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Surface acoustic waves on thin films of giant magnetostrictive alloys

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Abstract

Thin films of giant magnetostrictive (Tb,Dy)Fe_2 alloys were prepared and the magnetostriction and the velocity of a surface acoustic wave (SAW) were measured. This velocity depends on the mechanical constants of the material which can be changed under the influence of an applied magnetic field. The large magnetostrictions of the (Tb,Dy)Fe_2 materials can therefore be used for magnetically tunable SAW devices such as delay lines, signal converters and filters. $Tb_xDy_{1-x}Fe_2$ films of different concentrations were sputtered on piezoelectric $LiNbO_3$ substrates equipped with SAW-exciting interdigital electrodes. The influences of film composition, film thickness and magnetic field on SAW velocity and magnetostriction were investigated.

1. Introduction

The binary and pseudobinary cubic Laves phases of some rare earth metals and iron such as $TbFe_2$ and $Tb_{0.3}Dy_{0.7}Fe_2$ show very high magnetostriction and very large changes of elasticity (Young's modulus) during magnetization [1, 2]. Thin films of such alloys are interesting materials usable for microactuators, vibration-damping purposes and in electronic devices. In the last case, a magnetically tunable surface acoustic wave (SAW) device is a possible application [3]. In such a device, an input electrical signal excites an SAW on a piezoelectric material. This wave propagates on the surface and is then converted back to an output electrical signal. The velocity of the wave depends on the mechanical constants and magnetomechanic interactions of the material. By covering the path of the wave with a magnetostrictive material, these mechanical properties, *i.e.* the velocity and the delay of the signal, can be changed by an external magnetic field. In this work, the magnetically induced velocity change of SAWs on $LiNbO_3$ substrates covered with magnetostrictive films with different compositions $Tb_xDy_{1-x}Fe_2$ was measured.

2. Experimental details

An SAW delay line was made by fabricating a pair of interdigital transducer electrodes on a substrate using a photolithographic lift-off process (Fig. 1). The substrate was an $LiNbO_3$ single crystal 0.5 mm thick, cut normal to the 127.8° *Y* axis. The propagation direction of the SAW was the *X* direction. The distance between two electrode fingers was 99 μm, to excite a signal of about 20 MHz frequency and a wavelength of 198 μm. The distance between the two electrode pairs was about 20 mm. In a second step, a film of magnetostrictive material with thicknesses up to 5 μm was deposited between the electrodes. The whole sample was then placed in the gap of an electromagnet, in magnetic fields up to 10 KOe. The velocity of the surface elastic

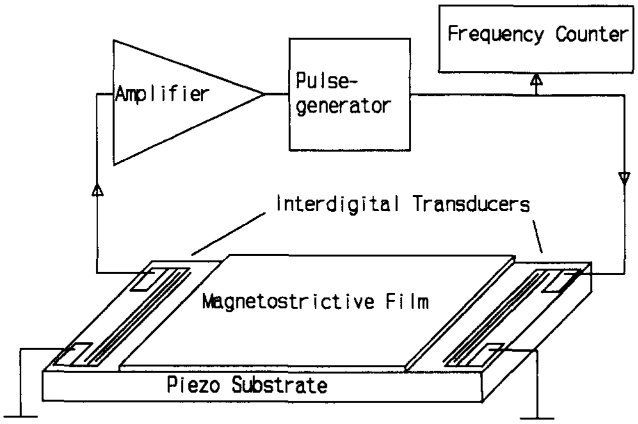

Fig. 1. Experimental arrangement to measure the change in SAW velocity.

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wave was measured by using the specimen as the frequency-determining part in a delay line oscillator (Fig. 1). An electric pulse excites a mechanical wave at the first transducer which propagates with the velocity of sound to the second transducer. The electrical signal there is amplified and triggers a new input pulse, so the whole circuit oscillates. Because delay times in the amplifier and pulse generator are small, the oscillation frequency depends only on the velocity of the SAW. From the frequency change of the oscillator in a changing magnetic field, the velocity change of this wave can be calculated. Also attenuation measurements were made for 20 MHz burst signals.

The preparation of the films was carried out by ion beam sputtering. This sputtering was performed in an ultrahigh vacuum apparatus equipped with a plasma filament argon ion source [4]. The sputter pressure was about 6.7×10^{-3} Pa; the deposition rate was about 1000 Å h^{-1}. Sintered and cast targets were used. Film composition was checked by Auger electron spectroscopy and inductively coupled plasma spectroscopy. Details are reported elsewhere [5].

The magnetostrictions of the films were determined in two different ways, firstly using an optical technique in which the magnetically induced bending of thin substrates covered with the film was measured and secondly by a strain gauge method. These methods are described elsewhere [6].

Magnetization curves were measured using a vibrating-sample magnetometer.

3. Results and discussion

Figure 2 shows the relative velocity change of an SAW on an $LiNbO_3$ substrate with a sputtered amorphous-like $Tb_{0.3}Dy_{0.7}Fe_2$ film 4.9 μm thick placed in three different configurations in the magnetic field. With the magnetic field parallel to the SAW, the maximum relative velocity change $(\Delta v/v)_{max}$ was about -0.14% at $H=1.8$ kG. The velocity change depends strongly on the film thickness. A thinner film of the same composition (0.6 μm) yielded a much smaller value of $(\Delta v/v)_{max}\approx-0.001\%$ at $H=1.5$ kG.

Figure 3 shows the relative velocity change of an SAW on an $LiNbO_3$ substrate with a 0.48 μm sputtered amorphous-like $Tb_{0.7}Dy_{0.3}Fe_2$ film placed in three different configurations in the magnetic field. With the magnetic field parallel to the SAW, the maximum relative velocity change $(\Delta v/v)_{max}$ was about -0.002% at $H=1.5$ kG and $+0.01\%$ at $H>6$ kG.

Figure 4 shows the relative velocity change of an SAW on an $LiNbO_3$ substrate with a sputtered amorphous-like $TbFe_2$ film 1.9 μm thick placed in three different configurations in the magnetic field. With the

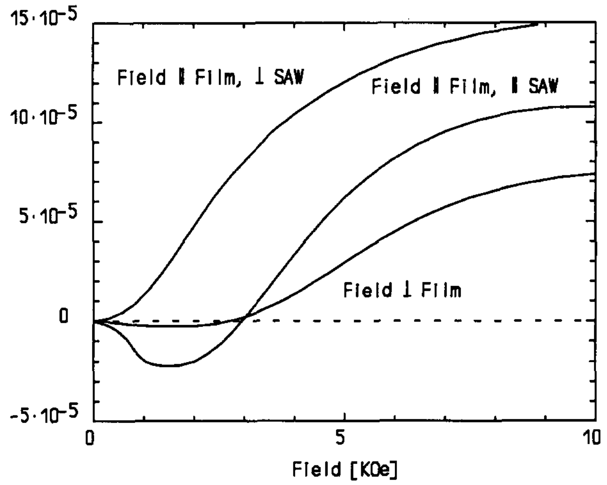

Fig. 3. Relative change in SAW velocity on a $Tb_{0.7}Dy_{0.3}Fe_2$ film 0.48 μm thick.

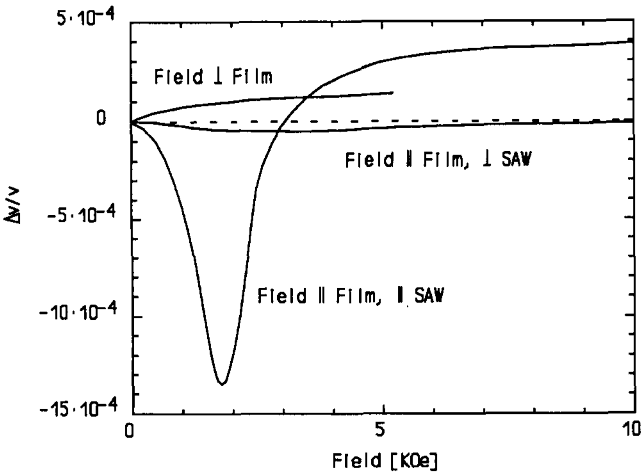

Fig. 2. Relative change in SAW velocity on a $Tb_{0.3}Dy_{0.7}Fe_2$ film 4.9 μm thick.

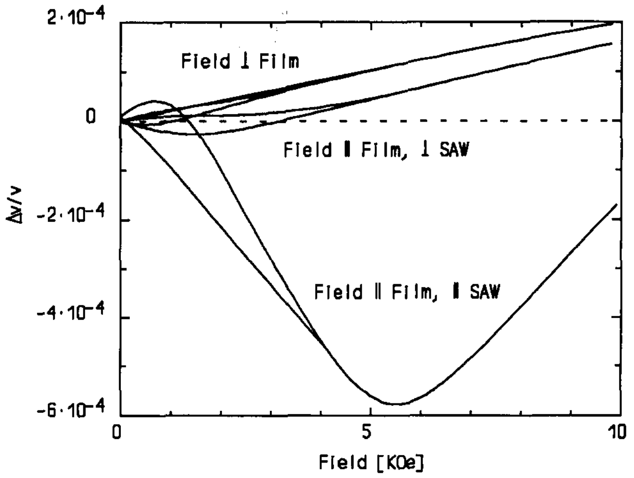

Fig. 4. Relative change in SAW velocity on a $TbFe_2$ film 1.9 μm thick.

magnetic field parallel to the SAW, the maximum relative velocity change $(\Delta v/v)_{\max}$ was about -0.06% at $H=5.5$ kG. A large hysteresis of about ±0.5 kG was found.

Figure 5 shows the magnetization curves of the three $Tb_xDy_{1-x}Fe_2$ films whose $\Delta v/v$ was shown in Fig. 2, Fig. 3 and Fig. 4 respectively, measured with a vibrating-sample magnetometer parallel to the film. The magnetization values are normalized by the saturation values at 15 kG. The $TbFe_2$ film shows a marked hysteresis. With increasing Dy content the hysteresis and the saturation field decrease.

Figure 6 shows the corresponding magnetostriction curves. The $TbFe_2$ film shows a marked hysteresis. The saturation magnetostriction decreases with increasing Dy content. A similar behaviour is known for bulk material where the anisotropy is minimized by adding Dy to $TbFe_2$ at a composition of $Tb_{0.3}Dy_{0.7}Fe_2$ at the expense of losing some degree of magnetostriction [1].

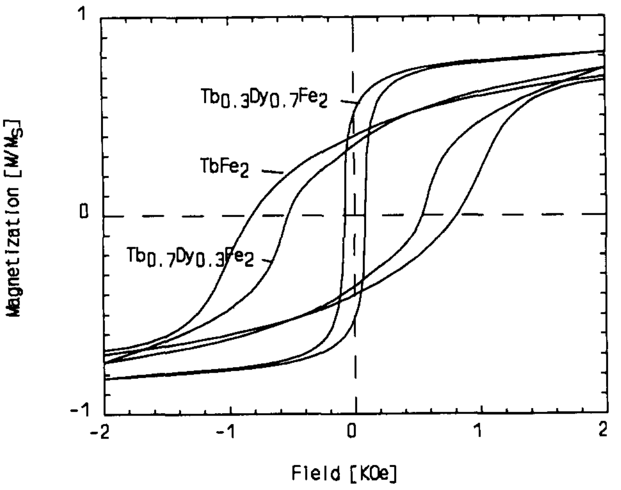

Fig. 5. Magnetization curves of different $Tb_xDy_{1-x}Fe_2$ films.

Figure 7 shows the attenuation coefficient α of a 20 MHz signal for different film thicknesses. α describes the attenuation in the film and is defined as $U/U_0=10^{-\alpha x}$, where U/U_0 is the ratio of output signals with and without film (for constant input signal) and x is the wave propagation length. Results for films of different Tb/Dy concentration ratios are plotted together. The attenuation increases steeply with increasing film thickness. This can be understood as an effect of eddy currents in the film, which dissipate energy. In the same figure the velocity of an SAW pulse for different film thicknesses is shown. The velocity decreases with increasing film thickness but is still much larger than expected values for the bulk material (1720 m s^{-1} for $Tb_{0.27}Dy_{0.73}Fe_{1.95}$ [7]).

Important technical parameters for tunable SAW devices are the maximum relative velocity change $(\Delta v/v)_{\max}$, the maximum dv/dH and the magnetic fields where these maxima occur, which should both be small. The relative velocity change $\Delta v/v$ of an SAW depends on both the magnetomechanical coupling factors and the ΔE effect in a not fully understood way. There is a qualitative similarity to longitudinal waves, where with a magnetic field parallel to the wavevector the relative velocity change is given as

$$\frac{\Delta v}{v}=\frac{1}{2}\left(\frac{\Delta E}{E_0}-k_{33}^2\right) \qquad (1)$$

where E is Young's modulus at zero field, ΔE is the change of E with magnetization and k_{33} is a magnetomechanical coupling factor [8]. This formula describes curves of similar shape to that in Fig. 2 for the field parallel to the film and parallel to the SAW. The fall in v at low fields is mainly due to the coupling, and the increase in v is due to the ΔE effect. Assuming analogous relations for SAWs, then for good tunability

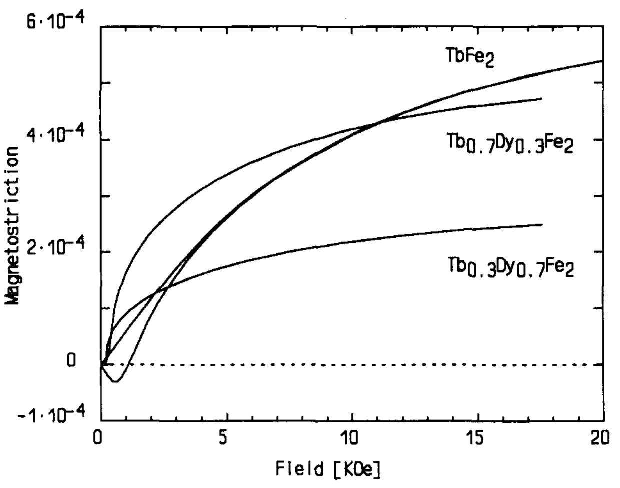

Fig. 6. Magnetostriction parallel to the magnetic field for different $Tb_xDy_{1-x}Fe_2$ films.

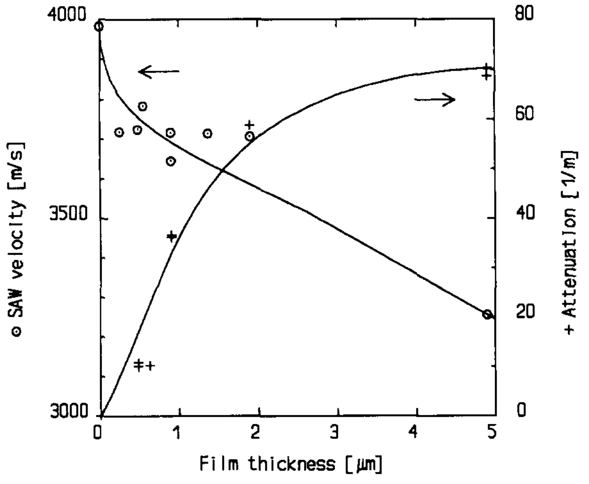

Fig. 7. Changes in SAW velocity (⊙) and attenuation coefficient α (+) for different film thicknesses.

it is important to have high couplings at low fields. Films with magnetostriction increasing steeply at low fields give high velocity changes.

These experiments were done at low frequencies. The wavelength of a 20 MHz SAW is about 200 μm, much larger than the film thickness. The depth of the wave is comparable with the wavelength, so the wave can be considered as a surface wave of a piezoelectric substrate, influenced by a magnetostrictive cover. This can also be seen by the still high velocity of the wave (Fig. 7). To enhance the velocity change, the film thickness can be increased, as can be seen in Figs. 2–4. However, more energy is then dissipated by eddy currents (Fig. 7) and the losses eventually become too large. To overcome these contradictory requirements, it may be necessary to construct a multilayer structure of magnetostrictive and isolating layers [9].

4. Conclusions

$Tb_{0.3}Dy_{0.7}Fe_2$ thin films on an $LiNbO_3$ substrate change the velocity of a 20 MHz SAW by up to about -0.14%. The field H_{max} for maximum velocity change is about 2 kOe. $Tb_{0.7}Dy_{0.3}Fe_2$ films display $H_{max} \approx 2$ kOe, $TbFe_2$ films have $H_{max} \approx 6$ kOe. The obtainable velocity change depends strongly on the thickness of the film. Lowering the magnetic anisotropy of $Tb_x Dy_{1-x}Fe_2$ films shifts the region of strong velocity change to lower magnetic fields.

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