Investigation of thermal resistance and power consumption in Ga-doped indium oxide (In2O3) nanowire phase change random access memory

Bo Jin, Taekyung Lim, Sanghyun Ju, Marat I. Latypov, Dong-Hai Pi, Hyoung Seop Kim, M. Meyyappan, and Jeong-Soo Lee

View online: http://dx.doi.org/10.1063/1.4868537
Published by the AIP Publishing

Articles you may be interested in
Investigation of electromigration in In2Se3 nanowire for phase change memory devices

Thermally efficient and highly scalable In2Se3 nanowire phase change memory

Dependence of the properties of phase change random access memory on nitrogen doping concentration in Ge 2 Sb 2 Te 5
J. Appl. Phys. 107, 104506 (2010); 10.1063/1.3383042

Phase-change memory devices based on gallium-doped indium oxide

Indium selenide nanowire phase-change memory
Investigation of thermal resistance and power consumption in Ga-doped indium oxide (In$_2$O$_3$) nanowire phase change random access memory

Bo Jin,$^1$ Taekyung Lim,$^2$ Sanghyun Ju,$^2$ Marat I. Latypov,$^3$ Dong-Hai Pi,$^3$
Hyoung Seop Kim,$^3$ M. Meyyappan,$^{4, a}$ and Jeong-Soo Lee$^{1, a}$

$^1$Division of IT Convergence Engineering, Pohang University of Science and Technology (POSTECH), Pohang 790-784, South Korea
$^2$Department of Physics, Kyonggi University, Suwon, Gyeonggi-Do 443-760, South Korea
$^3$Department of Materials Science and Engineering, Pohang University of Science and Technology (POSTECH), Pohang 790-784, South Korea
$^4$NASA Ames Research Center, Moffett Field, California 94035, USA

(Received 12 February 2014; accepted 2 March 2014; published online 14 March 2014)

The resistance stability and thermal resistance of phase change memory devices using ~40 nm diameter Ga-doped In$_2$O$_3$ nanowires (Ga:In$_2$O$_3$ NW) with different Ga-doping concentrations have been investigated. The estimated resistance stability (R(t)/R(0) ratio) improves with higher Ga concentration and is dependent on annealing temperature. The extracted thermal resistance (Rth) increases with higher Ga-concentration and thus the power consumption can be reduced by ~90% for the 11.5% Ga:In$_2$O$_3$ NW, compared to the 2.1% Ga:In$_2$O$_3$ NW. The excellent characteristics of Ga-doped In$_2$O$_3$ nanowire devices offer an avenue to develop low power and reliable phase change random access memory applications.

Phase change random access memory (PCRAM) has been widely investigated as a candidate for next generation nonvolatile memory.$^{1, 2}$ The phase change materials (PCMs) such as Ge$_2$Sb$_2$Te$_5$, GeSb, and In$_2$Se$_3$ have been characterized in terms of stability improvement, power reduction, and set/reset efficiency enhancement. Efforts to select a material with higher melting point or to add dopants in PCMs have also been reported wherein the operation voltage could be greatly reduced due to structural advantages and the electrical switching behavior was seen to depend on the Ga-concentration.$^{14}$ Here, we report on the resistance stability ($R(t)/R(0)$) and thermal resistance ($R_{th}$) related to power consumption of the Ga:In$_2$O$_3$ NW with three different compositions (Ga/(In + Ga) atomic ratio of 2.1%, 11.5%, and 13.0%). The Ga:In$_2$O$_3$ NW devices exhibit superior performance compared to other nanowires or thin films.

Single crystal Ga:In$_2$O$_3$ NWs were synthesized by vapor-liquid-solid (VLS) process in a horizontal tube furnace system. Three different amounts of Ga$_2$O$_3$ powder with a molar ratio of 0.05%, 0.1%, and 0.5% mixed with 0.5 g InAs were individually placed in the source zone, and a SiO$_2$/Si substrate coated with ~20 nm Au particles was placed in the growth zone downstream from the source. The temperatures in the source and growth zones were maintained at 730 ºC and 650 ºC, respectively, for 60 min. PCRAM devices were fabricated by using the as-grown Ga:In$_2$O$_3$ NWs with three different compositions on a SiO$_2$ (300 nm)/Si substrate. 100 nm-thick indium-tin-oxide (ITO) as source and drain electrodes were deposited by using radio frequency sputtering system at room temperature and patterned by conventional photolithography. The NW channel regions were passivated with SiO$_2$ thin film (100 nm) in order to keep the NW surface from any reaction with the ambient air.

The as-grown Ga:In$_2$O$_3$ NWs were characterized by a high resolution field emission scanning electron microscope (HR FE-SEM, LEO SUPRA35) and a high-resolution transmission electron microscope (HR-TEM, JEM-2100F) equipped with energy dispersive X-ray spectroscopy (EDS) for chemical composition analysis of individual NWs. The electrical characteristics of the devices were measured by a probe station Keithley 4200-SCS analyzer for current-voltage (I–V) and an Agilent 81110A voltage pulse-generator for set and reset operations, respectively. The external temperature was controlled by a ThermoChuck TPO3010 A/B.

Figure 1(a) shows FE-SEM images of the as-grown Ga:In$_2$O$_3$ NWs with a diameter of ~40 nm on a SiO$_2$ (300 nm)/Si substrate. All NWs with different Ga contents show the same morphology. The crystallinity of the nanowires was confirmed by the HR-TEM as in our previous study.$^{14}$ Figure 1(b) shows HR-TEM image of a 11.5%
Ga:In$_2$O$_3$ NW with diffraction patterns obtained by Fourier transforming as shown in the inset. The stoichiometry of Ga and In of 1.0:46.7, 3.6:27.6, and 3.7:24.7 for the source composition has been obtained from the EDS analysis, and thus, the Ga/(In + Ga) atomic ratio is confirmed as 2.1%, 11.5%, and 13.0%, respectively. Figure 1(c) shows a schematic of Ga:In$_2$O$_3$ NW device and top view SEM image of the fabricated device with ~1.8 μm channel length between two ITO electrodes.

In PCRAM, the resistance in amorphous phase shows a steady increase during the elapsed time, a phenomenon known as resistance drift effect, which is described by a power law

$$R(t) = \left(\frac{t}{t_0}\right)^x R_0,$$  

where $t_0$ is the initial time ($t_0 = 1$ s in this study), $t$ is the elapsed time, $R_0$ is the initial resistance, $R(t)$ is the drifted resistance after time $t$, and $x$ is the resistance drift coefficient. The measured $R(t)/R_0$ ratios for 2.1%, 11.5%, and 13.0% NW devices at room temperature are ~3, ~1.36, and ~1.2, respectively, as listed in Table I and shown in Figure 2(a).

The ratio becomes smaller as Ga-concentration increases, which leads to lower resistance drift according to Eq. (1).

Figure 2(b) shows the resistance at reset state increasing with time for the 11.5% Ga:In$_2$O$_3$ NW device at 300 K and 375 K, respectively. The extracted drift coefficient $x$ and $R(t)/R_0$ ratio were ~0.04 and ~1.36 at 300 K, and ~0.08 and ~1.78 at 375 K, respectively. Since $x$ is proportional to the annealing temperature ($T_A$), the $R(t)/R_0$ ratio increases with annealing temperature.

Studies on the thermal resistance of the devices related to programming power consumption are critical for developing thermally efficient PCRAM devices. Considering that the reset operation of PCRAM is the power limiting step, the higher thermal resistance in crystalline phase can be effective for the reduction in reset power consumption. The relationship between the programming power and temperature in programming operation, derived from Fourier’s equation, is given by

$$T_c = T_{300K} + R_{th} \times P_{prog},$$

where $T_c$ is the temperature of the active region in the NW device, $T_{300K}$ is the room temperature 300 K, $R_{th}$ is the thermal resistance, and $P_{prog}$ is the electrical programming power. Crystallization occurs when the PCM is heated up to its crystallization temperature but below the melting point, whereas amorphization occurs when heated up to its melting point. Here, we assume $T_c$ to be equal to 252°C corresponding to the melting point of Ga:In$_2$O$_3$ material. From Eq. (2), the thermal resistance in crystalline phase was extracted as low as 1.64 x 10$^5$ K/W for 2.1% NW device and 2.22 x 10$^6$ K/W for 11.5% NW device, respectively, as shown in Figure 3(a). Compared to the ~1.37 mW reset power of 2.1% NW device, the 11.5% NW device exhibits 90% reduction in the reset power (~0.1 mW) due to its higher thermal resistance. In order to compare with the thin film devices, the $P_{prog}$, $R_{th}$, and other parameters are summarized in Table II. The 13.0% NW device is not considered because of its discontinuous switching behavior as in our previous work. The thermal resistance of NW devices is higher than that of thin film devices. Moreover, as shown in Figure 3(b), the higher Ga content can lead to higher thermal

<table>
<thead>
<tr>
<th>Ga-concentration (%)</th>
<th>Drift coefficient $x$</th>
<th>$R(t)/R_0$ ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>0.134–0.186</td>
<td>~3</td>
</tr>
<tr>
<td>11.5</td>
<td>0.033–0.054</td>
<td>~1.36</td>
</tr>
<tr>
<td>13.0</td>
<td>0.016–0.042</td>
<td>~1.2</td>
</tr>
</tbody>
</table>

FIG. 2. (a) $R(t)/R_0$ ratio vs. Ga-doping concentration in Ga:In$_2$O$_3$ NW devices. (b) $R(t)/R_0$ ratio of 11.5% Ga:In$_2$O$_3$ NW devices at 300 K and 375 K, respectively.

FIG. 1. (a) FE-SEM image of as-grown Ga:In$_2$O$_3$ NWs on a SiO$_2$/Si substrate. (b) HR-TEM image of an individual 11.5% Ga:In$_2$O$_3$ NW with ~40 nm in diameter. The right top inset represents diffraction pattern obtained by Fourier’s transforming from an individual NW. (c) A schematic of Ga:In$_2$O$_3$ NW device and top view SEM image of the fabricated device with ~1.8 μm channel length between two ITO electrodes.
resistance, and the increased thermal resistance can reduce
the power consumption in reset operation. Figure 3(c)
shows a relation between the $P_{\text{prog}}$ and the $R_{\text{th}}$
of Ga:In$_2$O$_3$ NW and other NW PCRAM devices. One can clearly
observe that the 11.5% Ga:In$_2$O$_3$ NW device is relatively
promising for low-power PCRAM applications compared to
Ge$_2$Sb$_2$Te$_5$, GeTe, and In$_2$Se$_3$ NW devices. Finally, pure
indium and gallium oxide devices did not show any
switching behavior as they are not typical phase change
materials. The phase change mechanism of Ga:In$_2$O$_3$ NWs
will be investigated by in-situ TEM analysis in future work.

In summary, the thermal resistance and related power
consumption of Ga:In$_2$O$_3$ NW PCRAM devices with differ-
et Ga compositions have been investigated. The NWs were
synthesized by a VLS method, and two-terminal Ga:In$_2$O$_3$
NW devices were fabricated. The measured resistance stabil-
ity ($R(t)/R_0$ ratio) shows dependence on Ga-concentration
and annealing temperature with an improvement at higher
Ga-concentration. The extracted thermal resistances are
0.164 MK/W for 2.1% Ga:In$_2$O$_3$ NW and 2.22 MK/W for
11.5% Ga:In$_2$O$_3$ NW, which are much higher than that of
Ga:In$_2$O$_3$ thin film devices. Compared with other PCRAM
NW devices, the 11.5% Ga:In$_2$O$_3$ NWs show more than one
order of magnitude reduction in power consumption. The
enhanced characteristics indicate that Ga-doped In$_2$O$_3$ NWs
are promising for low power and reliable PCRAM
applications.

This research was supported by National Research
Foundation (NRF) (No. 2012R1A2A2A02010432); by the
Basic Science Research Program (2011-0023219) through
the Ministry of Science, ICT and Future Planning, Korea;
and a grant (Code No. 2011-0031638) from the Center for
Advanced Soft Electronics under the Global Frontier
Research Program of the Ministry of Education, Science and
Technology, Korea.

RESISTANCE, AND THE INCREASED THERMAL RESISTANCE CAN REDUCE THE POWER CONSUMPTION IN RESET OPERATION. ❘ FIG. 3. (a) Ga-doping concentration dependent thermal resistance for Ga:In$_2$O$_3$ NW and thin film$^a$ devices, respectively. (b) The higher thermal resistance of NW devices than that of thin film devices leads to a reduction in power consumption. The programming power for 11.5% NW device is as low as 0.1 mW for reset operation with the thermal resistance of 2.22 $\times$ 10$^3$ K/W. (c) 11.5% Ga:In$_2$O$_3$ NW has relatively higher thermal resistance than Ge$_2$Sb$_2$Te$_5$, GeTe, and In$_2$Se$_3$ NWs, leading to lower power consumption.

| TABLE II. Comparison of Ga:In$_2$O$_3$ NW and thin film$^a$ devices on thermal resistance and power consumption. |
|---|---|---|---|---|
| Ga:In$_2$O$_3$ device | Reset voltage $V_{\text{reset}}$ (V) | Electrical resistance $R$ (kΩ) | Power consumption $P_{\text{prog}}$ (mW) | Thermal resistance $R_{\text{th}}$ (MK/W) |
| 2.1% NW | 3.5 | 8.96 | 1.37 | 0.164 |
| 11.5% NW | 3.0 | 88.7 | 0.1 | 2.22 |
| 0.2% thin film$^a$ | 3.9 | 0.6 | 25.4 | 0.009 |
| 5% thin film$^a$ | 5.4 | 6.0 | 4.86 | 0.046 |

$^a$See Ref. 13.