Applying NiTi Shape-Memory Thin Films to Thermomechanical Data Storage Technology

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ABSTRACT

As the data storage density in cutting edge microelectronic devices continues to increase, the superparamagnetic effect poses a problem for magnetic data storage media. One strategy for overcoming this obstacle is the use of thermomechanical data storage technology. In this approach, data is written by a nanoscale mechanical probe as an indentation on a surface, read by a transducer built into the probe, and then erased by the application of heat. An example of such a device is the IBM millipede, which uses a polymer thin film as the data storage medium. It is also possible, however, to use other kinds of media for thermomechanical data storage, and in the following work, we explore the possibility of using thin film Ni-Ti shape memory alloy (SMA). Previous work has shown that nanometer-scale indentations made in martensite phase Ni-Ti SMA thin films recover substantially upon heating. Issues such as repeated thermomechanical cycling of indentations, indent proximity, and film thickness impact the practicability of this technique. While there are still problems to be solved, the experimental evidence and theoretical predictions show SMA thin films are an appropriate medium for thermomechanical data storage.

INTRODUCTION

Because of its physical and chemical robustness, NiTi shape memory alloy (SMA) is the most widely used of the shape memory materials. NiTi derives its unusual mechanical properties, including its ability to recover large amounts of strain by the shape memory effect, through a solid state phase change known as a martensitic transformation. Although it has been widely studied [1], opportunities still remain for the discovery of new behavior and new applications.

The micrometer to macroscopic-scale behavior of NiTi has been explored using uniaxial tensile and compressive loading as well as microindentation for both single crystal and polycrystalline samples [2,3]. The micrometer to nanometer-scale behavior of NiTi can also be addressed through indentation techniques. Indentation shape recovery through the shape memory effect in NiTi has been demonstrated on the microscale [4] and the nanoscale [5,6]. Our work also demonstrates a significant increase in the material's ability to recover at depths less than 100 nm [5]. This capacity of NiTi to deform under indentation and subsequently recovery the majority of the indentation depth with heating opens the possibility that it can be used as a thermomechanical data storage medium.

The superparamagnetic limit poses a problem for current high-density magnetic digital information storage media. IBM has invented one possible workaround. The Millipede uses an array of microfabricated cantilevers similar to those used in atomic force microscopy (AFM) to store binary data in the form of indentations on a polymer surface [7]. The device heats the cantilever tips to make indentations in the polymer surface, which can then be read back using the same cantilevers, and erased by heating the polymer again, thereby achieving the write, read

and erase operations necessary for data storage. Storage densities in the Tbit/in^2 range have been documented, as have data transfer rates up to a few Mb/sec. We have considered NiTi as an alternative to the polymer thin films and present result below which are related to this application.

EXPERIMENTAL

NiTi thin films were deposited at TiNi Alloy Co., San Leandro, CA. Oxidized silicon substrates were coated with Nitinol to depths of 10, 1.7, 0.7, 0.35, 0.15, 0.075 and 0.035 μm. Film composition was roughly 49.5 atomic % Ni. X-ray diffraction showed the films thicker than 0.5 μm to be martensite, and TEM was used to determine the 0.15 μm film to be a mixture of austenite and R-phase.

A Digital Instruments AFM system was used in conjunction with a Hysitron nanoindentation apparatus to perform indentation experiments. The combined nanoindenter / AFM used the diamond indenter to map surface topography, thereby allowing a desired location for an indent to be selected within several nanometers. Maximum indent load varied between 0.025 and 8 mN. Write, read, and erase operations were then conducted. After indentation (write), the sample's local surface topography was then imaged (read), and heated with a Peltier cell to 90 C in situ (erase), allowing the martensitic transformation to occur. Upon cooling, the indents were re-imaged, showing the recovery of part of the residual indent depth through the shape memory effect. A profiling feature of the Digital Instruments software was used to quantitatively measure this change.

RESULTS

Recovery of an indentation made in a NiTi thin film to a maximum load of 1 mN is shown in Figure 1. Upon heating past the transformation temperature, the AFM topographical data clearly shows a decrease in indent depth. To ensure the same cross section was examined before and after heating, profiles were taken along a line from the indent's deepest point to the vertex of the triangular residual indent. Some tip broadening may be present, due to the use of the relatively blunt indenter as the AFM probe, but this does not significantly affect the results shown.

Indentations can also be positioned in a patterned array that would allow for dense data storage. The indentation, or write step, is followed by a read step using the same indenter as a scanning probe as is shown in Figure 2. Erasure of a bit of information is achieved by heating the local material to recover the deformation. Recovery ratio has also been investigated as a function of film thickness [8]. The recovery ratio decreases markedly at film thickness less than 350 nm for both the 0.25 and 0.5 mN loads. The recovery ratio of the 710 nm film depended on applied load. While the 0.25 mN indent showed the same recovery as that of the 10 μm film, the 0.5 mN indent recovered significantly less. No discernable indentation recovery was observed in films of thickness 70 nm and below, or for a 1.7 μm film of amorphous NiTi.

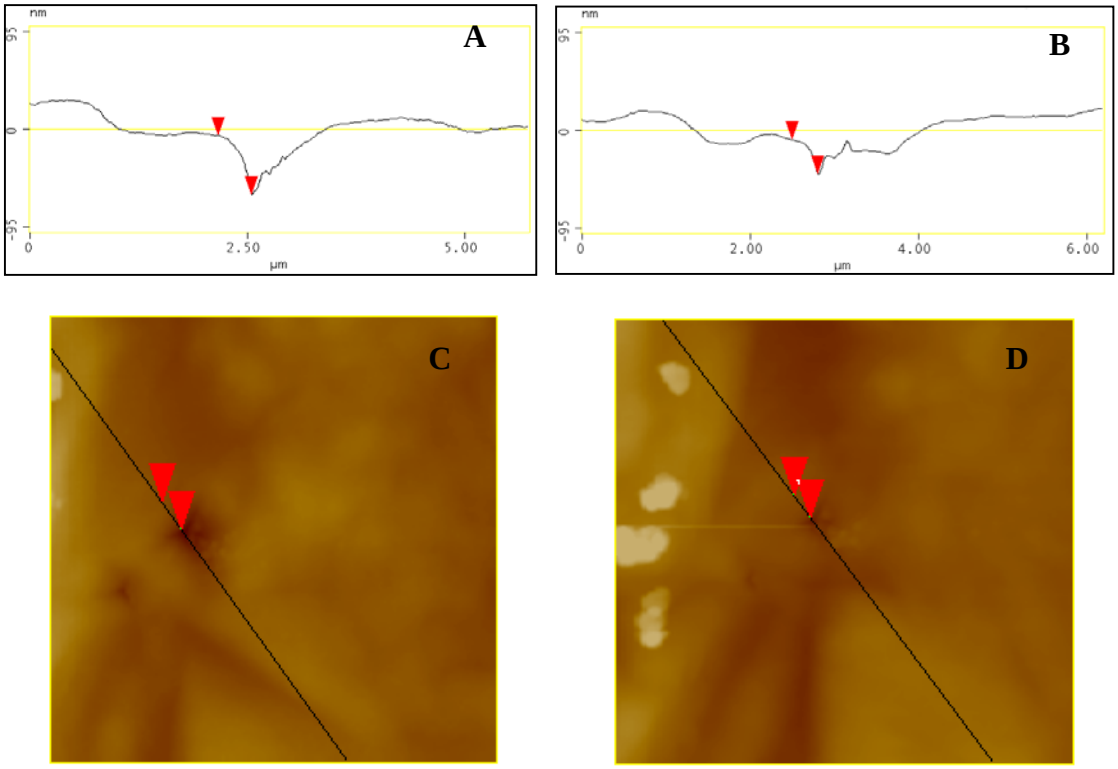

Figure 1. Shape memory recovery of a nanometer scale-indent. A and B show profiles of an indent (1 mN maximum load) made in a martensite-phase film of NiTi before and after heating, respectively. C and D show AFM topographical images of the same indent before and after heating, the profiles above are traced by the black line and red markers. Note that the indent depth recovery occurs even with the presence of another indent nearby.

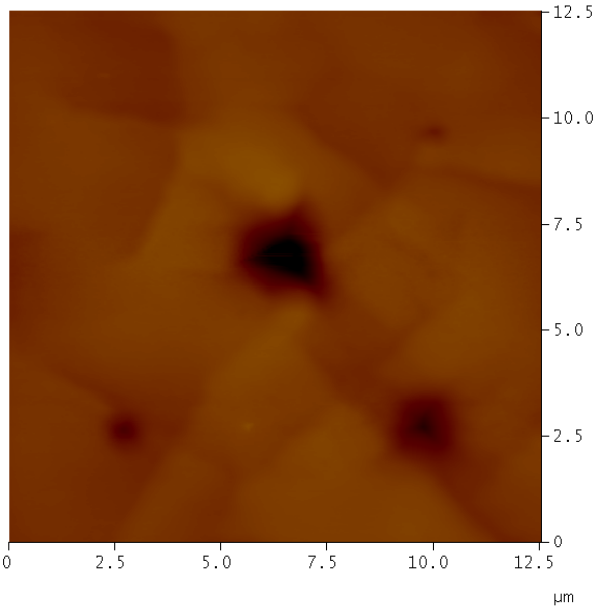

Figure 2. The topographical image created by scanning the indenter tip after the indentations were completed shows impressions from 5 indentations, the largest of which is in the center of the image. The indents were created on a 1.7 µm thick film at load levels ranging from 0.08 to 8 mN.

DISCUSSION

In addition to the fundamental write-read-erase process, there are numerous related questions that must be addressed to further evaluate NiTi thin film as a data storage system component. The footprint of a single indent at a given load and how neighboring indents affect each other governs data storage density. Additionally, in order to allow for rewritable memory repeating cycling at a given indent location and the materials ability to continue to recover upon heating is critical. Further discussion of the effect of repeated cycling and indent proximity will appear in another publication [9], but indent recovery with heating and substrate effects will be discussed below.

It is important to describe the processes occurring during indentation in order to optimize the recovery of indentations for data storage. The SMA can deform during indentation through elasticity, plastic yield, martensite twin rearrangement (in the case of a martensite-phase material) or martensitic transformation (in the case of an austenite-phase material). Stress is highest at the tip of the indenter, and decreases radially with distance. The processes occurring during indentation of an SMA can be described approximately as a series of hemispherical shells (Figure 3). Far from the indenter tip, stress is lowest, and is accommodated elastically. Approaching the tip, the stress level increases until the critical stress for martensite twin rearrangement (or the stress-induced martensitic transformation) occurs. In the area directly adjacent to the indenter, stress has exceeded the yield point of the material, and plastic deformation occurs. This picture lends itself to analysis through Johnson's spherical cavity model [10]. Assuming the indenter creates a hemispherical region of uniform pressure, one can locate the elastic-plastic boundary of a linear, isotropic elastic-perfectly plastic material using the equation

$$c = \frac{d}{\tan\beta}\left[\frac{E\tan\beta}{6Y(1-\nu)} + \frac{2-4\nu}{3-3\nu}\right]^{1/3}, \qquad (2)$$

where c is the elastic-plastic boundary, d is indentation depth, β is the angle between the face of the indenter and the surface, E is Young's modulus, Y is yield stress, and ν is Poisson's ratio.

Using equation 2, the radius of the hemispherical region within which deformation proceeds by martensite twin rearrangement, c_{mr}, can be estimated as a function of indent depth assuming E = 60 GPa [11] and Y = 0.2 GPa (the critical stress for martensite twin rearrangement). Similarly, the radius of the region within which deformation proceeds by plastic processes, c_{pl} can be estimated assuming Y = 0.8 GPa (the material yield stress) [1]. The material contained in the shell where deformation proceeds by martensite twin reorientation can contribute to the shape memory, as the indent recovers upon heating. The plastic deformation within the shell delineated by c_{pl} is not recoverable, and will remain as the unrecovered part of the residual indentation [5].

The effect of the substrate material on the measurement of the mechanical properties of thin film materials is also of interest. Our prior work has shown that substrate effects are quite important in the case of NiTi [8]. If the radius of the region bounding the shape memory zone is larger than the film thickness, indent recovery by the shape memory effect is inhibited. As film thickness decreases, this factor becomes important at shallower indent depths. Figure 3 illustrates the onset of substrate effects during indentation of a SMA. Care must be taken when

considering the use of NiTi thin films for thermomechanical data storage so that the substrate effects can be avoided, or appropriately accounted for.

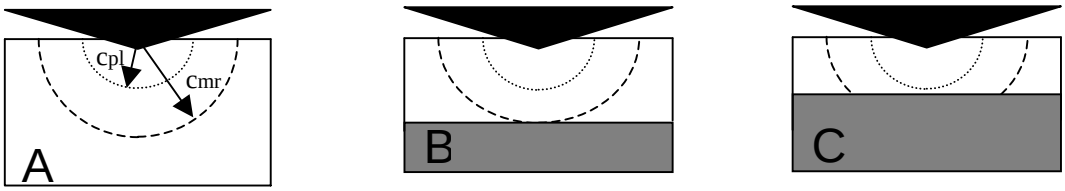

Figure 3. This schematic diagram illustrates the onset of substrate effects during indentation of a SMA. Diagram A shows the case for c_{mr} < film thickness, where no substrate effects are expected. The radius of the hemispherical boundary within which plastic deformation occurs is c_{pl} and the radius within which recoverable deformation occurs by martensite twin rearrangement is c_{mr}. Diagram B shows the case for c_{mr} = film thickness, at which point substrate effects should begin to be important. Diagram C shows the case for c_{mr} > film thickness, at which point substrate effects should become very important.

CONCLUSION

A strategy using NiTi thin film material is presented as an alternative data storage media. In this approach, data is written by a nanoscale mechanical probe as an indentation on a surface, read by the same probe, and then erased by the application of heat. It has been shown that nanometer-scale indentations made in martensite phase Ni-Ti SMA thin films recover substantially upon heating. The recovery has been shown to be influenced by repeated thermomechanical cycling of indentations, indent proximity, and film thickness, because indent recovery is inhibited as the region in which the shape memory effect occurs impinges on the silicon substrate in thinner films. While there are still several open issues to be addressed, the experimental evidence shows that NiTi SMA thin films are an appropriate medium for thermomechanical data storage.

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