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Highly sensitive magnetic array-based platform for neuronal signal recording

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Abstract

This work presents a platform for the detection of the neuronal magnetic signal arising from the propagation of the action potential along the axon, via an array of highly sensitive magnetoresistive sensors and a low noise front-end electronic setup. We report the results of calculations and experiments for estimating the limit of detection of such platform in terms of minimum detectable magnetic field. Furthermore, an experimental setup for recording the magnetic signal in a brain slice is presented.

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1. Main text

Understanding brain circuit mechanism is a crucial aspect in order to gain a deeper insight into neurologic diseases. In recent years, many studies, employing different technologies, have been carried out [1]. Nevertheless, a platform enabling non-invasive in-vitro investigation from single neuronal cells to a network level, with higher temporal and

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spatial resolution is still needed. In this work, we propose a novel magnetic array-based platform featuring highly sensitive magnetoresistive devices for on-chip detection of magnetic field generated from the propagation of neuronal currents, flowing along the axon during an action potential.

1.1. Detection platform

Sensors featuring tunnelling magnetoresistance were deposited by magnetron sputtering and structured by optical lithography, resulting in chip consisting of 12 magnetic tunneling junction (MTJ) sensors for two-point electrical measurement, with a sensor area of $3\ \mu\text{m} \times 40\ \mu\text{m}$. A linear sensor transfer curve with low hysteresis is needed in order to accurately track external signals. Such features were obtained by combining the effect of the shape anisotropy and the thickness of the free ferromagnetic layer in the superparamagnetic regime [2].

A custom multi-channel lock-in instrument, with a front-end noise down to $10\text{nV}/\sqrt{\text{Hz}}$ was developed in order to maximize the signal to noise ratio (SNR).

1.2. Neuronal signal simulations with artificial current lines

In order to simulate the propagation of the current across the neuronal cells and to evaluate the detection limit of the sensors, artificial current lines were fabricated on top of the MTJs.

Au current lines were microfabricated on top of the sensors via optical lithography and magnetron sputtering. The magnetic field generated by the current lines in correspondence of the sensor surface was estimated by modelling the current line as a plane with infinite length and a $10\ \mu\text{m}$ width.

Measurements were carried out by recording the change of the resistance of the sensor, when a current was injected on the Au line. Figure 1(a) shows the sensor response to different current pulses, measured applying a voltage of 10mV , modulated at a frequency $f = 40\text{kHz}$ in order to reduce the $1/f$ noise, across the MTJ, and a uniform external DC magnetic field of $4.5\ \text{mT}$. The latter bias field was applied in order to set the sensor in the most sensitive region of its characteristics. The change in the sign of the output signal upon supply of current pulses with opposite direction, confirms a magnetoresistive detection. Further measurements were carried out as a function of the voltage applied across the sensor and of the magnetic bias, in order to identify the best working conditions and the lowest detectable current. Preliminary results, shown in figure 2(b), reports a minimum detectable current up to $20\ \mu\text{A}$, with a $\text{SNR}=3$, to which corresponds a magnetic field up to $1\ \mu\text{T}$.

1.3. Perspectives

Despite our current detection limit, around $1\ \mu\text{T}$, makes the recording of the magnetic field arising from single neurons challenging, it enables the platform to be used with multiple cells are involved, as it is in the case of brain slices. In this framework, an experimental setup was developed in order to detect the currents arising from electrically stimulated brain slices. Such biological entities are expected to generate a magnetic field in the order of a few μT [3]. The platform, consisting of a culture chamber with the sensors, permanent magnets for biasing the sensors and patch-clamp pipettes for electrical stimulation, is depicted in figure 3(c).

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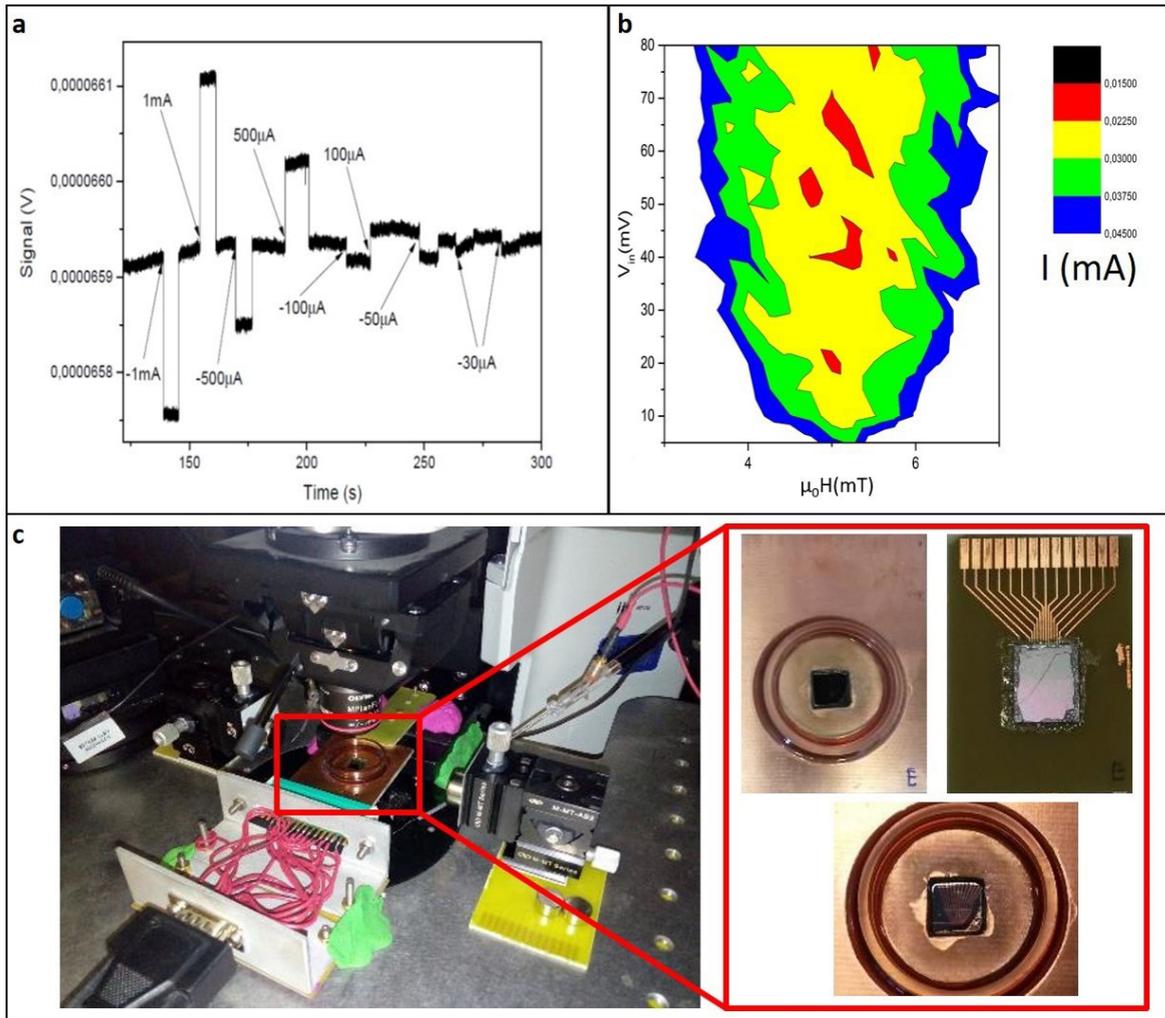


Figure 1. (a) Sensor response to the injection of current in the current line placed above the sensor area. (b) Minimum detected current as a function of the external magnetic field and the voltage across the sensor. (c) Experimental setup for the detection of neuronal signal arising from electrically stimulated brain slice. In the inset: zoom-in view of the culture chamber and the chip featuring a 12 MTJ-based sensor array.