STUDY OF MAGNETIZATION AND SPECIFIC HEAT CAPACITY OF MULTIFERROIC TWO DIMENSIONAL THIN FILM

By

Berhanu Tamirat

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This is to certify that the project prepared by **Berhanu Tamirat**, entitled "**Study of Magnetization and Specific Heat Capacity of Multiferroic Two Dimensional Thin Film**" and submitted in partial fulfillment of the requirements for the degree of **Master of Science**. compiles with the regulations of the University and meets the accepted standards with respect to originality.

Advisor: Prof. P.Singh Signature:_____ Date:_____

Examiner: Prof. V.Mal'nev Signature:_____ Date:_____

Abstract

In the first chapter of this work contain the introduction, defintion and orgin of multiferroics. Second and thrid chapters include the formulation of Heisenberg Model , variation of dispresion, magnetization, specific heat capacity and the fourth chapter contains the conclusion.

Generally, multiferroics are novel classes of materials that exhibit cross-coupling of mutually excluding phenomena, i.e. magnetism and ferroelectricity. In recent years, the coexistence of ferroelectricity and magnetic orderings has drawn considerable attentions due to the promising applications to these days technology. The microscopic origins of magnetism and ferroelectricity differ fundamentally, while the real mechanism of ferroelectricity is still under debate. In the present work, we have started from a simple Heisenberg hamiltonian and an interaction term resulting from electric field coupling with the magnetic spins with anisotropic energy, and have demonstrated that magnetization can be manipulated with electric field. In the multiferroic thin film system the magnetic field tends to play a role in stabilizing the spins in preferred orientations and induces a coupling of magnetism and ferroelectricity that opens a route to switch magnetization with electric polarazation.

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Above all, I would like to thank the almighty God who help me to accomplish this work. Next, I would like to express my sincere thanks to my advisor and instructor Prof. P.Singh, for his unlimitted guidance, assistance, supervision and contribution of valuable suggestions. Lastly, I would like to thank my dear family and all those persons who help me.

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Chapter 1

Introduction

In the past few years there has been a revival of interest in multiferroics, materials in which electric and magnetic ordering coexist. Multiferroics are considered now as promising materials for magnetic storage, spintronics devices and microwave technique as they provide a novel approach to the magnetic field or electric field conversion. The coupling of magnetic and electric subsystems results in magneto-electric (ME) effect (linear ME effect), i.e. the electric field induced magnetization and magnetic field induced electric polarization. In these materials magnetism and ferroelectric ordering coexist no matter how their course of existence varies [1]. The microscopic description of magnetism is based on the localized magnetic moments, mostly due to the partially filled d or f shell of transition metal or rare-earth elements electrons in which the exchange interactions between these localized moments exhibit magnetic orderings. The origin of ferroelectrics is wide range (can be due to: Charge ordering, lone pairs, etc.) and forbids the d shell electrons in contrast to magnetism [2,3]. They remarkably show strong coupling between charges, spins, lattice and orbital degrees of freedom and the interplay between various competing orders gives rise to interesting features and varieties to these classes of materials. The overlap of strongly correlated magnetic and ferroelectric orders enable one domain over the other [4-6]. For instance, in ferromagnetic materials the magnetization M is easily switchable parameter on an application of external stimulating magnetic field, H and in ferroelectrics the polarization P is also a controllable parameter by an external electric field, E. However,

on the other hand, in multiferroics these switchable order parameters, P and M are cross-linked, i.e. magnetization can be switched by external electric field and polarization can also be tunned by an applied magnetic field. The magnetoelectric spectra in $GaFeO_3$ is found to be proportional to the photon energy which depends on the direction of magnetization [7-9].

1.1 Defintion of multiferroics

Multiferroics have been formally defined as materials that exhibit more than one primary ferroic order parameter simultaneously (i.e. in a single phase[10]. The four basic primary ferroic order parameters are: ferromagnetism, ferroelectricity, ferroelasticity and ferrotoroidicity.

The latter still being under debate as there has been no proof for switching ferrotoroidicity till today. Many researchers in the field consider materials as multiferroics only if they exhibit coupling between the order parameters. On the other hand, the definition of multiferroics can be expanded so as to include non-primary order parameters, such as antiferromagnetism or ferrimagnetism. Typical multiferroics belong to the group of the perovskite transition metal oxides, and include rare-earth manganites and ferrites (e.g. $TbMnO_3$, $HoMn_2O_5$, $LuFe_2O_4$). Other examples are the bismuth compounds $BiFeO_3$ and $BiMnO_3$, and non-oxides such as $BaNiF_4$ and spinel chalcogenides, e.g. $ZnCr_2Se_4$. These alloys show rich phase diagrams combining different ferroic orders in separate phases. Apart from single phase multiferroics, composites and heterostructures exhibiting more than one ferroic order parameter are studied extensively. Some examples include magnetic thin films on piezoelectric substrates and metglass trilayer structures. Besides scientific interest in their physical properties, multiferroics have potential for applications as actuators, switches, magnetic field sensors or new types of electronic memory devices.

1.2 History of multiferroics

The term multiferroic was first used by H. Schmid in 1994. His definition referred to multiferroics as single phase materials which simultaneously possess two or more primary ferroic properties. Today the term multiferroic has been expanded to include materials which exhibit any type of long range magnetic ordering, spontaneous electric polarization, and ferroelasticity. In the most general sense the field of multiferroics was born from studies of magnetoelectric systems[12]. After an initial burst of interest, research remained static until early 2000 . In 2003 the discovery of large ferroelectric polarization in epitaxially grown thin films of $BiFeO_3$ [13] and the discovery of strong magnetic and electric coupling in orthorhombic $TbMnO_3$ and $TbMn_2O_5$ [14] restimulated activity in the field of multiferroics.

1.3 Mechanisms for ferroelectricity in multiferroics

A necessary but not sufficient condition for the appearance of spontaneous electric polarization is the absence of inversion symmetry. We can distinguish between proper and improper ferroelectric (FE). The difference lies in the driving force (the primary order parameter) that leads to ferroelectricity: In the case of proper FE, the primary order parameter is the ferroelectric distortion. One example of proper FE is $BaTiO_3$ where a covalent bonding between the transition metal and the oxygen happens to allow a polar state. In usual perovskite-based ferroelectrics like $BaTiO_3$, the ferroelectric distortion occurs due to the displacement of B-site cation (Ti) with respect to the oxygen octahedral cage. Here the transition metal ion (Ti in $BaTiO_3$) requires an empty d shell since the ferroelectric displacement occurs due to the hopping of electrons between Ti d and O p atoms. For technological applications it's highly desirable to combine ferroelectric and ferromagnetic order within one material, but it has become clear that usual displacive ferroelectric order, e.g. like in $BaTiO_3$, cannot coexist together with magnetic order. Where as

the latter requires at least partially filled d-shells (e.g.-orbitals) providing a non-zero magnetic moment, usual displacive ferroelectricity requires empty d-shells[15]. Therefore, new ferroelectric driving mechanisms must be present for electric and magnetic ferroic order to occur simultaneously. A variety of driving mechanism is described below.

1.3.1 Lone pair multiferroics

In usual perovskite-based ferroelectrics like $BaTiO_3$, the ferroelectric distortion occurs due to the displacement of B-site cation (Ti) with respect to the oxygen octahedral cage. Here the transition metal ion (Ti in $BaTiO_3$) requires an empty d" shell since the ferroelectric displacement occurs due to the hopping of electrons between Ti d" and O p" atoms. This normally excludes any net magnetic moment because magnetism requires partially filled d" shells. However, partially filled d" shell on the B-site reduces the tendency of perovskites to display ferroelectricity. In order for the coexistence of magnetism and ferroelectricity (multiferroic), one possible mechanism is lone-pair driven[16] where the A-site drives the displacement and partially filled d shell on the B-site contributes to the magnetism. Examples include $BiFeO_3$[17], $BiMnO_3$[18], $PbVO_3$. In the above materials, the A-site cation (Bi^{3+}, Pb^{2+}) has a stereochemically active $6s^2$ lone-pair which causes the Bi 6p (empty) orbital to come closer in energy to the O 2p orbitals. This leads to hybridization between the Bi 6p and O 2p orbitals and drives the off-centering of the cation towards the neighboring anion resulting in ferroelectricity.

1.3.2 Improper geometric ferroelectricity

In improper geometric ferroelectrics a structural phase transition at high temperatures causes the appearance of ferroelectricity. A prototypical compound is the family of hexagonal rare earth manganites (h-$RMnO_3$ with R=Ho-Lu, Y), showing a structural phase transition at around 1300 K providing the necessary symmetry lowering by tilting of the MnO_5 bipyramids. This allows for an electrostatically driven corrugation of the R-ion layers. The multiferroic phase is entered only

at cryogenic temperatures when antiferromagnetic order due to spin frustration arises. Thus only weak, indirect coupling between two disparate order parameters can occur. The exact microscopic mechanism of the ferroelectric ordering in hexagonal $RMnO_3$ is still questionable in the scientific community, i.e. it is still matter of debate whether only the corrugation of R-ions is the origin of the electric polarization or whether an off-centering of Mn ions also contributes to the polarization.

1.3.3 Charge ordering

A possible origin for a multiferroic state is charge ordering. Such an order can occur in a compound containing ions of mixed valence and with geometrical or magnetic frustration. These ions form a polar arrangement, causing improper ferroelectricity (i.e. no ionic displacement). If magnetic ions are present, a coexisting magnetic order can be established and may be coupled to ferroelectricity. One prominent example for a charge ordered multiferroic is $LuFe_2O_4$, which shows improper ferroelectricity below 330 K[19]. The arrangements of the electrons arise from the charge frustration on a triangular lattice with the mixed valence state of Fe^{2+} and Fe^{3+} ions. Ferrimagnetic behavior occurs below 240 K. In addition, charge ordered ferroelectricity is suggested in Fe_3O_4 and $(Pr,Ca)MnO_3$[20].

1.4 Magnetically driven ferroelectricity

Magnetically driven multiferroics[21] are insulating materials, mostly oxides, in which macroscopic electric polarization is induced by magnetic long-range order. A necessary but not sufficient condition for the appearance of spontaneous electric polarization is the absence of inversion symmetry. We can distinguish between proper and improper ferroelectric (FE). The difference lie in the driving force (the primary order parameter) that lead to ferroelectricity: In the case of proper FE, the primary order parameter is the ferroelectric distortion. One example of proper

FE is $BaTiO_3$ where a covalent bonding between the transition metal and the oxygen happens to allow a polar state. In the case of improper FE, the primary order parameter is not the ferroelectric distortion but another type of phase change, like magnetic ordering or a structural change. The FE distortion is a secondary order parameter in the sense that it is driven by the presence of other order parameters. One example of improper FE is when the inversion symmetry of a crystal is broken by magnetic structure like spiral magnetic ordering. This is the spin-driven ferroelectric. The microscopic mechanism of magnetoelectric (ME) coupling in spiral multiferroics involves spin-orbit coupling. The polarization is smaller than the one of proper FE. ME coupling is very strong because ferroelectricity is driven by magnetic order and do not exist without the latter. That means that any change in the magnetic order will have an impact on the ferroelectricity.

1.5 Domains

Like any ferroic material, a multiferroic system is fragmented into domains. A domain is a spatially extended region with a constant direction and phase of its order parameters. Neighbouring domains are separated by transition regions called domain walls.

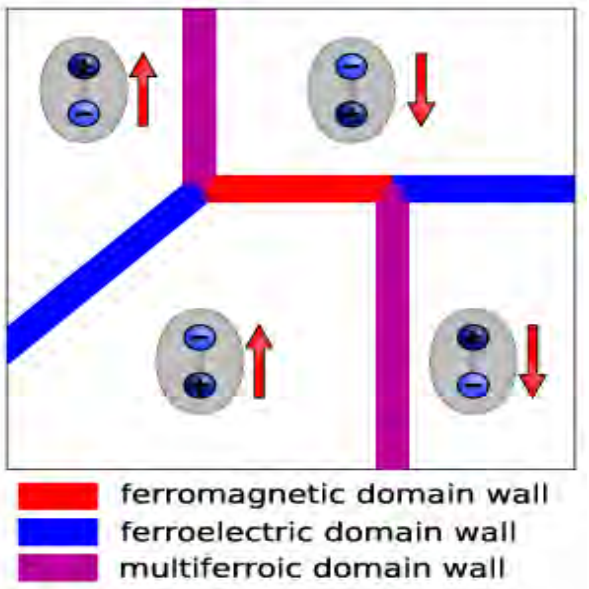

Figure 1.1: Schematic picture of the possible domain states of a ferroelectric and ferromagnetic material.

Both, the polarization (electric dipole indicated by charges) and the magnetization (red arrow), may have two orientations. The domains are separated by different types of domain walls, classified by the order parameter that is changed throughout the wall.

1.5.1 Properties of multiferroic domains

In contrast to materials with a single ferroic order, domains in multiferroics have additional properties and functionalities. For instance, they are characterized by an assembly of at least two order parameters[22]. The order parameters may be independent (typical yet not mandatory for a split-order-parameter multiferroic) or coupled (mandatory for a joint-order-parameter multiferroic). Many outstanding properties that distinguish domains in multiferroics from those in materials with a single ferroic order are consequences of the coupling between the order parameters. The coupling can lead to patterns with a distribution and topology of domains that is exclusive to multiferroics.

The order-parameter coupling is usually homogeneous across a domain, i.e., gradient effects are negligible. In some cases the averaged net value of the order

parameter for a domain pattern is more relevant for the coupling than the value of the order parameter of an individual domain[23]. Domain walls are spatially extended regions of transition mediating the transfer of the order parameter from one domain to another. In comparison to the domains the domain walls are not homogeneous and they can have a lower symmetry. This may modify the properties of a multiferroic and the coupling of its order parameters. Multiferroic domain walls may display particular static[24] and dynamic[25] properties. Static properties refer to stationary walls. They can result from: the reduced dimensionality, the finite width of the wall, the different symmetry of the wall, the inherent chemical, electronic, or order-parameter inhomogeneity within the walls and the resulting gradient effects[26].

Dynamic properties refer to moving walls. In a magnetic ferroelectric, the magnetoelectric interaction is, at its roots, usually synonymous to the movement of the multiferroic domain walls. Because of the order-parameter coupling this may reflect characteristic features of both, ferroelectric and magnetic domain wall movement.

Chapter 2

Theoretical Model

2.1 Heisenberg Model

The Heisenberg model is a very good startng point for studying magnetic properties of multiferroics. We consider the spin Hamiltonian of the multiferroic thin film system that exhibits frustrated spin interactions. The Hamiltonian of this anisotropic many body interaction system with external fields can be expressed by [26-28].

$$H = -\sum J_{ij} s_i . s_j - g\mu_B H \sum s_{iz} - \mu E \sum_i s_{iz} + D \sum_i S_{iz}^2 \qquad (2.1.1)$$

where $S_i(S_j)$ is spin operator at sites i(j). J_{ij} is the exchange coupling that depends on the relative positions of neigbhoring spins and is defined by $J_{ij} = J(R_i \ \ R_j)$. The constant g is the gyromagnetic ratio, and the second term of Equation (2.1) is the effective Zeeman field with an external deriving field while in this model chosen to be parallel to the +z axis to line up all the spins in the same direction. The third term includes an electric field E that interacts with the spins in the system. The constant μ describes the coupling strength between the spins and the radiation field that is either intrinsic or extrinsic [16,17]. The terms μ_B and D are the Bohr magneton and magnetic anisotropic (or spin wave stiffness) constants, respectively [17,18].

($\mu_B = 9.27 \times 10^{-23}$ J/T). The total spin operators in the Hamiltonian are:

$$s^2 = \sum_i (s_i)^2 \qquad (2.1.2)$$

$$s_z = \sum_i s_{iz} \tag{2.1.3}$$

Transferring the spin operator problems into many body interaction systems upon replacing with bosonic creation and annihilation operators expressed as [28]:

$$s_{i^+} = s_{ix} + s_{iy} = (2s)^{\frac{1}{2}}(1 - \frac{a_i^\dagger a_i}{2s})^{\frac{1}{2}} a_i \tag{2.1.4}$$

$$s_{i^-} = s_{ix} - s_{iy} = (2s)^{\frac{1}{2}}(1 - \frac{a_i^\dagger a_i}{2s})^{\frac{1}{2}} a_i^\dagger \tag{2.1.5}$$

where $a_i^\dagger$ and a_i are the creation and anihilation operators satisfaying the commutation relation $[a_i,a^\dagger] = \delta_{ij}$. It is possible to transform these bosonic operators to magnon variable operators b_k and $b_k^\dagger$, so these operators can be related to the bosonic operators.

$$b_k = N^{\frac{-1}{2}} \sum_i e^{ik.x_i} a_i \tag{2.1.6}$$

$$b_{k^+} = N^{\frac{-1}{2}} \sum_i e^{ik.x_i} a_i^\dagger \tag{2.1.7}$$

where the inverse transformation is

$$a_i = N^{\frac{-1}{2}} \sum_k e^{-ik.x_i} b_k \tag{2.1.8}$$

$$a_{i^+} = N^{\frac{-1}{2}} \sum_k e^{ik.x_i} b_k^\dagger \tag{2.1.9}$$

At low excitation,i.e., where the interaction is predominated by bilinear spin variables, neglecting the interaction corresponding to higher order terms, the reduced Hamiltonian is of the form

$$H = -JNS^2 + DNS^2 - g\mu_B HNS + \sum_k (-2JZS(\gamma_k - 1) - 2DS + g\mu_B H + \mu E) b_k^\dagger b_k \tag{2.1.10}$$

Here, z is defined to be the number of nearest neighbor spins. In this Hamiltonian we consider only the term bilinear to the magnon variables

$$H_m = \sum_k (-2JZS(\gamma_k - 1) - 2DS + g\mu_B H + \mu E) b_k^\dagger b_k \tag{2.1.11}$$

where $\gamma_k = \sum_\delta e^{-ik.\delta}$, this simplified interaction term is equivalently expressed as:

$$H_m = \sum_k n_k \omega_k \tag{2.1.12}$$

if we write ω_k in equation (2.12) as:

$$\omega_k = -2JZS(\gamma_k - 1) - 2DS + g\mu_B H + \mu E \tag{2.1.13}$$

The dispersion equation on the approximation that $|k.\delta| \ll 1$ can be reduced to

$$\omega_k = JSa^2k^2 - 2DSg\mu_B H + \mu E \tag{2.1.14}$$

so that:

$$\omega_k = \beta k^2 + \gamma \tag{2.1.15}$$

The above expression is a dispersion relation with some additional term $\gamma = -2DS + g\mu_B H + \mu E$ that tends to show how the dispersion term depends on the field components. Moreover, the constant $\beta = JSa^2$.

The figure 2.1 shows that the dispersion relation for different γ values.

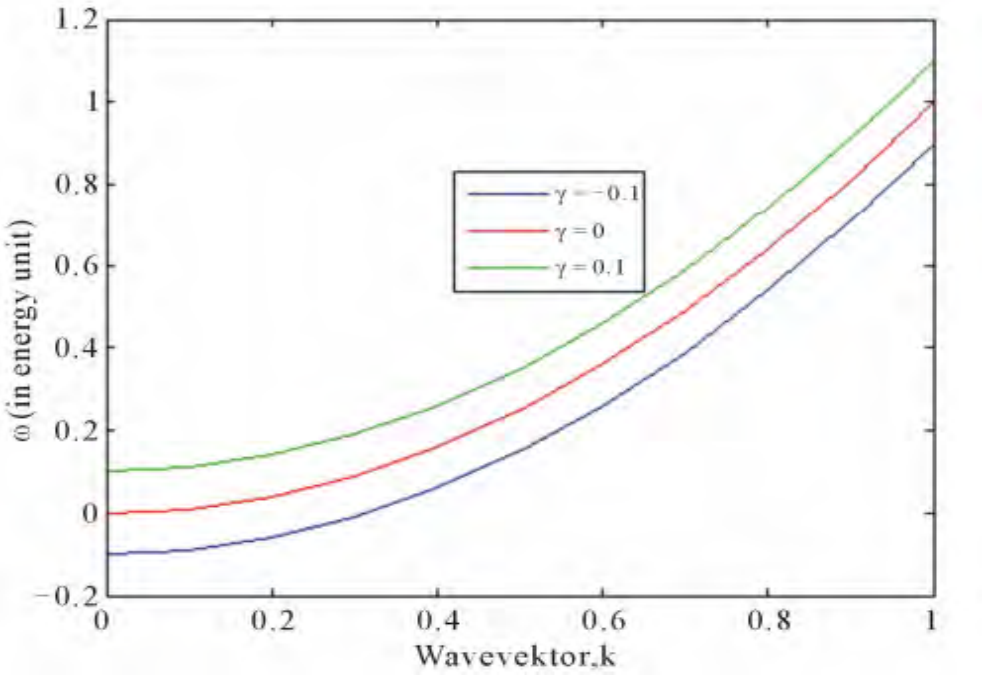

Figure 2.1: (color online) on the figure indicated shows the variation of dispersion function for different gamma values.

Based on equation (2.1.15) we can study the property of multiferroic i,e magnetization, magnetic susebitability, internal energy and specific heat capacity.

Chapter 3

Properties of multiferroics

3.1 Magnetization

Magnetization is the order parameter to study ferromagnetism in multiferroics, it is given by:

$$m = g\mu_B \sum_k \bar{n}_k \tag{3.1.1}$$

where $\bar{n}_k$ is the average ocupation number of magnons.

Magnons are bosons $\rightarrow$ they obey Bose - Enstein statistics.

$$\bar{n}_k = \frac{1}{e^{\frac{\omega_k}{k_B T}} - 1} \tag{3.1.2}$$

Using relation from equation (2.1.15) and (3.1.2) in to equation (3.1.1) we can compute magnetization of multiferroics.

$$\begin{aligned} m &= g\mu_B \sum_k \frac{1}{e^{\frac{\omega_k}{k_B T}} - 1} \\ m &= \frac{g\mu_B}{(2\pi)^2} \int_0^{\pi} \int_0^{\infty} \frac{k}{e^{\frac{\omega_k}{k_B T}} - 1} dk \sin\theta d\theta \\ m &= \frac{g\mu_B}{(2\pi)^2} \int_0^{\pi} \sin\theta d\theta \int_0^{\infty} \frac{k}{e^{\frac{\beta k^2 + \gamma}{k_B T}} - 1} dk \\ m &= \frac{2g\mu_B}{(2\pi)^2} \int_0^{\infty} \frac{k}{e^{\frac{\beta k^2 + \gamma}{k_B T}} - 1} dk \end{aligned} \tag{3.1.3}$$

$let \quad x = \beta k^2 + \gamma$

$dx = 2\beta$ kdk

with these the equation (3.1.3) takes the following form

$$m = \frac{g\mu_B}{(2\pi)^2 \beta} \int_{\gamma}^{\infty} \frac{1}{e^{\frac{x}{K_B T}} - 1} dx \tag{3.1.4}$$

we consider the low temperature case, and approximate:

$\frac{1}{e^{\frac{x}{k_BT}}-1} \approx \frac{1}{e^{\frac{x}{k_BT}}}$ hence, equation (3.1.4) reduced to:

$$m = \frac{g\mu_B}{(2\pi)^2\beta}\int_{\gamma}^{\infty} e^{-\frac{x}{k_BT}}dx$$

$$m = \frac{g\mu_B}{(2\pi)^2\beta}k_BTe^{-\frac{\gamma}{k_BT}} \tag{3.1.5}$$

We know that the magnetization of multiferroics is given by:

$$M(T) = g\mu_BNS - \frac{g\mu_BNS}{(2\pi)^2\beta NS}k_BTe^{-\frac{\gamma}{k_BT}}$$

$$M(T) = M(0) - \frac{M(0)}{(2\pi)^2\beta NS}k_BTe^{-\frac{\gamma}{k_BT}}$$

$$\frac{M(T)}{M(0)} = 1 - \frac{k_B}{(2\pi)^2\beta NS}Te^{-\frac{\gamma}{k_BT}}$$

$$\frac{M(T)}{M(0)} = 1 - \alpha Te^{-\frac{\gamma}{k_BT}} \tag{3.1.6}$$

where $\alpha = \frac{k_B}{(2\pi)^2\beta NS}$

The property of magnetization in equation (3.1.6) varies with field expressed in Figure 3.1.

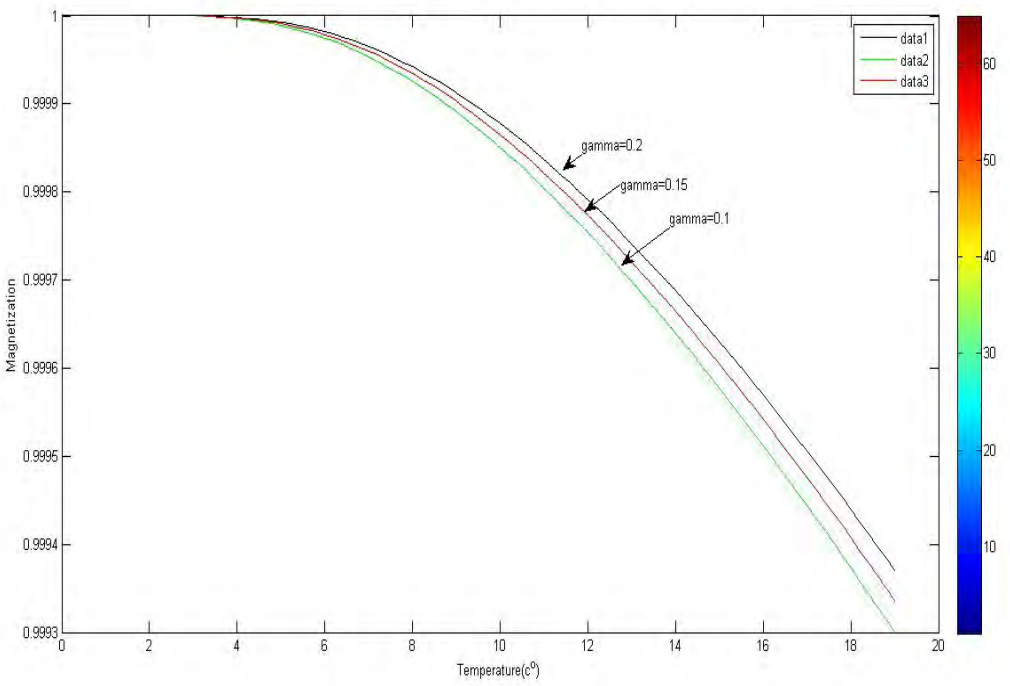

Figure 3.1: Dependece of magnetization on the parameter gamma, which can be tuned by explicitly on the applied fields and the nature of magnetic anisotropy.

3.1.1 Magnetic susceptibility

Magnetic susceptibility is quantitative measure of the extent to which a material may be magnetized in relation to a given applied magnetic field. The magnetic susceptibility of a material, commonly symbolized by χ_m, is equal to the ratio of the magnetization M within the material to the applied magnetic field strength H. This ratio, strictly speaking, is the volume susceptibility, because magnetization essentially involves a certain measure of magnetism (dipole moment).

Magnenetic susceptibility (χ_m) is given by:

$$\chi_m = \frac{\partial}{\partial H}\left[M(T)\right]_{H\to 0} \tag{3.1.7}$$

$$\chi_m = \frac{\partial}{\partial H}\left[M_0(1 - \frac{g\mu_B}{(2\pi)^2\beta}k_B T e^{-\frac{\gamma}{k_B T}})\right]_{H\to 0}$$

$$\chi_m = -\left[\frac{g\mu_B}{(2\pi)^2\beta}k_B T \frac{\partial}{\partial H}e^{-\frac{\gamma}{k_B T}}\right]_{H\to 0}$$

$$\chi_m = -\left[\frac{g\mu_B}{(2\pi)^2\beta}k_B T \frac{\partial}{\partial H}e^{-\frac{-2DS+g\mu_B H+\mu E}{k_B T}}\right]_{H\to 0}$$

$$\text{where,} \quad \gamma = -2DS + g\mu_B H + \mu E$$

$$\chi_m = -\left[\frac{g\mu_B}{(2\pi)^2\beta} k_B T e^{-\frac{-2DS+\mu E}{k_B T}} \frac{\partial}{\partial H} e^{\frac{-g\mu_B H}{k_B T}}\right]_{H\to 0}$$

$$\chi_m = \left[\frac{(g\mu_B)^2}{(2\pi)^2\beta} k_B T e^{\frac{-(-2DS+g\mu_B H+\mu E)}{k_B T}}\right]_{H\to 0}$$

$$\chi_m = \frac{(g\mu_B)^2}{(2\pi)^2\beta} k_B T e^{\frac{-(-2DS+\mu E)}{k_B T}} \tag{3.1.8}$$

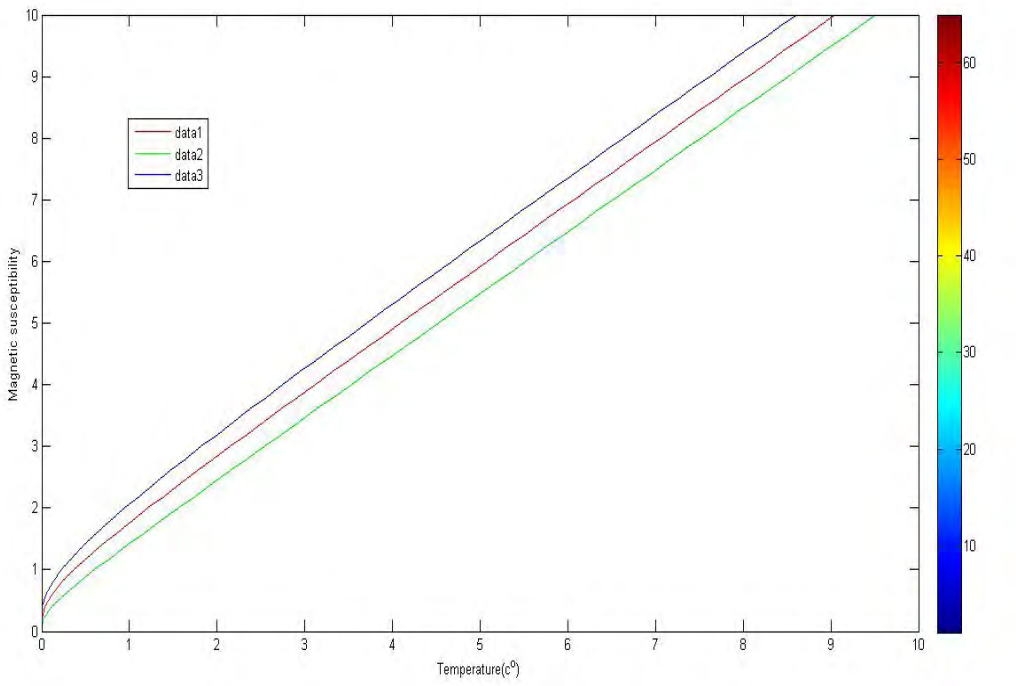

Figure 3.2: Figure show that the Magnetic suseptibility varries with applied extrernal field.

3.2 Specific heat capacity of multiferroic

3.2.1 Internal energy

If the low-lying exited states of the ferromagnet have exitation energies of the form:

$$U = \sum_k n_k \varepsilon_k \tag{3.2.1}$$

then the mean number of spin waves with wave vector “k” at tembperature “T” will be given by:

$$n_k(k) = \bar{n}_k = \frac{1}{e^{\frac{\epsilon_k}{k_B T}} - 1}$$

$\varepsilon_k = \beta k^2 + \gamma$ is dispression relation of multiferroics.

$$U = \sum_k \frac{\varepsilon_k}{e^{\frac{\varepsilon_k}{k_B T}} - 1}$$

$$U = \sum_k \frac{\beta k^2 + \gamma}{e^{\frac{\beta k^2 + \gamma}{k_B T}} - 1}$$

$$U = \frac{1}{(2\pi)^2} \int_0^{\pi} \int_0^{\infty} \frac{\beta k^2 + \gamma}{e^{\frac{\beta k^2 + \gamma}{k_B T}} - 1} k dk sin\theta d\theta$$

$$U = \frac{1}{(2\pi)^2} \int_0^{\pi} sin\theta d\theta \int_0^{\infty} \frac{\beta k^2 + \gamma}{e^{\frac{\beta k^2 + \gamma}{k_B}} - 1} k dk$$

$$U = \frac{2}{(2\pi)^2} \int_0^{\infty} \frac{\beta k^2 + \gamma}{e^{\frac{\beta k^2 + \gamma}{k_B T}} - 1} k dk \tag{3.2.2}$$

let t = $\beta k^2 + \gamma$

dt = $2\beta k dk$

substituting these relation in equation (3.2.2), gives:

$$U = \frac{1}{(2\pi)^2 \beta} \int_{\gamma}^{\infty} \frac{t}{e^{\frac{t}{k_B T}} - 1} dt \tag{3.2.3}$$

For low temperature, we can approximate $\frac{1}{e^{\frac{t}{k_B T}} - 1} \approx \frac{1}{e^{\frac{t}{k_B T}}}$

$$U \approx \frac{1}{(2\pi)^2 \beta} \int_{\gamma}^{\infty} \frac{t}{e^{\frac{t}{k_B T}}} dt$$

$$U \approx \frac{1}{(2\pi)^2 \beta} (k_B T + \gamma) k_B T e^{\frac{-\gamma}{k_B T}} \tag{3.2.4}$$

3.2.2 Specific heat capacity of multiferroics

Magnons obey Bose statistics and allow us for the calculation of the low- temperature thermal properties of magnetic materials. Only long-wavelength spin waves are excited at low temperatures. Specific heat doesnt depend on an objects mass, it depends on the type of material. Specific heat is therefore is used us to study a property of the multiferroic. Specific heat is defined as the amount of heat that

a unit mass of a material must gain or lose to change its temperature by a given amount.

$$c = \frac{\partial}{\partial T} U(T) \tag{3.2.5}$$

Equation (3.2.4) in equation (3.2.5) it gives:

$$c = \frac{\partial}{\partial T}\left(\frac{1}{(2\pi)^2\beta}(k_B T + \gamma) k_B T e^{\frac{-\gamma}{k_B T}}\right) \tag{3.2.6}$$

$$c = \frac{k_B}{(2\pi)^2\beta}\frac{\partial}{\partial T}[k_B T^2 e^{\frac{-\gamma}{k_B T}} + \gamma T e^{\frac{-\gamma}{k_B T}}]$$

$$c = \frac{k_B}{(2\pi)^2\beta}[k_B \frac{\partial}{\partial T}(T^2 e^{\frac{-\gamma}{k_B T}}) + \gamma \frac{\partial}{\partial T}(T e^{\frac{-\gamma}{k_B T}})]$$

$$c = \frac{k_B}{(2\pi)^2\beta}[k_B(2T e^{\frac{-\gamma}{k_B T}} + \frac{\gamma}{k_B} e^{\frac{-\gamma}{k_B T}}) + \gamma(e^{\frac{-\gamma}{k_B T}} + \frac{\gamma}{k_B T} e^{\frac{-\gamma}{k_B T}})]$$

$$c = \frac{k_B}{(2\pi)^2\beta}[k_B[k_B e^{\frac{-\gamma}{k_B T}}(2T + \frac{\gamma}{k_B}) + \gamma e^{\frac{-\gamma}{k_B T}}(1 + \frac{\gamma}{k_B T})]$$

$$c = \frac{k_B}{(2\pi)^2\beta}[2k_B T + \frac{\gamma^2}{K_B T} + 2\gamma] e^{\frac{-\gamma}{k_B T}} \tag{3.2.7}$$

The curve for the equation (3.2.7) in the range temperature (T) between 1 and 10 is given by figure 3.3, for different gamma (γ) values.

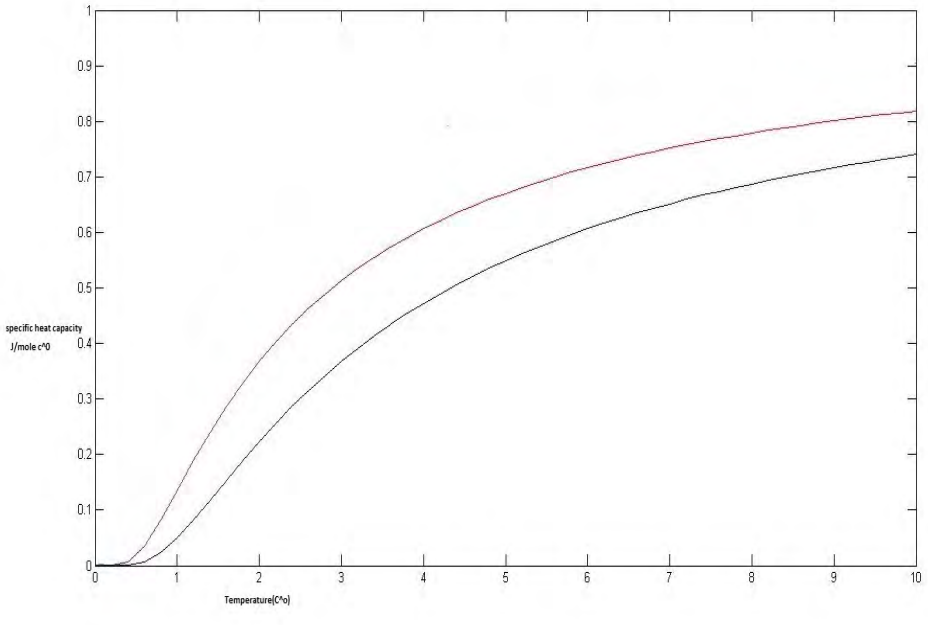

Figure 3.3: variation specific heat capacity, for fixed value of temperature in the range between (1,10) for two different gamma values, i.e, γ_1 (red color) = 0.5 and γ_2 (blue color) = 0.2).

3.2.3 Discussion

1). Fig.3.1 The relationship between magnetization and applied field can be affected by crystal shape, lattice structure, dislocation density, state of stress, etc., which give rise to possible anisotropy of the susceptibility. Furthermore, there are only a finite number of electronic moments within a given volume. When these are fully aligned, the magnetization reaches saturation. Thus, magnetic susceptibility is both anisotropic and non-linear with applied field.

2).Fig.3.2 To see the effect of electric field on magnetic susceptibility, we choose data 1 = 0.01, data 2 = 0.1 and data 3 = 0.001 (where data 1, data 2 and data 3 reperesents feild). Changing the electric feild has impact on magnetic susceptibility.i,e, any change in the magnetic order will have an impact on the ferroelectricity. Ferromagnetic materials, such as iron and cobalt, do not have constant susceptibilities; the magnetization is not usually proportional to the applied field strength. Measured ferromagnetic susceptibilities have relatively large positive values. Thus, within ferromagnetic materials, the magnetization may be larger than the external magnetizing field, because such materials are composed of highly magnetized clusters of atomic magnets (ferromagnetic domains) that are more easily lined up by the external field.

3).Fig.3.3 data 1 and data 2 reperesent the gamma values. γ_1(red color) = 0.5 and γ_2(blue color) = 0.2. we see that the the heat capacity vary as generally seen as gamma varies, it make the graph change in fixed time interval. As the gamma value incease the graph exponential decreasing, it use us to study the actual situation occurring in the temperature and field dependent behavior of specific heat in multiferroic.

Chapter 4

Conclusion

The properties of multiferroics have considerable attention due to the promising applications to these days technology. Multiferroic composite structures in bulk form are explored for: high sensitivity ac magnetic field sensors tunable microwave devices such as filters, oscillators and phase shifters in which the ferri-,ferro-or antiferro-magnetic resonance is tuned electrically instead of magnetically.

In multiferroic thin films, the coupled magnetic and ferroelectric order parameters can be exploited for developing magnetoelectronic devices. These include novel spintronic devices such as tunnel magnetoresistance (TMR) sensors and spin valves with electric field tunable functions. A typical TMR device consists of two layers of ferromagnetic materials separated by a thin tunnel barrier made of a multiferroic thin film.

In such a device, spin transport across the barrier can be electrically tuned. In another configuration, a multiferroic layer can be used as the exchange bias pinning layer. If the antiferromagnetic spin orientations in the multiferroic pinning layer can be electrically tuned, then magnetoresistance of the device can be controlled by the applied electric field. One can also explore multiple state memory elements, where data are stored both in the electric and the magnetic polarizations.

In the present work, magnetization, magnetic susceptibility and specific heat capacity have been calculated and it show that electric field can control these properties.

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This project is my original work, has not been presented for a degree in any other University and that all the sources of material used for the project have been dully acknowledged.

Name:Berhanu Tamirat

Signature: _____

This project has been submitted for examination with my approval as University advisor.

Name: Prof.P.Singh

Signature: _____

Place and time of submission: Department of Physics

Addis Ababa University

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