Growth Strategies for Altermagnet Mn_3Ga for Spintronic Applications

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What is Altermagnetism?

Beyond Conventional Magnetism:

- **Ferromagnets:** Net magnetization + Spin splitting
- **Antiferromagnets:** Zero magnetization + No spin splitting
- **Altermagnets:** Zero magnetization + Spin splitting

Key Feature: Broken PT Symmetry

- Parity-Time symmetry breaking
- Momentum-dependent spin polarization
- Spin-split bands without net magnetization

Fundamental Equation

$$[PT]\epsilon(s, \mathbf{k}) \neq \epsilon(s, \mathbf{k}) \tag{1}$$

Key Features & Properties

Fundamental Properties:

- Zero stray magnetic fields
- Large anomalous Hall effect
- Strong spin-coherence
- High transition temperatures
- Light element compatibility

Technological Advantages:

- No stray field interference
- High-density integration
- Robust against external fields
- THz-frequency operation
- Energy-efficient switching

Key Advantage

Combines benefits of both ferromagnets and antiferromagnets while eliminating their limitations

Classification of Altermagnets

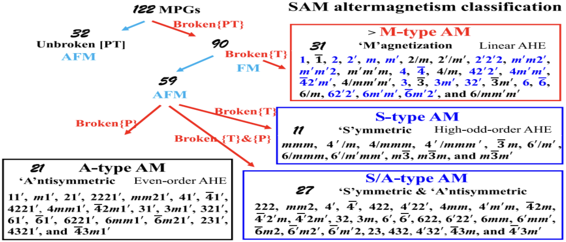


Figure: Three altermagnet types. M-Type (net M), S-Type (zero net M), A-Type (P broken, T unbroken). Adopted from Cheong et al

M-Type
- Broken T symmetry
- Non-zero net magnetization
- Linear anomalous Hall effect
- Example: Mn_3Ga

S-Type
- Broken T symmetry
- Zero net magnetization
- High odd-order AHE
- Symmetric spin splitting

A-Type
- Unbroken T symmetry
- Broken P symmetry
- Even-order AHE
- Antisymmetric spin splitting

Strong vs Weak Altermagnets

Spin Rotation Operation $\mathbf{S}_n(\mathbf{r})$

Rotates all spins by $2\pi/n$ around $\mathbf{r}$ axis without rotating crystal structure

Strong Altermagnets

- Spin splitting WITHOUT SOC
- At most ONE unbroken $\mathbf{S}_n(\mathbf{r})$
- All collinear M-type and S-type
- Large spin splittings

Weak Altermagnets

- Spin splitting ONLY with SOC
- TWO or MORE unbroken $\mathbf{S}_n(\mathbf{r})$
- All collinear A-type
- Smaller spin effects

Mn_3Ga as Prototypical Altermagnet

Crystal Structures:

- **Cubic:** Disordered $L1_2$, collinear AFM
- **Tetragonal:** Ordered $D0_{22}$, ferrimagnetic
- **Hexagonal:** $D0_{19}$, non-collinear AFM

Key Properties:

- High magnetic anisotropy
- Large anomalous Hall effect
- Room temperature operation
- High spin polarization (88%)

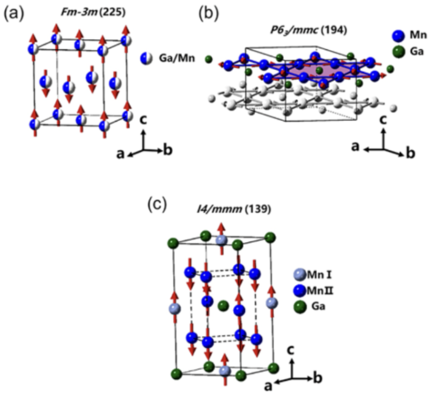


Figure: Mn3Ga phases (a)cubic phase (b)tetragonal phase and (c)hexagonal phase. Adopted from Song et al

Synthesis via Arc Melting

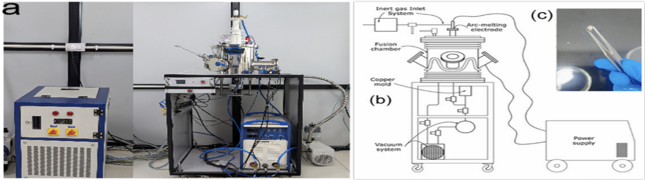


Figure: Arc-melting setup for MnGa sample preparation under inert atmosphere

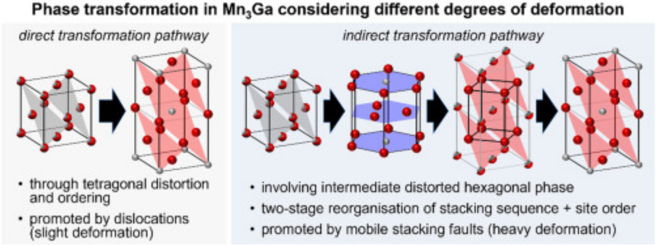
Arc Melting Setup:

- Water-cooled copper hearth
- Tungsten electrode
- Argon atmosphere
- High vacuum (10^{-3} Torr)

Procedure:

- High-purity Mn (99.999%) and Ga (99.999%)
- Stoichiometric Mn_3Ga (75:25 at.%)
- Multiple re-melting for homogeneity
- Rapid cooling on copper

Annealing and Phase Transformation



Phase Transformation Sequence

- **As-cast** → Cubic (γ-phase)
- **350-450°C annealing** → Tetragonal ($D0_{22}$)
- **600-800°C annealing** → Hexagonal ($D0_{19}$-β-phase)

Key Features:

- Cubic → Tetragonal: Ordering process
- Irreversible transformation to hexagonal

Structural Characterization - XRD

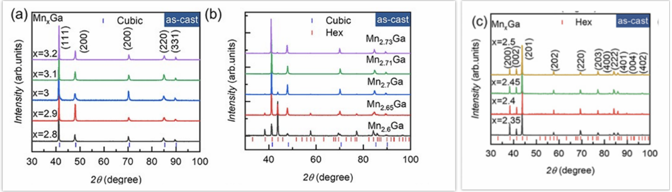


Figure: XRD spectra of Mn_3Ga for various concentrations and phase. Adopted from Song et al

Cubic Phase:

- Space group: $Pm\bar{3}m$
- Lattice: a = 3.7786 Å
- Disordered $L1_2$

Tetragonal Phase:

- Space group: $I4/mmm$
- Lattice: a = 3.9098 Å, c = 7.1011 Å
- Ordered $D0_{22}$

Hexagonal Phase:

- Space group: $P6_3/mmc$
- Lattice: a = 5.4084 Å, c = 4.3547 Å
- Non-collinear spins

Magnetic Properties

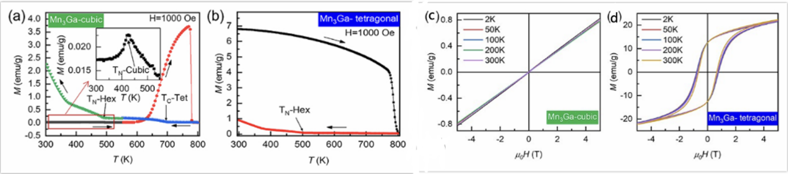


Figure: Temperature-dependent magnetization curves showing magnetic transitions in MnGa phases. Adopted from Song et al

Cubic Phase:

- Collinear antiferromagnetic
- Néel temperature: T_N 420 K
- Linear M-H curves

Tetragonal Phase:

- Ferrimagnetic ordering
- High coercivity (21.4 kOe)
- Large perpendicular anisotropy

Hexagonal Phase:

- Non-collinear AFM
- 120° in-plane spin ordering
- Large anomalous Hall effect

Transport Properties

Hexagonal Mn_3Ga Exhibits:

- Large AHE conductivity (500 Ω^{-1}cm^{-1})
- Anomalous Nernst effect
- Topological Hall effect (¡100 K)
- Spin-split bands without SOC

Application Potential:

- Spin-current generators
- Magnetic memory devices
- Energy harvesting systems

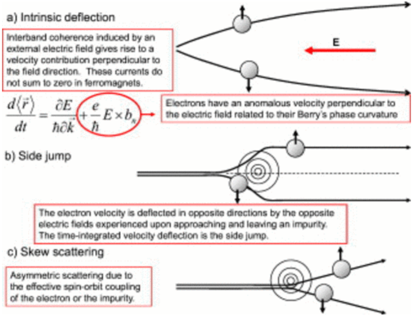


Figure: Three mechanisms of anomalous Hall effect in altermagnets: intrinsic Berry phase, side jump scattering, and skew scattering. Adopted from Nagaosa et al

Applications in Spintronics

Tetragonal Phase:

- Rare-earth-free permanent magnets
- Spin-injection sources
- Magnetic recording media

Hexagonal Phase:

- Antiferromagnetic spintronics
- Topological Hall effect devices
- MTJ pinning layers

Advantages:

- No stray fields
- High thermal stability
- CMOS compatibility
- THz operation
- Energy efficiency

Key Benefit

Enables high-density, energy-efficient spintronic devices without magnetic interference

Conclusion: Mn_3Ga as Versatile Altermagnet

Key Findings

- **Multifunctional Material**: Rich structural polymorphism (cubic, tetragonal, hexagonal) with distinct magnetic configurations
- **Room-Temperature Operation**: High Néel temperature ($\sim$420 K) enables practical device applications
- **Strong Altermagnetic Signatures**: Large anomalous Hall effect, zero stray fields, high spin polarization (88%)

Technological Advantages

- Combines benefits of ferromagnets and antiferromagnets.
- Energy-efficient switching and THz-frequency operation capability
- Robust against external fields with high-density integration potential

Acknowledgments & References

Acknowledgments

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- Department of Physics, IIT Ropar

References

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Thank You!