1. FINAL PUBLISHABLE SUMMARY REPORT - IBAHMA

The IBAHMA project was concerned with a new approach to providing ultra-stable (>50 years), ultra-high density (> 1Tbit/sq.in.) data storage for archival applications. We used ion-implantation to write nanoscale data into hydrogenated amorphous silicon carbide (a-SiC:H) films. The role of implantation conditions and post-implantation treatments on the achievable data density, readout contrast and data longevity was investigated, and optimised conditions determined. The likely limitations for practical application of this potentially important new approach to data storage have also been assessed.

The archival sector is becoming increasingly important, due in part to the introduction of new legal requirements governing the storage of governmental and commercial data, but also as a consequence of the ever-increasing amount of digital data generated by all aspects of our everyday life. Indeed, it has been estimated [1] that the total archival capacity required world-wide will exceed 60 ExaBytes by 2013, generating market values of in excess of $30 billion. For archival applications reliability, data integrity and media longevity feature much more prominently than in other storage sectors. The main recognised archival storage media currently in use are magnetic tape and optical disks, although it is estimated that around 50% of the archive data for commercial organisations is in fact held on magnetic hard disk drives. While optical disks for professional archiving are usually 'guaranteed' a lifetime of at least 50 years, magnetic tapes and disks have in general a much shorter predicted life-span. It is clear therefore that while archival storage is an exceedingly important application, conventional archival storage media are quite limited in terms of lifetime and in terms of storage density (bits per square inch). It is in this context that the IBAHMA project aim was to develop novel, ultra-stable and ultra-high density storage media for archival applications. Indeed, the approach of ion-implantation in SiC can potentially lead to extremely long (many hundreds of years) data lifetimes, which may find uses in the long-term preservation of important scientific and cultural assets.

To realise our goal of ‘permanent’ high-density storage we have used amorphous hydrogenated silicon carbide (a-SiC:H) as a storage medium, due to its promising material properties (e.g. high transparency in the visible region due to its wide optical band gap from 1.8 to 3.0 eV, as well as mechanical durability and chemical inertness [2]). The relative immunity of SiC to environmentally-induced degradation, in particular its high thermal stability (stable to temperatures in excess of 1500 ^{o}C) make it attractive for data storage applications, and promising results have been achieved by using ion-implantation to write micro- and nanoscale optical marks in SiC films; see **Fig S1**.

Ion-beam implantation is a standard technique for controlling the bandgap, and hence the electrical and optical properties of semiconductors [3]. The development of computer-controlled focused-ion-beam (FIB) systems have enabled the fabrication of sophisticated ion-implanted structures [4-6]. The focused-ion-beam diameter can be less than 10 nm, allowing the modification of the dielectric and optical properties of materials on this same nanoscale (10nm bit sizes is roughly equivalent to a data density of 10Tbit/sq.in.). Such nanoscale property changes in optical transmission and reflection offer ultra-high density optical data archives, the readout of which require a super-resolution (sub-diffraction) optical technique, e.g. scanning near-field optical microscopy (SNOM) [7] (see Fig.1 (a) and (b)). Of course imaging by SNOM, which is suitable for research purposes, is slow (and expensive), but for practical applications other super-resolution readout techniques, such as the use of solid-immersion lens (SIL) optics [8], the so-called super-RENS technique [9] or arrays of scanning near-field apertures might ultimately be used to achieve the necessary readout data rates (and required system cost).

The use of gallium as the ion implanted species is attractive since it is available in standard FIB machines, and in addition has been shown to be capable of generating large optical contrasts [4,5]. The fact that Ga has a very low melting point (T_m= 29.8^{0}C) and an unusual feature of volume contraction on melting are factors which favour Ga incorporation upon ion-implantation as dispersed clusters, or small nanoparticles. It was previously noted that Ga precipitation into nanoparticles can vary dramatically (in terms of particle size) with Ga concentration and small changes in surface implant temperature [10]. The precise role of implantation temperature effects, i.e. the target temperature during Ga^+ ion irradiation, on the forms of Ga incorporation in the SiC:H film, and hence on the optical contrast obtainable, has been therefore a key part of the research in the IBAHMA project. Appropriate post-implantation annealing treatments were also studied extensively in IBHAMA, since these are expected to offer further benefits in reducing the required ion dose and enhancing contrast, thus increasing the cost-effectiveness of the FIB bit-writing method.

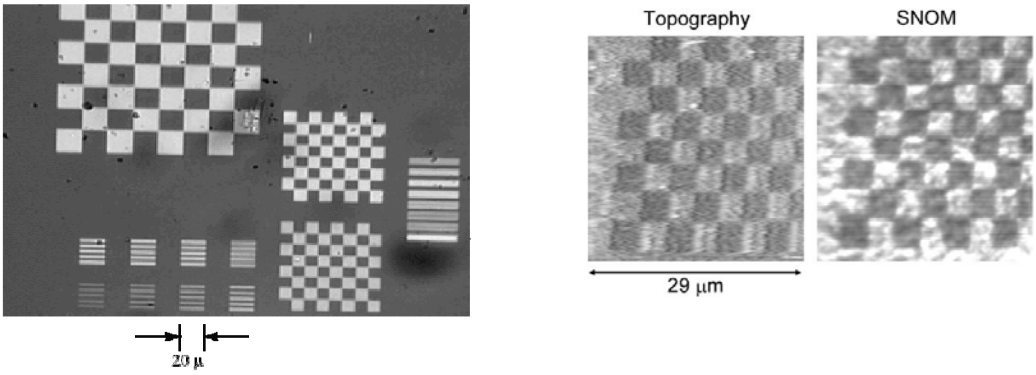

***Figure S1**: (left) Optical contrast pattern written in a SiC:H film using a focused Ga+ ion beam. The minimum feature size is 2.5 μm. (Right) Topographic image and corresponding SNOM image of a chess-board pattern created on an a-SiC:H thin film.*

Thus, Ga^+ broad-beam ion-implantation in a-SiC:H samples was carried out at different substrate temperatures (T1=RT, T2=LN_2(liquid nitrogen), and T3= +50°C) and some of the RT implanted samples were annealed post-implantation at higher temperatures in vacuum. The expected benefit for the optical data storage method, which relies for readout on reduced optical transmission detected by SNOM, was that a lower implantation temperature would result in an increased amount of defects leading to an absorption increase, and hence further decrease in transmission (greater readout contrast). This effect was indeed observed but was overridden by an effect of increased ion beam induced sputtering yield, which greatly reduced the film thickness and hence increased the transmission. The expected effect of higher implantation temperatures, or high temperature post-implantation annealing, was that there would be an increase in the optical reflectivity and decrease in transmission due to Ga clusters coalescing into bigger Ga colloids. This effect was indeed observed but was overridden by a decrease in absorption (increase in transmission) in the high temperature implanted or annealed samples, arising due to a decrease in defect concentration due to self annealing. In conclusion, the best conditions for optical data storage for archival storage applications when using Ga^+ ion implantation in a-SiC:H film were found with an optimal dose (e.g. $D=5x10^{16}$ cm^{-2}) at room temperatures. The fact that the optimum implantation temperature for storage applications has been found to be that of room temperature is fortuitous since it means that the required ion-implantation process is simplified and reduced in cost.

References

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