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Method and physical mechanism of initialization-free phase-change optical recording

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Abstract

A new method of initialization-free phase-change (PC) optical recording was proposed based on the crystallization kinetics of PC media. It was suggested that two special additional layers could be added to the disk to form a new disk structure for the initialization-free function. The physical mechanism of initialization-free PC optical recording was discussed. A model was proposed to explain the initialization-free method which combined the surface crystallization induced by the additional layer and the temperature change during the sputtering process. The simulation results of the initialization-free disk showed only a slight influence of the initialization-free structure on the writing/erasing properties of the PC recording layer. Experimental results verified the feasibility of the initialization-free method for PC optical recording.

1. Introduction

A rewritable optical disk can write, erase and overwrite information many times and preserve it for long periods without changing. It is widely used for data storage and backup, videos, movies, audio and multimedia. A phase-change (PC) rewritable optical disk has several intrinsic merits [1] compared with other rewritable optical disks, e.g. magneto-optical disks, such as its compatibility with the read-only memory (ROM) of a compact disk (CD)/digital versatile disk (DVD) drive and its excellent direct overwriting capability. Since Ovshinsky [2] reported the switching effect of chalcogenide compounds in 1968, two types of PC materials, GeSbTe-type film [3, 4] and AgInSbTe-type film [5, 6], have been successfully applied to rewritable optical disks such as the phase-change disk (PD), rewritable compact disk (CD-RW), digital versatile disk random access memory (DVD-RAM), rewritable digital versatile disk (DVD $\pm$ RW), digital video recording (DVR) and Blu-ray disk. A PC recording layer in a PC rewritable optical disk has two phases, amorphous and crystalline states. These two states have different optical constants, hence the reflectivities of the phases are different. Recording

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and erasing are achieved by the reversible changes between two phases of PC films when the films are heated by laser irradiation. The amorphous state is obtained by heating the material film with sufficient laser irradiation power to exceed its melting point, then rapidly quenching it to room temperature. The crystalline state is achieved by annealing the film at a temperature between the crystallizing temperature and the melting point. The information at the data storage position is determined by detecting the difference in the reflection of two phases, which are read as either '0' or '1'.

The as-deposited PC recording layer fabricated by a sputtering system is in the amorphous state. It is necessary to directly crystallize the as-deposited films before recording information. This crystallization process from the as-deposited amorphous state to the crystalline state is called 'initialization' [7]. If the as-deposited amorphous state is used as the background state of the PC optical disk, a 'ring-mark' will be left after erasing the recorded information because of the gaussian distribution of the laser beam energy [8] and direct overwriting cannot be achieved. Furthermore, this initialization process enables the reflectivity to be high enough for the focusing and tracking servo. Therefore, the initialization process is very necessary for the conventional PC optical disk.

Some methods have been reported for initializing a PC optical disk. One of the initialization methods is the use of a laser beam [9]. A large light spot is formed by means of a laser beam with a high output. By irradiating the light spot with a disk forwarding at a constant speed, many tracks can be crystallized in a single operation. Other methods to initialize the PD have also been proposed such as using a flashing light [10], dishing, oven heating and induction heating [11] methods. Now most manufacturers are using a laser beam for initializing rewritable PC optical disks because this method has the advantage of small thermal load and the disk is unlikely to crack when the disk is heated a small area at a time. However, the time required for the initialization process using a laser beam is significantly longer than that required for other manufacturing processes in the production line, even up to 6–10 times longer. Moreover, the initialization equipment is very expensive. Therefore the initialization process is the bottleneck in the manufacturing of PC optical disks.

In order to shorten the initialization time, some methods have been proposed. One of the methods is to set up more initializers in a production line, but the product cost would be further increased and the process time is not short enough. Therefore, this new method to eliminate the initialization process of PC optical disks is very interesting. The physical mechanism behind the initialization-free function is most attractive. Moreover, the initialization-free function is very necessary for the reduction of the production time and cost in the production line of rewritable PC optical disks.

In this paper, a new method to realize initialization-free PC optical recording is proposed, the physical mechanism of the initialization-free PC optical recording is discussed and the initialization-free PC optical disk is fabricated.

2. Initialization-free method

An 'initialization-free' method for PC optical recording means a method that can fully eliminate the initialization process of PC optical recording disks, which changes a PC recording layer from the as-deposited amorphous state to the crystalline state. Therefore for an initialization-free PC optical recording disk, its as-deposited state must be in the crystalline state because the PC recording layer in this disk is already crystallized during the sputtering process. For a conventional PC optical disk, the as-deposited PC recording layer fabricated by a sputtering system is in the amorphous state. The easiest method for the crystallization of the PC recording layer during the sputtering process (initialization-free) is to increase the substrate temperature

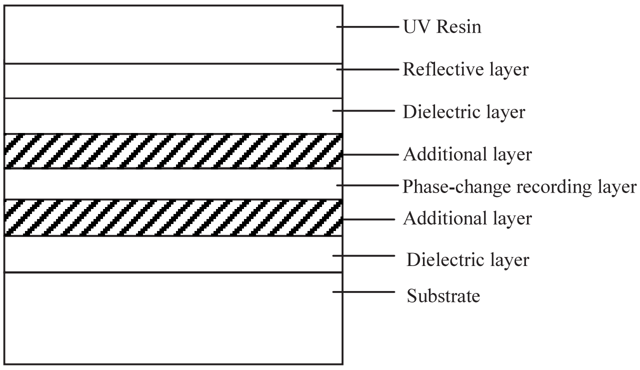

Figure 1. Disk structure of the initialization-free PC optical recording.

over the phase transition temperature of the PC recording layer. However, the phase transition temperatures of GeSbTe [12] and AgInSbTe [13] PC recording materials are higher than 120 °C, while the deformation temperature of polycarbonate substrates of optical disks is about 120 °C. If the substrate temperature is higher than 120 °C, the optical disks on the polycarbonate substrates cannot be successfully written and read out because of the deformation of polycarbonate substrates. Therefore, this method is not suitable for the initialization-free PC optical disk.

Under these circumstances, a new method based on the crystallization kinetics mechanism of PC recording media should be considered. Some discussions about the crystallization kinetics mechanism of PC media have been reported [14–16]. The crystallization kinetics of PC recording media is not only determined by the composition and film thickness of the PC recording layer, but is also significantly influenced by the disk structure and the materials of other layers in the disk, especially the layers (interface layer or dielectric layers) near the PC recording layer. For example, GeN interface layers, which sandwich the PC recording layer, not only lead to a significant improvement in overwrite cyclability because they can restrain sulfur atom diffusion from the dielectric layer to the PC recording layer, but they also accelerate the crystallization process of PC media [17]. Therefore, the material and crystallization properties of the nearby layers are very critical and useful for the crystallization of the PC recording layer.

Based on the above consideration, a new method to realize initialization-free PC optical recording is proposed. Two additional layers of special materials are added to the disk and the PC recording layer is sandwiched between these additional layers so that the crystallization of these adjacent additional layers is utilized to influence and induce the crystallization of the PC recording layer. The two additional layers, which meet some specific crystallization requirements, should first be crystallized during sputtering. Then, based on the known crystallization mechanism of the PC recording layer, it is suggested that they induce crystallization of the PC recording layer during the sputtering. Figure 1 shows the new proposed disk structure of the initialization-free PC optical disk.

3. Physical mechanism

The crystallization of GeSbTe PC media is regarded as being nucleation-dominated [14]. For a nucleation-dominated crystallization process, the nucleation takes place in the whole amorphous area, then new small crystallites grow rapidly. The nucleation speed determines the whole crystallization rate of the GeSbTe PC media. The probability of nucleation (for a particle in an amorphous state to become a crystalline nucleus) per unit time is given by [15, 16]:

$$P_n = \alpha \exp\{-[E_a + A/(\Delta G)^2]/k_B T\}$$

where T is the absolute temperature and A is related to interfacial surface free energy. At the first stage, the interface means the surface between the additional layer (already crystallized) and the PC layer. α is a frequency factor related to atomic vibrations, k_B is the Boltzmann constant, E_a is the activation energy associated with nucleation, ΔG is the excess Gibbs free energy of the amorphous phase over the crystalline phase and $A/(\Delta G)^2$ is the excess free energy for the formation of a stable nucleus.

In the new initialization-free disk structure, the crystallites of the additional layer at the interface between the additional layer and the PC recording layer can be used as the first crystallization centre or nucleus for the crystallization of the PC recording layer. Thus it is not necessary to surmount an energy barrier of thermodynamic origin connected with the formation of a nucleus [18] during the nucleation of a PC recording layer. Moreover, if the crystalline structures (type, lattice constants, atom size) of two materials (additional layer and PC recording layer) are close, the interfacial surface free energy becomes smaller because of a smaller lattice mismatch [19] and the probability of nucleation increases. This means that the interface between the additional layer (already crystallized) and the PC layer will catalyse and induce the surface crystallization of the PC recording layer if the material of the additional layer meets some special requirements. Of course, the temperature change caused by surface bombardment of high-energy sputtering ions during sputtering will significantly increase the probability of nucleation. Therefore, a new model, combining the surface crystallization induced by the additional layer and the temperature change during the sputtering process is proposed, and the new method of initialization-free PC optical recording can be explained by this model.

Based on the mechanism discussed above, the material used as an additional layer to realize the initialization-free function for PC optical disks should meet the following requirements: (1) high crystallization speed, (2) low crystallization temperature, (3) similar crystalline structure, (4) close lattice constant to PC media and (5) transparent at the operating wavelength. The first and second requirements imply that this additional layer can be crystallized during sputtering deposition because of the temperature change during the sputtering process and low crystallization temperature of the additional layer. The third and fourth requirements make the surface-induced crystallization of the PC recording layer available because of smaller lattice mismatch and smaller interfacial surface free energy. The last requirement allows the laser to pass through the additional layer to the PC recording layer.

According to the above five requirements for an additional layer, many materials have been analysed and studied. Among these materials, Sb_2Te_3 is very attractive because of its excellent fast-crystallization characteristics. Sb_2Te_3 film has a very high crystallization speed and the crystallization time is shorter than 30 ns [20]. The crystallization temperature of Sb_2Te_3 film is lower than 100 °C [20] and the deformation temperature of a polycarbonate substrate. Therefore, Sb_2Te_3 film can be crystallized during sputtering deposition because of the surface bombardment of high-energy sputtering ions and it does not cause substrate deformation. As-deposited Sb_2Te_3 film has already been proven to be in the crystalline state by our previous sputtering experiment. Moreover, the crystalline structure of Sb_2Te_3 film is rhombohedral (space group: $R\bar{3}m$) and the same as GeSbTe film. The lattice constants of Sb_2Te_3 film are close to those of GeSbTe film [21]. Therefore Sb_2Te_3 film is suggested as a possible candidate for the additional layer for the initialization-free function of GeSbTe PC recording media.

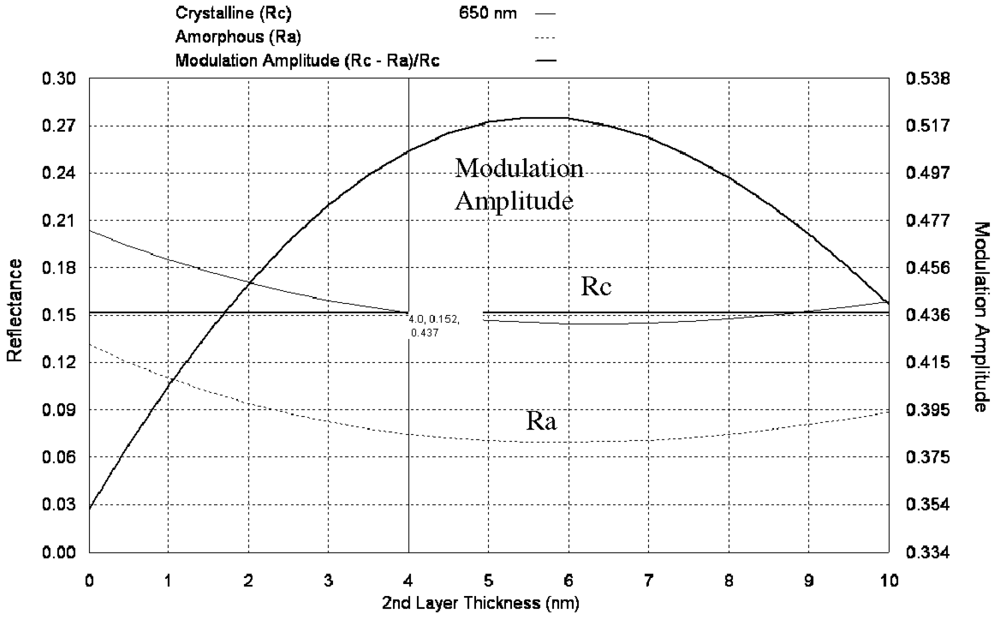

Figure 2. Reflectivity and modulation amplitude of the initialization-free disk with film thickness of LAL.

4. Computer simulation

Compared with conventional PC optical disks, the initialization-free disk structure for PC optical recording has two extra layers, and these additional layers are thermal absorbing layers the same as the PC recording layer. Because every layer, especially thermal absorbing layers, in the disk strongly influences the properties of the disk, the deposition of two additional layers in the initialization-free disk will significantly change the optical and thermal properties. In order to understand the influence of the new initialization-free disk structure on the writing/erasing/readout properties of the disk, the optical and thermal properties of the initialization-free PC optical disk have been simulated and compared. Moreover, the layer structure and the film thickness of each layer in the initialization-free PC optical disk have been optimized and the disk has been re-designed. The simulation was carried out by our in-house phase-change optical disk design (PCODD) software [22], design and analysis software for PC optical disks that provides an integrated design environment and allows users to carry out optical and thermal analyses of PC optical disks accurately and efficiently.

In our simulation, $(ZnS)_{80}(SiO_2)_{20}$, GeSbTe, Sb_2Te_3 and Al–Cr film was used as the dielectric layer, PC recording layer, additional layer and reflective layers in the initialization-free PC optical disk, respectively. The initialization-free disk structure shown in figure 1 was considered. The PC layer and two additional layers were considered as the thermal absorbing layers. The material parameters of the different layers used in our simulation are the same as in our previous paper [22]. The disk and test parameters, such as track pitch, groove geometry, laser, writing pulse shape and rotation speed, follow the DVD specifications for a rewritable disk (DVD-RAM ver 1.0).

The dependence of the reflectivity and modulation amplitude of the disk on the lower additional layer (LAL) is shown in figure 2. The requirements of high modulation amplitude and high reflectivity in the crystalline state (R_c) should be balanced. The modulation amplitude

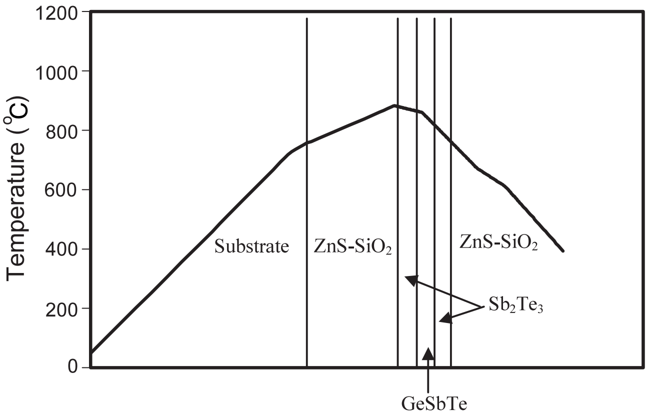

Figure 3. Temperature distribution in the initialization-free disk along the laser incidence.

has a maximum at LAL film thickness of 5.5 nm, but in this case the reflectivities in the crystalline state (R_c) and in the amorphous state (R_a) are too low. If the reflectivity is too low, the stable focusing/tracking servo and good quality read out signal cannot be achieved. Therefore, a LAL film thickness of 4 nm is chosen because of the high modulation amplitude (0.507) as well as a suitable reflectivity (0.152) in the crystalline state. This optical simulation result shows that the film thickness of about 4 nm is appropriate for the LAL. The thermal properties of the disk determine the writing, erasing and overwriting of the disk. The temperature distribution in the disk and writing/erasing properties of the disk were simulated and optimized. The temperature distribution in the disk along the laser incidence after optimization is shown in figure 3. The simulation result shows that the decrease of temperature from the LAL to the PC recording layer is very small. This means that, despite the two additional layers, the temperature on the PC recording layer in the initialization-free PC optical disk does not decrease significantly during the writing and overwriting processes. Therefore, the influence of the new disk structure on the writing/erasing properties of the PC recording layer is very slight based on the simulation.

5. Experimental verification and discussion

In order to verify the new method of initialization-free PC optical recording, PC optical disks with the proposed initialization-free disk structure (illustrated in figure 1) were deposited on DVD-RAM substrates with track pitch 0.74 μm by a Balzers Cube sputtering system. The $Ge_1Sb_2Te_4$ PC recording layer, the additional layer Sb_2Te_3 for the initialization-free function and Al alloy reflective layers were sputtered using the dc magnetron sputtering method. The $(ZnS)_{80}(SiO_2)_{20}$ dielectric layers were sputtered by the rf sputtering method. In the initialization-free PC optical disks, a 20 nm GeSbTe active layer in a conventional DVD-RAM disk is replaced with a 20 nm sandwich active layer, where the GeSbTe film is sandwiched between two Sb_2Te_3 additional layers. The sputtering parameters of different layers used in the initialization-free disk are the same as those of the conventional DVD-RAM disk in our previous papers [23, 24].

Sample A is a conventional PC optical disk. Sample B is a PC optical disk with the initialization-free disk structure illustrated in figure 1. The annealed sample is the sample after annealing by an initializer. The reflectivity of the disk was measured using a

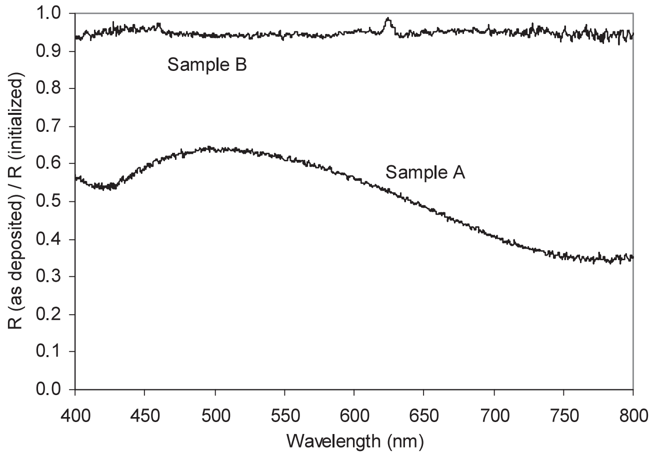

Figure 4. Reflectivity changes of samples A and B between the as-deposited and annealed states.

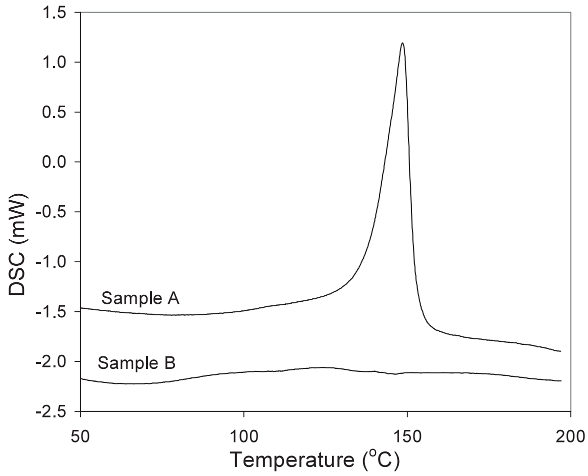

Figure 5. DSC curves of the as-deposited samples A and B.

scanning spectrophotometer (Shimadzu UV-3101PC). Figure 4 shows the reflectivity changes of samples A and B between the as-deposited and annealed states. The reflectivity of the as-deposited sample B is very close to that of the annealed sample.

The differential scanning calorimetry (DSC) heat curves of the samples were tested by a differential scanning calorimeter (Shimadzu DSC-50) system. The DSC curves of the as-deposited samples A and B are shown in figure 5. No exothermic peak is observed in the DSC curve of sample B. This indicates that no glass transition occurred in sample B during the heating process. Therefore, sample B is not in the amorphous state.

The x-ray diffraction data of the samples were collected by an x-ray diffractometer (Philips X'Pert-MRD) using Cu Kα radiation. Figure 6 shows the x-ray diffraction (XRD) patterns of the as-deposited samples A and B. The fcc(220) diffraction peak of sample B is the same as that of the annealed sample A.

The above results show that the as-deposited sample B has been crystallized during the sputtering deposition. This means that sample B is an initialization-free PC optical disk.

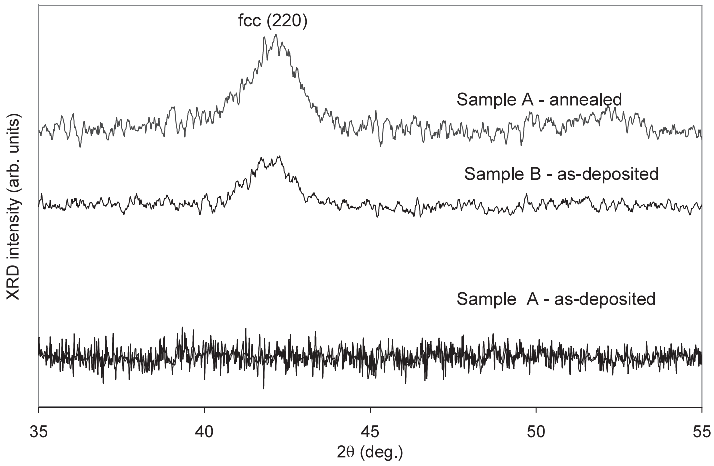

Figure 6. XRD patterns of the as-deposited samples A and B.

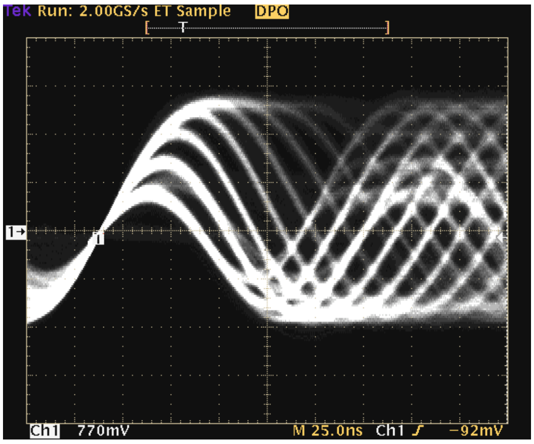

Figure 7. Eye-pattern of the initialization-free DVD-RAM disk.
(This figure is in colour only in the electronic version)

Therefore, the proposed method of initialization-free PC optical recording was proven to be possible and feasible.

While a PC optical disk with an initialization-free disk structure realizes the initialization-free function, this initialization-free disk structure for PC optical recording should avoid affecting the writing/erasing/reading properties of a disk. In order to verify the influence of the initialization-free disk structure on writing/erasing/reading properties of a PC optical disk, the dynamic properties (eye-pattern, jitter, carrier noise ratio (CNR), erasability) of the disks were tested by a Shibasoku LM330A DVD tester. The dynamic test conditions of the initialization-free DVD-RAM disk are the same as those for the test specifications of a conventional DVD-RAM disk.

Figure 7 shows the eye-pattern of the initialization-free PC DVD-RAM disk. The open eyes are clearly observed. The jitter dependence of the initialization-free PC DVD-RAM disk on the overwriting cycles is shown in figure 8. One thousand overwriting cycles were achieved.

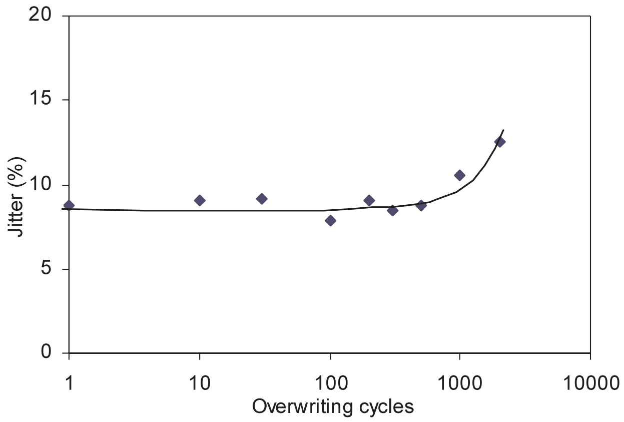

Figure 8. Jitter dependence of the initialization-free DVD-RAM disk on the overwriting cycles.

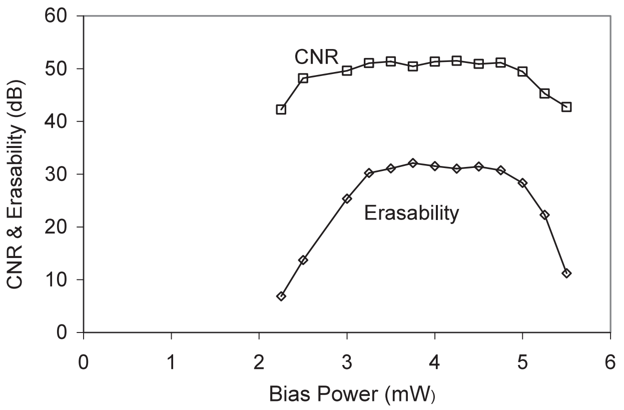

Figure 9. CNR and erasability of the initialization-free DVD-RAM disk on the bias power.

This is the same as for a conventional DVD-RAM disk with $Ge_1Sb_2Te_4$ media. Figure 9 shows the CNR and erasability of a 10 T signal for the initialization-free DVD-RAM disk on bias power. CNR is higher than 50 dB. The erasability is over 30 dB with a wide tolerance of bias power from 3.25 to 4.75 mW and is better than that for a conventional DVD-RAM disk.

These results show that no obvious deterioration is observed in the initialization-free DVD-RAM disk compared with a conventional DVD-RAM disk. Also, the Sb_2Te_3 film is confirmed as a suitable additional layer for the initialization-free PC optical disk.

Moreover, the additional layer can shorten the re-crystallization time of the PC recording layer because of the surface-induced crystallization of the PC recording layer induced by the additional layers during erasing and direct overwriting. Our experiments about the complete erasure time of an initialization-free disk using a static tester have shown that the erasing and overwriting processes can be performed even using a 15 ns laser pulse width. This result supports the proposed physical mechanism of the initialization-free method for PC optical recording.

6. Conclusions

A new method of initialization-free PC optical recording is proposed based on the crystallization kinetics of PC recording media. Two additional layers, which sandwich the PC recording layer, were used for the initialization-free PC optical recording. The physical mechanism of initialization-free PC optical recording is discussed. The combination of surface crystallization induced by the additional layer and the temperature change during the sputtering process gives us a new model to explain initialization-free PC optical recording. Five requirements for an additional layer are proposed and Sb_2Te_3 film is chosen as the most suitable candidate based on the discussion of the mechanism and material analysis. The optical and thermal properties of an initialization-free disk were simulated. The simulation results show only a slight influence of the initialization-free structure for PC optical recording on the writing/erasing properties of the PC recording layer. Initialization-free DVD-RAM disks with Sb_2Te_3 additional layers were successfully fabricated. The experimental results verify that the proposed method of initialization-free PC optical recording is feasible and also show that no obvious deterioration of writing/erasing properties was observed in the initialization-free disk compared with a conventional DVD-RAM disk. Moreover, the Sb_2Te_3 film is confirmed as a suitable additional layer for the initialization-free PC optical disk.

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