Computational Methods for the Design of Bioinspired Systems that Employ Nanodevices

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Abstract

Biological systems compute by exploiting the rich physics of their natural "nanodevices". In electronics, it is therefore attractive to design bioinspired computing paradigms, which exploit device physics more deeply than digital logic, in order to try and approach the energy efficiency of biological systems. Here, we show how computational tools can assist this research effort.

Introduction

Nanodevices provide large opportunities for electronic systems, offering new features in an extremely energy efficient way. However, they also possess less desirable features like variability. Biology can be an inspiration, in that it is able to compute using very variable nanodevices in a surprisingly efficient way, usually exploiting their device physics deeply, and in highly parallel and error-resilient architectures. It is therefore attractive to develop bioinspired computing paradigms, where device physics is at the core of computation. For example, bioinspired programming of memory nanodevices can naturally lead to complex inference engines, whose properties naturally emerge from device physics, as seen in Fig. 1 [1]. In such approaches, computational electronics tools are useful to investigate device physics, and also to design full architectures and investigate the impact of device properties on their performances.

Device Physics Investigation

When nanodevices are used for bioinspired applications, they are often used in subthreshold or near-threshold regimes where their behavior is richer and energy efficiency is higher. For example, transistors in weak inversion can naturally implement compact artificial neurons [2]. Magnetic tunnel junctions (MTJs, basic cells of magnetic RAM) programmed in weak programming conditions can naturally implement learning-capable "synapses" [1,3] and subthreshold magnetic oscillators can exhibit biosimilar synchronization features [4]. Computational electronics like Monte Carlo methods can allow us to investigate these often poorly understood regimes, as seen in the case of MTJs in Fig. 2 [4]. The result can assist us in designing compact models appropriate for designing bioinspired circuits and systems [4,6].

Architecture Level Work

Bioinspired architectures often require a high number of nanodevices to achieve complex tasks. Credible computational simulation is therefore essential before a system can be fabricated. System level simulations that abstract some features of a design provide the possibility to test large architectures. However, unlike conventional architectures, it is essential to include a relatively detailed description of device physics and not a highly abstracted version. This allows us to investigate the impact of all nanodevices imperfections like variability, noise or drift effects, to which bioinspired systems are often found to be surprisingly tolerant [1], as seen in Fig. 3.

Conclusion

Computational electronics techniques can be extremely useful tools to design bioinspired architectures with nanodevices, as the latter tend to rely on device physics. It is also essential to investigate the impact of nanodevices imperfections, which system level Monte Carlo simulations can address.

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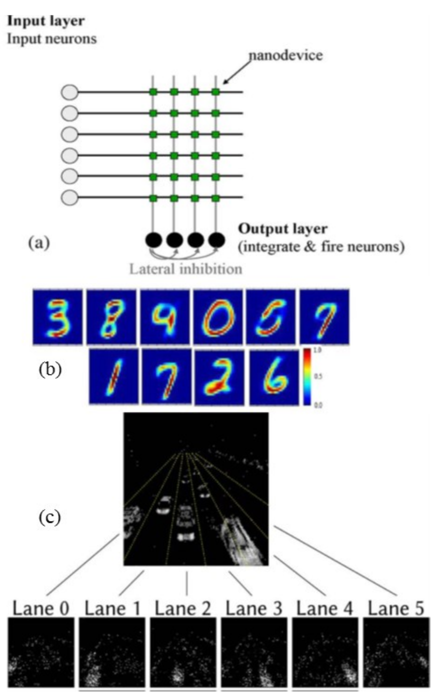

Fig. 1. (a) Basic and simplified schematic of a bioinspired classifier, where memory nanodevices implement artificial synapses. The detailed subthreshold or near-threshold physics of the nanodevices allows the system to learn tasks such as (b) handwritten character recognition or (c) car detection task within a video.

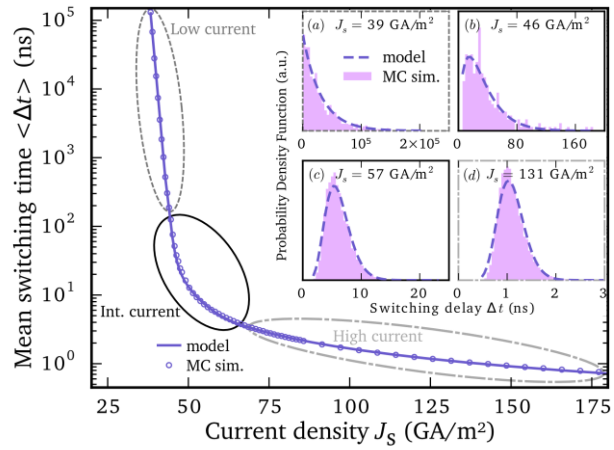

Fig. 2. Monte Carlo simulations of magnetization dynamics allows studying the behavior of MTJs in weak programming conditions. Plot: mean switching time as a function of programming current. Inset: detailed statistics of switching times for several programming currents.

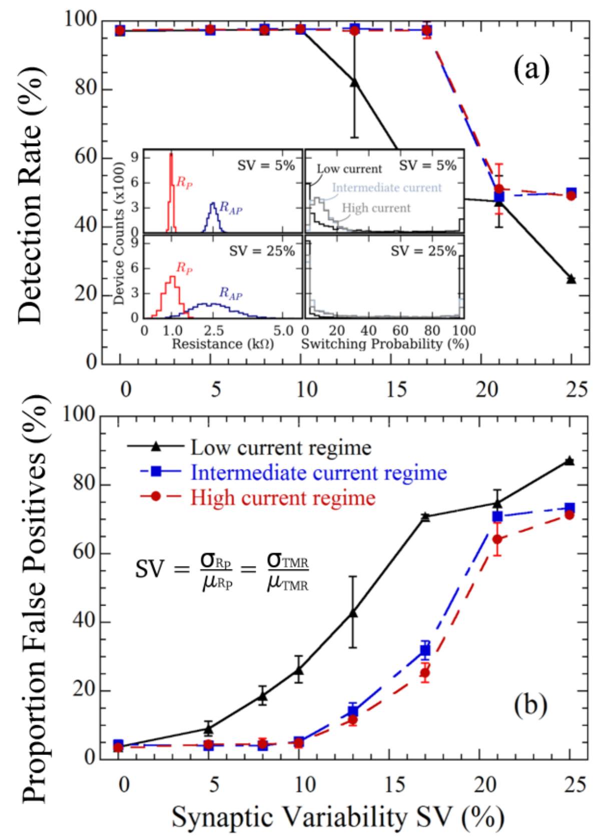

Fig. 3. Monte Carlo simulations of a full bioinspired system performing car detection task using MTJs in weak programming conditions. The simulations include a detailed analytical model of device physics that reproduces Fig. 2, and can include device variations. (a) Detection rate and (b) proportion of false positives on the full task as a function of device variability. Impressive robustness is seen (industrial MTJs have a typical device variability of 5%).