Magnetic tunnel junction sensor development for industrial applications

Introduction

Magnetic tunnel junctions (MTJs) are a new class of thin film device which was first successfully fabricated in the mid-1990s. In its simplest form, the MTJ is a tri-layer “sandwich” consisting of two layers of magnetic material separated by an ultra-thin insulating film. If a voltage is applied to the top and bottom of this structure, classical physics does not allow a current to flow; however, if the insulating layer (also referred to as the “barrier layer”) is sufficiently thin, electrons can flow by quantum mechanical tunneling through the barrier layer. The reason for the relative newness of this technology is that, for devices with a reasonable resistance values, the thickness of the insulating barrier layer must be extremely low (0.7 -1.6 nanometers, or 4-10 atomic monolayers). For tunneling between two magnetized materials, the tunneling current is maximum if the magnetization directions of the two electrodes are parallel and minimum then they are aligned anti-parallel. Therefore, the tunneling current, and therefore the resistance of the device, will change as external magnetic fields alter the magnetic orientation of these two electrodes.

Figure 1 shows a schematic of a recent MTJ layer structure. The two electrodes are fabricated from CoFeB, while the insulating barrier is composed of MgO, which, as discussed later, greatly enhances the properties of the device. The remaining layers in the structure are chosen to enhance the material and magnetic characteristics of the device. Typically, in order to achieve a linear, bipolar operation, one of the two magnetic electrodes (the “pinned layer”) in each sensor has its magnetization fixed by the exchange biasing phenomenon, while the remaining electrode (the “free layer”) is left free to respond to external fields. In this case, the pinned layer is fixed by the adjacent IrMn layer, which is termed the “pinning layer”.

The resulting structure has an electrical resistance which varies linearly as a function of the magnetic field strength over a substantial field range. Like the older and better-known anisotropic (AMR) and giant magnetoresistive (GMR) technologies, the magnetic tunnel junction is a magnetoresistive device. Such devices are often compared using magnetoresistance (MR) as the figure of merit. This quantity is defined as total change in resistance between the two saturated states, divided by the low (parallel-state) value. For the purposes of comparison, AMR sensors generally have a magnetoresistance of 2-3% and current GMR devices have MR values of 20-25%. By comparison, our current sensors feature magnetoresistance ratios of 100-200%, as explained below.

These devices can be fabricated using conventional semiconductor methods, making them potentially very cheap in large quantities. In addition, because of their two-terminal nature, they are customizable and easy to use. Since they were discovered, there has been a great deal of effort towards introducing magnetic tunnel junction technology into two potential billion-dollar markets: as read/write heads for the disk drive industry, and as the cornerstone of a new non-volatile magnetic memory technology for the semiconductor industry.

Since 2001, Micro Magnetics has been developing magnetic tunnel junction technology for introduction into a third class of applications: as miniaturized low-field sensors.

<u>AlOx-based MTJ sensors:</u>

From their realization in 1995 until two years ago, the vast majority of MTJ devices were grown using Al_2O_3 as the insulating barrier material. AlOx barriers are relatively simple to fabricate and allow for moderate magnetoresistance values of up to 35% with high yields. AlOx tunnel barriers are typically grown by depositing elemental aluminum and then using either a natural or plasma oxidation process to create the oxide.

Micro Magnetics has already brought AlOx-based magnetic tunnel junction sensors to the market with our SpinTJ product line, which was first introduced in 2004. The SpinTJ product line was spun out of our development effort on the Circuit Scan 1000 (CS1000) system, which uses magnetic fields to perform diagnostics on semiconductor die and packages.

Because the CS1000 requires very high spatial resolution to be able to see the tiny current paths which exist in today's integrated circuits, our effort was devoted towards developing sensors with high sensitivity and a high spatial resolution. As a result, all of the current product offerings in the SpinTJ product family feature sensors with active areas of a few microns or smaller. In addition, to counteract the magnetic instability which becomes problematic for devices with such small dimensions, our sensors have patterned permanent magnetic (PM) layers adjacent to the sensor film. These PM layers act as small bar magnets which can help stabilize the sensor output and reduce instability. SpinTJ devices provide micron-scale spatial resolution with a field sensitivity of 5-10 nT (0.00005-0.0001 gauss) and are available as custom sensor probes or mounted in a DIP-8 package (see Figure 1).

<u>MgO-based MTJ devices:</u>

In 2001, theoretical work predicted the possibility of extremely large magnetoresistance values in certain new tri-layer structures which used MgO as the barrier material. Due to a coherent tunneling effect, it was calculated that a properly prepared MTJ structure using an MgO barrier might exhibit up to 5000% magnetoresistance. In 2004, two groups independently reported record magnetoresistance ratios of over 200% in MgO-based MTJ devices.

In the case of AlOx-based junctions, the only conditions required for the barrier were that it be sufficiently non-conductive. In contrast, MgO-based junctions rely on the quantum mechanical properties of the MgO layer for the realization of ultra-high magnetoresistance. Because of this, creating successful tunnel junctions using MgO as the barrier layer is significantly more complicated. One major reason for this is that the coherent tunneling processes required for ultra-high magnetoresistance can only occur if the MgO layer has a certain crystal orientation. Achieving this crystal orientation requires tight control of deposition and annealing parameters, and only a handful of groups worldwide have reported success in fabricating MgO-based tunnel junction devices.

We have recently become the first company to offer magnetic tunnel junction sensors based on an MgO insulating barrier for scientific and research applications. Figure 3 demonstrates a saturation magnetoresistance of over 230% for a recent MgO-based MTJ device. The MgO-based devices retain the same small active area of our earlier AlOx-based SpinTJ sensors, but feature an improved response. Figure 4 shows the field versus resistance transfer curve of a typical micron-size MgO-based SpinTJ sensor.

Future directions:

As of this writing, the new MgO devices have not been optimized in terms of sensitivity or noise characteristics. In the coming months, Micro Magnetics plans to continue this work, while beginning work on expanding our sensor family to include devices with a larger active area, better linearity, higher sensitivity, and a lower price. We believe that the superior sensitivity of our MgO-based sensors will allow these new sensors to compete with established products based on AMR, GMR, and Hall-effect technologies.

We are in the process of developing a compact, high-sensitivity, low-field sensor based on MTJ technology, to be targeted toward industrial applications. The new MgO-based line of sensors, to be released later in 2006, will be available in several forms, including bare die or mounted into common IC packages. By relaxing the demanding size constraints required for our SpinTJ product line, we anticipate a sharp decrease in 1/f noise and a corresponding increase in field sensitivity to 0.1 nanotesla (1/500000th of the Earth's magnetic field) or better. These sensors will feature a simple, four-lead operation based on a bridge configuration, with an output voltage response proportional to the external field and to the input voltage, which will be variable over a wide range. This new class of sensors will meet demanding applications in position and direction sensing, navigation, current and flux detection, and biological and biomedical applications. We will also continue to offer MgO-based sensors with active areas as small as a few microns for applications requiring high spatial resolution.

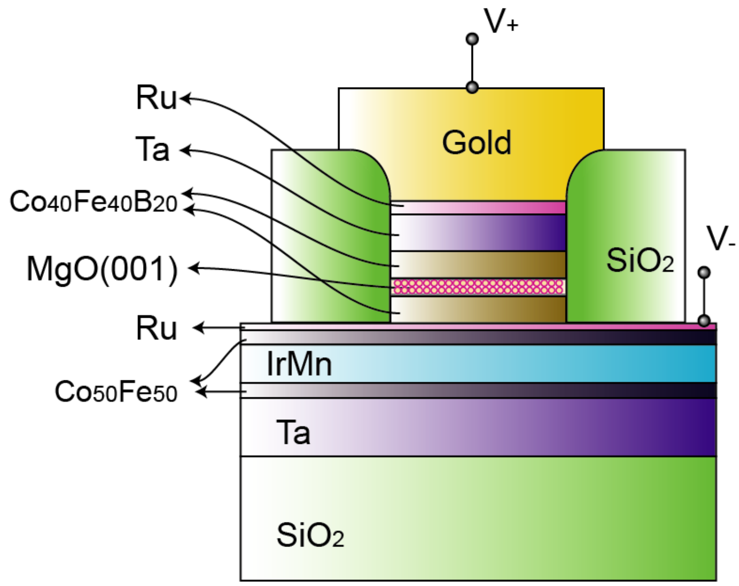

Figure 1. Schematic layer structure of an MgO-based magnetic tunnel junction sensor

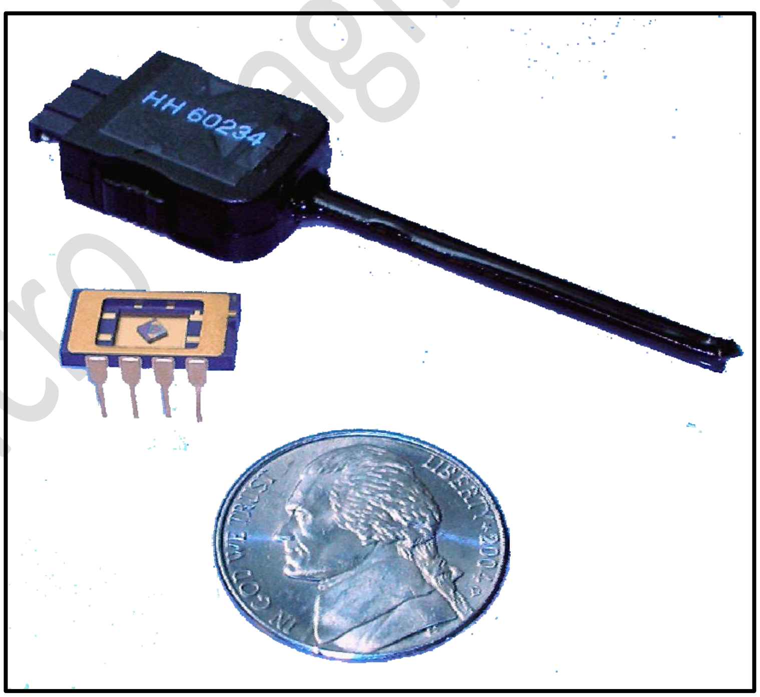

Figure 2. SpinTJ sensor configurations: probe and DIP8 package.

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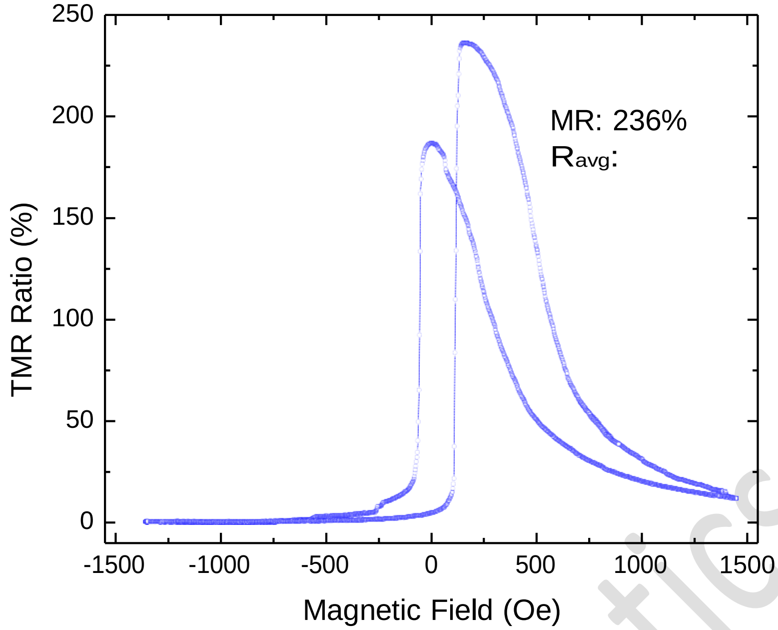

Figure 3. Magnetoresistance curve demonstrating magnetoresistance of 236% for prototype MgO-based magnetic tunnel junctions.

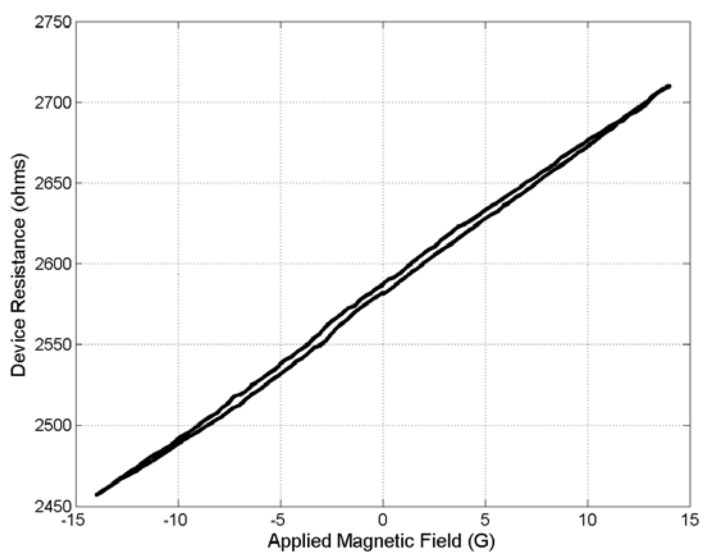

Figure 4. Typical minor magnetoresistance transfer curve of a micron-sized MgO-based magnetic sensor element over the field range -15 G to 15 G.

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