

Towards Gigayear Storage Using a Silicon-Nitride/Tungsten Based Medium

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Abstract

Current digital data storage systems are able to store huge amounts of data. Even though the data density of digital information storage has increased tremendously over the last few decades, the data longevity is limited to only a few decades.

If we want to preserve anything about the human race which can outlast the human race itself, we require a data storage medium designed to last for 1 million to 1 billion years. In this paper a medium is investigated consisting of tungsten encapsulated by siliconnitride which, according to elevated temperature tests, will last for well over the suggested time.

Keywords: Long term data storage, SiN-W, Storage medium, tungsten, silicon nitride

1. Introduction

The human race has achieved many things we consider worth storing. From paintings found in caves as shown in figure 1 to pieces currently on

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Figure 1: Cave painting from the El Castillo cave in Spain, estimated to be over 40 000 years old

display in musea. Whether it is music, art, literature or scientific breakthroughs, people have tried to ensure preservation of information for future generations.

Musea are filled with art and most of the music and movies today are accessible through the internet, but for how long? At some point humanity as we know it will cease to exist [1] and slowly all our achievements will disappear. Given sufficient time, all memory of humanity will be erased.

To ensure that knowledge about human life is available for many future generations or even future lifeforms we require a form of data storage suitable for storage at extreme timescales.

There are of course some requirements for such a data storage system. The system should be able to survive for at least the required time without losing its content. The data should be easily decodable and the data carriers should be stored in locations likely to change little over 1 million years to ensure that the data carrier does not end up at the bottom of the ocean after a million years. It is also necessary of course to determine what data is relevant to store. All aspects of such a storage system are combined in a multidisciplinary project called “the human document project” [2].

Although each of these aspects is of vital importance to ensure that the stored data will survive and is recognised as such, in this paper we will only focus on the fabrication of a data carrier which can survive for over one million years.

To preserve information for future generations, people have stored data in various ways. In recent years the storage capacity has increased tremendously due to the possibilities created by digital information storage. Where in 1956

the IBM 305 RAMAC was capable of storing 5 MB of data using fifty 24" diameter disks, currently 4 TB can be stored on four 3.5" diameter disks. This means a decrease of form factor and power consumption while greatly increasing the storage capacity. This increase in capacity has not yet reached its limit [3]. Although there has been a huge increase in storage density, the data longevity is limited to about a decade.

Storage systems like DVD's will not last much longer and tape storage will (if stored in a proper environment) last only several decades. Archival paper is expected to last up to 500 years but only if it is stored in a suitable environment.

A recent long-term data storage system is created by the 'Long Now Foundation' where the information is etched into a substrate and then electroformed in solid nickel [4]. The resulting disk contains 13 000 pages of information on more than 1500 human languages. A disadvantage of the disk is that its surface is fragile and can easily be scratched so an encasing for the disk is essential for long time survival and repeated readout might damage the surface of the disk.

If we want to store information for much longer timescales none of the above described media will be suitable and a new type of storage medium is required where the longevity of the data is more important than the storage density.

In order to store information for very long timescales, a medium is required which will survive for at least this period and still contain discernible data. We believe that the relevant storage time should be at least 1 million years and at most 1 billion years [1].

The type of storage medium suitable for these timescales should likely be fabricated especially for this project. There are many types of media which will be suitable, of which the most exotic is DNA based data storage within a living organism which reproduces itself [5]. We have chosen a disk based storage system because such a system can be created with technology which is already available and will likely be easier recognisable than a data carrier inside a living organism. Although magnetic based data storage is highly suitable for current purposes, its energy barrier is too low to survive for 1 million years. Moreover, the data could be erased or modified by strong magnetic fields.

We expect that the data that needs to be stored for the Human Document Project will have been thoroughly verified and is not subject to change. Therefore a 'write-once-read-many' (WORM) type data system would be

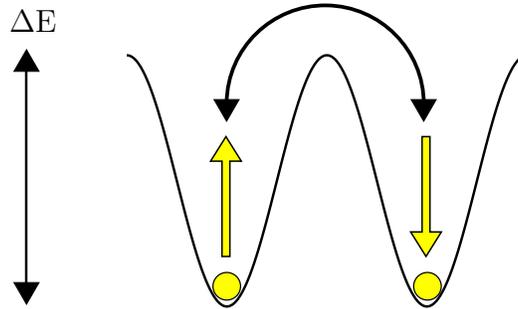


Figure 2: Data is stored in the state of a system, which can be in two or more energy minima.

sufficient.

Readback of the disk should be possible using electromagnetic waves which, we expect, any sufficiently developed society would be able to use. The disk can contain multiple levels of data with different data densities. Using visible light the low density data could be read by eye or using optical microscopy. Higher density data could be made visible by for instance electron beams. A dedicated readback system would in this case not be stored with the data carrier because such a system would also need to survive for at least as long as the disk. Plans to create a readback system could be part of the information on the data carrier.

2. Theory

All data is volatile so it is not possible to store data indefinitely. Even data engraved in a marble slab will eventually erode away. The longevity of a data carrier can of course be increased by storing it in a monitored environment such as in current paper archives where the humidity, temperature, pressure etc. are controlled. This however, would require that the environment also survives and is maintained for at least as long as the data carrier. We believe that the chances of such an environment surviving for a million years in operating conditions are slim, so we prefer a data carrier which has a high chance of surviving without such a dedicated environment.

In order to create a stable data carrier, able to preserve data for a million years, a high energy barrier against erasure is required. This thermal stability of data is a well studied aspect in magnetic data storage [6].

Using a simple but effective theory based on the Arrhenius law, as often used by scientists in the hard disk industry, we can determine the energy barrier required for a certain storage time. For the data storage system we assume that one bit of data is stored in a way much like in current magnetic storage systems. The data is stored in one of the energy minima of the system, which is separated from the other minima by an energy barrier ΔE , as indicated in figure 2. If the system would be kept at a temperature of 0 K, there would be no thermal fluctuations and the system would stay in this state indefinitely. However at elevated temperatures, the probability that the system will jump to another energy minimum after time t , P_{sw} is given by the Arrhenius law [7].

$$P_{sw} = 1 - \exp(-t/\tau(T)) \quad (1)$$

$$\tau(T) = f_0^{-1} \exp(\Delta E/k_B T) \quad (2)$$

Where τ is the decay time [s], k_B Boltzmann constant [J K^{-1}], T the absolute temperature [K] and f_0 the attempt frequency [Hz] which is related to the atomic vibrations and is in the order of 1 GHz for magnetic particles [8].

We assume that the probability of switching from one of the energy minima to another is low, so we can neglect secondary processes like switching back to the original energy minimum. We also assume that the switching behaviour of one element does not influence the switching behaviour of the others. In this case the number of incorrect bits of information in a large data set of N bits is given by $P_{sw}N$. In modern storage systems error fractions up to α of 1×10^{-5} can be comfortably corrected by suitable error codes. Rewriting equation 2 gives:

$$\tau > -t/\ln(1 - \alpha) \approx t/\alpha \quad \text{for } \alpha \ll 1 \quad (3)$$

$$\text{and} \quad \Delta E/k_B T > \ln(tf_0/\alpha) \quad (4)$$

For a data storage time of 1 million years with $\alpha=1 \times 10^{-5}$ and $f_0=1$ GHz, ΔE should be $63 k_B T$, for 1 billion years the energy barrier should be raised to $70 k_B T$ (1.8 eV at room temperature). These energy barriers are given for the ideal case, where there are no distributions of properties which lower the energy barriers. These values are well within the range of today's technology.

To prove that the data will in fact remain without uncorrectable errors for one million years is another challenge. To wait for a million years to be certain

Storage period	1 hour	1 week	1 year
1×10^6 years	461 K	411 K	380 K
1×10^9 years	509 K	455 K	420 K

Table 1: Testing at elevated temperatures to prove data retention for different timescales at T=300 K with $\alpha=1 \times 10^{-6}$

that the data remains would be slightly impracticable, so an accelerated ageing test is required. Starting from equation 4 there are three variables we can act upon, the testing time t_t , the observed number of errors during the test α_t and the temperature at which the tests are performed T_t .

$$\Delta E/k_B T_t > \ln(t_t f_0 / \alpha_t) \quad (5)$$

By observing many bits, we can determine error rates lower than 1×10^{-5} and extrapolate from there when this value will be reached. By testing at higher temperatures, we can increase the number of errors per time unit. Combining equation 4 and equation 5, the temperature at which the test is performed is given by:

$$T_t > T \frac{\ln\left(\frac{t f_0}{\alpha}\right)}{\ln\left(\frac{t_t f_0}{\alpha_t}\right)} \quad (6)$$

Taking for instance an observed error rate ten times better than the desired rate (so $\alpha_t=1 \times 10^{-6}$), the required testing temperature to prove that the data is stable for a million years within a year is 380 K. Table 1 lists values for different testing and storing times, which are well within the experimental range.

This simple model is a first step towards proving that data will be retained for at least one million years by means of an elevated temperature test. This method is also known as accelerated ageing [9]. The method does have its shortcomings however.

2.1. Attempt frequency

The simple Arrhenius model assumes that the attempt frequency to overcome the energy barrier is much higher than the reciprocal of the testing time (in other words, there should be many attempts to switch the entire bit within

the testing period). This condition is most likely met. Other causes of data loss, such as theft, meteor impact or the sun entering the red giant phase [1] cannot be revealed by accelerated ageing (fortunately).

2.2. Local minima

The model assumes that one single event switches the bit. Whereas this might be true for patterned magnetic disks, it certainly is not the case for all data storage systems. In the simple model, we assume that the system only possesses global minima, where local minima might exist which can serve as intermediate steps towards overcoming the energy barrier between global minima states. An example of such a system is the phase change medium (used in rewritable optical discs) where data is stored in the position of atoms, which can reside in a huge number of local minima. In this case the chance of switching should be calculated as a cascade of events, each possibly with their own attempt frequency. The process could then be described by an Arrhenius cascade [10].

2.3. Temperature dependence

The simple model assumes that the energy barrier is independent of the temperature. In most situations this will not be the case. In general the energy barrier will decrease with increasing temperature. An accelerated test will then underestimate the lifetime of the medium. The model also assumes that attempt frequencies are independent of the temperature. Fortunately, the attempt frequency appears in both the numerator and denominator of equation 6. A ten-fold increase in attempt frequency only reduces the temperatures in table 1 by 10 K. Detailed knowledge on the attempt frequency is of lesser importance, as is obvious from equation 4.

Despite the shortcomings of the single switch Arrhenius model, it is still of interest to perform actual accelerated tests on a real medium, especially at temperatures much higher than listed in table 1.

3. Fabrication

The suggested data storage system consists of a medium where the data is represented by one material embedded within a second, different material as schematically described in figure 3. We have selected as the base materials tungsten for the data and Si_3N_4 for the encapsulating material. Tungsten has a high melting temperature and high activation energy, furthermore it has a

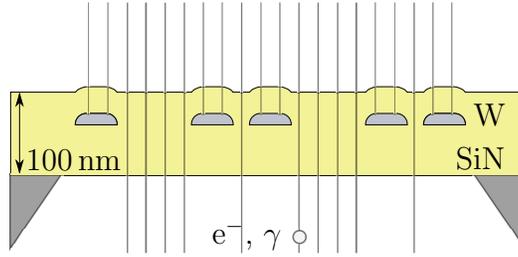


Figure 3: W-Si₃N₄ WORM medium, which is transparent to electron or photon beams

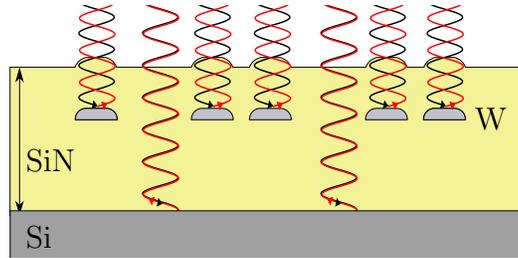


Figure 4: W-Si₃N₄ WORM medium, which is readable by constructive interference on the silicon base and destructive interference on the tungsten islands.

low thermal expansion coefficient. The Si₃N₄ has a high fracture toughness and low thermal expansion coefficient. Another important feature of the Si₃N₄ is its transparency to light. A very thin film would also be transparent to electron beams. These materials are readily available and generally used in microfabrication.

An alternative to the transparent medium is a medium with high contrast in reflection. Contrast can be enhanced by using an optical beam of a single wavelength. If the layer thickness is tuned correctly, constructive interference can occur in the parts where there is no metal and destructive interference in the parts where metal is present or vice versa, as shown schematically in figure 4. This makes it possible to have a much thicker base because the sample does not need to be optically transparent. It should however still be ensured that not all the light gets absorbed by the nitride layer. With light in the visible spectrum, this method can be used for low density data.

3.1. Optical readable data

As a demonstration, data is written in two-dimensional (matrix) barcodes, which can be read back by a camera and computer. These two-dimensional



Figure 5: Design of the HDP disk. Each pixel in the large QR codes consists of a QR code.

barcodes were introduced for cases where more information needs to be stored than can be accommodated by their one-dimensional predecessors, but are now becoming increasingly popular. The implementation we chose was the quick response (QR) code [11], which can be easily decoded by today's smartphones. The level of QR code containing the largest amount of information can lose up to 7% of the data before the code becomes unreadable.

For the encoding of the final disk, it is likely that a coding scheme would be required which focuses on easy decodability. By keeping the size of the QR code low, it is possible to read out the disk by an optical microscope. For the demonstration, the entire disk was covered with a centimeter sized QR code. Each pixel of the code consists of a set of much smaller QR codes with pixels of only a few micrometers in size as shown in figure 5.

For design of the thickness of the nitride layers and the tungsten layers, optical calculation software was used in order to determine the optimum thickness for maximum extinction and amplification in the layers. The wavelength was chosen to be 550 nm.

The medium consists of a 338 nm layer of LPCVD Si_3N_4 on a bare silicon wafer. The tungsten is patterned using optical lithography and a mask containing the QR codes. The pattern is etched using Ar ion beam etching and a top layer of PECVD nitride of 225 nm is deposited on top of the tungsten patterns. The process steps are schematically shown in figure 6 where the silicon removal in step 8 is not necessary.

3.2. Line patterns

Because readout by optical microscope means that the data density is low, it is also necessary to have a higher density storage method. The higher data density storage can be achieved by embedding the data in the nitride for readout by electron beam. Here we assume that the medium should be transparent to electrons, which means that the disk will be very thin and fragile.

For the high data density sample, tungsten lines are used instead of islands. With this sample it is possible to simulate high density data with a linewidth below 100 nm.

The lines will make it easier to create very small structures and inspect the sample after thermal exposure by means of an SEM. A drawback of these lines is the variation in stress in the sample in the direction along the lines compared to across the lines. The process steps are described in figure 6.

The test sample is created by depositing a layer of 230 nm silicon nitride on a cleaned bare silicon wafer by an LPCVD process. On top of the silicon a layer of 50 nm tungsten is deposited by magnetron sputtering. A layer of DUV 30-J8 bottom anti-reflective coating (BARC) is applied by spin coating, which limits the standing waves in the resist and improves the vertical sidewalls. On top of the BARC, a layer of PEK-500 positive resist is spun.

Laser interference lithography (LIL) is used to create the pattern of 100 nm wide lines [12]. For the actual data carrier either a standard lithography mask process could be used or a laser could be used to write the data in the resist. The resist is developed in OPD4262 after exposure. The process flow is depicted in figure 6 and a scanning electron micrograph of the developed sample is shown in figure 7 a.

A short O₂ reactive ion beam etching (RIBE) step is used to transfer the pattern into the BARC layer. The BARC pattern is transferred into the tungsten layer by argon ion beam milling as can be seen in figure 7 b.

The entire sample is subsequently covered with Si₃N₄ by a PECVD process to encapsulate the tungsten lines. The result is shown in figure 7 c. In the cross-section image from bottom to top, the silicon, the LPCVD silicon nitride, the tungsten lines and the PECVD silicon nitride can be seen. The Si₃N₄ in the final product is much thicker than the thickness schematically shown in figure 3 to observe possible spreading of the tungsten clearly.

For the optical transparent sample, the silicon needs to be removed from the bottom of the sample and a medium with tungsten lines encapsulated in

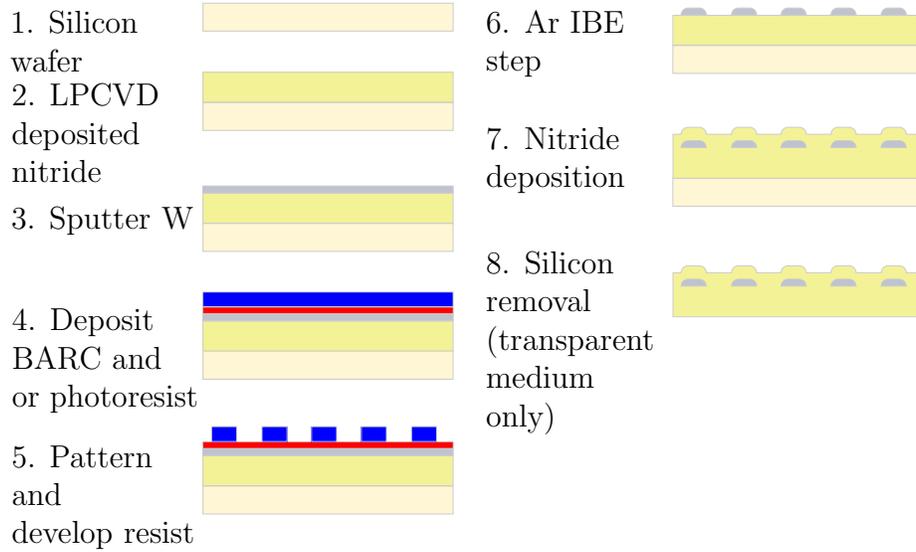


Figure 6: Design of the HDP disk. Each pixel in the large QR codes consists of a QR code.

a Si_3N_4 matrix remains. The silicon removal of step 8 shown in figure 6 is not performed to ensure mechanical stability of the sample.

4. Elevated temperature test

By testing the sample at relevant temperatures it can be shown that it should in principle be possible to store data for at least one million years. A second interesting test would be to investigate whether the sample would survive higher temperatures which would for instance occur during a house fire.

4.1. Optical readable data

The sample with the QR codes was exposed to temperatures of 513(5) K, 613(5) K and 713(5) K. Each temperature increase causes a reduction in the number of readable QR codes by the decoding algorithm. This is caused by cracking of the top Si_3N_4 as can be seen in figure 8. The unreadable QR codes are not visibly damaged and the tungsten is still present.

The misreading of the information is caused by the readout using an optical microscope without a monochromatic light source. The images are taken using a top mounted camera and contain a multitude of colours, caused

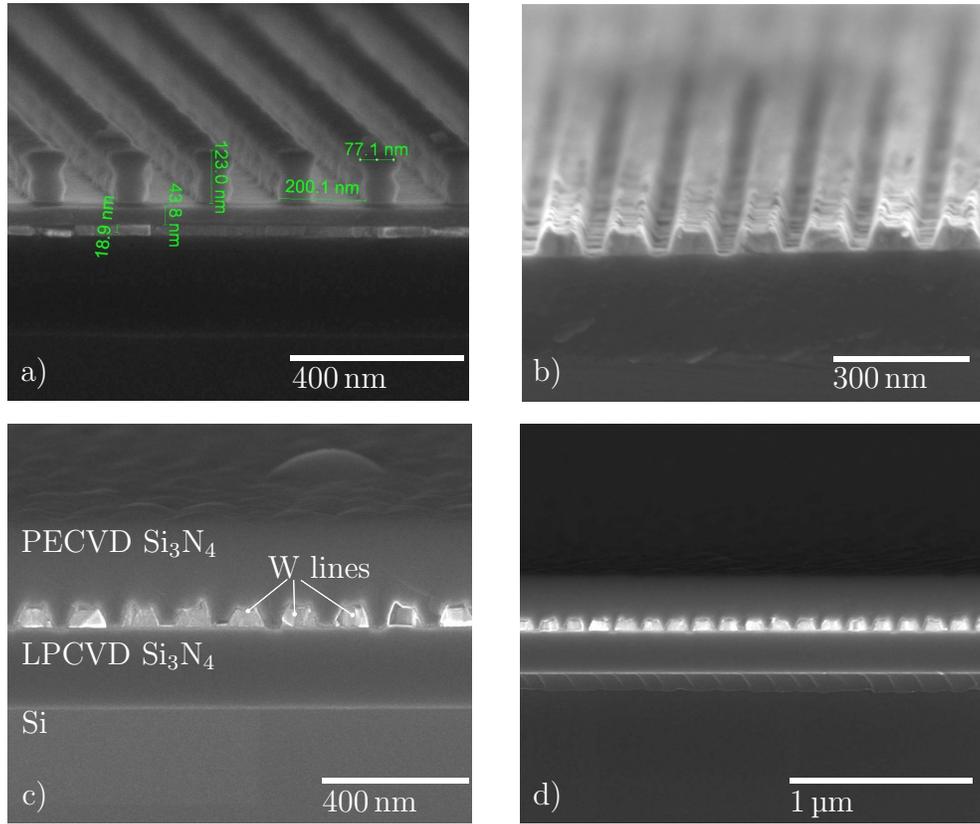


Figure 7: a) Scanning electron micrograph of the test sample before etching. b) Scanning electron micrograph of the test sample after etching containing W lines. c) Scanning electron micrograph of the cross-section of the encapsulated lines in the test sample d) Scanning electron micrograph of the sample after 1 hour at 473 K

by the variation in Si_3N_4 thickness due to the cracking. The very simple detection software was unable to correctly assign a black or white colour to multitude of colours caused by the cracking of the top siliconnitride layer.

Due to the complexity of the QR code, damage to some areas affects the readability more than other areas [11]. When for instance the finder patterns are damaged, the QR code can not be read anymore. This can be seen from the example in figure 9 where the finder patterns of a damaged QR code are manually repaired and the QR code becomes readable again.

A single wavelength microscope or more advanced detection software might solve this problem for the QR codes.

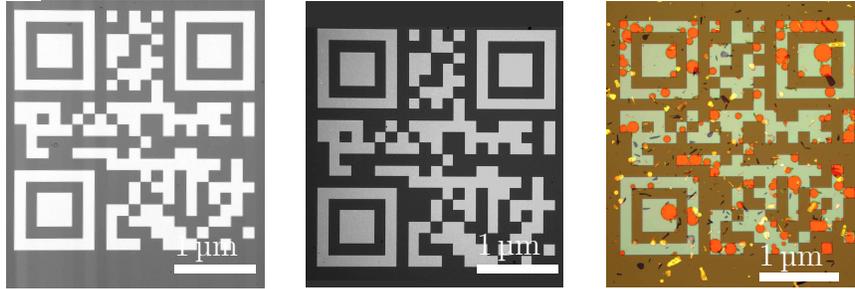


Figure 8: Optical microscope images of the same QR code left: after fabrication, center: after 2 hours at 613 K and right: 2 hours at 763 K

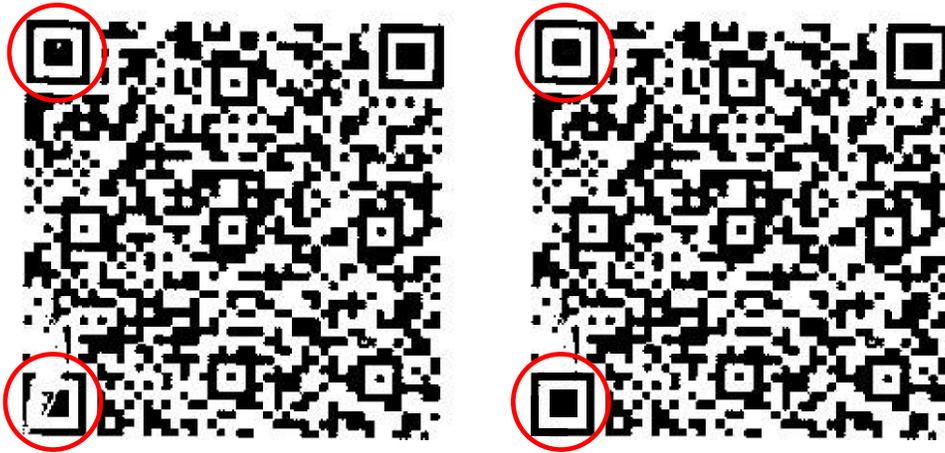


Figure 9: Manually repaired QR codes by fixing the finder patterns in the red circles.

4.2. Line patterns

Table 1 shows that an ageing test at 445 K for 1 hour is sufficient to prove that the line sample would survive for at least 1 million years. The sample was kept in an oven at 473 (5)K for approximately one hour. Figure 7 c and d show SEM images of the sample before and after the test. We observe no visible degradation of the sample, which indicates that this sample would still be error free after 1 million years. Lower temperatures have not been tested because the PECVD nitride is deposited at temperatures of ~ 573 K. This means that below this temperature damage would have occurred during deposition. The sample has furthermore been tested at 723(5) K and 848(5) K without visible damage to the sample.

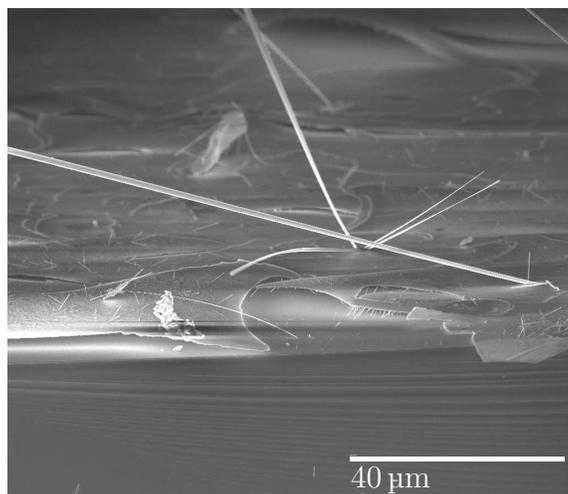


Figure 10: SEM image of the whiskers growing from the top of the sample

A test temperature of 1373(5) K for four hours, which can occur in a hot spot during a house fire, showed that the sample was completely destroyed and the tungsten lines could not be recognised anymore. The Si_3N_4 seems to have peeled off probably due to variations in thermal expansion coefficients of the top and bottom layer Si_3N_4 and the W.

After exposing the sample to a temperature of 923(5) K for 4 hours we observed “whiskers” growing from the top of the sample as can be seen in figure 10. Here we also see the peeling of the Si_3N_4 layer. After inspection using an SEM with EDX capabilities we found that the whiskers contain high levels of tungsten and oxygen as can be seen in figure 11. What likely has happened is that the top Si_3N_4 deposited by the PECVD process starts to exhibit cracks and oxygen can interact with the tungsten. Under the influence of oxygen and the high temperature, WO whiskers are formed, similar to the ones described by Cho et al. [13].

Higher temperatures should be possible when the thermal expansion coefficients of the top and bottom layers are matched with the metal layer and the lines are replaced by islands. Previously it was already found that a sample with small dots embedded in Si_3N_4 was able to survive temperatures up to 1073 K for 30 minutes without degradation [14]. Whether a sample with larger islands would also survive these temperatures remains to be investigated.

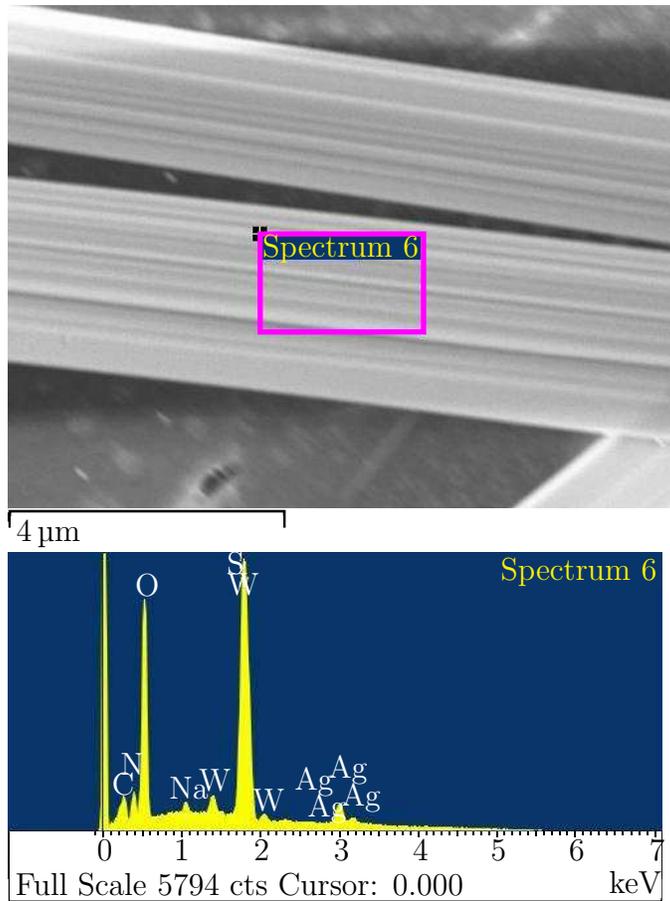


Figure 11: Top: SEM image of the whisker. Bottom: EDX information of the whisker showing large contents of W and O

5. Discussion

The initial attempt to create a medium containing embedded data which is able to survive for 1 million years is promising. The optical readable data in the form of QR codes was able to survive the temperature up to 713(5) K. The amount of readable QR codes decreases at higher temperatures, but this seems to be largely due to the detection scheme as the tungsten is still present. The medium can survive high temperatures, up to 1 hour at 848(5) K, without visible degradation of the medium but at higher temperatures the medium degrades rapidly.

At lower temperatures which corresponds to a storage time of 1 million

years or more, the data carrier survives. If we only take the Arrhenius law into account this should be sufficient to prove that data will survive for 1 million years.

It is likely however that the Arrhenius law that we use is too simple to describe the real ageing process. If the energy barrier consists of intermediate steps, a cascaded Arrhenius law would be required and data deterioration could occur much faster than expected from these results [10, 15].

We do believe however that diffusion of the tungsten is not the primary concern as shown by the cracks caused by the elevated temperature test. Prolonged exposure of the tungsten to oxygen could lead to the creation of the whiskers. Furthermore low attempt frequency processes like erosion, fracturing and vandalism might have a much larger influence on the lifetime of the disk than diffusion.

The suggested medium is also interesting for fire-proof archiving. Possible solutions to ensure that information could also survive temperatures in the excess of 973 K to 1173 K would be to have a better encapsulation process ensuring that the thermal expansion coefficients of top and bottom layers are matched with the metal layer. However house fires can contain hot spots with temperatures above 1473 K which might still prove to be too high for the medium to survive. The Si_3N_4 or other encapsulation material should be dense in order to limit the diffusion of oxygen. A different material acting as “data” could also solve the reaction with oxygen. Materials with a slightly lower melting point than the 3683 K of tungsten should be no problem.

When the sample survived a temperature of 848 K for one hour we would, according to the theory, have proven that the sample would last 9×10^{29} years, which is highly unlikely.

6. Conclusion

Initial calculations show that it is possible to store data for over 1 million years, or even 1 billion years, with reasonable energy barriers in the order of $70 k_B T$. To prove that the data will not disappear over this time period, one can perform accelerated ageing tests at moderately elevated temperatures (461 K for 1 hour to represent 1 million years).

A disk with data in the form of QR codes has been fabricated and was able to survive the temperature tests, and therefore will survive one million years of storage according to theory. Data readout failure at even higher

temperatures occurs because of the internal stress in the layer stack at elevated temperatures, which leads to fractures in the top layer, resulting in color changes in the readback image.

A model for a high density recording medium, consisting of W lines with a width below 100 nm embedded in a Si_3N_4 matrix, has been successfully fabricated. An accelerated ageing test was performed by storing the sample at 473 K for one hour. There was no visible degradation of the sample or the tungsten lines. If we only take diffusion into account this proves that the sample will survive for well over 1 million years when stored at 300 K.

Exposure of the medium to higher temperatures shows degradation due to the difference in thermal expansion coefficients between the two different types of Si_3N_4 and the W lines. The top layer of Si_3N_4 starts to show cracks and the W is exposed to the environment. This leads to the "whiskers" being grown under the influence of oxygen and high temperature.

7. Future work

Reduction of the amount of decodable QR codes is likely caused by the white light source of the microscope and the simple detection scheme. Solving the problem with the variation in stress between the nitride and the tungsten layers would probably also solve the readout issues of the QR codes.

Another influence on the sample could be etching of the nitride due to acids. There are known acids like phosphoric acid which can etch silicium nitride. Also erosion due to influences of for instance wind and sand can deteriorate the medium. A suitable container or storage location can decrease these influences. To properly investigate these influences more advanced tests will have to be performed on the medium.

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References

- [1] Miko C. Elwenspoek. Long-time data storage: relevant time scales. *Challenges*, 2(1):19–36, 2011. doi: 10.3390/challe2010019.

- [2] Andreas Manz. The human document project and challenges. *Challenges*, 1(1):3–4, 2010. ISSN 2078-1547. doi: 10.3390/challe1010003.
- [3] H. Muraoka and S. J. Greaves. Statistical modeling of write error rates in bit patterned media for 10 tb/in² recording. *IEEE Trans. Magn.*, 47(1 PART 1):26–34, 2011. ISSN 00189464. doi: 10.1109/TMAG.2010.2080354.
- [4] Long Now Foundation, 2013. URL <http://longnow.org/>.
- [5] Jan Petr, Vaclav Ranc, Vazslav Maier, Pavlana Ginterová, Joanna Znaleźiona, Radim Knob, and Juraj Avek. How to preserve documents: A short meditation on three themes. *Challenges*, 2(1):37–42, 2011. ISSN 2078-1547. doi: 10.3390/challe2010037.
- [6] S. H. Charap, P. L. Lu, and Y. He. Thermal stability of recorded information at high densities. *IEEE Trans. Magn.*, 33(1):978–983, 1997. doi: 10.1109/20.560142.
- [7] W. Wernsdorfer, E. Bonet Orozco, K. Hasselbach, A. Benoit, B. Barbara, N. Demoncy, A. Loiseau, H. Pascard, and D. Mailly. Experimental evidence of the Néel-Brown model of magnetization reversal. *Phys. Rev. Lett.*, 78(9):1791, 1997. doi: 10.1103/PhysRevLett.78.1791.
- [8] Dieter Weller and Andreas Moser. Thermal effect limits in ultrahigh-density magnetic recording. *IEEE Trans. Magn.*, 35:4423–4439, 1999. doi: 10.1109/20.809134.
- [9] X. Zou, T. Uesaka, and N. Gurnagul. Prediction of paper permanence by accelerated aging I. Kinetic analysis of the aging process. *Cellulose*, 3(4):243–267, 1996. ISSN 09690239. doi: 10.1007/BF02228805.
- [10] F. Bardou. Cooling gases with Lévy flights: using the generalized central limit theorem in physics. *ArXiv Physics e-prints*, 2000. URL <http://arxiv.org/abs/physics/0012049v1>.
- [11] S. Vongpradhip. Use multiplexing to increase information in QR code. In *8th International Conference on Computer Science and Education, ICCSE 2013*, pages 361–364, Colombo, 2013. doi: 10.1109/ICCSE.2013.6553938.

- [12] R. Luttge, H. A. G. M. van Wolferen, and L. Abelmann. Laser interferometric nanolithography using a new positive chemical amplified resist. *J. Vac. Sci. Technol. B*, 25:2476–2480, 2007. doi: 10.1116/1.2800328.
- [13] M. H. Cho, S. A. Park, K. D. Yang, I. W. Lyo, K. Jeong, S. K. Kang, D. H. Ko, K. W. Kwon, J. H. Ku, S. Y. Choi, and H. J. Shin. Evolution of tungsten-oxide whiskers synthesized by a rapid thermal-annealing treatment. *J. Vac. Sci. Technol. B*, 22(3):1084–1087, 2004. ISSN 10711023 (ISSN). doi: 10.1116/1.1738670.
- [14] Y. Pei, C. Yin, M. Nishijima, T. Kojima, T. Fukushima, T. Tanaka, and M. Koyanagi. Formation of high density tungsten nanodots embedded in silicon nitride for nonvolatile memory application. *Appl. Phys. Lett.*, 94(6):063108, 2009. ISSN 00036951 (ISSN). doi: 10.1063/1.3081042.
- [15] E. Bertin and F. Bardou. From laser cooling to aging: A unified Lévy flight description. *Am. J. Phys.*, 76(7):630–636, 2008. ISSN 00029505. doi: 10.1119/1.2888543.