Ultra-High Density Recording Technologies

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Introduction

The Engineering Research Center in Data Storage Systems at Carnegie Mellon University in cooperation with the National Storage Industry Consortium has selected goals of achieving 10 Gbit/in^2 recording density in magnetic and magneto-optic disk recording and 1 terabyte/in^3 in magnetic tape recording technologies. This talk will describe the approaches being taken and the status of research leading to these goals.

Future Recording Technologies

The capacities and performance which could be achieved from magnetic tape, magnetic disk and magneto-optic disk drives, assuming storage densities of 1 TByte/in^3 on magnetic tape and 1 Gbit/in^2 on magnetic disk and magneto-optic disk are illustrated in Fig. 1.

FUTURE STORAGE TECHNOLOGIES

Magnetic Tape

1 TByte/in^3
  200 kbpi
  5 ktpi
  0.125 mil tape
25 MByte/sec

500 GByte/QIC
40 GByte/RDAT

Magnetic Disk

10 Gbit/in^2
  400 kbpi
  25 ktpi
15 MByte/sec

150 GByte/3.5" drive
1.5 GByte/1" drive

Magneto-Optic Disk

10 Gbit/in^2
  165 kbpi
  64 ktpi
10 MByte/sec

6 GByte/2" removable disk

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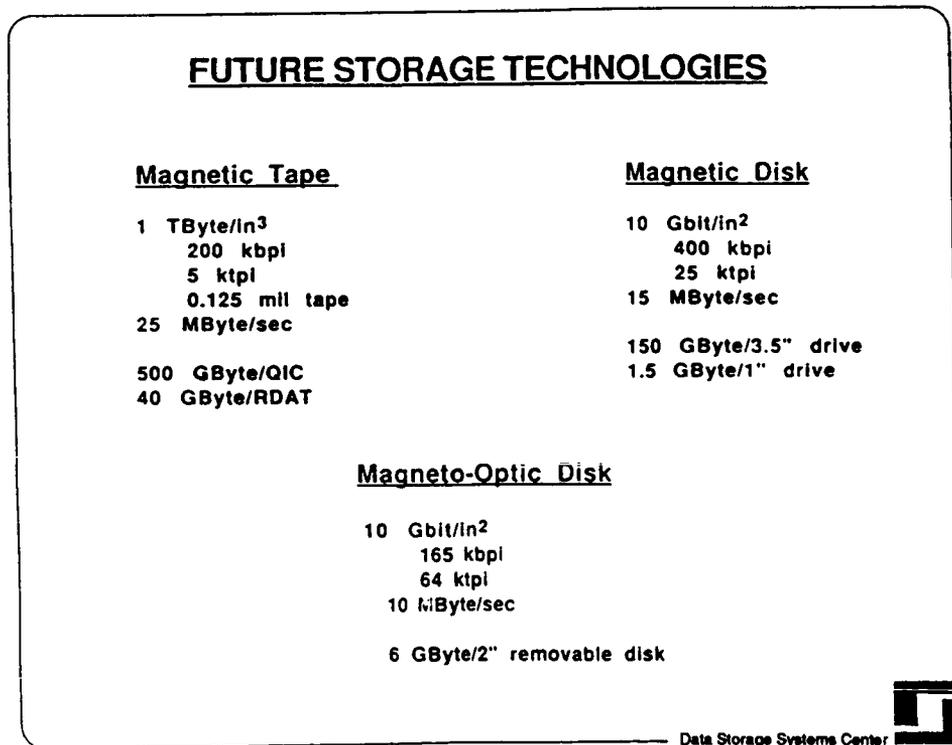
Fig. 1. Possible configurations for future ultra-high density magnetic tape, magnetic disk and magneto-optic disk drives.

It is proposed that 1 TByte/in^3 can be achieved on magnetic tape by using 0.125 mil tape and 1 Gbit/in^2 areal recording density. It is noted that 1 Gbit/in^2 areal recording density has already been achieved on a magnetic disk [C. Tsang et al., IEEE Trans. Magnet., MAG-26, 1689 (1990)]. It is suggested that a linear bit density of 200 kbpi and a track density of 5 ktpi will be approximately what are used. Building a transport capable of handling tape only 0.125 mils thick will be a challenge, but is believed to be possible. Data rates of 25 MByte/sec could be achieved from a single helical scan head or from a longitudinal recorder with multiple track heads.

Although cartridge sizes may well change significantly by the time such technology is available, it is interesting to note that a storage density of 1 TByte/in^3 would make it possible to store 500 GBytes in a Quarter Inch Cartridge and 40 GByte in a RDAT cartridge.

A storage density of 10 Gbit/in^2 on a magnetic disk drive would make it possible to store 150 GBytes in a 3.5-inch disk drive having 12 disks in it, or 1.5 GBytes on a single 1-inch disk. A data rate of about 15 MByte/sec could be achieved from the 3.5-inch disk by spinning it at 3600 rpm or from a 1-inch drive by spinning it at 10,800 rpm.

With a storage density of 10 Gbit/in^2, a 3.5-inch drive will probably be as large a disk drive as one would desire to build. A capacity of 150 GBytes is a lot for one spindle and larger disks would make the data rate too high for the semiconductor channel electronics. One inch or smaller drives are likely to be the high volume products when such storage density is available.

Although magneto-optic disk drives could in principle be made equally as small as hard drives, it is doubtful that they will use media smaller than 2 inches, because the media is removable. Smaller removable disks would be too easily lost. At 10 GBit/in^2 a 2-inch disk could store about 6 GBytes. Since magneto-optic recording uses a lower linear bit density than magnetic recording, a disk rotation rate of 10,800 rpm would be necessary to achieve a data rate of 10 MBytes/sec, still slower than a 1-inch magnetic hard disk spinning at the same speed.

Scaling Magnetic Recording Technology

The width of a recorded transition in magnetic recording media is affected by the media properties, the head field gradient and demagnetizing effects, as illustrated in Fig. 2. The finite switching field distribution, SFD, in the media convolved with the recording head field gradient cause a finite width transition. Demagnetizing fields in the media tend to broaden the transition. In a medium of thickness d exhibiting perfect squareness, the transition width may be written as

$$a = \sqrt{\frac{\delta^2}{16} + \frac{M_r \, \delta \, (d + \delta/2)}{\pi \, H_c}} - \frac{\delta}{4}$$

where M_r is the remanent magnetization of the medium, H_c is the coercive force, and d is the head-to-medium spacing. That the transition width broadens with increasing $M_r d / H_c$ is due to demagnetizing effects, while the dependence on $d + \delta/2$ is due to the reduction in head field gradient with increased spacing of the head from the medium.
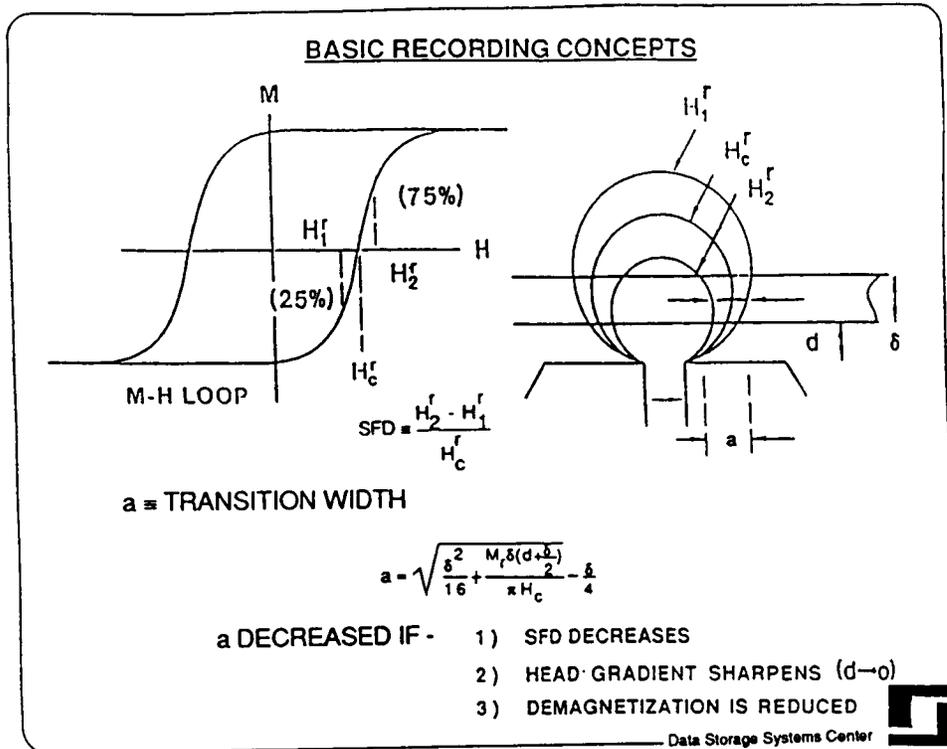
Fig. 2. Factors which determine the recorded transition width.

In addition to the widening of the recorded transition produced by increased head-to-medium spacing, increased spacing leads to a very rapid decrease in playback signal, as illustrated in Fig. 3. The readback voltage from the head varies exponentially with the ratio of d+δ/2 to b, the spacing between flux changes. This causes a reduction in signal of about 27 dB for every (d + δ/2)/b. This extremely rapid fall-off in signal with head-to-medium spacing means that, when the recording density is increased, it is extremely important that the head-to-medium spacing is simultaneously reduced.

SPACING LOSS

$$V \propto \exp\left[-\pi \left(d + \frac{\delta}{2}\right) / b\right]$$

$$\frac{V(d)}{V(o)} = -27 \frac{\left(d + \frac{\delta}{2}\right)}{b} \, dB$$

δ = media thickness or recording depth

b = spacing between flux changes

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Fig. 3. Spacing loss in magnetic recording.

In magnetic tape recording systems, the head runs in contact with the tape. Even so a finite head-to-medium spacing results as the head moves from asperity to asperity on the tape surface. To achieve a very small head-to-medium spacing, the tape must be very smooth.

Magnetic hard disk systems built today use an air bearing to fly the head slightly above the surface of the media. Head-to-medium spacings of the order of 4 microinches (100 nm) are being used today. To achieve 10 Gbit/in² recording density it is expected to be necessary to also run disk heads in contact with the medium. One approach to achieving this is illustrated in Fig. 4. A low mass secondary slider which runs in contact with the media is built into a larger primary slider which flies above the disk surface. The low mass of the secondary slider and its weak coupling with the more massive primary slider enable it to run in contact with the media without causing significant wear. This entire assembly can be micro-machined from single crystal silicon. An alternative approach is to use a whisker-like flexible probe head such as that being pursued by Censtor Corporation [H. Hamilton, et al., *IEEE Trans. Magnet.*, MAG-27, 4921 (1991)].
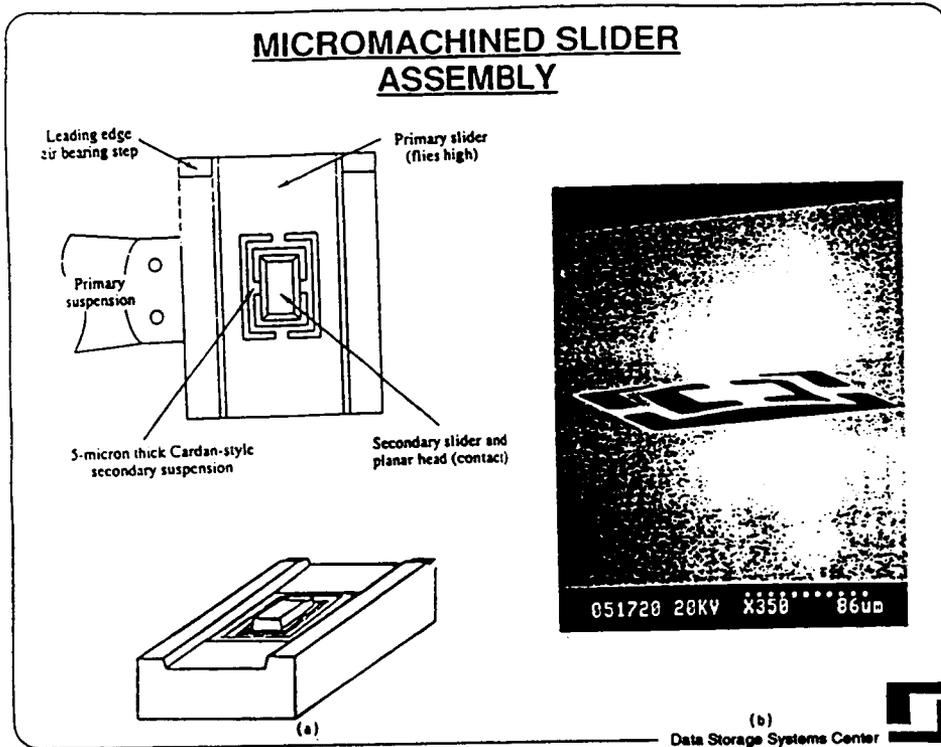
Fig. 4. (a) A diagram of a micromachined slider for contact
              recording in a disk system. The low-mass
              secondary slider runs in contact with the medium.

        (b) A SEM micrograph of a micro-machined
              secondary slider.

The ultimate noise level in a magnetic recording system is set by the noise properties of the medium. The media power signal-to-noise ratio was shown by Mallinson [*IEEE Trans. Magnet.*, MAG-5, 182 (1969)] to be approximately equal to the number of particles sensed by the recording head at any instant in time. Thus the power signal to noise ratio is given by

$$PSNR = nWb\delta,$$

where n is the number of magnetic particles per unit volume, W is the recorded trackwidth, b is the spacing between flux changes (one half the wavelength of recording) and δ is the medium thickness. The particle or grain sizes necessary to achieve 20 dB or 30 dB of signal-to-noise ratio in magnetic tape and disk media with densities of 1 Gbit/in^2 and 10 Gbit/in^2 recording densities, respectively are shown in Fig. 5. These particle and grain sizes are believed to be achievable.

MAGNETIC RECORDING MEDIA NOISE

For non-interacting grains:

$PSNR = nWb\delta$
n = particles/unit volume
W = trackwidth
b = spacing between flux changes
δ = medium thickness or recording depth

PSNR (dB)	1 GBit/in² Mag Tape ($\delta = 2b/3 = 0.1 \mu m$) <Vol>^{1/3} (nm)	10 GBit/in² Mag Disk ($\delta = 10$ nm) Grain size (nm)
20	60	30
30	28	10

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Fig. 5.   The particle sizes necessary to achieve given power signal to noise ratios in 1 Gbit/in² and 10 Gbit/in² recording densities in magnetic tape and disk systems, respectively.

The recorded transition width which might be expected in future barium ferrite and metal evaporated tape media for 1 Gbit/in² recording density are shown in Fig. 6. The depth of recording into a medium is given approximately by 2b/3 [J. C. Mallinson, *IEEE Trans. Magnet.*, MAG-5, 182 (1969)]. Hence the effective medium thickness for the barium ferrite media is taken to be about 0.1 micrometer, which is approximately 2b/3 for 200 kbpi recording. If a head-to-medium spacing of 25 nm or 1 microinch is used, then a transition width parameter of 8 nm results for barium ferrite media with 250 kA/m (3125 Oe) coercivity.

1GBIT/In2 MAGNETIC TAPE MEDIA

Transition Length Parameter
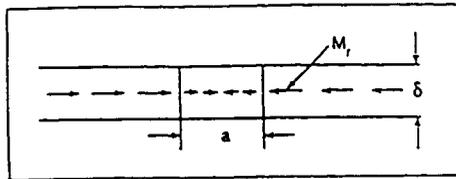
$$a = \sqrt{\frac{\delta^2}{16} + \frac{M_r \delta(d + \frac{\delta}{2})}{\pi H_c}} - \frac{\delta}{4}$$

	Ba - Ferrite Media	Metal Evap. Media
δ	100 nm	40 nm
d	25 nm	25 nm
Mr	50 KA/m (50 emu/cm³)	1000 KA/m (1000 emu/cm³)
Hc	250 KA/m (3125 Oe)	250 KA/m (3125 Oe)
a	8 nm	51 nm (demag limit)

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Fig. 6.   The transition length parameter for barium ferrite and metal evaporated recording media designed for 200 kbpi recording density.

The metal evaporated media was assumed to be less than 2b/3 in thickness in order that the transition length parameter a be less than b. Unless the media thickness is reduced to 40 nm, demagnetizing effects will limit the recording density to less than 200 kbpi in metal evaporated media with a remanent magnetization of 1000 kA/m (1000 emu/cm³).

The transition length parameter for a possible 10 Gbit/in² thin film disk medium is calculated in Fig. 7 and compared to parameters of media used in the 1 Gbit/in² recording demonstration by IBM [C. Tsang et al., *IEEE Trans. Magnet.*, MAG-26, 1689 (1990)]. With a (1,7) code, a recording density of 300 kfci yields a linear bit density of 400 kbpi and a bit spacing of 83 nm. A head-to-medium spacing of 20 nm (0.8 microinch) and a medium thickness of 10 nm (0.5 microinch) ensure that the spacing loss does not become significantly worse than in the 1 Gbit/in² demonstration.   Both the media remanent magnetization and coercivity are increased, yielding a transition length parameter of 14 nm for the 10 Gbit/in² media. This is well below the bit spacing of b = 83 nm.

463

ULTRA HIGH DENSITY THIN FILM DISK MEDIA

Transition Length Parameter

$$a = \sqrt{\frac{\delta^2}{16} + \frac{M_r \, \delta \left(d + \frac{\delta}{2}\right)}{\pi H_c}} - \frac{\delta}{4}$$

IBM 1Gbit/in² Demo (1989)

125 kfci = 167 kbpi
b = 200 nm
d = 56 nm   (2.25 μ inch)
δ = 25 nm   (1 μ inch)
M_r = 300 kA/m   (300 emu/cm³)
H_c = 135 kA/m   (1700 Oe)
a = 29 nm

Possible 10Gbit/in² Media

300 kfci = 400 kbpi
b = 83 nm
d = 20 nm   (0.8 μ inch)
δ = 10 nm   (0.5 μ inch)
M_r = 800 kA/m   (800 emu/cm³)
H_c = 240 kA/m   (3000 Oe)
a = 14 nm

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Fig. 7.   The recording media parameters for 1 Gbit/in² disk recording as demonstrated by Tsang et al. [IEEE Trans. Magnet., MAG-26, 1689 (1990)] and possible future 10 Gbit/in² disk recording.

Thin film disk media with parameters similar to those required for 10 Gbit/in² recording are currently under development. One such medium is SmCo/Cr, which was described by Velu and Lambeth [E. M. T. Velu and D. N. Lambeth, IEEE Trans. Magnet., Mag-27, 2706 (1992)] at the 1992 Intermag Conference. Velu and Lambeth noted that the (11$\bar{2}$0) face of SmCo provided an excellent lattice match to the (110) face of Cr. Hence they deposited Cr at low temperatures where the (110) orientation is typically obtained and then deposited SmCo on top of it. The result was a high coercivity medium with reasonable squareness and extremely low noise. The carrier to integrated noise ratio, CINR, and the overwrite performance of representative disks of this media are shown in Fig. 8. The CINR remains above 25 dB out to 50 kfci. The slight roll off above 35 kfci is believed to be due to limitations of the recording head and spacing loss rather than media noise problems, as measurements of the media noise showed no increase with recording density. In spite of the high coercivity of the medium (2320 Oe in Fig. 8), the overwrite performance is very good. Approximately 50 dB of overwrite is obtained when a 7.3 kfci signal is overwritten by a 14.6 kfci signal. Although the media for which data are plotted in Fig. 8 only have coercivity of up to 2320 Oe, Velu and Lambeth have made media with coercivities in excess of 3000 Oe. To date the recording performance of these ultra high coercivity disks have not been tested, as no recording heads with sufficiently high magnetization to prevent saturation have been available to test them.

CoSm/Cr(110) THIN FILM MEDIA
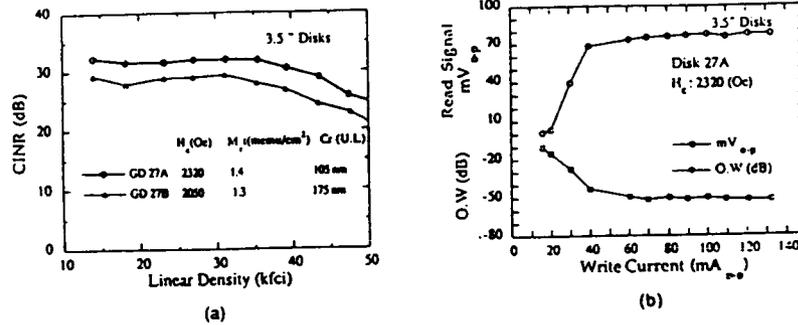
(a) Carrier to integrated noise ratio and (b) overwrite
performance (7.3 kfci/14.6 kfci) for SmCo/Cr thin film media

Fig. 8.   (a)   Carrier to integrated noise ratio and

(b)   overwrite performance (7.3 kfci/14.6 kfci) for
SmCo/Cr thin film media.

Recording head saturation is a problem which can be solved with higher magnetization soft magnetic alloys. Jeffers [Proc. of IEEE, 74, 1540 (1986)] pointed out that metal recording heads typically showed saturation effects when the deep gap field of the head H_g reached about 80% of M_S. By using the Karlqvist equations to describe the longitudinal head fields, setting $H_g = 0.8$ M_S and requiring that the longitudinal field be equal to the coercivity at the back of the media, the maximum coercivity media which may be recorded may be calculated and shown to be

$$H_{c,max} = 0.25 \ M_S \ tan^{-1} \ [g/2(d+\delta)]$$

This relationship may be used to calculate the maximum coercivity which may be recorded with a given recording head as shown in Fig. 9. It is seen there that, in a 100 nm thick tape medium and using a head-to-medium spacing of 25 nm (1 microinch), the maximum coercivity recording tape media which may be written with a recording head having a gapwidth of 200 nm and a magnetization of 800 kA/m is 138 kA/m (1720 Oe); whereas, if the magnetization were increased to 1600 kA/m, media with coercivity as high as 275 kA/m (3440 Oe) could be used.

465

HEAD SATURATION

$$H_x = \frac{H_g}{\pi} \tan^{-1} \frac{g}{2y},$$

To prevent saturation: $H_g < 0.8\ M_s$

Thick Tape Media (1 Gbit/in^2)

Thin Film Disk Media (10 Gbit/in^2)
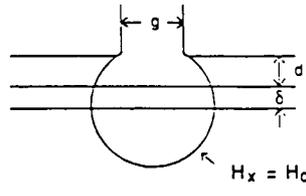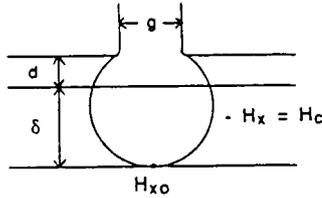
$H_{c,max} = 0.25\ M_s \tan^{-1} \frac{g}{2(d+\delta)}$

$H_{c,max} = 0.25\ M_s \tan^{-1} \frac{\frac{g}{2}}{2d+\delta}$

g = 200 nm, d = 25 nm, δ = 100 nm

g = 180 nm, d = 20 nm, δ = 10 nm

M_s	$H_{c,max}$	$H_{c,max}$
800 kA/m (800 emu/cm^3)	138 kA/m (1720 Oe)	215 kA/m (2700 Oe)
1600 kA/m (1600 emu/cm^3)	275 kA/m (3440 Oe)	430 kA/m (5400 Oe)

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Fig. 9.   The maximum coercivity tape and disk media which may be recorded with a given magnetization metal recording head.

For thin film disk media the maximum coercivity is calculated differently. To ensure complete saturation, the longitudinal field contour corresponding to the $H_x = H_c$ contour is made to fully penetrate the thin film media. In this case the maximum coercivity which may be used is

$$H_{c,max} = 0.25\ M_s \tan^{-1} [g/2(2d+\delta)].$$

In this case a head with a gapwidth of 180 nm and made of magnetic material having magnetization of 800 kA/m could be used with media having coercivity as high as 215 kA/m (2700 Oe) if the head-to-medium spacing and medium thickness were chosen to be be 20 nm (0.8 microinch) and 10 nm (0.4 microinch), respectively, as in Fig. 7. Increasing the magnetization to 1600 kA/m would make it possible to use media with coercivity up to 430 kA/m (5400 Oe). Thin media are thus seen to significantly reduce the problem of head saturation.

High magnetization alloys with good soft magnetic properties and high frequency performance appear to be available for ultrahigh density recording requiring a saturation magnetization of 1600 kA/m (B_s = 20,000 Gauss). Multilayer FeAlN/SiO$_2$ thin films have been made with coercivities of the order of 20 A/m (0.25 Oe) and flat high frequency response to beyond 200 MHz, as shown in Figs. 10 and 11. These materials also exhibit very low magnetostriction and have been shown to be similar to Permalloy in their corrosion characteristics.

M-H LOOP OF AN ANNEALED FeAlN/SiO$_2$ MULTILAYER FILM

Easy axis:
Hc: 0.22 Oe
$4\pi M_s$: 19.8 KG

FeAlN

SiO$_2$

Glass

Hard axis:
Hc: 0.26 Oe
$4\pi M_s$: 19.7 KG
H_K: 6.06 Oe
λ_s: -1×10^{-7}

$4\pi M_s$ (KGauss)

H (Oe)
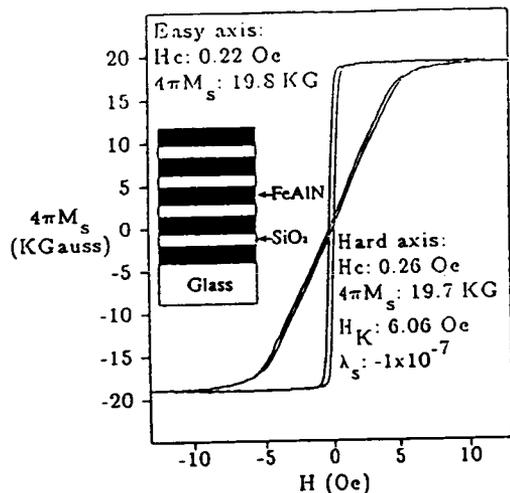
(0.57 μm thick, 5 FeAlN layers; 300°C, 1.3 KOe E.A. field)

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Fig. 10. The M-H loop of a FeAlN/SiO$_2$ multilayer film.
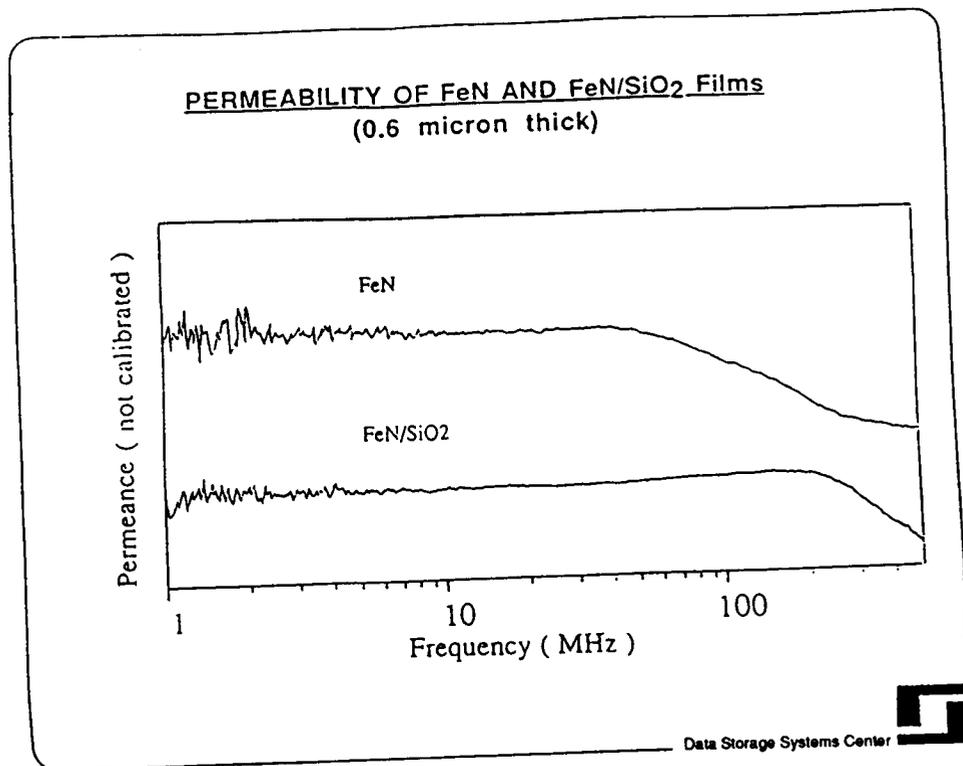
Fig. 11. The relative permeabilities of a 600 nm thick FeN film and a FeAlN/SiO$_2$ multilayer material as a function of frequency. The vertical scale for the two materials is displaced. Both materials have similar low frequency permeability.

Scaling of Magneto-Optic Recording Technology

A schematic diagram of a magneto-optic recording system is shown in Fig. 12. The recording medium consists of a magnetic thin film with preferred axis of uniaxial anisotropy perpendicular to the film plane. This medium has very high coercivity near room temperature, but low coercivity at temperatures near 200°C. To record on the medium, the beam of a diode laser is focussed onto the medium in the presence of an externally applied magnetic field directed opposite to the initial magnetization direction of the medium and pulsed for a short duration. The energy absorbed by the medium heats it to above 200°C, where the coercivity of the medium is low, and the magnetization in the heated region reverses in response to the applied magnetic field. Thus by controllably pulsing the diode laser, reverse domains, corresponding to bits of information may be recorded into the medium. To read previously recorded information out of the medium, the polar Kerr magneto-optic effect is used. The same diode laser is used, but at lower power output so the energy does not disturb the recorded information. The light from the diode is plane polarized and, upon reflection from the medium, suffers a change in polarization orientation which is dependent upon the direction of magnetization in the medium. This change in polarization state is converted to a change in light intensity by the analyzer and then detected with a photodetector.

468

Magneto-Optical Recording

Photodetector

Laser Diode   Collimating Lenses

Analyzer

Polarizer

Beam
Splitter

Direction of
Medium's Motion

Objective lens

Transparent Coating

Magneto-Optical Medium

Substrate

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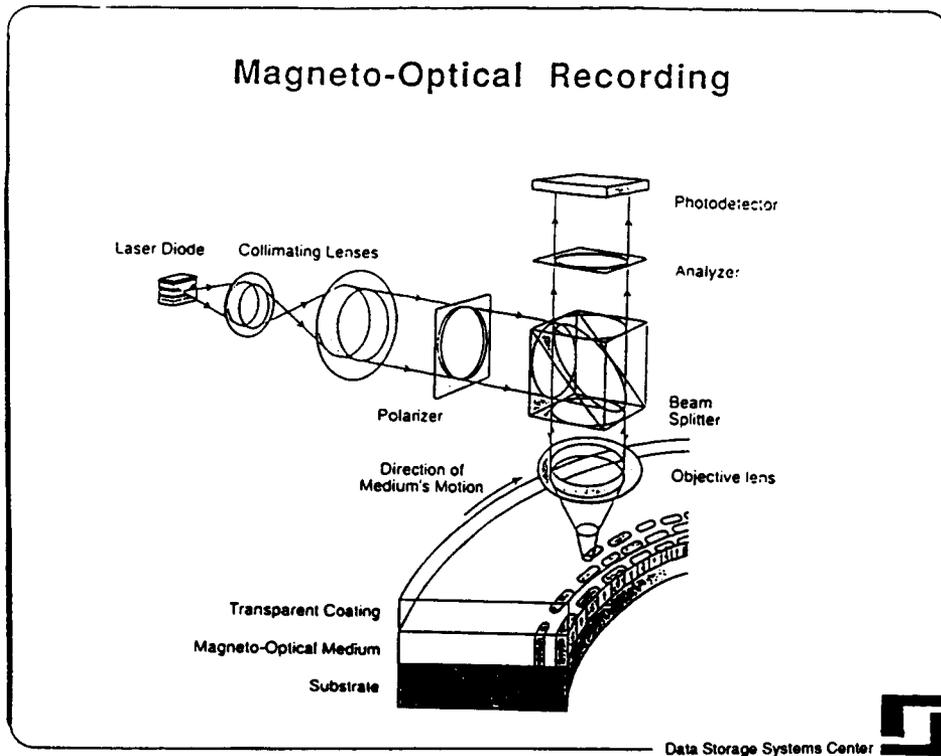
Fig. 12. A schematic diagram of a magneto-optic recording system.

Future magneto-optic recording devices are expected to have considerably higher densities than presently manufactured devices. Increased areal bit density is expected from a number of factors, as shown in Fig. 13. The spot size in magneto-optic drives manufactured today is about 0.8 micrometer; however, in the future spot sizes of 0.2 micrometer are expected. Smaller spot sizes are expected to result from the use of blue, rather than infra-red, light sources and higher numerical aperture objective lenses. In addition, the use of run-length limited pulse-width modulation codes, such as the (2,7) block code, instead of simple pulse-position codes, are expected to increase the linear bit density by a factor of 3. Track density will also be increased by a factor of 2 through the use of shorter wavelength light and by a factor of 1.3 through higher numerical aperture objectives. Moreover, alternative track following servo techniques could reduce the guard band between tracks to the order of the rms deviation of the tracking servo, increasing the track density by another factor of 1.6. Finally, zone bit recording, which is commonly employed in magnetic disk drives today, and packs the bits at equal density on the inner and outer radii of the disk, could increase the total storage capacity by another 50%. Multiplying all these factors together, approximately a factor of 50 improvement in storage density on a magneto-optic disk results, making a storage density of 10 Gbit/in^2. As will be shown later, magnetic super-resolution or optical super-resolution could potentially enable even higher densities.

ADVANCES IN MAGNETO-OPTIC DISK DENSITY

FEATURE	ADVANCES REQUIRED	DENSITY GAIN
165,000 Bits per Inch		
0.2 μm Spot	Blue Lasers	2X
	High NA Objective	1.3X
1.3 Bits/Transition	Modulation/EC Codes	3X
63,500 Tracks per Inch		
0.33 μm Track	Blue Lasers	2X
	High NA Objective	1.3X
0.07 μm Guard Band	Narrow Guard Band	1.6X
5 GBytes/Side		
Zone Bit Recording	Zone Bit Recording	1.5X
	Total	50X

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Fig. 13. Factors which are expected to contribute to future increases in the storage density of magneto-optic recording devices.

The increases in bit and track densities which arise from shortening the wavelength of light and increasing the numerical aperture of the objective lens are easily understood by considering the minimum resolvable spot size as determined by the laws of diffraction of light and illustrated in Fig. 14. The minimum linewidth which may be resolved with an optical system is given by

$$D = C\lambda/\sin\theta$$

where λ is the wavelength of the light used and $\sin\theta$ is the numerical aperture of the objective lens. The constant C can have values ranging from about 0.31 to 0.61, depending upon the modulation transfer function which is desired. It may be seen that halving the wavelength reduces the minimum resolvable spot size by a factor of two while also narrowing the minimum track width by a factor of two. Similarly, increasing the numerical aperture of the objective by a factor of 1.3 from the present value of 0.5 to 0.65, causes a similar increase in bit and track densities.

DENSITY LIMITS FOR
MAGNETO-OPTICAL RECORDING

Intensity
Distribution

$D = \dfrac{C\lambda}{\sin\theta}$

$0.31 \le C \le 0.61$
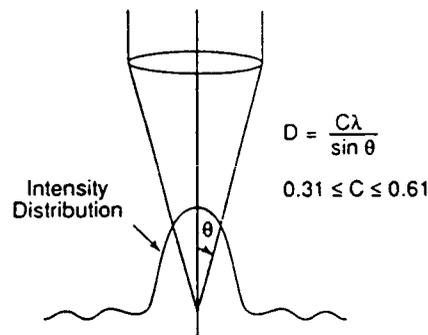
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Fig. 14. The minimum resolvable linewidth in an optical system.

Narrowing the guard band between tracks can potentially be done by a number of techniques. Presently manufactured media use grooves between tracks to define the tracks and provide a position error signal, which is used for track following. Current disks use a track pitch of 1.6 micrometers, but a laser beam size of only 0.8 micrometers. Thus there is effectively a guard band 0.8 micrometers wide between tracks. However, the rms deviation of the track following servo on optical drives has been measured to be less than 0.05 micrometers. Thus the groove between tracks is extremely wasteful of the surface area of the disk.

Alternative servo techniques can be expected to be developed which enable one to reduce the guard band. One possibility is to use a sector servo such as that pictured in Fig. 15. With this servo system, no grooves are used. Rather, isolated pits are located at the beginning of sectors and used to provide the position error signal for track following. When the laser is properly positioned, it follows the solid line through the pits and the output signals from the pits are equal in magnitude. However, if the laser is off track and follows the dotted line, the output signal from pit A is larger than the output signal from pit B. On the other hand, if the laser follows the dashed line the output signal from pit B is larger than from pit A. The difference in the output signals from pits A and B can thus be used as a position error signal. Since these pits are not continuous, tracks can be spaced closer together. In principle, the upper edge of one pit could serve as pit A for the upper track while the lower edge serves as pit B for a track immediately below it, effectively doubling the track pitch.

471
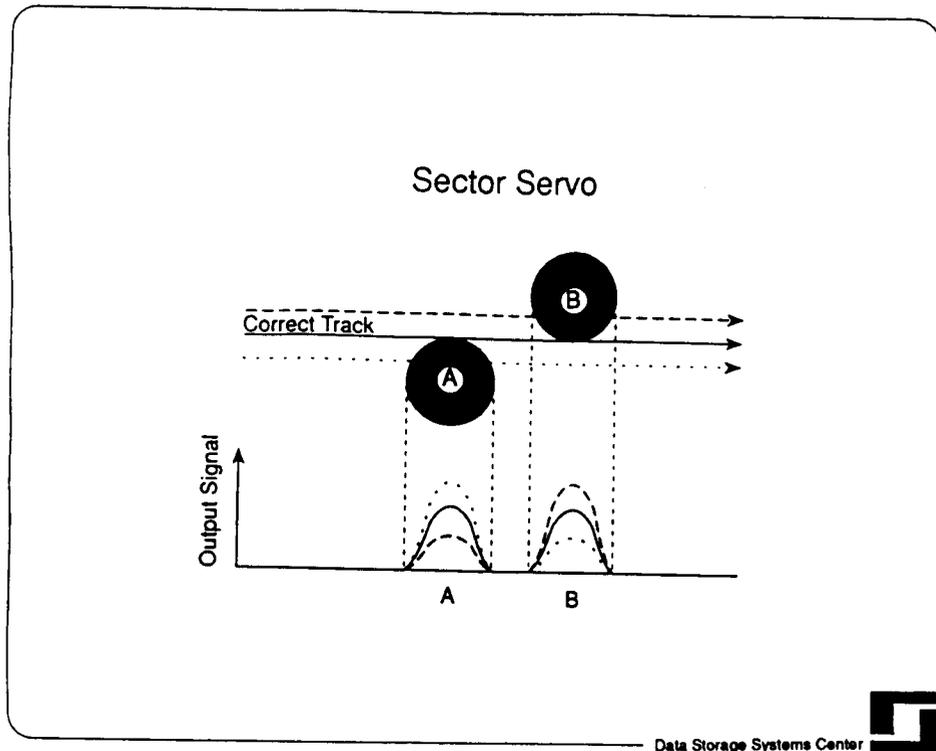
Fig. 15. A possible approach to sector servo which would allow
narrower track pitch than continuously grooved media.

Techniques to increase the areal bit density of magneto-optical recording by more than the factor of 50 illustrated in Fig. 13 include magnetic and optical super-resolution. With these techniques it is possible to exceed the limit of resolution determined by focussing optics alone. Magnetic super-resolution makes it possible to write and read marks smaller than the optically resolvable spot size even while using a large head-to-media spacing. Optical super-resolution uses an aperture, smaller than the diffraction limit, in very close proximity to the magneto-optic medium to define the spot size. This latter technique requires a similar head-to-medium spacing as magnetic recording to achieve an equivalent bit spacing.

Magnetic super resolution is achieved by using multilayer exchange coupled media like that shown in Fig. 15 [M. Ohta, et al., J. Magn. Soc. Jpn., 15, Suppl. No. S1, 319 (1991)]. The properties of the three layers are summarized in Table 1.

Table 1   Magnetic Properties of the Films used to Make Up the Magnetic Super Resolution Disk.

Layer	Material	Thickness (Å)	T_c (°C)	H_c (KOe)
readout	GdFeCo	300	>300	0.1
switching	TbFeCoAl	100	~140	
recording	TbFeCo	400	~250	>10

In this technique, recording is performed with a magnetic head flying close to the media to provide a magnetic field which is modulated at the recording frequency of the laser. Since the magnetic field, and not the laser spot size, determines whether the magnetization is directed upward or downward, mark size can be smaller than the laser spot. The information to be stored is recorded into all three exchange coupled layers shown in Fig. 16.
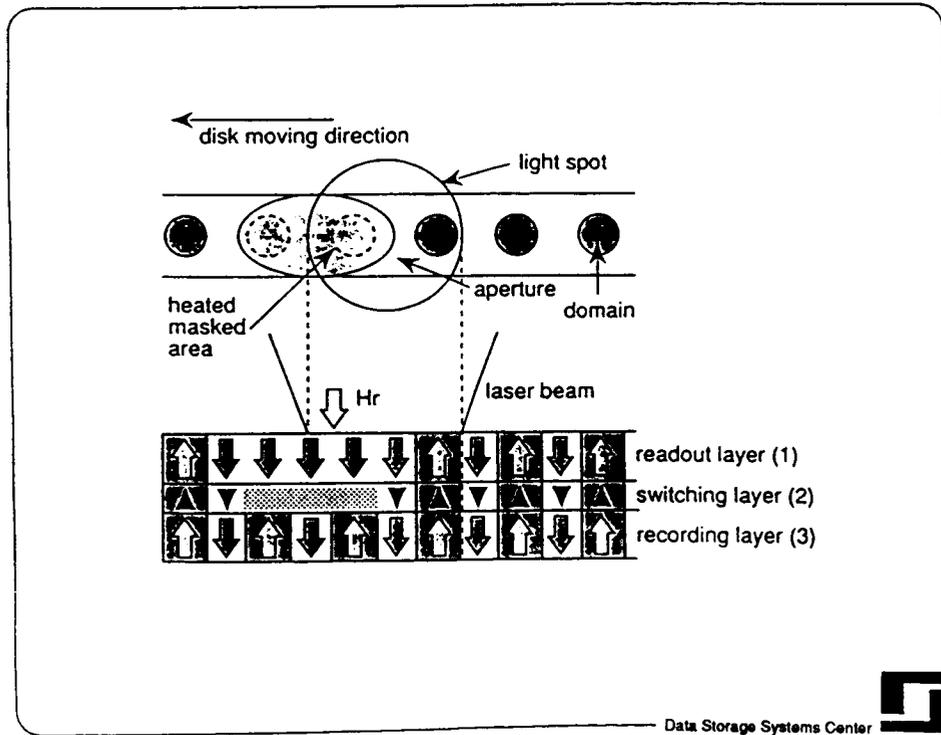
Fig. 16.   Readout by Magnetic Super Resolution [M. Ohta, et al., *J. Magn. Soc. Jpn.* 15, Suppl. No. S1, 319 (1991)].

To readout the information, a magnetic field H_r is applied downward as shown in Fig. 16. Sufficient energy is applied from the laser to reach the Curie temperature T_C of the switching layer. This breaks the exchange coupling between the readout and recording layers and allows any downward directed domains recorded in the readout layer to switch. Since the light spot encompasses the switching domain, when the domain switches, there is a change in the net magneto-optic rotation of the light, which may be detected. Hence, domains smaller than the beam diameter can be detected.

The readout mechanism is nondestructive, because when the switching layer cools below its Curie temperature, it again exchange couples the recording and readout layers. Since the recording layer has a very large coercivity and the readout layer has a small coercivity, the exchange coupling forces the readout layer to replicate the pattern in the recording layer.

Optical super-resolution is achieved by defining a very small aperture and bringing the magneto-optic medium into the near-field region of the aperture. In such a case the resolvable spot size is determined primarily by the aperture size, which can be much smaller than can be obtained with focussing optics. Recently, this technique was used by Betzig et al. [1992] to demonstrate recording and readback of an array of magnetic domains having a density of 45 Gbit/in^2. Even higher densities are believed possible.

Betzig et al. [1992] used an optical fiber which had been drawn down so it had approximately a 20 nm diameter at the end to define the aperture as illustrated in Fig. 17. The sides of the fiber were coated with an aluminium reflector in the region near the aperture to prevent the effanescent light energy from escaping where the fiber was too small to support an optically guided wave. By using polarizing optics and scanning the fiber above the surface of a Co/Pt multilayer film, magnetic domains as small as 60 nm were written and readback as shown in Fig. 18. By using a flying head this technique could, in principle, be used to achieve storage densities above 100 Gbit/in^2.
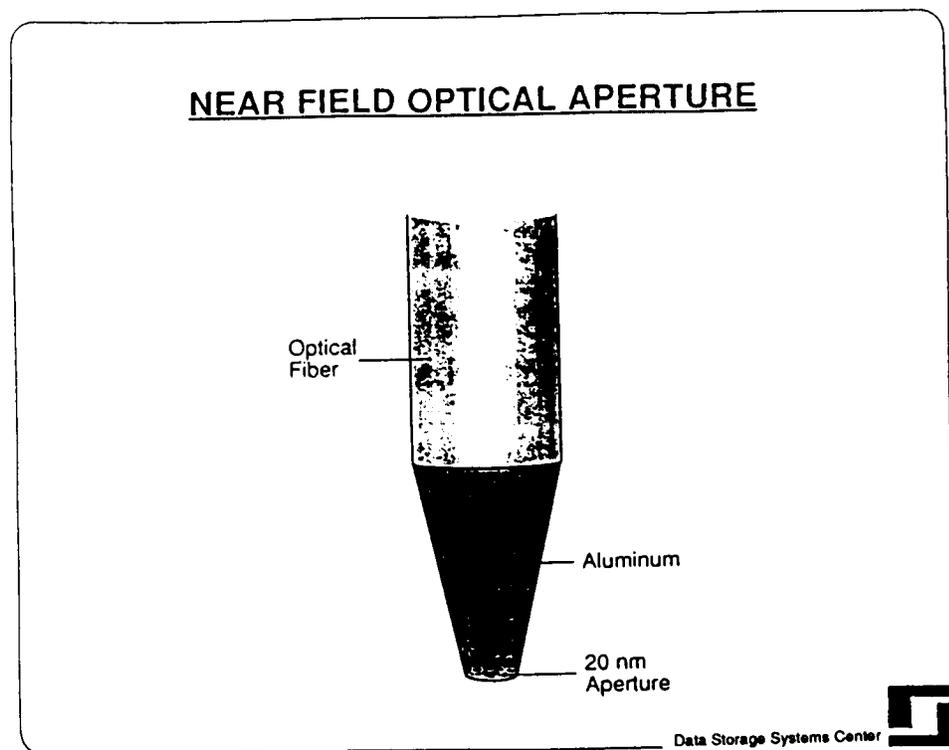
Fig. 17. An optical fiber is drawn down to produce a 20 nm aperture.
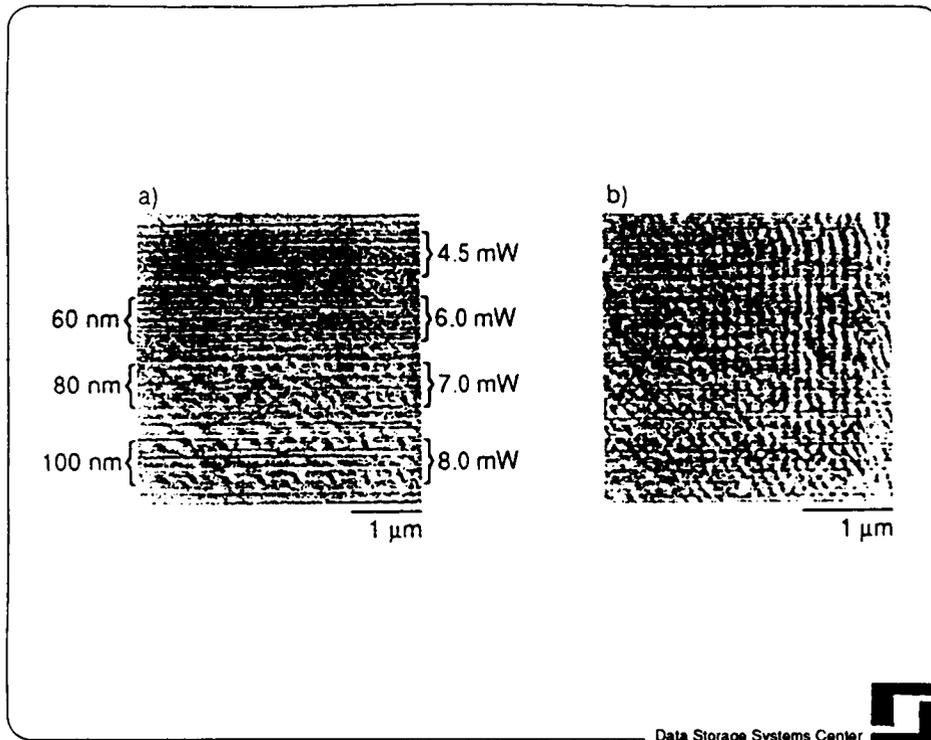
Fig. 18. (a) Submicrometer domains recorded using optical super resolution at different write powers and head-to-media spacings.

(b) A 20 X 20 array of domains with 120 nm periodicity in both directions, correpsonding to a storage density of ~45 Gbits/in^2 [Betzig, et al., *Appl. Phys. Lett.*, 61, 142 (1992)].

Conclusions

Magnetic recording technology has increased storage density by a factor of 50,000 over the past 35 years since it was first used in a disk format for computer data storage; however, there is no sign this rapid pace is slowing. Indeed fundamental limits, set by superparamagnetism are estimated to be several orders of magnitude from where we are today. Recent product announcements and developments in research labs suggest that the rate of progress is likely to accelerate. Storage densities of over 1 GBit/in^2 are likely by the end of this decade and densities of 10 GBit/in^2 appear likely in the early 21st Century. Multilayer thin film media, thin film write heads utilizing high magnetization thin film multilayer materials and magnetoresistive read heads are expected to be among the new technologies which make this occur.

Magneto-optic recording has only recently been introduced to the marketplace. It offers high areal density (about 2×10^8/in^2) on removable disk media. Presently the media costs about \$0.50 per megabyte. Although areal storage densities are high, the volumetric storage densities are less than in rigid magnetic disk drives containing multiple disks. Data rates and access times are currently about a factor of two or three times slower than on rigid disk drives, and costs at the drive level are higher than for rigid disks. The technology, however, is young and both cost reductions and improvements in storage density and performance are expected. Higher numerical aperture objectives, improved signal processing, improved track following servos and shorter wavelength laser sources combined with improved media for short wavelength recording are expected to increase the storage density. Over an order of magnitude improvement is likely. Both higher bit density and higher spindle rotation rates will lead to higher data rates. The higher spindle rotation speed will also shorten the latency time. A removable 2 inch magneto-optic disk which will store a few GBytes of data with data rates and access times only slightly poorer than those of rigid magnetic drives appears likely by the year 2000. The use of magnetic and/or magneto-optic super-resolution could eventually lead to magneto-optical drives with areal storage densities well beyond 10 Gbit/in^2.