Initialization-free Method and Physical Mechanism of Phase Change Optical Disc

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Abstract

The initialization-free method of phase change optical disc was proposed for shortening the process time and reducing the product cost. Two special additional layers were suggested to sandwich the phase change recording layer for initialization-free function. The physical mechanism of the initialization-free phase change optical disc was discussed. The simulation results of the initialization-free disc showed only a slight influence of the initialization-free structure. The Initialization-free DVD-RAM and Blu-ray discs were successfully fabricated. No obvious deterioration of writing/erasing properties was observed in the initialization-free discs compared with conventional discs. Moreover, the initialization-free disc is more suitable for high speed and multi-speed recording.

Keywords: Optical disc, Initialization-free, phase-change, DVD-RAM, Blu-ray

1. Introduction

Since Ovshinsky[1)] reported the switching effect of chalcogenide compounds in 1968, two types of phase-change (PC) materials, GeSbTe type film[2)] and AgInSbTe type film[3)], have been successfully applied to rewritable optical disks such as PD, CD-RW, DVD-RAM, DVD±RW, HD DVD and Blu-ray disc. A phase-change recording layer in a phase-change optical disk has two phases, amorphous and crystalline states. Recording and erasing are achieved by the reversible changes between two phases of PC films when the films are heated by laser irradiation.

The as-deposited phase-change recording layer fabricated by a sputtering system is in the amorphous state. It is required 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 as "initialization"[4)]. If the as-deposited amorphous state is used as the background state of phase-change optical disk, the mark ring will be left after erasing the recorded information because of the Gauss distribution of the laser beam energy[5)], the direct overwriting cannot be realized. Furthermore, this initialization process enables the reflectivity to be high enough for focusing and tracking servo. Therefore, the initialization process is very necessary for the conventional phase-change optical disk. Now most of the manufactures are using a laser beam for the initialization process of the phase-change optical disk because this method has the advantage of small thermal load and the disk is unlikely to crack when the disk is heated in a small area at one time. However, the time required for the initialization process using a laser beam is significantly longer than that other manufacturing processes in the production line, even up to 6~10 times. Therefore the initialization process is the bottleneck of the manufacturing of the phase-change optical disk.

In order to shorten the production time of phase-change optical disks, a new method to fully eliminate their initialization processes - “initialization-free” was proposed[6)] and it is most valuable for the cost-effective manufacturing. Initialization-free DVD-RAM disk, Initialization-free Blu-ray disc, Non-bulk laser erasing (NBLE) phase-change disc, Initialization-free SuperRENS disk have already been reported[7~11)].

In this paper, the initialization-free method and the physical mechanism of the initialization-free phase-change optical disk are discussed, the initialization-free and multi-speed phase-change optical disks are fabricated and compared with conventional disks.

2. Initialization-free Method and Physical Mechanism Discussion

The "initialization-free" disk means that the as-deposited disk is in the crystalline state because the phase-change recording layer in this disk has already been crystallized during the sputtering process. But for a conventional phase-change optical disk, the as-deposited phase-change recording layer fabricated by a sputtering system is in the amorphous state. If the substrate temperature is increased up to the phase transition temperature of phase-change recording layer, the optical disks on the polycarbonate substrates cannot be successfully written and read out because of the deformation of polycarbonate substrates. Therefore, a new method to realize the initialization-free phase-change optical recording based on the crystallization kinetics mechanism of phase-change recording layer was proposed[6)]. The crystallization kinetics of phase-change recording layer is not only determined by composition and film thickness of phase-change recording layer, but also significantly influenced by other layers nearby the phase-change recording layer. Fig.1 shows the initialization-free disk structure of the phase-change optical disk. Two additional layers with special materials are added into the disk and the phase-change recording layer is sandwiched between these additional layers, so that the crystallization of nearby additional layers is utilized to induce the crystallization of phase-change recording layer. Therefore, two additional layers, which can meet some crystallization requirements, should be crystallized firstly during the sputtering, then they are suggested to induce the crystallization of the phase-change recording layer during the sputtering based on the crystallization kinetics consideration of phase-change recording layer. The NBLE phase-change disc structure is different from above initialization-free disc structure and it includes a Sb film to partially separate the AgVInSbTe phase-change layer[9)].

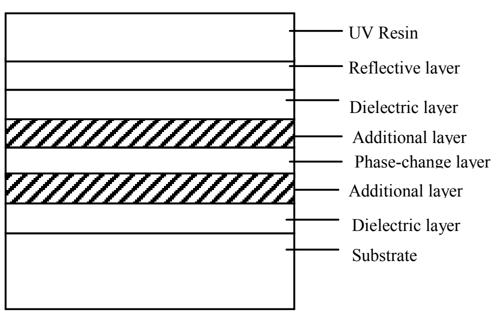

Fig.1 Disc structure of initialization-free phase-change optical recording

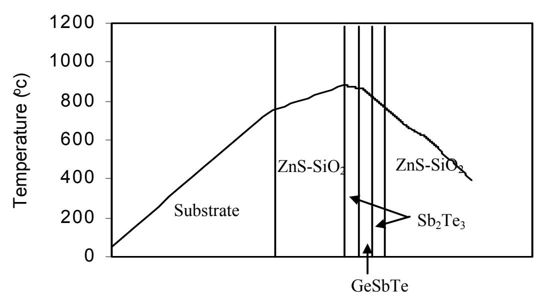

Fig.2 Temperature distribution along the laser incidence

The crystallization of GeSbTe phase-change recording layer is regarded as the nucleation-dominated[12)]. For the 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 GeSbTe phase-change media. The probability of nucleation (for a particle in amorphous state to become a crystalline nucleus) per unit time is given by[13~14)]:

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

where T is the absolute temperature, A is related to interfacial surface free energy. At the first step, the interface means the surface between the additional layer (already crystallized) and phase-change 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 initialization-free disk structure, the crystallite of the additional layer on the interface between the additional layer and phase-change recording layer can be used as the first crystallization center or nuclei for crystallization of phase-change recording layer. Thus it is not necessary to surmount an energy barrier of thermodynamic origin which is connected with formation of a nucleus[15] during the nucleation of phase-change recording layer. Moreover, if the crystalline structures (type, lattice constants, atom size) of two materials (additional layer and phase-change recording layer) are close, the interfacial surface free energy becomes smaller because of smaller lattice dismatch[16], then the probability of nucleation increases. This means that the interface between the additional layer (already crystallized) and phase-change layer will catalyze and induce the surface crystallization of phase-change recording layer if the additional layer material can meet some special requirement. Of course, the temperature increment from surface bombardment of high-energy sputtering ions during sputtering will significantly increase the probability of nucleation. Therefore, the surface crystallization induced by the additional layer and the temperature increment during sputtering process are regarded as the reasons of the initialization-free method of phase-change optical disk.

Based on above mechanism discussion, the material used as an additional layer to realize the initialization-free function for phase-change optical disks should meet the following requirements: (1) high crystallization speed, (2) low crystallization temperature, (3) similar crystalline structure, (4) close lattice constant to phase-change recording layer. The first and second requirements imply that this additional layer can be crystallized during sputtering deposition because of the temperature increment during the sputtering process and low crystallization temperature of additional layer. The third and fourth requirements make the surface induced crystallization of phase-change recording layer available because of smaller lattice dismatch and smaller interfacial surface free energy.

According to above requirements for an additional layer, many materials have been analyzed and studied. For example, Sb_2Te_3 is very attractive for GeSbTe recording layer because of its excellent fast-crystallization characteristic. Sb_2Te_3 film has a very high crystallization speed, and the crystallization time is shorter than 30ns[17]. The crystallization temperature of Sb_2Te_3 film is lower than 100°C[17] and the deformation temperature of polycarbonate substrate. Therefore, the 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 the substrate deformation. Moreover, the crystalline structure of Sb_2Te_3 film is rhombohedral (space group: $R\overline{3}m$) and the same as GeSbTe recording layer. The lattice constants of Sb_2Te_3 film are close to those of GeSbTe recording layer[18].

Compared with conventional phase-change optical disk, the initialization-free disk structure for phase-change optical recording has two more layers, these additional layers are thermal absorbing layers and will change significantly the optical and thermal properties. Therefore, the film thickness of each layer in the initialization-free phase-change optical disk has been optimized and the disk has been re-designed. The disk design and simulation were carried out by our in-house phase-change optical disc design (PCODD) software[19]. After optimized, the temperature distribution in the disk along the laser incidence is shown in Fig.2. The simulation result shows that the decrease of temperature from the lower additional layer to phase-change recording layer is very small. This means that the temperature on phase-change recording layer in the initialization-free phase-change optical disk does not decrease significantly during writing and overwriting process caused by two additional layers for the initialization-free function. Therefore, the influence of the new disk structure of the initialization-free phase-change optical recording on the writing/erasing properties of phase-change recording layer is very slight based on the simulation.

3. Initialization-free DVD-RAM Disk

The phase-change optical disks with the proposed initialization-free disk structure (illustrated in Fig. 1) were deposited on the DVD-RAM substrates with track pitch 0.74μm by a Balzers Cube sputtering system. The GeSbTe phase-change 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 DVD-RAM disks, 20nm GeSbTe active layer in a conventional DVD-RAM disk is replaced with a 20nm sandwich active layer, where the GeSbTe film is sandwiched between two Sb_2Te_3 additional layers.

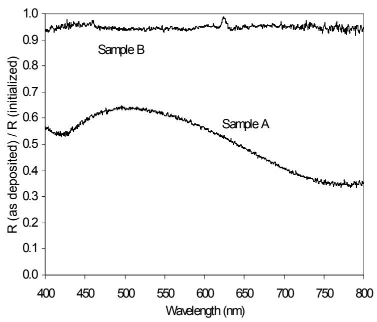

Fig.3 Reflectivity changes between as-deposited and annealed states

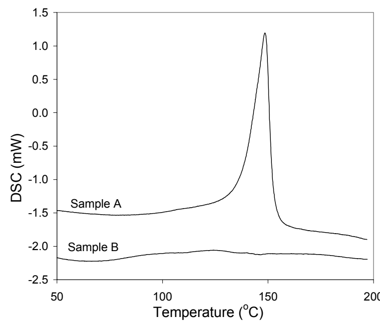

Fig.4 DSC curves

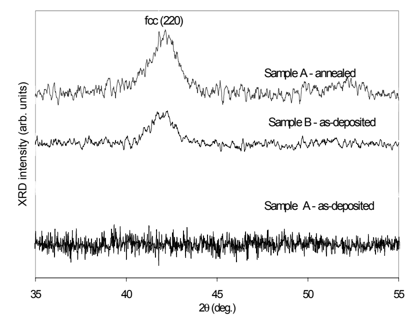

Fig.5 XRD patterns

Sample A is a conventional DVD-RAM disk sample. Sample B is a DVD-RAM disk sample with the initialization-free disk structure. The annealed sample is the sample after annealed by an shibasoku initializer. The reflectivity was measured using a scanning spectrophotometer (Shimadzu UV-3101PC). Fig. 3 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 DSC heat curves were tested by a differential scanning calorimeter (Shimadzu DSC-50) system. The DSC curves of the active layer of as-deposited samples A and B are shown in Fig. 4. No exothermic peak is observed in the DSC curve of sample B. This indicates that 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). Figure 5 shows the 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 initialization-free.

While a phase-change optical disk with an initialization-free disk structure realizes the initialization-free function, this initialization-free disk structure for phase-change optical disk should avoid affecting the writing/erasing/reading properties of disk. In order to verify the influence of the initialization-free disk structure on writing/erasing/reading properties of phase-change disk, the dynamic recording properties (eye-pattern, jitter, CNR, erasability) of the initialization-free DVD-RAM disks were tested by a Shibasoku LM330A DVD tester.

The jitter dependence of the initialization-free DVD-RAM disk on the overwriting cycles is shown in Fig.6. No significant increase of the jitter after 200,000 overwriting cycles was observed in the initialization-free DVD-RAM disk, and no obvious deterioration was shown in the initialization-free disk compared with the conventional DVD-RAM disk. The initialization-free disk structure after repeated overwriting still existed by referring to XPS measurement and TEM observation results about Superlattice-like structure[20]. Fig.7 shows CNR and erasability of

10T signal of initialization-free disk with bias power. CNR is more than 50dB, the erasability is over 30dB with a wide tolerance of bias power from 3.5mw to 4.75mw and better than conventional DVD-RAM disk.

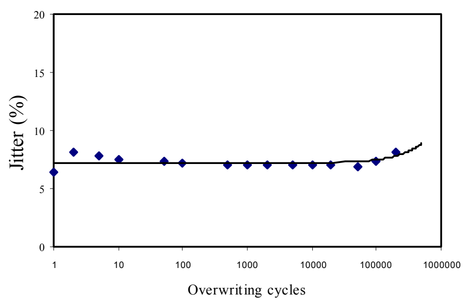

Fig.6 Jitter dependence on overwriting cycles

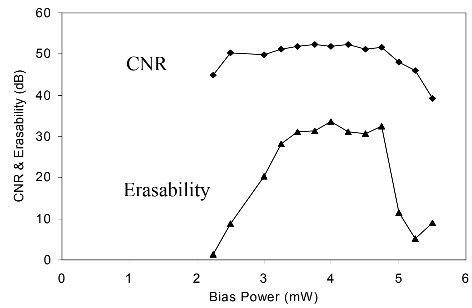

Fig.7 CNR and erasability on bias power

Rewritable phase-change optical disks have several different applications that require different recording speeds. For example, DVD phase-change rewritable optical disks for the video application are usually used at a low rotation speed, which is suitable for real time operation; DVD phase-change rewritable optical disks for the personal computer application are usually used at a high rotation speed to achieve a high data transfer rate. Even for the same application, the recording speed always changes for the customer demand. Therefore, it is necessary for rewritable phase-change optical disks to be compatible with a broad range of recording speed.

Disk structure optimization, thermal balance design and a new writing strategy are proposed to widen the recording speed range of initialization-free DVD-RAM disks for multispeed recording. The Ge-N interface layer, which suppresses the atomic diffusion between the additional layer/phase-change recording layer and the dielectric layer after repeated overwrites, was sputtered by reactive DC sputtering.

After optimized the initialization-free disk structure (such as material, sputtering parameters and film thickness of each layer), the initialization-free DVD-RAM was fabricated for multi-speed. Figure 8 shows the jitter dependence after 1000 times writing on the recording speed for the initialization-free DVD-RAM disk and conventional DVD-RAM disks with $Ge_1Sb_2Te_4$ and $Ge_2Sb_2Te_5$ recording layers. In view of a jitter value less than 13%, the initialization-free disk after disk structure optimization is suitable for the recording at disk rotation speeds from 3.49 to 17.45 m/s, which correspond to the rotation speeds of 1 to 5 times that of DVD-ROM, respectively.

To control the thermal absorption between a crystallized area and an amorphous mark area and improve the recording properties of the initialization-free disk at high speed, a thermal balance disk structure with a Sb thermal absorption control layer[21)] was deposited between the reflective layer and upper dielectric layer using DC magnetron sputtering. Figure 9 shows the jitter dependence after writing 1000 times on the recording speed for the initialization-free DVD-RAM disk with/without an Sb thermal absorption control layer. Results show the initialization-free disk with thermal balance design can support recording speeds from 3.49 to 20.94 m/s, which correspond to the rotation speeds of 1 to 6 times that of DVD-ROM, respectively;

A new writing strategy is proposed to weaken the heat accumulation and increase the cooling rate. This new writing strategy includes a lower peak power of the last write pulse, a new cooling power level between last write pulse and the erase pulse, and a new erasing power at the start of the multipulse train. The jitter of the initialization-free DVD-RAM disk with the new writing strategy including a lower peak power of the last write pulse was measured at a very high recording speed of 22.69 m/s, which correspond to 6.5 times the rotation speed of DVD-ROM. Figure 10 shows the jitter dependence of an initialization-free disk on the peak power of the last write pulse.

The minimum jitter of 14% is achieved at 14.5 mw. Consider a disk jitter of 16.9% with the old writing strategy, the jitter is improved by this new writing strategy which includes a lower peak power of the last write pulse and close to the acceptable level of 13% at a recording speed of 22.69 m/s (6.5 times that of DVD-ROM).

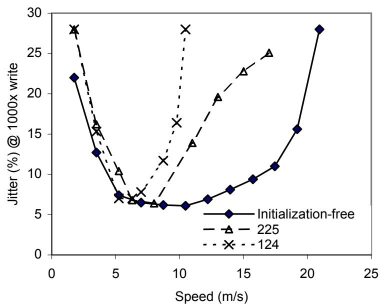

Fig.8 Jitter dependence after optimization

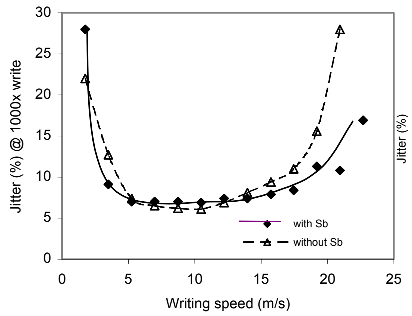

Fig.9 Jitter dependence with/without Sb layer

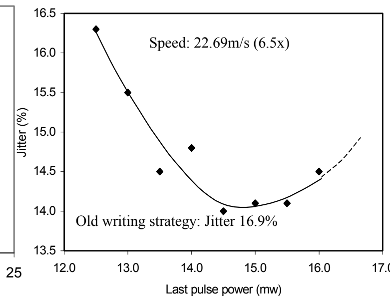

Fig.10 Jitter dependence on peak power of last pulse

Experimental results show the initialization-free DVD-RAM disk have a broad range of recording speeds of 3.49 to 20.94 m/s, which correspond to the rotation speeds of 1 to 6 times that of DVD-ROM, respectively. A crystallization acceleration effect induced by the additional layer and a rapid cooling rate caused by the disk structure of the initialization-free disk are proposed to explain the high speed and multi-speed recording.

4. Initialization-free Blu-ray Disc

The initialization-free Blu-ray Discs (disk structure illustrated Fig.11) were fabricated onto polycarbonate Blu-ray substrates (track pitch: 0.32 μm) using a Balzers Cube sputtering system. The AgInSbTe phase-change recording layer, the additional layer, Sb_2Te_3, $Sb_{70}Te_{30}$, Sb or SnTe, for the initialization-free function, and Al alloy reflective layers were sputtered by DC magnetron sputtering. $(ZnS)_{80}(SiO_2)_{20}$ dielectric layers were deposited by RF sputtering. After the sputtering deposition, the Blu-ray Disc was bonded with a polycarbonate cover layer (thickness: 75μm) using a Steag Hamatech bonding machine. The dynamic recording properties of discs were characterized by a Pulstec DDU-1000 tester with 405 nm wavelength and 0.85 NA using conventional equalizer mode.

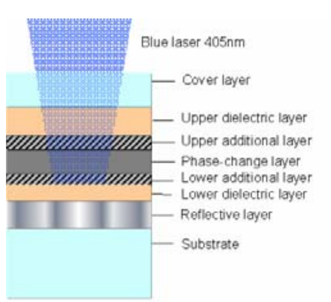

Fig.11 Disc structure of Initialization-free Blu-ray disc

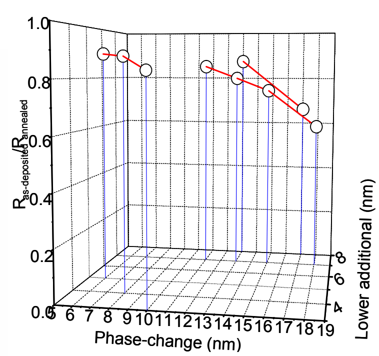

Fig.12 Normalized reflectivity on phase change layer and lower additional layer

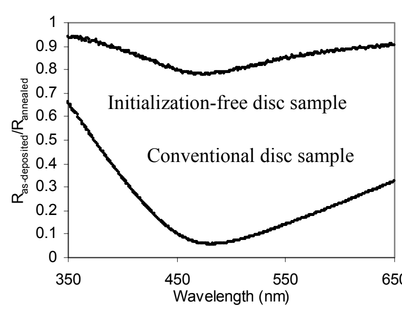

Fig.13 Normalized reflectivity of Initialization-free Blu-ray disc sample

In a Blu-ray Disc, the incident laser passes through the cover layer; thus the temperature increment caused by the sputtering deposition of the reflective layer and the subsequent lower dielectric layer in an initialization-free Blu-ray Disc becomes important. Moreover, a AgInSbTe phase-change recording layer is used in the initialization-free Blu-ray Disc compared with GeSbTe in an initialization-free DVD-RAM disc. Therefore, the different disc structure, additional layers and material matching should be considered. Moreover, the sputtering parameters and thickness of each layer in an initialization-free Blu-ray Disc should be optimized.

To achieve the initialization-free effect by optimized the thicknesses of the phase-change recording layer, additional layers and dielectric layers, the reflectivities of the disc samples in the as-deposited state and the annealed state were compared. Figure 12 shows the dependence of the normalized reflectivity at a 405 nm wavelength on the thicknesses of the phase-change recording layer and lower additional layer. Fig.13 shows the normalized reflectivity of the initialization-free Blu-ray Disc and the conventional Blu-ray Disc. The normalized reflectivity at 405nmn wavelength, i.e. the ratio of the reflectivity in the as-deposited state to the reflectivity in the annealed state, of over 90% was achieved. The results reveal that the as-deposited sample was crystallized during sputtering; this indicates that the Blu-ray Disc sample with the initialization-free disc structure is initialization-free.

The initialization-free disc structure for a Blu-ray Disc should not affect the writing/erasing/reading properties of the disc. Figure 14 shows the jitter dependence of the initialization-free Blu-ray Disc on the direct overwriting cycles at a 5.28 m/s velocity. 2000 direct overwriting cycles with a jitter value less than 13% were achieved, which is the same as that of the conventional Blu-ray Disc. These results show that no obvious deterioration is observed in the initialization-free Blu-ray Disc compared with a conventional Blu-ray Disc. Moreover, the erasability is higher than that of the conventional Blu-ray Disc because the additional layer can accelerate the re-crystallization of the phase-change recording layer as a result of surface-induced crystallization. The initialization-free Blu-ray Disc will be more suitable for high speed recording than the conventional Blu-ray Disc.

After further optimized the disk structure and writing strategy, the initialization-free Blu-ray Disc was fabricated for multi-speed recording. Figure 15 shows the jitter dependence on the direct overwriting cycles for the initialization-free Blu-ray Disc at velocities of 5.28m/s (1x speed), 10.56m/s (2x speed), 13.2m/s (2.5x speed), 15.84m/s (3x speed) and the commercial Blu-ray Disc at velocities of 10.56m/s (2x speed). Results show that the jitter values of the initialization-free disc are less than 13% after 1000 times direct overwriting at the recording speeds from 1x to 3x. However, the jitter of the commercial Blu-ray Disc is high than 20% even after 2^{nd} times direct overwriting at 2x speed. Experimental results show initialization-free Blu-ray Disc has a broad range of recording speeds of 1 time to 3 times, which correspond to the velocities of 5.28m/s to 15.84m/s, respectively.

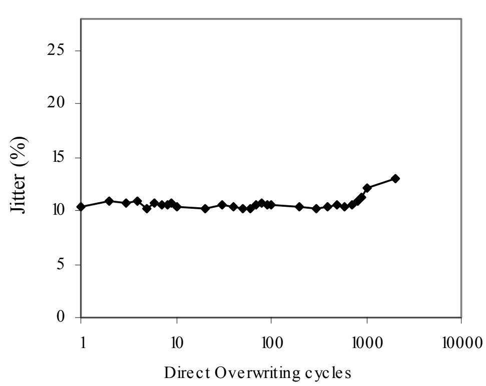

Fig.14 Jitter dependence on overwriting cycles at 5.28m/s

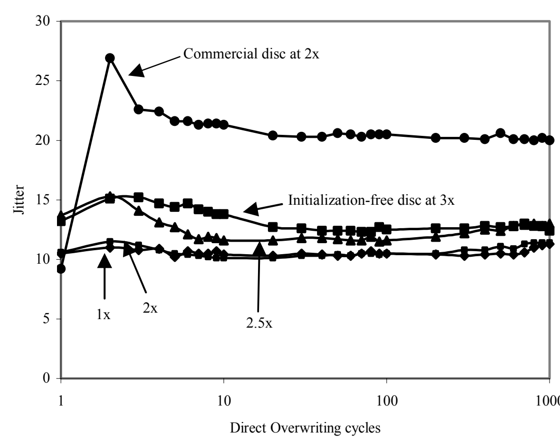

Fig.15 Multi-speed recording of Initialization-free disc

5. Conclusions

The initialization-free method for shortening the process time and reducing the product cost of phase-change optical disks is proposed based on the crystallization kinetics of phase-change recording layer. Two additional layers, which sandwich phase-change recording layer, are used for the initialization-free phase-change optical disks. The physical mechanism of the initialization-free phase-change optical recording is discussed. The combination of surface crystallization induced by the additional layer and the temperature increment during sputtering process is regarded as the reason of the initialization-free method. The simulation results show only a slight influence of the initialization-free structure for phase-change optical disks on the writing/erasing properties of phase-change recording layer. The initialization-free DVD-RAM disks and initialization-free Blu-ray discs were successfully fabricated. The experimental results show that no obvious deterioration of writing/erasing properties is observed in the initialization-free disks compared with conventional disks.

The initialization-free phase-change optical disk has successfully been developed for the multi-speed recording. The initialization-free DVD-RAM disk and Initialization-free Blu-ray disc show the multi-speed recording capability and have a broad range of recording speed of 1 time to 6 times for DVD and from 1 time to 3 times for Blu-ray, respectively. The crystallization acceleration effect induced by the additional layer and a rapid cooling rate caused by the disk structure of initialization-free disk are proposed to explain the multi-speed recording method with an initialization-free phase-change disk.

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