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Flexible Magnetic Reading/Writing System: Characterization of a Read/Write Head

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Abstract

Intrinsically and locally stored information on components is one of keys technologies for the next industrial revolution. One possibility is an integration of a magnetic storage into a component. Magnetic recording technologies from hard disk drives is adapted and used to create a flexible magnetic reading/writing system that can store information on component surfaces. In this work, a characterization of the flexible read/write head is performed. A transfer characteristic of resistance change of an anisotropic magnetoresistance (AMR) read head is measured inside a homogeneous AC magnetic field. Inductive write tests are performed on a medium with a coercivity of 32kA/m. Generated data tracks are observed by means of a magneto-optic effect. The information gained from those experiments is necessary for gauging performance of the flexible read/write system.

Keywords: Flexible Substrate, magnetic recording, magnetic sensor

Introduction

Lately, product individualization and fast-paced product development are trends that manufacturers follow in order to distinguish themselves from competitor and to catch up with market dynamics. This in turn leads to increasing demand of individual product information obtained through its lifecycle [1]. Sensing and identifying such individual information during production and usage as well as storing and transferring obtained information are vital keys and also the active research in the Collaborative Research Centre (CRC) 653 “Gentelligents Components in Their Lifecycle”. In this context, a flexible read/write head for magnetic data storage on surfaces of components was developed and its characterization will be presented.

Generally, it is preferable to intrinsically and locally store information on components because it implies individuality and flexibility for information exchange. One solution is an integration of a hard magnetic material into a component and use the component surfaces as a magnetic storage, [2]. Magnetic recording technologies from hard disk drives can be adapted for data recoding [3]. However, a very small rigid write head is susceptible to mechanical shock and is strictly applicable in certain production environments. To overcome such limitation, a flexible read/write head was proposed. The development started from a flexible substrate suitable for thin film fabrication [4]. An anisotropic magnetic resistance (AMR) effect on the flexible substrate was studied in [5] and was used as a guideline for a design of a read head. Design criterions and techniques used for development of a write head can be found in [6]. In this work, a characterization of a flexible read/write head is performed.

Flexible read/write head

A flexible read/write head is shown in Fig. 1a. The head consists of a flexible magnetic core of a write head, an AMR read head, both fabricated on a polyimide substrate by means of thin film techniques, two head coils and a magnetic sheet served as a top core of a write head. The flexible magnetic core is inserted through the coils and folded over the magnetic top core to complete a magnetic circuit of a write head. An enlarged portion of Fig. 1a reveals trapezoidal poles at the bottom of the write head and a read head above these poles. The read head consists of an AMR sensor and electrical conductors. The AMR sensor is a NiFe layer fabricated using a physical vapor deposition (PVD) technique and has a form of a meander structure with 200 nm nominal thickness as depicted in Fig. 1b.

From the previous work done in [6], a prototype of a flexible write head can magnetize a storage medium with a coercivity H_c of 32 kA/m. The prototype head has 15 µm air gap and no pole cap. The new write head presented here, however, has 50 µm air gap in order to accommodate the AMR read head. However, this long air gap causes a higher magnetic reluctance which in turn leads to a reduced magnetic field strength in the gap. To compensate the high magnetic reluctance, a trapezoidal pole cap with 100 µm pole width is employed to concentrate a magnetic field in the air gap (Fig. 1c).

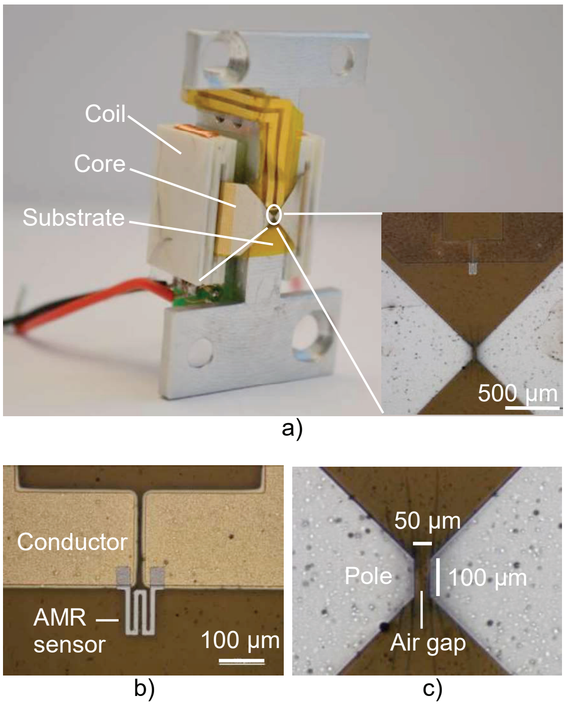

Fig. 1: a) a flexible read/write head, b) a read head d) trapezoidal poles and an air gap

Characterization

An impedance of a write head as well as its current waveform determines the maximum write speed and operating frequency. The write head generates a write field in an air gap according to data stream to be written. During writing, the write field magnetizes a storage medium underneath and by controlling head movements the length of a data bit can be defined. A simplified model of a write process is given in Fig. 2.

A size of a data bit on a medium directly affects a transition region between bits which in turn determines attainable data density. Generally, a shorter data bit length means higher data density. However, due to bit overlapping, too short data bit length causes too small or blurred transitions and hence negatively renders read back signals from a read head. To clarify the head characters above, an impedance measurement, transient measurement, and write test are done in a head characterization.

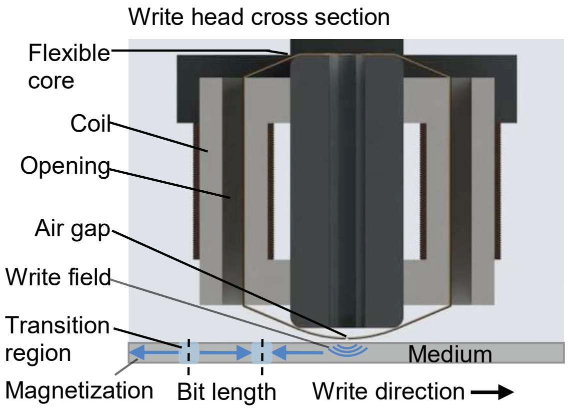

Fig. 2: a write head generates a write field which magnetizes a medium during a write process

An impedance of a flexible write head is measured using Fluke PM6306 RCL meter which can output up to 1 MHz test signal. Calibration of a test fixture is performed to minimized measurement errors before an impedance measurement. For a transient measurement, the head is connected to a push-pull driver with internal clamp diodes (L293D) and driven with pulse test signals. Transient signals from the head are observed using Tektronix TDS 2014 oscilloscope.

In a write test, a flexible read/write head is mounted on a rail system of a precision XYZ translation stage developed in-house. The configuration of the experimental system is depicted in Fig 3. The stage is equipped with stepper motors and can be driven in x- and z-direction with 4 µm step resolution.

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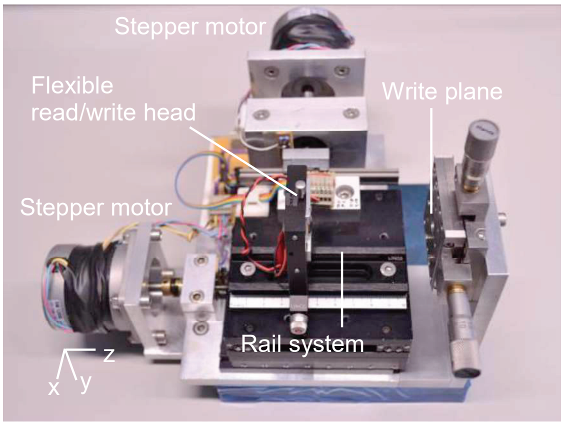


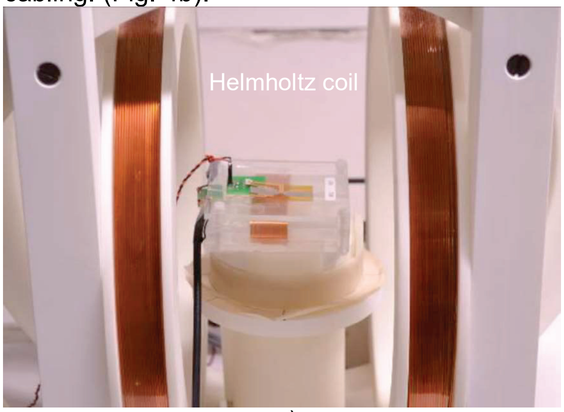
Fig. 3: a flexible read/write head mounted on a precision XYZ translation stage

An ICE I/type I cassette tape is selected as a storage medium in a write test. The medium coercivity H_c is 32 kA/m which is comparable to our target storage medium (20-32 kA/m). The tape is attached on a fixture and mounted on a write plane indicated in Fig. 3. Data tracks consist of a 101010… bit pattern is written in x-direction. During a write process, the flexible read/write head is positioned in a way that the head poles contact the medium at the write plane.

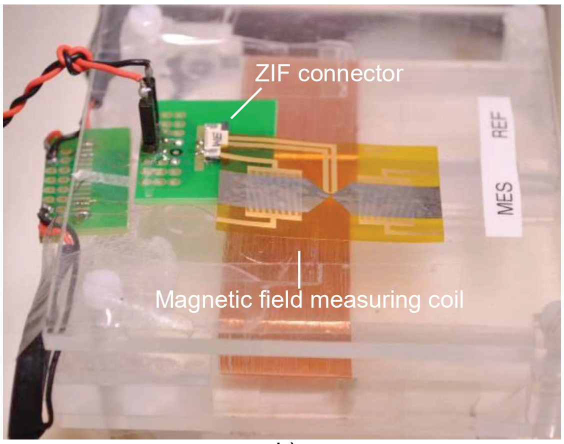
A typical performance gauge of an AMR read head is a transfer characteristic of resistance change. A resistance of an AMR element depends on an orientation between an electrical current path and magnetization of the element. In the simplest form, when an AMR element is subjected to an external magnetic field, there is a force that tries to rotate element magnetization in a direction of the external field, thus resulting in a resistance change.

In a transition region, a magnetic field from a medium changes its direction and strength. By moving an AMR read head pass this region and detecting a resistance change using a signal detection circuit, data stored in the medium can be read back. In order to design a signal detection circuit, important parameters, namely the maximum resistance change, a sensitivity range and deviations from a simple model of an AMR read head must be known. Those necessary parameters can be determined from the head response in a homogeneous magnetic field.

A response of an AMR read head is characterized inside a homogeneous AC magnetic field generated by a Helmholtz coil. The Helmholtz coils can generate a 50 Hz sinusoidal magnetic field up to 12 kA/m peak. A flexible read/write head and a magnetic field measuring coil are placed in the middle of the Helmholtz coil (Fig. 4a). Because the flexible read/write head has a large magnetic core, there is a force exerted on the head due to a magnetic field causing head vibration. Thus, the head must be firmly fixed in place. Conductors of an AMR read head are inserted into a ZIF connector and connected to a measuring bridge using a 2-wire twisted pair cabling. (Fig. 4b).



a)



b)

Fig. 4: a) a Helmholtz coil, b) a magnetic measuring coil and a flexible read/write head connected to a ZIP connector

An AMR sensor of a read head, modelled as a resistor, is at a measuring branch of a bridge circuit drawn in Fig. 5. A precision potentiometer is placed in the measuring branch for zeroing the bridge. A bridge signal is amplified by an instrumentation amplifier (AD620) and measured using Tektronix TDS 2014 oscilloscope. Measurements are performed at various peak magnetic field levels. The field is gradually increased from zero to a peak level and, after a measurement, gradually decreased to zero. This ensures a demagnetized state of an AMR sensor at the beginning and at the end of each measurement. For each measurement, a sensor, noise and a background signals are recorded.

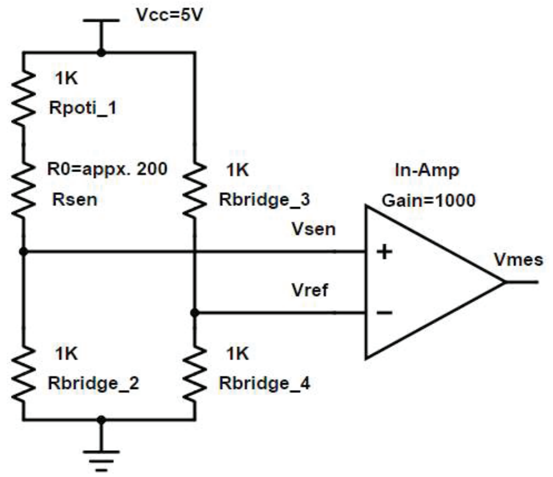


Fig. 5: *A bridge circuit for characterization of an AMR read head*

Results and discussion

Before an analysis of responses from an AMR read head can be done, a basic equation governing a behavior of an AMR element will be briefly discussed. Assume that an AMR element is uniformly magnetized and in a single domain state. When the AMR element is subjected to a magnetic field as depicted in Fig. 6, a resistance change of the AMR element can be expressed approximately as [9]:

The ratio of resistivity change $\Delta\rho$ to initial resistivity ρ_0 and H_k can be normalized for simplicity since only a form of a resistance change is relevant in this work. Resistance changes as a function of H_x and ε are calculated using Eq. 1 and plotted in Fig. 7. Shapes of those curves are important means to the analysis of the AMR read head.

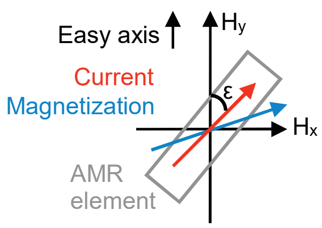


Fig. 6: *A simplified model of an AMR element in a homogeneous magnetic field*

$$\frac{\Delta R}{R_0} = \frac{\Delta\rho}{\rho_0}\left(\cos^2\varepsilon - \cos 2\varepsilon \frac{H_x^2}{\left(H_y + H_k\right)}\right)^2 + \sin 2\varepsilon \frac{H_x}{\left|H_x\right| + H_k}\sqrt{1 - \frac{H_x}{H_y + H_k}} \qquad (1)$$

H_k : *anisotropic field*

H_x : *magnetic field normal to an easy axis*

H_y : *magnetic field parallel to an easy axis*

ε : *angle between a current and an easy axis*

ρ : *resistivity of an AMR element*

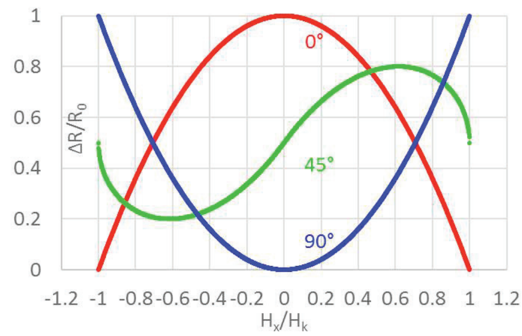


Fig. 7: *ΔR/R0 of an AMR element calculated using Eq. 2. as a function of ε and a magnetic file normal to an element easy axis (H_y=0)*

Recall from the previous section that the AMR read head was connected to the bridge circuit shown in Fig. 5. In order to obtain a real measurement signal V_{mes}, noise and background signals were removed from a measured head signal. Then, a resistance change ΔR of an AMR sensor was calculated using Eq. 2.

$$\Delta R = \frac{\mathrm{Gain}\cdot \mathrm{V_{cc}}\cdot \mathrm{R_{bridge}}}{\mathrm{V_{sen}} + \mathrm{Gain}\cdot \mathrm{V_{ref}})} - 2\cdot \mathrm{R_{bridge}} \qquad (2)$$

$$V_{sen} = V_{measure} - V_{noise} - V_{background}$$

$$R_{sen} = R_0 + \Delta R$$

$$R_0 + R_{poti} = R_{bridge}$$

In Fig. 8, a ratio of ΔR to an initial resistance ($R_0\,|_{H=0}$) is plotted as a function of an excitation magnetic field H. Closely examination of those responses revealed that the read head behaved in a low-field and in a high-field (>2.5kA/m) region distinctly. On one hand, in the low-field region, the responses resembled a resistance change of an AMR element with ε equal to 90°. On the other hand, in the high-field region, the responses could be estimated via a superposition of resistance changes with ε equal to 0°, 45° and 90°.

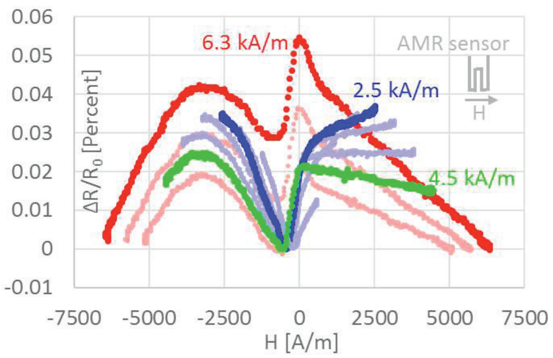


Fig. 8: $\Delta R/R_0$ of an AMR read head subjected to homogeneous AC magnetic fields

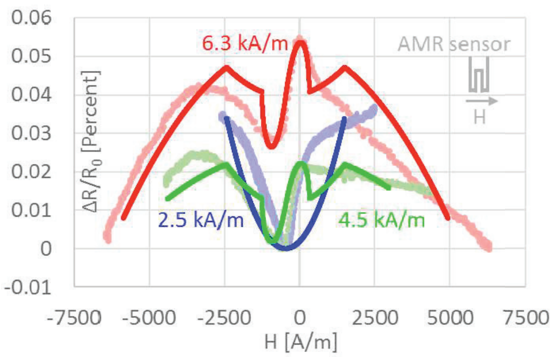


Fig. 9: An approximation of $\Delta R/R_0$ of an AMR read head using a superposition of AMR elements

By varying H_k and $\Delta\rho/\rho_0$ in Eq. 2, an approximation of $\Delta R/R_0$ of an AMR read head was done and illustrated in Fig. 9. Also, the corresponding parameters are given in Tab. 1. A cause of these head behaviors is domain pinning due to stress in the NiFe layer of the AMR sensor. As a result, an easy axis of the sensor does not lie parallel (as generally expected from an AMR sensor with a meander structure) but normal to the length of the sensor. This was confirmed with the head responses in the low-field region. If the H field is high enough, magnetization in pinned domains start to rotate. Hence, effects of magnetization rotation in pinned and unpinned domains sum up yielding head responses in the high-field region. The maximum $\Delta R/R0$ in the low-field and in the high-field regions are 0.035% and 0.06% respectively.

In spite of a complex behavior of a head and a low AMR effect, it is possible to implement a simple signal detection circuit for the data read back. In a transition region where a magnetic field H changes its direction, a fast rising/falling edge of $\Delta R/R_0$ occurs. An appropriate differentiator and comparators could be employed to generate a pulse representing the transition region.

Tab. 1: Estimated parameters of an AMR read head at various field levels

Parameter		H [kA/m]		
		2.5	4.5	6.3
H_k [kA/m]	0°	-	5.5	5.5
	45°	-	0.8	0.8
	90°	2.0	2.0	2.0
$\Delta\rho/\rho_0$ [%]	0°	-	0.03	0.035
	45°	-	0.03	0.04
	90°	0.03	0.012	0.012

The frequency response of a flexible write head is shown in Fig. 10. An impedance of the head can be modelled in a low frequency region (<0.1 MHz) as a series L-R_s equivalent circuit, since the impedance of the head is in a low-medium impedance range (<1 kΩ) [8]. The measured series resistance was 23.6 Ω. The inductance calculated from the frequency response was 700 µH. In a high frequency region above 0.1 MHz, an effect of a head parasitic parallel capacitance C_p between turns of coils and core loss modelled as parasitic parallel resistance R_p clearly appeared and could be seen from a decreasing phase. By curve fitting technique, a calculated C_p and R_p were 2 pF and 10 kΩ respectively. A corresponding self-resonance frequency (SRF) of the head was estimated to be at 4.25 MHz.

Transient responses of the flexible write head driven at various voltage levels is shown in Fig. 11. Rise times required for a current signal to change from 10 % to 90% and from 0% to 95% of its maximum value were 44 µs and 64 µs respectively. For comparison, a transient response was simulated using the head impedance and plotted in Fig. 11 as well. Note also that the calculated curve yielded a higher maximum current value. This is because parasitic resistance, e.g. contact resistance, and wire resistance, is not included in the simulation model.

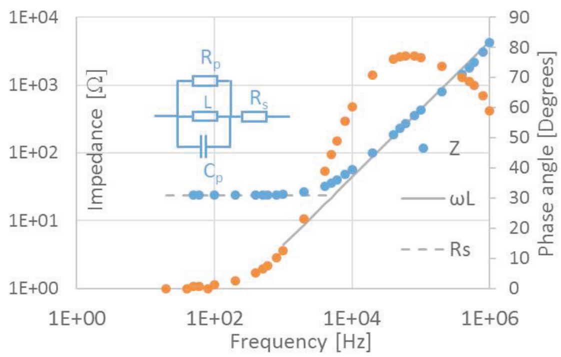


Fig. 10: Frequency response of a flexible write head

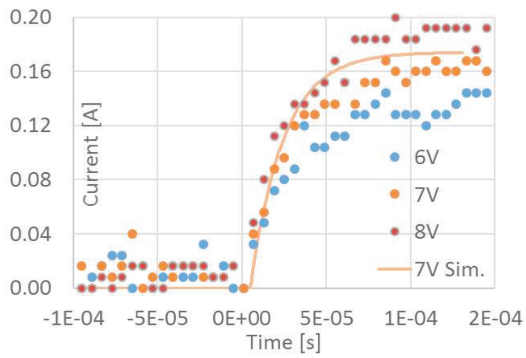


Fig. 11: Transient responses of a flexible write head

Comparing with typical metal-in-gap (MIG) heads employed in hard disk drive, the inductance of the flexible write head was 3 order of magnitude higher than those of MIG heads [7]. In spite of the fact that a high inductance limits a write speed to 22,000 flux changes per second, this is still very fast for our application. The maximum write speed is indeed limited by how fast the head can move over a storage medium. Table 2. lists parameters of the flexible head and a typical MIG head.

Tab. 2: Comparison of electrical parameters between MIG and flexible heads

Head	L [H]	R_s [Ω]	C_p [pF]	SRF [MHz]
Flex	0.7 m	23.6	2	4.25
MIG	1.6 µ	4.4	5	25.0

An image of data tracks written on a cassette tape was made visible by means of a magneto-optical Faraday effect and depicted in Fig. 12. Note that the image was created by merging many micrographs of the tracks along a write direction. Those micrographs were taken using a polarized light microscope, that is equipped with a magneto-optical sensor (bismuth-substituted yattrium iron garnet, Bi:YIG). A length of data bits in the top data track was fixed at 400 µm and used as a reference scale. Lengths of data bits in the bottom data track were varied in order to determine the minimum bit length. Black and white strips are transition regions between ‘0’ and ‘1’ bits. Down to a data bit length of 40 µm, the transition regions were distinct and clearly visible. A size of a transition region was measured 25 µm in length by 112 µm in width approximately. The transition length was half the air gap length (50µm). Note also that for a data bit length of 40 µm, the transition length is a little bit shorter, which means that data bits start to overlap each other. The transition width was slightly longer than the air gap width (100 µm), which is a result of a side-fringing field. This additional width, called a side track, was measured 6 µm. Considering a size of a read head, a 52 µm data bit size should be employed, thus yielding 18 kbit/cm^2 data density.

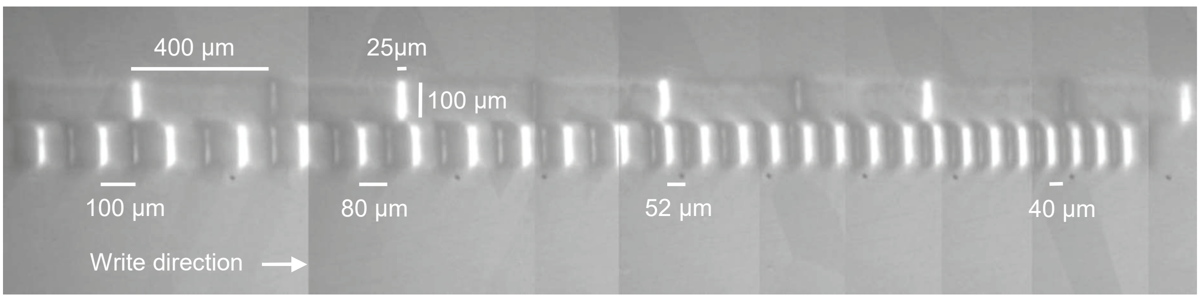


Fig. 12: an image of data tracks on an ICE I/type I cassette tape written using a flexible write head

Conclusion

Characterization of a flexible magnetic read/write head for a magnetic storage application on surfaces of components was presented in this work. The head consists of an AMR read head and an inductive write head with a trapezoidal pole caps. Due to stress in a NiFe layer of an AMR sensor of the read head, a resistance change $\Delta R/R_0$ of the read head is divided into two distinct regions, i.e. a low-field and a high-field region. In the low-field region, the read head behavior resembled a typical AMR element whose easy axis is normal to a current path. In the high-field region, the read head behavior was modelled as a superposition of AMR elements with different easy axis directions. The maximum $\Delta R/R0$ in the low-field and in the high-field regions are 0.035% and 0.06% respectively. An inductance and a series resistance of the inductive write head were measured. A parasitic capacitance and a parasitic resistance of the write head as well as its corresponding self-resonance frequency were calculated. Write tests on a storage medium with H_c of 32 kA/m were done successfully. The maximum write speed found from a transient response of the write head is 22000 flux changes per second. The appropriate data bit size was 52 µm yielding the maximum 18 kbit/cm^2 data density.

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References

[1] B. Denkena, T. Mörke, M. Krüger, J. Schmidt, H. Boujnah, H. J. Meyer, P. Gottwald, B. Spitschan, M. Winken: Development and first applications of gentelligent components over their lifecycle, *CIRP Journal of Manufacturing Science and Technology* 7, 139-150 (2014); doi: 10.1016/j.cirpj.2013.12.006

[2] C. Demminger, C. Klose, P. Taptimthong, H. J. Maier: Material-inherent data storage using magnetic magnesium-cobalt alloys, *Procedia Technology* 15, 188-197 (2014); doi:10.1016/j.protcy.2014.09.071

[3] A. Belski, M. C. Wurz, L. Rissing: Redesign and fabrication of a Magnetic Head for Gentelligent™ products, *Proc. of 11th euspen Inter. Conf.*, Como, Italy, (2011)

[4] P. Taptimthong, J. Rittinger, M. C. Wurz, L. Rissing: Flexible magnetic writing/reading system: polyimide film as flexible substrate, *Procedia Technology* 15, 230-237 (2014); doi:10.1016/j.protcy.2014.09.076

[5] J. Rittinger, P. Taptimthong, L. Jogschies, M. C. Wurz, L. Rissing: Impact of different polyimide-based substrates on the soft magnetic properties of NiFe thin films, *Proc. SPIE* 9517 (2015); doi: 10.1117/12.2178765

[6] P. Taptimthong, J. Rittinger, M. C. Wurz, L. Rissing: Flexibles magnetisches Lese-/Schreibsystem: Design eines Schreibkopfes, *Proc. MikroSystemTechnik Kongress* 2015, Karlsruhe, Germany, ISBN 978-3-8007-4100-7

[7] K. G. Ashar: Magnetic Disk Drive Technology, IEEE PRESS (1997); ISBN 0-7803-1083-7

[8] Agilent Technologies Inc.: Impedance Measurement Handbook, A guide to measurement technology and techniques 4th Edition (2013)

[9] S. Tumanski: Thin film magnetoresistive sensors, IOP Publishing Ltd (2001); ISBN 0-7503-0702-1