APPROACHES TO 100 $Gbit/in^2$ RECORDING DENSITY

Mark H. Kryder
Engineering Research Center for Data Storage Systems
Carnegie Mellon University
Pittsburgh, PA 15213-3890
Tel: +1-412-268-3513
Fax: +1-412-268-6978
e-mail: margie@gauss.ece.cmu.edu

A recording density of 10 Gbit/sq. in. is being pursued by a number of companies and universities in the National Storage Industry Consortium. It is widely accepted that this goal will be achieved in the laboratory within a few years. In this paper approaches to achieving 100 Gbit/sq. in. storage densities are considered.

A major obstacle to continued scaling of magnetic recording to higher densities is that as the bit size is reduced, the grain size in the magnetic media must be reduced in order that media noise does not become so large that the signal to noise ratio (SNR) degrades sufficiently to make detection impossible (1). At 100 Gbit/sq. in., the bit size is only 0.006 square micrometers, which, in order to achieve 30 dB SNR, requires a grain size of about 2.5 nm. Such small grains are subject to thermal instability, and the recorded information will degrade over time unless the magnetic anisotropy of the materials used is increased significantly, or the media thickness is made much larger than expected on the basis of scaling today's longitudinal media thickness.

Perpendicular recording may enable one to use larger media thicknesses and therefore increase the volume of the grains, making it possible to overcome the thermal stability issues. However to record at such high densities onto perpendicular media will require that contact recording be used. Probe heads such as the Micro Flexhead(TM) components proposed by Censtor may provide a solution to this problem (2).

Another solution may be to use structured media in which the bit cells are defined by lithographic or otherwise created structure in the recording media. If the bit cells are defined, then each bit can be stored on a single particle, and instead of requiring 1000 grains per bit, it is possible that 1 grain per bit would be adequate. In this case recording densities as high as 10 Tbit/sq. in. would theoretically be thermally stable with today's materials.

Alternatively, bits could be recorded in the form of cylindrical domains in perpendicularly oriented, exchange-coupled magnetic media, like those used for magneto-optic recording today. With careful design of the magnetic parameters of such media, it is possible to balance the inward directed force of the domain wall surface tension against the outward directed force of the demagnetizing field. This produces a magnetic domain which is easily stabilized by moderate coercivity. Using near-field magneto-optic recording, domains have already been written and readback at a density of 45 GBit/sq. in. in such media (3). These domains have been shown to be thermally stable for several years in these media.

Whatever form of recording media is utilized, it is likely that some form of near-field magnetic or optical probe head will be required to record and playback the data. In order to achieve the desired resolution, the head will likely have to operate with a head-media spacing of less than 10 nm. Although it is too early to say for sure that such heads could not be "flown" above the media surface on a slider, it currently appears more likely that either the probe head would be run in contact with the media, or that some form of active feedback would need to be used to keep the probe head in close proximity to the media similarly to how feedback is used to control the head-media spacing in atomic force microscopes (AFM) today. If the AFM approach is used, then some means must be found to enable an adequate data rate. Theory and experiment indicate that, if a probe head is used with feedback, the data rate from a single head will be limited to a few megahertz (4).
One approach to achieving higher data rates would be to use an array of probe heads. L. R. Carley, et al. have been micromachining arrays of probe heads, actuators and control electronics for head positioning on a silicon wafer (5). This offers one approach to achieving the high data rates that are required.

In conclusion, storage densities of 10 Gbit/sq. in. are likely to be achieved with longitudinal recording; however, densities of 100 Gbit/sq. in. appear to require some changes in approach. Perpendicular recording, structured media and exchange coupled media all offer possible solutions to the thermal instability which is expected to result from too small a grain size. Because of resolution requirements, some form of probe head spaced less than 10 nm from the media is anticipated to be required.

1. Pu-Ling Lu and Stanley H. Charap, *IEEE Trans. Magnet.*, **30** (1994) 4230.
2. H. Hamilton, R. Anderson and K. Goodson, *IEEE Trans. Magnet.*, **27** (1991) 4921
3. R.E. Betzig, J.K. Trautman, R. Wolfe, E.M. Gyorgy, P.L. Finn, M.H. Kryder and C-H. Chang, *Appl. Phys. Lett.*, **61** (1992) 142
4. H.J. Mamin, L.S. Fan, S. Hoen and D. Rugar, "Micromechanical Data Storage with Ultra Low-Mass Cantilevers", Technical Digest of Solid State Sensor & Actuator Workshop, June 13-16, 1994, p. 17.
5. L.R. Carley, "Data Storage System Based on an Array of MEMS-Activated STM Tips" 1992-1993 DSSC Annual Report for Industry, Data Storage Systems Center, Carnegie Mellon University, 1993.

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Mark H Kryder

Engineering Research Center
in
Data Storage Systems

Carnegie Mellon University

APPROACHES TO 100 Gbits/in^2

Contact Magnetic Recording

Near-Field Magnetic Recording

Scanning Probe Recording

THERMAL RELAXATION

Relaxation Time = $\tau = 10^{-9} \exp(K_uV/kT)$

$\tau = 72$ sec	for	$K_uV/kT = 25$
$\tau = 7.5$ year	for	$K_uV/kT = 40$
$\tau = 3.6 \times 10^9$ years	for	$K_uV/kT = 60$

Demagnetizing fields in transitions shorten the relaxation time.

Possible Media

Case 1:

- $K_u = 4 \times 10^6$ erg/cm^3 (Anisotropy of pure Co)
- $M_s = 650$ emu/cm^3
- $H_c = 5350$ Oe
- δ = Media Thickness = 7.5 to 10 nm

Case 2:

- $K_u = 6 \times 10^6$ erg/cm^3
- $M_s = 650$ emu/cm^3
- $H_c = 8000$ Oe
- δ

Simulation of Thermal Stability in High Density Longitudinal Magnetic Recording

- **Method:** Combination of a Monte Carlo method and a molecular dynamics;

Molecular dynamics to find the equilibrium state

- Molecular dynamics: Micromagnetic model

Stoner Wohlfarth particles; Uniaxial anisotropy;
Interactions; LLG equation;

Monte Carlo method: to simulate the random reversal process with thermal excitation

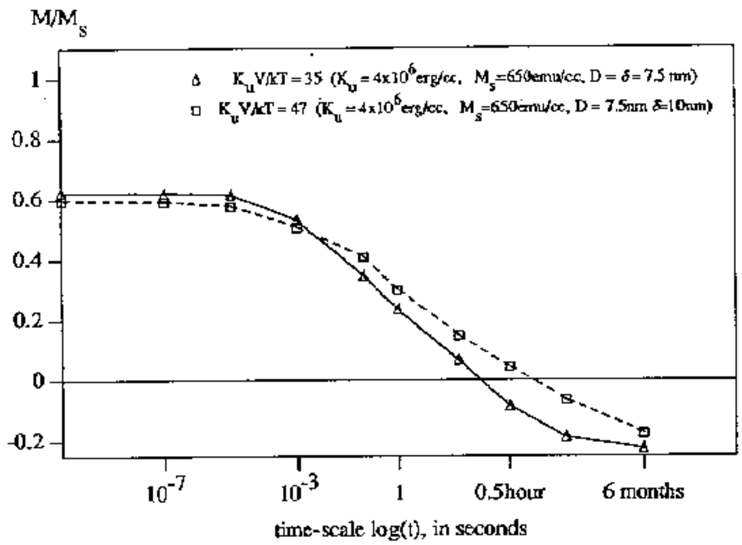
- Calculate the energy barrier and the probability of reversal for each grain.
- Find the reversal rate of the assembly and sample the time Δt. The elapsed time $t = \Sigma \Delta t$.
- Choose a moment to reverse according to the probability.

$t > t_{desired}$

No (back to molecular dynamics)

yes → End

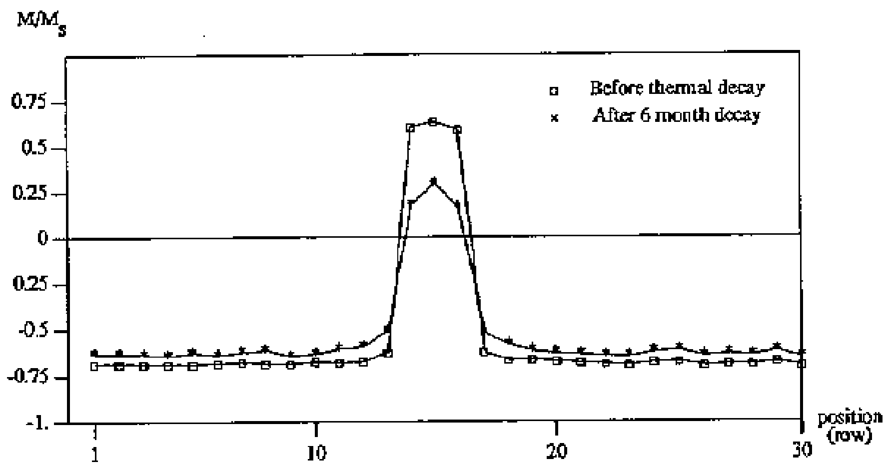
Magnetization at the center of di-bits versus time



$H_c = 5350\ O_e$

Di-bit transition before and after thermal decay

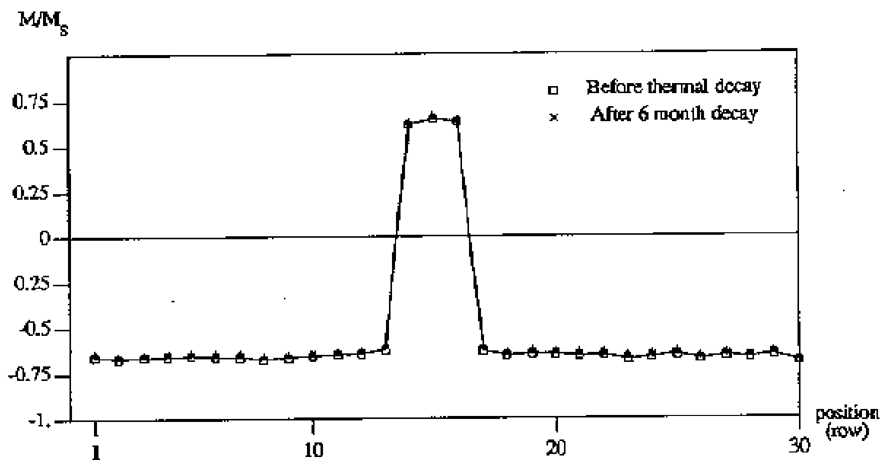
$K_u V/kT = 53$ ($K_u = 6\times10^6$ erg/cc, M_s=650emu/cc, D = δ = 7.5 nm)



$H_c = 8000\ O_e$

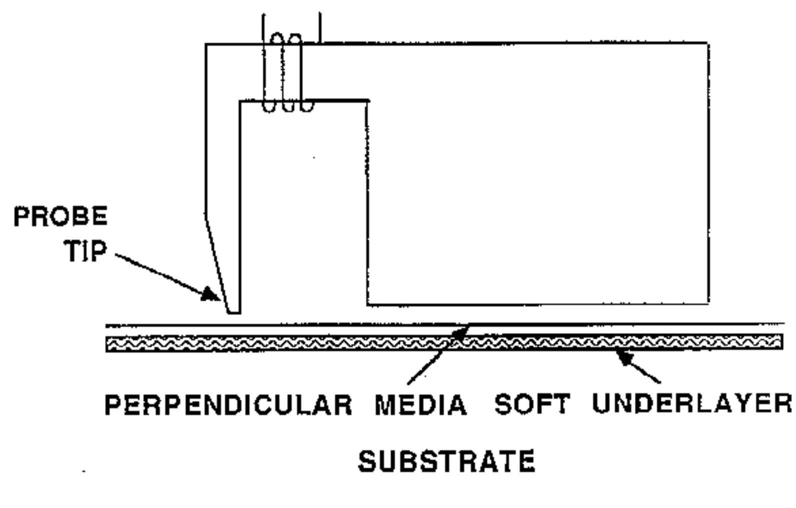
Di-bit transition before and after thermal decay

$K_u V/kT = 53$ ($K_u = 6 \times 10^6$ erg/cc, M_s=430emu/cc, $D = \delta = 7.5$ nm)



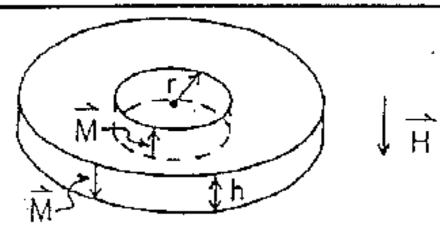
$H_c = 11000\ O_e$

PERPENDICULAR RECORDING



- $100\ Gbit/in^2$
  40 nm domains on 80 nm centers

DOMAIN STABILITY



(Normalized $\frac{\text{Force}}{\text{Area}}$) (Wall Surface Tension) (Demagnetizing Field) (Coercive Force)

$$\left|\frac{\Delta E}{\Delta r}\cdot\left(\frac{1}{2\pi r h}\right)\right| = \left|-\frac{\sigma}{r} + 4\pi M^2 \cdot \frac{h}{r} F\left(\frac{2r}{h}\right)\right| \leq \left|2M H_c\right|$$

$$\left|-3.5 \times 10^6 \text{ dyne/cm}^2 + 1.9 \times 10^6 \text{ dyne/cm}^2\right| \leq 2.1 \times 10^6 \text{ dyne/cm}^2$$

Assuming, $r = h = 20$ nm

$\Rightarrow F\left(\frac{2r}{h}\right) = 0.8$

$\sigma = 4\sqrt{A\ Ku}$

For Co/Pt Multilayers:

$A = 3 \times 10^{-7}$ erg/cm

$K_u = 10^7$ erg/cm^3

$M_s = 430$ emu/cm^3

$H_c = 2500$ Oe

$\Rightarrow$ **A cylindrical domain with 20 nm radius is stable!**

SUPERPARAMAGNETIC LIFETIME

Relaxation Time

$$\tau = 10^{-9} \exp(\Delta E/kT)$$

$$\Delta E = \left[2MH_c - \frac{\sigma}{r} + 4\pi M^2 \frac{h}{r} F\left(\frac{2r}{h}\right)\right] 2\pi rh\,\delta$$

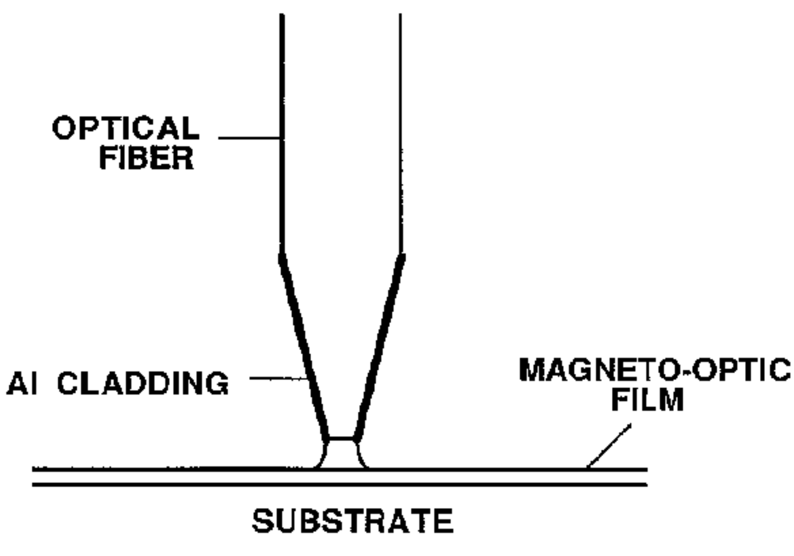
where δ = wall width = $\pi\sqrt{A/Ku}$

$\Delta E = 6.836 \times 10^{-12}$ ergs = 165 kT

$\tau = 4.5 \times 10^{62}$ secs > 10^{55} years

An acceptable lifetime!

NEAR-FIELD MO RECORDING



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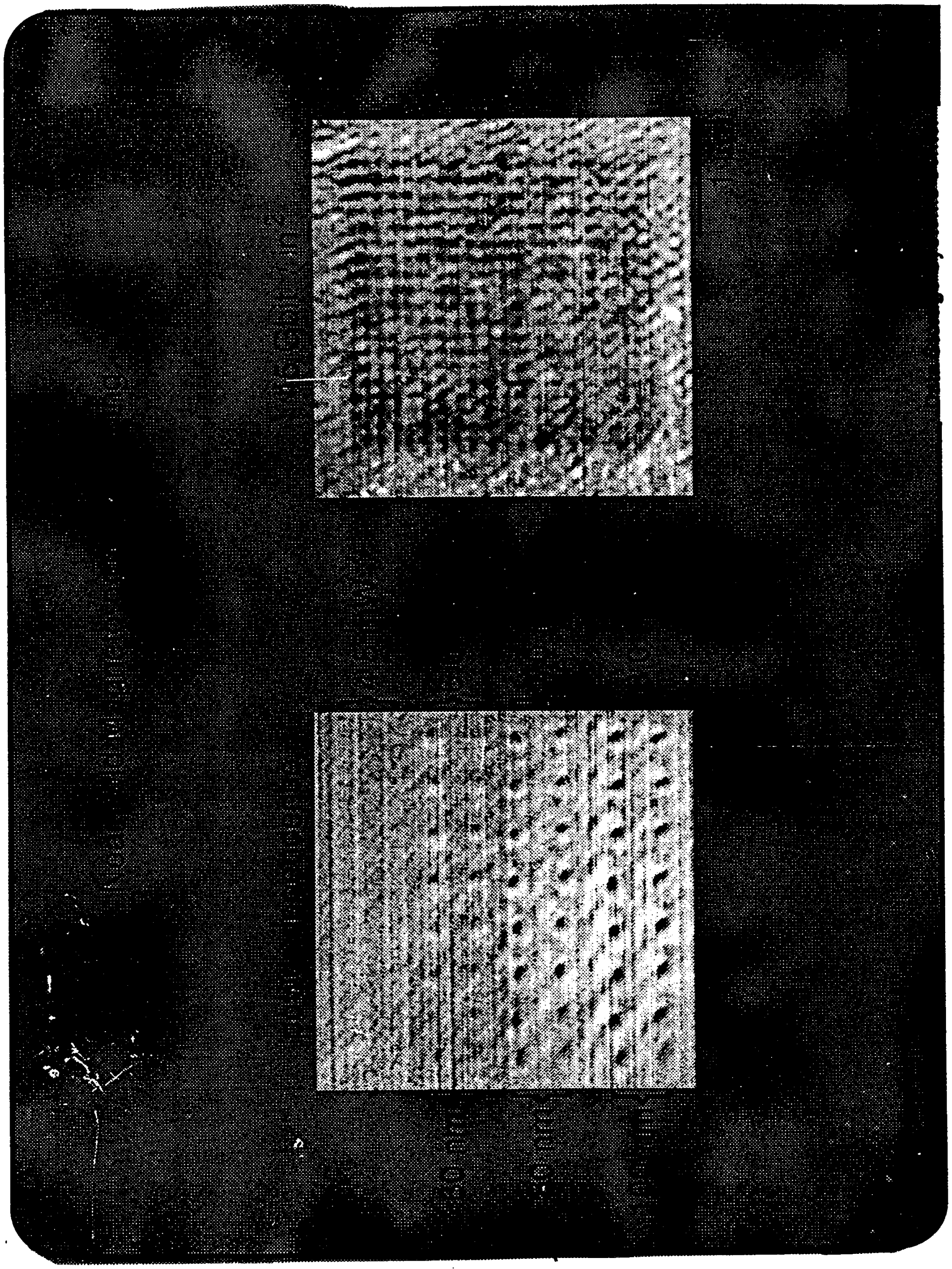

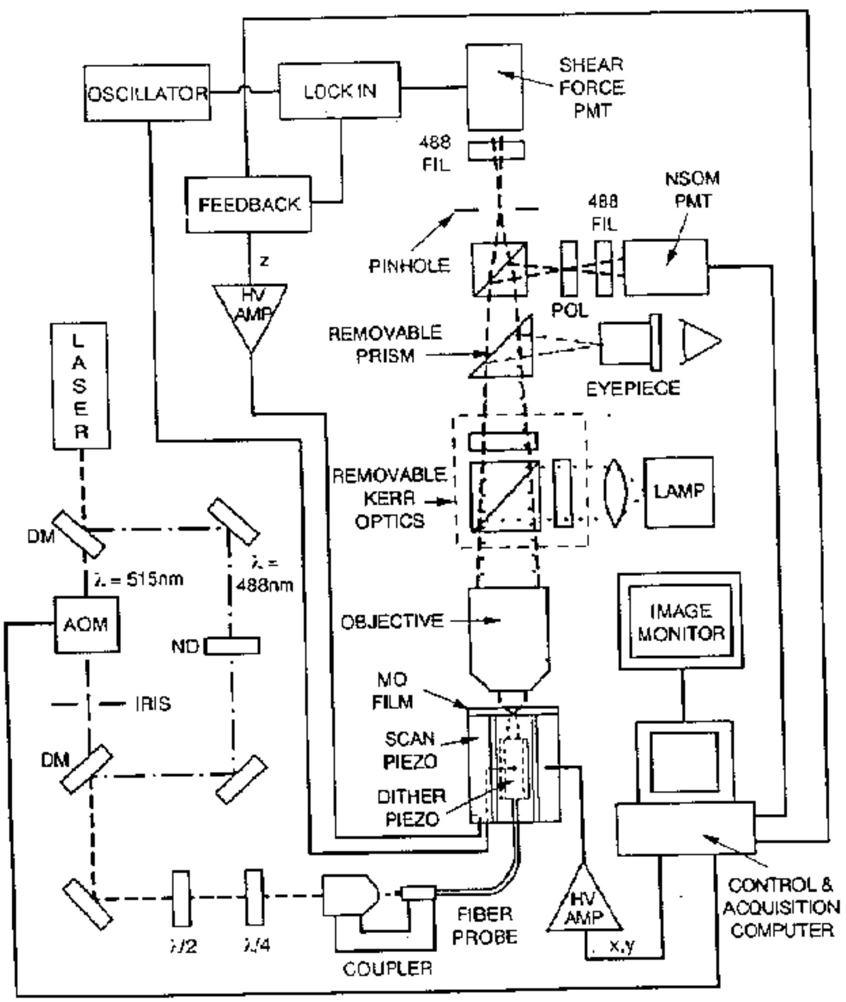

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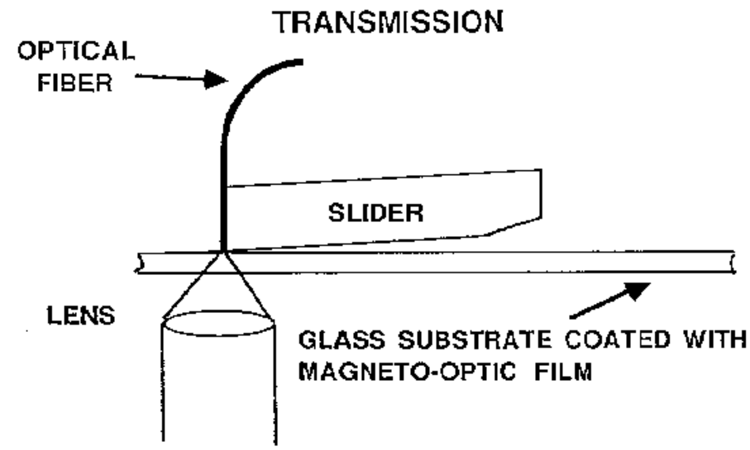
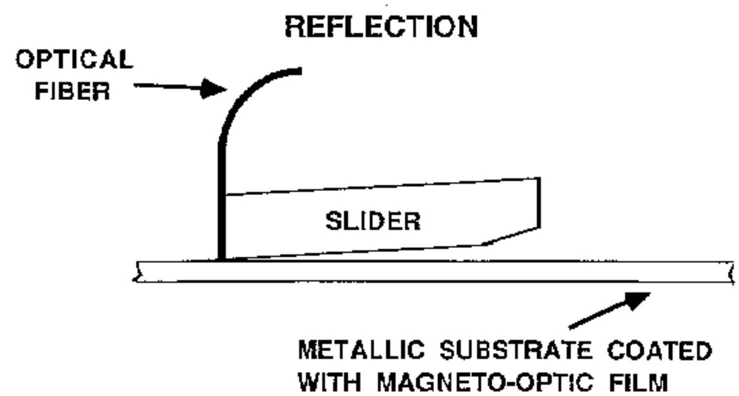
NEAR-FIELD MAGNETO-OPTICAL RECORDING





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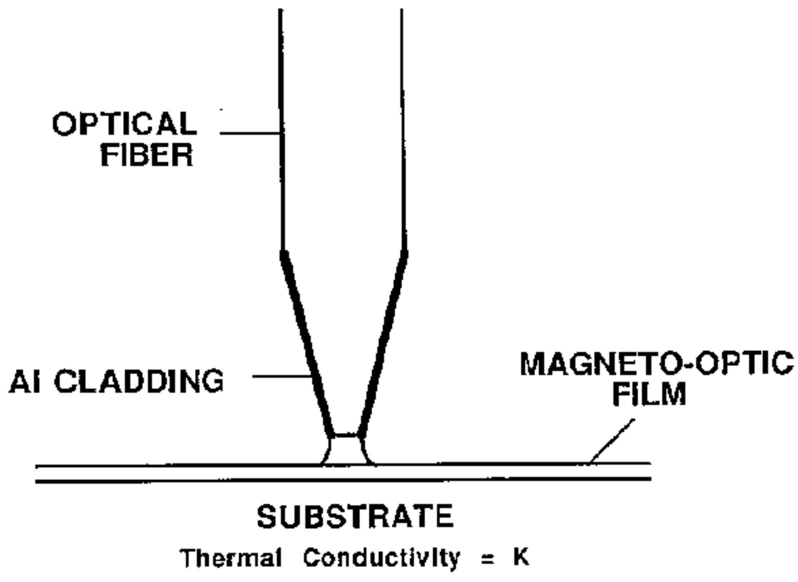
MAXIMUM READOUT POWER IN NEAR-FIELD MO RECORDING



Radiation profile with radius $r_o = 20$ nm

Maximum power for steady state temperature rise $\Delta T = 50°C$

$$P_{max} = \frac{\pi}{2} K r_o \Delta T$$

	K (W/M · °K)	P_{max} (μW)
Bulk	70	108

SIGNAL TO SHOT-NOISE RATIO IN MAGNETO-OPTIC RECORDING

Shot Noise Current

$$I_N = \sqrt{2eB\eta PR}$$

Signal Current

$$I_S = \eta PR \sin 2\theta$$

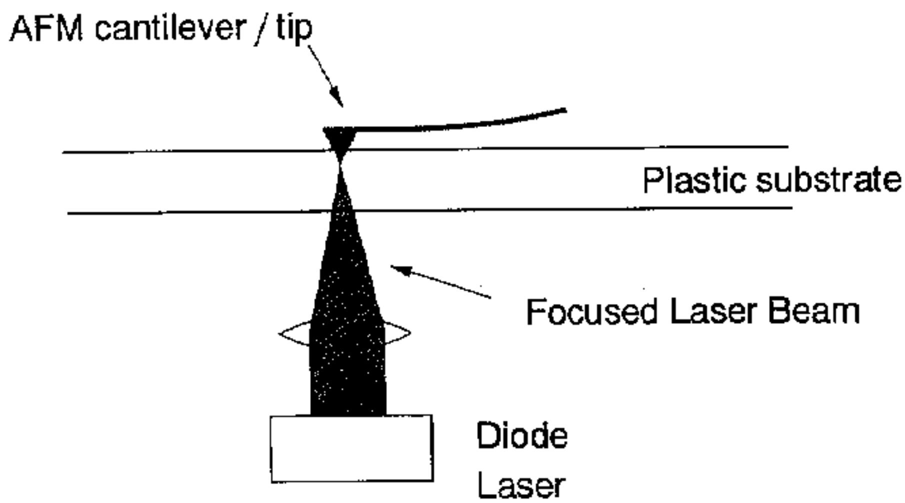
$$PSNR = 10 \log (2\eta PR \sin^2\theta / eB)$$

(for $\theta \ll 1$ rad)

η = Sensitivity of Photodiodes	= 0.35A/W
R = Reflectance (or Transmittance)	= 0.25
θ = Kerr Rotation Angle	= 1°
e = Electronic Charge	= 1.6×10^{-19}C
B = Bandwidth	= 100 MHz
P = Average Power	= 108 µW

PSNR = 25 dB

Thermo-mechanical Writing with an AFM Tip



- Tip is illuminated by focused laser beam
- Tip acts as nanometer-scale local heat source
- Plastic is heated above softening point
  - Local stress creates indentation

D. Rugar and H.J. Mamin
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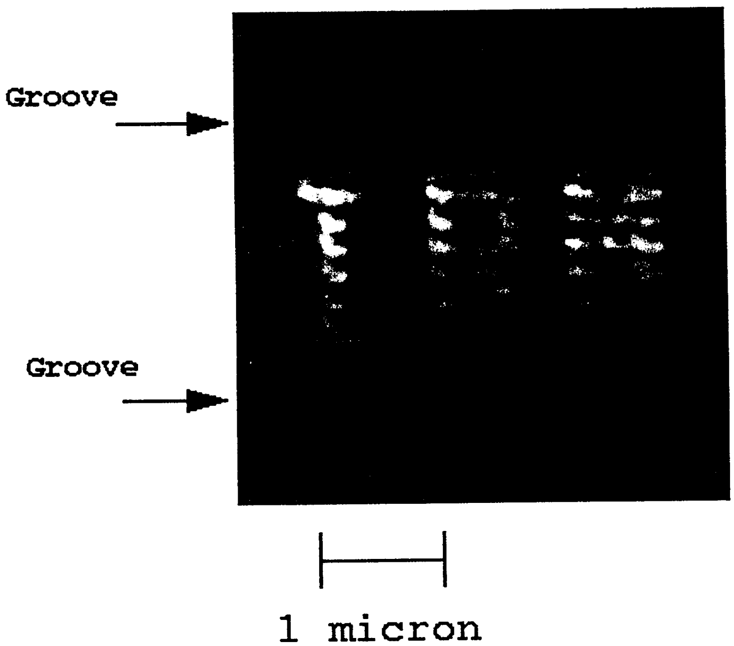
"IBM" written between the grooves of an optical disk

Approx. 25 Gbit per square inch



H. J. Mamin and D. Rugar

AFM Data Rate Limits

- Terrain following limit:

$$f_{max} = f_0\left(\frac{2z_L}{h}\right)^{1/2} = 0.46\left(\frac{F_L}{mh}\right)^{1/2}$$

f_{max} = Max. sine wave frequency

h = Pit depth

z_L = Load displacement of cantilever

F_L = Loading force

m = Mass of cantilever

- Example

  Si cantilever, 50 μm × 10 μm × 1 μm

  m = 1.16 × 10^{-12} kg

  h = 10 nm

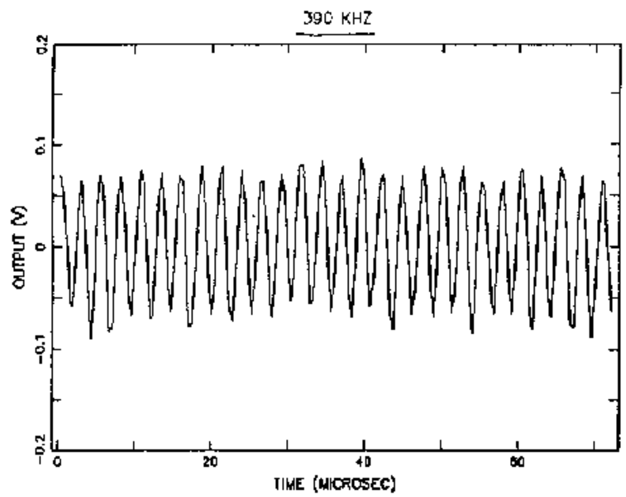
  F_L = 10^{-6} N

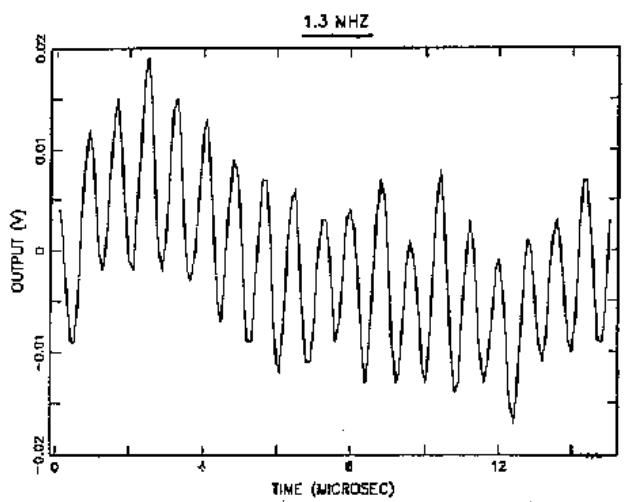
  f_{max} = 4.3 MHz or 13 Mbit/sec with (2,7) code

- Signal-to-Noise ratio
  - 10^{-4} nm/(Hz)$^{1/2}$ - typical sensor noise
  - 0.4 nm noise in 20 MHz bandwidth
  - 28 dB SNR for 10 nm pit depth

D. Rugar

HIGH SPEED AFM READING





1.3 MHz ⇒ 3.9 Mbit/sec with PWM (2,7)

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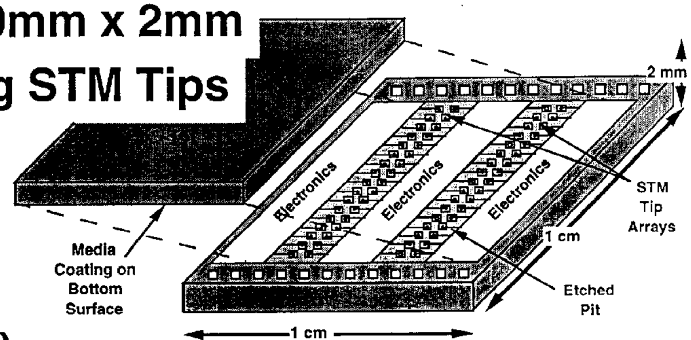
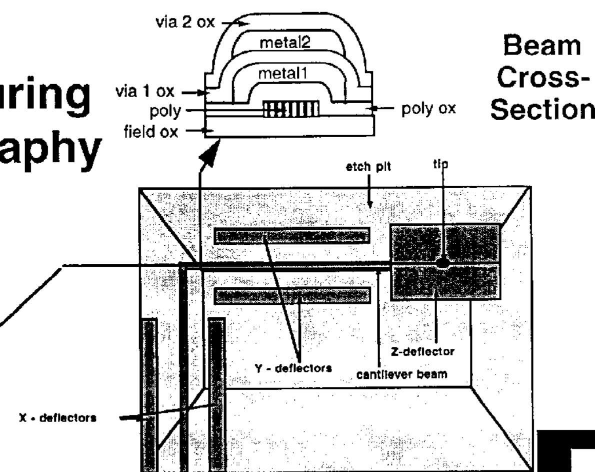
Exploratory: MEMS Data Storage

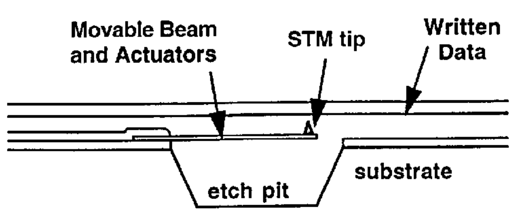
Store 10GB in 10mm x 10mm x 2mm
Write-Once Storage using STM Tips
(ARPA Sponsored)



Large Array of STMs
- Reliability (like RAID)
- Data Rate (parallelism)

Need VLSI "Style" Manufacturing
- Parallel Creation / Lithography
- Integrate Electronics & Sensors & Actuators





CONCLUSIONS

- Thermal instability will likely limit longitudinal recording in polycrystalline films to less than 100 $Gbit/in^2$.
- Perpendicular cylindrical domains are stable to beyond 100 $Gbit/in^2$.
- Perpendicular magnetic recording with a probe head or near-field MO recording could achieve 100 $Gbit/in^2$.
- Densities well beyond 100 $Gbit/in^2$ are possible with STM or AFM based systems, but single channel data rate is limited.
- Micromachined arrays could enable high data with STM or AFM systems through parallelism.