Electro-optical investigations of Ovonic chalcogenide memory devices

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Abstract

The large differences in electrical conductivity and optical reflectivity between the crystalline and amorphous phases of some chalcogenide alloys are used for storing and reading information in Ovonic memory devices. In this paper we present data for a hybrid chalcogenide device that can be programmed with an electric pulse and read optically or vice versa. Such a device could be used for building an hybrid Ovonic cognitive computer or to speed up the operation of a conventional computer as operations induced electrically in one location could be read and transferred optically another.

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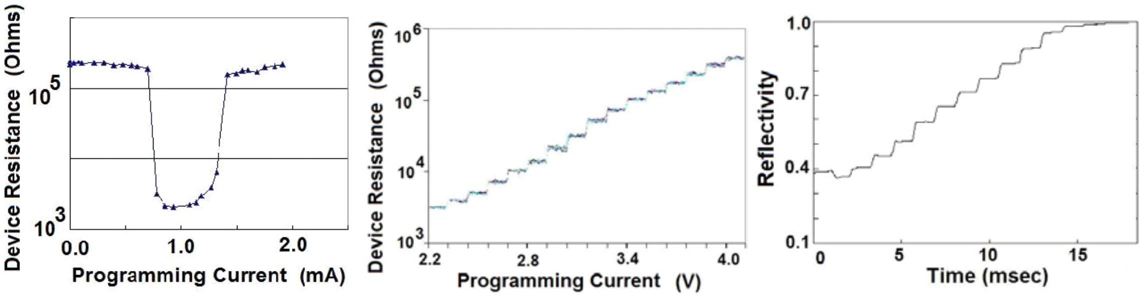
Introduction

From the 1960's the pioneering work of Stan Ovshinsky on switching [1] and memory effects in chalcogenide alloys motivated the field of amorphous semiconductors. Today's developments in device engineering and the demand for commercial products reinvigorated development of Ovonic phase change technologies. The six orders of magnitude change in electrical conductivity and the 2x change in optical reflectivity of the Ovonic chalcogenide alloys enables applications in non-volatile memory switches, rewritable CD, DVDs and BluRay disks. Increasing commercial attention in the Ovonic Universal Memory (OUM) [2] derives from its higher speed, longer life, higher density and greater scalability. These attributes coupled with its non-volatile nature make it an attractive alternative to flash memory devices.



(a) (b) (c)

Fig.1 (a) Programmed resistance vs. various amplitude pulses for OUM devices. (b) multi-state electrical phase change memory and (b) optical multi-state phase change data storage.

A typical change in the resistance of an Ovonic memory device after the application of variable amplitude pulses [2] is shown in Fig.1a. A more careful study of the region on the left hand side of this curve shows that it is possible to have a simple, submicron semiconductor device with function similar to that of neurons, which accumulate input pulse from synaptic connections and fire when a threshold is reached [3, 4]. An amorphous Ovonic memory device accumulates energy from application of multiple constant amplitude pulses to reach a percolation threshold where crystalline material forms a continuous path between two electrodes and the conductivity changes dramatically. Such functionality could be used for encoding information; factoring numbers and most importantly providing the basic device for building the Ovonic cognitive computer. Electrical [4, 5] and optical [6] Ovonic cognitive information processing were announced in 2003.

The right hand side of Fig. 1a, where a gradual transition from the crystalline to the amorphous phase occurs, shows a multi-state storage capability. It has been shown that multiple bits can be stored electrically [2] as shown in Fig. 1b, and optically [6, 7] as shown in Fig.1c. As we will describe, hybrid multi-state storage capability and hybrid cognitive behavior is also possible.

1. Experimental

A Ovonic electrical memory device was used in the multi-state mode of operation. In the hybrid mode of operation the device was programmed electrically and read optically or vice versa. A wire-bonded die was put on an x-y micrometric stage. Two-dimensional reflectivity scans using a 780 nm laser beam were made to locate a particular device. The low reflectivity of the dielectrics (shown as dark color areas in fig. 2, top row) distinguished them easily from the high reflectivity electrodes (light color areas). The point of interest is the via, in the middle of the electrode gap that is filled with the Ovonic memory alloy. The reflectivity and the electrical conductivity depend on the structural state of the device. The fully amorphous phase has the lowest reflectivity and the highest resistance while the purely crystalline phase has the highest reflectivity and the lowest resistance. Intermediate structural states have reflectivity and resistance values between these values.

The devices were initialized to a substantially amorphous state having resistance in the order of 10 kΩ. Electrical or laser pulses with varying duration and amplitude were used to crystallize or amorphize the device and the reflectivity and the electrical resistance were recorded. Crystallization is a slower process than amorphization, so longer pulse durations were used for crystallizing devices and shorter durations were used for amorphizing them. Each device could be programmed electrically and later optically. The sequence could be repeated and/or reversed without changing the performance.

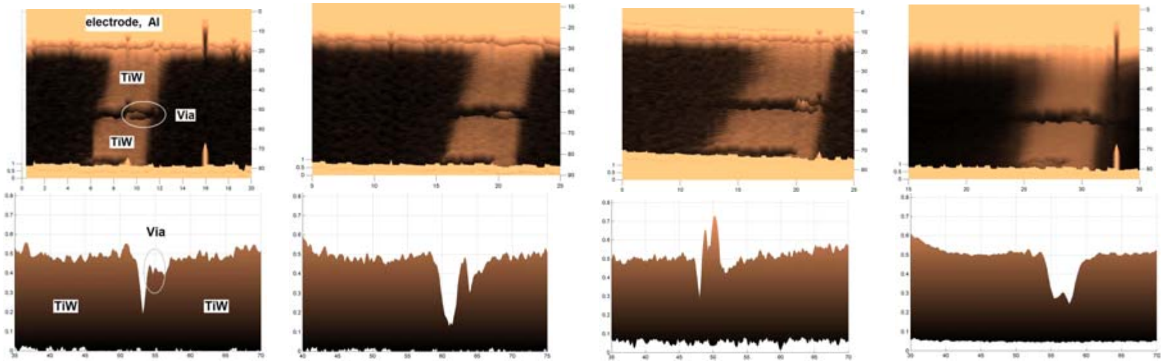
2. Results and discussion

The device was programmed to the amorphous phase (R= 30 kΩ) from the state resulting from a previous programming cycle. A reflectivity scan of the device was made and the data are shown in Fig.2a. In this figure, the top row shows the top view of the electrodes and the via in the middle, and the lower row shows a side view of the same set of data where the relative reflectivity of the via to the electrode material is more evident. Pulses of varying duration and amplitudes were used for programming the device to desired structural states as shown in Figs. 2b to 2d. The device continues to cycle after this experiment.

Major properties of the Ovonic memory devices are based on carefully controlled nucleation and crystal growth processes. The composition of the material was designed to provide the correct number of cross-link bonds and abundant lone pair electrons. This type of composition avoids phase separation during the amorphous/crystalline transitions and guarantees high speed and high life time (>10^{13} cycles) of the device.

The energy of each set pulse (electrical or optical) increases the degree of crystallization of the Ovonic memory alloy, which can be detected by measuring the reflectivity and/or the electrical resistance of the alloy. Fig. 2 shows that intermediate structural states having reflectivity between the lowest of the amorphous phase and the highest of the crystalline phase are easily detectable and the hybrid multi-state storage capability (see Fig. 1b &1c) of those devices is demonstrated.

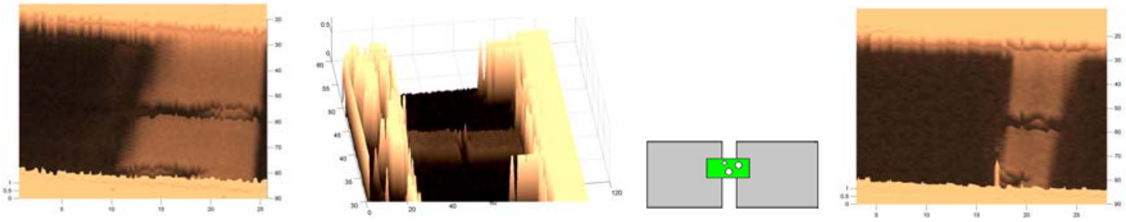
Similarly, hybrid cognitive behavior using either electric or optical pulses could be demonstrated using those devices. It is known that accumulated energy can be used to change the phase of the Ovonic alloy in the cognitive regime. The structural state itself is a record of the accumulated energy [5]. The threshold transition of the device resistance, from high to low values resulting from formation of a percolation path can be detected by measuring the electrical resistance of the device. Similarly, threshold effects can be induced using laser pulses.



a) Reset: R=30 kΩ b) Set: 7.8 kΩ c) Set: 691 Ω d) Reset: R=966 kΩ

Fig. 2. A typical electrical programmed cycle with optical reading. Selective number of intermediate states is shown. Top row, shows the top view of the electrodes and via and lower row, the side view of the same data, where the relative reflectivity intensity of the via to the electrodes is more profound.

In the following we discuss devices that were initialized electrically in the reset/ amorphous phase (Fig. 3a) and then programmed optically. Several laser pulses were applied in different positions of the device. No change in the electrical conductivity was observed. On the other hand, a reflectivity scan shows three small reflectivity peaks in places where the laser beam crystallized the active material (Fig. 3b). A schematic diagram of the location of the dots is shown in Fig. 3c. As seen in Figs. 3b & 3c the spots that define the areas of crystallization do not form a conductive path that could result in a decrease in the electrical conductivity.



(a) (b) (c) (d)

Fig. 3. The change in the reflectivity map of a device after optical programming. (a) as received (amorphous/reset state) and (b) & (d) after laser pulse illumination. (c) is a sketch of the laser crystallization pattern of 3b.

Also, when laser pulses having the appropriate duration and energy were used for resetting a device to a lower resistance (amorphous) state, a decrease of the reflectivity in parts of the via was observed. Fig. 4d shows the reflectivity at the sides of the via, where the laser hit the device, is reduced to levels lower than those of the initial device, resulting almost a ‘triangular’ reflectivity trace.

Our desire to get higher optical power density induced us to focus the laser beam to spots smaller than the electrode separation in our relatively large devices. The laser power did not cover the electrode gap and therefore the induced crystallization and amorphization occurred only in small areas of the via that could not be detected electrically. This technical limitation does not prevent us from believing that the optically induced phase change, detected by changes in the reflectivity, would not be able to induce a change in the electrical resistance of the alloy if all the area between the electrodes was illuminated uniformly.

3. Conclusions

We show that hybrid operation of an Ovonic phase change device is possible. New horizons are opened for a number of applications such as hybrid multi-state data storage, higher speed in conventional computers and providing the hybrid Ovonic cognitive device where the energy is accumulated using electric or laser pulses up to the percolation limit where a large change in the electrical resistance is realized.

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