# The Characteristics of a Dual-Layer Optical Disk with Read-Only and Erasable Functions

Bor-Wen Yang and Han-Ping D. Shieh

***Abstract*—A dual-layer optical disk comprised of a read-only layer and a phase-change layer was designed to perform the read-only and erasable dual-functionality in an optical disk. With the properly designed dual-layer disk structure, 23 mW of write power was adequate to write data marks on the erasable phase-change layer; simultaneously, equal magnitude of sufficient radio-frequency readout signals could be obtained on both its data layers. The analyzes of its recording characteristics demonstrated the feasibility of the dual-functional optical disk.**

***Index Terms*—Dual-functional optical disk, dual-layer optical disk, interlayer crosstalk, optical disk.**

## I. INTRODUCTION

OPTICAL DISKS consisting of multiple data layers were proposed to multiply the recording density by volumetric optical storage [1]. A number of multilayer optical disk structures were suggested for higher density storage applications [2]–[6]. For example, two embodiments of dual-layer read-only optical disk announced by Philips/Sony and 3M companies became the pioneers of dual-layer digital versatile disk–read-only memory (DVD-ROM) [3], [4]. Thereafter, constructions of dual-layer write-once read-many (WORM) optical disks were devised by applying nonreversible phase-change material or dye mixture, respectively [5], [6], so that volumetric optical storage technology could be extended to the world of recordable data recording.

On the contrary, it requires more effort to contrive a dual-layer digital versatile disk–random access memory (DVD-RAM) composed of two reversible data layers. In general, the upper data layer which is the first data layer defined to be the laser incident side layer of a dual-layer optical disk is designed to be semitransparent to make the lower data layer which is the second data layer accessible [7]; however, due to the requirement of metallic cooling layer for high speed thermal recording and temperature descending [8], the currently available erasable media, including magnetooptical or phase-change, have not sufficient transmissivity to be the semireflective layer. This is one of the important issues why a reliable dual-layer DVD-RAM is still challenging nowadays.

To resolve the problem, a semireflective read-only layer with sufficient transmissivity is proposed to replace the upper RAM layer to make the lower RAM layer accessible; simultaneously, a new application with two different storage functions—read-only and erasable [9], can be practiced on two data layers of an optical disk, respectively. In this work, the recording and readout characteristics of a phase-change/read-only memory (PC-ROM) optical disk employing a semitransparent read-only (ROM) layer and a total-reflective phase-change (PC) layer are analyzed to demonstrate its feasibility. The properties of other designs of dual-layer erasable optical disks shall be compared to reveal the features and advantages of the PC-ROM optical disk.

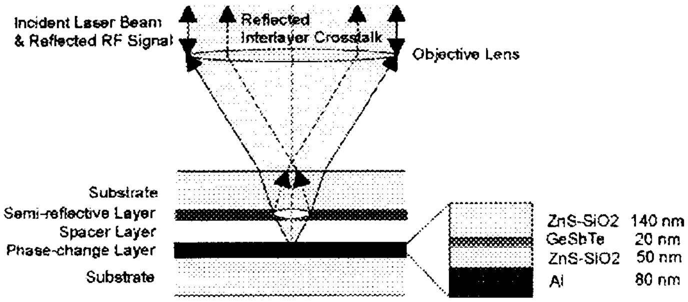

Fig. 1. The laser beam was focused to access the phase-change layer of a PC-ROM disk. Random marks on the semireflective layer illuminated by the enlarged laser spot might result in interlayer crosstalk.

## II. SIMULATION

### A. Modeling of PC-ROM Optical Disks

The dual-layer PC-ROM optical disk in the modeling was comprised of two 0.6 mm polycarbonate substrates, which were coated with a semitransparent Al film of the upper data layer of a ROM disk and a phase-change active medium with optimally designed thin-film structure [8], respectively, as shown in Fig. 1. The air spacer of 50 mm was employed to separate the two data layers and to reduce the interlayer crosstalk induced in readout. A 650-nm laser beam focused by an objective lens of 0.60 NA was irradiated on a PC-ROM optical disk rotating at a linear speed of 3.84 m/s.

### B. Writing on Phase-Change Layer

In the recording analysis, the pulsed laser light with Gaussian-distributed profile was modeled to write the phase-change media of the PC-ROM disks. By thin-film theorem and metric optics [10], [11], the reflectivity, transmissivity, and

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absorption coefficient of the two data layers were calculated by

$$\begin{aligned} R &= \left(\frac{\eta_0\beta-\gamma}{\eta_0\beta+\gamma}\right)\times\left(\frac{\eta_0\beta-\gamma}{\eta_0\beta+\gamma}\right)^{*} \\ T &= \frac{4\eta_0\,\mathrm{Re}(\eta_m)}{(\eta_0\beta+\gamma)(\eta_0\beta+\gamma)^{*}} \\ A &= \frac{4\eta_0\,\mathrm{Re}(\beta\gamma^{*}-\eta_m)}{(\eta_0\beta+\gamma)(\eta_0\beta+\gamma)^{*}} \end{aligned} \tag{1}$$

where the $\eta_0$ and $\eta_m$ represent the optical admittances [11] of the input and output thin-film medium, respectively; the $\beta$ and $\gamma$ denote the matrix elements of the resultant product of all relating thin-film optical matrices, respectively; the signs of asterisk $(*)$ are added to terms on which the complex conjugates are taken. The temperature rising and descending process effectuated by the laser spot irradiated on the phase-change layer was analyzed by the dynamic heat diffusion equation [12]. The writing pulses were applied to heat the phase-change layer above its melting point (~600 °C) to record amorphous data marks on it. Reasonable write power of about 23 mW shall be proved to be sufficient to record reliable data marks on the phase-change layer through the semitransparent read-only data layer.

### *C. Modeling of RF Readout Signal and Interlayer Crosstalk*

The RF readout signals detected from both data layers were derived from the readout modeling, so that the optimal disk structure with balanced readout on both data layers could be designed. To derive the RF readout signals, the DC readout laser beam with Gaussian profile was first modeled. Then, the read-only and phase-change data marks were simulated on the corresponding data layers, respectively, by a series of random phase pits and amorphous data marks. Eventually, the optical energy $S(t)$ detected by the objective lens reflected from the focused data layer was derived by taking the convolution of the diffraction-limited spot and the irradiated data marks, as shown in Fig. 2:

$$S(t) = \iint f(x(t),y)^{*}h(X(t)-x(t),y)\,dx\,dy \tag{2}$$

where the $h(x,y)$ denotes the Gaussian energy distribution of the laser spot; $f(x,y)$ is a function which describes the reflectivity distribution of the read-only or phase-change data surfaces. On the read-only layer, the reflectivity difference exists between the embossed data marks and the land area; on the phase-change layer, the reflectivity difference is induced by the amorphous data marks and the unrecorded crystalline area.

When the phase-change layer is read out, the semireflective layer shall reflect back part of the laser beam, which may couple into the readout channel and induce interlayer crosstalk. Besides the diffraction-limited laser spot focused on the total-reflective layer, an enlarged laser spot is generated on the semireflective layer; hundreds of data marks recorded on this out-of-focus layer are simultaneously illuminated and read out, thus result in interlayer crosstalk [13].

It is essential to reduce interlayer crosstalk in designing a dual-layer optical disk because it shall degrade the RF signal and deteriorate the readout contrast [13]. By the readout modeling, the interlayer crosstalk could likewise be derived by taking the convolution of the enlarged laser profile and the reflectivity distribution of the out-of-focus data surface. The disk structure of a PC-ROM shall be optimized by suppressing the interlayer crosstalk induced in readout.

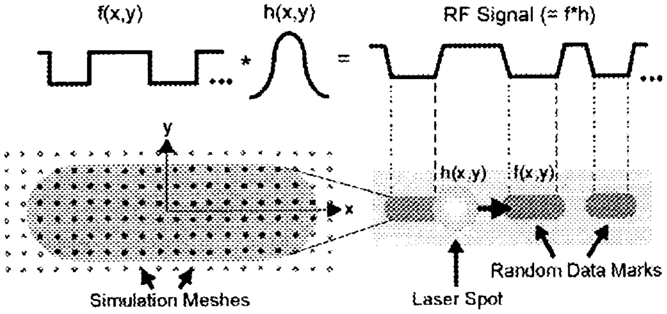


Fig. 2. The RF readout signal of a PC-ROM optical disk was derived by the convolution of the focused laser spot with the data marks recorded on either data layer.

TABLE I
OPTICAL AND THERMAL PARAMETERS OF THE MATERIALS USED IN THE PC-ROM OPTICAL DISKS

| Thin-film material | Index: n | Extinction coefficient: k | Heat capacity: C ($J/cm^3 \times k$) | Thermal conductivity K ($J/cm \times k \times s$) |
|---|---|---|---|---|
| Polycarbonate substrate | 1.58 | 0 | 1.5 | 0.00223 |
| Al | 2.06 | 7.03 | 2.454 | 2.144 |
| $ZnS-SiO_2$ | 2.03 | 0 | 2.055 | 0.00628 |
| GeSbTe (Crystalline) | 5.39 | 3.18 | 1.288 | 0.0058 |
| GeSbTe (Amorphous) | 4.53 | 1.21 | 1.288 | 0.0058 |

## III. RECORDING ON PHASE-CHANGE LAYER

To write the phase-change layer of the PC-ROM, the laser power needs to be properly increased to compensate the optical energy lost in transmitting through the semireflective layer. The optical and thermal parameters of the materials used in the PC-ROM's in the recording simulation are listed in Table I [8]. By the thermal modeling, the phase-change layer can be locally heated to record amorphous marks of about 0.35 mm by 12-mW laser beam of 80-ns pulse duration (writing frequency = 6.25 MHz, and duty cycle = 50%) in absence of the semireflective layer, as shown in Fig. 3(a). However, if the 12-mW laser pulse is irradiated onto a PC-ROM disk with a 25-Å-thick semireflective layer of the upper ROM disk, as shown in Fig. 3(b), only about 5 mW of laser power can transmit through the semireflective layer, thus fails to write on the phase-change layer. Larger portion of the energy loss is caused by optical absorption rather than optical reflection on the semireflective film, which is indicated by the absorption coefficient $(A)$ and reflectivity $(R)$ of the semireflective film, as shown in Fig. 4. Have the write power increased to 23 mW, data marks of about 0.35 mm can now be recorded on the lower data layer of the phase-change layer of the PC-ROM disk with a 25-Å-thick semireflector, as shown in Fig. 3(c). The thicker the semireflective layer is, the less optical energy the phase-change layer receives, and thus the higher effective write power is required.

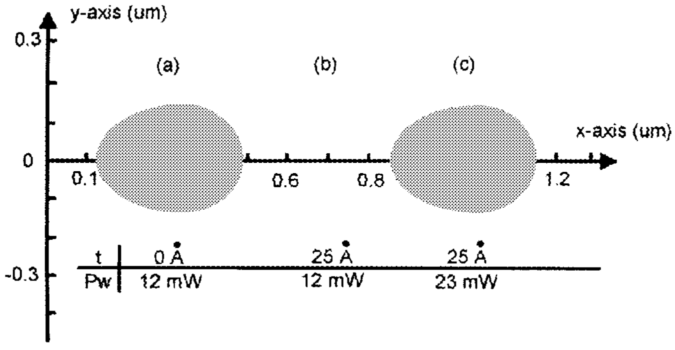


Fig. 3. The amorphous marks recorded on the phase-change layer of the PC-ROM optical disks with different thickness of semireflectors ($t$) and write powers ($Pw$).

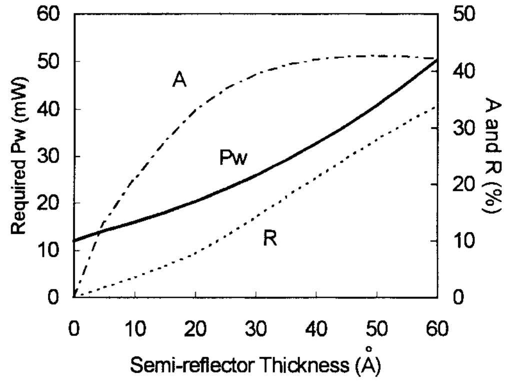


Fig. 4. The absorption coefficient ($A$), the reflectivity ($R$) of the semireflective layer, and the write power ($Pw$) required to record signals on a PC-ROM disk, as a function of semireflector thickness.

## IV. Readout on Both Data Layers

There are two modes in reading a PC-ROM optical disk: for example, the laser beam is focused to read the lower data layer of the phase-change layer in mode-1, and to read the upper data layer of the read-only layer in mode-2. To preclude the effect of magnitude of the read power in the readout modeling, the RF signal $F_{\text{signal}}$ (or interlayer crosstalk $F_{x\text{talk}}$) is normalized by dividing the read power carrying the RF readout signal (or interlayer crosstalk) by the incident read power.

By readout analyzes on both data layers, the disk structure of a PC-ROM is optimized by suppressing the interlayer crosstalk induced in readout. In read mode-1, the $F_{\text{signal}}$ is proportional to $T_1 \times R_2 \times T_1$ and the $F_{x\text{talk}}$ is proportional to $R_1$, to the first-order approximation, where the $T1_{,}R_2$, and $R_1$ denote the transmissivity of semireflective layer, the reflectivity of total-reflective layer and semireflective layer, respectively; contrarily, in mode-2 to read the read-only layer, the $F_{\text{signal}}$ is proportional to $R_1$ and the $F_{x\text{talk}}$ is proportional to $T_1 \times R_2 \times T_1$, as shown by the curves depicted in Fig. 5. In reading the phase-change layer, a semireflective layer too much thicker than 25 Å (the intersection value of the $F_{\text{signal}}$ and $F_{x\text{talk}}$ curves) blocks the read beam incident to the phase-change layer, thus derives insufficient RF signal to compete with the interlayer crosstalk noise. On the contrary, a PC-ROM disk with semireflective film too much thinner than 25 Å is not suitable for readout on the ROM layer, since large part of laser energy is leaked to the phase-change layer to derive interlayer crosstalk more intense than the RF signal. Thus, the thickness of semireflective layer is optimally designed around 25 Å to suppress interlayer crosstalk in readout.

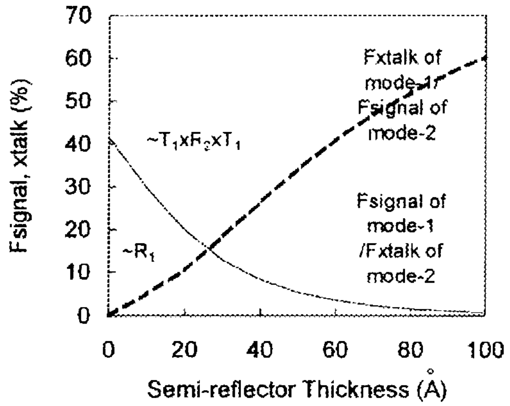
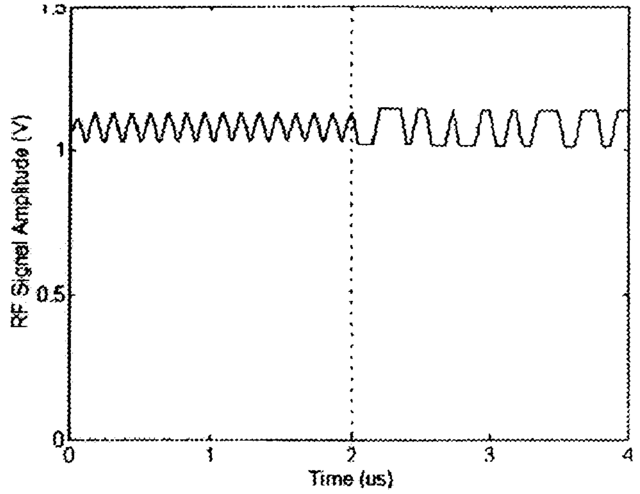


Fig. 5. The normalized RF signal ($F_{\text{signal}}$) and interlayer crosstalk ($F_{x\text{talk}}$) of PC-ROM disks derived in two readout modes, as a function of semireflector thickness.

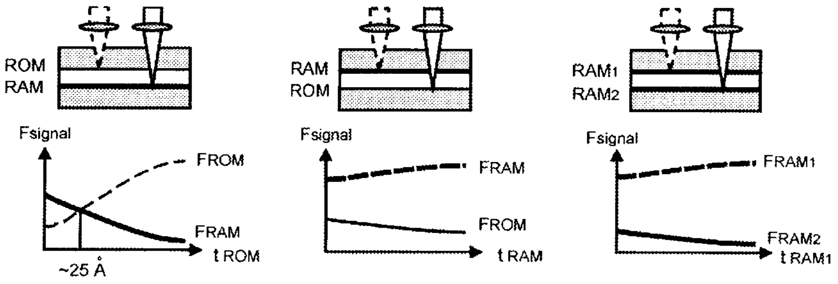


(a) (b)

Fig. 6. The simulated RF signal in reading (a) phase-change and (b) ROM layers of a PC-ROM disk with a 25-Å-thick semireflective layer.

Due to the existence of semireflective layer, the RF signal magnitude derived from either data layer may be distinct from the other, thereby results in unbalanced readout, which leads to difficulty in design of readout electronics [2]. Balanced RF signals were achieved on the optimized structure with a 25-Å-thick semireflector because the normalized RF signal Fsignal of read mode 1 is just identical to that of read mode 2 at the intersection point, as shown in Fig. 5.

To derive the RF readout signal in unit of volts, the detection channel (from the objective lens to the optical detector) is modeled as a linear system, so that the RF readout signal (in volts) extracted from the optical detector can be derived by the readout optical energy $S(t)$ detected by the objective lens. The measured RF signal of a conventional CD is used as a standard to characterize the detection channel to transform the inputted $S(t)$ to the outputted RF signal amplitude in volts. By this way, the RF signal of the phase-change layer of a PC-



(a) (b) (c)

Fig. 7. The possible three designs of erasable dual-layer optical disks and the corresponding RF readout signal ($F_{\mathrm{signal}}$, such as $\mathrm{F}_{\mathrm{ROM}}$, $\mathrm{F}_{\mathrm{RAM}}$, $\mathrm{F}_{\mathrm{RAM1}}$, and $\mathrm{F}_{\mathrm{RAM2}}$) as a function of semireflector thickness ($t$, such as $t_{\mathrm{ROM}}$, $t_{\mathrm{RAM}}$, and $t_{\mathrm{RAM1}}$). (a) PC-ROM. (b) Dual-layer disk with a semireflective RAM layer and a total-reflective ROM layer. (c) Dual-layer DVD-RAM.

ROM disk with a 25-Å-thick semireflective layer was derived, as shown in Fig. 6(a), where the peak signals were derived by the crystalline area with higher reflectivity, while the valley levels were by the amorphous marks recorded by 23 mW of 80-ns laser pulse, as shown in Fig. 3(c); similar magnitude of RF signal in random data sequence was derived from the read-only layer of the PC-ROM disk, as shown in Fig. 6(b), where the peak signal levels were derived by the land area with higher reflectivity, while the valley levels was derived by the concave random data marks. Thus, with the semireflective film coated around 25 Å, balanced RF readout signals are derived from both data layers of the PC-ROM disk, which can effectively simplify the design of readout electronics.

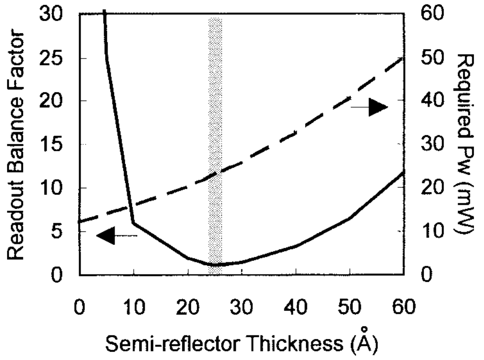


Fig. 8. The readout unbalance factor and write power for a PC-ROM disk as a function of semireflective layer thickness. The semireflector thickness of the shaded area is (25±5%) Å.

## V. DISCUSSION

The recording/readout characteristics of possible designs of dual-layer optical disks with recording function were examined to reveal the advantages of PC-ROM. The optimized PC-ROM optical disk, as shown in Fig. 7(a), is with merits of balanced readout and reasonable power requirement, as described above. A dual-layer optical disk with a semireflective RAM layer and a total-reflective ROM layer is shown in Fig. 7(b). Due to the requirement of sufficient optical absorption and reflection for writing and readout, the transmissivity of the RAM layer is in general less than 10% [8], [14], so that the total-reflective ROM layer of this dual-layer optical disk is hardly detectable. Accordingly, by readout simulation, the RF signal derived from the ROM layer of the disk was much lower than that of the semireflective RAM layer, thus the balanced readout was hard to be achieved. The similar issue exists in a dual-layer DVD-RAM, as shown in Fig. 7(c). Moreover, by recording simulation, the blocking effect of the upper RAM layer drastically increases the power required to write the lower RAM layer of the dual-layer DVD-RAM, typically larger than 35 mW.

The dual-layer PC-ROM optical disk is promising to be put into practice since its significant features, such as low write power and balanced readout, remains almost unchanged under the presence of significant fabrication variance. The degree of readout unbalance (the readout unbalance factor) $\eta$ is defined as the higher RF signal derived from one of the data layers divided by that of the lower signal derived from the other. The factor is thus always larger than or equals unity, wherein the balanced readout is achieved when the factor equals 1.0. By the recording and readout analyzes described above, the write power and the readout unbalance factor of the optimized PC-ROM disk with a 25-Å-thick semireflector were 23 mW and 1.0, respectively, as illustrated in Fig. 8. An assumed manufacturing variance of semireflector thickness of ±5% at the nominal value of 25 Å still keeps the write power requirement and readout balance factor below 24 mW and 1.2, respectively, which is capable of accommodating to today's diode laser [15] and signal process[1] technologies. Too large power requirement and/or too high readout unbalance factor are among the main factors to prohibit the dual-layer erasable optical disks, as shown in Fig. 7(b) or (c), from being practicable nowadays.

## VI. CONCLUSION

The recording and readout characteristics of a dual-functional PC-ROM optical disk were analyzed to demonstrate its feasibility. The PC-ROM disk was optimized with a semireflective layer of around 25 Å thick to suppress the interlayer crosstalk. Data recording on the phase-change layer of the optimal PC-ROM disk is achieved at reasonable write power of about 23 mW; simultaneously, balanced readout on both data layers can be acquired. A fabrication tolerance of semireflector thickness of ±5% is allowable for the PC-ROM disk since it will not induce significant writing or

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[1] The Compact Disk-Read Only Memory (CD-ROM) red book.

readout characteristics variation. Newly developed phase-change materials or structures with sufficient transmissivity may expand the varieties in design of multilayer optical disks; however, owing to the temporary lack of erasable media with high enough transmissivity to be the semireflective layer of a dual-layer DVD-RAM, the PC-ROM optical disk is well promising to practice read-only and erasable dual functions.

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