

# **New Magnetoelastic Device With Circumferential Anisotropy for Sensing Applications**

## **Research Team**

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## **Introduction**

In this paper a new magnetostrictive delay line set-up for sensor applications is proposed. The tri-layer set-up consists of an inner cylindrical copper core, an intermediate thin insulating layer and an outer circumferential magnetoelastic thin film. Packaging reasons require a coating-insulating layer on top the set-up. Different Fe-Ni compositions have been tried for the magnetostrictive film. Characterization of the devices showed that negative magnetostrictive films operated as a magnetostrictive delay line set-up, even without magnetic and heat treatment. Concerning positive magnetostrictive films, heat treatment was necessary to allow the propagation and detection of elastic pulses.

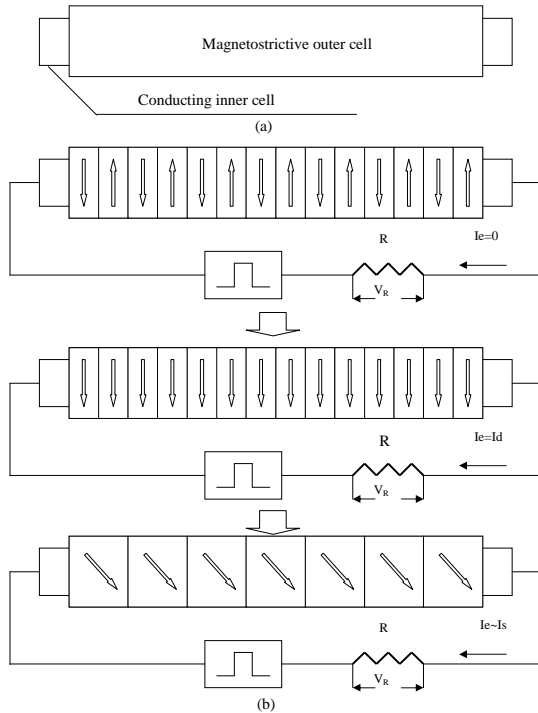
Magnetoelastic devices have been used for many sensing applications [1]. Among them, the magnetostrictive delay line (MDL) technique has also been used for the realization of sensing elements, like position and stress sensors, load-cells, pressure gauges, field sensors, non destructive testing etc. An increasing interest towards the realization of more sophisticated sensors based on this technique also exists, able to measure mechanical quantities with competitive levels of uncertainty [2]. Having as motivation the above mentioned targets, a magnetoelastic device has been conceived, which is able to operate as MDL.

## **The magnetoelastic device**

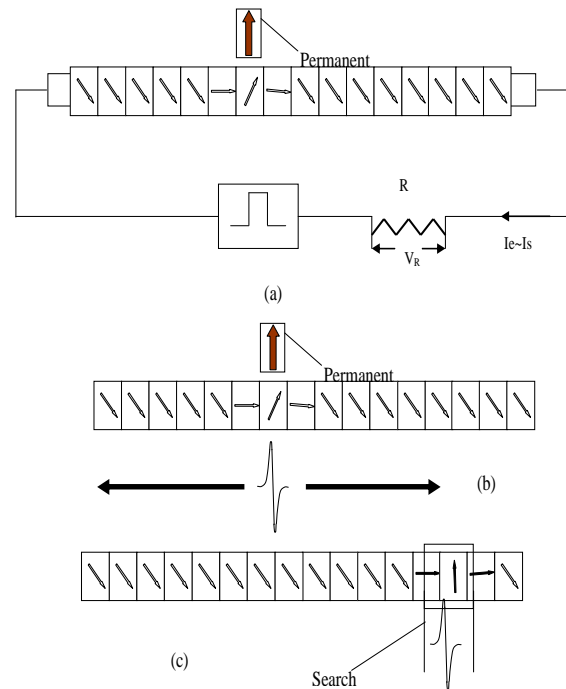
The schematic of the magnetoelastic element is illustrated in Figure 1. A cylindrical conductor is used as the substrate of an insulating layer, on which a cylindrical magnetostrictive film is deposited as shown in Figure 1(a). Passing pulsed current through the inner conducting wire results in transmitting pulsed circumferential magnetic field at the outer magnetoelastic film. Such field results in local micro-elongation or stresses due to the magnetostriction effect which, more or less, cancel each other due to the magnetoelastic uniformity of the outer film as shown in Figure 1(b).

Local break of the magnetic symmetry results in a local break of the symmetry of the dynamic micro-strains, as depicted in Figure 2(a), thus generating an elastic pulse, which propagates along the length of the film, provided that such a propagation can take place (Fig. 2(b)). The propagating pulse can be received by means of a pulsed voltage output induced at a search coil at the one end of the device, due to the inverse

magnetostriction effect (Fig. 2(c)). The time position of this pulsed voltage indicates the position of the magnet and its amplitude indicates the amplitude of the local magnetic field non-symmetry. This effect can be caused by a small permanent magnet travelling along the length of the device or by a local magnetic field anomaly. Therefore, it can be seen that such a device can be used as either position/displacement sensor or distribution NDT sensor on magnetic surfaces.



**Figure 1.** The MDL device.



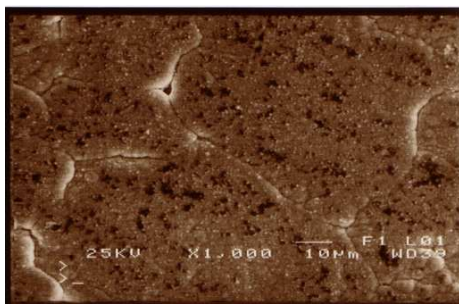
**Figure 2.** Operation of the MDL.

The realization of such a device took place in the following three steps. The first step was the development of the insulating interface layer between conductor and magnetoelastic film. Although at the beginning this has been obtained by using a 0.1 mm copper wire thermally oxidised at  $\sim 550$  °C for 10 minutes, thus resulting in a relatively thin oxide layer, with acceptable geometrical characteristics, for repeatability and automatic production purposes, a magnetron sputtering device was used to deposit  $\text{SiO}_2$  film on the same 0.1 mm copper wire. Measurements of this oxide film thickness using cross section metallographic microscopy, resulted in a thickness of  $1 \mu\text{m} \pm 10 \text{ nm}$ , which is considered as acceptable.

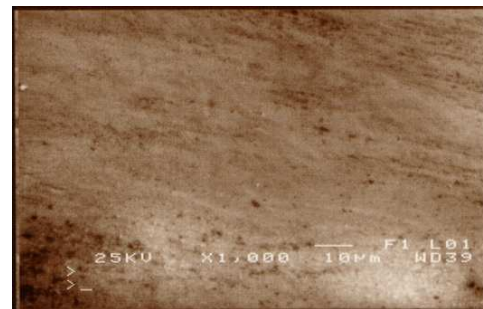
Next step was the deposition of the magnetostrictive circumferential thin film, using the same magnetron sputtering facility. Our reported first experiments were realised by depositing Fe-Ni alloys. The geometrical uniformity of the cross section of the films was also determined by cross section metallographic microscopy and was found to be  $1 \mu\text{m} \pm 20 \text{ nm}$ . XRD structural characterization on the powder of the deposited magnetostrictive film indicated amorphous state. In parallel, elementary magnetoelastic measurements were performed in parallel with structural characterization using SEM in order to determine the optimum conditions of films. It was found that the most

significant structural problem was the generation of cracks on the magnetoelastic film. In cases that films suffered from such surface cracks like the ones illustrated in Figure 3, it was impossible to develop films on which elastic pulses could propagate with acceptable repeatability and output gain. The best results (films without defects having some magnetoelastic response) have been found for films of thickness lower than 2  $\mu\text{m}$ .

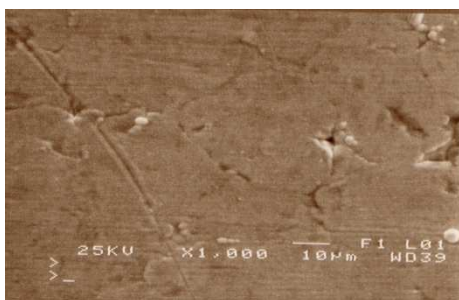
The third and final manufacturing procedure was the coating of the magnetic films with a protecting-insulating layer for packaging purposes. Trials for such deposition were realized by depositing  $\text{SiO}_2$  film. In such a development, a significant problem was the appearance of “point” defects (as illustrated in Figure 4), which introduced stresses on the surface of the film. The absence of such defects was realized by controlling the coating deposition parameters, the key one being the initial vacuum conditions before the coating deposition. Finally, the best procedure of coating deposition was if it took place just after the magnetic film deposition. Bearing in mind that a heat treatment is necessary to minimize coating-magnetic film interface stresses in order to obtain acceptable elastic wave propagation and detection, the final device was heat treated in  $\sim 450^\circ\text{C}$  for 10 minutes. Problems of overheating, like the ones observed in Figure 5, could cause increase of such interface stresses. A nice coated film offering good magnetoelastic behavior and shape induced anisotropy is illustrated in Figure 6.



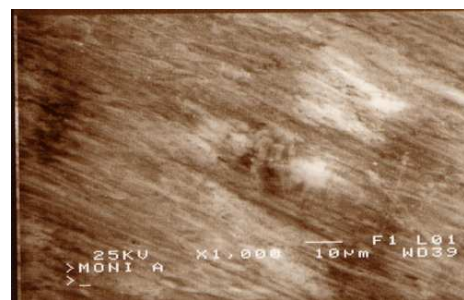
**Figure 3.** Micrograph of a layer with cracks



**Figure 4.** Micrograph of unsuccessful coating



**Figure 5.** Micrograph of unsuccessful thermal treatment after coating.



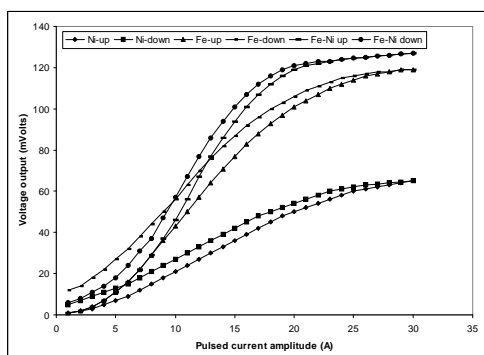
**Figure 6.** Micrograph of a film, after successful treatment.

### **Magnetoelastic response and discussion**

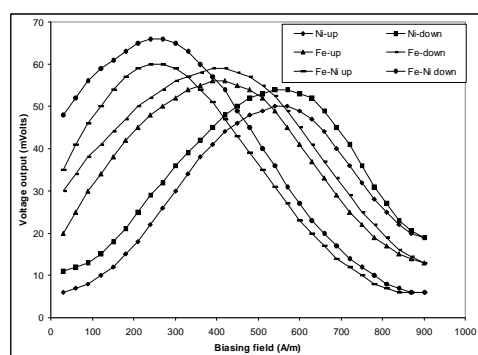
Magnetoelastic measurements obtained as illustrated in [3], using the standard MDL characterization set-up. Magnetoelastic measurements were realized after setting a small Nd-Fe-B permanent magnet at the middle of the films in order to allow an elastic pulse to be generated. Most of the as-cast uncoated and coated films demonstrated poor

magnetoelastic measurements. In fact positive magnetostrictive compositions illustrated MDL behavior in the case of uncoated films, while coated negative magnetostrictive elements illustrated magnetoelastic response even without treatment. These properties were much improved by using heat treatment at 300 °C for 1 hr and consequent magnetic annealing at 300 °C for 1 min and simultaneously passing 15 A pulsed current with 1% duty cycle and 1 ms period, through the inner copper wire [4]. Indicative results will be shown, for positive and negative magnetostrictive elements.

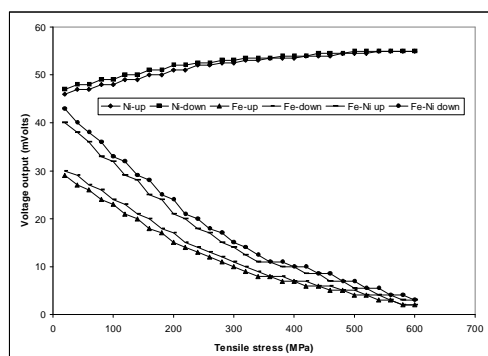
The MDL voltage output dependence on the pulsed excitation field is illustrated in Figure 7, concerning uncoated Fe, Ni and Fe<sub>50</sub>Ni<sub>50</sub> films. It can be seen that the positive magnetostrictive films have a better response, although in all films a hysteretic behavior is observed. Similar response can be observed in Figure 8, which illustrates the biasing field dependence of the same films. The tensile stress dependence of these uncoated films can be seen in Figure 9. The difference in positive and negative magnetostrictive films is clear.



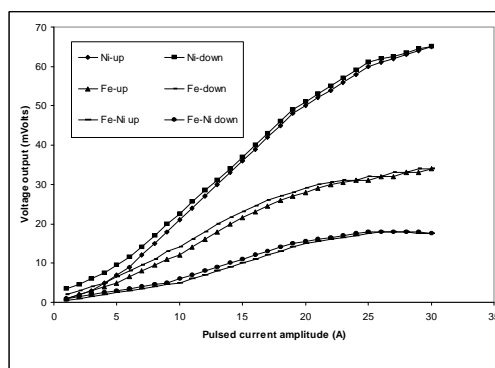
**Figure 7.** MDL response dependence on pulsed excitation field in uncoated films.



**Figure 8.** MDL field dependence on biasing field in uncoated films



**Figure 9.** MDL stress dependence on tensile stress in uncoated films

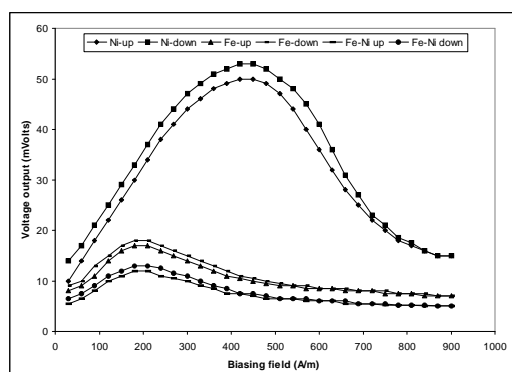


**Figure 10.** MDL dependence on applied excitation field concerning coated films.

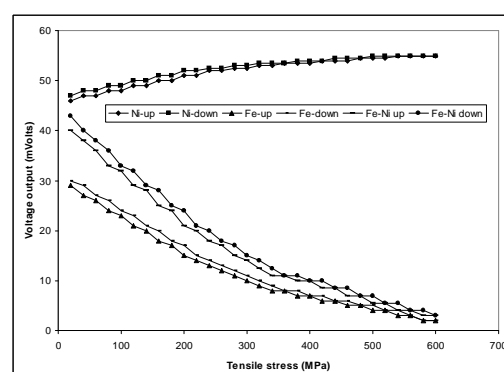
The response of the same magnetoelastic films after coating changes significantly. Some films, those with negative magnetostrictive behavior, as above mentioned, operated even without heat and magnetic annealing. This is attributed to the different dependence of the positive and negative magnetostrictive elements to tensile stress. Positive magnetostrictive elements, tends to orient their magnetic moments towards the applied

stress, while the opposite happens for the case of the negative magnetostrictive elements. The coating insulating layer of SiO<sub>2</sub> applies a tensile stress on these films. Therefore, the elastic signal in the case of positive magnetostrictive films becomes smaller, while the opposite occurs for the case of negative magnetostrictive films. Of course heat annealing and consequent magnetic annealing helps in different ways these two kinds of magnetostrictive films. For the case of positive of denature magnetostrictive films it removes the interface stresses and additionally re-orientates the magnetic structure, increasing the magneto-mechanical coupling factor, while for the case of negative magnetostrictive films in affects only the magnetic structure.

The MDL voltage output dependence on the pulsed excitation field of coated Fe, Ni and Fe<sub>50</sub>Ni<sub>50</sub> films is illustrated in Figure 10. It can be seen that the negative magnetostrictive films have now a better response, although in all films a hysteretic behavior is still observed. The biasing field response of Figure 11 is in accordance with the results of Figure 10. The tensile stress dependence of the coated films can be seen in Figure 12. It is clear that negative films are advantageous with respect to the positive ones.



**Figure 11.** MDL field dependence of coated films

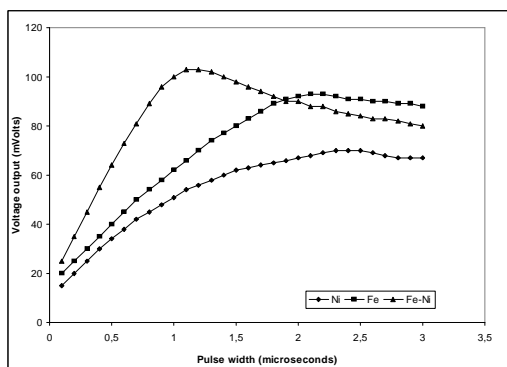


**Figure 12.** MDL stress dependence of coated films

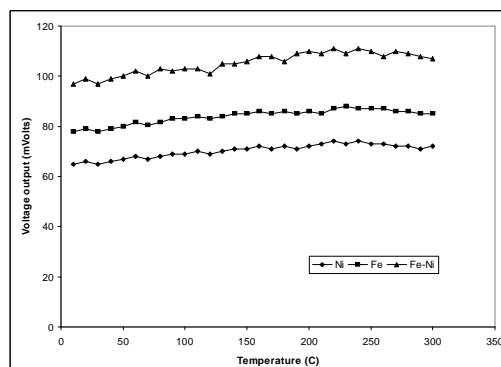
Parametric control of the other MDL properties has also been performed. Figure 13 illustrates the MDL voltage output dependence on the pulsed excitation current width, indicating the optimum required frequency bandwidth for each type of film. Temperature dependence of MDLs is given in Figure 14, demonstrating remarkable stability for this device up to 300°C. Finally, MDL resolution was measured following the definitions and procedures given in [5], illustrating a not significant difference for all tested samples.

Bearing in mind to solve the problem of the hysteretic behavior of this device, the Barkhausen noise of these elements was analyzed. It is believed that Barkhausen jumps are responsible for the most important part of the hysteretic behavior of these films. Such a magnetic noise could be decreased if the size of the magnetic domains or grains decreases, keeping in mind that this is desirable for the case of negative magnetostrictive elements. Therefore, following the same manufacturing procedure, we have developed Co<sub>70</sub>Fe<sub>5</sub>Nb<sub>2</sub>Si<sub>8</sub>B<sub>15</sub>, which can be nanocrystalline after heat treatment, keeping some magnetoelastic properties. After coating it with SiO<sub>2</sub> insulating – protecting layer its magnetoelastic response was unhysteretic within the limits of our experimental set-up.

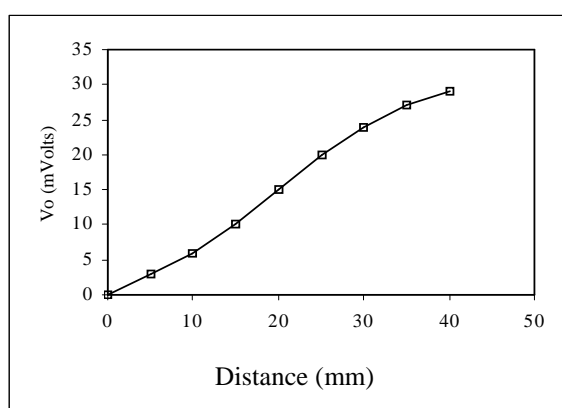
This result signifies the impact of the developed device in sensing elements based on it. The use of such a device as position and load sensor is illustrated in Figures 15 and 16 respectively. The device has also been tested in non destructive testing, being able of measuring cracks and defects in ferromagnetic substances up to 30  $\mu\text{m}$ .



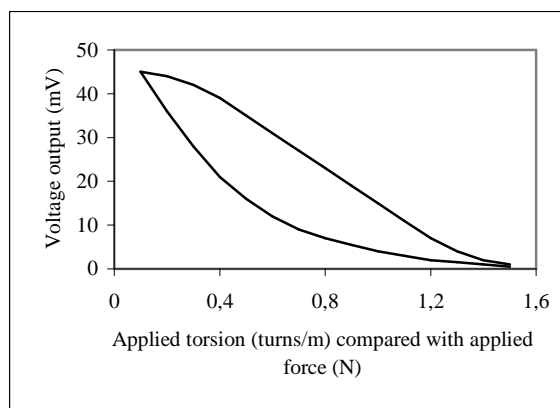
**Figure 13.** Frequency response of MDLs



**Figure 14.** Temperature response of MDLs



**Figure 15.** MDL set-up output dependence on the displacement of a NdFeB permanent magnet set orthogonal to the MDL axis.



**Figure 16.** MDL set-up dependence on torsion - tensile stress along the MDL, after magnetic orientation with AlNiCo magnet.

## References

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