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Magnetic tunnel junction based eddy current testing probe for detection of surface defects

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In recent years, magnetoresistive sensors have been applied to a large spectrum of applications from biomedical devices to industrial devices. Their high sensitivity and high spatial resolution are of special interest for eddy current based non-destructive testing. In this particular application, giant magnetoresistive sensors have been recently used for detecting surface and buried defects. Nevertheless, although very promising, magnetic tunnel junctions (MTJs) are still barely used in this application. In this work, two sensors with 6 and 10 MTJs in series were successfully fabricated, characterized, and tested on an aluminum mock-up including defects 100 μm wide and with a depth ranging from 0.2 to 1 mm. The sensors including 6 MTJ in series showed sensitivities of 50.8 mV/mT, while the sensor with 10 MTJ in series showed a sensitivity of 84.5 mV/mT. Due to its high sensitivity the latter was able to detect the smallest defect with a signal to noise ratio of 50, which seems promising for more challenging applications. © 2014 AIP Publishing LLC.

In recent years, magnetoresistive (MR) sensors have been integrated and used in many applications from biomedical devices to industrial devices.4 In particular, in non-destructive eddy current testing of conducting materials, sensors based on the giant magnetoresistive (GMR) effect and magnetic tunnel junctions (MTJ) have been successfully used for the detection of buried and surface defects.2,3,5 When compared to inductive sensors, which remain the most used sensor in eddy current testing of conducting materials, sensors based on anisotropic magnetoresistive (AMR) and GMR sensors for detection of surface defects.4,5 At our knowledge the studies performed up to now only relied on anisotropic magnetoresistive (AMR) and GMR sensors for the detection of surface defect.

In this work, an eddy current probe based on MTJ sensors is presented. This probe takes advantage of the high sensitivities of these sensors.6 In the present device, a series of MTJs is used in order to increase the signal to noise ratio of the sensor.7 Furthermore, the probe was designed in order to maintain a pitch of 100 μm between sensors. This value is lower than the smallest induction arrays (1 mm pitch) and therefore, improved spatial resolution can be achieved in the detection of very small defects (<100 μm).

With these constrains in mind, two geometries of sensors are proposed and tested on an aluminum mock-up with defects down to 100 μm in width and 200 μm in depth.

The microfabrication of the chips with MTJ sensors first started with the deposition of a MgO-based MTJs stack at INL (SingulusTimaris tool) with the following stack: Ta 5/CuN 25/×6/Ta 5/Ru 5/IrMn 20/Co70Fe302/Ru 0.85/CoFe40B202.6/MgO 1.5/CoFe40B202/Ta 0.21/NiFe 4/Ru 0.20/IrMn6/Ru 2/Ta 5/Ru 10 (thicknesses in nm). The resistance-area product of the stack was 20kΩ μm2. The sensor’s linearity was achieved by an appropriate sequence of annealing steps to set the free layer perpendicularly to the pinned layer.6,8 Then, at INESC-MN, two different sensors configurations were patterned into arrays of 8 sensors with 100 μm pitch (Figure 1) by optical lithography and a two step ion beam milling was used to define the top and bottom contacts. The two sensors configuration consisted in: (i) sensor A: a series of 6 MTJs with 3.5 × 10 μm2 each; (ii) sensor B: a series of 10 MTJs with 3.5 × 10 μm2 each, disposed in two rows (Figure 2 inset). The sensors were then connected in series by depositing an Al98.5SiCu0.5 300 nm/TiWN2 15 nm using a sputtering tool (Nordiko 7000) and defining the contacts by lift-off. Finally, chips were diced and wirebonded on a printed circuit board (PCB) chip carrier containing a current line which was further used to create the magnetic field required for eddy current generation (Figure 1).

After the microfabrication and encapsulation, the tunneling magnetoresistance (TMR) and resistance at parallel
magnetic saturation of the sensors was measured. Both sensors showed TMR of \((155 \pm 6)\%\) and resistance at parallel saturation of \((3570 \pm 6180)\) \(\Omega\) and \((5445 \pm 270)\) \(\Omega\) for sensor A and sensor B, respectively. As observed in Figure 2, the sensors showed a linear response between \(+/- 3\) mT with a hysteresis of about 0.2 mT. Although the sensors exhibited hysteresis, upon their excitation with a high frequency (1 MHz) magnetic field, no signs of random telegraph noise were observed in the oscilloscope (data not shown).

The fabricated probe was then connected to a vertical support where different instruments could be connected (Figure 3). A heterodyning technique was used to isolate the magnetic signal from the electromagnetic induced current. This technique relied on biasing the sensor with an AC sinusoidal current at 999 kHz and excite the material with an AC sinusoidal field at 1 MHz. The MR sensors work as a multiplier and therefore, the signal at the difference of the frequencies \((1 kHz)\) will carry the variation of the sensed magnetic field. This signal is then measured by a lock-in amplifier (Signal Recovery 7265). A low pass filter \((10\ kHz\ bandwidth)\) was used to avoid the saturation of the lock-in input stage due to the signals at the field excitation and current bias frequencies. The current bias was adjusted with a potentiometer of 100 k\(\Omega\) and a signal generator (Agilent 33220 A) set at a frequency of 999 kHz. The 1 MHz excitation field was generated by a signal generator (Agilent 33220 A) connected to a dedicated current amplifier (whose transconductance gain is 1 A/V) to produce a 2 Amp current in the excitation current line (Figure 3).

An aluminum alloy (AA2024) mock-up (Olympus SRS-0824 A) including defects with a width of 100 \(\mu\)m, a depth \((d)\) of 0.2 mm, 0.5 mm, and 1 mm, and a length of 25 mm was used for testing the two sensors and compare their signals. The probe was moved perpendicularly to the length of the defect (Figure 3).

The two sensors under study were first characterized in terms of sensitivity. As depicted in Figure 4, sensor B
showed a larger sensitivity than sensor A for the same bias currents. This is due to the fact that sensor B has an accumulated effect in the sensitivity of 10 MTJs in series (10 times the sensitivity of each MTJ) while sensor A only have this accumulated effect for 6 MTJ.

In the experiments for detecting defects, an AC sinusoidal current of 180 $\mu$A is applied to both sensors so they could be compared. At this current (90 $\mu$A), sensor B showed a sensitivity of 84.5 mV/mT and sensor A showed a sensitivity of 50.8 mV/mT (Figure 4). From these data, it would be expected that sensor B would show better performance than sensor A since it has a sensitivity 1.67 times higher than sensor A. However, in eddy current non-destructive testing, the magnetic fields at the level of the sensing elements more apart from the material will be lower than the ones at the level of the sensing elements closer to the material. Therefore, in sensor B geometry, the MTJs in the second row may sense lower magnetic field modification than the ones in the first row. To test this assumption, two probes including sensor A and sensor B were tested on the mock-up with 3 defects.

The sensors were first put into close contact with the Aluminium 2024 surface in a place with no defects. Signals ranging between 300 and 400 $\mu$V$_{rms}$ were acquired in the lock-in amplifier. In theory, for a perfect conductor material and a sensor in perfect contact with the material, the absolute signal sensed should be zero. This is not the case here because (i) the Aluminium 2024 is not a perfect conductor and; (ii) there is always a separation between the sensor and the material to avoid damaging both material and sensor during the scanning. For the performed tests, the separation between sensor and material was estimated to be between 100 and 200 $\mu$m.

Furthermore, the mock-up and the probe may have a slight angular disalignment meaning that the separation may vary during the scanning. In Figure 5, this phenomenon can be observed. Outside the defect zone, the signal variation is closer to zero in the negative positions than in the positive positions. This means that there is a larger separation between the probe and the mock-up in the positive positions. Moreover, this signal variation is higher in the sensor B. This is due to the fact that this sensor has a higher sensitivity than Sensor A. Nevertheless, the signal variations due to the presence of the defects showed much higher signal variations than this small angular disalignment.

In fact, as observed in Figure 5, both sensors were able to detect the defects with very good signal to noise ratio (more than 25) and as expected, the signal variation increased with the depth of the defect. When comparing the amplitude of the peaks obtained for each defect, it was observed that the signal variation of sensor B is $1.64 \pm 0.05$ times higher than sensor A. This is the same factor that relates the sensitivities of both sensors. Therefore, it can be concluded that for these geometries of sensors and excitation line, the fact that sensor B had two rows of MTJs has negligible influence in the observed signal. Furthermore, due to its high sensitivity in mV/mT, sensor B is a better option for detecting smaller and more challenging defects.

Two sensors with 6 MTJs in series (sensor A) and 10 MTJs in series (sensor B) were successfully fabricated, mounted on a PCB to form an eddy current probe, characterized and tested on the detection of defects on an Aluminium mock-up. Although with the same magnetoresistance, sensor B showed sensitivities of 84.5 mV/mT, while sensor A showed a sensitivity of 50.8 mV/mT for the same 90 $\mu$A current bias. This difference was found to be an advantage for detecting superficial defects with a width of 100 $\mu$m and a depth of 200 $\mu$m achieving a large signal to noise ratio ($\sim 50$ for sensor B). The results obtained with sensor B improved geometry sustain future designs using eventually more rows of MTJs but still maintaining a small pitch between sensors to achieve higher signal variations due to defects. This new sensor geometry appears as a promising approach for the detection of more challenging defects (i.e., aluminum welding joints cracks and few micron superficial defects in Ti).

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