High density optical memories for safe archival data

Abstract

Ion nano-beams are used to write data bits of nanometer diameter into storage materials and photon near-field technology is employed to read this novel kind of digital memory.

Keywords: nano-technology, Tbit memory capacity.

I. Experimental

A very important application of Xe nanobeams pertains to the fabrication of permanent (non-volatile) opticaL data memories (WORM type) of Tbit capacity. A first outline of this idea was presented about 10 years ago, without, however, specifying a reading process. [1] This latter task is addressed in the following. Bit creation makes use of local phase transitions of initially monocrystalline silicon layers (c-Si) to the amorphous state (a-Si) locally changing optical absorption for incident photons of energies $h\nu \leq 3.0$ eV. Irradiation with ion nano-beams with fluences of about 10^{13} Xe ions/cm^2 of 15 keV energy will amorphise irradiated Si-areas of about 10 nm diameter to a depth of 20 nm, comprising a bit volume of about $2{\cdot}10^{-18}$cm^3 constituting a solid state equivalent of 10^5 Si atoms. Fig. 1 displays calculated ion trajectories of a total of 10^5 ions of a 15 keV Xe sub -nm ion beam in c Si. Evidently, the implantation profile will vary with beam energy and size, so that both smaller and larger bit sizes can be produced. In this way, a memory storage density n of bits b of diameter $D = 2R$ amounts to

$$n \sim 10^2\ (D[\mathrm{nm}])^{-2}\ \mathrm{Tb/cm}^2 \qquad (1)$$

Thus, for D = 10 (100) nm, a standard disk of 100 cm^2 would provide space for 100 (1) Tbit of data, favorably comparable to recently reported maximum densities of about n ~2.5Tbit/in^2 ~0.4 Tb/cm^2.[2] Suitable storage material is silicon-on-sapphire. It is available as single-crystalline hetero-epitaxial c-Si layers of about 100 - 1000 nm thickness grown on transparent monocrystalline Al_2O_3 substrates (commercially available as silicon-on-sapphire or 'SOS' from Kyocera, Japan). But also other wider band-gap semiconductors such as c-SiC and pc-diamond may be considered [1]. c-Si has absorption coefficients of $\alpha_c \sim 10^4$ cm^{-1} at $h\nu \sim 2.5$ eV and a-Si up to $\alpha_a \sim 10^6$ cm^{-1}, providing sufficient contrast by differing transmissions T_c and T_a of an incident light beam [1]. Detailed annealing studies have shown that these amorphised Si-regions do not recrystallise below temperatures of about 600°C; so that the stored information is of practically unlimited lifetime at temperatures in all global climates, in contrast with all presently available storage technologies. Also, its immunity against strong electromagnetic transient fields and virus attacks is an important feature for many civil and military environments.The very major technical challenge is the optical reading of such memories. Near-field technology seems a viable approach.

II . Theoretical

The topic of light transmission through subwavelength apertures has a long history, starting with the initial 'scalar' theoretical approach by Kirchhoff, followed by several 'vectorial' treatments with Bethe's predicting the total transmitted light power P_t of the incident photon flux density I_0 through sub-wavelength apertures R.[3]

$$P_t = c((kR)^4 (R^2 I_0). \qquad (2)$$

Experiments with 1 mW laser radiation incident onto 1 mm^2 area in the focal plane of a screen confirmed the R^6-dependence of the transmitted power over a wide range of sub-wavelength-aperture radii R [4]. c is a constant of order of unity for normal incidence of light and the wave vector is $k = 2\pi/\lambda = 0.0126\ nm^{-1}$ for $\lambda = 500$ nm. Let I_0 be the laser light intensity within a monomode fibre with kernel radius $R_k = 2.5$ µm (fig. 2). We assume $I_0 = 10mW/\pi R_k^2 \sim 5\cdot10^8 W/m^2$, equivalent to a photon flux areal density of $I_{0,p} \sim 1.3 \cdot 10^{27}$ $h\nu/m^2s$). The screen is usually coated onto the front end of the fibre. For simplicity we assume homogeneous intensity across the kernel cross section. Out of the total power P_t transmitted through the aperture a fraction $P_{c(a)}$ will reach the photo diode in case of transmission $T_{c(a)}$ through a c(a)-bit area:

$$P_{c(a)} = q \cdot T_{c(a)} \cdot P_t \qquad (3)$$

The reduction factor q depends on the exact geometry of the optical arrangement. A value of q ~ 10% may serve as a rough estimate of the solid angle subtended by the bit area in fig. 2 where equal diameters D of aperture and bit area are presumed. This is further illustrated by fig. 2, where incident laser light of intensity I_0 and wavelength $\lambda \sim 500$ nm, or energy $h\nu \sim 2.5$eV, provides digital information with contrast $(T_c - T_a)/T_c$ of the order of 1, to be recorded by an ultrafast photon detector. The memory disk will rotate at appropriate speeds, of say 10 m/s, or 10^{10} nm/s, at a close distance of present-day realisable separation of some 10 nm, as practised in magnetic memory reading, in order to provide fast data recognition. This engineering task appears completely solvable. Further improvements are possible by optimising silicon layer thickness, ion implantation parameters, and photon energy, enhancing the optical effects. Even at moderate laser intensities a memory density of at least 10^{10} b/cm^2 appears readable as shown below.

In further specifying the reading process we consider $q = 0.1$, $T_c \sim 1$ and a lower (upper) bound of aperture radius R = 10(100) nm, and $I_{0,p} = 1.3 \cdot 10^{27} h\nu/(m^2s)$. The corresponding transmission cross section of the aperture is $k^4R^6 = 2.5 \cdot 10^{2(+4)}$ nm^2

according (2). The power received at the photo diode by passing a c-bit is then $P_c = 3.3 \cdot 10^{6(12)}\, h\nu$/s according (3). With scan frequencies of $f = 1/\tau = 10^{7\{9\}}$ Hz the number of detectable photons per scanned c bit will be $N_c = P_c \cdot \tau$ photons. N_c may present the digit 1. As said above, the corresponding figure for the digit 0, representing the photon beam passing an amorphous zone is much smaller and constitutes a threshold level of $N_a << N_c$ so that a sufficient signal contrast is achieved in the response of the fast photo diode.

In fig. 3 the results for N_c are plotted within the considered ranges. For $R > 20$ nm and a dwell time of $\tau \sim 10^{-7}$ s/bit we have signals $N_c > 10$ photons, sufficient for safely reading the bits in view of the quantum efficiency of present photodiodes exceeding 50 %. The smallest, about 10 nm wide bit areas, achieved by ion implantation in ref. [1], however, can be read only at about 100 kHz rates with the light intensity considered here – not practical for a complete reading of multi-Tbit memories. Ultrafast photodiodes have rise times ~2ns and hence can handle well above 10^8 signals per second. Exploiting a limit of f ~ 100 MHz would require a bit radius $R > 30$ nm and allow for a disk of 3 Tb/100cm^{2} :. By optimisation of the numerous input parameters useful operational values for a 10 Tb memory seem accessible.

Richard Feynman's intriguing question: Why cannot we write the entire 24 volumes of the Encyclopedia Britannica on the head of a pin?; based on a pixel size of 8 nm,can be answered with: Yes, we now can!

ACKNOWLEDGEMENT

The author is greatly indebted to E.W. Otten for his advice concerning the use of focused laser technology for the memory reading process and for critical reading of the ms.

References

[1] S: Kalbitzer: *Novel concepts for the mass storage of archival data,* Nucl. Instr. and Methods B218 (2004) 343-354

[2] EE Times,08/18/2010 quoting Toshiba results.

[3] H.A. Bethe *Theory of Diffraction by Small Holes.* Phys. Rev. 66 (1944) 163-182

[4] A. Roberts: *Coupling of radiation into a near-field probe.* J.Appl.Phys.70.8 (1991) 4045-4049.

[5] Computer Code SRIM 2012, by J.F.Ziegler. J.P. Biersack and M.D.Ziegler. University of California at Los Angeles. CA 90066 (www.SRIM:org.)

Figure captions

Fig.1: Implantation profile of a pencil beam of 10^5 Xe ions of 15 keV into c-Si with the main range parameters shown: Ion longitudinal range: L_l~20 nm, lateral radial diameter: L_r~10 nm. (Color on line). Calculation with the computer code SRIM. [5].

Fig. 2: Scheme of the optical reading arrangement: A 5 μm wide kernel of a monomode fibre carries laser light of wavelength λ ~ 500 nm (2.5 eV) and intensity I_0 =10 mW/(π(2.5μm)^2) (equivalent to $1.3 \cdot 10^{27}$ photons/m^{2}s. The light falls onto a D=20 (200)nm wide aperture of an opaque screen (S). The transmitted power P_t of $3.3 \cdot 10^{7(13)}$ $h\nu$/s hits the rotating memory disk (MD) consisting of transparent, crystalline (c) or opaque, amorphous (a) silicon bit areas. The light power $P_{c(a)}$, passing bit areas c(a) generate bit signals $N_{c(a)}$ in the fast photo diode (PD). (Color on line)e (PD). (Color on line)

Fig.3: Number of photons N_c passing a c-bit area and hitting the photo diode for beam dwell times of τ = 100, 10, and 1 ns/bit as function of aperture radius R. (Color on line) Other conditions as in figure 2- caption.

Fig: 1

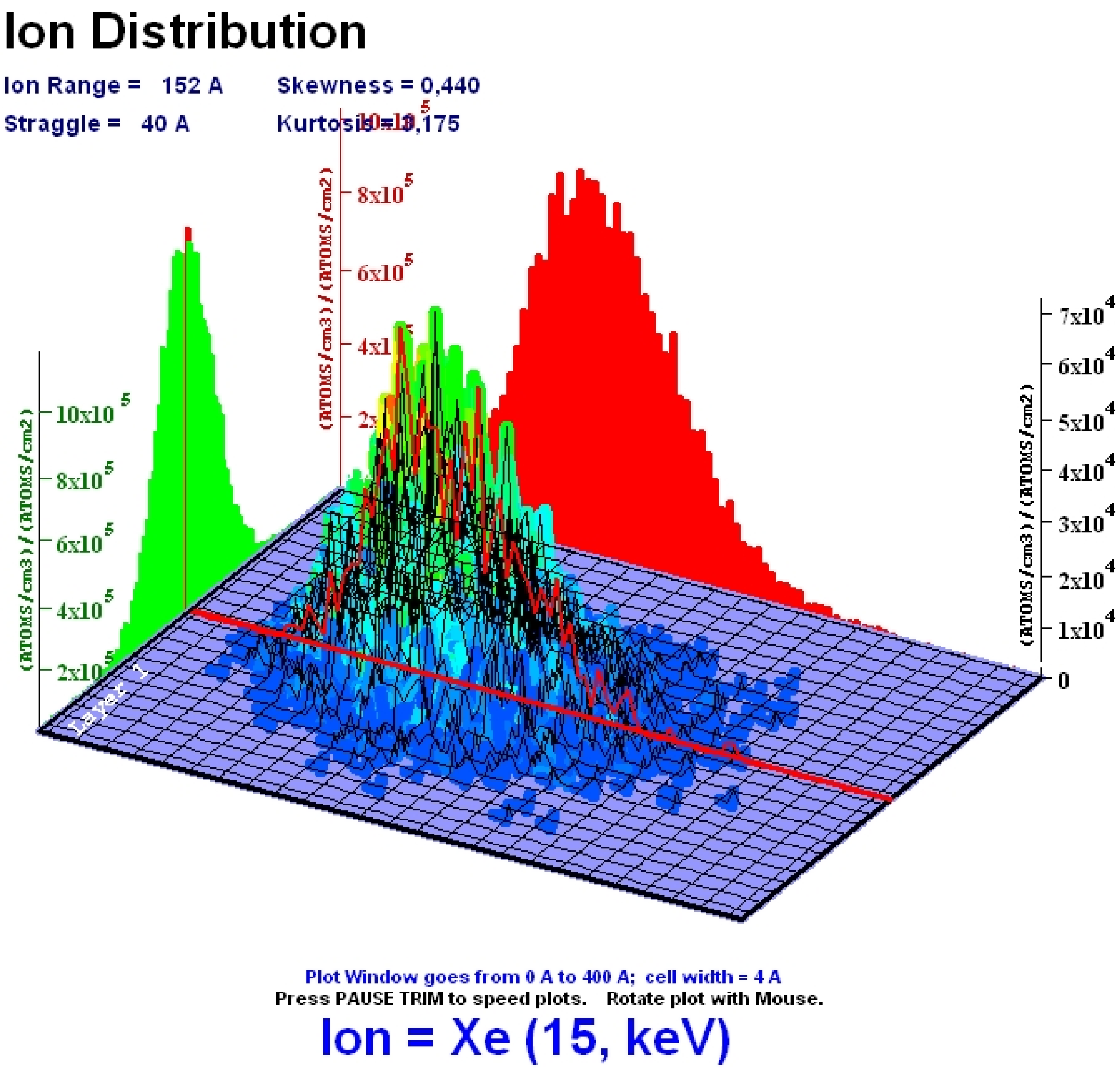

Ion Distribution
Ion Range = 152 A
Skewness = 0,440
Straggle = 40 A
8x10^5
6x10^5
(ATOMS/cm3) / (ATOMS/cm2)
10x10^5
8x10^5
6x10^5
4x10^5
(ATOMS/cm3) / (ATOMS/cm2)
7x10^4
6x10^4
5x10^4
4x10^4
3x10^4
2x10^4
1x10^4
0
(ATOMS/cm3) / (ATOMS/cm2)
Layer 1
Plot Window goes from 0 A to 400 A; cell width = 4 A
Press PAUSE TRIM to speed plots. Rotate plot with Mouse.
Ion = Xe (15, keV)

Fig. 2

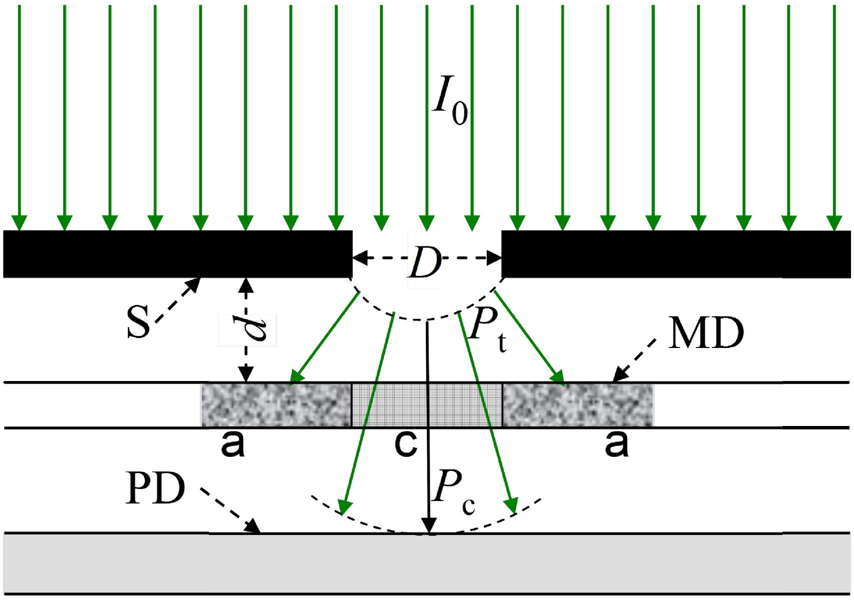
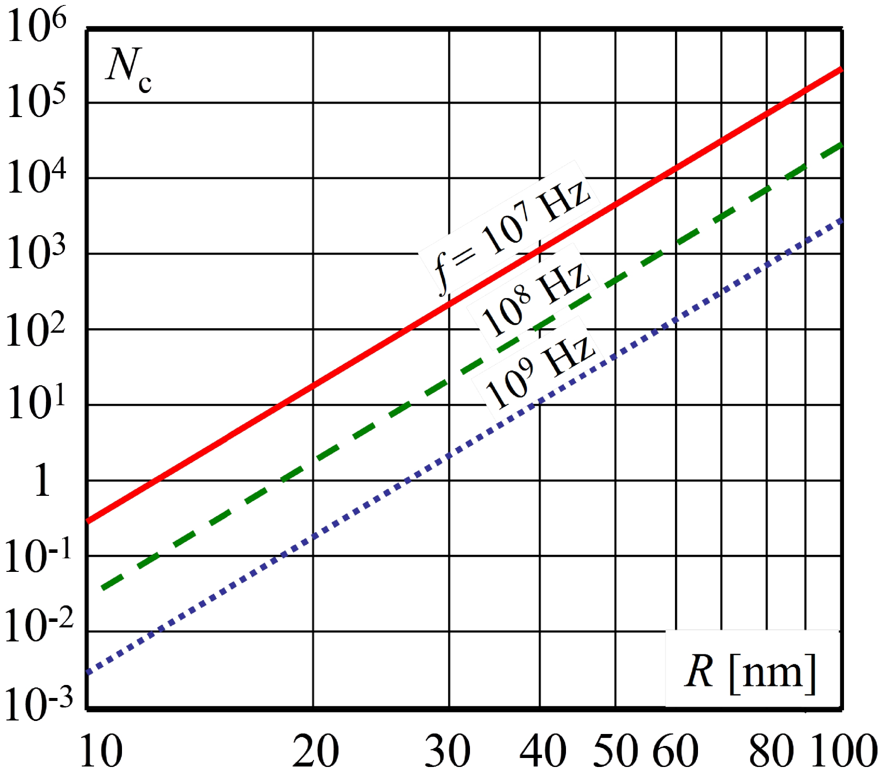


Fig. 3


10^6
10^5
10^4
10^3
10^2
10^1
1
10^{-1}
10^{-2}
10^{-3}
N_c
$f = 10^7$ Hz
10^8 Hz
10^9 Hz
R [nm]
10
20
30
40
50
60
80
100