Media Development for DVD+RW Phase Change Recording

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ABSTRACT

In 2001, the rewritable 4.7 GB DVD+RW format for video recording and PC usage was launched. The first format description supported Constant Angular Velocity (CAV) and Constant Linear Velocity (CLV) recording from 3.49 to 8.44 m/s (1× to 2.4× DVD speed). This speed range was enabled by the use of growth-dominated phase change materials like GeInSbTe. In 2002 the operation range was extended to 1 – 4× and currently development is in progress for high speed DVD+RW, where different phase change compositions and new write strategies are needed. This paper describes the developments in test methods, phase-change materials and write-strategies aimed at demonstrating the technical feasibility of DVD+RW writing speeds up to 16×.

Keywords: Optical disc, groove recording, phase-change recording, rewritable disc, DVD.

1. INTRODUCTION

The development of recordable and rewritable DVD heralded an important new phase in optical recording which is still unfolding. The most dramatic growth in DVD recorders has been in the PC area where the high data capacity is proving invaluable. Even in the consumer area, however, the growth of DVD recorders primarily as a replacement for VHS VCRs has been significant and is expected to continue (Fig.1a). Of these products, 90% are capable of recording on DVD+R(W). On the media side, the major growth has been seen in DVD recordable (Fig.1b) but the annual market for DVD rewritable media is expected to reach 600 million discs by 2006 which is still a substantial market prompting significant investment in research in this area. For comparison, the production quantities of CD-R and CD-RW in 2004 are expected to equal 12 billion and 230 million respectively.

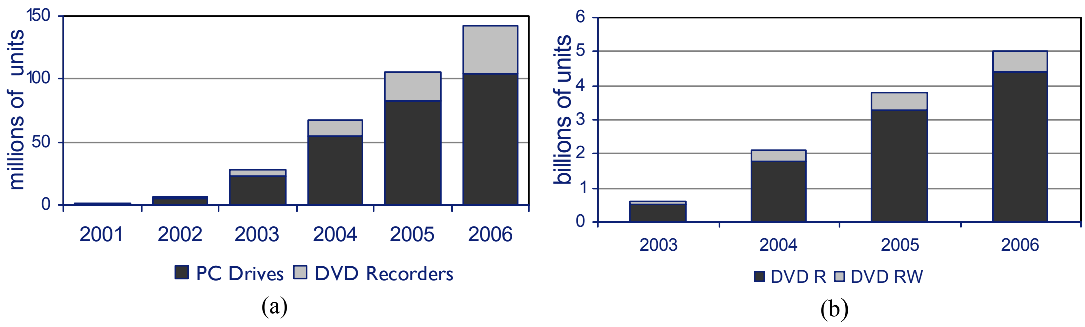

Fig.1 (a) Sales of DVD R/RW devices; (b) DVD R/RW disc demand forecast

Phase change recording materials for rewritable discs fall into two main families – materials such as ternary $Ge_2Sb_2Te_5$ alloys in which crystal growth is initiated by nucleation within the material, and high-growth materials such as doped Sb-Te alloys (e.g. AgInSbTe or GeInSbTe) in which crystallization of amorphous areas is initiated by the surrounding crystalline environment . In these latter materials, the Sb concentration is typically about 65-70% and Sb/Te ratios vary from 3 to 4.

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For land-groove recording formats such as DVD-RAM, $Ge_2Sb_2Te_5$ phase-change materials have been preferred because of their excellent direct-overwrite (DOW) capability of more than 100 000 cycles. For groove-only recording formats such as DVD+RW, developed to maintain backward compatibility with DVD-Video and DVD-ROM players, the crystallization mechanism of $Ge_2Sb_2Te_5$ alloys provides insufficient linear density to achieve the required data capacity of 4.7 Gbytes. The DVD+RW format was made possible by the use of fast-growth doped Sb-Te materials[1,2]. Their crystallization mechanism allows data to be written with much higher linear density, enabling the DVD data capacity of 4.7 Gbyte to be achieved. During recrystallization, however, doped Sb-Te alloys form a mixture of crystalline phases which it is generally assumed to have a negative impact of direct overwrite (DOW) cyclability, and indeed the cyclability of AgInSbTe materials, at 1000 to 10 000 cycles, is significantly lower than that of $Ge_2Sb_2Te_5$ materials. This is more than sufficient, however, for the majority of video and data-storage applications.

2. THE DVD+RW FORMAT

The first DVD format description was issued in March 2001. It describes the specifications of 4.7 Gbyte DVD+RW discs that can be used at recording speeds from 1 to 2.4× DVD, i.e. from 3.5 to 8.4 m/s, both in Constant Linear Velocity (CLV) and in Constant Angular Velocity (CAV) mode. To maximize backward compatibility with existing DVD video players and ROM drives, the readout characteristic specification was based on the specification of DVD-video and DVD-ROM discs. Moreover, to facilitate the use of phase change technology for rewritable discs, the specification for the reflectivity of recorded discs (18%) was derived from the DVD dual-layer standard. The bottom jitter specification for DVD+RW was increased from 8% (DVD standard) to 9% to create greater margin in the design and development of rewritable stacks that combine sufficient write power window over 1000 DOW cycles with a wide speed range both in CAV and in CLV mode. The constraints on the disc design were further relieved by specifying a numerical aperture (NA) of 0.65 for recording on the discs. Finally, despite the higher bottom jitter specification, the tilt margin of DVD video and ROM discs was maintained by reducing the thickness tolerances of the substrate from 0.6 ±0.03 mm to 0.6 ±0.02 mm, and by reducing the maximum radial deviation from 0.8° to 0.7°.

During writing, a high-frequency wobble of 32T length provides a measurement of disc velocity and facilitates lossless linking of random and sequential data. The linking accuracy is within ±5 channel bits, where one channel bit is 133 nm. Phase modulation of the wobble is used to create sync. signals and to encode address and format information in the pre-groove.

The latest specification for DVD+RW media describes two CAV operation ranges: the first from 1 to 2.4× and the second one from 1.7 to 4×. This format can be used in any current DVD+RW drive or recorder. For the development of 1 to 4× DVD+RW media, several technical hurdles needed to be overcome: laser power limitations, lossless linking without uncorrectable errors and direct overwrites between different recording velocities and drives. The maximum write power in the low-speed range is limited to 16 mW by the early DVD+R and RW recorders, while for the 1.7 to 4× range, up to 22 mW laser power can be used. For good erasability at 4× speed, fast growth phase-change materials are needed. These phase-change materials tend to show more self-erasure or re-crystallization during writing unless the layer stacks are sufficiently cooled between the write pulses to allow fast quenching of the laser-induced phase-change temperature or unless the cooling time between subsequent write pulses within one mark is sufficiently long. However, both strong cooling and long inter-pulse cooling times require more laser power. The second hurdle has been the wide variety of writing speeds and DOW cycles that need to be dealt with in combination with the lossless linking requirements. This has imposed strong demands on Write Strategy (WS) optimization to make sure that no uncorrectable errors occur due to too high slicing-level jumps at linking position between different recording speeds and/or DOW cycles. Finally, overwriting data recorded on another drive at another speed and even with write powers within typical laser power tolerances must not lead to uncorrectable errors. Despite the above challenges, many companies have already been qualified to produce 1 to 4× DVD+RW media[3].

3. DEVELOPMENT TOOLS

Several tools and analytical methods have proven valuable in the development of rewritable media. Reflection and transmission measurements are used to characterize the optical dispersion curves of individual thin-film materials. The data can be used to optimize the optical contrast and phase difference between crystalline and amorphous states within the stack. Transmission Electron Microscopy (TEM) has enabled the visualization of written effects and has helped to improve our understanding of the writing mechanism. Detection techniques like XRF (X-ray fluorescence) spectroscopy and Rutherford back scattering enable the analyses of, for instance, phase-change compositions made by co-sputtering, or enable us to study the effect of capping layers in rewritable layer stacks after enhanced interdiffusion studies[4]. In the next sections several tests specifically developed for optical recording will be discussed. These include Complete Erasure Time (CET) tests, amorphous stability tests, modulation reduction tests, erasability tests and melt erase power analyses. Finally, we discuss a thermal modeling tool that can explain and predict mark formation in rewritable discs.

3.1. CET MEASUREMENTS

Information about the crystallization behaviour and speed of a phase-change material can be obtained by measuring the CET of amorphous marks in a static tester setup[5]. Marks written by high-power laser pulses are erased (recrystallized) by applying pulses of varying power and length. The CET is the minimum time needed to completely recrystallize an effect. For nucleation-dominated phase-change materials, the CET is relatively independent of the amorphous mark size but is determined by the nucleation rate. In contrast, for growth-dominated materials, the CET is proportional to the diameter of the amorphous mark: wider marks have longer CET times since crystallization starts at the amorphous crystalline boundaries of the effects. The mark diameter can be estimated from the measured optical modulation if the read-out spot profile and the optical contrast between the amorphous and crystalline state are known.

3.2. ARCHIVAL LIFE TEST

The archival life of recorded data is the maximum storage time after which the data can be retrieved without uncorrectable errors. For DVD+RW media, typically a minimum of 100 years archival life for storage under office conditions (50% relative humidity, 20-30 °C) is specified. In rewritable discs, the maximum attainable archival life is determined by the stability of the amorphous marks against crystallization (i.e. erasure). The maximum storage time is measured at different elevated temperatures and subsequent Arrhenius plots predict the maximum archival life at room temperature. Typically the reduction in modulation is measured to estimate the maximum storage time, where 5% relative modulation reduction generally corresponds to end-of-life. The reduction in modulation usually shows a linear dependence on storage time, in contrast to jitter or error rate. Moreover, modulation can be measured without the need for write strategies optimized for jitter and error rate.

Archival life tests on optical discs are usually time-consuming since the polycarbonate substrates must not be heated above about 90 °C. Higher temperatures would reduce the test time needed to observe "end-of-life". In phase-change composition development, fast feedback of data on amorphous stability is obviously very valuable. This can be achieved through the use of phase-change stacks on glass, which enable stability testing up to temperatures well above 100 °C. Amorphous marks are recorded on the glass disc without a groove pattern. During heating, the increase in reflection is monitored and this is directly related to the reduction in modulation. Although the high test temperatures and indirect archival life estimations inhibit precise determination of the maximum attainable archival life at room temperature, it is a powerful tool to quickly characterize the effects of modifications in the phase-change compositions on stability[6,8].

3.3. MELT THRESHOLD POWER TEST

The optical stack in DVD+RW media consists essentially of a phase-change layer sandwiched between two dielectric layers and backed by a metal mirror, usually Ag or Ag-alloy. The metal mirror and the dielectric layer separating the metal mirror from the phase-change material largely determine the thermal properties of the disc, i.e. how much power is needed for writing amorphous effects and how fast the molten state of the phase-change layer is quenched after each write pulse. The melt threshold power test can

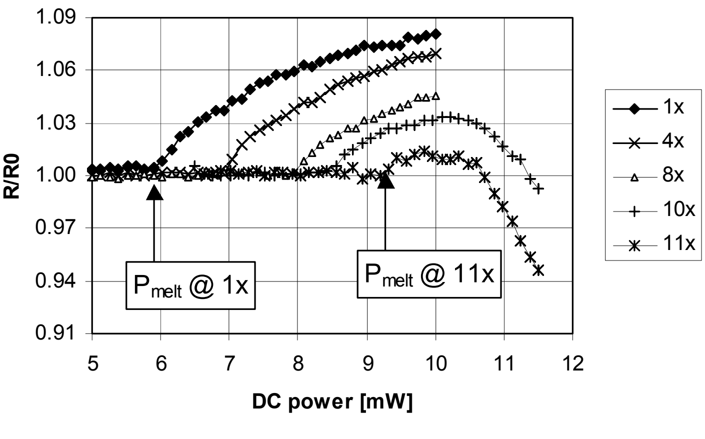

Fig.2 Melt threshold curves at 1× to 11× DVD speed for a high-speed DVD+RW discs

be used to quantify the sensitivity of a stack without the need to find the optimum WS. Fig.2 shows an example of this test for high speed DVD+RW discs. At constant linear speed, the DC melt power is increased until the reflection starts to increase. The onset of the increase provides an indication of the melt threshold power at that speed. The test can also give an indication of the maximum allowed speed of the disc. Fig 2 shows that at 10× and 11×, the reflection decreases after an initial increase above the melt threshold. This is due to incomplete recrystallization of the molten track, i.e. the phase-change material is too slow to fully recrystallize at 10 to 11× DVD speed.

3.4. MODULATION REDUCTION

The modulation reduction test can be performed on an experimental writing tester. It measures the amount of recrystallization during writing of a long amorphous mark using a multi-pulse strategy. The recrystallization is induced by re-heating the latest written amorphous dot within an amorphous mark at the moment the laser pulse is turned on to write the next dot. For a 1T write strategy in DVD+RW, the write pulses within a mark are spaced only 133 nm apart, while the laser spot diameter is about 1 μm. It is clear that in this case significant re-heating of the next to last written dot occurs. In high-speed DVD+RW discs, this re-heating would cause too much recrystallization in a 1T strategy as can be seen in Fig.3. This shows modulation reduction curves for three different high-speed DVD+RW discs. I11 single tones have been written at 6× DVD speed (1T = 6.4 ns) using 3.2 ns write pulses. The relative modulation is plotted vs the relative cooling gap between the writing pulses. In this case only the sensitivity of the three discs was changed where disc 3 is the most sensitive, but a similar effect could have been obtained for discs with equal sensitivity but different crystallization speeds[6]. In general, disc/write strategy combinations that give more than 10% intrinsic modulation reduction result in too much jitter. So in Fig.3, disc 1 needs a cooling gap of 0.9T whereas disc 3 needs at least 1.5T cooling time between write pulses. All three high-speed discs therefore need a 2T write strategy in which marks with length N are written with N/2 write pulses[2].

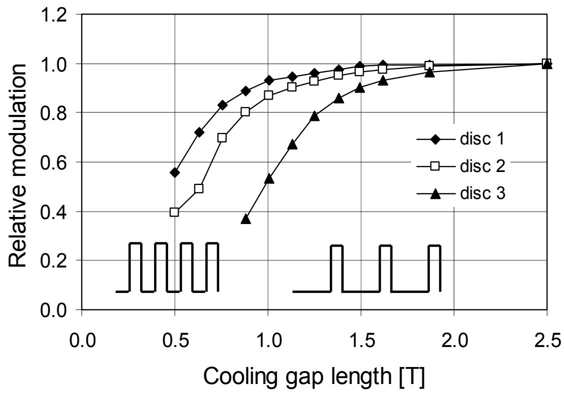

Fig.3 Modulation reduction curves of high speed DVD+RW discs with different sensitivity, measured at 6× DVD speed. The pulse trains at the bottom indicate the change in length of the cooling gaps used to write the I11 single tones.

Although the modulation reduction test does not discriminate between changes in sensitivity and in crystallization speed, it has a very direct link to the optimum WS and it can compare different RW stacks without the need for optimizing the WS first for optimum jitter.

3.5. ERASABILITY TEST

In erasability tests, long amorphous marks are erased by a DC power at increasing linear velocities. The maximum speed of the rewritable stack is reached when the erasability is less than –25 dB. The modulation of the amorphous marks should be carefully chosen since the erasability of fast-growth phase-change materials depends on the amorphous mark width. The erase power should be close to the power used in the final write strategy.

3.6. THERMAL MODELING OF MARK FORMATION

A clear understanding of the melting and crystallization characteristics of phase-change material is vital for developing the best material combination in the phase-change layer stack at the required bit rate. A numerical model based on crystal growth has been developed to study formation and erasure of amorphous marks in phase-change stacks based on fast-growth materials. The model incorporates a moving heat source with a Gaussian intensity distribution in the radial direction that represents the laser spot. The intensity distribution in the normal direction is calculated from the refractive index and absorption coefficients of the individual layers in the recording stack and disc, while the thermal properties used for the different layers in the stack came from melt-threshold experiments[7].

Fig. 4 gives an example for writing of a long mark. The mark is written with an N-1 strategy, forming an N-channel-bit long amorphous mark. In this case, a sequence of six write pulses produces a mark of seven channel bits long. The time between consecutive write pulses is such that the molten areas partly overlap. The temperature rise induced by a following write pulse causes crystal growth at the mark edge of an earlier written amorphous dot. This recrystallization results in a serrated side edge as is seen from the simulation result. The temperature rise induced by the heat from the erase power after the last write pulse causes the severe recrystallization at the trailing edge of the mark. In a TEM picture of such a long mark (Fig. 4c), both the serrated edge and the recrystallization at the trailing edge are clearly visible, illustrating the good correspondence between the model results and recorder experiments.

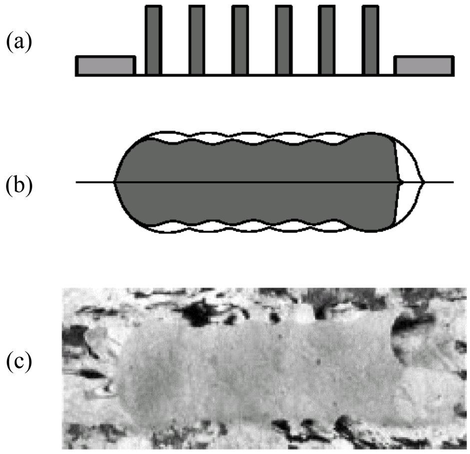

Fig 4 Simulation and recorder results of a long amorphous mark recorded in a DVR IPIM stack at LV = 8.1 m/s. (a) WS, (b) predicted mark shape. The solid line indicates the molten area, the filled contour denotes the resulting mark shape after recrystallization. (c) TEM picture

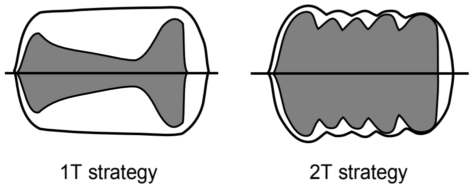

Fig.5 Numerical simulations of a rewritable DVD+RW stack recorded using a 1T or 2T write strategy

Numerical simulations have been used to visualise the recrystallization that may occur in phase-change stacks. Fig.5 compares the results for a 1T and a 2T pulsed write strategy. The grey area represents the amorphous mark left after writing, the white area the part that was molten and subsequently recrystallized during writing. Using a 1T strategy, significant recrystallization occurs in this stack. Applying a 2T strategy on the same disc significantly increases the width and consequently the modulation of the amorphous mark.

4. PHASE CHANGE MEDIA DEVELOPMENT

DVD+RW media developed at Philips for speeds from 1× to 4× are based on $Ge_3In_5Sb_{72}Te_{20}$. This material combines sufficient crystallization rate with excellent amorphous stability and low media noise. Moreover, the estimated archival life stability of written marks is well over 100 yrs. At speeds beyond 4×, however, a new balance has to be found between crystallization speed, amorphous stability and media noise, whilst maintaining good optical contrast. The next section focuses on our development efforts towards high-speed phase-change materials[6,8].

4.1. DOPED SB-TE MATERIALS FOR HIGH-SPEED DVD+RW MEDIA

The crystallization speed of doped Sb-Te materials depends on the ratio between Sb and Te. Fig.6 plots CET versus calculated mark radius for different Sb-Te phase-change materials doped with Ge: higher Sb/Te ratios being associated with shorter erasure times. The choice of dopant also strongly influences CET: highest crystallization rates being obtained for Sb-Te compositions doped with Ga or In whereas Ge or Ag increase the CET.

Another indication of the crystallization rate comes from erasability measurements as shown in Fig.7 for In and Ge-doped Sb-Te compositions. This shows the maximum disc velocity at which the carrier signal can be reduced by 25 dB For In-doped Sb-Te material , good erasability can be achieved up to velocities above 40 m/s indicating very high crystallization speeds.

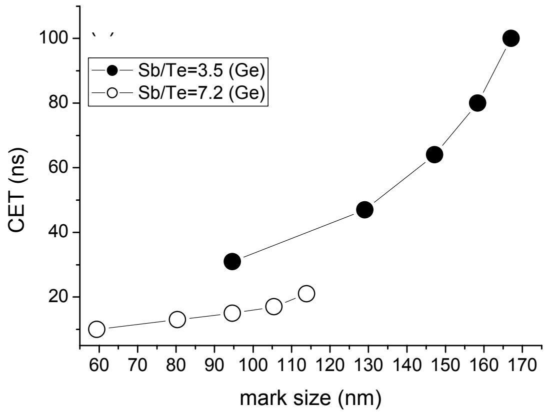

Fig.6 CET as a function of mark size for Ge-doped Sb-Te phase-change material with various Sb/Te ratios. Experiments performed using the static tester setup with λ = 670 nm and NA = 0.6

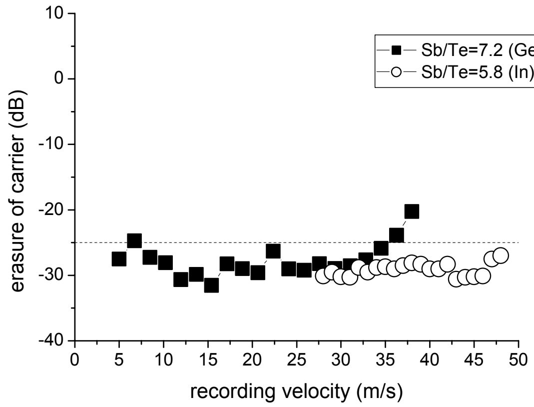

Fig.7 DC erasability as a function of recorder velocity for In and Ge-doped Sb-Te phase-change material

4.2. ARCHIVAL LIFE STABILITY OF HIGH SPEED SB-TE BASED MATERIALS

Fig.8 shows the archival life stability of different Sb-Te phase-change materials. In the figure, the markers represent experimental data. The dotted lines show the extrapolations at room temperature. The figure clearly illustrates the influence of the dopant on the stability against crystallization. Adding Ge leads to extremely good archival life stability, whilst doping with In gives insufficient amorphous stability. The exact concentrations of In and Ge can be tuned for the optimum combination of speed and stability. For In-doped phase-change compositions without Ge and with a high (5.8) Sb/Te ratio, an extremely low archival life has been measured. Marks were completely recrystallized after as little as 6 day's storage at room temperature.

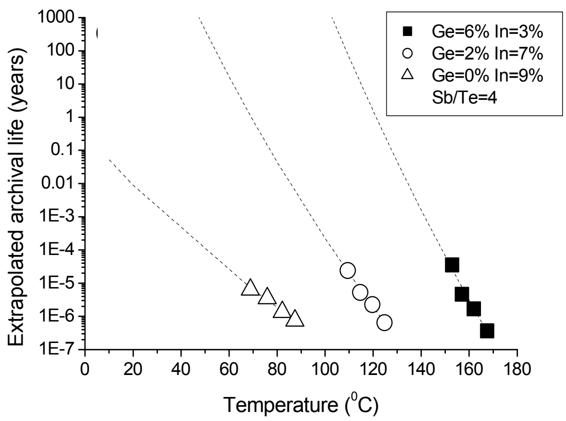

Fig.8 Archival life stability of written amorphous mark for doped Sb-Te phase-change materials for various combinations of In and Ge doping.

4.3. MEDIA NOISE

High-speed DVD±RW based on doped Sb-Te material has been found to have much higher media noise than its low-speed counterparts[8]. Fig.9 shows the noise spectra of DVD±RW discs with Ge-doped Sb-Te phase-change materials. The noise spectrum of a track was measured at a disc velocity of 7 m/s, DC reflection of 750 mV (read-power was adjusted), resolution BW of 30 kHz and video BW of 10 Hz. The noise increases with Sb/Te ratio. Since crystallization speed also increases with Sb/Te ratio, noise-induced jitter problems can be anticipated for high-speed recording. Moreover, the noise in the amorphous state is found to be significantly lower than that in the crystalline state leading to the conclusion that the crystallization process induces the noise. Possible causes for the noise may be diffraction on the crystallite boundaries, variations in crystal orientation or amorphous inclusions.

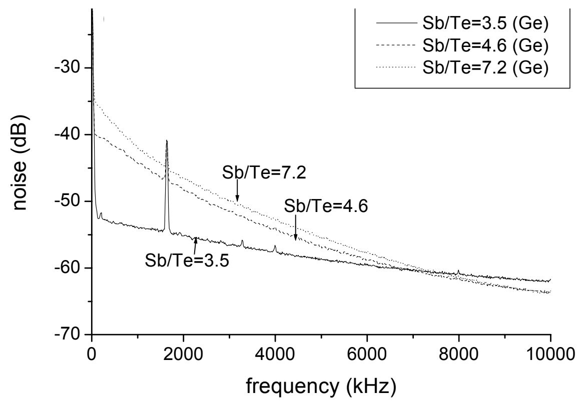

Fig.9 Noise spectrum for crystalline tracks of Ge-doped Sb-Te phase-change composition measured on a DVD+RW recorder

The role of the dopant on the noise of doped Sb-Te phase-change materials has also been investigated[8]. Doping with Ge and In gives similar noise values, while media noise is lower when Ag is used as a dopant. Finally, at constant Sb/Te ratio, noise increases with dopant concentration.

4.4. ENCOUNTERING THE SPEED LIMIT WITH DOPED SB-TE MATERIAL

Doped Sb-Te phase-change materials offer excellent recording performance for speeds up to 4× under DVD+RW conditions, and it is clear that an increase of the crystallization rate for even higher speeds is possible by optimizing the phase-change material. Such actions, however, may also influence other material parameters such as archival life and/or media noise. The requirements for an effective phase-change material for high-speed recording therefore seem conflicting which leads to the conclusion that doped Sb-Te phase-change material is unlikely to be suitable for recording speeds higher than 8× DVD.

4.5. STABLE, LOW-NOISE MEDIA FOR ULTRAHIGH-SPEED DVD REWRITING

The development of still faster growth materials based on Ge-Sn-Sb phase-change compositions is expected to lead to ultrahigh speed DVD rewriting with linear disc velocities comparable with those now attained with ultrahigh speed CD-RW. Doped Sb-based phase-change compositions such as Ge-Sb combine fast crystallization with high amorphous phase stability[9], whilst the addition of Sn has been found to lower media noise[10].

Fig.10 shows the DC erasability for two Ge-Sn-Sb-based phase-change materials designed for DVD+RW speeds of 4× and 16×. The 16× material shows good erasability up to velocities of 58 m/s.

For Ge-Sn-Sb-based phase-change materials, the crystallization rate depends on the precise phase-change composition. Fig.11a shows the maximum DC-erase velocity as a function of the Ge content and illustrates the fact that by reducing the Ge concentration from 30% to 10%, the erase velocity can be increased from about 10 to 60 m/s. It can be deduced from Fig.11b that substitution of Ge by Sn or In increases the crystallization rate, while substitution by Cu, Ag or Ga decreases the crystallization rate.

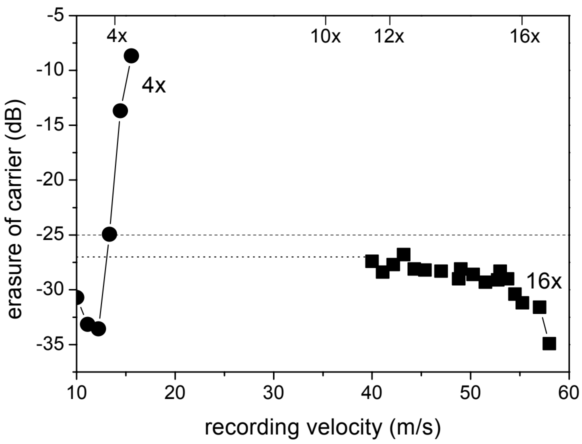

Fig.10 DC erasability as a function of linear velocity for Ge-Sn-Sb-based phase-change compositions

For ultrahigh speed phase-change recording, increasing the maximum erasability speed and minimizing the amount of recrystallization during writing are conflicting goals. This can be overcome, however, with the correct choice of write strategy. Fig.12 shows the time gap between write pulses as a function of maximum erase velocity for Ge-Sn-Sb based phase-change compositions (the crystallization rate is varied by changing the Ge concentration). The gap is divided by the period T (9.55 ns at 4×), resulting in a parameter that is independent of the write velocity. The figure shows that back growth increases for discs with higher maximum erasability.

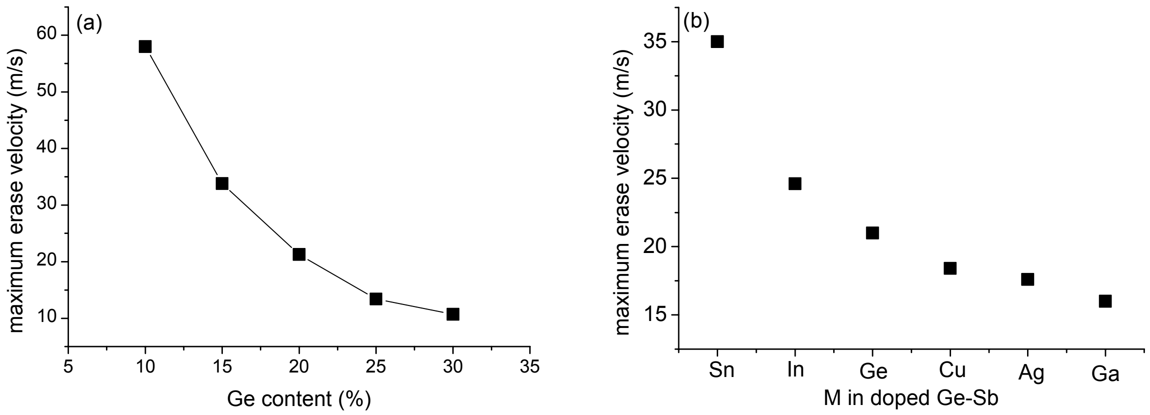

Fig.11 Maximum erase velocity as a function of Ge concentration (a) and (b) for doped Ge-Sb-based phase-change compositions in concentrations of 5%. The Ge concentration in (b) was 15%

In Fig.12, the length of the write pulses was 3 ns for all write strategies. The broken lines (1), (2) and (3) represent the boundaries between different write strategies. For the phase-change stacks in Fig.12, recording up to about 6× DVD (21 m/s) is possible with a 1T WS (with 3 ns pulses), recording up to 10× DVD (35 m/s) is possible with a 2T WS, whilst even higher speeds up to 16× DVD (~56 m/s) are attainable using a 3T WS.

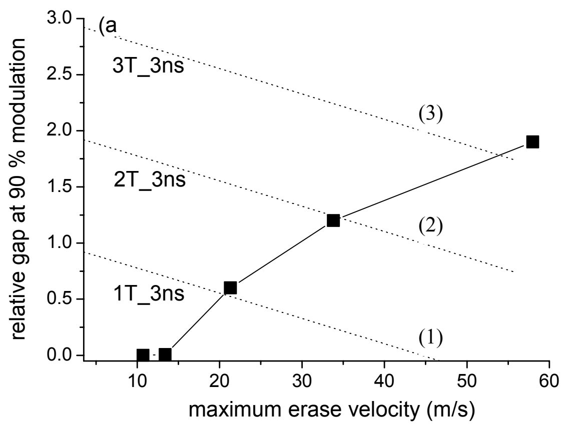

Fig.12 Time gap at a relative modulation of 90% as a function of the maximum DC-erase velocity for different phase-change compositions. The modulation is normalized to 1 for maximum modulation.

5. NEXT STANDARD: 3.3 TO 8×

Currently, development and standardization of high-speed DVD+RW media is in progress. The next standard will describe DVD+RW media that can be used up to 8× DVD speed and that can also be used in CAV drives from 3.3 to 8× DVD speed. Slimline drives will be limited to 75 Hz rotation frequency (= 8× DVD on outer diameter) to limit power consumption. In PC drives, the linear velocity on the inner radius is limited to 6×, which corresponds to the angular velocity of 150 Hz safely allowed in optical discs. The high-speed media will be recorded using a 2T WS.

Fig.13 shows power margin curves of an 8× DVD+RW disc at 3.3×, 6× and 8× speed measured after 10 DOW cycles. Although both doped Sb-Te and Ge-Sn-Sb phase-change materials are capable of recording at 8× DVD speed, the disc is based on Ge-Sn-Sb because of its proven higher potential for even greater speed increases in the future. All speeds show more than ±10% power margin. Fig.14 shows a multi-track jitter-DOW cycle curve recorded at 8× speed. At most DOW cycles, the jitter is below 9%. At DOW = 2, further improvement in initialisation conditions and write strategy is required.

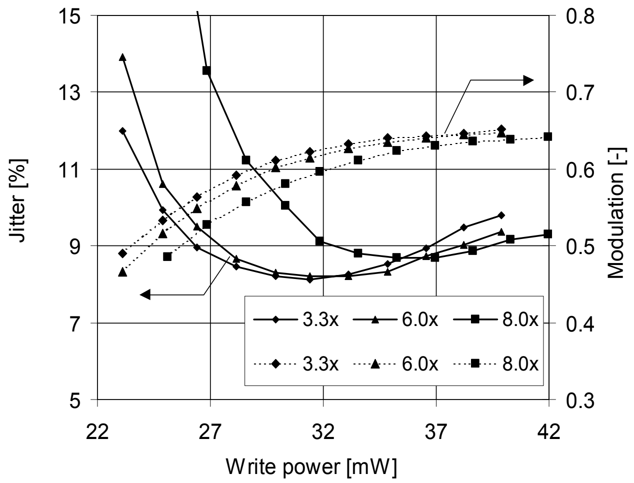

Fig.13. Power margin curves of modulation (dashed lines) and data-to-clock jitter after 10 DOW cycles for an 8× DVD+RW disc

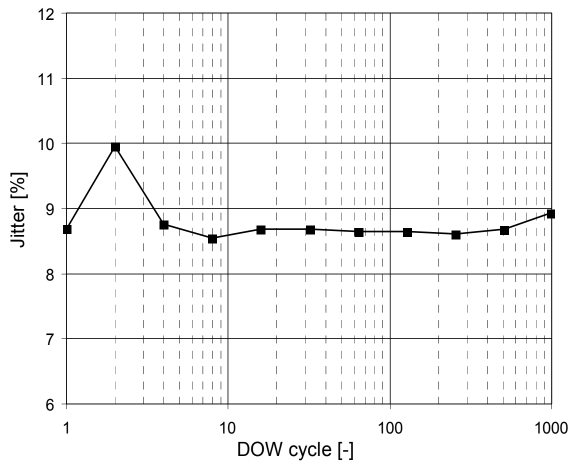

Fig.14 Multitrack-Jitter / DOW curve of an 3 – 8× DVD+RW discs at 8× speed.

6. NEXT STEPS

Although current phase-change technology has proven to be capable of recording at 16× DVD speed using 3T write strategies, the next high-speed DVD+RW standard and the current focus of research is aimed at increasing the maximum recording speed to 10 – 12× while maintaining compatibility with 3 to 8× drives capable of handling 2T write strategies on DVD+RW media.

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