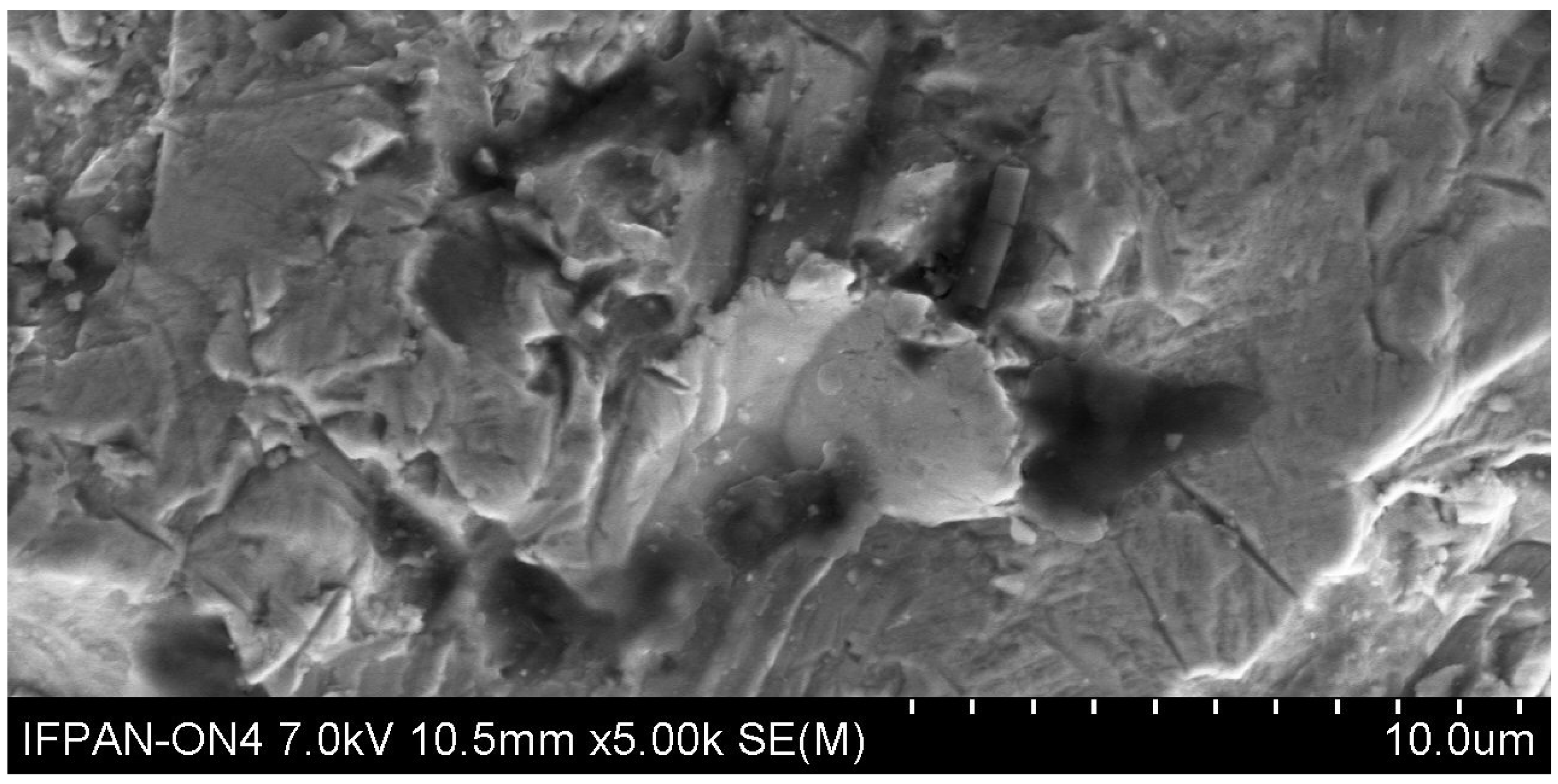


Fig. 2. Secondary phase microinclusions (enriched Te) in the 1292/2 $Ge_{1-x-y}Sn_xMn_yTe$ (× 5000).

Recognizing this intrinsic micro-heterogeneity allows for a critical enhancement of the 0D–3D cluster model [1]. The primary driver of the complex magnetic response $\chi_{ac}(T)$ is not the uniform thermal vibration of an ideal lattice, but rather the interface effects at the boundaries between the Te-enriched microinclusions and the main matrix. These boundaries act as intense centers for phonon scattering. Furthermore, the local lattice strain at these interfaces causes a sharp, exponential dependence of the p-d exchange interaction constant ($J_{pd}$) on the overlap of wave functions [3]. Even minute displacements of magnetic ions ($Mn^{2+}$) within these highly strained boundary regions result in significant modulations of the local magnetic order.

Thus, the refined 0D–3D cluster model, grounded in direct micro-XRF evidence, demonstrates that the macroscopic magnetic anomalies in $Ge_{1-x-y}Sn_xMn_yTe$ are governed by the dynamic interplay and boundary scattering effects between structurally distinct, thermodynamically inevitable micro-phases, rather than purely by uniform thermal lattice dynamics.

[1] V. Slynko et al., "Dynamic cluster magnetic subsystems in diluted magnetic semiconductor $Ge_{1-x-y}Sn_xMn_yTe$", Low Temp. Phys. 52, 262 (2026). DOI: 10.1063/10.0042378
[2] P. Rudolph, M. Mühlberg, "Basic problems of vertical Bridgman growth of CdTe", Mater. Sci. Eng. B 16 (1-3), 8-16 (1993). DOI: 10.1016/0921-5107(93)90005-8
[3] A. Abragam, B. Bleaney, Electron Paramagnetic Resonance of Transition Ions, Oxford Univ. Press (1970). ISBN: 978-0198512509.