UV Futures for Optical Disc Storage

(What's Next for DVD after Blu-ray?)

by

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Preface

Until the advent of the 405nm blue/violet laser, increasing optical disc capacity was easy: use laser diodes with shorter wavelengths and objective lenses with higher numerical apertures. More recently, multiple layers per disc surface have been proven feasible (two in production for DVD-ROM (DVD-9). DVD-R DL, and Blu-ray; four demonstrated, but not in production).

At this point in time, Blu-ray Disc (BD) uses a blue-violet laser emitting at 405nm and a numerical aperture (NA) of 0.85. Those knowledgeable about optical storage engineering understand that these are practical limits (at least in the visible part of the spectrum for laser diodes). In simple terms, the basic technology has approached or possibly reached its limits.

What next then? Some have proposed, for example, near-field recording (NFR) or holography. But alternative technologies are more complex compared to the relatively simple designs of CD, DVD, and even BD. Reliability, backward compatibility, and cost are also issues for Consumer Electronic (CE) products.

Nevertheless, I propose considering moving into the ultraviolet (UV) regime. I have actually performed holographic and spot recording optical storage experiments in the 350-360nm wavelength range, using argon and krypton lasers with special mirrors. It was very difficult work. But this was more than 30 years ago. Current photonic technologies make the design and implementation somewhat easier. The first problem to solve is, of course, development of a reliable, compact, and inexpensive UV laser diode.

To illustrate the possibilities, I created some *pro forma* specifications for small form factor and 120mm optical discs. For a UV light source, I assumed frequency doubling 650nm and 405nm laser diodes to get 325nm and 202.5nm UV light. Although this is a hypothetical exercise, it defines the potential.

Z1 DVD Micro-Optical Disc

The DVD standards define both 120mm (4.7 GB capacity/layer) and 80mm (1.4 GB capacity/layer) disc diameters. The same is true for CD standards (650MB and 180 MB capacity, respectively). A "business card" CD (about 50 MB capacity) is often used to distribute product information. Essentially, disc capacity is traded off for a smaller drive foot print.

A primary motivation for 80mm discs was to enable "mobile storage" business and consumer electronics (CE) products (for example, digital still and moving picture cameras, MP3 audio devices, advanced cell phones, hand-held computers, PDAs, gaming devices, set-top boxes, storage nodes for home networks, and e-books). This required the design of drives much smaller than the standard half-high 5.25" drives.

For high-end business and CE products this was an adequate, but not defining, solution. For the majority of emerging mobile (often wireless) products, the size, weight, and cost of 80mm optical disc storage were a poor fit to the applications. One of the only real alternative was Flash memory cards, which initially were almost prohibitively expensive ($20-25/MB at introduction; less than $0.50/MB today).

In 1999, start-up company DataPlay announced that it would develop a "micro-optical disc" storage technology (drive and disc) for the nascent mobile device market. The disc was only 32mm in diameter and had a surface capacity of 250 MB (500 MB double sided). It supported ROM, write-once, and PROM modes of data storage (erasable was under development). The DataPlay disc cartridge was comparable in size and weight to most memory cards. The big difference was cost: the DataPlay disc cartridge had a list price of only $5 for 250 MB of storage ($0.02/MB), more than 100x less than shipping memory cards at this time. The DataPlay product was introduced at CES 2001, and was well received by OEMs, end users, and the trade press. Figure Z1-1 shows the DataPlay drive and micro-optical disc cartridge; although well miniaturized, it is still relatively large for a mobile device.

Unfortunately, despite doing almost everything right, DataPlay could not obtain the necessary funding to begin the volume manufacturing phase, and it was shut down in October 2002. In addition to funding problems, DataPlay failed the key “time-to-market” test. The company’s OEM customers were forced to look for alternatives, and many found them in memory cards, whose price and capacity points had become attractive for both business and consumer applications.

About the same time as DataPlay’s demise, Philips pre-announced a 1 GB capacity (single-layer, single side), 30mm-diameter, phase change micro-optical disc storage product. The key features are a blue laser, the world’s smallest plastic objective lens, and very small physical volume; Philips calls it a Blu-ray extension. The drive has a height of only 7.5mm (the final product will be only 5mm high), thanks to the very small objective lens, and is ideal for mobile business and CE devices. A prototype drive was demonstrated using a read-only disc; rewritable discs are planned. First shipment of this product is scheduled in 3-5 years, according to Philips (but it could, and perhaps should, ship in less than 2 years). Figure Z1-2 shows the Philips prototype blue micro-optical disc system; notice how much smaller it is, compared to DataPlay.

The roadmap for micro-optical disc must take into account competitive mobile storage technologies. First among these are memory cards. If current trends continue, memory cards with 8-16 GB capacity and costing about $100 will be shipping in about 5 years. A wild card is MRAM, which could be both superior to and less expensive than Flash memory cards. Another wild card is Millipede storage (IBM), which could be shipping 5-10 years from today. A certainty is the micro-hard disk drive. Hitachi-IBM announced a 4 GB model at CES 2003; initial street price should be about the same as it was for the current 1 GB model (about $499). Future products may reach 16-24 GB capacities in 5-10 years.

The variety and fit of competing technologies are driven by market potential. In 5 years the worldwide CE product market will be at least $125-150 billion in size. The mobile component of this market could be worth $25-30 billion (this assumes the continued successful roll out of wireless devices). A market of this size with excellent long-term growth potential is well worth a significant investment.

Given the likely capacity and price points of future mobile storage technologies, micro-optical disc storage must have a competitive response. The Philips blue micro-optical disc initiative is a good start for today, but will probably be uncompetitive in less than 5 years. This logically leads to adaptation in some form of the recently proposed (February 2002) Blu-ray technology (similar proposed technologies, such as AOD, might also serve). This proposed standard specifies a blue laser for read/write and an optical disc supporting two layers per side. Although not all the details for the Blu-ray initiative have been revealed, some reasonable assumptions can be made to arrive at a *pro forma* “reference specification” for micro-optical storage.

Unfortunately, simply scaling down Blu-ray technology to a 30mm disc might not produce the right product. Competitive analysis suggests that some additional advances are required; most importantly, the use of a near ultraviolet (UV) laser (a 375nm laser diode is chosen). This reference specification defines “Blu-ray UV micro-optical disc” (BUD).

Table Z.1 summarizes and compares the basic design parameters for the BUD solution. Similar parameters are listed for the DataPlay and Philips micro-optical disc designs. For the DataPlay micro-optical disc, a recording annulus defined by r-min ~ 6mm and r-max ~ 15mm was assumed. Most of the other design parameters are in the public domain, and are presented unmodified. For the Philips blue and Blu-ray UV micro-optical discs, a recording annulus defined by r-min ~ 6mm and r-max ~ 14mm was assumed. All capacities are user level. Philips has not made available publicly complete details about its blue micro-optical disc; hence, many design parameters are not listed. The Blu-ray UV micro-optical disc is based on the proposed Blu-ray standard data, but otherwise makes assumptions that parallel the (proven) DataPlay design.

The proposed Blu-ray micro-optical reference specification will be responsive to all currently envisioned competing mobile storage technologies 5-10 years in the future. Its single-sided capacity of 5 or 10 GB (10 or 20 GB double sided), 36 Mbps data rate, and robust, standardized storage media will meet the competition of most, if not all, competing mobile storage technologies.

The challenges in implementing Blu-ray UV micro-optical disc, however, are manifest. Among technology and engineering areas requiring pre-competitive research, the following are essential:

- Laser diodes emitting in the near UV (Nichia has already proven feasibility for 375nm LDs; shorter wavelength devices appear possible).
- Multi-layer optical disc design and materials
- Faster phase change thin films
- More accurate and faster tracking and focusing servos
- More efficient and powerful ECC (lower signal and higher noise are expected for UV wavelengths)
- Advanced channel coding and digital signal processing
- Mastering and replication of 2/4 layer and single-/double-sided discs

A fully functional prototype of a Blu-ray UV micro-optical disc is probably 3-5 years in the future. Considerable R&D will be required. However, a successful product development effort will ensure optical storage a bright future in the mobile computing and entertainment markets.

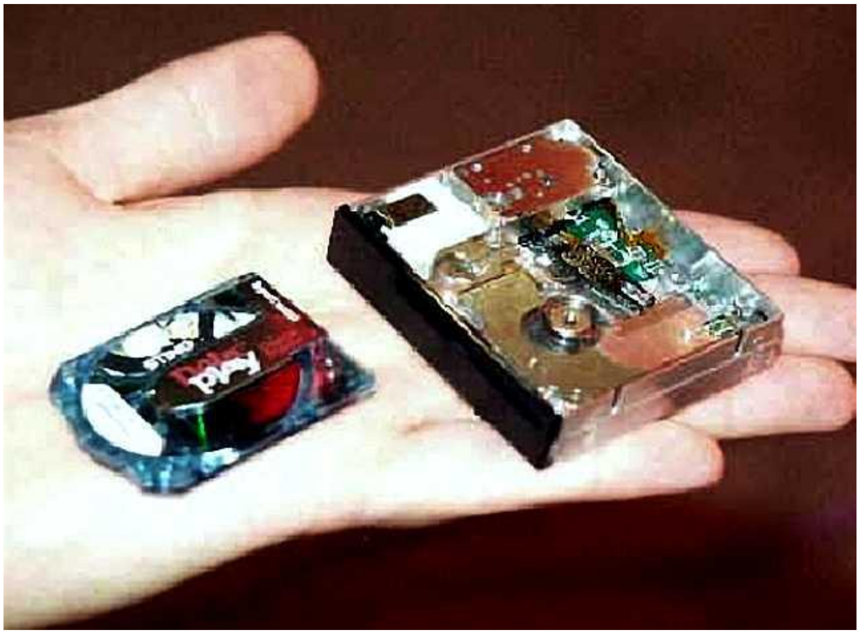

Figure Z1-1 DataPlay drive and micro-optical disc cartridge.

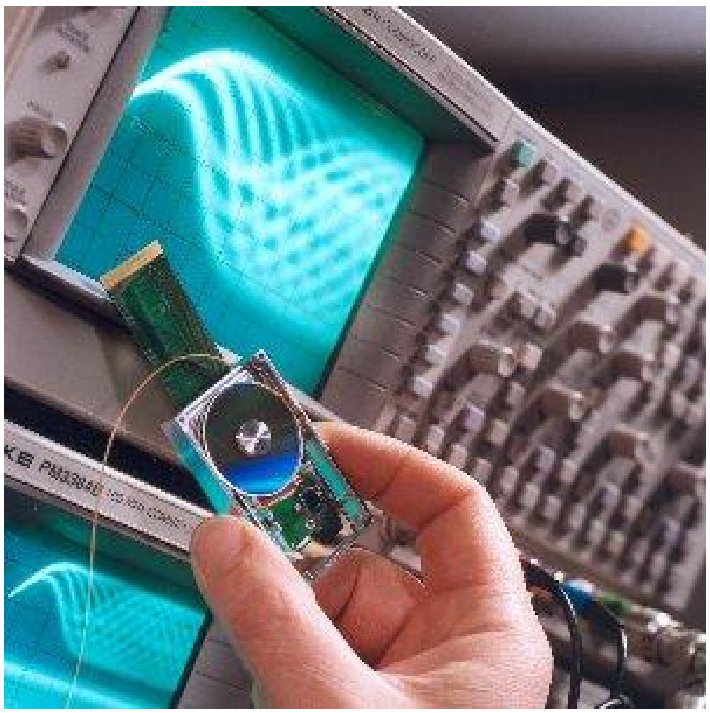

Figure Z1-2 Philips prototype blue micro-optical disc system.

Table Z-1: DVD Micro-Optical Disc Storage

	DataPlay Micro-Optical	Philips Blue Micro-Optical	Blue-ray UV Micro-Optical
capacity per layer (GB)	0.25	1	2.5
capacity per side (GB)	0.25	1	5 or 10
cart. capacity (GB)	0.50	1	10 or 20
disc diameter (mm)	32	30	30
substrate	polycarbonate	polycarbonate	polycarbonate
thickness (mm)	0.6		0.6
storage layer	phase change	phase change	phase change
types	ROM, WO, PROM	ROM, RW	ROM, WO, RW
cartridge	yes	yes	yes
sides/layers	1 or 2 / 1	1 /1	1 or 2 / 2 or 4
baseline technology	DVD derivative	proprietary	BD derivative
spiral groove	yes	yes	yes
laser wavelength (nm)	650 (red)	405 (blue)	375 (near UV)
NA	0.6	0.85	0.85
track pitch (nm)	740		246
track density (tpi)	34,324		103,188
bit density (bpi)	83,820		319,371
areal density (Gb/in^2)	2.88		33
rotation speed (rpm)	4,230 ~ 1,798		4,557 ~ 1,953
linear velocity (mps)	3		2.86
raw data rate (Mbps)	9.9		36
ave. access time (msec)	200		100
height (mm)	11	7.5 (5.0 planned)	5.0
length x width (mm)	52.3 x 47.5	56 x 34	56 x 34
weight (g)	50		~/< 40

Z2 Ultraviolet DVD Optical Disc Storage

The future of DVD optical storage beyond Blue Disc (BD) is very difficult to assess. The technology and components that lead to significantly higher capacity are not obvious. Moreover, identification of a realistic “killer application” proved frustrating (although, historically, all agreed that end users have always found a way to use available capacity).

The basic technology challenges are easy to understand. To achieve higher storage densities than BD optical storage, laser wavelengths in the ultraviolet (UV) part of the electromagnetic (EM) spectrum must be used to read and write. Significant problems exist; appropriate lasers, optics and storage materials have not been identified and/or may not exist. UV photons are destructive to organic materials (for example, polycarbonate and PMMA) and are badly absorbed and/or scattered by many inorganics (for example, fused silica).

UV light is roughly defined as EM radiation with wavelengths in the band 380nm ~ 10nm. This wavelength range is typically divided as follows:

- 380nm~320nm is UV-A (sometimes 400nm is used as the upper bound)
- 320nm~280nm is UV-B (the focus of current research for UV LDs and LEDs for defense applications)
- 280nm~200nm is UV-C (248nm is used for semiconductor lithography applications)
- 200nm~100nm is UV-D (generally exists only in a vacuum; 193nm is used for semiconductor lithography applications; the industry is migrating to 157nm).

Although it is replete with difficulties, UVD optical storage can look to other areas of R&D and other industries for assistance. Foremost among these is the semiconductor industry, which has worked with UV lithography for more than a decade, and is now mastering the extreme UV (EUV) region at 157nm. Developers of UVD optical storage can look to the semiconductor industry for help in components (for example, light sources, lenses, mirrors, and servoed positioning to nanometer resolutions), materials (for example, photoresists and coatings), and test and measurement (particularly, metrology). Defense applications requiring UV LDs and LEDs for bio and chemical weapons detection are being supported in industry and university labs. Optical communications requires the use of UV for the fabrication of various photonic components (for example, Bragg fiber gratings). Many university and industrial labs are working on MEMS and nanotechnology devices which require UV lithography.

The key to UVD is the UV laser diode. The current generation of 405nm blue/violet LDs is well known; 405nm is on the upper threshold of the UV spectral region. Less well known is R&D by Nichia and others to achieve lasing at even shorter wavelengths. Some examples follow:

- Nichia has announced a 375nm LD with 2 mW CW power output (also: 70 psec pulses at 40 MHz repetition rate with 100 mW power). This device is shipping in small volumes.
- Researchers at the University of California (Berkeley) have discovered means to build UV LD arrays using zinc oxide nanowires (room temperature operation).
- Researchers at the Institute of Physical and Chemical Research, Waseda University, and the Tokyo Institute of Technology have demonstrated UV radiation in the 230-280 nm range from $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ multi-quantum wells (MQWs). Al content was close to 80%, and the structure featured wide-bandgap-AlGaN barriers. These experiments were conducted at 77^oK. They also achieved high-intensity radiation in the 280-340-nm wavelength range from quaternary indium (In)AlGaN–based MQWs at room temperature (with power outputs comparable to those of commercially available blue InGaN emitters).

Many other UV laser systems exist (for example, alexandrite for 248nm and 193nm, F_2 for 157nm, diode pumped solid state (DPSS) for frequency tripling (354.7nm) and quadrupling (266nm), and eximer (248nm)). None of these systems are currently suitable for UVD optical storage systems. DPSS lasers have potential for integration and miniaturization, but are currently too expensive. They do, however, represent the best alternative to UV LDs.

If the availability of required technology, components and materials in 5 and 10 year time frames is assumed, DVD UVD can be specified in analogy to DVD BD. The objective is to put on the DVD futures roadmap two reference specifications (a 5-year out phase 1 and a 10-year out phase 2). The reference specifications are derived by scaling the known specifications of the proposed Blu-ray standard to UV LDs emitting at

325nm (frequency-doubled 650nm; UV-B) and 202.5nm (frequency-doubled 405nm; UV-C). The phase 1 specification provides a 55% density (capacity) increase; the phase 2 specification a 300% increase.
Table Z2-1 summarizes the design parameters for the phase 1 and phase 2 reference specifications. Capacity and data rates are user (21% overhead assumed). Maximum capacity per side is 167.2 GB for phase 1 and 432 GB for phase 2. Maximum cartridge capacities are 334 GB and 864 GB respectively. A polycarbonate substrate and a spiral groove for tracking is still used in phase 1. For phase 2, the polycarbonate substrate may require replacement by a glass-ceramic substrate owing to the very high areal density. In fact, the success of phase 2 may require the use of patterned media both for tracking and bit confinement. This greatly depends, of course, on the storage layer. Phase change alloys may be suitable, or a new technology may be required. Note the significant reduction in cover layer thickness to 0.05mm and 0.025mm, respectively. The material used may have to be calcium fluoride or fluoride-doped silica. The other data in the table are familiar to most who work in the field of optical storage.

Ten years from now, technology may have advanced to the stage where it might be reasonable to advocate a 1-2 TB UVD reference specification (achieved with a 4-layer per side, double-sided disc). However, the unknowns greatly outnumber the certainties. For now, the phase 1 and phase 2 reference specifications are aggressive enough, but still in keeping with the history of CD/DVD optical storage (meaning the large capacity jumps between new generations).

Almost every aspect of UVD will generate the need for pre-competitive research. Some of the more obvious requirements are:

- Compact, reliable and low-cost UV LDs
- Reflective optical components and holographic optical elements for the optical head.
- More complete integration of the entire optical read/write head (with the goal of a head per surface drive design)
- New storage layers optimized for UV read/write
- Mastering and replication processes optimized for UV read/write

Table Z-2: UV DVD (UVD) Optical Disc Storage

	UVD (phase 1)	UVD (phase 2)
capacity per layer (GB)	41.8	108
capacity per side (GB)	41.8, 83.6 or 167.2	108, 216, or 432
cartridge capacity (GB)	83.6, 167, or 334	216, 432, or 864
disc diameter (mm)	120	120
substrate	polycarbonate	polycarbonate
recording annulus (mm)	22 ~ 58	22 ~ 58
thickness (mm)	0.6	0.6
storage layer	phase change	TBD
cover layer thickness (mm)	0.05	0.025
types	ROM, WO, RW	ROM, WO, RW
cartridge	yes	yes
sides/layers	1 or 2 / 1, 2 or 4	1 or 2 / 1, 2 or 4
baseline technology	Blu-ray derivative	Blu-ray derivative
disc structure	spiral groove	patterned
laser wavelength (nm)	325 (UV-B)	202.5 (UV-C)
NA	0.85	0.85
track pitch (nm)	257	160
track density (tpi)	98,832	158,750
minimum pit length (nm)	110.7	69
bit density (bpi)	305,819	490,821
areal density (Gb/in^2)	30.3	78
rotation speed (rpm)	2,100 ~ 797	2,100 ~ 797
linear velocity (mps)	4.84	4.84
user data rate (Mbps)	46	72
ave. access time (msec)	75	50
first prototype (years)	~ 5	~10