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# Ferromagnetic Resonance

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Additional information is available at the end of the chapter

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## 1. Introduction

Ferromagnetism is used to characterize magnetic behavior of a material, such as the strong attraction to a permanent magnet. The origin of this strong magnetism is the presence of a spontaneous magnetization which is produced by a parallel alignment of spins. Instead of a parallel alignment of all the spins, there can be an anti-parallel alignment of unequal spins. This results in a spontaneous magnetization which is called ferrimagnetism.

The resonance arises when the energy levels of a quantized system of electronic or nuclear moments are Zeeman split by a uniform magnetic field and the system absorbs energy from an oscillating magnetic field at sharply defined frequencies corresponding to the transitions between the levels. Classically, the resonance event occurs when a transverse  $ac$  field is applied at the Larmor frequency.

The resonance behaviour usually called magnetic resonance (MR) and nuclear magnetic resonance (NMR). Main types of resonance phenomenon can be listed as nuclear magnetic resonance (NMR), nuclear quadrupole resonance (NQR), electron paramagnetic/spin resonance (EPR, ESR), spin wave resonance (SWR), ferromagnetic resonance (FMR), antiferromagnetic resonance (AFMR) and conductor electron spin resonance (CESR). The resonant may be an isolated ionic spin as in electron paramagnetic resonance (EPR) or a nuclear magnetic resonance (NMR). Also, resonance effects are associated with the spin waves and the domain walls. The resonance methods are important for investigating the structure and magnetic properties of solids and other materials. These methods are used for imaging and other applications.

The following information can be accessed with the help of such resonance experiments. (i) Electrical structure of point defects by looking at the absorption in a thin structure. (ii) The line width with the movement of spin or surroundings isn't changed. (iii) The distribution of the magnetic field in solid by looking at the of the resonance line position (chemical shift and etc.). (iv) Collective spin excitations.

The atoms of ferromagnetic coupling originate from the spins of *d*-electrons. The size of  $\mu$  permanent atomic dipoles create spontaneously magnetized. According to the shape of dipoles materials can be ferromagnetic, antiferromagnetic, diamagnetic, paramagnetic and etc.

Ferromagnetic resonance (FMR) technique was initially applied to ferromagnetic materials, all magnetic materials and unpaired electron systems. Basically, it is analogous to the electron paramagnetic resonance (EPR). The EPR technique gives better results at unpaired electron systems. The FMR technique depends on the geometry of the sample at hand. The demagnetization field is observed where the sample geometry is active. The resonance area of the sample depends on the properties of material. The FMR technique is advantageous because it does not cause damage to materials. Also, it allows a three dimensional analysis of samples. The FMR occurs at high field values while EPR occurs at low magnetic field values. Also, line-width of ferromagnetic materials is large according to paramagnetic materials. Exchange interaction energy between unpaired electron spins that contribute to the ferromagnetism causes the line narrowing. So, ferromagnetic resonance lines appear sharper than expected.

The FMR studies have been increased since the EPR was discovered in 1945 (Zavosky, 1945; Kittel, 1946, 1947, 1949, 1953, 1958; Kip, 1949; Bloembergen, 1950, 1954; Crittenden, 1953; Van Vleck, 1950; Herring, 1950; Anderson, 1953; Damon, 1953; Young, 1953; Ament, 1955; Ruderman, 1954; Reich, 1955; Kasuya, 1956; White, 1956; Macdonald, 1956; Mercereau, 1956; Walker, 1957; Yosida, 1957; Tannenwald, 1957; Jarrett, 1958; Rado, 1958; Brown, 1962; Frait, 1965; Sparks, 1969). The beginnings of theoretical and experimental studies of spectroscopic investigations of basic sciences are used such as physics, chemistry, especially nanosciences and nanostructures (Rodbell, 1964; Kooi, 1964; Bhagat, 1967, 1974; Sparks, 1970(a), 1970(b), 1970(c), 1970(d); Rachford, 1981; Dillon, 1981; Schultz, 1983; Artman, 1957, 1979; Ramesh, 1988(a), 1988(b); Fraitova, 1983(a), 1983(b), 1984; Teale, 1986; Speriosu, 1987; Vounyuk, 1991; Roy, 1992; Puzskarski, 1992; Weiss, 1955). The FMR technique can provide information on the magnetization, magnetic anisotropy, dynamic exchange/dipolar energies and relaxation times, as well as the damping in the magnetization dynamics (Wigen, 1962, 1984, 1998; De Wames, 1970; Wolfram, 1971; Yu, 1975; Frait, 1985, 1998; Rook, 1991; Bland, 1994; Patton, 1995, 1996; Skomski, 2008; Coey, 2009). This spectroscopic method/FMR have been used to magnetic properties (Celinski, 1991; Farle, 1998, 2000; Fermin, 1999; Buschow, 2004; Heinrich, 2005(a), 2005(b)), films (Özdemir, 1996, 1997), monolayers (Zakeri, 2006), ultrathin and multilayers films (Layadi, 1990(a), 1990(b), 2002, 2004; Wigen, 1993; Zhang, 1994(a), 1994(b); Farle, 2000; Platow, 1998; Anisimov, 1999; Yıldız, 2004; Heinrich, 2005(a); Lacheisserie, 2005; de Cos, 2006; Liua, 2012; Schäfer, 2012), the angular, the frequency (Celinski, 1997; Farle, 1998), the temperature dependence (Platow, 1998), interlayer exchange coupling (Frait, 1965, 1998; Parkin, 1990, 1991(a), 1991(b), 1994; Schreiber, 1996; Rook, 1991; Wigen, 1993; Layadi, 1990(a); Heinrich, 2005; Paul, 2005), Brillouin light scattering (BLS) (Grünberg, 1982; Cochran, 1995; Hillebrands, 2000) and sample inhomogeneities (Artman, 1957, 1979; Damon, 1963; McMichael, 1990; Arias, 1999; Wigen, 1998; Chappert, 1986; Gnatzig, 1987; Fermin, 1999) of samples. Besides using FMR to characterize magnetic

properties, it also allows one to study the fundamental excitations and technological applications of a magnetic system (Schmool, 1998; Voges, 1998; Zianni, 1998; Grünberg, 2000, 2001; Vlasko-Vlasov, 2001; Zhai, 2003; Aktaş, 2004; Birkhäuser Verlag, 2007; Seib, 2009). The various thickness, disk array, half-metallic ferromagnetic electrodes, magnon scattering and other of some properties of samples have been studied using the FMR techniques (Mazur, 1982; da Silva, 1993; Chikazumi, 1997; Song, 2003; Mills, 2003; Rameev, 2003(a), 2003(b), 2004(a), 2004(b); An, 2004; Ramprasad, 2004; Xu, 2004; Wojtowicz, 2005; Zakeri, 2007; Tsai, 2009; Chen, 2009). The magnetic properties of single-crystalline (Kambe, 2005; Brustolon, 2009), polycrystalline (Singh, 2006; Fan, 2010), alloy films (Sihues, 2007), temperature dependence and similar qualities have been studied electromagnetic spectroscopy techniques (Özdemir, 1998; Birlikseven, 1999(a), 1999(b); Fermin, 1999; Rameev, 2000; Aktaş, 2001; Budak, 2003; Khaibullin, 2004). The magnetic resonance techniques (EPR, FMR) have been applied to the iron oxides, permalloy nanostructure (Kuanr, 2005), clustered, thermocouple connected to the ferromagnet, thin permalloy layer and et al. (Guimarães, 1998; Spoddig, 2005; Can, 2012; Rousseau, 2012; Valenzuela, 2012; Bakker, 2012; Maciá, 2012; Dreher, 2012; Kind, 2012; Li, 2012; Estévez, 2012; Sun, 2012(a), 2012(b), 2012(c); Richard, 2012). Magneto-optic (Paz, 2012), dipolar energy contributions (Bose, 2012), nanocrystalline (Maklakov, 2012; Raita, 2012),  $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$  films (Golosovsky, 2012),  $\text{La}_{0.67}\text{Ba}_{0.33}\text{Mn}_{1-y}\text{A}_y\text{O}_3$ , A - Fe, Cr (Osthöver, 1998), voltage-controlled magnetic anisotropy (VCMA) and spin transfer torque (Zhu, 2012) and the typical properties of the inertial resonance are investigated (Olive, 2012). The exchange bias (Backes, 2012), Q cavities for magnetic material (Beguhn, 2012), MgO/CoFeB/Ta structure (Chen, 2012), the interfacial origin of the giant magnetoresistive effect (GMR) phenomenon (Prieto, 2012), self-demagnetization field (Hinata, 2012),  $\text{Fe}_3\text{O}_4/\text{InAs}(100)$  hybrid spintronic structures (Huang, 2012), granular films (Kakazei, 1999, 2001; Sarmiento, 2007; Krone, 2011; Kobayashi, 2012), nano-sized powdered barium ( $\text{BaFe}_{12}\text{O}_{19}$ ) and strontium ( $\text{SrFe}_{12}\text{O}_{19}$ ) hexaferrites (Korolev, 2012),  $\text{Ni}_{0.7}\text{Mn}_{0.3-x}\text{Co}_x\text{Fe}_2\text{O}_4$  ferrites ( $\text{NiMnCo}$ :  $x = 0.00, 0.04, 0.06, \text{ and } 0.10$ ) (Lee, 2012), thin films (Demokritov, 1996, 1997; Nakai, 2002; Lindner, 2004; Aswal, 2005; Jalali-Roudsar, 2005; Cochran, 2006; Mizukami, 2007; Seemann, 2010),  $\text{Ni}_2\text{MnGa}$  films (Huang, 2004), magnetic/electronic order of films (Shames, 2012),  $\text{Fe}_{1-x}\text{Gd}(\text{Tb})_x$  films (Sun, 2012), in  $\epsilon\text{-Al}_{0.06}\text{Fe}_{1.94}\text{O}_3$  (Yoshikiyo, 2012). 10 nm thick Fe/GaAs(110) film (Römer, 2012), triangular shaped permalloy rings (Ding, 2012) and  $\text{Co}_2\text{-Y}$  hexagonal ferrite single rod (Bai, 2012) structures and properties have been studied by FMR techniques (Spaldin, 2010). Biological applications (Berliner, 1981; Wallis, 2005; Gatteschi, 2006; Kopp, 2006; Fischer, 2008; Mastrogiacomo, 2010), giant magneto-impedance (Valenzuela, 2007; Park, 2007), dynamics of ferromagnets (Vilasi, 2001; Rusek, 2004; Limmer, 2006; Sellmyer, 2006; Spinu, 2006; Azzerboni, 2006; Krivoruchko, 2012), magneto-optic kerr effect (Suzuki, 1997; Neudecker, 2006), Heusler alloy (HA) films (Kudryavtsev, 2007), ferrites (Kohmoto, 2007), spin polarized electrons (Rahman, 2008) and quantum mechanics (Weil, 2007) have been studied by FMR technique in generally (Hillebrands, 2002, 2003, 2006). In additional, electric and magnetic properties of pure,  $\text{Cu}^{2+}$  ions doped hydrogels have been studied by ESR techniques (Coşkun, 2012).

The FMR measurements were performed in single crystals of silicon-iron, nickel-iron, nickel and hcp cobalt (Frait, 1965), thin films (Knorr, 1959; Davis, 1965; Hsia, 1981; Krebs, 1982; Maksymowich, 1983, 1985, 1992; Platow, 1998; Durusoy, 2000; Baek, 2002; Kuanr, 2004), CoCr magnetic thin films (Cofield, 1987), NiFe/FeMn thin films (Layadi, 1988), single-crystal Fe/Cr/Fe(100) sandwiches (Krebs, 1989), polycrystalline single films (Hathaway, 1981; Rezende, 1993) and ultrathin multilayers of the system Au/Fe/Au/Pd/Fe (001) prepared on GaAs(001) (Woltersdorf, 2004). The FMR techniques have been successfully applied peak-to-peak linewidth (Yeh, 2009; Sun, 2012), superconducting and ferromagnetic coupled structures (Richard, 2012) and thin Co films of 50 nm thick (Maklakov, 2012). The garnet materials (Ramesh, 1988 (a), 1988 (b)), polar magneto-optic kerr effect and Brillouin light scattering measurements (Riedling, 1999), giant-magnetoresistive (GMR) multilayers (Grünberg, 1991; Borchers, 1998) and insulated multilayer film (de Cos, 2006; Lacheisserie, 2005) are the most intensely studied systems.

The technique of FMR can be applied to nano-systems (Poole, 2003; Parvatheeswara, 2006; Mills, 2006; Schmool, 2007; Vargas, 2007; Seemann, 2009; Wang, 2011; Patel, 2012; De Biasi, 2013). The FMR measurement on a square array of permalloy nanodots have been compared with a numerical simulation based on the eigenvalues of the linearized Landau-Lifshitz equation (Rivkin, 2007). The dynamic fluctuations of the nanoparticles and their anisotropic behaviour have been recorded with FMR signal (Owens, 2009). Ferromagnetic resonance (FMR) modes for Fe<sub>70</sub>Co<sub>30</sub> magnetic nanodots of 100 nm in diameter in a monodomain state are studied under different in-plane and out-of-plane magnetic fields (Miyake, 2012). The FMR techniques have been successfully applied to magnetic microwires and nanowire arrays (Adeyeye, 1997; Wegrowe, 1999, 2000; García-Miquel, 2001; Jung, 2002; Arias, 2003; Raposo, 2011; Boule, 2011; Kraus, 2012; Klein, 2012). In addition, FMR measurements have been performed for nanocomposite samples of varying particles packing fractions with demagnetization field (Song, 2012). The ferromagnetic resonance of magnetic fluids were theoretically investigated on thermal and particles size distribution effects (Marin, 2006). The FMR applied to nanoparticles, superparamagnetic particles and catalyst particles (de Biasi, 2006; Vargas, 2007; Duraia, 2009).

In the scope of this chapter, we firstly give a detailed account of both magnetic order and their origin. The origin of magnetic orders are explained and the equations are obtained using Fig.1 which shows rotating one electron on the table plane. Then, the dynamic equation of motion for magnetization was derived. We mentioned MR and damping terms which have consisted three terms as the Bloch-Bloembergen, the Landau-Lifshitz and the Gilbert form. We indicated electron EPR/ESR and their historical development. The information of spin Hamiltonian and *g*-tensor is given. The dispersion relations of monolayer, trilayers, five-layers and multilayer/*n*-layers have regularly been calculated for ferromagnetic exchange-coupled systems (Grünberg, 1992; Nagamine, 2005; Schmool, 1998). The theoretical FMR spectra were obtained by using the dynamic equation of motion for magnetization with the Bloch-Bloembergen type damping term. The exchange-spring (hard/soft) system which is the best of the sample for multilayer structure has been explained by using the FMR technique and equilibrium condition of energy of system. The

FMR spectra originated from the iron/soft layers as shown in the exchange spring magnets in Fig.9. Finally, superparamagnetic/single-domain nanoparticles and their resonance are described in detail.

## 2. Magnetic order

Magnetic materials are classified as paramagnetic, ferromagnetic, ferrimagnetic, antiferromagnetic and diamagnetic to their electronic order. Magnetic orders are divided in two groups as (i) paramagnetic, ferromagnetic, ferrimagnetic, antiferromagnetic and (ii) diamagnetic. The magnetic moments in diamagnetic materials are opposite to each other as well as the moments associated with the orbiting electrons so that a zero magnetic moment ( $\mu$ ) is produced on macroscopic scale. In the paramagnetic materials, each atom possesses a small magnetic moment. The orientation of magnetic moment of each atom is random, the net magnetic moment of a large sample (macroscopic scale) of dipole and the magnetization vector are zero when there is no applied field.

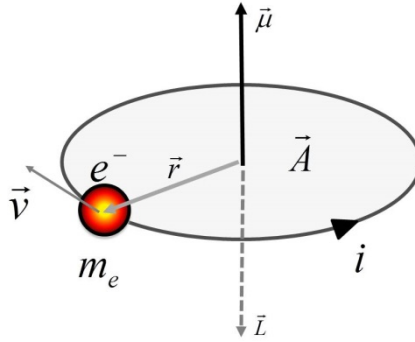
Nanoscience, nanotechnology and nanomaterials have become a central field of scientific and technical activity. Over the last years the interest in magnetic nanostructures and their applications in various electronic devices, effective opto-electronic devices, bio-sensors, photo-detectors, solar cells, nanodevices and plasmonic structures have been increasing tremendously. This is caused by the unique properties of magnetic nanostructures and the outstanding performance of nanoscale devices. Dimension in the range of one to hundred nanometers, is called the nano regime. In recent years, nanorods, nanoparticles, quantum dots, nanocrystals etc. are in a class of nanostructures (Yalçın, 2012; Kartopu & Yalçın, 2010; Aktaş, 2006) studied extensively. As the dimensions of nano materials decrease down to the nanometer scale, the surface of nanostructures starts to exhibit new and interesting properties mainly due to quantum size effects.

## 3. Origin of magnetic moment

The magnetization of a matter is derived by electrons moving around the nucleus of an atom. Total magnetic moment occurs when the electrons such as a disc returns around its axis consist of spin angular momentum and returns around the nucleus consist orbital angular momentum. The most of matters which have unpaired electrons have a little magnetic moment. This natural angular momentum consists of the result of charged particle return around its own axis and is called spin of the particle. The origin of spin is not known exactly, although electron is point particle the movement of an electron in an external magnetic field is similar to the movement of the disc. In other words, the origin of the spin is quantum field theoretical considerations and comes from the representations of the Poincare algebra for the elementary particles. The magnetism related to spin angular momentum, orbital angular momentum and spin-orbit interactions angular momentum. The movement of the electron around the nucleus can be considered as a current loop while electron spin is considered very small current loop which generate magnetic field. Here, orbital angular

momentum was obtained by the result of an electron current loop around the nucleus. Thus, both it is exceeded the difficulty of understanding the magnetic moment and the magnetic moment for an electron orbiting around the nucleus is used easily. The result of orbital-angular momentum ( $\vec{L}$ ) adapted for spin-angular momentum ( $\vec{S}$ ) (Cullity, 1990).

One electron is rotating from left to right on the table plane as shown in Fig.1. The rotating electron creates a current ( $i$ ) on the circle with radius of  $r$ .



**Figure 1.** Schematic representation of the precession of a single electron on the table plane.

The magnetic moment of a single electron is defined as below

$$\vec{\mu} = i \cdot \vec{A}. \tag{1}$$

Where,  $\vec{A}$  is the circle area. The magnetic moment is written as follows by using the current ( $-e = i \cdot t$ ), one cycle ( $2\pi r = v \cdot t$ ) and angular momentum ( $L = m_e \cdot v \cdot r$ ) definition.

$$\vec{\mu} = -\frac{e}{2m_e} \vec{L} \tag{2}$$

Where  $\gamma = e/2m_e$  and  $\vec{L}$  is the gyromagnetic (magneto-mechanical or magneto-gyric) ratio and the orbital-angular momentum, respectively. Therefore, the magnetic moment  $\vec{\mu}$  is obtained from Eq. (2) as below

$$\vec{\mu} = -\gamma \vec{L}. \tag{3}$$

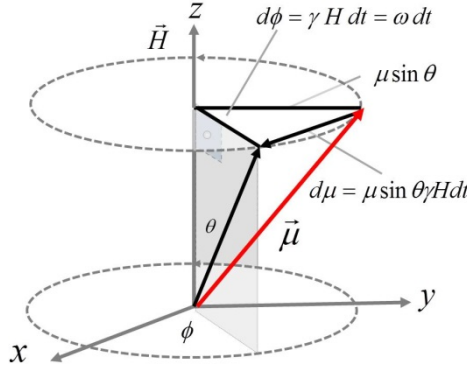
The following expression is obtained when derivative of Eq.(3)

$$d\vec{\mu} + \gamma d\vec{L} + \vec{L}d\gamma = 0. \tag{4}$$

For our purpose, we only need to know that  $\gamma$  is a constant and  $d\gamma = 0$ . From this results,  $d\vec{\mu} + \gamma d\vec{L} = 0$ . The derivative of time of this equation, the equation of motion for magnetic moments of an electron is found as below

$$\frac{1}{\gamma} \frac{d\vec{\mu}}{dt} = \frac{d\vec{L}}{dt} = \vec{\tau}. \quad (5)$$

This equation is related to  $\vec{\tau} = d\vec{L}/dt$  in two dimensional motions on the plane and  $\vec{F} = d\vec{P}/dt$  in one dimensional motion. This motion corresponds to Newton's dynamic equations. When an electron is placed in an applied magnetic field  $\vec{H}$ , the magnetic field will produce a torque ( $\vec{\tau}$ ) on the magnetic moment ( $\vec{\mu}$ ) of amount  $\vec{\mu} \times \vec{H}$ . The equation of motion for magnetic moment ( $\vec{\mu}$ ) is found by equating the torque as below



**Figure 2.** Schematic representation of precession of a single magnetic moment  $\vec{\mu}$  in the external magnetic field around the z-axis.

$$\frac{1}{\gamma} \frac{d\vec{\mu}}{dt} = \vec{\mu} \times \vec{H}. \quad (6)$$

This expression is called the equation of motion for magnetic moment ( $\vec{\mu}$ ). The motion of magnetic moment ( $\vec{\mu}$ ) forms a cone related to  $\vec{H}$  when the angle  $\theta$  of magnetic moment and external magnetic field does not change. Therefore, in time ( $dt$ ), the tip of the vector  $\vec{\mu}$  moves an angle  $(\gamma H)dt$ . The magnetic moment vector make precession movement about  $\vec{H}$  at a frequency of  $\gamma H/2\pi$ . This frequency,  $\nu = \omega/2\pi = \gamma H/2\pi$ , is called the Larmor frequency. In general this Larmor frequency is used this form  $\omega = \gamma H$  in literature.

#### 4. Magnetic resonance

Magnetic Resonance (MR) is a research branch which examines magnetic properties of matters. The magnetic properties of atom originate from electrons and nucleus. So, it is studied in two groups such as electron paramagnetic resonance (EPR)/electron spin resonance (ESR) and nuclear magnetic resonance (NMR). At ESR and NMR all of them are the sample is placed in a strong static magnetic field and subjected to an orthogonally amplitude-frequency. While EPR uses a radiation of microwave frequency in general, NMR is observed at low radio frequency range. The energy absorption occurs when radio

frequency is equal with energy difference between electrons two levels. But, the transition must obey the selection rules. The splitting between the energy levels occurs when total angular moment of electron is different from zero. On the other hand, the splitting of energy levels has not been observed in the filled orbit. The precession motion of a paramagnetic sample in magnetic field is seen schematically in Fig. 2. If microwave field with  $\nu$ -frequency at perpendicular is applied to the static field, it comes out power absorption when precession ( $\omega_0$ ) is same with  $\nu$ -frequency. The power increases when these frequencies come near to each other and it occurs maximum occurs at point when they are equal. This behaviour is called magnetic resonance (MR).

The magnetic materials contain a large number of atomic magnetic moment in generally. Net atomic magnetic moment can be calculated by  $\vec{M} = N \vec{\mu}$ . Where,  $N$  is the number of atomic magnetic moment in materials.

$$\frac{1}{\gamma} \frac{d\vec{M}}{dt} = \vec{M} \times \vec{H}_{eff} \quad (7)$$

This precession movement continue indefinitely would take forever when there is no damping force. The damping term may be introduced in different ways. Indeed, since the details of the damping mechanism in a ferromagnet have not been completely resolved, different mathematical forms for the damping have been suggested. The three most common damping terms used to augment the right-hand side of Eq. (7) are as follows:

(i) The Bloch-Bloembergen form:  $-\frac{\vec{M}_{\theta,\phi}}{T_2} - \frac{\vec{M}_z - M_0}{T_1}$

(ii) The Landau-Lifshitz form:  $\frac{-\lambda}{|\vec{M}|^2} \vec{M} \times \vec{M} \times \vec{H}$

(iii) The Gilbert form:  $\frac{\alpha}{|\vec{M}|} \vec{M} \times \frac{d\vec{M}}{dt}$

Bloch-Bloembergen type damping does not conserve  $M$  so it is equivalent to the type of Landau-Lifshitz and the Gilbert only when  $\alpha$  is small and for small excursion of  $\vec{M}$ . For large excursion of  $M$ , the magnitude of  $\vec{M}$  is certainly not protected, as the damping torque is in the direction of the magnetization component in this formularization. Hence, the observation of  $M$  in the switching experiments in thin films should be provide a sensitive test on the appropriate form of the damping term for ferromagnetism since  $\vec{M}$  which is conserved during switching. This would suggest that the form of the Bloch-Bloembergen damping term would not be applicable for this type of experiment. The Gilbert type (Gilbert, 1955) is essentially a modification of the original form which is proposed firstly by Landau and Lifshitz (Landau & Lifshitz, 1935). It is very important to note that the Landau-Lifshitz and Gilbert type of damping conserve while the Bloch-Bloembergen (Bloembergen,



1950) type does not. Landau and Lifshitz observed that the ferromagnetic exchange forces between spins are much greater than the Zeeman forces between the spins and the magnetic fields in their formulation of the damping term. Therefore, the exchange will conserve the magnitude of  $\vec{M}$ . In this formulation, since the approach of  $\vec{M}$  towards  $\vec{H}$  is due completely to the relatively weak interaction between  $\vec{M}$  and  $\vec{H}$ , we must require that  $\lambda \ll \gamma M$ . In this small damping limit, the Landau-Lifshitz and the Gilbert forms are equivalent so that whether one uses one or the other is simply a matter of convenience or familiarity. However, Callen has obtained a dynamic equation by quantizing the spin waves into magnons and treating the problem quantum-mechanically (Callen, 1958). Subsequently, Fletcher, Le Craw, and Spencer have reproduced the same equation using energy consideration (Fletcher, 1960). In their reproduction, they found the mean rate of energy transfer between the uniform precession, the spin waves (Grünberg, 1979, 1980) and the lattice.

## 5. Electron paramagnetic resonance

Stern and Gerlach (Gerlach, 1922) proved that the electron-magnetic moment of an atom in an external magnetic field originates only in certain directions in the experiment in 1922. Uhlenbek and Goudsmit found that the connection between the magnetic moment and spin angular momentum of electron (Uhlenbek, 1925), Rabi and Breit found the transition between the energy levels in oscillating magnetic field (Rabi, 1938). This also proved to be observed in the event of the first magnetic resonance. The EPR technique is said to be important of Stern-Gerlach experiment. Zavoisky observed the first peak in the electron paramagnetic resonance for  $\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$  sample and recorded (Zavoisky, 1945). The most of EPR experiments were made by scientists in the United Kingdom and the United States. Important people mentioned in the experimental EPR studies; Abragam, Bleaney and Van Vleck. The historical developments of MR have been summarized by Ramsey (Ramsey, 1985). NMR experiments had been done by Purcell et al. (Purcell, 1946). Today it has been used as a tool for clinical medicine. MRI was considered as a basic tool of CT scan in 1970s. The behaviors of spin system under the external magnetic field with the gradient of spin system are known NMR tomography. This technique is used too much for medicine, clinics, diagnostic and therapeutic purposes. General structure of the EPR spectrometer consist four basic parts in general. (i) Source system (generally used in the microwave 1-100 GHz), (ii) cavity-grid system, (iii) Magnet system and (iv) detector and modulation system. EPR/ESR is subject of the MR. An atom which has free electron when it is put in magnetic field the electron's energy levels separate (Yalçın, 2003, 2007(a), 2007(b)). This separation originates from the interaction of the electrons magnetic moment with external magnetic field. Energy separating has been calculated by the following Hamiltonian.

$$\hat{H} = g \mu_B \vec{H} \cdot \hat{S} \quad (8)$$

It is called Zeeman Effect. If the applied magnetic field oriented z-axis energy levels are;

$$E_{M_s} = g \mu_B H \cdot M_s. \quad (9)$$

Here,  $g$  is the  $g$ -value (or Landé  $g$ -value) (for free electron  $g_e = 2.0023193$  and proton  $g_N = 2.7896$ ),  $\mu_B$  is Bohr magneton ( $\mu_B = (eh/4\pi m_e) = 9.2740 \times 10^{-24} \text{ J/T}$ ) and  $M_s$  is the number of magnetic spin quantum. If the orbital angular momentum of electron is large of zero ( $L > 0$ )  $g$ -value for free atoms is following

$$g = 1 + \frac{S(S+1) - L(L+1) + J(J+1)}{2J(J+1)}. \tag{10}$$

The anisotropy of the  $g$ -factor is described by taking into account the spin-orbit interaction combined (Yalçın, 2004(c)). The total magnetic moment can be written at below;

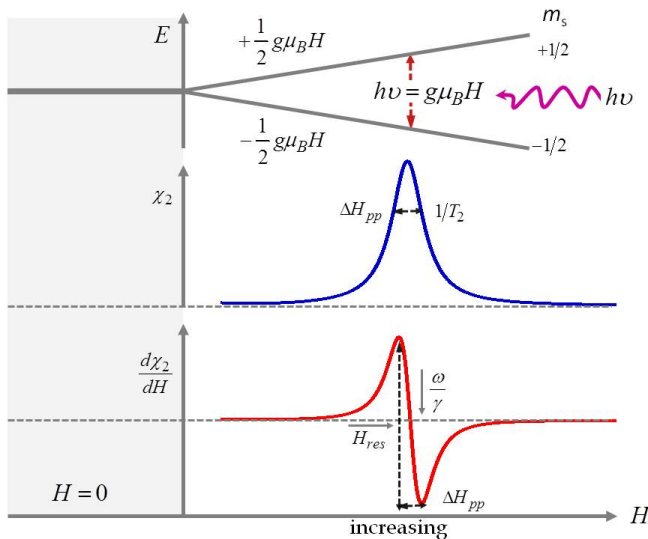
$$\mu_{\text{eff}} = g \mu_B \sqrt{J(J+1)}$$

The values of orbital angular momentum of unpaired electrons for most of the radicals and radical ions are zero or nearly zero. Hence, the number of total electron angular momentum  $J$  equals only the number of spin quantum  $S$ . So, these values are nearly 2. For free electron ( $M_s = \pm 1/2$ ) and for this electron;

$$\Delta E = E_{+1/2} - E_{-1/2} = g \mu_B H. \tag{11}$$

When the electromagnetic radiation which frequency  $\nu$  is applied to such an electron system;

$$h\nu = g \mu_B H. \tag{12}$$



**Figure 3.** The energy levels and resonance of free electron at zero field and increasing applied magnetic field. In this figure, while the value of magnetic field increases, the separating between energy levels increase. Arbitrary units used in vertical axes for  $\chi_2$  and  $d\chi_2/dH$ .

If this equation is provided the system absorbs energy from applied electromagnetic wave (see Fig. 3). It is called resonance effect. Material absorbs energy in two different ways from applied electromagnetic wave by according to the Eq.(12). Firstly, in Eq.(12), frequency of electromagnetic wave doesn't change while the external magnetic field changes. Secondly, its opposite can be provided.

In this Fig.(3) it has been seen that magnetic susceptibility  $\chi_2$  versus magnetic field. At the same time it is said the absorption curve. The magnetic field derivative beneath of this figure is FMR absorption spectrum ( $d\chi_2/dH$ ). Here,  $\Delta_{pp}$  and  $1/T_2$  are linewidth,  $H_{res}$  is resonance field,  $\omega/\gamma$  is resonance frequency.

### 5.1. Spin Hamiltonian

The spin Hamiltonian is total electronic spins and nucleon spin  $\bar{I}$  which have crystal lattice under the static magnetic field following;

$$\hat{H} = \mu_B \bar{H} \cdot \bar{g} \cdot \hat{S} + \hat{S} \cdot \bar{D} \cdot \hat{S} + \bar{S} \cdot \bar{A} \cdot \hat{I} - \mu_N \cdot \bar{H} \cdot \bar{g}_N \cdot \hat{I} + \hat{I} \cdot \bar{P} \cdot \hat{I} \quad (13)$$

$\hat{S}$  and  $\bar{I}$  operators of electronic and nucleus, respectively. In this equation, first term is Zeeman effect, second one is thin layer effects, the third one is the effect of between electronic spin and nucleus-spin of ion and it is known that thin layer effects. The fourth term is the effect of nucleus with the magnetic field. The last one is quadrupole effect of nucleus. It can be added different terms in Eq.13 (Slichter, 1963).

### 5.2. $\bar{g}$ tensor

The total magnetic moment of ion is  $\bar{\mu} = g \mu_B \bar{J}$ .  $\bar{J}$  is the ratio of total angular momentum to Planck constant. Landé factor  $g$  is depend on  $\bar{S}, \bar{L}, \bar{J}$ . For the base energy level if  $\bar{L}$  is zero,  $g$  factor is equal free electron's  $g$ -factor. But,  $g$ -factor in the excited energy levels separated from the  $g$ -factor of free electron. The hamiltonian for an ion which is in the magnetic field is following (Weil, 1994).

$$\hat{H} = \mu_B \bar{H} \cdot (\hat{L} + g_e \hat{S}) + \lambda \hat{L} \cdot \hat{S} \quad (14)$$

In this equation, first term is Zeeman effects, second one is spin-orbit interaction. The first order energy of ion which shows  $|J, M\rangle$  and it is expected not degenerate is seen at below.

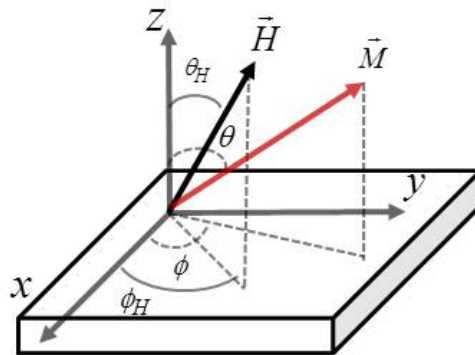
$$E_J = \langle J, M | g_e \mu_B H_z \hat{S}_z | J, M \rangle + \langle J, M | (\mu_B H_z + \lambda \hat{S}_z) | J, M \rangle \quad (15)$$

We can write the hamiltonian equation which uses energy equations. There is two terms in the hamiltonian equations. The first term is the independent temperature coefficient for paramagnetic for paramagnetic, the last terms are only for spin variables. If the angular moment of ion occurs because of spin,  $\bar{g}$ -tensor is to be isotropic.

## 6. Ferromagnetic resonance

The most important parameters for ferromagnet can be deduced by the ferromagnetic resonance method. FMR absorption curves may be obtained from Eq.(12) by changing frequency or magnetic field. FMR signal can be detected by the external magnetic field and frequency such as EPR signal. The field derivative FMR absorption spectra are greater than in EPR as a generally. The linear dependence of frequency of resonance field may be calculated from 1 GHz to 100 GHz range in frequency spectra (L-, S-, C-, X-, K-, Q-, V-, E-, W-, F-, and D-band). The resonance frequency, relaxation, linewidth, Landé  $g$ -factor (spectroscopic  $g$ -factor), the coercive force, the anisotropy field, shape of the specimen, symmetry axes of the crystal and temperature characterized FMR spectra. The broadening of the FMR absorption line depend on the line width (so called  $1/T_2$  on the Bloch-Bloembergen type damping form). The nonuniform modes are seen in the EPR signal. The nonlinear effects for FMR are shown by the relationship between the uniform precessions of magnetic moments. The paramagnetic excitation of unstable oscillation of the phonons displays magneto-elastic interaction in ferromagnetic systems. This behaviour so called magnetostriction. The FMR studies have led to the development of many micro-wave devices. These phenomenon are microwave tubes, circulators, oscillators, amplifiers, parametric frequency converters, and limiters. The resonance absorption curve of electromagnetic waves at centimeter scale by ferromagnet was first observed by Arkad'ev in 1913 (Arkad'ev, 1913) .

The sample geometry, relative orientation of the equilibrium magnetization  $\vec{M}$ , the applied  $dc$  magnetic field  $\vec{H}$  and experimental coordinate systems are shown in Fig.4.



**Figure 4.** Sample geometries and relative orientations of equilibrium magnetization  $\vec{M}$  and the  $dc$  components of external magnetic field,  $\vec{H}$  for thin films.

The ferromagnetic resonance data analyzed using the free energy expansion similar to that employed

$$\begin{aligned}
E_T &= E_Z + E_a + E_d + E_{ex} + \dots \\
E_Z &= -M \cdot H (\sin \theta \sin \theta_H \cos(\phi - \phi_H) + \cos \theta \cos \theta_H) \\
E_a &= K_{u1} \sin^2 \theta + K_{u2} \sin^4 \theta + K_{u3} \sin^6 \theta \dots \\
E_d &= -2\pi M^2 \sin^2 \theta \\
E_{ex} &= -JS_i S_j
\end{aligned} \tag{16}$$

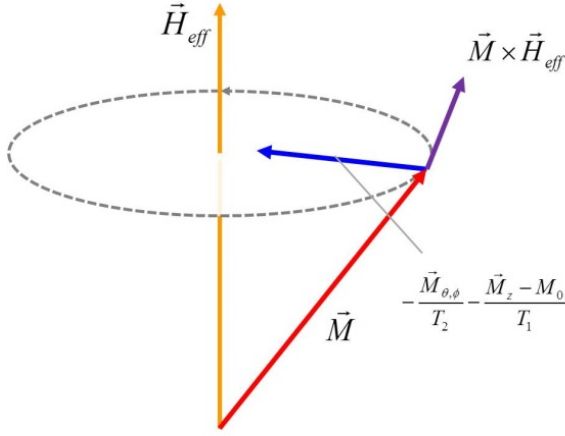
Where,  $E_Z, E_a, E_d, E_{ex}$  are Zeeman, magnetocrystalline anisotropy, demagnetization and ferromagnetic exchange energy.  $(\theta, \phi)$  and  $(\theta_H, \phi_H)$  are the angles for magnetization and applied magnetic field vector in the spherical coordinates, respectively. Magnetic anisotropy energy arises from either the interaction of electron spin magnetic moments with the lattice via spin-orbit coupling. On the other hand, anisotropy energy induced due to local atomic ordering. The  $\theta$  in anisotropy energy is the angle between magnetization orientation and local easy axis of the magnetic anisotropy.  $K_{u1}$  and  $K_{u2}$  are energy density constants. The demagnetization field is proportional to the magnetic free pole density. The exchange energy for thin magnetic film may be neglected in generally. Because associated energies is small. But, this exchange energy are not neglected for multilayer structures. This energy occurs between the magnetic layers, so that this energy called interlayer exchange energy. This expression is seen at the end of this subject in details.  $K_{eff} = \pi M^2 + K_U$  is the effective uniaxial anisotropy term and  $K_u$  takes into account some additional second-order uniaxial anisotropy and  $H_{eff} = 2\pi M_S + (2K_u/M_S)$  is the effective field for a single magnetic films. The equilibrium values of polar angles  $\theta$  for the magnetization vector  $\vec{M}$  are obtained from static equilibrium conditions.  $E_\theta, E_\phi, E_{\theta\theta}$  and  $E_{\phi\phi}$  can be easily calculated using the Eq. (16). Neglecting the damping term one can write the equation of motion for the magnetization vector  $\vec{M}$  as

$$\frac{1}{\gamma} \frac{d\vec{M}}{dt} = \vec{M} \times \vec{H}_{eff}. \tag{17}$$

Here the  $\vec{H}_{eff}$  is the effective magnetic field that includes the applied magnetic field and the internal field due to the anisotropy energy. The dynamic equation of motion for magnetization with the Bloch-Bloembergen type damping term is given as Eq.(18).

$$\frac{1}{\gamma} \frac{d\vec{M}}{dt} = \vec{M} \times \vec{H}_{eff} - \frac{\vec{M} - \delta_{iz} M_0}{T}. \tag{18}$$

Here,  $T = (T_2, T_2, T_1)$  represents both transverse (for  $M_x$  and  $M_y$  components) and the longitudinal (for  $M_z$  components) relaxation times of the magnetization. That is,  $T_1$  is the spin-lattice relaxation time,  $T_2$  is the spin-spin relaxation time, and  $\delta_{iz} = (0, 0, 1)$  for  $(x, y, z)$  projections of the magnetization. In the spherical coordinates the Bloch-Bloembergen equation can be written as below;



**Figure 5.** Damped precession of a magnetic moment  $\vec{M}$  toward the effective magnetic field  $\vec{H}_{eff}$  according to the Bloch-Bloembergen type equation (Aktaş, 1993, 1994; Yalçın, 2008(a)).

$$\frac{1}{\gamma} \frac{d\vec{M}}{dt} = \frac{\vec{M}}{|\vec{M}|} \times \vec{\nabla} E - \frac{\vec{M}_{\theta,\phi}}{\gamma T_2} - \frac{\vec{M}_z - M_0}{\gamma T_1}. \quad (19)$$

Where, the torque is obtained from the energy density through the expression

$$\vec{\nabla} E = - \left( \frac{\partial E}{\partial \theta} \right) \hat{e}_\theta + \frac{1}{\sin \theta} \left( \frac{\partial E}{\partial \phi} \right) \hat{e}_\phi. \quad (20)$$

For a small deviation from the equilibrium orientation, the magnetization vector  $\vec{M}$  can be approximated by

$$\vec{M} = M_s \hat{e}_r + m_\theta \hat{e}_\theta + m_\phi \hat{e}_\phi. \quad (21)$$

Where the dynamic transverse components are assumed to be sufficiently small and can be given as

$$\begin{aligned} m_\theta(z,t) &= m_\theta^0 \exp i(\omega t \pm kz) \\ m_\phi(z,t) &= m_\phi^0 \exp i(\omega t \pm kz) \end{aligned} \quad (22)$$

Dispersion relation for films can be derived by using these solutions (Eq.(22)) in Eqs. (19) and (20). On the other hand, the eigen frequency of thin films mode is determined by the static effective field and can be derived directly from the total free energy for magnetic system/ferromagnet. It is given by the second derivatives of the total energy with respect to the  $\theta$  and  $\phi$  (Smit, 1955; Artman, 1957; Wigen, 1984, 1988, 1992; Baseglia, 1988; Layadi, 1990; Farle, 1998). The matrices form for  $m_\theta$  and  $m_\phi$  is calculated using the Eq.(19) with Eq.(20, 21, 22).

$$\begin{pmatrix} i\frac{\omega}{\gamma} + \frac{1}{\gamma T_2} + \frac{E_{\theta\phi}}{M_s \sin \theta} & \frac{E_{\phi\phi}}{M_s \sin^2 \theta} \\ -\frac{E_{\theta\theta}}{M_s} & i\frac{\omega}{\gamma} + \frac{1}{\gamma T_2} - \frac{E_{\theta\phi}}{M_s \sin \theta} \end{pmatrix} \cdot \begin{pmatrix} m_\theta \\ m_\phi \end{pmatrix} = 0 \quad (23a)$$

$$\left(\frac{\omega}{\gamma}\right)^2 = \frac{1}{M^2 \sin^2 \theta} (E_{\theta\theta} E_{\phi\phi} - E_{\theta\phi}^2) + \left(\frac{1}{\gamma T_2}\right)^2 \quad (23b)$$

Here  $(\omega/\gamma) = g\mu_B H$  is the Larmour frequency of the magnetization in the external *dc* effective magnetic field. This dispersion relation can be related as the angular momentum analogue to be linear momentum oscillator described  $\omega = \sqrt{\kappa/\mu_i}$ . Here, restoring force constant  $\kappa$  is the second derivative of the potential part in the energy of system  $\kappa = E_{xx}$ . The inverse mass  $\mu_i^{-1}$  is given by the second derivative of the kinetic part in the energy with respect to linear momentum  $\mu_i^{-1} = E_{pp}$ . The restoring constant in this chapter corresponds to  $E_{\theta\theta}$ . The inverse mass is proportional to  $E_{\phi\phi}$ . The  $E_{\theta\phi}$  arises when the coordinate system is not parallel to the symmetry and last term originated from relaxation term in Eq.(23) (Sparks, 1964; Morrish, 1965; Vittoria, 1993; Gurevich, 1996; Chikazumi, 1997)

The power absorption from radio frequency (*rf*) field in a unit volume of sample is given by

$$P = \frac{1}{2} \omega \chi_2 h_1^2. \quad (24)$$

where  $\omega$  is the microwave frequency,  $h_1$  is the amplitude of the magnetic field component and  $\chi_2$  is the imaginary part of the high-frequency susceptibility. The field derivative FMR absorption spectrum is proportional to  $d\chi_2/dH$  and the magnetic susceptibility  $\chi$  is given as

$$\chi = 4\pi \left( \frac{m_\phi}{h_\phi} \right)_{\phi=0} \quad (25)$$

The theoretical absorption curves are obtained by using the imaginary part of the high frequency magnetic susceptibility as a function of applied field (Öner, 1997; Min, 2006; Cullity, 2009)

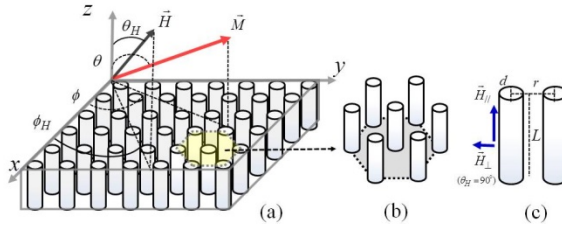
$$\chi = \chi_1 + i\chi_2 = \frac{4\pi M_s \left( \frac{E_{\theta\theta}}{M_s} \right) \left( \left( \frac{\omega_0}{\gamma} \right)^2 - \left( \frac{\omega}{\gamma} \right)^2 + i \left( \frac{2\omega}{\gamma^2 T_2} \right) \right)}{\left( \left( \frac{\omega_0}{\gamma} \right)^2 - \left( \frac{\omega}{\gamma} \right)^2 \right)^2 + \left( \frac{2\omega}{\gamma^2 T_2} \right)^2} \quad (26)$$

The dispersion relation can be derived by substituting Eq.(16) into Eq. (23) (Aktaş, 1997; Yağın, 2004(a), 2004(b), 2008(a); Güner, 2006; Kharmouche, 2007; Stashkevich, 2009)

$$\left(\frac{\omega}{\gamma}\right)^2 = \left[ H \cos(\theta - \theta_H) + H_{eff} \cos(2\theta) \right] \cdot \left[ H \cos(\theta - \theta_H) + H_{eff} \cos^2 \theta \right] + \left( \frac{1}{\gamma T_2} \right)^2 \quad (27)$$

here,  $\omega_0 = 2\pi\nu$  is the circular frequency of the EPR spectrometer. Fitting Eq.(27) with experimental results of the FMR measurement at different out-of-plane-angle ( $\theta_H$ ), the values for the effective magnetization can be obtained.

Figure 6 uses of both experimental and theoretical coordinate systems for the nanowire sample geometry. Equilibrium magnetization  $\vec{M}$  and *dc*-magnetic field  $\vec{H}$  are shown in this figure and also the geometric factor and hexagonal nanowire array presentation of nanowire are displayed. The ferromagnetic resonance theory has been developed for thin films applied to nanowires with the help of the following Fig.6. The effective uniaxial anisotropy term for nanowire arrays films  $K_{eff} = \pi M^2(1-3P) + K_U$  is written in this manner for arrayed nanowires. The first term in the  $K_{eff}$  is due to the magnetostatic energy of perpendicularly-arrayed NWs (Dubowik, 1996; Encinas-Oropesa, 2001; Demand, 2002; Yalçın, 2004(a); Kartopu, 2009, 2010, 2011(a)) and constant with the symmetry axis along wire direction. The second term in the  $K_{eff}$  is packing factor for a perfectly ordered hcp NW arrays. The packing factor is defined as  $P = (\pi/2\sqrt{3})(d/r)^2$ . The packing factor ( $P$ ) of nanowires increases, nanowire diameter increases, the preferential orientation of the easy direction of magnetization changes from the parallel to the perpendicular direction to the wire axis (Kartopu, 2011(a)). As further, the effective uniaxial anisotropy ( $K_{eff}$ ) for a perfectly ordered hcp NWs should decrease linearly with increasing packing factor.  $H_{eff} = 2\pi M_S(1-3P) + (2K_u/M_s)$ , which is the effective anisotropy field derived from the total magnetic anisotropy energy of NWs Eq. (16). The values for total magnetization have been obtained by fitting  $H_{eff}$  with experimental results of FMR measurements at different angles ( $\theta_H$ ) of external field  $\vec{H}$ . The experimental spectra are proportional to the derivative of the absorbed power with respect to the applied field which is also proportional to the imaginary part of the magnetic susceptibility.



**Figure 6.** (a) Schematic representation of the cobalt nanowires and the relative orientation of the equilibrium magnetization  $\vec{M}$  and the *dc* component of the external magnetic field  $\vec{H}$ , for the FMR experiments and their theoretical calculations. (b) Hexagonal NW array exhibiting a total of seven wires and the dashed lines bottom of the seven wires indicate the six fold symmetry. (c) Sample parameters used in the packing factors  $P$  calculation.



The experimental data were analyzed by using magnetic energy density for a system consisting of  $n$  magnetic layers with saturation magnetization  $M_s$  and layer thickness  $t_i$ . The magnetic energy density for the nanoscale multilayer structures the energy per unit surface area can be written as below

$$E = - \left( \begin{aligned} & \sum_{i=1}^n t_i M_s H (\sin \theta_i \sin \theta_H \cos(\phi_i - \phi_H) + \cos \theta_i \cos \theta_H) + \\ & \sum_{i=1}^n t_i K_{a,i} \sin^2 \phi_i \cos^2 \theta_i + \sum_{i=1}^n t_i K_{b,i} \sin^4 \phi_i \cos^4 \theta_i + \\ & \sum_{i=1}^{n-1} A_{i,i+1} (\sin \theta_i \sin \theta_{i+1} \cos(\phi_{i+1} - \phi_i) + \cos \theta_i \cos \theta_{i+1}) + \\ & \sum_{i=1}^{n-1} B_{i,i+1} (\sin \theta_i \sin \theta_{i+1} \cos(\phi_{i+1} - \phi_i) + \cos \theta_i \cos \theta_{i+1})^2 \end{aligned} \right) \quad (28)$$

Where,  $\theta_i$  is the polar angle of the magnetization  $M_s$  to the z-axis and  $\phi_i$  is the azimuth angle to the x-axis in the film plane. The first term is the Zeeman energy. The second and third terms correspond to first and second order magnetocrystalline energy with respectively. These energies due to the demagnetization field and any induced perpendicular anisotropy energy. On the other hand, these energies qualitatively have the same angular dependence with respect to the film normal. The second order magnetocrystalline energy term can be neglected for most of the ferromagnetic systems. The last two terms corresponds to bilinear and biquadratic interactions of ferromagnetic layers through nonmagnetic spacer via conduction energies.  $A_{i,i+1}$  and  $B_{i,i+1}$  are bilinear and biquadratic coupling constants, respectively. The bilinear exchange interaction can be written from Eq.16.  $A_{i,i+1}$  can be either negative and positive depending on antiferromagnetic and ferromagnetic interactions, respectively. The antiparallel/perpendicular and parallel alignments of magnetization of nearest neighboring layers are energetically favorable for a negative/positive value of  $B_{i,i+1}$ . Biquadratic interaction for spin systems have been analysed for Ising system in detail (Chen, 1973; Erdem, 2001). The biquadratic term is smaller than the bilinear interaction term. Therefore, it can be neglected for most of the ferromagnetic systems. The indirect exchange energy depends on spacer thickness and even shows oscillatory behavior with spacer thickness (Ruderman, 1954; Yosida, 1957; Parkin, 1990, 1991(a), 19901(b), 1994). The current literature on single ultrathin films and multilayers is given in below at table (Layadi, 1990(a), 1990(b); Wigen, 1992; Zhang, 1994(a), 1994 (b); Goryunov, 1995; Ando, 1997; Farle; 1998; Platow, 1998; Schmool, 1998; Lindner, 2003; Sklyuyev, 2009; Topkaya, 2010; Erkovan, 2011).

This type exchange-coupling system is located in an external magnetic field, the magnetic moment in each layer. The suitable theoretical expression may be derived in order to deduce magnetic parameter for  $ac$  susceptibility. The equation of precession motion for magnetization of the  $i^{th}$  layer in the spherical coordinates with the Bloch-Bloembergen type relaxation term can be written as

$$\frac{1}{\gamma} \frac{d\vec{M}}{dt} = \frac{1}{t_i} \frac{\vec{M}}{M_{i,s}} \times \vec{\nabla}_{M_i} E - \frac{\vec{M}_{\theta_i, \phi_i}}{\gamma T_2} - \frac{\vec{M}_{z,i} - M_{i,s}}{\gamma T_1}. \quad (i = 1, n) \quad (29)$$

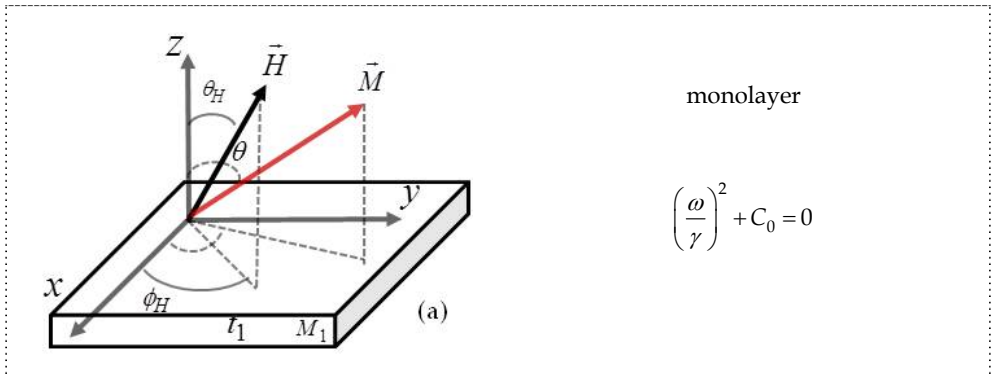
The matrices form for  $m_{\theta,i-1}$ ,  $m_{\phi,i-1}$ ,  $m_{\theta,i}$ ,  $m_{\phi,i}$ ,  $m_{\theta,i+1}$  and  $m_{\phi,i+1}$  of each magnetic layers calculated using the Eq.(29) with Eq.(20, 21,28).

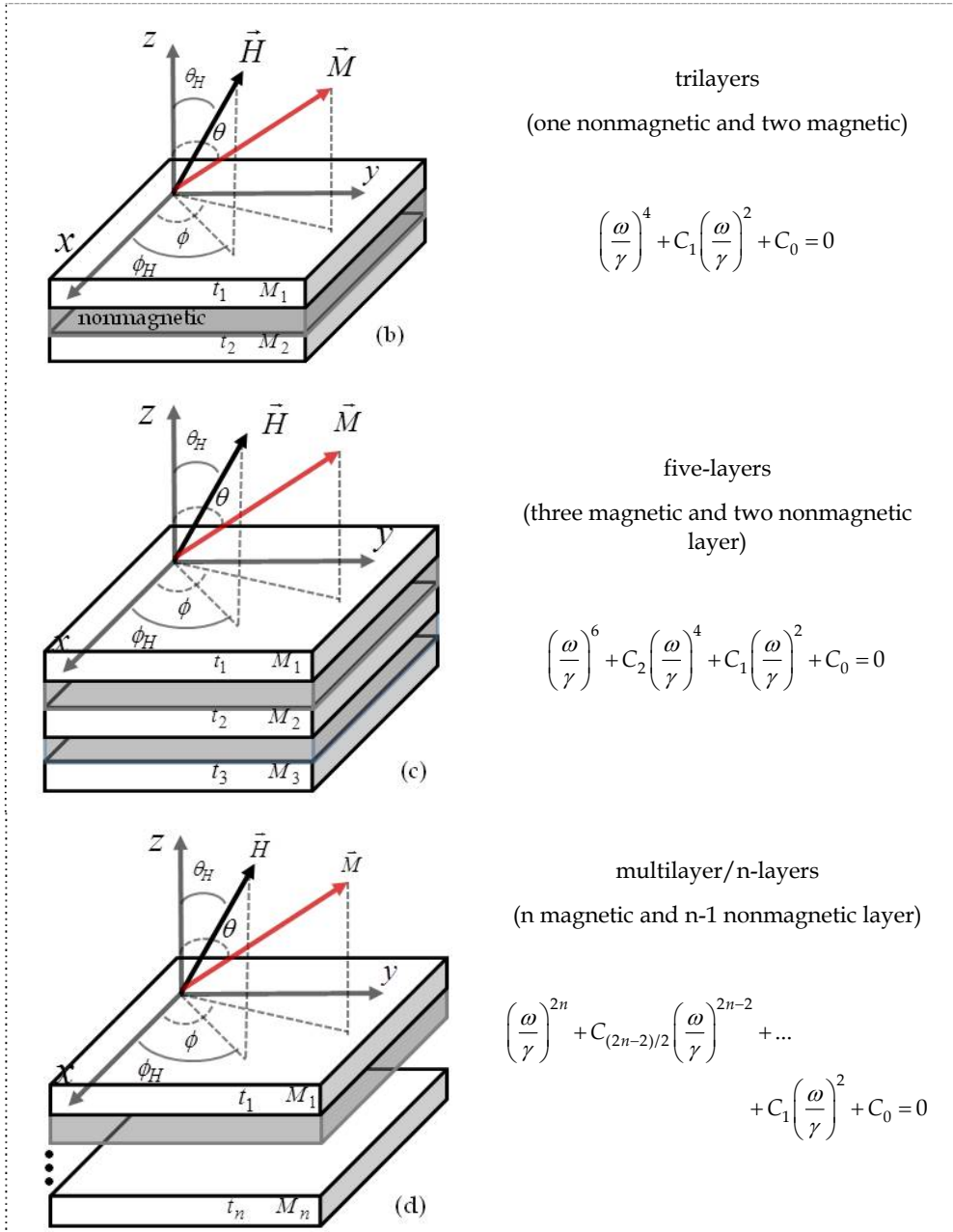
$$\left( \begin{array}{cccccc} \Omega + \frac{E_{\theta_1\phi_1}}{t_1 M_s \sin \theta_1} & \frac{E_{\phi_1\phi_1}}{t_1 M_s \sin^2 \theta_1} & \frac{E_{\theta_2\phi_1}}{t_1 M_s \sin \theta_1} & \frac{E_{\phi_1\phi_2}}{t_1 M_s \sin \theta_1 \sin \theta_2} & \frac{E_{\theta_2\phi_2}}{t_1 M_s \sin \theta_1} & \frac{E_{\phi_2\phi_2}}{t_1 M_s \sin \theta_1 \sin \theta_3} \\ \frac{E_{\theta_1\theta_1}}{t_1 M_s} & \Omega - \frac{E_{\theta_1\phi_1}}{t_1 M_s \sin \theta_1} & \frac{E_{\theta_1\theta_2}}{t_1 M_s} & -\frac{E_{\theta_1\phi_2}}{t_1 M_s \sin \theta_2} & -\frac{E_{\theta_1\theta_3}}{t_1 M_s} & -\frac{E_{\theta_1\phi_3}}{t_3 M_s \sin \theta_3} \\ \frac{E_{\theta_1\phi_2}}{t_2 M_s \sin \theta_2} & \frac{E_{\phi_1\phi_2}}{t_2 M_s \sin \theta_1 \sin \theta_2} & \Omega + \frac{E_{\theta_2\phi_2}}{t_2 M_s \sin \theta_2} & \frac{E_{\phi_2\phi_2}}{t_2 M_s \sin^2 \theta_2} & \frac{E_{\theta_2\phi_3}}{t_2 M_s \sin \theta_3} & \frac{E_{\phi_2\phi_3}}{t_2 M_s \sin \theta_2 \sin \theta_3} \\ -\frac{E_{\theta_2\theta_2}}{t_2 M_s} & -\frac{E_{\theta_2\phi_1}}{t_2 M_s \sin \theta_1} & -\frac{E_{\theta_2\theta_2}}{t_2 M_s} & \Omega - \frac{E_{\theta_2\phi_2}}{t_2 M_s \sin \theta_2} & -\frac{E_{\theta_2\theta_3}}{t_3 M_s} & -\frac{E_{\theta_2\phi_3}}{t_3 M_s \sin \theta_3} \\ \frac{E_{\theta_2\phi_1}}{t_3 M_s \sin \theta_3} & \frac{E_{\phi_1\phi_1}}{t_3 M_s \sin \theta_1 \sin \theta_3} & \frac{E_{\theta_2\phi_2}}{t_3 M_s \sin \theta_2} & \frac{E_{\phi_2\phi_2}}{t_3 M_s \sin \theta_2 \sin \theta_3} & \Omega + \frac{E_{\theta_3\phi_3}}{t_3 M_s \sin \theta_3} & \frac{E_{\phi_3\phi_3}}{t_3 M_s \sin^2 \theta_3} \\ -\frac{E_{\theta_3\theta_3}}{t_3 M_s} & -\frac{E_{\theta_3\phi_1}}{t_3 M_s \sin \theta_3} & -\frac{E_{\theta_3\theta_3}}{t_3 M_s} & -\frac{E_{\theta_3\phi_2}}{t_3 M_s \sin \theta_2} & -\frac{E_{\theta_3\theta_3}}{t_3 M_s} & \Omega - \frac{E_{\theta_3\phi_3}}{t_3 M_s \sin \theta_3} \end{array} \right) \cdot \begin{pmatrix} m_{\theta_1} \\ m_{\phi_1} \\ m_{\theta_2} \\ m_{\phi_2} \\ m_{\theta_3} \\ m_{\phi_3} \end{pmatrix} = 0 \quad (30)$$

1, 2, 3 number in this Eq.(30) corresponds to  $i-1, i$  and  $i+1$ , respectively. Here  $\Omega = i \left( \frac{\omega}{\gamma} \right) + \frac{1}{\gamma T_2}$ . Then dispersion relation for ferromagnetic exchange-coupled  $n$ -layers has been calculated using the  $(2n \times 2n)$  matrix on the left-hand side of Eq. (30) in below in detail.

$$\left( \frac{\omega}{\gamma} \right)^{2n} + C_{(2n-2)/2} \left( \frac{\omega}{\gamma} \right)^{2n-2} + \dots + C_1 \left( \frac{\omega}{\gamma} \right)^2 + C_0 = 0 \quad (31)$$

Here,  $n$  is the number of ferromagnetic layer.  $C_0, C_1, \dots$  etc. are constant related to  $t_i, M_s, E_{\theta_i\theta_i}, E_{\phi_i\phi_i}, E_{\theta_i\phi_i}, \sin \theta_i$  and  $\sin^2 \theta_i$ . The dispersion relations for monolayer, trilayers, five-layers obtained from the Eq.(31). For tri-layers detail information are seen in ref. (Zhang, 1994(a); Schmol, 1998; Lindner, 2003). It is given that the dispersion relation for monolayer, trilayers, five-layers and multilayers/ $n$ -layers in Fig. 7.





**Figure 7.** Schematic representation of the (a) one layer, (b) three layer, (c) five layer and (d) n magnetic layer and their relative orientation of the equilibrium magnetization  $\vec{M}$  and the dc component of the external magnetic field  $\vec{H}$  for the FMR experiments and their theoretical calculations.

## 6. Example: Exchange spring (hard/soft) behaviour

The Bloch wall, Néel line and magnetization vortex are well known properties for magnetic domain in magnetic systems. The multilayer structures are ordered layer by layer. The best of the sample for multilayer structure are exchange-spring systems. The equilibrium magnetic properties of nano-structured exchange-spring magnets may be studied in detail for some selected magnetic systems. The exchange systems are oriented from the exchange coupling between ferromagnetic and antiferromagnetic films or between two ferromagnetic films. This type structure has been extensively studied since the phenomenon was discovered (Meiklejohn, 1956, 1957). Kneller and Hawing have been used firstly the “exchange-spring” expression (Kneller, 1991). Spring magnet films consist of hard and soft layers that are coupled at the interfaces due to strong exchange coupling between relatively soft and hard layers. The soft magnet provides a high magnetic saturation, whereas the magnetically hard material provides a high coercive field. Skomski and Coey explored the theory of exchanged coupled films and predicted that a huge energy about three times of commercially available permanent magnets (120 MGOe) can be induced (Skomski, 1993; Coey, 1997). The magnetic reversal proceeds via a twisting of the magnetization only in the soft layer after saturating hard layers, if a reverse magnetic field that is higher than exchange field is applied. The spins are sufficiently closed to the interface are pinned by the hard layer, while those in deep region of soft layer rotate up to some extent to follow the applied field (Szlaferek, 2004). To be more specific, the angle of the rotation depends on the distance to the hard layer. That is the angle of rotating in a spiral spin structure similar to that of a Bloch domain wall. If the applied field is removed, the soft spins rotate back into alignment with the hard layer.

The general expression of the free energy for exchange interaction spring materials at film ( $\theta_{i,j\pm 1} = \pi/2$  and  $\theta_H = \pi/2$ ) plane in spherical coordinate system as below.

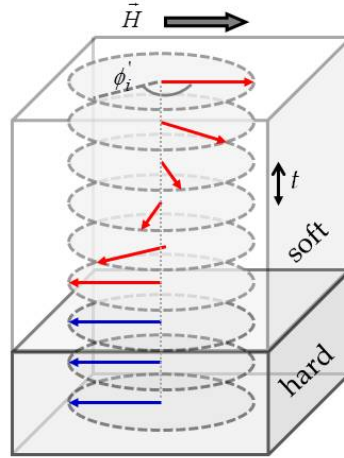
$$E = - \sum_{i=1}^N \vec{H} \cdot \vec{M}_i - \sum_{i=1}^N K_{a,i} \cos^2 \phi_i - \sum_{i=1}^N K_{b,i} \cos^4 \phi_i - \sum_{i=1}^{N-1} \frac{A_{i,i\mp 1}}{t^2} \cos(\phi_{i\mp 1} - \phi_i) - \sum_{i=1}^{N-1} \frac{B_{i,i\mp 1}}{t^2} \cos(\phi_{i\mp 1} - \phi_i)^2 \quad (32)$$

The expression is obtained as following using  $\phi_i \rightarrow \phi_i'$  for magnetization's equilibrium orientations of each layer at a state of equilibrium under the external magnetic field.

$$\tan \phi_i' = \frac{HM_i t^2 \sin \phi_H + A_{i,i\mp 1} \sin \phi_{i\mp 1} + 2B_{i,i\mp 1} \sin \phi_{i\mp 1} \cos(\phi_i - \phi_{i\mp 1})}{HM_i t^2 \cos \phi_H + 2t^2 K_{a,i} \cos \phi_i + 4t^2 K_{b,i} \cos^3 \phi_i + A_{i,i\mp 1} \cos \phi_{i\mp 1} + 2B_{i,i\mp 1} \cos \phi_{i\mp 1} \cos(\phi_i - \phi_{i\mp 1})} \quad (33)$$

In this example, second-order anisotropy term ( $K_{b,i} = 0$ ) and biquadratic interaction constant ( $B_{i,i\pm 1} = 0$ ) considered and the result obtained show as following as adapted with

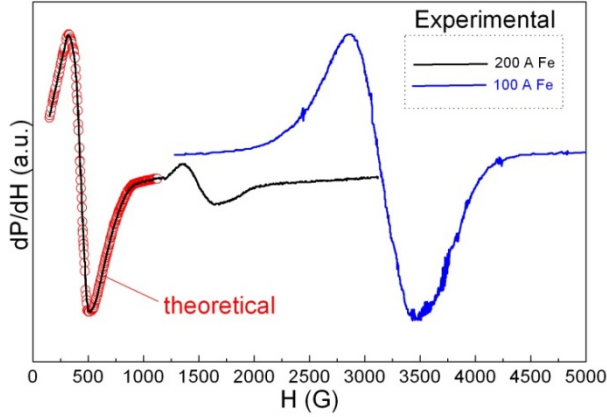
spring magnets SmCo(hard)/Fe(soft). For theoretical analysis, the exchange-spring magnet SmCo/Fe is divided into subatomic multi-layers ( $d=2 \text{ \AA}$ ), and the spins in each layer are characterized by the average magnetization  $M_i$ , and the uniaxial anisotropy constant  $K_i$ , (Fig.8).



**Figure 8.** Schematic illustration of phases of exchange spring magnets.

Sublayers are coupled by an exchange constant  $A_{i,i+1}$  (Astalos, 1998; Fullerton, 1998, 1999; Jiang, 1999, 2002, 2005; Grimsditch, 1999; Scholz, 2000; Hellwig, 2000; Pollmann, 2001; Dumesnil, 2002).  $\phi_i$  is the angle formed by the magnetization of the  $i$ th plane with the in-plane (where the external field is always perpendicular to the film normal) easy axis of the hard layer (Yıldız, 2004(a), 2004(b)). The FMR spectra for exchange-spring magnet of SmCo/Fe have been analyzed using the Eqs. (26, 27, and 33) in Fig.9. Sm-Co (200 Å)/Fe (200 Å and 100 Å) bilayers have been grown on epitaxial 200 Å Cr(211) buffer layer on single crystal MgO(110) substrates by magnetron sputtering technique (Wüchner, 1997). To prevent oxidation Sm-Co/Fe film was coated with a 100 Å thick Cr layer. The FMR spectra for exchange-spring magnets of 200 Å and 100 Å Fe samples for different angles of the applied magnetic field in the film plane are presented in Fig.9.

There are three peaks that are one of them corresponds to the bulk mode and the remaining to the surface modes for 200 Å Fe sample. For more information about the FMR studies exchange spring magnets look at the ref. (Yildiz, 2004(a), 2004(b) ). Exchange-spring coupled magnets are promising systems for applications in perpendicular magnetic data recording-storage devices and permanent magnet (Schrefl, 1993(a), 1993(b), 1998, 2002; Mibu, 1997, 1998).



**Figure 9.** FMR spectra for SmCo(200 Å)/Fe(200 Å) (black line) and SmCo(200 Å)/Fe(100 Å) (blue line) samples. These FMR spectra originated from the iron/soft layers.

### 7. Superparamagnetic resonance

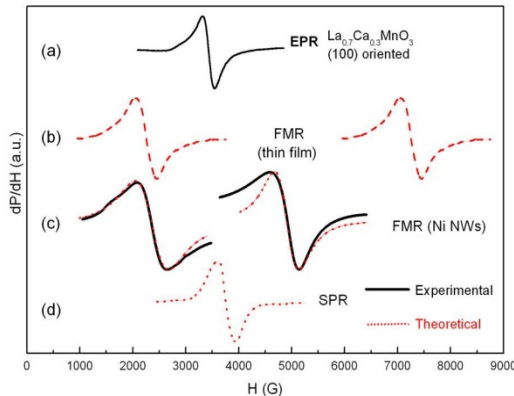
Magnetic nanoparticles have been steadily interested in science and nanotechnology. As the dimensions of magnetic nanoparticles decrease to the nanometer scale, these nanoparticles start to exhibit new and interesting physical properties mainly due to quantum size effects (Yalçın, 2004(a), 2008(b), 2012). A single domain particle is commonly referred to as superparamagnetic (Held, 2001; Diaz, 2002; Fonseca, 2002). The superparamagnetic/single-domain nanoparticles are important for non surgical interfere of human body. Even the intrinsic physical characteristics of nanoparticles are observed to change drastically compared to their macroscopic counterparts. Stoner-Wohlfarth (Stoner, 1948) and Heisenberg model (Heisenberg, 1928) to describe the fine structure were firstly used in detail. A simple (Bakuzis, 2004) and the first atomic-scale models of the ferrimagnetic and heterogeneous systems in which the exchange energy plays a central role in determining the magnetization of the NPs, were studied (Kodama, 1996, 1999; Kodama & Berkowitz, 1999). Superparamagnetic resonance (SPR) studies of fine magnetic nanoparticles is calculated a correlation between the line-width and the resonance field for superparamagnetic structures (Berger, 1997, 1998, 2000(a), 2000(b), 2001; Kliava, 1999). The correlation of the line-width and the resonance field is calculated from Bloch-Bloembergen equation of motion for magnetization. The SPR spectra, line width and resonance field may be analyzed by using the Eq.(34) in below. The equation of motion for magnetization with Bloch-Bloembergen type relaxation term for FMR adapted for superparamagnetic structures from Eqs.(18) and (19) in below.

$$\chi_2(H) = \frac{1}{\pi} \frac{\Delta_H (\Delta_H^2 + H^2 + H_r^2)}{(\Delta_H^2 + (H - H_r)^2) \cdot (\Delta_H^2 + (H + H_r)^2)} \tag{34}$$

Here,  $\Delta_H = 1/\gamma T_2$ ,  $H_r = -(\omega/\gamma)$ . This equation for SPR system so called modified Bloch for fine particle magnets. The SPR microwave absorption is proportional to the imaginary part of the dynamic susceptibility. The line shape and resonance field for superparamagnet is obtained. The temperature evolution for the SPR line-width for nanoparticles can be calculated by  $\Delta_H = \Delta_T L(x)$ . In this expression  $\Delta_T$  is a saturation line-width at a temperature  $T$ ,  $L(x) = \coth(x) - (1/x)$  is the Langevin function with  $x = MVH_{eff}/k_B T$ ,  $V$  is the particle volume. The superparamagnetic (Chastellain, 2004; Dormer, 2005; Hamoudeh, 2007), core-shell nanoparticles and nanocrystalline nanoparticles (Woods, 2001; Wiekhorst, 2003; Tartaj, 2004) have been performed for possible biological applications (Sun, 2005; Zhang, 2008). In addition, superparamagnetic nanoparticles have been used for hydrogels, memory effects and electronic devices (Raikher, 2003; Sasaki, 2005; Heim, 2007).

## 8. Result and discussions

The EPR, FMR and SPR signals have been observed in Fig.10. The EPR signal has reached approaching peak level about 3000 G as seeing at Fig.10. It's symmetric and line width are narrower than resonance field, in generally. If EPR samples show crystallization, resonance field value starts to change. The EPR signal can be observed at lower temperature about 3000 G and the signal can show crystalline property. The signal is observed in two different areas at FMR spectra as the magnetic field is parallel and perpendicular to the film. The FMR spectra are observed at low field when the magnetic field is parallel to the film, in generally. On the other hand, the FMR spectra are observed at highest field when the magnetic field is perpendicular to the film. For other conditions FMR signals are observed between these two conditions for thin films. FMR spectra can be seen a wide range of field so as to the thin films are full.



**Figure 10.** (a) The EPR/ESR experimental signal for  $\text{La}_{0.7}\text{Ca}_{0.3}\text{MnO}_3$  samples at room temperature (see, Kartopu, 2011 (b)). (b) Theoretical FMR spectra calculated from Eq. (26) with Eq.(27) at parallel ( $\theta = 90^\circ$ ; ~2000 G) and perpendicular ( $\theta = 0^\circ$ ; ~7000 G) position of OPG case. (c) The theoretical (red-dot line in online) and experimental FMR spectra for Ni NWs ( $P= 29,6$ ;  $L=0,8 \mu\text{m}$ ,  $\tau=13$ ) (see for detail, Kartopu, 2011 (a)). (d) The theoretical SPR signal for superparamagnet by Eq.(34) at room temperature.

FMR spectra are similar to thin films at nanowire samples. In case of occupancy rate is that as the theoretical  $P < 33\%$  for Nickel (Ni) it behaviors like thin film. But, in case of occupancy rate is that as the theoretical  $P < 33\%$  it behaviors different from thin film. This situation is clearly visible from  $H_{eff} = 2\pi M_S(1-3P) + (2K_u/M_s)$ . If the occupancy rate is  $P < 33\%$  sample's signals show the opposite behavior according to thin film FMR signals. Look at for more information (Kartopu, 2011 (a)). This is perceived as changes the direction of the easy axis. The changes of easy axes depend on magnetization (Terry, 1917) and porosity (Kartopu, 2011 (a)) for magnetic materials/transition elements. The SPR signal is similar to EPR signal. SPR peak may show symmetrical properties both at room temperature and low temperatures. The SPR signal is in the form of Lorentzian and Gaussian line shapes at all temperature range. Specially prepared nanoparticles SPR peak exhibit shift in symmetry. The line width of SPR peak expands at low temperature.

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