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The ultrasonic behaviour of ferrimagnetic yttrium iron garnet (YIG) crystal under pressure

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Abstract

This paper describes the ultrasonic behaviour of an yttrium iron garnet (YIG) crystal as function of pressure and magnetic field at room temperature, and reveals that there is magnetic–acoustic interaction in YIG. Similar ultrasonic behaviour under pressure has been revealed by measurements of sound velocity and attenuation of yttrium aluminium garnet (YAG) and YIG. Obviously, this could be attributed to the same garnet crystal structure. However, the ultrasonic behaviour of ferrimagnetic YIG and non-magnetic YAG is different when an external magnetic field is applied.

1. Introduction

From previous measurements of sound velocity and attenuation in YAG and YIG (yttrium aluminium garnet and yttrium iron garnet), we found that the ultrasonic behaviour in YAG and YIG is similar [1, 2] whether under atmosphere or under pressure. This can be attributed to the fact that they have the same garnet crystal structure. However, as is known, YAG is a non-magnetic material and YIG is a ferrimagnetic material. While the Al^{3+} ion has no magnetic moment, the Fe^{3+} ion, which occupies in YIG the same sites occupied in YAG by Al^{3+} ions, has a non-zero magnetic moment. Owing to this difference, we are interested in their ultrasonic properties at different pressures with an applied external magnetic field. Some results on the magnetic effect have been reported [3–5].

2. Experiment

Ultrasonic waves of longitudinal mode and transverse mode were generated in the sample by 0° x-cut and 0° y-cut quartz transducers respectively. The fundamental frequency of the transducers was 10 MHz. They were bonded to the sample with honey. The velocity of sound and attenuation for longitudinal and transverse waves propagating along the [100] direction were measured under pressure without and with an external magnetic field. The experiments were carried out using a Matec Ultrasonic System.

A hydrostatic pressure of up to 1.5 GPa was generated in a piston-cylinder apparatus. The loading of the piston was provided by a 150 ton material testing machine. The pressure-transmitting medium was a 1:1 mixture of transformer oil and kerosene. The pressure was determined by a precalibrated manganin gauge having a zero pressure resistance of 95.5 Ω with an accuracy of 1%. The sound velocity was measured by the "pulse echo overlap" technique and the attenuation was recorded automatically by a Matec Attenuation Recorder 2470B. The relative accuracy of the delay time was 10^{-5}, the sensitivity of the delay time measurement was 0.5 ns and the sensitivity of the attenuation coefficient was 0.1 db. When the sound velocity and attenuation for longitudinal waves were measured under a magnetic field, the d.c. magnetic field was applied parallel to a [100] crystallographic direction, and sound propagated along the [100] crystallographic direction. The field strength was 1000 Oe for the longitudinal wave. After each pressure increment (of about 2.0×10^7 Pa), the sound velocity and attenuation were measured after allowing at least 5 min for the crystal and system to reach thermal equilibrium, monitored by a thermocouple. When the sound velocity and attenuation of transverse waves were measured, the d.c. magnetic field was applied perpendicular to a [100] crystallographic direction, and parallel to the wave polarization direction. The field strength was kept constant at 3000 Oe.

3. Results and discussion

We did not find any difference in the pressure dependences of the sound velocities and attenuations

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when an external magnetic field was applied or not applied [1, 2] in the non-magnetic YAG.

Instead, we found anomalous changes in sound velocity and attenuation (for both transverse and longitudinal waves) at high pressure in the ferrimagnetic YIG crystal when an external magnetic field was applied. The attenuation exhibited a pronounced peak and the sound velocity exhibited an obvious plateau at lower pressure than was the case with no magnetic field. The effect of an external magnetic field is to shift both the velocity plateau and attenuation peak to a lower pressure. The effect of the magnetic effect is more evident in longitudinal waves than in transverse waves. The experimental results for a YIG sample are shown in Figs. 1–4. There are two curves in each figure, one corresponds to no magnetic field and the other corresponds to a magnetic field applied.

As we have described [1, 2], when a magnetic field is not applied, non-magnetic YAG and ferrimagnetic garnet crystal have similar ultrasonic behaviour. This could be attributed to the same garnet crystal structure. However, when an external magnetic field is applied, the ultrasonic behaviours of ferrimagnetic YIG and non-magnetic YAG are different.

As we know, Fe^{3+} ions in YIG crystal can be magnetized in an external magnetic field, but Al^{3+} ions in YAG cannot be magnetized. This is a possible reason for the observed difference. In YIG, the magnetic field induces a change in domain motion and the ordering of Fe^{3+} in tetrahedral and octahedral sites, which may be the reason for the negative shift in velocity plateau and attenuation peak.

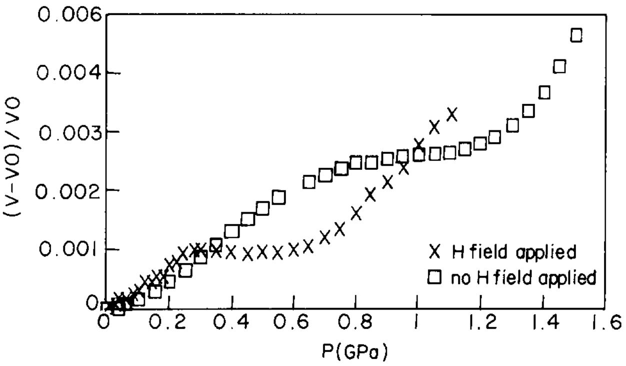

Fig. 1. Change in sound velocity with pressure for the shear wave of YIG.

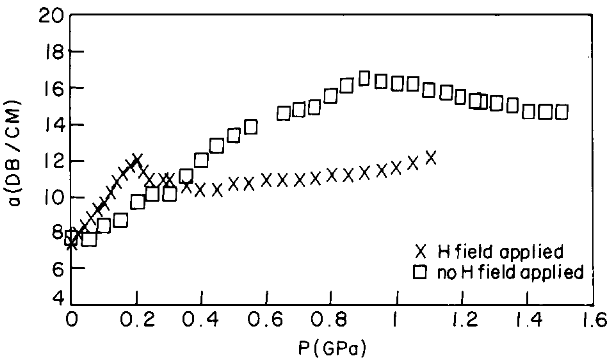

Fig. 2. Change in attenuation with pressure for the shear wave of YIG.

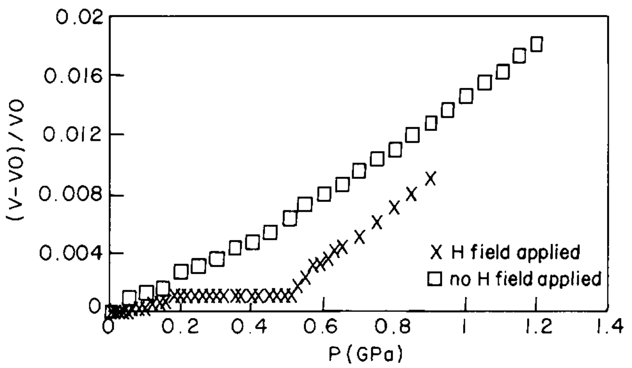

Fig. 3. Change in sound velocity with pressure for the longitudinal wave of YIG.

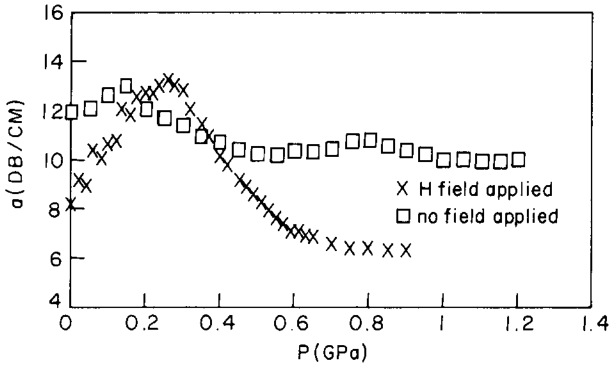

Fig. 4. Change in attenuation with pressure for the longitudinal wave of YIG.

When an external magnetic field is applied, the external stress can induce elastic strain or non-elastic effects. Two sources of such non-elastic strain are probably present. One is the stress induced domain motion (magnetostriction effect) and the other is the stress induced ordering of Fe^{3+} among the octahedral and tetrahedral sites [3]. Therefore, for an applied stress σ, the total strain ϵ is given by the following formula:

$$\epsilon = \epsilon_{\text{elastic}} + \epsilon_{\text{domain-motion}} + \epsilon_{\text{ordering}} = \epsilon_1 + \epsilon_2 + \epsilon_3 \qquad (1)$$

So the observed modulus

$$M = \sigma/\epsilon = \sigma/(\epsilon_1 + \epsilon_2 + \epsilon_3)$$

is less than the true elastic value. Generally, the moduli of crystalline solids will increase at high pressure, thus a plateau may appear with pressure. However, the relaxed motion of electrons between Fe^{3+} ions, induced by lattice deformation [4, 5] due to the alternating stress, may be the origin of the attenuation peak. This consideration is based on a model in which the action of the external stress reduces the elastic strain energy by the electron diffusion process.

The data are reproducible on cycling the pressure. It seems that the magnetic field forces the YIG crystal to become orthorhombic, changing the dimensions of the cubic lattice [4, 5].

In conclusion, in ferrimagnetic YIG the ultrasonic behaviour when an external magnetic field is applied differs from the case of no external magnetic field. We believe that these phenomena are caused by magnetic–acoustic interaction in YIG.

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