Selective Laser Annealing of xMR Sensors

Monolithic Magnetic Sensors Manufactured by Selective Laser Annealing

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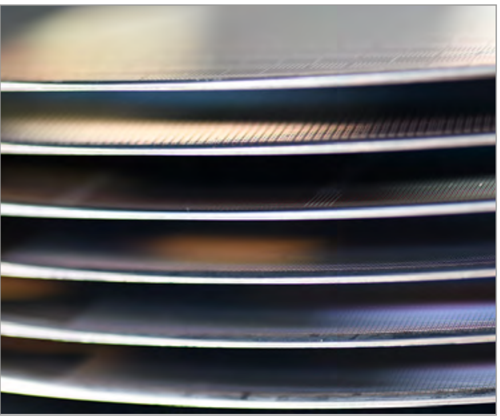

Introduction

A world with intelligent electronic devices in every machine and every pocket needs a wide range of sensor technologies. One rapidly growing technology is the sensing of magnetic fields, which can be used in numerous industrial applications such as the angular detection of the precise position of a steering wheel in a car, the detection and control of the rotation in a brushless DC-motor, the measurement of position and interaction of objects for Internet of Things (IoT) applications, the contactless detection of electrical currents, and position detection by e-compass for many different mobile devices including virtual reality (VR) systems. Very sensitive magnetic sensor chips can be realized by using GMR or TMR (Giant or Tunneling Magneto-Resistance) sensors in a Wheatstone bridge circuit (*Figure 1*). Stable output and high sensitivity that is cost efficient can be achieved with a Wheatstone bridge sensor circuit built in a monolithic design, including read-out electronics.

This paper gives an overview of the design, function, operation, and production results for a laser-based annealing technology, called microVEGA xMR, which enables the programming of advanced sensor structures at the wafer-level.

Limitations of Current Magnetic Sensor Programming Methods

A simple GMR or TMR sensor consists of two magnetic layers within an electrical circuit. As shown in *Figure 2*, the electrical resistance is lower when the two directions of magnetization of the layers are parallel, and higher when they are not parallel. If the magnetization of one of the layers is fixed, then the variation in electrical resistance follows the direction of magnetization of the other layer, resulting in sensor functionality, by the so-called spin-valve or tunnel-valve effect. The programming of a GMR or TMR magnetic sensor structure involves the setting of the magnetic orientation of the reference (fixed) magnetic layer (upper magnetic layer in *Figure 2*) in the desired sensitivity direction. The chosen magnetization orientation defines the sensitivity axis, also represented by the white arrows in *Figure 1*. This programming, also known as pinning, can be accomplished by heating the sensor structure above the magnetic blocking temperature of the antiferromagnetic (AFM) film that is adjacent to and that normally freezes the reference layer magnetization (green cap layer in *Figure 2*), while applying an external magnetic field large enough to saturate the reference layer in the new chosen direction. Upon cooling in the external field, the saturated reference layer becomes fixed (pinned) in the programmed direction. Alternatively, the magnetic shape anisotropy of elongated sensor elements can also be used to define the programming direction during cooldown.

The simplest way to achieve this process is to use a large magnetic annealing furnace, which can heat the whole wafer (or multiple wafers) in an adjustable uniform magnetic field. The advantage of such an approach is the possibility of batch processing of large numbers of wafers simultaneously, although a related

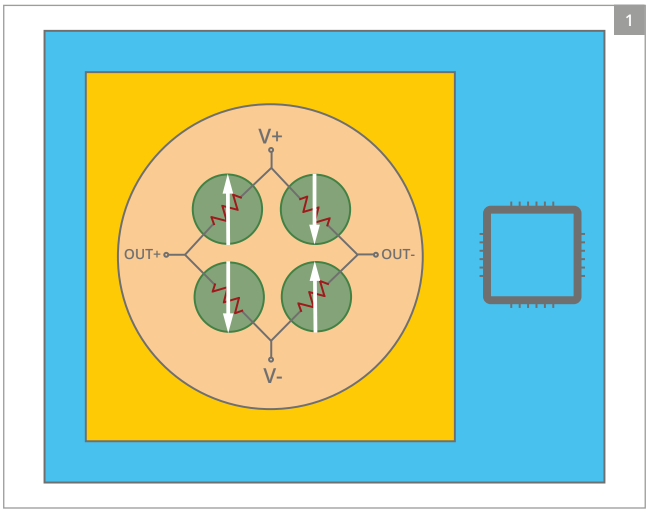

Fig. 1: Four magnetic sensors (green circles) with two different orientations in a Wheatstone bridge (amber circle) as part of a monolithic integrated sensor chip (blue).

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disadvantage is the possible non-uniformities of processing (temperature or magnetic field conditions) within wafers, or from wafer-to-wafer in batch processing. Another significant disadvantage is the difficulty to target different parts of the same wafer for different programming conditions. This is necessary, for example, to organize two or four separate sensors within a single sensor chip in standard Wheatstone-bridge configurations, which is often done to boost sensitivity and improve temperature stability. Multiple-die approaches to solve this problem are expensive and difficult to implement accurately, resulting in limited miniaturization, lower performance, and higher cost. The total process time (including heating and cooling), floor space, and utility costs for this approach are also significant and contribute to the total cost of production (see *Figure 3*).

An alternative approach that increases the flexibility of sensor programming is to integrate local resistive heating lines on-wafer. These lines can be designed to locally heat only a single sensor, or one branch of a Wheatstone bridge, in order to set its sensitivity axis independently from its neighbors. Heaters can be accessed and activated using standard industrial wafer probing techniques, and fields can be applied locally by an external electromagnet or permanent magnet. This allows sensors to be programmed at the wafer-level in a fully flexible manner to define different sensitivity axes or bridge structures. On the other hand, the step-and-repeat probing process is relatively slow and therefore requires substantial capacity for manufacturing volumes. In addition, it is difficult to achieve a high degree of reproducibility and reliability for the electrical contacts and thin-film heater lines, and therefore wafer homogeneity and process reproducibility are also a challenge.

All these approaches limit the obtainable throughput for the proper programming of complex sensor wafers, and generate high production cost in combination with potential yield loss due to processing complexity.

A Novel Approach based on Selective Laser Annealing

TThe key feature of the new microVEGA xMR technology is the combination of a selective laser spot with a local, in-situ rotatable magnetic field. The laser spot heats up exactly one sensor area while the magnetic field with the correct orientation is applied. Different sensor dimensions can be handled by using a recipe-controlled motorized mask to achieve the appropriate spot dimensions.

The laser is a unique tool for selective heating: the heat affected zone beyond the sensor area is only in the few-micrometers range. As a result, individual sensors can be placed closer to one another and logic circuits such as read-out electronics can be

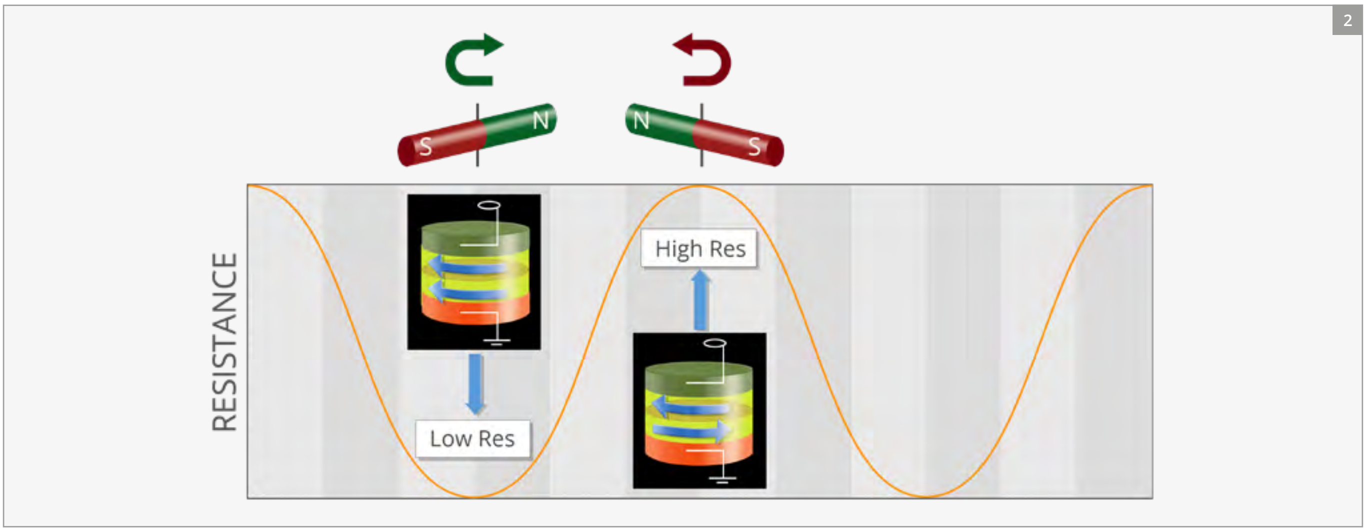

Fig. 2: Resistance as a function of magnetic field orientation by using a TMR Sensor.

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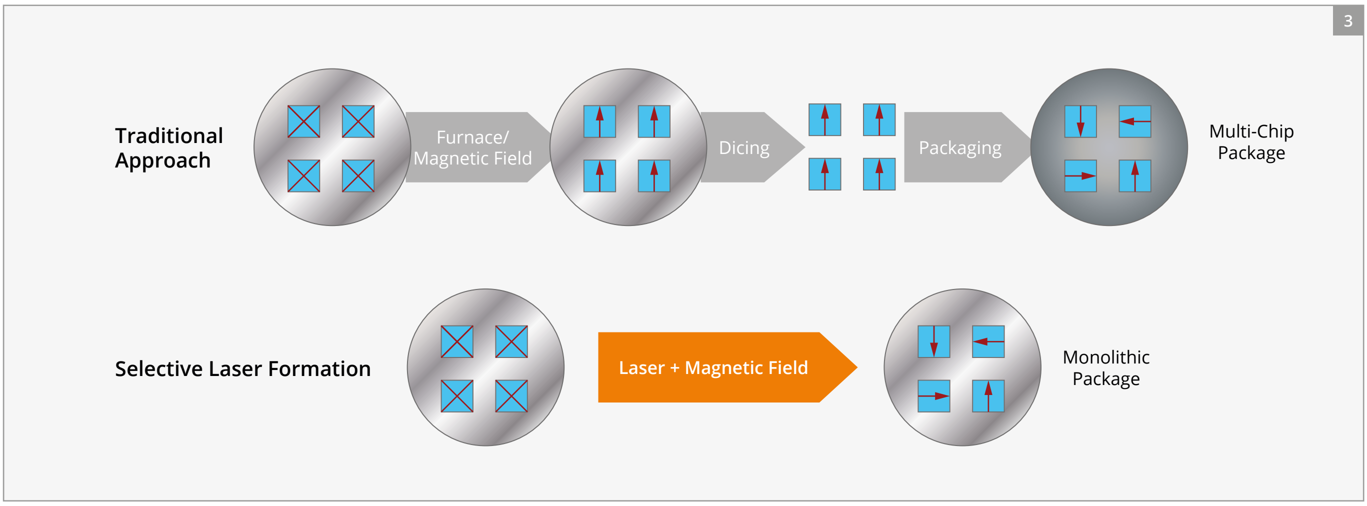

Fig. 3: Magnetic sensor production by multi-chip-packaging.

placed closer to or below sensor elements. The laser energy can be controlled sensitively enough to not damage protective layers. This allows the installation of the programming tool outside of the cost-intensive backend cleanroom.

In the microVEGA xMR system, a near-infrared (NIR) laser with nanosecond-pulse length is used. The nanosecond-pulse length delivers optimum heat propagation, while the NIR wavelength combines the most cost-effective and reliable laser design with good absorption for many different materials for this application. The required heating for any chosen material properties as well as for different sensor areas can be tuned by programmable laser pulse energy.

The effective applicable pulse energy differs for the individual products. The tool allows the pulse energy to be set in a very wide range in order to accommodate the processing of different materials and designs. The pulse energy is controlled by a recipe-controlled motorized attenuator. Possible pulse energies are in a wide range between 0 and 500 mJ/cm². The spot size can be changed in any rectangular shape between 10 × 10 µm² and 300 × 300 µm² using a motorized mask assembly.

A strong magnetic field is provided by a combination of permanent magnets. The magnet unit design was optimized for homogeneity by numerical simulations, also enabling field magnitudes close to 1 T. The precise magnetic flux at the wafer surface can be varied by changing the z-distance between the magnet unit and the wafer surface (range of 1 mm to 50 mm). The magnet unit can be rotated with high precision (±0.01°) to any angle.

Throughput is optimized by using an on-the-fly programming mode. In this mode, magnetic sensor elements that are to be programmed with identical orientation are placed equidistant and along one straight line across the wafer to allow the most effective synchronization of the laser pulses with the stage-based motion system. Other random-access or step-and-repeat modes are possible and can be used for specific tests and R&D. For high-volume manufacturing, synchronized on-the-fly processing is clearly the optimal approach.

The resulting selective annealing and programming approach, which is enabled by the combination of the laser and magnetic field, is the key to a one-step process for sensor device production. Neither dicing and re-mount nor slow mechanical positioning and contacting in a prober-like work mode are required.

Advantages of Selective Laser Annealing

Selective laser annealing for sensor programming offers a number of significant advantages compared to the conventional approaches discussed above.

Compared to furnace heating, laser programming provides complete flexibility in picking the precise wafer location to heat under particular field conditions. It therefore easily enables the creation of efficient multi-axis sensors and Wheatstone

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bridge designs with smaller sensor dice. Its speed also results in overall lower processing times and higher throughputs. More importantly, the laser power can be finely adjusted to achieve optimum reference layer alignment and overall optimized sensor characteristics over the entire wafer.

Compared to on-wafer heating elements, laser programming results in a simpler wafer process with fewer processing steps (no fabrication of heating elements needed) and therefore lower cost. In addition, heating power is highly uniform over the entire wafer surface, and not dependent on the uniformity of fabricated heating lines. Heated regions can also be divided as needed into smaller areas and arbitrary shapes to adapt to complex sensor geometries and avoid the heating of selected features on the wafers. It avoids the stress generation that can result from global heating in the furnace or by prober-like mechanical contacting of local heating elements. The whole process is contactless, free of tool wear, and does not require any consumables beyond standard utilities.

Conclusion

microVEGA xMR for selective laser programming of magnetic sensors is an industrial production-approved technology with many advantages. By enabling a one-step process, this solution significantly reduces the costs for sensor chip manufacturing. Selective laser pinning on microVEGA xMR is by far the most efficient technology in terms of cost, throughput, yield and quality (sensitivity) to accurately program magnet sensor devices.

The microVEGA xMR is fully automated and can be programmed for different sensor and wafer designs by recipe. The conversion from GMR to TMR is done only by selecting the correct recipe. All important tool data during programming can be organized by product type, saved in log files and — if required — transmitted via standard data interfaces.

Fig. 4: microVEGA xMR selective laser annealing system for monolithic magnetic sensor formation.