Analysis of charge-transport properties in GST materials for next generation phase-change memory devices

Fabio Giovanardi
Tutor: Prof. Massimo Rudan
The use of phase-change chalcogenide alloy films to store data electrically and optically was first reported in 1968 and in 1972, respectively.

Early phase-change memory devices used tellurium-rich, multicomponent chalcogenide alloys with a typical composition of $\text{Te}_{81}\text{Ge}_{15}\text{Sb}_{2}\text{S}_{2}$.

Rapidly crystallizing chalcogenide alloys were later reported by several optical memory research groups. These new material compositions, derived from the Ge-Te-Sb ternary system, did not phase segregate upon crystallization like the earlier Te-rich alloys, but instead exhibited congruent crystallization with no large scale atomic motion.

Phase-change materials have been in use for many years for high-volume rewritable CDs and DVDs. With the start of production of phase-change materials for electronic memory, PCM begins to deliver on its promise to expand the usage of nonvolatile memory.
Chalcogenide-GST materials (e.g., Ge$_2$Sb$_2$Te$_5$) can suitably be exploited for manufacturing phase-change memory devices [Ovshinsky, PRL 21 (1968); Kau et al., Proc. IEDM09 (2009)].

While crystalline GST shows an almost Ohmic $V(I)$ curve, amorphous GST exhibits a snap-back behavior.

Modeling the threshold behavior is of the utmost importance for exploiting the GST material in the fabrication of alternative, nonvolatile memories.
Outline

- Qualitative analysis
- Macroscopic model
- Fitting experimental data
- Conclusions
Qualitative analysis

The device is current driven, so the experiments yield one-valued, N-shaped $V(I)$ curves.

N-type behavior in current-driven devices is typically accompanied by the formation of filaments [Ridley, Pr. Phys. Soc. 82, 954 (1963)].

However, in the present case the cross-sectional area is so small that filamentation is not likely to occur.

This investigation keeps the idea of filaments, but makes them to occur only in energy, not in space.

The main transport mechanisms are:

- At low current → hopping processes through localized states [Mott & Davis (1961); Buscemi et al., JAP 106 (2009)].
- At high current → conduction due to electrons occupying extended states (here termed “band electrons”) [Rudan et al. IEEE TED vol.58 no.12 (2011)].
The electron tunnels between traps and remains a low-mobility trap electron.

The electron crosses a thin barrier and becomes a high-mobility band electron.
The whole device is described as a one-dimensional structure made of the series of the amorphous GST material of area $A$, length $L$, with conductance

\[ G_C = \left( \frac{A}{L} \right) q \left( \mu_T n_T + \mu_n n \right) \]

and of a constant resistance $R_S$ due to the heater, crystalline cap, and upper contact.

Letting $G_{CT}$, $G_{CB}$ be the conductance of the trap and band electrons the total resistance can be written as:

\[ R = R_S + \frac{1}{G_C} = R_S + \frac{1}{G_{CT} + G_{CB}} \]
Transition interval — I

Limiting cases

Low conductance

High conductance

$I' = I''$

Low conductance

High conductance

$V$

$I'$

$I''$

$I'$

$I''$

F. Giovanardi
Positive differential conductance

Negative differential conductance

Low conductance

High conductance

Transition interval — II
As impact ionization is not considered and the density of states is taken independent of position, all phenomena are local and spatial uniformity holds. On the other hand, the device is globally neutral. This implies charge neutrality:

\[ n_T + n - N = 0, \quad N \geq n_T, n. \]

Given the general expression of the conductance,

\[ G_C = \left( \frac{A}{L} \right) q \left( \mu_T n_T + \mu_n n \right), \quad N = n_T + n \]

\[ G_C = \frac{A}{L} q \mu_T N \left( 1 + \frac{\mu_n - \mu_T}{\mu_T} \frac{n}{N} \right) \]
A model for the dependence on the driving force is derived by combining the phonon-assisted net recombination with the field-emission generation in steady state \((J, J_K > 0, \ n_{eq} \leq n < N)\) [Rudan et al. IEEE TED vol.58 no.12 (2011)]:

\[
n = \sqrt{\frac{n_I^2}{4} + N n_I} - \frac{n_I}{2}
\]

The ratio between the trap-emission and trap-capture rates for the phonon-assisted transitions is given by:

\[
n_I = n_B \quad \text{and} \quad n_{eq} \ll n_T \approx N + \mu_T e^{\nu(J_I)}
\]

The threshold parameter for the electron emission is:

\[
n_C
\]

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<th>(n_B)</th>
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Experiments show that the low-current branch of the $V(I)$ curve is linear only near the origin, whereas, at relatively higher currents, it exhibits an exponentially increasing behavior. In the model discussed so far, the branch is linear because the mobility of the trap electrons is kept independent of the field.

The following expression has been assumed for the mobility of the trap electrons before snapback:

$$\mu_T = \mu_{T0} \exp \left( \frac{J}{J_F} \right)$$

with $J_F$ being a parameter.
Clearly, an unlimited increase in $\mu_T$ is unphysical. However, at snapback, the vanishing of the trap electron concentration occurs, which makes the contribution of the conductance $G_T$ irrelevant.

The region where the conductance saturates is not affected by the field-enh. phenomenon.

The derivative of $r(J)$ with respect to the current density determines the sharpness of the transition between the low- and high-conductance conditions.
The comparison with experiments has been carried out on devices like the one on the left, shown in F. Xiong, A. Liao, E. Pop, APL 95, 243103 (2009).

Electrodes are made of a broken carbon nanotube, coated with a 10-nm GST layer.
The geometrical factor $A/L$ in the above devices ranges from $10^{-8}$ to $10^{-7}$ cm.

Note:
In the experiments used here the upper branch is related to the crystalline phase.

However, the subthreshold behavior and the switching current are fairly reproduced.

The trap concentration favorably compares with the data reported in Ielmini and Zhang, JAP 102, 054517 (2007).
Increasing or decreasing the length leaves the threshold current unchanged, whereas increasing or decreasing the cross-sectional area leaves the threshold voltage unchanged.

\[ V = \left( R_s + \frac{1}{G_C} \right) \cdot I; \quad I = J \cdot A; \quad G_C = \frac{A}{L} (\mu_T n_T + \mu_n n); \quad V \propto \frac{J \cdot L}{q \cdot (\mu_T n_T + \mu_n n)} \]
The lower branch at low currents can be considered near to equilibrium. If $T$ becomes larger the concentration $n$ of the band electrons becomes dominant. Assuming for simplicity a non-degeneracy condition, the above yields:

$$G_C \approx C_0 + C_1 \exp\left[-E_a/(k_B T)\right], \quad E_a = E_C - E_F > 0$$

with $k_B$ the Boltzmann constant and $C_0, C_1, E_a$ parameters. Note that this result does not contradict the low-temperature conductance expression (Mott’s law of variable-range hopping):

$$G_C \propto \exp\left[-(T_0/T)^{1/4}\right]$$
The above expression has been fitted to the experimental data by Ielmini and Zhang (left) and Pop (right):

It is interesting to note that $E_a = 0.33 \pm 0.01$ eV in both cases.

Parameter $C_0$ is directly related to physical quantities of interest:

$$C_0 = q \frac{A}{L} \mu_T N$$
A model for the voltage snap-back in amorphous-GST memory devices has been proposed.

It describes the device behavior also for the simple, one-dimensional and uniform case.

The model has been tested against experimental $V(I)$ curves.

Agreement has also been found with low-current temperature behavior, this supporting the idea of extended states in the material.