University of Groningen

Influence of electron beam exposure on crystallization of phase-change materials

Pandian, Ramanathaswamy; Kooi, Bart J.; De Hosson, Jeff Th. M.; Pauza, Andrew

Published in:
Journal of Applied Physics

DOI:
[10.1063/1.2710294](https://doi.org/10.1063/1.2710294)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2007

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Pandian, R., Kooi, B. J., De Hosson, J. T. M., & Pauza, A. (2007). Influence of electron beam exposure on crystallization of phase-change materials. *Journal of Applied Physics*, 101(5), 053529-1 - 053529-6. [053529]. <https://doi.org/10.1063/1.2710294>

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Influence of electron beam exposure on crystallization of phase-change materials

Ramanathaswamy Pandian, Bart J. Kooi,^{a)} and Jeff Th. M. De Hosson

Department of Applied Physics, Zernike Institute for Advanced Materials, and Netherlands Institute for Metals Research, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands

Andrew Pauza

Plasmon Data Systems Ltd., Whiting Way, Melbourn Royston, Hertsfordshire, SG8 6EN, United Kingdom

(Received 2 November 2006; accepted 10 January 2007; published online 15 March 2007)

Isothermal crystallization of amorphous Sb_xTe films capped with ZnS-SiO_2 or GeCrN layers was performed using *in situ* heating within a transmission electron microscope. The effect of the electron beam of the microscope on the crystallization process was investigated. It was found that electron irradiation during the crystallization process leads to a continuous increase in the crystal growth velocity. For Sb_xTe sandwiched between ZnS-SiO_2 the effect of the electron beam was equivalent to a temperature rise of about 10 K, without affecting the activation energy for growth. However, for Sb_xTe sandwiched between GeCrN the activation energy for growth was also decreased due to electron beam exposure. The observed variations in the crystal growth rates are attributed to relaxations within the initial amorphous phase initiated by thermal energy and/or electron irradiation. © 2007 American Institute of Physics. [DOI: 10.1063/1.2710294]

I. INTRODUCTION

Phase-change data storage technology is based on the (reversible) switching between two sufficient (meta-) stable phases, amorphous and crystalline, and exploits the differences in physical properties between the phases. Studying the crystallization kinetics of phase-change materials is vital for optimizing the device performance and developing potential materials for storage applications. Doped alloys derived from *eutectic* Sb_xTe , so-called fast-growth materials, hold strong cards for both high-speed and high-density storage requirements.^{1–6} This material is currently used in (the rewritable) optical disk formats including digital versatile disk (DVD), Blu-ray disk,⁷ and high-density DVD (HD-DVD),⁸ and also proposed for the line concept “phase-change random access memory” (PRAM).⁹

Transmission electron microscopy (TEM) is one of the versatile tools used to analyze the crystallization kinetics of phase-change layers, especially when detailed information on both nucleation and growth is required. We have determined both the nucleation and growth parameters separately for Sb_xTe alloy films using *in situ* transmission electron microscopy.¹⁰ It was realized that exposing the sample, during the crystallization process, to the illuminating electron beam of the TEM can significantly alter the crystallization properties.^{11–13} Ignoring the effect of electron beam on the crystallization process could cause a considerable error in the estimated crystallization parameters. For this reason, the effect of electron beam on crystallization should be carefully considered and examined. This work aims at analyzing and understanding the influence of the electron beam of TEM on the isothermal crystallization of amorphous Sb_xTe films sandwiched between various dielectric layers.

II. EXPERIMENT

The TEM sample geometry used in our experiments is schematically shown in Fig. 1. A 20 nm thick amorphous phase-change layer is sandwiched between 3 nm thick amorphous dielectric layers, and this trilayer stack is deposited on a 25 nm thick amorphous Si_3N_4 membrane, which is electron transparent and supported by a Si substrate. These electron-transparent substrates are commercially available, and actually prepared by etching a 500 square micron window on one side of a Si wafer containing Si_3N_4 on the other side. Direct current (dc) and radio frequency (rf) magnetron sputtering techniques were used to deposit the phase-change and dielectric layers, respectively. Phase-change layers with four different Sb/Te ratios ($x=3.0, 3.3, 3.6$, and 4.2) were used for detailed examination. A constant “dopant” level of about

FIG. 1. Sample structure used in TEM experiments.

^{a)}Author to whom correspondence should be addressed; FAX: + 31 50 3634881; electronic mail: b.j.kooi@rug.nl

8 at. % of Ge+In was maintained for all the Sb/Te ratios. This dopant is of crucial importance for the performance of the phase-change material, in particular providing a high activation energy for growth that enables the combination of a good archive stability (low growth rates at low temperature) and high-speed direct overwriting (high growth rates at high temperature). The dielectric capping layers were composed of either 80 at. % ZnS–20 at. % SiO₂ (ZnS-SiO₂) or GeCrN.

A JEOL 2010F TEM operating at 200 kV was used to monitor the crystallization process. The samples were isothermally annealed at various temperatures ranging between 150 and 185 °C within the microscope using a Gatan 652 double-tilt heating specimen holder (model 652 with a model 901 SmartSet hot stage controller). A proportional integral derivative (PID) controller equipped with the holder controls the heating stage temperature within ± 0.5 °C accuracy and provides also a fast ramping rate to attain the set-point temperature without any overshoot.

Note that we measure the temperature of the heating stage, not the temperature of the specimen area that comes only under investigation. The temperature of the analyzed area will be slightly lower than the monitored temperature and will follow the heating stage temperature with a small time lag. This delay in time and the temperature difference between the heating stage and analyzed specimen area will be larger at higher annealing temperatures. As we work below 190 °C, the temperature difference will be on the order of only a few degrees Celsius. Moreover, we performed TEM measurements close to the edges of the Si₃N₄ window. This is because we observed that the temperature difference increases with increasing distance from the edge to the center of the window.

In order to differentiate the effect of electron beam on the crystallization process, the samples were crystallized via two different methods. The samples with Sb/Te ratios 3.0, 3.6, and 4.2 were monitored by TEM throughout the crystallization process; i.e., the samples were at the transformation temperatures continuously exposed to electrons with fixed current densities (~ 1 nA/ μm^2). On the other hand, for the samples with Sb/Te ratio 3.3, the crystallization was carried out without electron beam exposure and for fixed time intervals (in a discontinuous manner). After each interval, the samples were cooled to nearly room temperature (below 30 °C) for measurements; i.e., these samples were not exposed to electron beam at elevated temperatures.

Nucleation and growth of crystals was monitored in bright-field mode of the TEM on a fluorescent screen and the images were digitally recorded using a charge-coupled device (CCD) camera. An optimum magnification of 40 000 $\times$ (corresponding to 10.4 μm^2 field of view on the camera) within the TEM was selected. This magnification was high enough to clearly see the crystal front and at the same time low enough to monitor the growing crystals for a number of frames. During each isothermal crystallization process, the crystal radius was accurately measured as a function of the annealing time.

FIG. 2. TEM images showing growing crystals, in an amorphous matrix, as a function of annealing time without electron exposure. The images were recorded during crystallization, at 180 °C, of a Sb_{3.3}Te film sandwiched between GeCrN layers.

III. RESULTS

A. Determination of the growth parameters

During the process of crystallization at elevated temperatures, nucleation starts after a certain incubation time, which is defined as the time taken by the sample, after reach-

FIG. 3. Position of the crystal-growth front as a function of annealing time (t) for an electron-beam exposed and unexposed Sb _{x} Te sample. An increase of the growth rate with time is observed for both samples crystallized with and without electron irradiation. Such an increase indicates relaxation of the amorphous phase allowing faster growth rates.

ing the annealing temperature, to show a visible nucleus. We found a variation in incubation time with annealing temperature, Sb/Te ratio, and capping layer type. Example TEM images of the isotropic growth of Sb _{x} Te crystallites in an amorphous matrix as a function of annealing time are shown in Fig. 2. This example is for a GeCrN sandwiched Sb_{3.3}Te film annealed at 185 °C. During the isothermal annealing process, the size of the crystal increases more or less linearly with time; i.e., the crystal growth velocity is nearly constant, implying an interface controlled growth mechanism. Careful analysis, however, shows that the growth rate is slowly, but significantly increasing with time. We observed such an increase in both type of samples, i.e., in the (i) samples crystallized under the electron beam exposure and (ii) samples crystallized in the absence of the electron beam. Hereafter, the above-mentioned two sample types will be referred to in brief as “exposed” and “unexposed” samples, respectively. In the unexposed Sb_{3.3}Te films the increase in growth rate with time cannot be an artifact caused by a slowly increasing temperature during the course of growth (whereas it is difficult to prove this artifact to be absent in the case of the exposed films). An example of the increasing growth rate with time from both exposed and unexposed Sb _{x} Te samples is presented in Fig. 3. This increase in growth rate is attributed to *thermally* activated relaxations. It will be shown below that relaxations activated by electron irradiation also result in an increase in growth rate.

The growth velocity increases strongly when the isothermal crystallization (annealing) temperature is increased. An example of the variation in crystal radius as a function of time at various annealing temperatures without electron exposure is shown in Fig. 4. This example holds for Sb_{3.3}Te film sandwiched between ZnS-SiO₂ layers. Neglecting the time dependence, the growth velocity can be described by Arrhenius-type temperature dependence,

FIG. 4. Average crystal radius (r) as a function of time (t) at various isothermal annealing temperatures in Sb_{3.3}Te films sandwiched between GeCrN layers indicating a growth rate that is strongly activated by temperature.

$$V_g(T) = C_g \exp\left(\frac{-E_g}{k_B T}\right), \quad (1)$$

with V_g : growth velocity, T : annealing temperature, E_g : activation energy for crystal growth, C_g : pre-exponential constant, and k_B : Boltzmann’s constant. The activation energy can be calculated from the slope of the straight line obtained by plotting $\ln(V_g)$ vs $1/T$. The intercept corresponds to the pre-exponential constant. Such Arrhenius plots were drawn for the electron beam exposed and unexposed Sb _{x} Te films. The effect of the electron beam on the crystallization of ZnS-SiO₂ and GeCrN capped Sb _{x} Te films are discussed in the following two sections.

B. Effect of electron beam on ZnS-SiO₂ capped Sb _{x} Te films

Figure 5 compares the Arrhenius plots of ZnS-SiO₂ capped Sb _{x} Te films crystallized with and without the electron beam exposure. Activation energy for crystal growth calculated for these samples is listed in Table I. The results show that the activation energy does not change significantly due to the exposure to the electron beam during crystallization. Note that the comparison made between the electron beam exposed and unexposed samples is not straightforward, since

FIG. 5. Arrhenius plots of the growth rate (V_g) as a function of the annealing temperature (T) showing the effects of electron beam exposure on the crystallization of Sb _{x} Te films sandwiched between ZnS-SiO₂ layers. From the figure it can be deduced that the growth rate is accelerated (independent of temperature) about 3 times by electron irradiation.

TABLE I. Activation energy for crystal growth (E_g) for Sb_xTe films sandwiched between ZnS-SiO_2 layers.

Sb/Te ratio	Electron beam exposure	E_g (eV)
3.3	Unexposed	2.7 ± 0.4
3.0	Exposed	2.7 ± 0.1
3.6	Exposed	3.1 ± 0.3
4.2	Exposed	2.9 ± 0.1

the electron beam exposed samples ($\text{Sb}_{3.0}\text{Te}$, $\text{Sb}_{3.6}\text{Te}$, and $\text{Sb}_{4.2}\text{Te}$) differ in composition from the unexposed sample ($\text{Sb}_{3.3}\text{Te}$). However, by (linearly) interpolating the results for $\text{Sb}_{3.0}\text{Te}$, $\text{Sb}_{3.6}\text{Te}$, and $\text{Sb}_{4.2}\text{Te}$ a good comparison with the result for $\text{Sb}_{3.3}\text{Te}$ can still be made. From Fig. 5, it is clear that the growth velocity increases when the crystallization is performed under electron beam exposure. The growth velocity is at least three times higher in the electron beam exposed samples than the unexposed one. This difference, which is independent of temperature, can be explained consistently by a temperature increase of about 10 K due to the electron irradiation. However, instead of just a temperature change other physical processes actually can be at the basis of the observed change in growth velocity.

C. Effect of electron beam on GeCrN capped Sb_xTe films

In Fig. 6, the growth velocity is plotted as a function of annealing temperature for the exposed and unexposed Sb_xTe films sandwiched between GeCrN layers. Activation energies calculated for these samples are listed in Table II. The samples exposed to the electron beam during crystallization show at least 30% lower activation energies than the unexposed one. The electron beam exposed samples show increased crystal growth velocities compared to the unexposed sample. Difference in the growth velocity, between the exposed and unexposed samples, decreases with increasing annealing temperature. Quantitative measurements show that the growth velocity increases more than 50 times at lower annealing temperatures ($\sim 150^\circ\text{C}$), and increases about 4

FIG. 6. Arrhenius plots of the growth rate (V_g) as a function of the annealing temperature (T) showing the effects of electron beam exposure on the crystallization of Sb_xTe films sandwiched between GeCrN layers. From the figure it can be deduced that the electron beam increases the growth rate about 50 times at 150°C and about 4 times at 185°C .

TABLE II. Activation energy for crystal growth (E_g) for Sb_xTe films sandwiched between GeCrN layers.

Sb/Te ratio	Electron beam exposure	E_g (eV)
3.3	Unexposed	3.0 ± 0.4
3.0	Exposed	1.8 ± 0.1
4.2	Exposed	2.0 ± 0.2

times at higher temperatures ($\sim 185^\circ\text{C}$). This difference in growth velocity probably will disappear at higher temperatures.

IV. DISCUSSION

As-deposited films prepared by sputtering techniques are generally in noncrystalline state with a considerable amount of residual stresses. These stresses are mainly due to the presence of sputtering gas (argon) atoms within the film and/or continuous bombardment of ions/particles on the growing film. The free-energy state of the as-deposited film is not stable and hence will try to attain a relatively stable state. There are two relatively lower free-energy states associated with the multielement phase-change alloy films, namely (1) crystalline and (2) relaxed or partially relaxed amorphous state. The term relaxed or relaxation means here local atomic rearrangements leading to a release of residual stresses and/or Ar atoms. In a relaxed amorphous phase the residual stress level will be zero or at least lower than the as-deposited samples. Relaxation in the solid state is generally initiated by thermal energy. However, it can also occur under the influence of nonthermal means (e.g., photons) or by both thermal and nonthermal processes.

In agreement with this discussion is our observation that relaxation effects are pronounced in the presently studied sputtered films (see also Ref. 13) and were not detected in our previous study on electron-beam evaporated phase-change films.^{11,12} However, a possible role of the dielectric layers cannot be excluded, because in our previous study the phase-change layer was directly evaporated on the Si-nitride membrane, whereas in the present work they are also sandwiched between thin dielectric layers and the Si-nitride is thicker (25 instead of 10 nm). Therefore, the relaxations (of stresses or the release of Ar from the film) within the present phase-change films are more constrained here, may not occur very quickly, and are therefore more apparent.

Previous literature shows that the free-energy state of a fully or partially relaxed amorphous phase is in between the unrelaxed (as-deposited) and crystalline states.¹⁴⁻¹⁷ The relaxed material, therefore, can significantly differ in physical properties compared to the unrelaxed one. Figure 7 shows the free-energy states of the as-deposited, relaxed, and crystalline phases.

Laser-induced relaxation was studied by Morilla *et al.* in sputtered amorphous $\text{Sb}_{0.87}\text{Ge}_{0.13}$ films.¹⁷ They found that the relaxed material had a lower crystallization temperature, a lower activation energy for crystal growth, and a higher crystal growth velocity than the as-deposited one. Vega *et al.* obtained a relaxed amorphous phase of Ge by melting and rapidly solidifying the as-sputtered amorphous phase using a

FIG. 7. Schematic representation of various (stable- and metastable) phases and their free-energy states associated with a sputtered phase-change film. G_{a1} , G_{a2} , and G_c are the Gibbs free energies of the as-deposited amorphous, relaxed amorphous, and crystalline phases, respectively. ΔG_1 and ΔG_2 are the change in Gibbs free energy of the as-deposited amorphous and relaxed amorphous phases with the crystalline phase, respectively. This figure is adapted from Ref. 15.

laser.¹⁶ It was found that the relaxed amorphous phase needed a relatively lower laser energy (density) to crystallize it. Thermally activated relaxation in amorphous Ge films (prepared by noble gas, Ar or Xe, implantation technique) was studied by Donovan *et al.* and the reduction in Gibbs free energy of the as-deposited amorphous material due to relaxation process was reported.¹⁴

The effect of the electron beam on the crystal growth velocity and activation energy for crystal growth in Sb_xTe film we observed is quite comparable with the observations of Morilla *et al.* (Ref. 17). They showed a large reduction in activation energy (>80%) as an effect of laser relaxation. This is a much stronger effect as compared to our case, where we found about 30% reduction in activation energy due to the electron beam in GeCrN capped Sb_xTe films. Morilla *et al.* put forward an explanation based on the Gibbs free energy, which reduces when the as-deposited material is relaxed. However, we present an alternative explanation based on a reduced viscosity or a better structural matching at the amorphous/crystalline interface in the phase-change material. These phenomena can lead to the observed reduction in the activation energy for growth.

As a starting point a more general equation than Eq. (1) for the interface velocity can serve,¹⁸

$$V_g = C_g \exp\left(-\frac{E_g}{kT}\right) \left[1 - \exp\left(\frac{\Delta G}{kT}\right)\right], \quad (2)$$

which can be derived at the atomic scale where two atomic positions on both sides of an (amorphous-crystalline) interface are considered with a Gibbs free-energy difference ($\Delta G < 0$). E_g is an activation energy required for an atom to jump across the interface and C_g is equivalent to an attempt frequency (ν) times jump distance (d). Note that ν can also be strongly temperature dependent (see below). At the melting temperature (T_m), ΔG is zero for the bulk amorphous and crystalline phases and its value becomes increasingly more negative at lower temperatures. All the relevant previous measurements (e.g., of Morilla *et al.*), including ours, were performed at relatively low temperatures (just) above the glass transition temperature T_g , but well below T_m . There-

fore, it can be expected that ΔG is not small and also not strongly changing within the temperature interval of the measurements. Hence, the last term in Eq. (2) cannot be relevant to explain the observed changes. Even more important, relaxations within the amorphous phase definitely reduce the driving force ΔG for the growth process (cf. Fig. 7) and thus should reduce the growth rate. This is contrary to the present and all the previous (referred) observations. This reduced driving force after relaxation definitely will be there, but is apparently overwhelmed by a reduced E_g and/or increased C_g .

Relaxation within the amorphous phase may lead to a much better compatibility at the interface with the growing crystal and consequently may reduce E_g and/or increase C_g . Relaxations within the amorphous phase may also lead to a reduced viscosity at the same temperature of the phase-change material. The viscosity is often taken according to the Stokes-Einstein relation directly proportional with the reciprocal of the jump attempt frequency $1/\nu$.^{19–21} In some cases the viscosity is described by an Arrhenius temperature dependence.^{21–24} However, in most cases the strongly temperature-dependent Vogel-Fulcher-Tammann (VFT) relation, which holds particularly in the appropriate temperature range here, $T_g < T < T_g + 100$ K, is used to describe the viscosity η .^{25–29} In both cases changes in viscosity due to relaxations can change the effective activation energy for growth as obtained using Eq. (1) and as measured in this way by us and Morilla *et al.* It will definitely have a large impact on the growth rates, because at low temperatures (e.g., just above T_g) the viscosity is the dominant physical quantity governing the crystal growth rate, as the driving force for crystallization is high, but the atomic mobility is (too) low.

Within this context it is particular interesting to mention the potential effects of irradiation with high-energy electrons, which apart from a small thermal effect are, for instance, bond breaking (radiolysis), knock-on-collisions that displace whole atoms, and for semiconductors the production of electron-hole pairs. Also, for phase-change materials it has been put forward that laser irradiation not only melts the material by heat, but also creates electron-hole pairs which “generates a new fluidlike state,” i.e., effectively reduces the melting temperature of the phase-change material.³⁰ Therefore, most of the effects of the electron beam may promote atomic mobility, i.e., reduce the viscosity and increase the growth rate in accordance with the observations.

The role of various dielectric capping layers on the crystallization, without exposure to an electron beam, of Sb_xTe film was reported in our previous article.¹⁰ It was clearly observed that the growth rate depends on the capping layer type. This dependence is observed in the present work as well for both the electron beam exposed and unexposed samples. The effect is small in the unexposed samples but large in the exposed samples. It is, therefore, clear that the electron beam relaxation effect on the growth properties of Sb_xTe films is capping layer dependent. Sandwiching Sb_xTe films with ZnS-SiO_2 layers provides more screening to the relaxations induced by electron beam, whereas GeCrN sandwiching, in particular at low temperatures (150 °C), shows a dramatic increase in growth rates due to electron irradiation.

Although the reason for the influence of capping layer type on the growth properties of the electron beam exposed samples is at present unclear, this is nevertheless of interest for applications because radiation hardness, in this case to high-energy electrons, can be influenced by sandwiching the phase-change layer between a suitable capping material.

V. CONCLUSIONS

Isothermal crystallization of sputtered amorphous Sb_xTe films sandwiched between two types of capping layers, GeCrN and ZnS-SiO_2 , was analyzed using a transmission electron microscope with *in situ* annealing. Crystallization was performed in the microscope with and without electron beam exposure. The crystal growth velocity was strongly increased and the activation energy for growth decreased when the sample was exposed to an electron beam (200 kV, $\sim 1 \text{ nA}/\mu\text{m}^2$) during crystallization. The results are consistent with the previous studies on the laser-induced relaxation in amorphous phase-change layers. Apart from relaxations resulting from electron or laser irradiation, we also observed it due to thermal energy. The increased growth rate and reduced activation energy for growth are explained by relaxations that lead to a better structural matching at the amorphous/crystalline interface in the phase-change material and/or a reduced viscosity of the amorphous phase-change material.

¹H. J. Borg, M. van Schijndel, J. C. N. Rijpers, M. H. R. Lankhorst, G. Zhou, M. J. Dekker, I. P. D. Ubbens, and M. Kuijper, *Jpn. J. Appl. Phys.*, Part 1 **40**, 1592 (2001).

²N. Oomachi, S. Ashida, N. Nakamura, K. Yusu, and K. Ichihara, *Jpn. J. Appl. Phys.*, Part 1 **41**, 1695 (2002).

³P. K. Khulbe, T. Hurst, M. Horie, and M. Mansuripur, *Appl. Opt.* **41**, 6220 (2002).

⁴Y.-C. Her and Y.-S. Hsu, *Jpn. J. Appl. Phys.*, Part 1 **42**, 804 (2003).

⁵M. H. R. Lankhorst, L. van Pieterse, M. van Schijndel, B. A. J. Jacobs, and J. C. N. Rijpers, *Jpn. J. Appl. Phys.*, Part 1 **42**, 863 (2003).

⁶Y.-C. Her, H. Chen, and Y.-S. Hsu, *J. Appl. Phys.* **93**, 10097 (2003).

⁷J. Hellmig, A. V. Mijiritskii, H. J. Borg, K. Musialkova, and P. Vromans, *Jpn. J. Appl. Phys.*, Part 1 **42**, 848 (2003).

⁸D. Chang, D. Yoon, M. Ro, I. Hwang, I. Park, and D. Shin, *Jpn. J. Appl. Phys.*, Part 1 **42**, 754 (2003).

⁹M. H. R. Lankhorst, B. W. S. M. M. Ketelaars, and R. A. M. Wolters, *Nat. Mater.* **4**, 347 (2005).

¹⁰R. Pandian, B. J. Kooi, J. Th. M. De Hosson, and A. Pauza, *J. Appl. Phys.* **100**, 123511 (2006).

¹¹B. J. Kooi, W. M. G. Groot, and J. Th. M. De Hosson, *J. Appl. Phys.* **95**, 924 (2004).

¹²B. J. Kooi and J. Th. M. De Hosson, *J. Appl. Phys.* **95**, 4714 (2004).

¹³B. J. Kooi, R. Pandian, J. Th. M. De Hosson, and A. Pauza, *J. Mater. Res.* **20**, 1825 (2005).

¹⁴E. P. Donovan, F. Spaepen, D. Turnbull, J. M. Poate, and D. C. Jacobson, *J. Appl. Phys.* **57**, 1795 (1985).

¹⁵H. Situ, Z. T. Wang, and A.-L. Jung, *J. Non-Cryst. Solids* **113**, 88 (1989).

¹⁶F. Vega, R. Serna, C. N. Afonso, D. Bermejo, and G. Tejeda, *J. Appl. Phys.* **75**, 7287 (1994).

¹⁷M. C. Morilla, C. N. Afonso, A. K. Petford-Long, and R. C. Doole, *Philos. Mag. A* **73**, 1237 (1996).

¹⁸D. A. Porter and K. E. Easterling, *Phase Transformations in Metals and Alloys* (Van Nostrand Reinhold, New York, 1981), pp. 132–136.

¹⁹B. Hyot, L. Poupinet, V. Gehanno, and P. J. Desre, *J. Magn. Magn. Mater.* **249**, 504 (2002).

²⁰S. Senkader and C. D. Wright, *J. Appl. Phys.* **95**, 504 (2004).

²¹I. Avramov, Ts. Vassilev, and I. Penkov, *J. Non-Cryst. Solids* **351**, 472 (2005).

²²J. Kalb, F. Spaepen, T. P. Leervad Pedersen, and M. Wuttig, *J. Appl. Phys.* **94**, 4908 (2003).

²³K. A. Sharaf, A. H. Abou El-Ela, and A.-Abd. El-Maboud, *Fiz. A* **9**, 67 (2000).

²⁴M. Fontana, B. Arcondo, M. T. Clavaguera-Mora, and N. Clavaguera, *Philos. Mag. B* **80**, 1833 (2000).

²⁵D. R. Uhlmann, *J. Non-Cryst. Solids* **7**, 337 (1972).

²⁶J. Rault, *J. Non-Cryst. Solids* **271**, 177 (2000).

²⁷B. Hyot, L. Poupinet, J. Marty, X. Durand, and P. J. Desre, in *Proceedings of E*PCOS-2004* (www.epcos.org/pdf_2004/09paper_hyot.pdf).

²⁸I. Avramov, *J. Non-Cryst. Solids* **351**, 3163 (2005).

²⁹H. C. F. Martens, R. Vlutters, and J. C. Prangsma, *J. Appl. Phys.* **95**, 3977 (2004).

³⁰M. Okuda, H. Inaba, and S. Usuda, in *Proceedings of MRS Fall Meeting*, Vol. 803, HH5.1 (2003).