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Ferromagnetic resonance spectra in Co/Nb multilayers with large Co thickness

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The perpendicular ferromagnetic resonance spectra for four Co/Nb multilayered films have been studied. Three of these multilayers had the same thickness of Co (210 Å) with Nb layer thicknesses varying between 18 and 135 Å. The fourth film was a trilayer sandwich film. A multimode spectrum was observed for all the films. The results indicated that the Co films are magnetically coupled even when the Nb film thickness was 135 Å. A new approach to understand the multimode ferromagnetic resonance in magnetic/nonmagnetic multilayer thin film structures was worked out. In this approach, the equation of motion is solved in the magnetic layers, which are assumed to be coupled through a boundary condition. The theoretical calculations gave a good agreement with the experimentally observed field positions when it was assumed that the magnetic properties of the top and the bottom Co layers are slightly different from the intermediate ones. © 2002 American Institute of Physics. [DOI: 10.1063/1.1428793]

I. INTRODUCTION

There has been a lot of interest during the last decade in the study of the magnetic properties of multilayers because of their potential applications and many new and interesting problems they pose.1,2 Of particular interest are the magnetic/nonmagnetic multilayers, in which the alternate layers are nonmagnetic. New types of magnetic interactions have been proposed recently to explain the various phenomena observed in such films.2–9 One of the problems in such a type of multilayers is to understand the coupling between magnetic layers through nonmagnetic ones. Ferromagnetic resonance (FMR) is one of the experimental techniques, which can give information about such a coupling. Many recent studies have, therefore, used FMR to study magnetic/nonmagnetic multilayers.10–13 Unfortunately, the observed FMR spectra in such films are quite complicated and consist of a large number of modes without any obvious systematics either in field position or mode intensities. This is especially so when the number of modulations and the thickness of the magnetic layers are large. Many theoretical attempts to explain10–14 such spectra are, therefore, limited to the sandwich types of films (i.e., those containing only two magnetic layers) and films with a somewhat smaller thickness of the magnetic layers separated by a small thickness of nonmagnetic layers. Some of these attempts even assume that magnetic moments are parallel within a magnetic layer.10–16 This is an assumption that is strictly valid only when the thickness of the magnetic layer is small. In spite of this, a clear understanding of FMR spectra in terms of field and intensity of the absorption modes has not been possible.

Recently Acharya et al.17 made an attempt to explain the field and intensity pattern of perpendicular FMR spectra (the dc magnetic field applied normal to the film plane) of magnetic/magnetic multilayers. They used a model similar to that proposed by Wilts and Prasad18 for studying ion-implanted bubble films. Using their model, Acharya et al. could show that in Fe/Ni multilayers there is mixing at the interface. After modeling the mixing, their calculated spectrum agreed well with the experimental one. However, their method cannot be directly adopted to study the magnetic/nonmagnetic multilayers.

In this paper we report a modification of the model used by Acharya et al.17 so that it can also be applied to magnetic/nonmagnetic multilayers. Further, we use this modified model to study the perpendicular FMR spectra on three Co/Nb multilayers. These films have been chosen because of the following features. First, the thickness of Co film is 210 Å in all of them. This is reasonably large in comparison to multilayers generally studied.19 Therefore, one cannot apply models in such a film that assume all the spins to be parallel in a magnetic layer. Our model, on the other hand, is

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particularly useful for thicker films, where the angle between the successive spins in a layer cannot be ignored. Second, in these films, the thickness of Nb is varied from 18 Å to 135 Å. This allows us to study the coupling between magnetic layers over a reasonably large range of nonmagnetic layer thicknesses. In addition to these three, we examined a sandwich-type multilayer film on a Si substrate, consisting of 150 Å thick Nb film between two 410 Å Co layers. We have studied this film to compare the results with our results on the three multilayers.

II. EXPERIMENTAL DATA

The FMR spectrum was recorded at 9.8 GHz on all the samples in perpendicular geometry. Figure 1 shows the experimental observations. Figure 2 shows a plot of the experimental field values obtained from Fig. 1 as a function of “decreasing” thickness of the Nb layer ($t_{Nb}$) for the first three films. In Fig. 2, resonance field has been plotted as a function of decreasing thickness to facilitate comparison with the theoretical calculation to be described later. This is because, as Nb thickness decreases, the coupling between the two magnetic layers increases.

The following points clearly emerge on the examination of Fig. 1 and Fig. 2:

1. A substantial difference is observed between the spectra for different Nb thicknesses.
2. Field position of the first mode (the one corresponding to the highest field) increases with the decrease in thickness of Nb layer.
3. The field separation between the modes tends to increase with the decrease of Nb thickness.
4. The field separations between various modes are much smaller in comparison to those observed in the case of magnetic/magnetic multilayers.

The first point mentioned above clearly indicates that the coupling between magnetic layers exists even when the thickness of nonmagnetic layers is as large as 135 Å. This is because, if the coupling was absent, the multiple resonances can be seen only because of spin wave excitation in a single Co layer. In such a case, the field separation between the modes has to be much larger than the observed one, because of small layer thickness. The last two points can also be intuitively understood in terms of the extent of the coupling. With the increase in the thickness of the Nb layer, the coupling goes down causing a lower separation between the modes. This is like the effect of reducing the exchange constant in the standing spin wave spectra of single layer films. Similarly, in the case of magnetic–magnetic multilayers, the coupling is expected to be very strong which would cause large exchange shifts and thus large separation between the modes.

The theoretical calculation of the resonance spectrum would involve a clear understanding of the coupling mechanisms present between the two magnetic films through a nonmagnetic one. However, as mentioned in point (1) above, despite the nature of the coupling, it is effective even when the thickness of the nonmagnetic layer is as large as 135 Å. It is generally not expected that a direct exchange mechanism would be effective over such a large thickness. Recently, many workers have discussed the oscillatory coupling mechanism to be present in multilayers. This type of coupling mechanism could be effective over thicknesses that are of the order of mean free path of electrons. Work has also been reported on magnetostatic coupling between the magnetic layers.

It is also possible that different types of coupling mechanisms dominate in different thickness ranges of the nonmagnetic layer. There have been some attempts to include some of these mechanisms in earlier theoretical attempts in order to explain the ferromagnetic resonance spectrum of multilayers with thin magnetic layers. These will be discussed later in an appropriate sections.

III. THEORY

In the case of perpendicular resonance in a uniform thin film, the equation of motion is given as follows:

$$\frac{2A}{M} \frac{d^2m}{dz^2} = \left( H_0 - \frac{\omega}{\gamma} + \frac{H_k - 4 \pi M}{\gamma} \right) m.$$  (1)
Here $m$ is the magnitude of the rf deflection of the magnetization from static equilibrium and $z$ is the position coordinate along the thickness of the film, $A$ is the exchange constant, $4\pi M$ is the saturation magnetization, $H_0$ is the applied static magnetic field, $H_k$ is the anisotropy field, and $\gamma$ is the gyromagnetic ratio.

In the case of magnetic/magnetic multilayers, Acharya et al.\textsuperscript{17} solved Eq. (1) in individual layers by substituting the standard values of constants for that layer and for a particular value of applied field $H_0$. The $m$ vs. $z$ curve was mapped by applying Wilts and Prasad\textsuperscript{18} boundary conditions at each film–film interface. The field was then varied until $m$ satisfied the natural boundary condition at the film-air and film-substrate interface and also had a required number of crossings with the $z$-axis. The $n$th order mode (called mode number $n$) would have $n-1$ crossings with the $z$-axis.

The algorithm used by Acharya et al. cannot be directly applied to magnetic/nonmagnetic multilayers as it requires the substitution of magnetic properties of each layer in order to map $m$ as a function of $z$. We have, therefore, used a different strategy in such a case. We have assumed that the coupling between the magnetic layers results from an interlayer exchange interaction and the effect of the nonmagnetic layer is only to change the amount of this interaction. However, one cannot use the Wilts and Prasad boundary conditions in such a case, as it does not contain any parameter that is dependent on the coupling between the layers.

A long time ago, Hoffman derived the boundary conditions\textsuperscript{22,23} which contain an additional parameter $A_{12}$, which depends on the coupling strength between two magnetic layers. According to Hoffman, if there are two magnetic layers with exchange constants $A_1$ and $A_2$ and saturation magnetization $M_1$, and $M_2$ that are coupled through an interlayer exchange parameter $A_{12}$, the $m$ and its derivative follow the boundary conditions stated below:

\[
\frac{A_1}{M_1} \frac{\partial m_1}{\partial z} + A_{12} \left[ \frac{m_1}{M_1} - \frac{m_2}{M_2} \right] = 0,
\]

\[
\frac{A_2}{M_2} \frac{\partial m_2}{\partial z} + A_{12} \left[ \frac{m_1}{M_1} - \frac{m_2}{M_2} \right] = 0. \tag{2}
\]

The Hoffman boundary conditions have recently been a subject of controversy.\textsuperscript{24–28} The basic objection to these boundary conditions has been that, in the case in which they are applied at the interface of two identical magnetic materials, i.e., when $M_1 = M_2$, $A_1 = A_2 = a A_{12}$; $a$ being lattice constant of the material, one does not get the expected $m_1 = m_2$ and $\partial m_1 / \partial z = \partial m_2 / \partial z$. We instead get $m_2 - m_1 = a (\partial m_1 / \partial z)$ and $\partial m_1 / \partial z = \partial m_2 / \partial z$. The application of these boundary conditions, therefore, creates an artificial boundary.\textsuperscript{24,28} This may mean an unphysical reflection of the spin wave when it is getting transmitted across the interface. Cochran and Heinrich\textsuperscript{25} supported the Hoffman boundary conditions and pointed out that they are correct in the continuum limit. They also mentioned that to the same order of accuracy that is used to derive the spin equations of motion for the long wavelength limit, the Hoffman boundary condition satisfies the requirement that there is no reflection of spin waves when the boundary between the two layers is made to disappear. Pashaev and Mills\textsuperscript{24} derived another set of boundary conditions that do not suffer from the deficiency mentioned above. Barnas\textsuperscript{28} examined the applicability of the Hoffman boundary conditions in detail. According to him, the deficiency of the Hoffman boundary condition would have negligible effect, in the weak coupling limit, i.e., when the interlayer exchange is much smaller compared to that within the film. We have, therefore, decided to carry out the calculations using Hoffman boundary conditions. This is because, in our case, the thickness of the nonmagnetic layer is reasonably large and the condition of weak coupling limit is definitely applicable.

Barnas et al.\textsuperscript{28} modified the Hoffman boundary conditions to include the contributions of interfacial anisotropy as well. If the interface anisotropy constant is $K_z$, the boundary conditions can be written as

\[
A_1 \frac{\partial m_1}{M_1 \partial z} + A_{12} \left[ \frac{m_1}{M_1} - \frac{m_2}{M_2} \right] + \frac{m_1}{M_1} K_z = 0, \tag{3}
\]

\[
A_2 \frac{\partial m_2}{M_2 \partial z} + A_{12} \left[ \frac{m_1}{M_1} - \frac{m_2}{M_2} \right] - \frac{m_2}{M_2} K_z = 0.
\]

The boundary conditions given by Eqs. (2) and (3) take into consideration the torques on an interfacial spin due to exchange interactions from the two sides. Other types of coupling mechanisms not described by these equations may also play a role in the coupling of the magnetic layers. It is not easy to incorporate all types of coupling mechanisms into the calculation. Even after considering their contribution, the calculations do not always give consistent results. As an example, there has been an attempt to include the magneto-static coupling in a simplified fashion in the evaluation of the first mode of the FMR spectrum of magnetic/nonmagnetic multilayers. This gave an agreement with the experimental result on Co/Pt multilayers, only when a value of saturation magnetization of Co, that is less than half of the bulk, was assumed.\textsuperscript{29} We, therefore, decided to use Eqs. (2) and (3) for the calculation of our FMR spectrum. The value of $A_{12}$ used, thus, should then be an “effective” interlayer exchange parameter and would include the average effect of other types of coupling as well. We feel that $A_{12}$ is not a bad parameter of coupling because as discussed earlier in Sec. II, the separation between the modes seems to follow a behavior that is somewhat similar to standing spin wave resonance spectrum in a single layered film. Moreover, this makes the calculation reasonably simple, which helps us to get some insight into the multimode spectrum of our films.

An algorithm similar to Acharya et al.,\textsuperscript{17} but with two modifications, was used in this work to predict the FMR response. Equation (1) was solved only in magnetic layers and applied boundary conditions used were those given by Eq. (2) or (3) instead of the Wilts and Prasad boundary conditions. The influence of the nonmagnetic layer was incorporated with an appropriate value of $A_{12}$. The parameters used to characterize magnetic layers were $4\pi M$ of the material, exchange constant $A$, and $\gamma$ the gyromagnetic ratio. The thickness of the magnetic layer is used to map $m$ vs. $z$ curve and to find the value of $m$ and $\partial m / \partial z$ at the next interface. In our work, we have taken the values of $4\pi M$, $A$, and $g$ for Co...
as 17.593 G, 2.75 × 10^{-6} \text{ erg/cm}, and 2.2, respectively.\(^{30}\) As shown later, unlike the case of magnetic/magnetic multilayers, the intensities of the modes are more difficult to explain than the position of the modes. Hence the initial part of the calculation focused on the resonance field positions.

**IV. CALCULATIONS FOR AN IDEAL MULTILAYER**

**A. Calculated results and comparison with experiment**

By an ideal multilayer, we mean that it has sharp interfaces, without any interface anisotropy or diffusion. It would also be assumed that the magnetic properties of all the magnetic layers are identical. Figure 3 shows the variation of the calculated resonance fields as a function of the interlayer exchange coupling constant, \(A_{12}\), for such a film using Eqs. (2) as the boundary condition. It is clear from the figure that, when \(A_{12}\) is very small, the first five resonance modes (because of five Co layers) merge into a single resonance field, which corresponds to uniform precession mode of Co films. This result is expected because if \(A_{12}\) is very small, all the layers resonate independent of each other. As \(A_{12}\) increases, the layers get coupled and the field value of all the other modes except the first one goes down. This is similar to the case when five potential wells are brought together; the levels will be fivefold degenerate in the case of negligible coupling. The degeneracy is removed when the interaction between the wells is significant.

A comparison of this theoretical calculation with the experimental results (Fig. 2) brings out the following observations:

- Five resonance modes are observed only for the case of \(t_{Nb} = 45 \text{ Å}\) as predicted by the theory. For other Nb film thicknesses, lesser number of modes are observed. It is, however, likely that some of the modes have negligible intensity and thus are not observed in the experiment.

- The first field position is observed to increase with the decrease of Nb thickness in the experiment, while theoretical results predict this to be nearly constant.

- The observed field values are smaller than the theoretically estimated values. A similar discrepancy was also obtained in the case of magnetic/magnetic multilayers and in that case it was explained on the basis of diffusion between the layers.\(^{17}\)

- The field separation between the modes increases with increase of \(A_{12}\), which is in agreement with the experimental observation.

The last point stated above is obvious from Fig. 4, where the experimental values of \(H_1 - H_2\) have been plotted as function of \(t_{Nb}\). Here, \(H_n\) is the field for the \(n\)th mode for a particular Nb thickness and \(H_1\) is the field value for the first mode for the same thickness of Nb. A closer look at Fig. 4 shows the following features:

- The field separation between the first and the second “observed” mode is higher for the \(t_{Nb} = 135 \text{ Å}\) sample than for \(t_{Nb} = 45 \text{ Å}\). This is not expected, because a decrease in the thickness of the Nb layer increases the field difference between these modes (Fig. 3). A mode, therefore, should exist between the first two observed modes in the \(t_{Nb} = 135 \text{ Å}\) film, which is not seen due to negligible intensity.

- A large field separation exists between the first two “observed” modes in the \(t_{Nb} = 18 \text{ Å}\) film. This separation is almost twice that of the one observed in the next two modes of the same film. Looking at Fig. 3, one sees that the separation between the modes increases with the mode number. This means that two “unobserved” modes should exist between the first two observed modes in the \(t_{Nb} = 18 \text{ Å}\) film.

To illustrate the points mentioned above we have joined the mode positions in Fig. 4 by lines, each of which represent a mode number. The assignment of these mode numbers is vital for further calculation.

**B. Variation of \(A_{12}\)**

After realizing that the first and last observed modes in these films are the first and fifth modes in all the three multilayers, the value of \(A_{12}\) was varied until the field difference between the first and the fifth mode becomes equal to the experimentally observed one for a particular \(t_{Nb}\). For the \(t_{Nb} = 45 \text{ Å}\) sample, this value of \(A_{12}\) is found to be 0.14 erg/cm\(^2\), which is three orders of magnitude smaller than that observed in magnetic/magnetic layers.\(^{31}\) This is expected, be-
cause in this work the magnetic layers are getting coupled through nonmagnetic layers. Figure 5 shows the experimental data for the fields for all the five modes in the form of a bar chart. The theoretical values have also been shown in the same figure. The matching of the difference in field positions for other modes is noteworthy.

The values of \( A_{12} \) obtained for the three samples are 0.22, 0.14, and 0.08 erg/cm\(^2\) for \( t_{\text{Nb}} = 18, 45, \) and 135 Å, respectively. It would be interesting to compare these \( A_{12} \) values with those obtained by other workers, even though they have used different models. Zhang et al.\(^{32,33} \) have used the concept of an effective anisotropy field to explain FMR for Co/Pt multilayers. The effective anisotropy field, used by them, included contributions both from bulk crystalline anisotropy and the interfacial anisotropy directly in the effective anisotropy field of the individual layer. They assumed \( A_{12} \) to decay exponentially in the form \( A_{12} = A_{12}^0 \exp(-t/t_0) \), where \( A_{12}^0 \) and \( t_0 \) are constants and \( t \) is the thickness of the nonmagnetic layer. They obtained a value of \( A_{12}^0 \) as 70±5 erg/cm\(^2\) and \( t_0 \) as 7±1 Å for their data. If we calculate the \( A_{12} \) values, using \( A_{12}^0 \) and \( t_0 \), given above and the thickness values of our samples, we would get 5.3, 0.11, and 3×10\(^{-7}\) erg/cm\(^2\) for \( t_{\text{Nb}} \) of 18 Å, 45 Å, and 135 Å, respectively. Rojdestvenski et al.\(^{29} \) criticized the results of Zhang et al.\(^{32} \), even though they assumed the same phenomenological \( A_{12} \) variation. They recalculated the spectra obtained by Zhang et al.\(^{32} \) on the basis of a different model, which was based on transfer matrix formalism. This gave a value of \( A_{12}^0 \) as 20 erg/cm\(^2\) and \( t_0 \) as 3.7 Å. If we use these values for our thicknesses, we would get \( A_{12} \) to be 0.15, 1×10\(^{-4}\), and 3×10\(^{-15}\) erg/cm\(^2\) for \( t_{\text{Nb}} \) of 18 Å, 45 Å, and 135 Å, respectively. We thus see that even though the value of \( A_{12} \) in our samples falls rapidly with thickness, it maintains a large value even for \( t_{\text{Nb}} = 135 \) Å. Here, it must be pointed out that the exponential dependence of \( A_{12} \) in earlier work was found using the experimental data on multilayers, with nonmagnetic layer thickness less than 18 Å. It is, therefore, clear that for the larger thickness of nonmagnetic layer, this type of dependence would not be valid.

\[ t_{\text{Nb}} \]


C. Discussion

Two of the major discrepancies between experimental field values and the values calculated using the above formulation are:

1. The observed field values are lower than the theoretical one.
2. The first field position increases with the decrease of \( t_{\text{Nb}} \).

In an idealized multilayer structure, one cannot observe a mode at a higher field than the uniform precession in the magnetic layer. In the case of Co, this field is 20.78 kOe. The calculated field value for the first mode in our multilayers is very close to this value for all the samples. Even though the experimental field increases with decrease of \( t_{\text{Nb}} \), at no point does it exceed the value for uniform precession. The data of Zhang et al.\(^{32} \) on Co/Pt multilayers also show a similar behavior.

Acharya et al.\(^{17} \) attributed the discrepancies in the first mode field in magnetic/magnetic Fe/Ni multilayers to the mixing at the interface. Zhang et al.\(^{33} \) assumed an effective surface anisotropy field which increases with Pt layer thickness and shows an exponential dependence, in order to explain the increase of the first mode field with Pt layer thickness. Rojdestvenski et al.\(^{29} \) could explain the increase of the first mode field with Pt layer thickness by the use of transfer matrix formalism. However, as mentioned before, they had to use an abnormally low value of saturation magnetization of Co.

In our case, we make three modifications to our model. In the first modification, we introduce the interface anisotropy through the modified boundary condition (3). In the second modification we assume diffusion at the interface. Finally, we use the concept of an effective saturation magnetization to evaluate the FMR spectrum.

V. THE MODIFICATIONS TO THE MODEL

A. The effect of interfacial anisotropy

In the first modification to the model presented in Sec. IV, we assumed a multilayer structure without any interdiffusion and used Eqs. (3) as the boundary conditions in place of Eqs. (2). Initially \( K_s \) was fixed and \( A_{12} \) was varied. We found that unlike before, the field position of the first mode depends on \( A_{12} \). But, contrary to experimentally observed increase, it shows a decrease with \( A_{12} \). The only way to explain the first field position by using this modification was to assume an increase in the value of \( K_s \), with the increase of \( t_{\text{Nb}} \). Even after this it was not possible to explain the position of higher numbered modes. For example, we found that for large values of \( K_s \), the field difference between the first two modes becomes very small.

B. The effect of interdiffusion

Calculations were performed again by assuming that a small inter-diffusion has occurred between the Co and Nb layers. While we expect the magnetic properties to gradually change within this diffused layer, the diffused layer was re-
placed with a number of discrete layers for calculation. The magnetic properties were assumed to be constant within a layer but gradually varied between the layers. Figure 6 shows such a structure where the diffused layer has been replaced by three layers. As can be seen in the figure, even though the number of interfaces, where boundary conditions are to be applied have increased, the nonmagnetic layer exists only between the last pair of diffused layer (marked as $A_{12}$ in the figure). We applied the usual Hoffman boundary condition at this interface only. All other interfaces, marked by discontinuous arrows, are between two magnetic layers and are, therefore, strongly coupled. For them, we used much larger values of interlayer exchange parameter, which were calculated from the average values of the exchange constants of adjacent layers.

Assuming diffusion of the type described above, we find that the field for the first mode decreases from the one obtained without the diffusion. This is similar to the observation made by Acharya et al.\textsuperscript{17} in the case of magnetic–magnetic multilayers. We initially tried to fit the ferromagnetic resonance spectra for $t_{\text{Nb}}=45$ Å as we see all the five modes in this sample. For fitting, $4\pi M_A$, the thickness of the diffused layers and $A_{12}$ were systematically varied until the best agreement was obtained between the calculated and the experimental fields. If the agreement was not satisfactory, the number of diffused layers was increased. We found that, unlike Acharya et al.,\textsuperscript{17} it was not possible to get a good agreement using a single interfacial layer. A reasonable fitting with experiment could be found only after we divided the diffused layer into five layers of thicknesses 10, 8, 3, 2, and 1 Å each. The values of $4\pi M$ for these layers were obtained to be 12 000, 6000, 3000, 1000, and 250 G, while the values for $A$ were obtained to be $1.6\times10^{-6}$, $1.0\times10^{-6}$, $0.8\times10^{-6}$, $0.5\times10^{-6}$, and $0.2\times10^{-6}$ erg/cm. This structure implies that 24 Å of each side of the Co layer has been affected by diffusion. This is rather large, but it becomes necessary to use this in order to obtain a reasonable fitting with the experimental data. Acharya et al.\textsuperscript{17} also obtain a similar thickness for diffused layer in the case of Fe/Ni multilayers.

The theoretically calculated field values obtained by this model and the experimental data are given in Table I. We note from this table that the fitting is excellent for all the modes except the last one. The value of $A_{12}$ obtained for the best fitting was 0.09 erg/cm$^2$, which is smaller than the value of 0.14 erg/cm$^2$ obtained in the earlier section. However, in the present case a good match of the absolute field positions was obtained and not just a match of their differences.

If Nb thickness is varied, ideally it should be possible for us to explain the ferromagnetic resonance spectra using a similar mixed layer structure but with a changed $A_{12}$. However, for such a case, the calculated field value for the first mode shifts again in the opposite direction to the experimental values. Hence, this model can explain the field position only if we assume that the structure of mixed layer changes as Nb thickness is changed. If we assume a different mixed layer structure for $t_{\text{Nb}}=135$ Å we find the $A_{12}$ value to be 0.05 erg/cm$^2$. Here the intermixing layer of Co had to be assumed to be 35 Å. This $A_{12}$ value is comparable with the value obtained from the difference of field value (0.085 erg/cm$^2$). A reasonably good fit of the experimental field values for all the modes was also obtained.

### C. Effective Saturation Magnetization Method

Calculations were also performed using the effective saturation method. In this method, different layers of Co were assumed to possess an effective saturation magnetization. This effective saturation magnetization is assumed to take care of all anisotropy fields including bulk and interface anisotropies. No inter-diffusion was assumed and the Hoffman boundary condition was applied at the interface. The values of the $4\pi M_{\text{eff}}$ and exchange constant $A$ were taken to be identical in all the three intermediate Co layers. The first and the last Co layers were assumed to have different values of $4\pi M_{\text{eff}}$ and $A$, because of different symmetries seen by these layers. Similar asymmetry was also considered by Zhang et al.\textsuperscript{32} to explain their FMR spectra. The basic structure of multilayer used in this calculation is shown in Fig. 7.

Calculations were performed by systematically varying $4\pi M_{\text{eff}}$ and $A$ of the layers keeping the basic model same as described above. The value of $A_{12}$ was also varied, until the best agreement with the experimental data is found. Table II shows the experimental and the fitted data based on this model. The values of effective saturation magnetization and

---

**TABLE I. Field and intensity values for $t_{\text{Nb}}=45$ Å in the diffusion model.**

<table>
<thead>
<tr>
<th>Field</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental (kOe)</td>
<td>Calculated kOe</td>
</tr>
<tr>
<td>19.99</td>
<td>20.01</td>
</tr>
<tr>
<td>19.94</td>
<td>19.93</td>
</tr>
<tr>
<td>19.87</td>
<td>19.87</td>
</tr>
<tr>
<td>19.79</td>
<td>19.80</td>
</tr>
<tr>
<td>19.66</td>
<td>19.74</td>
</tr>
</tbody>
</table>
the exchange constants found from the fitting are given in Table III. As can be seen from this table, agreement between the theory and the experiment is very good.

The values of $A_{12}$ obtained from the fitting are shown in Table II. The value of $A_{12}$ obtained for $t_{Nb}=5\,\text{Å}$ is 0.114 erg/cm$^2$. This value is smaller than the value obtained in Sec. IV B when we focused only on the difference of first and fifth mode ($\sim 0.22$ erg/cm$^2$). The values of $A_{12}$ for other two samples are also smaller (0.05 erg/cm$^2$ for $t_{Nb}=45\,\text{Å}$ and 0.04 erg/cm$^2$ for $t_{Nb}=135\,\text{Å}$) than the one which was obtained from the difference of first and last field (0.14 and 0.085 erg/cm$^2$, respectively, for $t_{Nb}=45\,\text{Å}$ and $t_{Nb}=135\,\text{Å}$).

VI. INTENSITY OF MODES

The intensities of different modes are given by the following equation:

$$I = \frac{(\int_{0}^{1} m \, dz)^2}{\int_{0}^{1} m^2 \, dz}.$$  \hfill (4)

In the calculation carried out by us, in the ideal multilayer, we find only the intensity of the first mode to be nonzero. This is because of the symmetrical nature of the excitation of modes that makes the numerator of Eq. (4) equal to zero. This is similar to the case of a thin film without pinning, where only uniform precession mode is observed. When this symmetry is broken, the intensities of other modes become nonzero. For all the cases described in Sec. V, this symmetry is broken and the intensities of other modes become nonzero. In this section we shall discuss the intensity of modes for the case of interdiffusion model and the effective saturation magnetization model. It is for these two models that we get good fit with the experimental field positions.

In both cases the intensities of the modes were found to depend on the assumed multilayer structure and on the value of $A_{12}$. A small asymmetry created either in the form of difference in the magnetic properties of substrate and the air end of the film in diffusion model, or in the values of the parameters of the first and the last layer in case of effective saturation magnetization model, created a large impact on the intensities of the modes. It thus became difficult to fit the intensities directly. Moreover, it was found from the calculation that for both models the intensities varied systematically with $A_{12}$, most of the time decreasing with it. However, no

<table>
<thead>
<tr>
<th>Mode No.</th>
<th>Field (kOe)</th>
<th>Intensity (%)</th>
<th>Structure of multilayer</th>
<th>$t_{Nb}$ Å</th>
<th>$t_{Co}$ Å</th>
<th>$A_{12}$ erg/cm$^2$</th>
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</thead>
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<tr>
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<td>100</td>
<td>Si+(t_{Nb}/t_{Co})$^5$</td>
<td>18</td>
<td>210</td>
<td>0.114</td>
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<td>Si+(t_{Nb}/t_{Co})$^5$</td>
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<td>100</td>
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</table>

a) Field values which are not experimentally observed.
systematic variation of the experimental intensity values (Table II) as a function of $t_{\text{Nb}}$ is observed. As an example, the intensity of the second mode is zero both for $t_{\text{Nb}} = 18$ and 135 Å film but is quite high for $t_{\text{Nb}} = 45$ Å.

We found that in the case of diffusion model it was much more difficult to fit the experimental intensities and especially to make the intensity of the second mode zero for $t_{\text{Nb}} = 18$ and 135 Å films. Table I which also gives the calculated intensity of the modes for 45 Å film shows that the intensity of second mode is higher than the first one, contrary to the experimental observations. In the case of effective saturation magnetization model, on the other hand, adjusting the intensity of the second layer was easier. The intensities calculated on the basis of this model are shown in Table II. We can see from it that the agreement with the experimental values is not very satisfactory except for a few modes.

### VII. DISCUSSION

In the present work, the calculations were carried out using a model that took into consideration, the variation of $m$ inside the magnetic layers. However, if the multilayer is assumed to be ideal, it was not possible to explain the experimental spectra. Two of the problems, viz., the lower experimental field values and the variation of the first mode field with $t_{\text{Nb}}$ have been discussed in Sec. IV C. In addition to this, the intensity of all the modes except the first is found to be zero. Therefore, the observation of a multimode spectrum confirms that the multilayers are not ideal.

We incorporated three modifications in the basic structure of the multilayer. Each of these modifications reduced the absolute value of the calculated fields closer to the experimental values. They also lead to nonzero intensity for other modes. However, in order to explain the increase of the first mode field with the decrease of $t_{\text{Nb}}$, we had to choose parameters that are dependent on Nb thickness. This was also observed by earlier workers.32,33 Ideally, once a basic structure for a multilayer has been reached by fitting the data for one sample, it should be possible to fit the same for other samples just by changing $A_{12}$. There could be several reasons why this did not happen. If we had taken a combination of various modifications into the calculation, better results could have been expected. Unfortunately, this would introduce a large number of parameters, which are difficult to handle. The second possibility is that our assumption that the coupling can be represented by Hoffman type of boundary condition with an average value of $A_{12}$ is not fully valid when the thickness of the nonmagnetic layer is large.

Out of all the modifications used in the present work, the effective magnetization method gave the best results, especially for the intensity. In this model, no explicit mixing or interfacial anisotropy was used in the calculation. The changed values of effective magnetization were expected to take care of mixings and the surface and bulk anisotropies. We would like to mention that in a recent paper, Alvarado et al.35 mentioned that the interfacial anisotropy could be a deciding factor for multilayer with thick nonmagnetic spacer layers. Our calculation is probably not the best way to handle the situation but is the simplest one; and the agreement with the experiment shows that this is a good approximation.

From Table II it is clear that the fitting is excellent both for field position and the intensity for a sandwich type of multilayer structure, with only two Co layers. This shows that the effective magnetization model works very well if the structure is simple and the numbers of observed modes are small. Further, we notice from Table III that the values of $4\pi M_{\text{eff}}$ of different layers decrease as Nb thickness increases. This is consistent with the observation of increase in anisotropy with Pt thickness in Co/Pt multilayers.32,33

We found the $A_{12}$ value to be 0.114 erg/cm$^2$ for $t_{\text{Nb}} = 18$ Å, in the effective magnetization model. We obtained the same value of $A_{12}$ for 45 Å and 135 Å Nb thicknesses in this model. This shows that a strong coupling between the magnetic films persists even for large thicknesses of nonmagnetic layers. Such coupling could arise because of many reasons. Recently there has been a lot of work about the magnetic coupling between magnetic layers through a nonmagnetic spacer layer.1,2,16,37 Keaveny et al.38 have carried out a Mössbauer effect study on the interlayer coupling between Fe layers through spacer layers of noble metals. They obtained clear evidence of oscillatory coupling between these layers. They also found this coupling to extend to large thicknesses of spacer layer. It is, therefore, likely that the coupling in our samples is initially exchange dominated, which is taken over by some other form, for large Nb thicknesses. However, with limited experimental data, it is not possible for us to make any further comment on this aspect.

### CONCLUSION

A perpendicular FMR study on Co/Nb multilayers with a large thickness of magnetic layers was carried out. Multiple resonance spectra were observed for all the films. It was shown that the coupling between the magnetic layers is significant, even when the thickness of the nonmagnetic layer is as large as 135 Å. Calculations were carried out to explain the FMR spectra of these multilayers. It was found that the
separation between the modes could be understood even when we assume an ideal multilayer structure. However, in order to understand the absolute field positions and the intensities of the modes, it is necessary to depart from an ideal multilayer structure. We obtained best results by the use of effective magnetization model. This model gave an excellent fitting for the field and the intensity of the modes in the sandwich film. For other multilayers, the fitting with the experimental field positions was good. We could get a quantitative estimate of the coupling constant for all the multilayers as a function of Nb thickness.