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# A physics-based three dimensional readout model for phase-change probe memory

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## ABSTRACT

A physics-based three dimensional model is developed for the first time to assess the readout performance of phase-change probe memory. The isolated bit responses for reading a crystalline bit with an amorphous background and an amorphous bit with a crystalline background are investigated using this model under a calculated safe readout potential, resulting in a practicable readout current. The readout performances of multiple bit arrays for both cases are also evaluated to establish the influence of noise sources on the readout signal in terms of the inter-track interference and the inter-symbol interference. The results reveal that the configuration having an amorphous bit with a crystalline background exhibits a better anti-interference characteristic than the crystalline counterpart.

## 1. Introduction

The popularity of the digitalisation service for every industry today and the proliferation of the on-line data aggressively trigger the growth of the global digital information at an incomprehensive rate, which has already surpassed 2.8 ZettaBytes in 2012 [1], and will rush toward 40 ZettaBytes by 2020 [1]. Under this circumstance, the increase in the storage capacity of the current data storage devices is strongly anticipated so as to fulfil the need from consumers to store such considerable data. Unfortunately, the current mainstream forms of storage technologies like magnetic hard disks, optical storage discs, and Flash storage suffer from the super paramagnetic limit [2,3], optical diffraction limit [4,5], and device scaling limits [6,7] respectively. In this case, it is urgent to explore alternative storage technologies in order to outperform the growing pace of the digital information.

Phase-change probe memory, as the youngest member of the probe-based memory family, has recently received an intensive attention mainly due to its ability to change the electrical property of the recording media within nanoscale region that can represent binary data [8–18]. In phase-change probe memory, recording is realised by applying an electrical potential via a conductive tip to switch the phase of the recording layer between a highly resistive amorphous phase and a highly conductive crystalline phase. Such a change in the electrical resistivity between these two phases can be detected by means of the readout current, which is used to achieve the readout process. The recording layer used for phase-change probe memory often makes use of $Ge_2Sb_2Te_5$ alloy [19–23], owing to its relative easiness for phase transformation, good stability, and large reading contrast. The consolidation of the performance superiority of $Ge_2Sb_2Te_5$ media together with the extraordinary write/read mechanism makes phase-change probe memory as one of the prospective contenders for next-generation data storage device. As a consequence, phase-change probe memory has recently been studied by worldwide researchers, resulting in some remarkable achievements on the aspects of both simulations [8–13] and experiments [14–18].

However, most of these achievements were only focused on the assessment of the write performance, whereas a detailed study for the readout performance is rarely reported. Due to authors' best knowledge, the readout performance of phase-change probe memory was evaluated so far by only one group of researchers [8] who proposed a 2-D theoretical model to calculate the readout current for an isolated bit case. Although this 2-D model is very time-efficient and provides a preliminary approximation of the readout current, the output data obtained based on this 2-D structure only corresponds to a current per unit track width rather than the 'real' current. In addition, it should be realised that the interference effects that may either result from the inter-track region or from the bits in the adjacent track are inevitable for a

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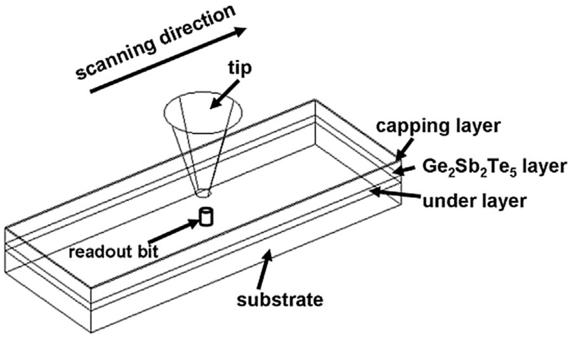

**Fig. 1.** The 3-D geometry of the modelled system.

practical system [24,25]. However, it is not possible for this 2-D model to investigate these interference effects due to the dimension limit. Therefore, in order to overcome these limitations, and to deeply understand the underlying factors that may affect the readout performance of phase-change probe memory, it is very important to develop a physics-based 3-D model to utmostly mimic the practical environment.

## 2. Model outline

An optimal media stack structure that was previously designed for the write performance of phase-change probe memory is adopted for this developed 3-D readout model [8], as shown in Fig. 1.

It consists of a 30 nm $Ge_2Sb_2Te_5$ layer, sandwiched by a 2 nm diamond-like carbon (DLC) capping layer and 10 nm DLC under layer, which are deposited on the top of a Si substrate. The shape of the readout bits in this model were obtained from the previous writing simulation [8]. As depicted in Fig. 2, the crystalline bit was represented by a cubic extending through the entire $Ge_2Sb_2Te_5$ layer, while the amorphous bit was assumed to be semi-ellipsoidal and localised at the top portion of the $Ge_2Sb_2Te_5$ layer.

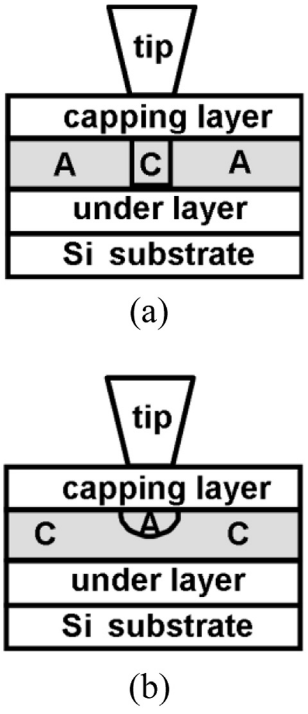

**Fig. 2.** The 2-D cross section of the readout configuration with (a) crystalline bit extending through the whole recording layer, and (b) amorphous bit located on the top portion of the recording layer.

The bit diameter is assumed to be 20 nm for both cases, corresponding to the previous findings [8,10]. The electrical conductivities of the crystalline bit and the amorphous bit are assigned to be 1000 $\Omega^{-1}$ $m^{-1}$ and 0.1 $\Omega^{-1}$ $m^{-1}$, respectively. As the readout functionality completely depends on the measurement of the readout current, it is crucial to design an algorithm that can accurately predict the readout current for a given electric potential. A slightly more general form than Ohm's law to describe the relationship between current density and electric field is given by:

$$J = \delta E, \tag{1}$$

where $J$ is the current density, $\delta$ is the electrical conductivity, and $E$ is the electric field.

As the time span of the readout potential (in the order of ms) [26] is much longer than the charge relaxation time (in the order of ns) [27], the readout system has reached the static state at the end of the applied potential. The static form of Eq. (1) is expressed as:

$$\nabla \cdot J = 0. \tag{2}$$

Considering $E = \nabla V$ ($V$ is the applied potential), Eq. (1) is introduced into Eq. (2) to substitute, resulting in:

$$\nabla \cdot (\delta \nabla V) = 0. \tag{3}$$

Therefore, solving Eq. (3) will give rise to the electric field distribution throughout the $Ge_2Sb_2Te_5$ layer for a given potential, and the current density can be thereafter obtained from Eq. (1). The resulting current density is subsequently used to calculate the readout current by integrating the current density over the area of the bottom electrode (underlayer in this case). All calculations were performed using a finite-element method in Comsol Multiphysics™. The applied potential was connected to the top of the tip (which is roughly equivalent to connecting to the cantilever on which the tip is mounted), while the bottom boundary of the under layer was maintained as ground potential. The corresponding boundary condition required for solving Eq. (3) is illustrated in Fig. 3. It is obvious that the introduction of this 3-D geometry allows for the calculation of the 'real' current as well as the effective cross-talk evaluation since in this case more than one data track can be placed in the recording layer.

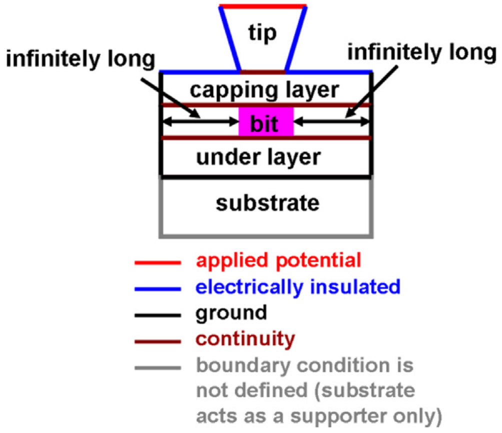

**Fig. 3.** Boundary condition settings for the developed model.