Integrated Flux Concentrator
Improves CMOS Magnetotransistors

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Abstract

A magnetic microsystem based on CMOS technology merged with electroplating as a post-processing step is reported. The system makes use of a lateral dual-collector magnetotransistor with suppressed-sidewall-injection (SSIMT) and a highly permeable and soft magnetic microstructure of permalloy. This structure increases the magnetic flux density in the sensitive SSIMT region. It is deposited on top of the sensor chip using a CMOS compatible electroplating technique [1]. The system sensitivity is increased by at least one order of magnitude over the conventional SSIMT.

1 Introduction

The properties of bipolar dual collector magnetotransistors are favorable for industrial applications requiring inexpensive magnetic field sensors. They can be batch fabricated using different industrial IC technologies such as bipolar, CMOS and BiCMOS processes. Therefore, the sensor element can be integrated together with read-out circuitry, operational amplifier and analog-digital converter on the same chip [2].

The SSIMT is sensitive to magnetic field directions parallel to the chip plane. It shows a high relative magnetic sensitivity

$$S_r = \frac{\Delta I_C}{B I_C} \qquad (1)$$

when defined as the collector current imbalance ΔI_C per magnetic induction B, normalized with respect to the total collector current $I_C = (I_{C1} + I_{C2})$ [3]. Usually, the design of such devices faces a trade-off between high relative sensitivity and low power consumption [4]. Despite all sensor optimization efforts, the magnetic response of all types of silicon magnetic field sensors is limited due to the low carrier mobility in silicon.

The sensitivity of magnetic field sensors can be enhanced by taking advantage of ferro- or ferrimagnetic materials with high relative permeability μ_r. Various types of sensors have been proposed in this field. Among them are magnetoresistors or hybrid solutions consisting of iron elements guiding magnetic flux and silicon magnetic field sensors.

New micromachining techniques now offer the possibility to easily and inexpensively combine the advantages of high permeable materials and batch fabricated silicon sensors. They are based on commercially available photoresists and conventional photolithography steps and allow the fabrication of thick metallic microstructures (i.e., 10-1000 µm) with high aspect ratios [1,5]. They open an easy and economical way for applications in surface micromachining, where the extreme resolution and sidewall steepness of the LIGA process is not demanded [6].

In this paper, we present a magnetic sensitive microsystem bringing together the advantages of a CMOS SSIMT and of a permalloy microstructure with high permeability. The large extension and shape of this flux concentrating structure allows to capture external magnetic flux and guide it directly to the sensing region of the SSIMT. In this way, a strongly enhanced magnetic sensitivity of the microsystem is achieved without increasing the transistors power consumption.

The nickel-iron microstructure is deposited on top of the chip passivation in a post-processing sequence by using a CMOS compatible polyimide molding and electroplating technique. This technique is low cost and easily scalable to large areas. It can be applied to every kind of chips or wafers subsequently to the foundry IC process. The working principle of the integrated flux concentrator can enhance the sensitivity of every semiconductor magnetic field sensor, which is sensitive to fields parallel to the chip plane.

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2 Magnetotransistor

A schematic cross section of the SSIMT is shown in Fig. 1. The sensor is fabricated in a standard industrial CMOS technology. The base region of the transistor is defined by the n-well. The emitter is surrounded by a highly doped n+ guard ring to increase the magnetic sensitivity of the device. The collectors C1 and C2 are placed symmetrically on both sides of the emitter. The base contacts are formed by n+ diffusions, the substrate contacts are defined by p+ diffusions. The SSIMT has an emitter-collector distance d_{EC} of 10 μm. The depth of the n-well is about 3.5 μm.

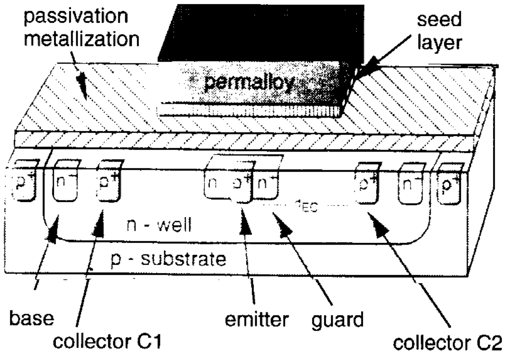

Fig. 1: Schematic cross section of a magnetotransistor with suppressed sidewall injection (SSIMT) fabricated in CMOS technology.

Due to the symmetrical geometry in an ideal device the two collectors carry the same collector current when no magnetic field is applied. In the presence of a magnetic induction B the Lorentz force acts on the moving carriers leading to galvanomagnetic effects in the sensor. They cause an imbalance of the current distribution and, therefore, a collector current difference $\Delta I_C = I_{C1} - I_{C2}$. In moderate magnetic fields up to one Tesla, this difference is proportional to the magnetic induction B. Hence, the relative sensitivity S_r of a conventional SSIMT at fixed collector current I_C can be considered as constant due to the linear behavior of ΔI_C.

For the SSIMT with integrated flux concentrator we obtain a nonlinear signal output resulting from the nonlinear magnetic properties of the ferromagnetic nickel-iron concentrator. Therefore, for the characterization of this type of sensor, we define a generalized relative sensitivity S_R as the derivation

$$S_R \equiv \frac{\partial \Delta I_C}{\partial B} \cdot \frac{1}{I_C} \qquad (2)$$

This definition (2) is equivalent to (1) in case of a linear dependence of the sensor signal on the magnetic induction B.

Numerical simulations show that the prevailing galvanomagnetic effects in an SSIMT are emitter injection modulation and Lorentz deflection of minority carriers [7]. Both effects occur in the neutral base region of the transistor between emitter and the two collectors. Therefore, it is most efficient to increase the magnetic flux density in this region.

It is important to notice, that sensor plane and concentrator plane are vertically separated due to the deposition of the flux concentrator on top of the chip passivation (see Fig. 1). Hence, the concentrator shape and thickness has to be optimized in order to maximize the magnetic stray field penetrating the sensitive base volume of the SSIMT below the concentrator plane.

3 Flux Concentrator

The flux concentrator captures external magnetic flux and guides it directly to the sensing region of the SSIMT. It is deposited as a ferromagnetic and high permeable nickel-iron film structure on the chip in a CMOS compatible post-processing sequence. Due to the vertical extension of the SSIMT and the vertical separation of sensor and concentrator, a film thickness of several microns is necessary.

Material

Among available ferromagnetic materials, nickel-iron alloys are promising because of their favorable magnetic and mechanical properties. In particular, the Ni(81%)-Fe(19%) composition permalloy offers a soft ferromagnetic behavior with maximum permeability and low minimum coercive force. In addition, this material has excellent stainless-steel like mechanical properties and a very low magnetostriction. Permalloy films with thicknesses up to several tens of microns can be easily deposited using electroplating techniques [8,9]. The film properties can be controlled by the plating bath composition and by the AC and DC plating conditions, namely by current density, pulse frequency or pulse shape [10,11,12].

For the fabrication of the electroplated flux concentrating microstructure a process based on photosensitive polyimide was applied [1]. DC electroplating was carried out in a nickel-sulphate and iron-sulphate electrolytic solution buffered with boric acid [5].

Microprobe (WDX) analysis of the electroplated permalloy films was performed on the concentrator surface as well as in depths up to 1 μm. The measurements reveal a correct quantitative chemical film composition of nickel (81 %) and iron (19 %) with good homogeneity and reproducibility over the whole concentrator area.

The magnetic film properties were investigated using a vibrating sample magnetometer in thin film geometry. This method determines the magnetic moment of a sample as a function of the applied external magnetic field H. The material magnetization and the magnetic induction B can be calculated from this data. A smooth and continuous hysteresis curve is found for the electroplated permalloy films as shown in Fig. 2. The corresponding field dependence of the relative permeability μ_r derived from an initial magnetization measurement is shown in the insert of Fig. 2. The magnetic characteristics of the electroplated films strongly depend on the electroplating conditions. A maximum relative permeability $\mu_{r,max}$ of about 350 and a saturation field of 1.1 T is typically achieved in our electroplated films.

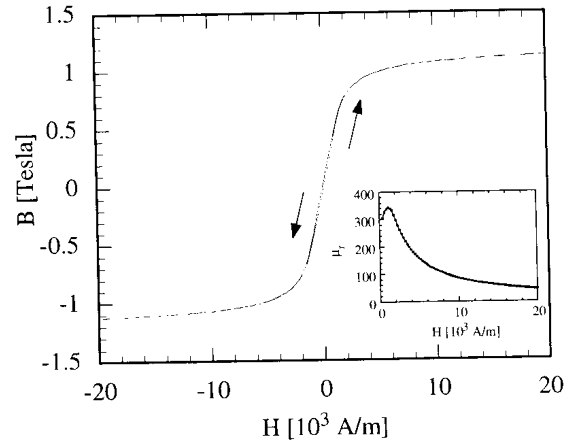

Fig. 2: Experimental B-H curve of an electroplated permalloy film. The insert shows the field dependence of the relative permeability μ_r

Shape

The scanning electron micrograph in Fig. 3 shows an overview of a CMOS chip containing the SSIMT and the integrated permalloy flux concentrator on top of the chip. The concentrator consists of two single, bottleneck-shaped permalloy structures with a total size of 1.8 x 0.8 mm^2 and a thickness of about 10 µm. The narrow regions of the two structures are separated by an air gap. The highest magnetic flux density occurs close to this gap. Hence, the emitter of the SSIMT is centered under the gap there as shown more in detail in Fig. 4. A cut of this figure along A-B corresponds to the cross section of the SSIMT in Fig. 1. The surface of the electroplated film is usually very smooth, but depends on the chip topography. In the presented case, the permalloy is deposited on the silicon-nitride chip passivation as well as on the aluminum metalization of the CMOS process.

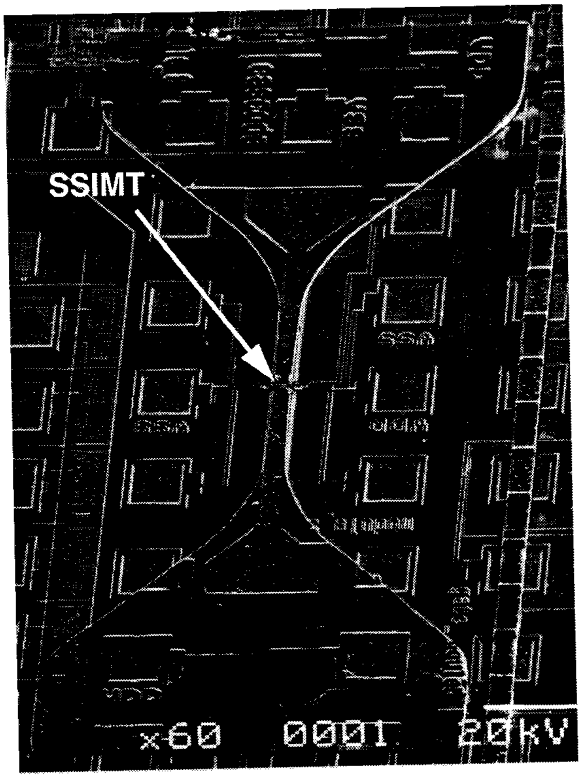

Fig. 3: Scanning electron micrograph of a chip containing SSIMT in CMOS technology with integrated permalloy flux concentrator.

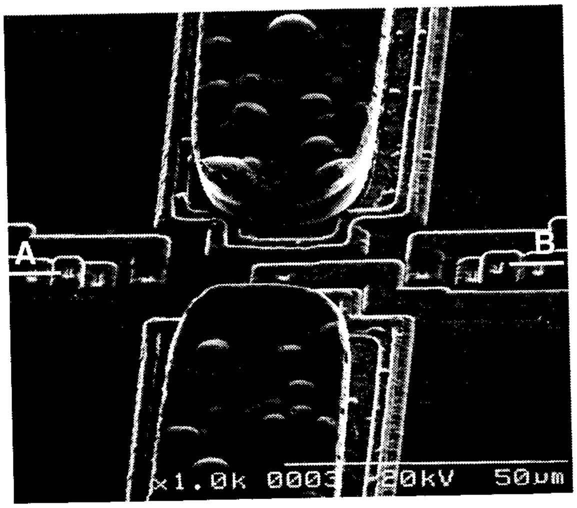

Fig. 4: Scanning electron micrograph of the SSIMT centered under the air gap of the flux concentrator.

The hillocks on the concentrator surface (Fig. 4) result from the roughness of the aluminum layer below.

Fabrication

The process for the fabrication of the permalloy flux concentrator is based on photosensitive polyimide as electroplating mask. It consists of the following steps as illustrated schematically in Fig. 5: A metal-silicon sandwich is sputtered on the chip and the photosensitive polyimide is spun on top of this layer. The polyimide is soft baked and structured by standard UV photolithography. The polyimide mold is filled with electroplated permalloy. Finally, the chip is cleaned by stripping the polyimide and etching the metal-silicon sandwich.

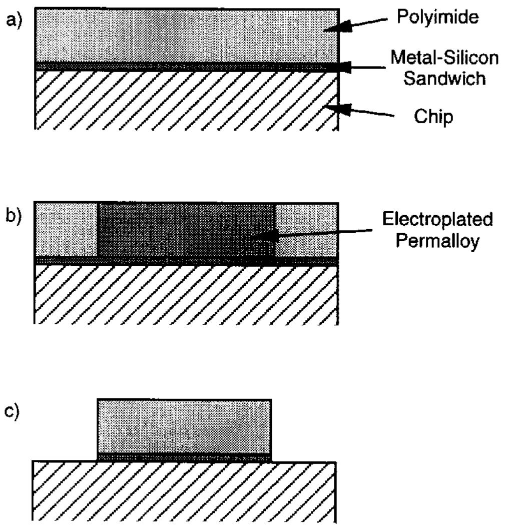

Fig. 5: Fabrication of the flux concentrator in a post processing sequence: a) sputtering of metal-silicon sandwich and polyimide deposition; b) photostructuring of polyimide and electroplating of permalloy; c) chip cleaning.

A typical fabrication process is described in the following. A CMOS chip containing an SSIMT structure is used as substrate as delivered from the IC foundry. A three-layer metal system is sputtered in situ directly on the chip passivation. The layers in order of deposition are 150 nm chromium, 500 nm copper and 150 nm chromium. The copper is used as electroplating seed layer. The top layer of chromium is necessary to prevent copper oxidation during the post-processing. Then, a 200 nm silicon film is sputtered on the chip. This layer acts as an absorber for UV light to allow photolithography on the uneven chip surface. For improved adhesion of the polyimide, adhesion promoter (Ciba Geigy Adhesion Promoter QZ 3289) is spun on the silicon top layer and soft baked at 80°C. Photosensitive polyimide (Ciba Geigy Probimide 348) is spun on the adhesion promoter and soft baked in two steps at 80°C and 100°C resulting in a 15µm-thick polyimide film. Lithographic exposure is carried out using a maskaligner with UV lightsource. The polyimide pattern is developed in Ciba Geigy QZ 3301 developer in an ultrasonic bath and rinsed in Ciba Geigy QZ 3312 rinse.

The silicon layer in the polyimide openings is removed by RIE etching in a RF plasma with SF_6. The top layer of chromium is etched immediately before electroplating using a 1: 1 solution of hydrochloric acid and deionized water with an aluminum depassivation. Then, the chip is rinsed in deionized water and immediately immersed into the plating bath. The polyimide mold is filled with permalloy by DC electroplating at room temperature at a current density of about 2 mA/cm^2 corresponding to a plating rate of 0.1 µm/min.

Finally, the polyimide is stripped in N-methyl-2-pyrrolidone in an ultrasonic bath at 80°C. The bonding pads are cleaned by silicon dry etching and selectively wet etching of the metal layers.

4 Results and Discussion

For characterization the SSIMT's were operated in common emitter mode. The emitter-collector voltage as well as the emitter-substrate voltage was set to -3V. The base current was adjusted to ensure a total collector current I_C of -100 µA. This corresponds to a total current $I_T = (I_C + I_S)$ of -2.4 mA, where I_S denotes the substrate current.

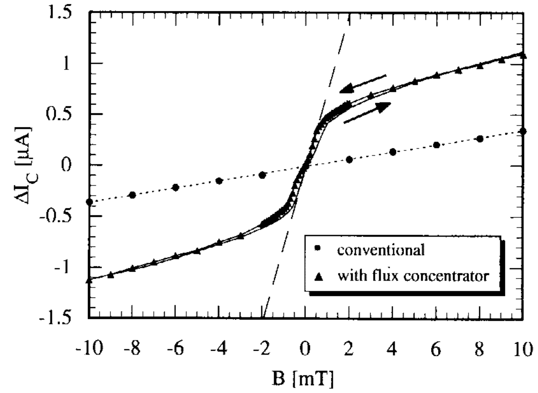

Fig. 6: Collector current difference ΔI_C for conventional SSIMT and for SSIMT with integrated flux concentrator as a function of applied magnetic induction B in the low field range. Signal offsets are set to zero.

The conventional SSIMT without flux concentrator shows a linear dependence of the collector current difference ΔI_C on the applied magnetic induction B, which is shown in Fig. 6. The constant relative sensitivity of the sensor is found to be about 36 %/T.

The SSIMT with integrated flux concentrator shows a nonlinear behavior of ΔI_C depending on the magnetization history of the concentrator. Therefore, a closed magnetic field loop from 10 mT down to -10 mT and back to 10 mT was performed. This measurement leads to the hysteresis curve shown in Fig. 6 with triangles and plain line. The measurement points are plotted only for the field decreasing part of the curve. The analogy between the sensor output and the B-H curve of permalloy in Fig. 2 is obvious. The relative sensitivity S_R of the sensor system depends not only on the shape and on the extension of the flux concentrator, but also on the relative permeability of the concentrator material. Therefore, the relative sensitivity of the system depends on the applied magnetic induction B.

For fields smaller than 1 mT, we find a strongly increased relative sensitivity of the microsystem over the conventional SSIMT. A maximum value for S_R of about 850 μA/T related to the maximum curve slope is achieved.

In this low field region, the permalloy has a high relative permeability and the flux concentrator captures effectively the external magnetic flux. This flux is guided through the concentrator to the narrow structure part and is forced to leave the permalloy at the air gap. The highest flux density is probably occurring at the upper and lower edges of the permalloy tips. In this way, a large amount of the magnetic flux is forced to penetrate the base region of the SSIMT below the flux concentrator. The maximum relative sensitivity S_R above corresponds to an enhancement of the magnetic induction B in the sensor of more than a factor of 20.

At magnetic inductions higher than 5 mT, the concentrator saturates, especially in the narrow structure regions close to the air gap. In this case, the relative sensitivity of the SSIMT with integrated flux concentrator is strongly reduced due to the lowered permeability μ_r of the permalloy.

For moderate magnetic fields between 0.1 T and 0.5 T, the SSIMT with integrated flux concentrator responds linearly on the magnetic induction B as shown in Fig. 7. A relative sensitivity S_R of about 42 μA/T is found for the microsystem.

In this field region, the relative permeability μ_r of the concentrator material is very low and can be assumed as constant. Then, the concentrator only slightly increases the relative sensitivity of the SSIMT by a field independent factor close to unity.

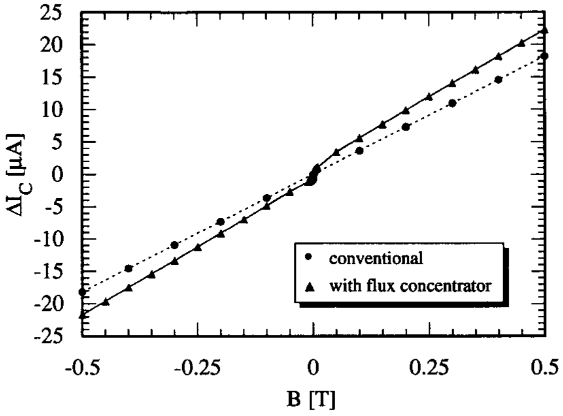

Fig. 7: Collector current imbalance at moderate magnetic inductions B.

5 Conclusion

A microsystem with enhanced magnetic sensitivity was realized by combining an SSIMT structure fabricated in CMOS technology and an electroplated permalloy flux concentrator deposited on top of the chip.

For low magnetic fields below 1 mT, the relative sensitivity of the SSIMT with integrated flux concentrator is increased by at least one order of magnitude over the conventional SSIMT and reaches a maximum value of about 850 μA/T. This value corresponds to an enhancement of the magnetic induction in the base region of the SSIMT of more than a factor of 20. In the low field region, the response of the microsystem is approximately linear. In fields larger than 0.1 T, the concentrator saturates. Then, the magnetic influence of the concentrator is strongly reduced and the microsystem shows only a slightly increased relative sensitivity compared to the conventional SSIMT.

Due to the fabrication of the flux concentrator in a postprocessing sequence on top of the sensor chip, the concentrator can be used to enhance the sensitivity of any kind of solid state magnetic field sensor sensitive to fields parallel to the chip plane without any modification of the sensor fabrication process.

6 References

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