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MAGNETIC DISK

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Magnetic disk recording was invented in 1953 and has under gone intensive development ever since. As a result of this 38 years of development, the cost per byte and the areal density have halved and doubled respectively every 2-2 1/2 years. Today, the cost per byte is lower than 10^{-6} dollars per byte and areal densities exceed 100 10^6 bits per square inch.

In this talk, the recent achievements in magnetic disk recording will first be surveyed briefly. Then the principal areas of current technical development will be outlined. Finally, some comments will be made about the future of magnetic disk recording.

PRESENT ACHIEVEMENTS

High end disk drives today operate at areal densities of between 50 and 100 10^6 bits per square inch, with, typically, 2500 tracks per inch and 30,000 flux reversals per inch. When "run length limited" coding is used, the effective linear bit density is 40,000 bits per inch. Areal densities tend to be higher the smaller the diameter of the disk.

Data rates run as high as 6 Megabytes per second (48 Megabits per second) per single head-disk channel. Parallel access disk systems, with as many as 10 heads in parallel have been manufactured which provide the full CTIR 4:2:2 component digital video output rate (216 Megabits per second).

Since as many as 6 disks can be fitted in the standard 5 1/4" full height form factor package, 5 1/4" drive data capacities exceeding 2 Gigabytes are now available from several manufacturers.

In summary, it may be said that the magnetic disk products being manufactured today offer access times, data rates and drive bit capacities considerably in excess of those offered by optical disk drives. Areal density is the only parameter which currently falls below that of optical disks, by a factor of 3-4.

AREAS OF TECHNICAL DEVELOPMENT

The overwhelming success of magnetic disk products over the last three or four decades has led to the establishment of a $50 billion per year world wide business in disk drives. This enormous business support research and development into every conceivable aspect of disk recording technology in order to permit continuing increases in performance. Only the major areas of such research and development can be discussed below.

IMPROVED RECORDING MEDIA

Virtually all modern disk drives now use thin film metallic media with coercivities close to 1000 Oe. It may be expected that coercivities exceeding 2000 Oe will be used in the next few years. Higher coercivities lead to both sharper output pulses of greater amplitude and also to improved signal-to-noise ratios.

IMPROVED WRITING HEADS

As the medium coercivity increase, it is necessary to increase the saturation induction of the writing head pole tip materials. Presently, Alfesil and Permalloy with maximum inductions of 10-12,000 G are used. Materials such as Co-Ru and Fe-N with maximum induction of 16,000 and 19,000 G may be expected to be introduced.

NARROWER TRACKWIDTHS

It has been realized for two decades that, when seeking higher areal densities, it is better to use narrower trackwidths than higher linear densities. Operation with trackwidths substantially narrower than normal (10μm) leads to a number of very fundamental questions concerning the operation of the track following servo system. In particular, the outstanding question is "what is the source of the tracking error signal?". In magnetic disks today the source is a previously written magnetic disk servo track and it is only possible to operate the tracking servo when reading but not when writing. In optical disks, which operate at 5-6 times the track density, the source is always some physical feature (pits, grooves, bumps, etc.) and the tracking servo system is then operable during both reading *and writing*. This leads to another question: "Will magnetic disks eventually use optical tracking servo systems?".

IMPROVED READING HEADS

As trackwidths decrease, it becomes increasingly difficult to keep the channel signal-to-noise ratio media-noise limited because the output voltage of an inductive head falls proportionally with the trackwidth. It is anticipated that the next generation of high end disk drives will use magneto-resistive (M-R) reading heads where the magnetic fields from the medium changes the electrical resistance of a thin film M-R element. Considerably higher output voltages are available with M-R heads and they are independent of head-medium relative velocity.

IN-CONTACT OPERATION

Today's disk drives operate with a deliberate head-to-disk spacing of, typically, 6-8 microinches (0.15μm). It is known that both the writing and reading processes on magnetic disks improve when the spacing is reduced. All disks today are overcoated (Ag-Sn, ArO_2 amorphous C, ZiO_2, etc.) in order to control friction and wear and it seems very likely that, together with redesigned heads of significantly lower mass, continuous operation in contact may become possible. This is particularly true at low head-to-disk relative velocities.

SMALLER DISK DIAMETERS

An interesting sequence of design changes becomes possible following a reduction in the head-to-disk spacing. First, a higher linear density may be written. Second, because the data rate has now become too high, the disk diameter or spindle RPM must be reduced. Third, at the reduced head-to-disk velocity, it now becomes possible to reduce the head-to-disk spacing even further because any mechanical impact now transfers less energy. Fourth, if a smaller disk diameter has been chosen, the mechanical tolerances (flatness, areal runout, etc.) are reduced which again permits the head-to-disk spacing to be reduced even further. This sequence has led the drive industry from 5 1/4" to 3 1/2" to 2 1/2" to 1 1/2" diameters with increasing areal density. Still smaller diameters and higher areal densities are anticipated.

As an example of the levels of performance attainable when many of these developments are combined, consider the 1989 IBM 1.1 Gigabit (1100 Megabit) per square inch technology demonstration:

Medium coercivity - Cobalt-Platinum - 1700 Oe
Write Head-thin film-trackwidth 4μm
Read Head - magneto-resistive - trackwidth 2-3μm
Head-to-disk spacing - about 1 microinch
Linear density - about 160,000 bpi
Track density - about 7,000 tpi

With this demonstration, IBM showed that magnetic disk recording has the potential to exceed today's optical disk areal densities by about a factor of 2.

THE FUTURE

The IBM 1989 demonstration proved 1.1 Gigabit per square inch feasibility. Today's research papers (see, for example Intermag '91 paper MA-01) discuss demonstrations of 2 Gigabit per square inch (at 17,000 tpi and 120,000 frpi). It seems to be abundantly clear that the magnetic disk recorders could range from the 50-100 Megabit per square inch of today's manufactured hardware to future products with areal densities perhaps as high as 16 times greater.

It used to be said that the great advantage of optical (versus magnetic) recording was that it was not necessary to fabricate anything with dimensions comparable to the wavelength of light in order to achieve very high areal densities because the lens could focus the light down to Lord Rayleigh's' diffraction limit.

Nowadays, it seems that a very fundamental change in philosophy has occurred. Indeed, it is frequently stated that the real advantage of magnetic versus optical recording lies in the fact that the only effective limits operating today concern just how small can certain features and objects be made and that their dimensions are *not limited by* mere physical diffraction of light! For example, the gap-length in mass-produced 8 mm VCR heads is 10 microinches, which is but one third the wavelength of red light.

The steady increase in areal density, by a factor of 2 every 2-2 1/2 years, has been mentioned already. By this criterion alone, it appears then that magnetic disk recording technology can sustain another 20 years of growth (a factor of 16 = 2^4; 4 x 2.5 = 10 years) on the basis of demonstrables which exist in the laboratories today.

To move from scientific extrapolation to the realm of technical speculation, it seems to be very likely that 1 Gigabit (10^9) per square inch areal densities will appear in disk (and video tape) drives in considerably less than 20 years. Indeed some industry observers have opined that 5 1/4" full height drives with 100 Giga-byte capacity will appear before the year 2000: this represents a doubling of the historic rate of increase. Given the magnitude of the research and development activities in magnetic disk recording being undertaken worldwide, even such surprising estimates do not appear, to this writer, to be unduly optimistic!

AREAL DENSITY

= TRACK DENSITY x BIT DENSITY
(TPI) (BPI)

VOLUME DENSITY

$$= \text{AREAL DENSITY} \times \frac{1}{\text{THICKNESS}}$$

TYPICAL AREAL DENSITIES, CAPACITIES AND COSTS TODAY

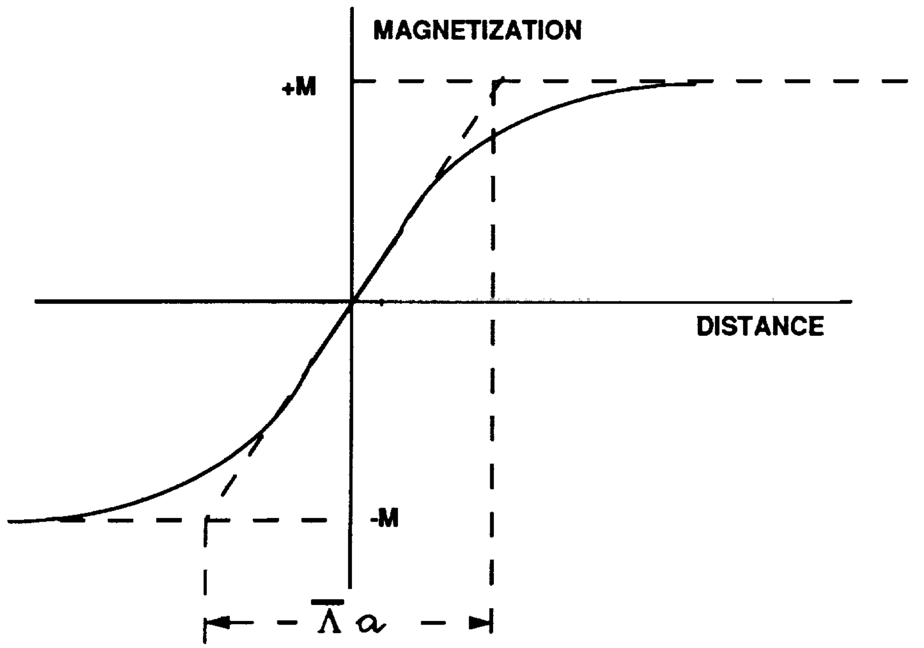
	AREAL	CAPACITY	COST
HI-END (LARGE)	$60\ 10^{6}$	$10\ 10^{9}$	\$100K
HI-END (SMALL)	$100\ 10^{6}$	$2\ 10^{9}$	\$2000
HI-END (SMALL)	$20\ 10^{6}$	$0.1\ 10^{9}$	\$400

NOTE: 10^{-4} CENTS/BYTE
10^{-5} CENTS/BIT

AREAL IS IN BITS/SQUARE INCH

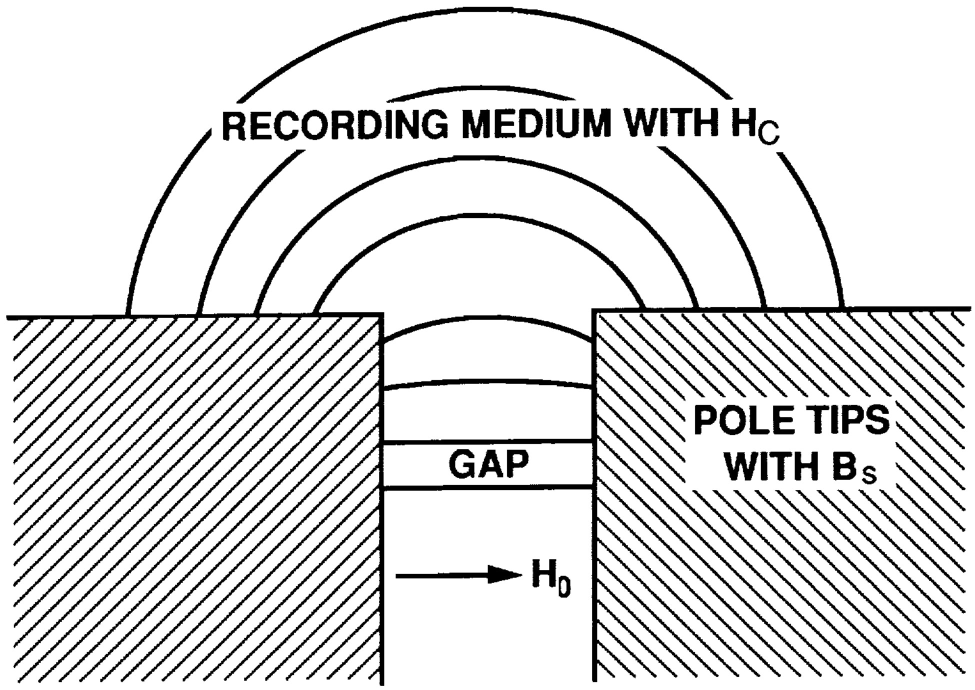
CAPACITY IS IN BYTES

EFFECT OF RAISING H_c



$a \propto \sqrt{H_c}$

DATE	H_c (OE)
1980	300
1986	600
1989	900
Now	1200-1400
Future	2800 Reported in Literature



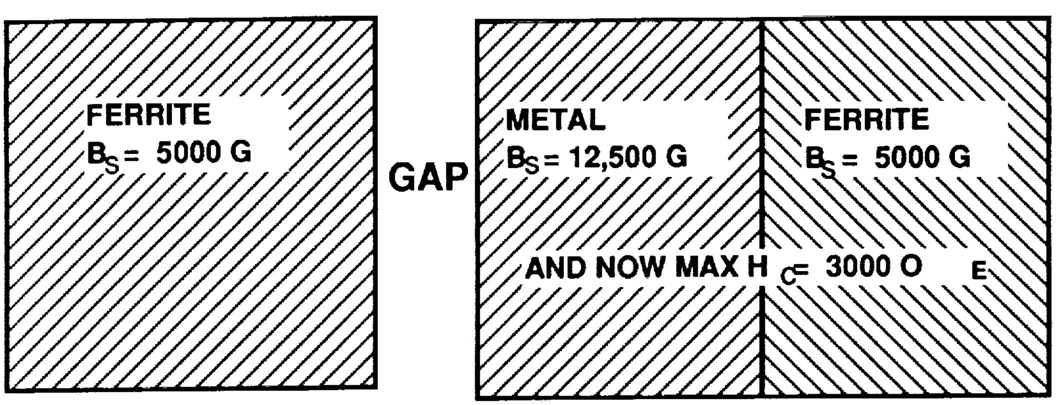
$H_O \approx 2.5\ H_C$ (TO WRITE PROPERLY)
$H_O \leq 0.6\ B_S$ (TO AVOID POLE TIP SATURATION)

FOR EXAMPLE: WITH FERRITE POLE TIPS $B_S = 5000$ G

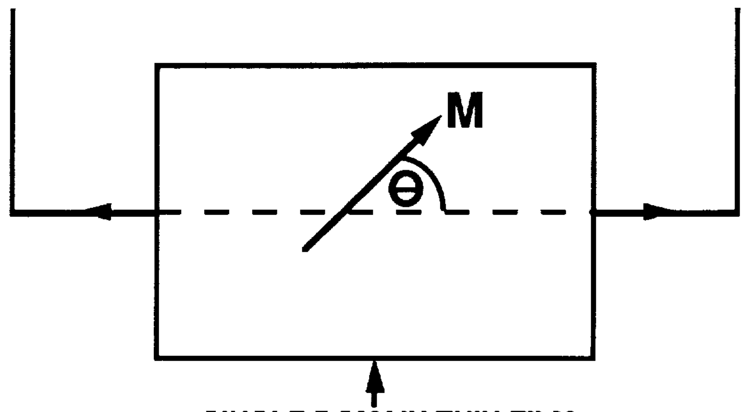
$0.6\ B_S = 3000$ G

$\therefore$ MAX $H_C = 1200$ OE

METAL-IN-GAP HEADS



MAGNETO-RESISTIVE HEADS



SINGLE DOMAIN THIN FILM

RESISTANCE VARIES AS (COSINE θ)^2

$$V\ (MRH) = \frac{20{,}000\ V\ (INDUCTIVE)}{SPEED \times NO\ OF\ TURNS}$$

SUPPOSE DISK SPEED IS 200 IPS:

V (MRH)	= 20,000 x V (INDUCT) FOR	N = 1
	= 2,000	N = 10
	= 200	N = 100
	= 20	N = 1000

MRH ARE THE KEY TO HIGHER TPI's WITH SMALL DIAMETER DISKS.

"IN CONTACT" DISKS

THE TRACK FOLLOWING ISSUE

OPTICAL DISKS	ATTAIN 10-15,000 TPI
	ALL USE DIFFRACTION OF LIGHT OFF MECHANICAL FEATURES
MAGNETIC DISKS	CURRENTLY ATTAIN 2-3,000 TPI
	ALL USE A FEATURELESS SURFACE WITH MAGNETIC SERVO TRACKS

IDEALLY, THE SOURCE OF THE TRACK FOLLOWING SERVO SIGNALS SHOULD BE INDEPENDENT OF THE RECORDED DATA, SO THAT THE TRACK FOLLOWING SERVO CAN OPERATE AT ALL TIMES.

WILL MAGNETIC DISKS ADOPT OPTICAL TRACKING?

SMALL DISK EVOLUTION

A) MAKE DISK SMOOTHER

B) LOWER FLYING HEIGHT

C) INCREASE LINEAR DENSITY

D) REDUCE SPEED
- LOWER RPM
- SMALLER DISK

E) SMALL DISK IF FLATTER
∴ LOWER FLYING HEIGHT AGAIN

OR F) ACCELS LOWERR AT LOWER RPM
∴ LOWER FLYING HEIGHT AGAIN

G) REPEAT CYCLE (C)

IBM'S 1 GIGABIT/INCH^2 DEMONSTRATION

DECEMBER, 1989

Metallic Thin Film Disk	H C δ	= 1800 Oe = 300A Co-Pt-Cr
Inductive Thin Film Write Head	W	= 4μm } 6-7000 TPI
Magnetoresistive Read Head	W	= 3μm
50% Roll-Off Density		= 110,000 FRPI
Linear Bit Density		= 160,000 BPI
Data Rate		28 Mbs
Error Rate		= 10^{-8} - 10^{-9}
Signal-to-Noise Ratio		= 23 dB
Areal Density		= 1.18 10^9 Bits/inch^2

$$\frac{\text{SIGNAL POWER}}{\text{NOISE POWER}} = \text{No OF GRAINS/BIT CELL}$$

IBM'S DEMO HAD 500 Å (2μ INCH) METALLIC GRAINS

THE BIT CELL WAS ABOUT 6μ " LONG X 120μ " WIDE

$\therefore$ No OF GRAINS/BIT CELL $\approx$ 200

$\therefore$ SNR = 200 OR 10 LOG^{10} 200 = 23 dB

- This demonstrates that the basic laws governing recording hold to Giga-bit densities.
- Note that a doubling in areal density costs a halving (-3 dB) in SNR with thin media.

THE FUTURE

SUPPOSE 2X AREAL DENSITY

EVERY 2 1/2 YEARS HOLDS

DATE	AREAL DENSITY
1991	100 10^6
1994	200 10^6
1996	400 10^6
1999	800 10^6
2002	1600 10^6

This evolution appears to be reasible on the basis of today's laboratory demonstrations.

A PROFOUND CHANGE IN DESIGN PHILOSOPHY

OLD CREDO — The advantage of optical recording is that dimensions comparable to optical wavelengths do not have to be manufactured.

NEW CREDO — The advantage of magnetic recording is that the effective limits are governed by how small can objects be made and this limit far exceeds optical diffration.