Characterisation and Modelling of a Magnetic Biosensor

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Abstract – This paper presents the characterisation and modelling of a magnetic biosensor included on a portable hand-held microsystem for biomolecular recognition (DNA hybridisation, antibody antigen interaction, etc.). The system, which is based on a fully integrated magnetoresistive biochip (fig. 1), uses magnetic field arraying of magnetically tagged biomolecules and can potentially be used to detect single or few biomolecules. The biochip is based on a matrix array of magnetic tunnel junctions and thin-film diodes (fig. 2) which are here characterised and modelled. Experimental results show the proposed models may be used for biochip characterisation and the matrix structure is adequate for the envisaged microsystem.

Keywords – MTJ, TFD, magnetoresistive sensor, biochip, biomolecular recognition.

I. INTRODUCTION

Nowadays magnetoresistive biochips are considered for fully integrated biomolecular recognition assays, using target biomolecules marked with magnetic particles [1]. Subsequently, the labelled targets are recognised by biomolecular probes immobilised on the surface of the chip over sensing sites. Among the various types of magnetic sensors (giant magnetoresistive sensors, spin valve resistors, magnetic tunnel junctions), magnetic tunnel junctions (MTJs) assume great importance because of their greater flexibility in resistance design and because they benefit from recent research and technological advances aiming the design of future ultra high density magnetic memory chips and higher magnetic sensitivity, when compared with other types of magnetic sensors, which enables the detection of smaller magnetic labels. [2], [3]

A. Hand-held Microsystem

The magnetic biosensor that is characterised and modelled is included on a hand-held microsystem based on a fully integrated magnetoresistive biochip (fig. 1) for biomolecular recognition (DNA hybridisation, antibody antigen interaction, etc.) [4]. The biochip uses magnetic field arraying of magnetically tagged biomolecules and high sensitivity sensors which potentially can be used to detect single or few biomolecules.

Figure 1. Magnetoresistive biochip photograph.

Figure 2. Magnetoresistive biochip simplified electrical scheme.
B. Biochip Structure

The biochip structure is based on a matrix-array of 16 × 16 sensor sites which not only increases the number of sensor sites but it also makes the biochip fully scalable, which is of great importance in all applications where analysis of a large number of different targets in parallel is needed. Such biochips could, for instance, be used in clinical diagnostics of genetic diseases characterised by a large number of mutations (over one hundred), like in cystic fibrosis. The magnetoresistive biochip (fabricated at INESC-MN using standard microfabrication techniques) has 256 biosensor detection sites. Each magnetoresistive sensor consists of a thin-film a-Si:H diode (TFD), \( D_{i,j} \), in series with a magnetoresistive sensor, based on a MTJ, \( S_{i,j} \) (fig. 2). Each TFD, \( D_{i,j} \), has two main functions: i) to act as a switching device enabling the connection between column \( C_j \) and row \( R_i \) of the matrix and ii) to act as a temperature sensor of each biosensor site, \( B_{i,j} \). Each MTJ element is very close to the TFD and operates as a sensor of the planar magnetic field, \( H \), transversal to its length. Although the MTJ response is also slightly temperature dependent, its sensitivity is much lower than the TFD’s and may be neglected, as it will be shown.

Biochip sensor characterisation and modelling is fundamental to sense local temperature, perform temperature control through a heater/carrier (fig. 2) and to achieve system calibration. In the following, biochip magnetoresistive sensors are characterised and modelled.

II. BIOSENSOR MODELLING

Considering the biosensor usage for DNA hybridisation detection, the site over each MTJ transducer is formerly functionalised with a DNA probe. The target DNA, tagged with paramagnetic nanoparticles, is transported in fluid and focused at sensing sites using alternating magnetic field gradients. Subsequently, DNA target hybridises with available complementary probe and finally, magnetic labels remain bound to the surface of the sensors after chip washing with a buffer solution.

An external magnetic field induces a magnetic moment on the nanospheres and each MTJ sensor will detect this change of the sensors after chip washing with a buffer solution. The target DNA, tagged with para-

III. TFD CHARACTERISATION AND MODELLING

A. TFD with Small Currents

For small current values the TFD junction behaviour is characterised by the Schockley equation [5] of a crystalline semiconductor junction:

\[
v_J = n V_T \ln \left( \frac{i_D}{I_S} + 1 \right)
\]

leading to \( v_D = v_J \) (fig. 3, eq. 1). Although eq. 3 parameters are all temperature dependent (\( n \), the emission coefficient, \( V_T = KT/q \), the thermal voltage, and \( I_S \), the diode saturation current) only the \( V_T \) dependency is known. In order to
use the TFD as a temperature sensor characterised by $S_T^{vD}$, it is necessary to know how $n$ and $I_S$ depend on temperature.

For a set of three small current values (5, 10 and 100 nA) held constant, the TFD response to temperature was measured, through $v_D$ registration while temperature was decreasing. Experimental data are depicted in fig. 5 (circle marks). Assuming a direct linear fit over data, sensitivity values of $-1.61, -1.56, -1.38$ mV/°C are expected for these current values. From the measured $v_D(T)$ values, $n$ was determined for each temperature (square marks in fig. 6). Knowing $n(T)$, values for $I_S(T)$ were then determined (square marks in fig. 7). From these experiments TFD temperature dependence, for small currents, is completely characterised.

The obtained results lead to models for $n(T)$ and $I_S(T)$ [6]:

$$n = n_1 + \frac{n_2}{T}$$

$$\log I_S = k_1 - \frac{k_2}{T}$$

with $n_1 = 0.78186, n_2 = 566.411, k_1 = -6.06078, k_2 = 1208.4531$. These models are confronted with experimental data in figs. 6 (solid line) and 7 (dashed line) and show an excellent accordance between models and experimental data.

In order to technologically characterise the TFD, a model taking into account technologic junction parameters ($c_S, n, \omega$ and $v = qE_G$) is considered:

$$I_S = c_S T^\omega e^{-\frac{nVT}{kT}}$$

were it is assumed that $n$ depends on temperature, as previously modelled (eq. 4), but the remaining parameters, $c_S$, $\omega$ and $v$, do not have any temperature dependence.

From the obtained experimental data and the considered models, technological parameters were estimated and $c_S = 12.671 \mu A$, $\omega = 2.6327$ and $v = 0.73333 eV$ were obtained. These estimated values are compared with experimental data through the proposed model both for $I_S(T)$ (solid line in fig. 7).

The sensitivity of the V-T characteristic, for low $I_D$ values, may be calculated at an $(I_D, n, T)$ quiescent point as:

$$S_T^{vD} = \frac{1}{T} \left[ \frac{n_1}{n} (V_D - v) - \omega V_T \left( 1 + \frac{n_2 \ln T}{n} \right) \right]$$

which, for a certain temperature range, corresponds to an almost linear characteristic.

The V-T sensitivity is depicted in fig. 8 for the three imposed current values (solid lines). The obtained curves show a good agreement with the anticipated values that were previously predicted from a simple linear fit over data. Figure 8 also depicts the TFD saturation current sensitivity with temperature for the considered model with the estimated parameters (dashed line).

For high current values the temperature of each biochip matrix element carries relevant information to characterise and analyse the DNA hybridisation and, besides, the biochip may be heated by a heater/carrier (fig. 2) by adequate pulsed current drive. The V-T characteristic of the TFD is used to measure the
temperature, because the TFD is very close to the MTJ and has a very good thermal connection with it.

B. TFD with High Currents

The I-V characteristic of an amorphous TFD is slightly different from the I-V characteristic of a crystalline semiconductor junction due to the space charge current limited phenomenon (SCLC) typically occurring in amorphous semiconductor films [5], [6]. This phenomenon occurs in the bulk access to the junction and leads to a voltage drop in the bulk region that varies nonlinearly with current. For high current values the TFD electrical behaviour may be modelled as a sum between the junction voltage drop (eq. 3) and the voltage drop over a nonlinear resistor $R$:

$$v_D = n V_T \ln \left( \frac{i_D}{i_S} + 1 \right) + (R i_D)^\alpha \quad (8)$$

This proposed model achieves a good TFD characterisation for current values below $\sim 70\mu A$ which is the practical upper limit for MTJ proper operation.

In order to completely characterise the TFD electrical and temperature behaviour, experimental data were obtained for several of the 256 TFDs of the biochip [4] at a set of different temperatures both for low and high current imposed values ($2nA - 0.1\mu A$ and $0.08\mu A - 80\mu A$). The corresponding TFD voltage drop was measured and results are depicted in fig. 9 (marks). This experimental characterisation evidences that for currents above $100nA$ the I-V characteristic diverges from eq. 3 and the bulk voltage drop has to be considered.

Square marks in figs. 10 and 11 represent $R(T)$ and $\alpha(T)$ (eq. 8) obtained from experimental data. Temperature dependence is then considered through:

$$\log R = r_1 - r_2 T, \quad \alpha = \alpha_1 - \alpha_2 T \quad (9)$$

Model parameters were then estimated from the available data and $r_1 = 9.5561$, $r_2 = 16.407E-3$, $\alpha_1 = 1.2635$ and $\alpha_2 = 2.2276E-3$ were obtained. From the derived model a resistance $R \approx 50k\Omega$ may be expected at room temperature.

With these and the models determined in the previous section, the TFD voltage drop was calculated and results, for the same temperature set at which data was collected, are shown in fig. 9 as solid lines. It can be seen that the proposed models may characterise the biochip TFDs for current levels almost until $70\mu A$. It can also be observed that a better characterisation is obtained for higher operating temperatures because for lower temperatures and very high currents ($>70\mu A$) I-V curves deviates and rise superlinearly.

To test the proposed models experimental results were obtained for two biochip TFDs at room temperature. Experimental conditions were different from those considered before because now it is the voltage that is forced and the current that is measured. Experimental results are depicted in fig. 12 (square and circle marks). Although model parameters were extracted from data obtained at higher operating temperatures ($27.2^\circ C$ was the minimum) it can be seen that the proposed model (solid line in fig. 12) achieves a good match with experimental data and may be considered as a practical characterisation of the biochip TFDs.

To complete the TFD electrical characterisation its dynamic resistance $r_d$ (first factor in eq. 2) is now considered. From the proposed model, the TFD incremental resistance is:

$$r_d = \frac{nV_T}{i_D} + \alpha R^\alpha i_D^{-1} \quad (10)$$

Figure 13 shows the TFD $r_d$ calculated directly from experimental data (same conditions as before) and through the considered model. As in the I-V characteristic, it can be seen that...
the proposed model makes a good characterisation of the TFD dynamic resistance except for very high current values where the biochip will not operate.

IV. MTJ CHARACTERISATION AND MODELLING

A. MTJ Electrical and Temperature Characterisation

Biochip MTJs have an I-V characteristic that may be very accurately modelled by a quadratic function. This parabolic shape may be envisaged in fig. 14 where the marks correspond to data collected when the MTJ was driven by $1 \mu A - 40 \mu A$ currents at several operating temperatures (only three operating temperatures are shown). Nevertheless, from a practical point of view, the I-V characteristic may be seen as having an almost linear characteristic, meaning it may be locally modelled by a straight line:

$$i = i_0 + R_0^{-1} v$$  \hspace{1cm} (11)

where $i_0 \neq 0$ indicates that the model only corresponds to a valid ohmic behaviour in the vicinity of the measured data points. From the experimental data, $R_0(T)$ and $i_0(T)$ were determined (square and diamond marks in fig. 15) and linear models were considered for their temperature dependence:

$$R_0 = R_x + \beta T, \quad i_0 = i_x + \gamma T$$  \hspace{1cm} (12)

A $\beta = -11.9 \Omega/\degree C$ was obtained. Solid lines in fig. 14 show the results obtained with these models and their match with experimental data show that models may be used to characterise biochip MTJs.

Due to the ultra low thickness of the dielectric needed to obtain tunnelling effect, typical MTJs may breakdown for applied voltages over 1.1V. This limits the maximum secure driving current at room temperature to $\approx 70 \mu A$ for a biochip with a nominal $R_0 = 15.3k\Omega$ (fig. 15).

Figure 16 presents $S_T^{v0}$ determined from the extracted models for each operating current. For a driven current of $1 \mu A$, $S_T^{v0} = -17.8 \mu V/\degree C$ which is negligible when compared with
$S_{T}^{V}$ exhibited by the TFD that is in series with it. It is then possible to use each biochip TFD as a temperature sensor and neglect the MTJ very low temperature sensitivity.

**B. MTJ Magnetic Characterisation**

MTJ resistance varies with the transversal component of an applied magnetic field and its sensitivity is measured by the tunnelling magnetoresistance ratio, TMR. A maximum variation occurs when no voltage is applied to the MTJ:

$$TMR(0) = \frac{R_{\text{max}} - R_{\text{min}}}{R_{\text{min}}} \times 100\%$$  \hspace{1cm} (13)$$

where $R_{\text{max}}$ and $R_{\text{min}}$ are the maximum and minimum resistance values obtained with magnetic opposite saturation fields (typically $\pm 10\, \text{Oe}$, $\Delta H_{\text{max}}$). TMR is almost constant until 30 mV ($TMR(0) \approx 27\%$ was obtained) and then decreases almost linearly with bias voltage increase. In the range $300 - 500\, \text{mV}$ (where TMR drops to half its initial value) it is possible to model:

$$\frac{TMR(V)}{TMR(0)} = 1 - \frac{V}{2V_{1/2}}$$  \hspace{1cm} (14)$$

showing MTJ TMR dependence on the applied DC bias voltage. However a bias voltage reduction implies a driving current reduction, which increases $r_{d}$, reducing the reading voltage, $v_{M}$ (fig. 4). Driving current optimisation is then needed in order to maximize $v_{M}$.

Although TMR decreases with bias voltage increase, if a very small current is applied to the MTJ in order to have full TMR, MTJ voltage will also be very small and the voltage variation, $\Delta V$ (voltage at high MTJ resistance minus voltage at low MTJ resistance), will also be very low. This means that there is a tradeoff between these two phenomena and $\Delta V_{\text{max}}$ is observed at a certain current. This current depends on the MTJ resistance: the higher the resistance, the lower will be the currents.

Increasing MTJ resistance decreases the current required to maximize signal output but at the expense of increased sensor noise (mostly $1/f$ for low frequency applications). By lowering MTJ resistance pushes the maximum signal peak to higher currents.

$$S_{T}^{V} = S_{H}^{RS} \times i_{M}, \quad S_{H}^{RS} = TMR(V) \frac{R_{S}}{\Delta H_{\text{max}}},$$  \hspace{1cm} (15)$$

and may be estimated as $V_{1/2}/R_{S}$. Experimental characterisation of one of the biochip MTJs showed a resistance of $14.4\, \text{k}\Omega$ and $\Delta V_{\text{max}}$ occurs for a drive current of $\approx 30\, \mu\text{A}$ (see fig. 18). Device simulations for three different MTJ resistances are also shown and agree well with experimental data. All curves show a maximum $\Delta V \approx 50\, \text{mV}$. The decrease of $\Delta V$ for higher bias currents is caused by TMR decrease at increasing bias voltage. For biochip applications, a voltage variation maximum is required.

V. CONCLUSION

Electrical, temperature and magnetic modelling and characterisation of TFDs and MTJs, included on a magnetoresistive biochip for biomolecular recognition, were performed. Experimental results in accordance with the proposed models indicates that they may be used for the biochip characterisation and calibration.

REFERENCES