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Flexible magnetic writing / reading system: Polyimide film as flexible substrate

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Abstract

In the frame work of Collaborative Research Center (CRC) 653, magnetic data storage on surfaces of components has been developed. The principle is based on magnetic data storage of hard disk drives. Rigid magnetic writing heads successfully developed so far still have limited capabilities; they cannot be adapted to rough or curved surfaces and cannot withstand high mechanical shock. To overcome such drawbacks, a new design of a writing head based on a flexible substrate is proposed. This publication focuses on an investigation of a material which serves as a required substrate for this application. Baseline examinations for asserting compatibility of the flexible substrate to production processes for microelectromechanical systems (MEMS) are presented. Successfully fabricated micro structures using simple fabrication techniques based on photolithography and thin film processes are demonstrated as well. Obtained results through this work indicate that the polyimide film, namely Kapton film, is suitable as the flexible substrate for the flexible magnetic writing / reading system.

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Keywords: Thin film; Flexible Substrate; Polyimide; Permalloy (NiFe 81/19); Magnetic writing and reading head

1. Introduction

Collaborative Research Centre (CRC) 653 “Gentelligent Components in their Lifecycle” strives to physically store important processing information during production as well as load experienced during usage directly in

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components. Utilization of this inherently stored information in the components shifts paradigms in production engineering [1]. Flexible and fault tolerant production processes, precisely predicted maintenance and fast product optimizations are examples of direct benefits obtained through this paradigm shift.

Nomenclature

Compound substrate	A Kapton film (a flexible substrate) laminated with a pressure sensitive adhesive silicone layer and bonded to a silicon wafer (a carrier)
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1.1. A magnetic writing / reading system

One of key technologies developed in CRC 653 is a magnetic writing / reading system which allows direct recording of data on a surface of a component. This section gives a short overview of the current state of the magnetic writing / reading system. Technologies similar to those found in classical magnetic hard disk drives form a basis of the magnetic writing / reading system. The system consists of an inductive magnetic writing head, a giant magnetoresistance (GMR) reading head and a storage medium. The writing head is made of a soft magnet (MnZn) core with a small air gap between core legs. Coils are wound on both core legs [3]. A magnetic field generated during a writing process spreads out at the air gap and magnetizes magnetic particles in the storage medium [4]. By modulating data into the magnetic writing field, data tracks can be created on a surface of a component (Fig. 1). Materials capable as of serving as storage medium are magnetic magnesium alloys. Magnesium is inherently a paramagnetic material and cannot be used as a storage medium. However, magnesium alloyed with hard magnetic particles, e.g. γ -Fe₂O₃ [6] and cobalt [7], is ferromagnetic and thus can be used as a storage medium. A commercial GMR sensor in a bridge configuration is adapted and employed as a reading head. Due to the inhomogeneous distribution of hard magnetic particles in the component, readout signals trend to fluctuate and thus a special algorithm for data detection and demodulation is required [5].

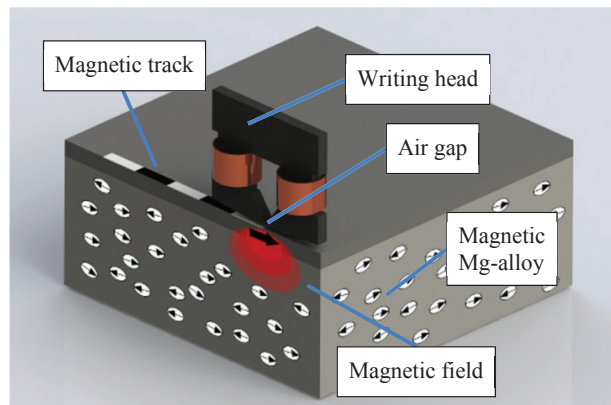


Fig. 1. A modulated magnetic writing field spreads out of an air gap and magnetizes hard magnetic particles in a component, made of magnetic Mg-alloy, resulting in a magnetic track stored inside the component.

1.2. Flexible substrate for a magnetic writing / reading system

The magnetic writing / reading system is created using the same principle employed in magnetic data storage of hard disk drives. However, the most important criterion is not maximum data density but reliable operability of system components, namely a storage medium and a writing head. For example, writing on a medium with a rough surface using a rigid magnetic writing heads is difficult because a defined gap between the writing head and the

surface of the storage medium is hard to maintain. A variation of the gap may cause a writing failure because the strength of the writing magnetic field and the writing region vary according to the gap. Also high mechanical shocks can easily cause damage to the head. Besides, optimal contact between the writing head and curved surfaces is not always possible if the surfaces have concave profiles. To overcome such limitations, a new design of a writing head based on a flexible substrate has been proposed and the general feasibility using a hybrid fabrication technique was confirmed in [2]. Nevertheless, only fabrication processes based on standard thin film fabrication processes, e.g. photolithography, physical vapor deposition and dicing for microelectromechanical system (MEMS) should be employed in order to ensure higher flexibility of the system. Since these standard thin film fabrication processes are optimized for solid planar substrates, an investigation on a selection of a material serving as a flexible substrate and baseline information for asserting compatibility of the flexible substrate to production processes must be carried out.

2. Experiment

2.1. Material selection

Elastic polymer materials are generally used as flexible substrates. Critical properties that flexible substrates must retain in MEMS production using thin film technology are primarily thermal stability, chemical stability and vacuum compatibility. In physical deposition and etching, the flexible substrates experience high temperature stress and high vacuum. Cleaning agents like acetone and isopropyl alcohol are commonly used solvents in photolithography and are aggressive to polymers. Considering these factors, polyimides are appropriate as the flexible substrates because of their superior properties [8]:

- High thermal stability (up to 300°C)
- High chemical resistance to acetone and isopropyl alcohol.
- Low outgassing under high vacuum

Among other polyimides, Kapton is selected as the flexible substrate because of its availability. Kapton is commercially available both in roll and in sheet format with standard thickness of 0.0254 to 0.127 mm (Fig. 2a). Fixation of the Kapton film on a carrier is necessary for thin film deposition and photolithography. This requires an adhesive layer between the Kapton film and the carrier. Such a layer should be flexible, compatible with both the film and the carrier, chemically stable and dimensionally stable over a wide temperature range. Kapton films laminated with a pressure sensitive adhesive (PSA) layer are commonly available. The PSA layer is made of an acrylic (polyacrylate) or a silicone (polysiloxane). The latter is preferable and is selected because of its better chemical resistance and higher thermal stability. Silicone withstands acetone and isopropyl alcohol and is thermally stable up to 180°C.

2.2. Substrate preparation

A 25 μm thick Kapton film laminated with a 40 μm thick silicone adhesive layer was manually bonded to a cleaned carrier, a 4-inch silicon wafer. It must be ensured that no air bubble is trapped between the carrier and the Kapton film. Also, a smooth and defect free surface of the film is a key to successful production in the next step. From now on, a carrier with an attached Kapton film as a whole is called a compound substrate. The PSA silicone layer provides adhesion through hydrogen bonding and has immediate tack. However, the PSA silicone layer is semi-cured and the adhesion continues to build up over a longer time [10]. For this reason, the compound substrate was rested at ambient temperature for 24 hours; this process is called wetting. The dimensional stability of the Kapton film depends on a coefficient of thermal expansion of Kapton and residual stresses in the Kapton film. The latter causes the Kapton film to shrink on its first exposure to elevated temperature [8, 9]. To set the compound substrate to its stable form, a pre-bake process defined in Table 1 was done. The pre-bake process also removes solvent residuals in the PSA silicone layer and moisture in the film. Both the temperature gradient and the baking temperature are critical in the pre-bake process. Too high temperature gradient will cause locally trapped vapors and a buildup of bubbles. Too high baking temperature will cause degradation of the PSA silicone layer. After the pre-bake process, the compound substrate was ready for fabrication (Fig. 2b). The surface of the film was smooth and

there was no bubble trapped in the film. If the compound substrate was not immediately used for fabrication, it was stored in a desiccator.

Table 1. Pre-bake profile.

Process	Temperature rate (°C / min)	Temperature (°C)
Heat up	< 4	From room temperature
Baking	0	150
Cool down	< 3	< 50

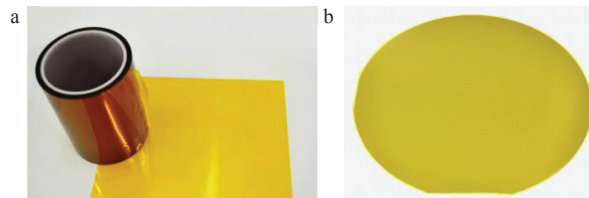


Fig. 2. (a) Kapton film is available in roll and sheet formats; (b) a compound substrate ready for fabrication.

2.3. Physical vapor deposition (PVD)

Gold (Au) and permalloy (NiFe 81/19) are main materials for production of the flexible magnetic writing / reading system. They were physically deposited using sputtering systems on the compound substrates. Process parameters for the deposition are defined in Table 2.

AZ® 9260, a positive photoresist, and AZ® 5214, an image reversal photoresist, from MicroChemicals were used for the photolithography processes. The photoresists were spin coated on compound substrates yielding film thickness of 13µm for AZ® 9260 and 3µm for AZ® 5214. Small grating structures and magnetic flux guides were used as test structures. Acetone was employed as a remover in a lift-off process. The pressure sensitive adhesive Scotch tape was applied in the film adhesion test (IPC-TM-650-2.4.1.0).

Outgassing of the compound substrate under high temperature and high vacuum (a common environment in PVD processes) is undesired. Outgassing interferes with vacuum and deposition processes; in an extreme case, system contamination occurs. To assert process compatibility, the pre-baked compound substrates were tested using a vacuum oven. The pressure of a test vacuum has been < 1e-6 mbar and a temperature test profile has been similar to one defined in Table 1.

Table 2. PVD process parameters.

Parameter	Value
Base pressure	< 1 e-6 mbar
Sputter pressure	7 – 8 e-3 mbar
Sputter gas	50 sccm of Ar
Sputtering power	200 W

2.4. Debonding

Unlike a conventional substrate where separation of an individual system after fabrication is done by sawing or dicing, a compound substrate requires an additional process, namely debonding, to release a flexible substrate from a carrier. Chemical etching or softening of a sacrificial layer and a complete etching of a carrier are main methods used in debonding. Since xylene softens a silicone adhesive layer, the chemical softening method is selected. The

compound substrate was immersed in a bath of Roticlear®, a harmless xylene like solvent from Carl Roth [11]. When the silicone adhesive layer softens, tweezers were used to peel off the flexible substrate from the carrier. Silicone residuals on the flexible substrate were gently wiped out. Finally, the flexible substrate was rinsed with acetone and isopropyl alcohol.

3. Results

3.1. Pre-bake process

According to section 2.2 and 2.3, outgassing during deposition processes should be prevented using the pre-bake process. A detailed investigation on the pre-bake process was carried out in order to reveal two critical issues, namely a period of time required for the pre-bake process and moisture absorbed by the film. Fig. 3 below depicts records of mass loss of Kapton films and describes process chronicle used in this investigation.

After Kapton films were bonded to carriers and rested for 24 hours (wetting), slight mass loss of Kapton films were observed (2nd process). Following pre-bake processes further reduced mass of the films and up to two hours of pre-bake process was required to almost completely remove moisture from the Kapton films (4th process). Storing the compound substrates after pre-bake processes in a desiccator helps preventing moisture reabsorption into the films (5th process). By comparing the 6th process with the 7th process, the slight mass loss was observed in a high vacuum and high temperature test. This indicated that the substrates outgassed slightly even after the pre-bake process. If the compound substrates were not stored in the desiccator, they reabsorbed moisture (8th process).

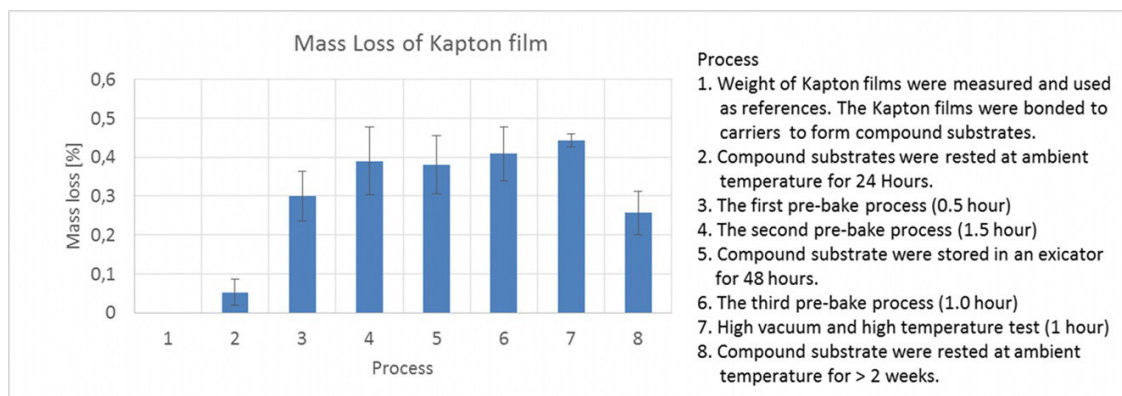


Fig. 3. Mass loss of Kapton films indicates that up to two hours of the pre-bake process were required to almost completely remove moisture from compound substrates.

3.2. Film quality

Deposition of gold and permalloy thin films on compound substrates yielded desired results. AZ® 9620 and AZ® 5214 photoresists were successfully lifted-off by immersing the compound substrates in an acetone bath and rinsed with isopropyl alcohol. Ultrasonic cleaning could be used to help removing photoresist residuals High resolution structures were intact and possessed sharp edges (Fig. 4a, 4b). Large structures had smooth surfaces with no crack. Both gold and permalloy structures passed the adhesion test according to IPC-TM-650-2.4.1.0.

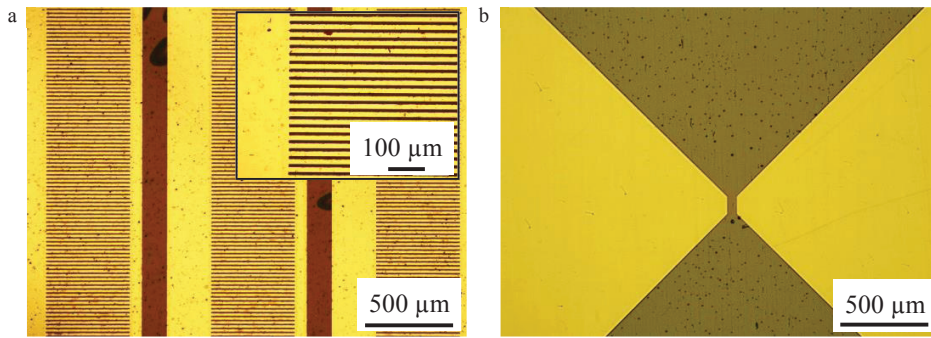


Fig. 4. (a) 100nm thick grating structure with sharp edges; (b) 500 nm thick permalloy (NiFe81/19) magnetic flux guide.

3.3. Debonded flexible substrate

Softening of pressure sensitive adhesive silicon layers started 24 hours after immersion of compound substrates in a Roticlear® bath. Softening time varied depending on a density of structures fabricated on a Kapton film. The softening time extended up to 72 hours before mechanical releasing of the Kapton film using tweezers could take place. Fig. 5 shows an example of a debonded flexible substrate on which Au grating structures were fabricated. A close-up reveals intact structures and thus a successful debonding was confirmed.

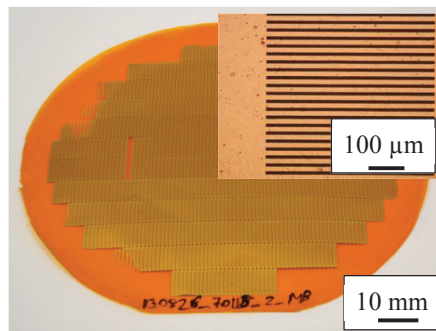


Fig. 5. 100 nm thick Au grating structures on flexible substrate after a debonding process; Grating structures are intact and have no crack indicating successful debonding.

4. Discussion

After the wetting process, mass loss of the Kapton films was detected (Fig. 3), indicating partial evaporation of solvent in the PSA silicone layers. The pre-bake process cures and removes solvent residuals in the PSA silicone layers [12, 13]. The pre-bake process also removes moisture in the Kapton film and at the same time sets the Kapton film to its stable form. The key parameters in the pre-bake process are the temperature gradient, the curing temperature and the baking time. Use of an inappropriate pre-bake profile causes degradation of a PSA silicone layer, trapped bubbles in a Kapton film and rendered a compound substrate unusable. Since the Kapton film absorbs moisture, an inappropriate treatment on a compound substrate, e.g. rinsing in deionized water or storing the substrate in an uncontrolled environment, leads to high outgassing during sputter deposition of thin films. Storing pre-baked compound substrates in a desiccator is recommended to minimize moisture reabsorption. Nonetheless, correctly processed and stored compound substrates outgassed slightly. However, a total mass loss of the Kapton film with the laminated PSA silicone layer is less than 0.1%. According to ASTM E 595, the compound substrates pass one of low outgassing requirements.

During a physical vapor deposition process, both temperature gradient and maximum temperature to which a compound substrate is exposed must be controlled, especially when a thick layer is sputtered. A long continuous sputter period with high sputter power causes following problems:

- Bubbles trapped between a carrier and a Kapton film
- Outgassing and vacuum chamber contamination in extreme case
- Cracks in deposited thin films

One source of those problems is softening and partly decomposing of a PSA silicone layer at high temperature. An underlining cause relating to thermal decomposition of the PSA silicone layer is out of a scope of this work. The other is a mismatch of thermal expansion between the Kapton film (20 ppm/°C [9]) and deposited thin films (14 ppm/°C for gold and approximately 10 ppm/°C for permalloy).

A chromium (Cr) layer is commonly employed as an adhesive layer in thin film deposition on a silicon wafer and this is also true for a Kapton film. It is well known that Cr promotes adhesion in metal/polyimide interfaces. However, due to subtle mechanical and chemical adhesive interactions between Cr and polyimides, Cr layer is brittle and fractures even at low strain [14, 15] and hence can complicate determinations of adhesion of gold and permalloy on the Kapton film. For these reasons, the Cr layer was excluded from the experiment.

A combination of chemical softening and mechanical releasing proposed for debonding a flexible substrate from a carrier offers many benefits over a complete etching of a carrier. For example, it is more cost effective because the carriers can be reused. Hence, production cost is reduced particularly if carrier preparation is expensive. Also, a long softening time can be reduced by utilizing a more aggressive solvent.

5. Conclusion

An investigation on a flexible substrate was done. A polyimide film, particularly a Kapton film, was employed as a flexible substrate for a production of a flexible magnetic writing / reading system. A Kapton film laminated with a pressure sensitive adhesive (PSA) silicone layer was bonded on a carrier, a silicon wafer; this as a whole formed a compound substrate. The compound substrates underwent treatments and tests to ensure compatibility to conventional thin film and photolithography processes. Grating structures and large magnetic flux guides, as test structures, were successfully fabricated on the compound substrates by means of physical vapor deposition (PVD). The fabricated test structures possessed good film quality. Debonding was done to the compound substrates by means of chemical softening and mechanical releasing. Test structures on released Kapton films were intact and thus the successful debonding was confirmed.

The investigation accomplished in this work delivers fruitful results. These results make a new ground in using the cost effective and commercially available Kapton film as the flexible substrate. Using standard thin film technology in combination with fabrication techniques developed for this flexible substrate, parts of the flexible magnetic writing / reading system were successfully fabricated. This example definitely shows potential usage of the Kapton film as an easily obtainable flexible substrate for the creation of MEMS.

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