Thermal flash treatment in a controlled atmosphere under a magnetic field for magnetic tunnel junctions (MTJ)

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Abstract

A Magnetic Tunnel Junction (MTJ) consists of an ultra-thin insulator placed as tunnel barrier between two metallic ferromagnetic (FM) layers. Si(100) / Co(20nm) / MgO(2nm) / Co(5nm) / Cr(3nm) was the MTJ stack composition. Magnetic field cooling treatment was used in order to freeze the spin structure to a particularly ordered phase. This was obtained by increasing the temperature to 450°C, close to magnetic disorder, keeping a magnetic field during the cooling of the sample. A DPSS laser with output power of 20 W at 1064 nm system was employed while the magnetic field was applied through the polar expansion during the increase of the temperature.
The annealing was performed also employing a boron nitride radiating oven, heating the sample in an inert atmosphere (1mTorr of Ar). The laser treatment was applied in a load-lock, where sample was transferred by a translational manipulator.

Keywords: Magnetic Tunneling Junctions, Laser Rapid Thermal Annealing

1 Introduction and Experimental

1.1 Magnetic Tunneling Junctions

The typical structure of a MTJ device is composed by an inner hard ferromagnetic (FM) material and an outer soft FM separated by an insulating barrier, all in the form of thin films, deposited on an atomically flat substrate using different Phisical Vapour Deposition (PVD) techniques. Spin-dependent transport properties and tunnel magnetoresistance effect (TMR) in these heterostructures have enabled several technological applications that include magnetic field sensors (as read-head) [1] and magnetoresistive random access memories (MRAM) for data storage [2]: the change in relative orientation of FM layers' magnetisations induces variations in the electrical resistance due to the scattering of spin-polarised electrons tunnelling across the insulator barrier.
Several studies have been reported on the influence of a thermal annealing of these systems in order to improve the junction properties depending on the degree of order in the barrier lattice and the smoothing of the FM-to-insulator interfaces [3]. Generally these treatments include a heating step operated by a radiative oven up to temperatures around 350 °C for 15 minutes, to promote interfacial diffusion and reconstruction.
In this work an MTJ was prepared by RF magnetron sputtering with the following composition: Si(100)/ Co(20nm) / MgO(2nm) / Co(5nm) / Cr(3nm), in 10 mTorr of Ar in a vacuum chamber with a base pressure of ~10^{-8} Torr.

1.2 Laser induced flash thermal annealing

A new thermal treatment method has been performed to investigate the effects of a high heating rate annealing at high temperature on the magnetoresistive properties of our device. After the fabrication, the sample was transferred from the main vacuum chamber to a load lock chamber by a translational manipulator and heated in inert atmosphere (1 mTorr of Ar) shining a laser source through a deep UV silica glass viewing port. In order to freeze the magnetization of Co electrodes in the film plane and improve the device response, a uniform magnetic field (600 Oe), generated by an electromagnet was applied throughout the annealing process.
The laser processing system employed for the flash annealing treatment of MTJs is composed by a:

- Load lock chamber in which multilayered samples are loaded from the main process chamber (fig. 1-B and 1-A respectively)

- Microla Optoelectronics DPSS laser system

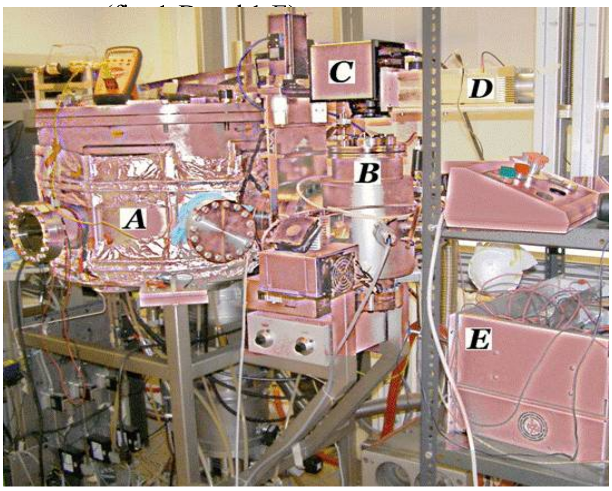
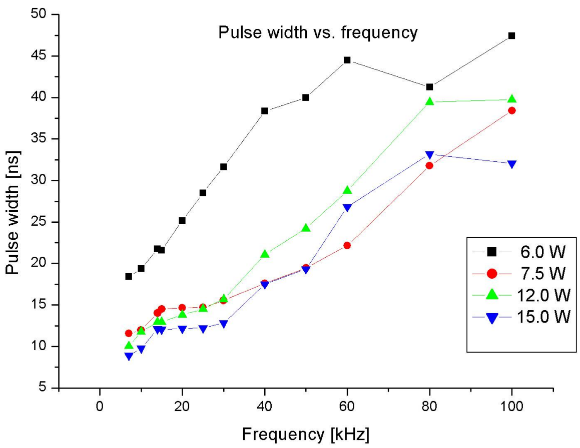


Figure 1: image of the laser annealing system setup.

A DPSS laser system made by Microla Optoelectronics (MLQ-20 series) was used. This DPSS laser system has an end-pump configuration. Pumping system gives a maximum pumping power of 45 W with a 808 nm wavelength. An optical fibre with a core of 600 µm transports the pumping signal into the resonator. The active medium is a Nd:YVO_4 crystal doped 0.3% Nd. It produces a laser beam with a wavelength of 1064 nm linear polarized. Its highest density of power is 1300 W/



cm^2. This laser can be used in q-switching mode with a 1-200 kHz range of frequency. The shortest pulse width is 8 ns (fig. 2).

Figure 2: characterization of MLQ-20 pulse width.

A galvanometric head was used to drive laser beam to the Si substrate. In order to focalize the laser beam on the Si substrate, a 254 mm focal θ-lens was used.
With the support of Zemax simulator (fig. 3), we simulated the laser beam dimension in different points of optical path. By using this tool we found a laser beam of 40,6 µm in the focus point (fig. 3).

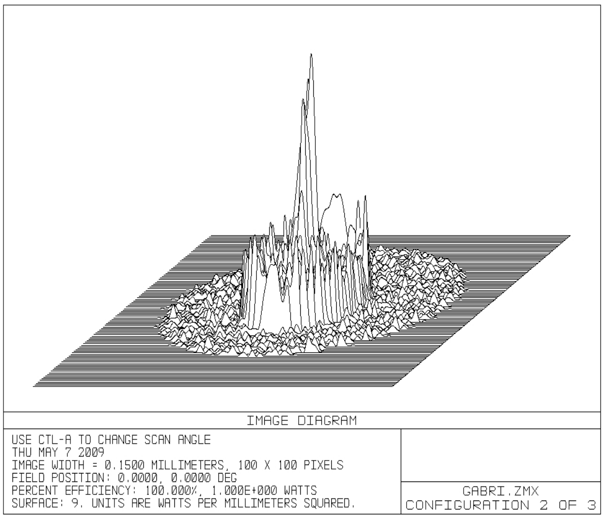


Figure 3: Zemax simulation of the laser beam in the focus point optical system with a 254 mm θ-lenses.

In this laser annealing process the following beam parameters were used:
- laser power: 15W
- laser speed (galvo head velocity): 20 cm/s
- working q-switch frequency: 10 kHz.

1.3 Temperature profile measurement

The annealing temperature profile (fig. 4) was monitored ex-situ, shining the laser beam on a self-fabricated laser-welded micro-thermocouple (N-type, maximum working temperature 1300 °C, wire diameter 600 µm), with a high sampling speed acquisition setup (mean response time 25 ms). The N-type (nisil – nicrosil alloy) has been chosen because of a higher thermal stability at high temperatures and because of the absence of the short range magnetic order transition that gives rise to electromotive force instabilities in other thermocouple types [4].

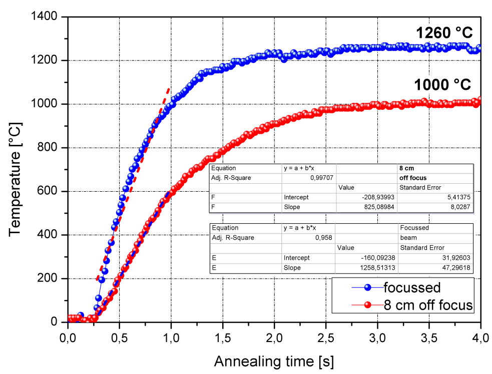


Figure 4: typical thermal heating profiles, related to 100 mm focal length, at the focal point (blue curve) and at 8 cm below the focal point (red curve). Indicated in

the figure frame are the linear fit parameters and the mean maximum temperature reached during the experiment.

The heating temperature profile was measured in different conditions, leading to a heating rate as high as 1050±50 °C/s for the focused beam and 825±10 °C/s for the off-focus beam (linear fit of fig. 4, computed in the time lapse represented by the interval [250 ms, 1000 ms]).

2 Results and Discussion

In order to compare the effects of the flash laser induced annealing treatment, also a conventional annealing has been done on a similar MTJ device, performed employing a boron nitride-coated graphite radiating oven at 350 °C for 15 minutes. In this case the magnetic field was applied exclusively during the cooling segment in Ar atmosphere (1 mTorr). A precise thermal control over the radiating oven is achieved with a PID controller equipped with a contact K-type thermocouple, directly placed on top of the boron nitride coating.
TMR measurements of both differently annealed MTJs are reported: these measurements basically consist in a resistance curve acquired at constant DC current injected into the device applying an external magnetic field, generated by means of an Helmholtz coil pair. Every curve is acquired with a constant current of 1 μA at room temperature, while the maximum field is swept from a high positive value to a high negative one across zero, and back from negative to positive. Absolute maximum field in our case was 250 Oe (major loop measurement).
We found that a conventional thermal treatment brings our structures to a TMR amplitude that is in the order of 1 % (fig. 5). The amplitude step is measured as the ratio between the high resistance state to the low resistance one.

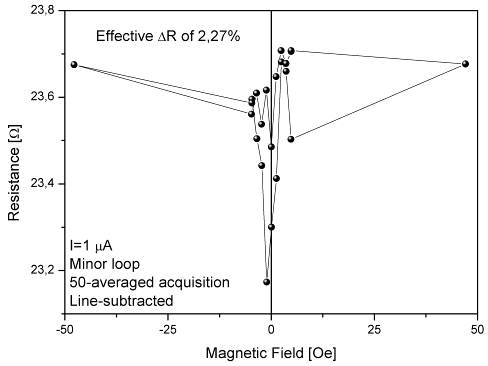
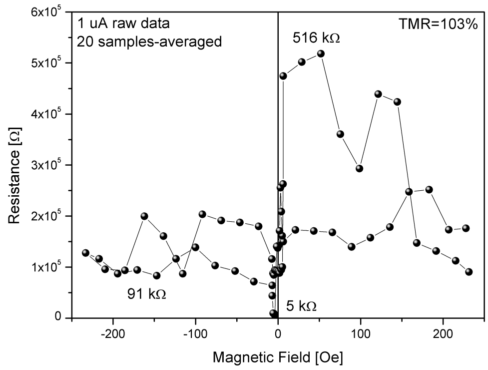


Figure 5: TMR measure of a traditionally annealed MTJ, resistance versus magnetic field, in the range ±50 Oe (so called minor loop) at room temperature. A steady current of 1 μA was applied continuously, while each experimental point is an average of 50 samples. The corresponding maximum TMR is 2.3 %.

Surprisingly we found that a laser annealed sample shows a peculiar response, whose amplitude is greater than 100 % (fig. 6).

Figure 6: TMR measure of a laser annealed MTJ, resistance versus magnetic field, in the range ±250 Oe (so called major loop) at room temperature. A DC current of 1 μm was used, while each experimental



point is an average of 20 samples. The corresponding maximum TMR is surprisingly above 100 %.

A possible key for the explanation of this unexpected encouraging result is the high temperature reached by the FM layers, close to the Curie point and hence high enough to allow realizing an almost perfect spin alignment with the magnetic field.
Conventional techniques, characterized by a much slower heating rate, don't allow to reach temperatures above 450 °C without seriously compromising the device functionality and integrity.
We believe that a full comprehension of the physics involved in this flash annealing treatment of MTJs will be extremely interesting also from the industrial point of view. The market of spintronic devices is demanding for high TMR amplitude structures to realize either more stable transistors for data storage or more sensitive devices for magnetic field sensing. A simplification of the processes (faster treatments) accompanied by an improvement in the electronic transport properties is strongly encouraged.

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