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A novel structure for three-dimensional silicon magnetic transducers to improve the sensitivity symmetry

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Abstract

A three-dimensional silicon magnetic transducer with symmetric sensitivities in the *x*-, *y*- and *z*-directions and small cross sensitivity has been demonstrated. Devices are based on a design of a vertical Hall structure using the surrounding trench and symmetric design to suppress the cross sensitivity. The fabrication process is simple and can be used as a part of a standard integrated circuit process. The results show that almost equal sensitivities in all three components of magnetic field can be obtained by coating Ni/Co thin films on the backside of the substrates. The cross sensitivity is only 1.3% of the sensitivity.

Keywords: Magnetic transducers; Silicon; Symmetric sensitivity

1. Introduction

Development of fully integrated magnetic-field transducers which are able to measure simultaneously more than two components of the magnetic field *B* has attracted much attention. Possible applications of such three-dimensional (3-D) magnetic transducers include magnetic vector measurements, measurement of the earth's magnetic field for navigational or geological purposes, proximity switches and contactless angular position encoders, etc. [1–3]. Recently, 3-D magnetic-field transducers were designed employing various structural configurations [1–13]. However, these 3-D magnetic-field transducers either utilize a more complex structure [1,3,6] or exhibit an unsymmetric sensitivity [1–6]. Almost all published papers focus on improvements in sensitivity, resolution and device structure, etc. In this work, our focus is on the improvement of the sensitivity symmetry and simplifying the structure. The device structure shown in this paper is simple and similar to the structure proposed by Paranjape et al. [8], but with some modification to improve the symmetry of the sensitivity and reduce the cross sensitivity.

2. The 3-D vertical Hall magnetic-field transducer design

The basic structure of the Hall device for detecting 3-D magnetic field is shown in Fig. 1. The contact C_0 is used as

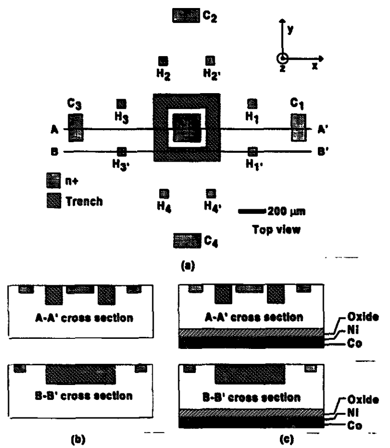

Fig. 1. (a) Plan view of the 3-D Hall device; (b) cross-sectional view of the device without Ni/Co coating; (c) cross-sectional view of the device with Ni/Co coating.

the central current contact and C_1, C_2, C_3, C_4 are connected and serve as the outside current contacts. The four pairs of

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Hall probe contacts, H_n–$H_{n\prime}$ ($n=1$, 2, 3 or 4) are placed symmetrically with respect to the central contact and facilitate the measurement of the generated Hall potential. The Hall potential is measured from the Hall probe contact. The central contact has the dimensions 200 μm × 200 μm, the outside contacts have the dimensions 200 μm × 100 μm, and the Hall probe contacts have the dimensions 60 μm × 60 μm. In this structure, the trench around the central contact has a width of 100 μm and a depth of 2 μm, which could suppress the lateral current flow and focus the current flow toward the substrate (perpendicular to the surface). More detailed dimensions are labelled in Fig. 1.

The device operates when a constant current I is supplied to the central current contact C_0, while the outside contacts, C_1 to C_4, are grounded. When the magnetic field is absent, the current densities through the four outside contacts are equal, thus the Hall voltage between each Hall probe is zero. When an in-plane magnetic field (x- or y-component) is applied, the action of the Lorentz force is dominated by the lateral current flow deflected in an upward or downward (vertical) direction. However, if a magnetic field is applied perpendicular to the device surface (z-component), the action of the Lorentz force is dominated by the in-plane current-flow deflection. This matter is developed in detail in Refs. [11–13]. The Ni/Co films deposited on the backside of the substrate are used to induce a denser magnetic flux through the device.

3. The fabrication process

The details of the fabrication processes are as follows. First, about a 1 μm thick photoresist layer was spin-coated on a 75 mm n-type silicon (100) wafer. The thickness of the wafer is about 400 μm. This film serves as the mask for trench etching. The trench region was plasma etched to a depth of 2 μm. After stripping the photoresist, a 300 nm thick oxide layer was deposited by plasma-enhanced chemical-vapour deposition (PECVD). The second photomask was used to define the central contact, outside contact and Hall probe contact regions. These regions were etched by dipping in BOE. $POCl_3$ diffusion was performed at 900°C to form the n^+ region for contacts. Again a 300 nm thick oxide was deposited by PECVD. The contact areas were defined by the third photomask. Finally, a 500 nm thick Al film was deposited by thermal evaporation and patterned. The device was subsequently sintered at 400°C in an N_2 ambient for 30 min to obtain good contact characteristics. Another device with the same structure described above was made with addition of 300 nm PECVD oxide/100 nm Ni/100 nm Co films deposited on the backside of the devices. The cross-sectional views are shown in Fig. 1(b) and (c). Then these completed Hall devices were cut and wire-bonded for measurement.

4. Results and discussion

To detect a 3-D magnetic field, characterization is performed by measuring the potential difference between appropriate Hall probe contacts. The spatial coordinate is defined in Fig. 1. The devices with and without Ni/Co coating have been characterized by measuring Hall voltages versus magnetic field for different input currents. Fig. 2 illustrates the Hall voltage measured between Hall probes H_1 and $H_{1\prime}$ (or H_3 and $H_{3\prime}$) with respect to the x-directional magnetic field, B_x. Fig. 3 illustrates the Hall voltage measured between Hall probes H_2 and $H_{2\prime}$ (or H_4 and $H_{4\prime}$) with respect to the y-directional magnetic field, B_y. Fig. 4(a) illustrates the Hall voltage measured between Hall probes H_n and $H_{n\prime}$ ($n=1$, 2, 3 or 4) with respect to the z-directional magnetic field, B_z. Because of the symmetric design, the response to B_x and B_y is symmetric. Also, the response is linear in the measurement region. Finally, we find that the response to B_z in the device without Ni/Co coating is about one order of magnitude lower than that to the in-plane (x- or y-direction) magnetic field.

The idea of coating Ni/Co films on the backside of the device is used to induce more magnetic flux through the device for improving the response to B_z. The results in Fig. 2 and Fig. 3 show that the response to B_x and B_y of the device

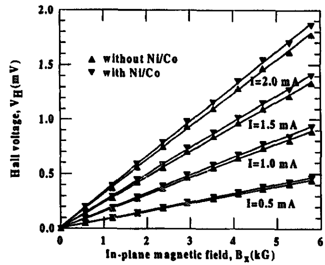

Fig. 2. The Hall voltage V_H measured from the Hall probe pair H_1–$H_{1\prime}$ (or H_3–$H_{3\prime}$) as a function of in-plane magnetic field, B_x, for varying biasing current, I, for devices without and with Ni/Co coating.

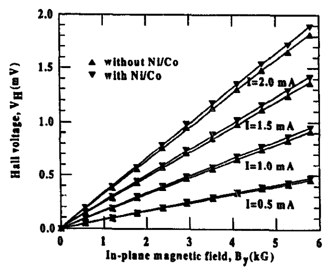

Fig. 3. The Hall voltage V_H measured from the Hall probe pair H_2–$H_{2\prime}$ (or H_4–$H_{4\prime}$) as a function of in-plane magnetic field, B_y, for varying biasing current, I, for devices without and with Ni/Co coating.

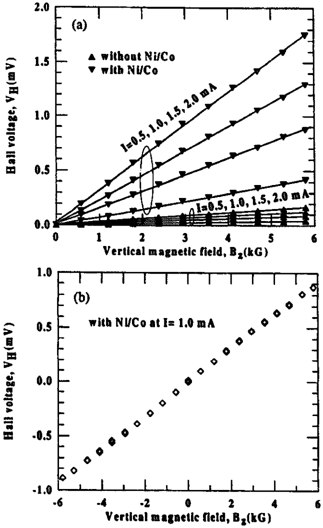

Fig. 4. (a) The Hall voltage V_H measured from the Hall probe pair H_n–$H_{n'}$ (n = 1, 2, 3 or 4) as a function of vertical magnetic field, B_z, for varying biasing current, I, for devices without and with Ni/Co coating. (b) The Hall voltage V_H measured from the Hall probe pair H_n–$H_{n'}$ (n = 1, 2, 3 or 4) as a function of vertical magnetic field, B_z (B_z = 0 to 600 mT to 0 mT to −600 mT to 0 mT) to check whether hysteresis exists.

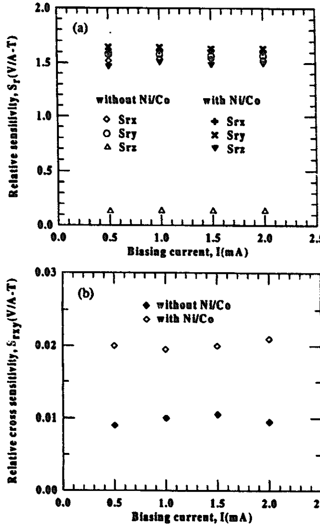

Fig. 5. (a) The relative sensitivity and (b) relative cross sensitivity as a function of biasing current, I, for devices without and with Ni/Co coating.

with Ni/Co coating is almost the same as that of the device without Ni/Co coating. Fig. 4(a) shows that the response to B_z of the device with Ni/Co coating is about 10 times larger than that of the device without Ni/Co coating. This is due to the high permeability in ferromagnetic materials (such as Fe, Co, Ni, etc.) The ferromagnetic materials induce a denser magnetic flux around them and also increase the local magnetic flux through the device. From our measurement (see Fig. 4(b)), hysteresis was not found. This may be because the Ni/Co films are very thin. But the real mechanism is unclear and there is probably another reason.

The cross-sensitivity effect is an important issue related to 3-D magnetic-field transducers. This value should ideally be zero or much smaller than the diagonal (x-, y- and z-direction) sensitivity. However, there are cross-component terms from the in-plane current flow. Thus, the relative cross sensitivity [4], S_{rxy} is defined by

$$S_{rxy}=\frac{V_{H_x}}{I}\frac{1}{B_y}$$

S_{rxy} is defined for an applied B_y on the x-component of a dominantly y-direction velocity vector [4]. A similar definition holds true for the S_{ryx}. Fig. 5(a) shows the relative sensitivity, S_r, versus biasing current I at a magnetic field of 0.5 T for devices with and without Ni/Co coating. Fig. 5(b) shows the relative cross sensitivity, S_{rxy} (or S_{ryx}) versus biasing current I at a magnetic field of 0.5 T for devices with and without Ni/Co coating. The cross sensitivity, which is only about 1.3% of the sensitivities in the x-, y- and z-directions for devices with Ni/Co coating, is very small and can be neglected. The low cross sensitivity is due to the symmetry of the device in suppressing the non-diagonal current flow.

5. Conclusions

A 3-D silicon magnetic transducer based on a vertical Hall structure has been fabricated and characterized. The transducer exhibits linear responses in all three components of a magnetic field (0–600 mT). A Ni/Co thin film deposited on the backside of the substrate can dramatically improve the z-directional sensitivity. No hysteresis was found in this work. Symmetric sensitivity can be obtained with this device. The cross sensitivity is small in this structure with or without Ni/Co coating on the device backside. The cross sensitivity is only 1.3% of the sensitivities in the x-, y- and z-directions. These results indicate that the structure can be further improved in order to obtain a 3-D magnetic transducer with higher sensitivity and lower cross sensitivity.

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Biographies

Hsiao-Yi Lin was born in Hualien, Taiwan, in 1968. He received the B.S. degree in physics from National Central University in 1991, and the M.S. degree in electronics engineering from National Chiao Tung University in 1993. He is currently working toward the Ph.D degree in the Department of Electronics Engineering, National Chiao Tung University.

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Tan Fu Lei was born in Keelung, Taiwan, in 1944. He received the B.S. degree in electrical engineering from National Cheng Kung University in 1967, and M.S. and Ph.D. degrees in electronics engineering from National Chiao Tung University in 1970 and 1979, respectively.

From 1970 to 1979, he was with the Fine Products Microelectronics Corporation, Taiwan, as an engineer. From 1980 to 1982, he was the Plant Manager, Photronic Corporation, Taiwan. In 1983, he joined the faculty of National Chiao Tung University, as an associate professor in the Department of Electronics Engineering. From 1984 to 1986, he was the Director of the Semiconductor Research Center, National Chiao Tung University. Presently, he is a professor and director of the Institute of Electronics in that department. His research interests are in semiconductor devices and optoelectronics.

Jz-Jan Jeng was born in Tainan, Taiwan, in 1970. He received the B.S. degree in electrical engineering from Feng Chia University in 1993, and the M.S. degree in electro-optical engineering from National Chiao Tung University in 1995.

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Ci-Ling Pan received the B.S. degree in physics from Tunghai University in 1971. He reveived M.S. and Ph.D. degrees in physics from Colorado State University (CSU), Fort Collins, Colorado, in 1975 and 1979, respectively. He was then a postdoctoral research scientist at the Chemistry Department of CSU before joining the Institute of Electro-optical Engineering, National Chiao Tung University, in 1981. During the academic year 1986–1987, he was on sabbatical at the University of California, Berkeley. Since 1987 he has been a full professor at the Institute and was its director form 1992 to 1995. He has worked on a wide spectrum of topics in optics, lasers and related fields, including single-atom detection, non-linear optics, frequency-stabilized lasers and precision optical measurement. The main thrust of his present work is in lasers and their applications in ultrafast optics and optoelectronics. Since 1991 he has published more than 50 papers in journals of international learned societies.

Chun-Yen Chang was born in Kaoshing, Taiwan, in 1937. He received the B.S. degree in electrical engineering from National Cheng Kung University in 1960, and M.S. and Ph.D. degrees from National Chiao Tung University in 1962 and 1970, respectively.

From 1962 to 1970, he was a research assistant and then an instructor at Chiao Tung University working on organizing a semiconductor research laboratory. During 1966 to 1976, he was first an associate professor and later a professor in solid-state electronics and semiconductor physics and technologies; he was also chairman of the Department of Electrophysics, Chiao Tung University, and has been a professor and director of the Institute of Electrical Engineering, National Cheng Kung University, from 1977 to 1987, where he has established a strong research and development base in electrical and computer engineering. In 1981, he became a member of the technical staff at Bell Laboratory, Murray Hill, NJ, working in the VLSI Device Group. He was a visiting professor at the University of Florida, Gainesville, in 1987 and the University of Stuttgart, Stuttgart, Germany, in 1989, where he taught MBE technologies and devices. He has consulted for ERSO/ITRI, Nippon Seiki Co., UMC, etc., on VLSI physics and technologies including III–V compound devices and materials using MBE and MOCVD, and amorphous-silicon devices. He has contributed to carrier-transport theory and specific contact resistivity in metal–semiconductor systems (1970, 1971). He invented a method for MOS surface stabilization (1966), the method of low-pressure MOCVD using a TEG source (1981), amorphous Si phototransistors (1986), and the bipolar–unipolar transition negative resistance transistor (BUNDR) (1987), etc. He is now a professor and the first dean of the College of Electrical Engineering and Computer Sciences of National Chiao Tung University where about 200 faculty members are involved, and the director of National Nano Device Laboratories, Taiwan.

Dr Chang is a member of Phi Tau Phi, the American Electro-Magnetics Academy, the Chinese Institute of Electrical Engineers, the American Physical Society and the Electrochemical Society. He has been elected an IEEE fellow for "his contribution to semiconductor devices development and to education." He was the recipient of an academic achievement award in engineering from the Ministry of Education and distinguished research award of the National Science Council, ROC, as well as the recipient of the 1989–1990 international travelling award granted by the China Foundation to the distinguished scholars in the ROC.