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Hybrid antenna–magnetoresistive sensor for radio frequency field detection

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A self-powered, hybrid sensor integrating a resonant microfabricated antenna with a spin valve sensor was fabricated. The device was activated by a radio frequency (RF) external electromagnetic source. This hybrid device was designed to behave as a series resonant circuit at 130 MHz. The self-powered sensor (powered by the RF field through the antenna) was capable of measuring the amplitude of the perpendicular RF excitation field crossing the antenna, down to 2.5 \( \mu \)T when excited with a RF field of 130 MHz. © 2011 American Institute of Physics. [doi:10.1063/1.3537816]

INTRODUCTION

Wireless technology and low power electronics have recently attracted considerable attention due to their potential uses in a variety of applications. The development of miniature wireless sensors to be located where devices with batteries would be inconvenient is challenging. Several emerging applications make use of energy harvesting.1,2 Magnetoresistive (MR) sensors have been widely used for detection and measurement of magnetic fields, taking advantage of the high magnetic field sensitivity of the MR sensor, small dimensions, integration capability, and reduced cost.3,4 This work presents a self-powered hybrid device,5 powered by a driving radio frequency (RF) field and able to detect and measure the amplitude of the perpendicular excitation field.

The hybrid sensor device had three components: a microfabricated three-loop resonant antenna, a spin valve (SV) sensor in series with the external loop, and a RF external electromagnetic source. The microfabricated antenna included a constriction (CT), aligned over the SV sensor and electrically isolated through an oxide. Figure 1(a) shows a schematic view of the microfabricated device. In the presence of a driving RF field, an electromotive force is induced on the antenna, generating an AC current. Part of this current is used to bias the SV sensor. Since the SV and the CT are in parallel, a portion of this AC current passes through the CT as well, creating an AC field that will be sensed by the SV sensor located underneath.

The spin valve sensor voltage output is expressed by the sum of two terms: one is from the biasing of the sensor and a second, \( \Delta V \), gives the SV sensor response to the field created by the constriction \( B_{CT} \):\footnote{\( B_{CT} \) is the effective field dominated by the free layer demagnetizing field; and \( I_{SV} \) is the amplitude (0–p) of the current passing through the SV.}

\[
V_{SV} = R_{SV}^0 \cdot I_{SV} + \Delta V \Rightarrow V_{SV} = R_{SV}^0 \cdot I_{SV} - (\Delta R / 2B_k^0) I_{SV}^2 B_{CT},
\]

where \( R_{SV}^0 \) is the SV resistance at zero field; \( \Delta R = R_{AP} - R_P \), where \( R_{AP} \) and \( R_P \) are the SV resistances in the antiparallel and parallel states; \( B_k^0 \) is the free layer effective anisotropy field dominated by the free layer demagnetizing field; and \( I_{SV} \) is the amplitude (0–p) of the current passing through the SV.

For a driving sinusoidal RF field of frequency \( f_1 \), and considering \( B_{CT} = \alpha I_{CT} \), where \( \alpha \) is a geometric factor relating the field at the sensor with the current in the constriction \( I_{CT} \), the previous equation can be rewritten as

FIG. 1. (Color online) (a) Schematics of the hybrid device incorporating a 3-turn antenna and a SV sensor. (b) Detail of the CT of the antenna on top and in parallel with the SV.

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$$V_{SV} = R_{SV}^0 I_{SV}^0 \sin(2\pi f_1 t) - (\Delta R/2B_{eff}^2) I_{SV}^0 \sin(2\pi f_1 t) \times 2I_{CT}^0 \sin(2\pi f_1 t).$$

(2)

Replacing $\sin^2(2\pi f_1 t)$ for $1/2[1 - \cos(4\pi f_1 t)]$ in Eq. (2), one term at $2f_1$ emerges:

$$V_{SV} = R_{SV}^0 I_{SV}^0 \sin(2\pi f_1 t) - (\Delta R/2B_{eff}^2) I_{SV}^0 I_{CT}^0 (x/2) \times [1 - \cos(4\pi f_1 t)].$$

(3)

From Eq. (3), two peaks are expected in the SV sensor voltage spectrum: at $f_1$, with amplitude

$$[R_{SV}^0 I_{SV}^0 x],$$

and at $2f_1$, with amplitude

$$0.5 (\Delta R/2B_{eff}^2) I_{SV}^0 I_{CT}^0 x.$$

(4a)

From Eqs. (4a) and (4b), information on the exciting RF field can be obtained, for example, from the SV sensor response at $2f_1$ (field measured at the sensor coming from the current $I_{CT}$, itself proportional to the RF field through the antenna).

The microfabricated hybrid device described in this paper was designed to incorporate $3 \times 9 \mu m$ (width x distance between electrical leads) SV sensors integrated with a 3-turn loop with an internal area of $2 \times 2 \text{mm}^2$. Top pinned SV sensors were fabricated by ion beam deposition (Nordiko3600 system) with the following structure (thickness in nm): glass/ Ta (2)/NiFe (2.5)/CoFe (2.5)/Cu (2)/CoFe (2.5)/MnIr (6)/Ta (2)/TiW(N) (15), where CoFe, NiFe, MnIr, and TiW(N) stand for Co$_{90}$Fe$_{10}$, Ni$_{90}$Fe$_{10}$, Mn$_{77}$Ir$_{23}$, and Ti$_{10}$W$_{90}$(N) in atomic percent. The 150 Å thick Ti$_{10}$W$_{90}$(N) passivation layer was deposited by magnetron sputtering. The easy axes of the free and pinned layers were set parallel to each other by applying a 10 mT aligning field during deposition and aligned with sensor width during sensor patterning.

The first level of metal consists of Al$_{98.8}$Si$_1$Cu$_{0.2}$ 300 nm/Ti$_{10}$W$_{90}$N$_2$ 30 nm—thick contact leads deposited by magnetron sputtering and defined by lift-off. The fabricated spin valve sensors showed a two-probe magnetoresistance signal of 5.71%, resistance ranging from 79.8 to 84.4 $\Omega$, and a sensitivity $(\Delta R/2B_{eff}^2)$ of 2.3 $\text{m}\Omega/\text{mT}$.

The sensors were passivated with sputtered Al$_2$O$_3$ (300 nm). Vias were defined to enable a later contact to the metal constriction layer (L1 and L2 in Fig. 1) and to measure the output of the sensor (A and B in Fig. 1).

In the second metal level a 3-turn square Al$_{98.8}$Si$_1$Cu$_{0.2}$ (150 nm)/Ti$_{10}$W$_{90}$N$_2$ (15 nm)/Al$_{98.8}$Si$_1$Cu$_{0.2}$ (300 nm)/Ti$_{10}$W$_{90}$N$_2$ (15 nm) antenna was defined by optical lithography and lift-off (each leg of the antenna had a width of 50 μm, and the turn-to-turn spacing was 10 μm). The CT was 4 μm wide x 500 μm long. One of the contacts of the hybrid device was defined in this step [contact D in Fig. 1(a)]. A final sputtered Al$_2$O$_3$ passivation layer (300 nm thick) was deposited all over the device, with a via left open by lift-off in the extremity of the inner loop [in Fig. 1(a)]. A third metallization level Al$_{98.8}$Si$_1$Cu$_{0.2}$ (300 nm)/Ti$_{10}$W$_{90}$N$_2$ (15 nm) was used to bring the inner loop contact to the external loop contact region [see contact C in Fig. 1(a)]. Figure 1(a) shows the full device schematic with the three metal levels shown in different grey scales (colored online).

The microfabricated wafer was diced into individual dies and wire-bonded to a Printed Circuit Board (PCB) platform [Fig. 2(b)]. The final device, composed of the flat squared metallic antenna in series with the parallel of SV and CT, shows a resistance (measured between contacts C and D) of approximately 87.58 $\Omega$. The resistance value found for the antenna was 56.5 $\Omega$ (measured between contacts A and C) and for the SV/CT 34.45 $\Omega$ (measured between contacts A and B). The impedance response versus frequency was measured between terminals C and D using a network/spectrum analyzer (HP 4195A). From this measurement, the resistance at DC, and the inductance and capacitance of the hybrid device were determined (84.11 $\Omega$, 55.52 nH, and 1 pF, respectively). In order to turn the device into a resonant antenna at 130 MHz, a 21 pF capacitor was mounted between C and D [Fig. 1(a)], effectively closing the antenna loop. Figure 2(a) shows the impedance measurement of the series resonant circuit with the expected impedance minimum at 130 MHz.

The activation/excitation of the hybrid SV sensor—antenna was done using a 3-turn, 7 mm diameter antenna (resistance 60 $\Omega$ at 130 MHz) connected to a RF source (HP8645A), which by Ampere’s law creates a RF field [Fig. 2(c)]. This excitation antenna was placed on top and centered with the receiving antenna of the hybrid device.

In order to test the appropriate frequency tuning of the resonant MR sensor–antenna, the output of the SV sensor (at $2f$) was measured for two different RF fields, with amplitudes of 15 dBm and 19 dBm and varying frequency. Figure 3
shows that, as expected for a resonant circuit, the hybrid device had output maximum at the resonant frequency (where the impedance of the device was minimum).

Figure 4(a) shows the spectrum of the SV sensor from 100 to 300 MHz, acquired with a bandwidth of 100 kHz (no external field applied). For this experiment the RF driving frequency was 130 MHz (the resonance value for the device) with an amplitude of 19 dBm. For these conditions a current of 36.3 mA passed through the excitation antenna, creating a field of 19.5 μT at its center. The distance between the antenna of excitation and the receiving antenna was 2.60.5 mm, leading to a RF field of 4.27 μT in the active area of the receiving antenna and a current induced in the hybrid device (IHYP) of 478 μA. Knowing the values for the resistance of SV//CT (37.57 Ω), RSV (82.6 Ω), and IHYP, the value of the current expected to be biasing the sensor can be calculated: 199 μA.

Figure 4 shows the two expected peaks at f1 and 2f1. The amplitude measured for the peak at f1 was 18.67 mV and the expected value was 16 mV [calculated using Eq. (4a) and considering RSV = 82.6 Ω and ISV = 199 μA]. The experimental value at 2f1 was 9.71 μV. The theoretical value of this peak, calculated using Eq. (4b), was 8.95 μV (AR/2Bkeff = 2.3 Ω/mT, ISV = 199 μA, Ict = Iihyp − I0SV = 279 μA, \(x = 0.14 \text{T.A}^{-1}\)).

Figure 5 shows the spin valve output at 2f for varying RF field amplitude at frequencies of 90, 110, and 130. The calculated amplitudes using Eq. (4b) are also shown (for 130 MHz). The 20% deviation of the experimental values from the predicted values can be explained by the error in the measurement of the distance between the excitation and receiving antennas.

In conclusion, a RF powered hybrid antenna–magneto-resistive sensor resonant device was microfabricated. The final device was tested using a driving RF field with frequencies ranging from 90 to 130 MHz and with a wide range of amplitudes. Measurements of the spin valve sensor output at a 2f peak as a function of the RF driving field amplitude clearly demonstrate the field sensing capability of the device. The lowest field measured in this work with the hybrid MR sensor–antenna was \(\sim 2.5 \mu\text{T}\).

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