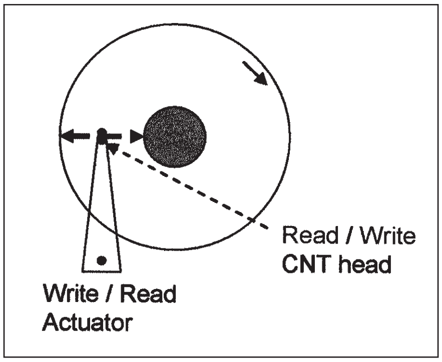

Figure 1. Typical disk drive recorder.

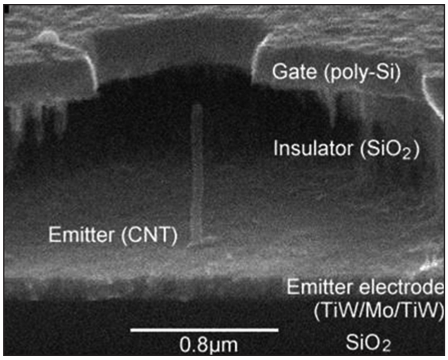

Figure 2. CNT emitter in gated cavity.

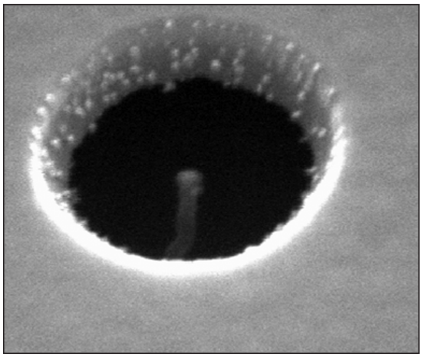

Figure 3. SEM photo of CNT gated emitter with 800 nm diameter cavity.

3-chip high-definition system rate is approximately 3 Gbits/sec at 24 frames/sec, and the Blue Herring camera developed by Lockheed Martin has a 12 Gbit/sec data rate at 24 frames/sec. These high data rates and resultant storage requirements provide key system requirements that were passed down as design requirements to the carbon nanotube electron gun design discussed in this paper. The small size of the CNT device makes possible high capacity, high ingest data rate recording devices in the camera head itself.

Electron Beam Recording

The art of recording analog or digital signal data by irradiating recording media with a focused electron beam and thereby causing a recorded mark by thermal or electrochemical means is well known. Recording devices have been fabricated using a wide variety of media and have employed various means of generating a modulated electron beam (e-beam), or in some cases a multiplicity of beams. In prior approaches, the emitting source has been large, compared to the desired recorded mark size requiring complex electron lenses and apertures to modify the beam(s) and focus them onto the recording media. Further, these systems have invariably required the recording media and the e-beam source to be contained in the same vacuum so as to enable propagation of the electron beam through the lens system to the recording media without being substantially scattered by air molecules. Historical brightness values of 2×10^8 A.st^{-1}.m^{-2} V^{-1} have been achieved producing e-beam currents of a few microamps in systems with electrons accelerated by a potential of a few tens of kilovolts, producing beam diameters in the range of a few microns, and typically limited by electron lens designs (e.g., spherical aberration) and the velocity spread of electrons leaving the emitter. Current electron guns employ either a cold field emission gun or a Schottky emitter and result in relatively large e-gun assemblies ill-suited to a disk drive type application that requires mounting the emitter on an actuator, as in Fig. 1.

The usefulness of an electron source in recording depends on several main parameters that include both the energy and the energy spread of the emitted electrons and the source brightness. A CNT sourced electron beam has both a significantly smaller virtual source and brightness more than an order of magnitude greater than other sources, that is about 3×10^9 A.st^{-1}.m^{-2} V^{-1}. A multiwalled carbon nanotube diameter of about 30 nm is achievable and provides a small virtual source size, for example, 20 nm. With about a 50V potential, the nanotube tip emits up to 2 mA that can be focused into a nearly collimated beam with a small range of electron velocities. The current is extracted from the CNT by a field established by placing a voltage on an annular electrode located about 1μ from the CNT.

Modulation of the extraction voltage allows the emitted current to be modulated (gated) at a gigahertz rate. Figures 2 and 3 show gated CNT emitters fabricated during the program.

A typical emitted current versus voltage curve is shown in Fig. 4. These beam characteristics together with the very small physical size of the CNT emitter head permit a radically different design approach to e-beam data recording.

Enabling Nanometer Scale Recording: In beam (e.g., laser) recording, the recorded mark size is directly dependent on the beam (laser) wavelength, and mark

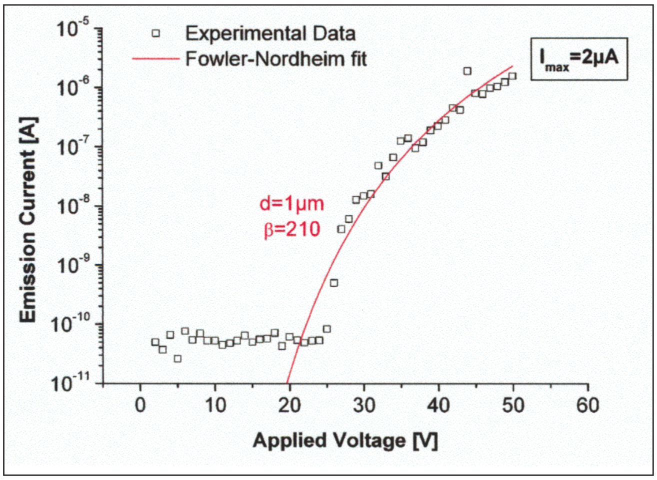

Figure 4. Current versus voltage of gated CNT emitter.

sizes of less than one wavelength are not practical. An electron passing through electron lenses obeys essentially the same propagation and focusing laws as light, but an electron has an equivalent wavelength much smaller than the wavelength of visible light, leading to much smaller recorded mark sizes. Limiting beam-related factors in the design of a CNT e-beam recorder are expected to be the spherical aberration of electron lenses used in the system. A typical CNT head-based design might apply an accelerating voltage of perhaps 1500V to the e-beam after beam modulation and exit from the gated CNT cavity.

Electron Wavelength: The kinetic energy imparted to an electron of unit electric charge e and mass m falling through a potential V to reach a velocity s is given by $eV = (1/2)\ ms^2$, where m is the electron mass. The momentum of an electron is p = ms, so that $eV = p^2/2m$ and $p = (2meV)^{1/2}$, where e is the electron charge. The equivalent wavelength of a particle of momentum p is given by $\lambda = h/p$, where h is Planck's constant. Hence $\lambda = h/(2meV)^{1/2}$. Inserting the known values for m, e, and h gives $\lambda = 1.2/V^{1/2}$, where λ is in nanometers and V is in volts. For V = 1000 volts, the electron wavelength is 0.038 nm, 11,000 times shorter than 420 nm blue light.

Electron Beam Penetration: The extent to which low-energy electron beams penetrate and are absorbed into a material essentially depends on only the beam energy and the material density. Electrons will penetrate thin materials (membranes) which therefore act as windows. Each electron maintains its original energy until it collides with a molecule of the material. Hence, the number of original electrons decreases as the beam propagates into the material. Figure 5 shows the relative loss of beam energy as a function of penetration distance for an electron beam where the extrapolated practical range is R_p and the maximum range is R_m. The useful range R_u, taken to be where about 75% of the beam energy is transmitted, is about 50% of the practical range R_p. Figure 6 shows the practical range R_p as a function of absorber density and the beam energy and applies to essentially all materials of any density, for example, air or metal. Dividing a value of R_p by a material density in gms.cm^3 gives the range R_p in cm. The data in both Figs. 5 and 6 are based on experimental results published in handbooks.

Electron Transmission in Air: Figure 6 shows the practical range, R_p for electrons of energy 1000eV is about $R_p = 1.2 \times 10^{-5}$ gm/cm^2. The density of dry air at 300° K is nominally 1.2×10^{-3}gm/cm^3, thus the practical range in air is $1.2 \times 10^{-5}/1.2 \times 10^{-3} = 1 \times 10^{-2}$ cm, or about 100μ. From Fig. 5 with Rp = 100μ, 75% of the electrons will remain unabsorbed after passing through half this distance, about 50μ. Reducing the air pressure by half will double the useful range, and doubling the electron energy will increase the useful range by slightly more than a factor of 2.

Electron Transmission Through Semipermeable Membranes: The same absorption characteristics apply to both insulators and metals, enabling the penetration of electrons through a thin window to be estimated. A typical window material, boron nitride, of density 2.185 gm/cm^3, gives the thickness vesus electron energy relationship shown in Fig. 7, for several transmissions. As can be seen, a window 0.025μ (25 nm) thick will pass 90% of a 1.5 kV beam, although some scattering will occur.

Electron Absorption in Recording Media: The penetra-

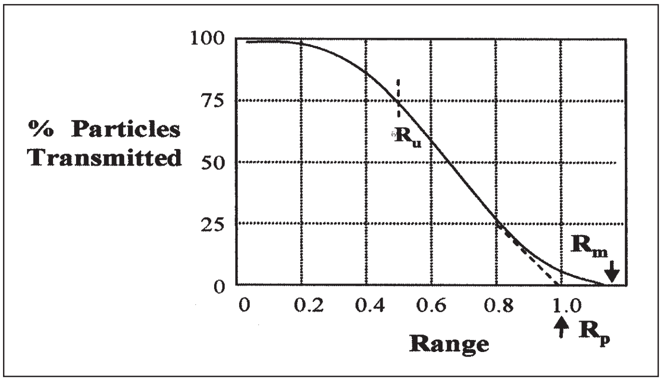

Figure 5. Particle relative transmission range.

tion of electrons into a material is determined by the density of the medium in which the beam is propagating, regardless of the molecular weight of the material. Hence, Fig. 6 can also be used to determine the minimum thickness of the recording layer needed to achieve complete absorption of the impinging beam. Most metals have a density of approximately 7gm/cm^3, giving a practical range of about 17 nm for 1000V electrons with zero electron penetration beyond a material thickness of R_m (= 1.2 R_p) of 21 nm. Higher velocity electrons will penetrate into the material to an extent slightly greater than linearly, that is, at twice the energy the electrons will penetrate about 2.2 times as far. Typically the media absorption depth should approximate the recorded mark size.

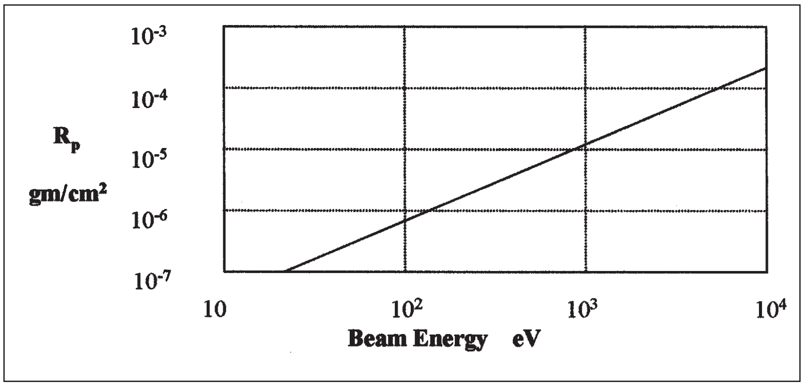

Figure 6. Practical range R_p versus beam energy.

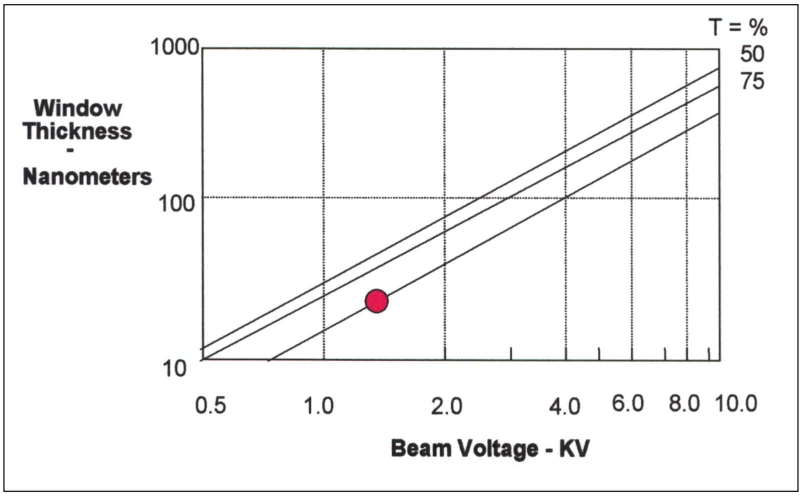

Figure 7. Boron nitride window, transmission versus thickness and beam energy.

Data Storage Applications: The primary goal is to establish the viability of the proposed approach and develop a technology that overcomes or sidesteps the limitations of current data-recording technologies and provides advanced performance in compact form factors. The developed technology should provide high storage capacity, high read/write data rates, and fast access that is economically affordable. The technology should be compatible with either removable or embedded media and have either erasable or archival media characteristics. Products with all of these characteristics would apply to several large market segments now addressed by numerous current products such as hard disk drives, optical disks, including CD-ROMs and smaller discs, floppy discs, and all tape drive systems. Figure 8 shows the expected user capacity for various standard-sized disks as a function of recorded mark size. Track spacing is assumed to be twice the mark size.

The basic CNT e-beam technology can be embodied in disk drives that fall into two principal categories:

(1) Larger media disk sizes such as 120 mm diameter (CD sized) using removable media and having capacities in excess of 1 Tbyte. Removable media implies in-air media operation and therefore transmission of the e-beam through some air distance. This further implies a CNT structure that is sealed inside a vacuum-tight head with the electrons passing through a semipermeable membrane to the media. A further implication of in-air operation is that the head window must be within 50μ or less of the disk surface for the beam to be adequately transmitted and may or may not require a flying head, depending on the disk vertical run-out. Smaller fly heights will permit greater transmission and lower beam spread due to scattering by air molecules. Current magnetic head fly heights are as low as 10 nm.

(2) Smaller disk sizes, 2.5 in. or less using embedded nonremovable media. For this design option, both the CNT head and the media can be sealed in a single vacuum enclosure and an e-beam window is not required, enabling smaller mark sizes. This approach enables lower beam voltages and with lower disk vertical run-out, a vertically fixed head can be used.

Either design approach is compatible with read-only media (ROM), write-once media, or erasable media, depending on the intended application, although the

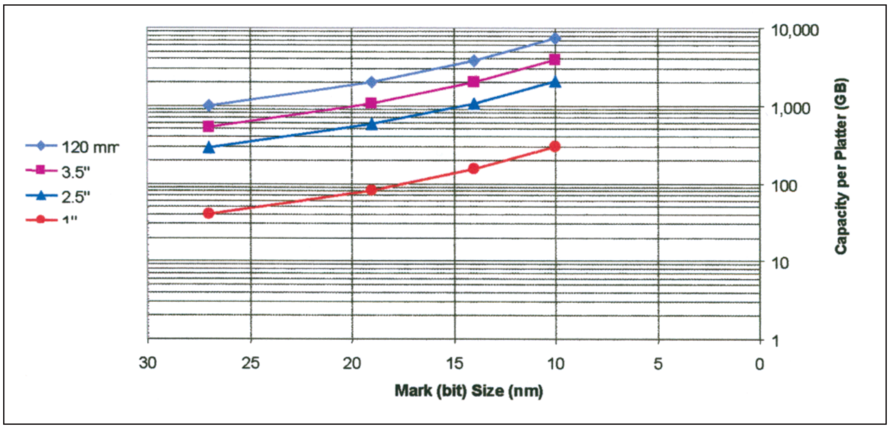

Figure 8. User capacity versus disk size and mark size.

various media require development.

One possible application is low-cost mass storage of truly archival media (100+ years) that is removable and robot compatible. Archival data storage is not viable using magnetic hard disc drives and the only other currently employed option is magnetic tape. However, magnetic tape is not archival, nor is it cost-effective, because of the high cost of storing thousands of removable low-data density tape cartridges in robotic servers. Further, data access is slow due to long tape wind times, and tape is inherently a fragile media. Both issues are aggravated by thinner and longer tape used to increase cartridge capacity. Magnetic tape technology therefore no longer meets the need of capturing and retrieving Tbytes of data per day, and storing the data in an easily accessible archival database is rapidly becoming obsolete. It would soon be abandoned, except that, unfortunately, today's users have no other alternative.

Another application of interest is small high-capacity removable drives. As shown in Fig. 8, a two-sided 3.5 in. disk in a removable drive with a 27 nm mark size could store 500 Gbytes of user data. With a 10 nm mark size, the capacity would exceed 3.5 Tbytes.

Track Following During Read/Write: One requirement of read/write recording systems is the need for the read beam to closely follow the written data track on signal playback. In a disk recorder, employing perhaps 27 nm wide tracks with 50 nm track spacing the need for accurate track following is critical. To avoid unacceptable signal loss the read-back beam must follow the track center to within about ±15% of the mark width, about ±4 nm for a 25 nm-wide mark. Fortunately, the mass of an electron is very low and electrostatic or electromagnetic beam deflection techniques are easily implemented for tracking. The main issue is that disks will need to be preformatted and each disk loaded into the drive so that the center of the preformatted pattern is aligned to the center of rotation. This will be challenging, particularly if the disks are user-removable.

Media Characteristics: Although the ability to record nanoscale marks by e-beam radiation is not in doubt, the read mechanism is less certain, but is likely to be based on emission of secondary electrons on media irradiation by a read e-beam. Many media options exist. Secondary emission data for magnesium oxide (MgO), a typical potential media component, is shown in Fig. 9. The ratio of secondary to primary electrons (SE coefficient, δ) is usually greater than unity and depends on the primary electron energy as well as the material. Generally, there is a specific electron energy that gives a maximum value of δ for each material. Initially δ increases with the primary energy until a maximum value is reached. At higher primary energies, the secondary electrons are generated deeper into the material

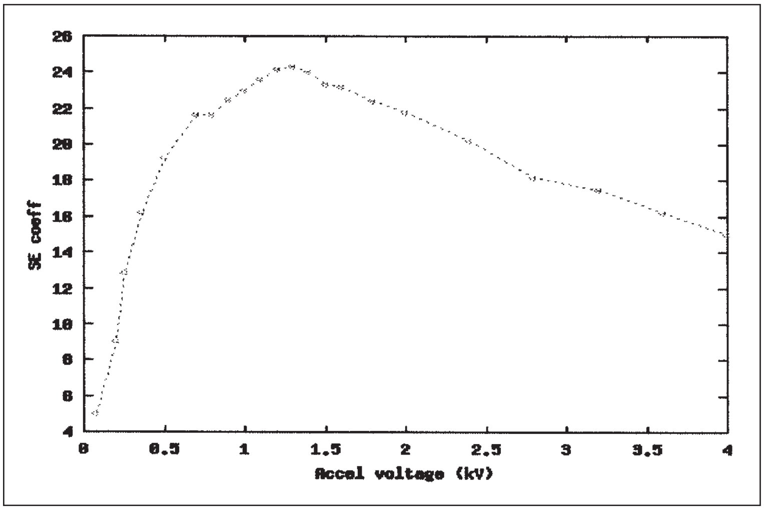

Figure 9. Secondary electron emission versus electron landing voltage. (The SE coefficient is the number of secondary electrons emitted per incident electron.)

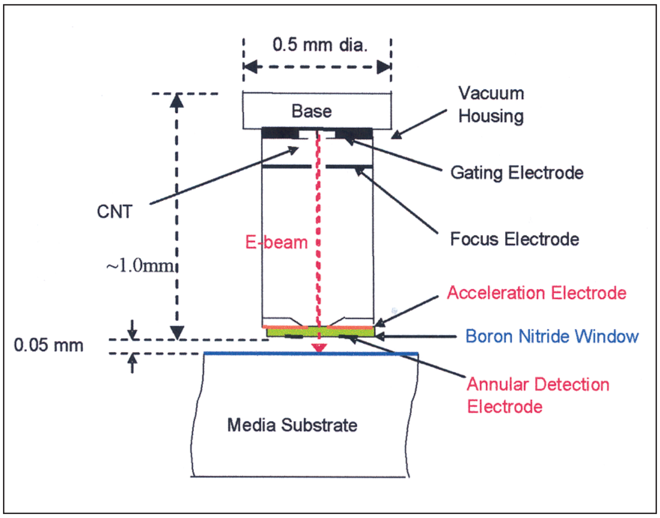

Figure 10. Basic CNT read/write head layout.

and are reabsorbed, resulting in a lower δ. In a "straw man" head design a detection electrode is located on the head just above the media surface. On reading, this electrode will capture the secondary electrons emitted by the media, and efficiently so, if it is at a positive potential. The read voltage should therefore be that at which the maximum δ is obtained.

Straw Man Design, Removable Media: The initial design approach employs a rotating disk with an e-beam-sensitive media layer and a CNT-based read/write head, as shown in Fig. 10. The complete read/write head assembly is nominally a 0.5mm-diameter cylinder 1mm long, mounted on a radial actuator arm. The entire CNT sub-assembly is located in a vacuum housing with the CNT at one end and the e-beam exiting the structure through a semipermeable boron nitride membrane. The multwalled CNT of any chirality has a length of about 800 nm and is nominally 30 nm in diameter. A first gating aperture electrode is located concentric to, and approximately 1µm from the CNT tip and is nominally at a 50V potential to the CNT, so as to provide a beam current of nominally one tenth micro amps (0.1µA; over 1µA is available). A second focusing aperture electrode is located concentric to the CNT at a distance of 1mm from the gating electrode and is nominally at the CNT potential. A boron nitride window approximately 20 nm thick is located as a seal at the end of the vacuum enclosure and 1mm from the CNT. An aperture electrode concentric to the CNT is located on the inside of the window and a positive accelerating voltage of about 1.5 kV is applied. The focusing voltage is adjusted so that the e-beam is brought to a focus at a distance of 10µ from the window exterior surface. The media-sensitive layer is located 10µ from the closest head structure member. With a window transmittance of 90%, the beam energy exiting the window is nominally 0.9 x 0.1 x 10^{-6} x 1500 = 135 x 10^{-6} W. After passing through 10µ of air (T = 95%), the beam energy will be about 130 MW. If focused into a diameter of 27 nm, a power density of 2.27 x 10^{7} W/cm^{2} is obtained.

The read signal detector is an annular electrode located concentric to and on the outside of the window. The detector should capture electrons scattered from the media-sensitive layer by the read beam with the flux dependent on the phase state of the media. With a given detection electrode, capacitance capture of electron charge will generate a signal voltage proportional to the electron flux.

Conclusion

As with any new technology in an early development stage, there are a number of issues that need to be addressed, one of which is recording media selection and optimization. Given the current beam intensities and typical write/read times, it is anticipated that signal-to-noise ratios of 20 dB or better can be obtained with at least a gigabit data rate with several types of media. Achieving this signal-to-noise ratio considerably reduces the error correction circuitry required, compared to magnetic hard drives. Future work will characterize the read/write head assembly in greater detail and will also include development of both archival and rewritable media.

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THE AUTHORS

William S Oakley has specialized in data storage systems since 1978 and previously worked on a wide variety of optical systems. He has a BSc in physics (Honors) from the University of London and is presently CEO of NanoScale Storage Systems.

Robert W. McGriff is the chief engineer for the Signals Information Systems Div. of Lockheed Martin. He has various signal processing, R, F, and optical systems design experience going back to 1985. McGriff has a MS degree in nuclear engineering from Kansas State University.