Resistivity percolation of co-sputtered amorphous Si/Ti films

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1. Introduction

The monolithic integration of micro-electro-mechanical systems (MEMS) sensors and actuators directly on top of their driving and signal processing electronic circuitries has attracted considerable interest as it enables tighter integration of MEMS and associated circuitry (IC), leading to cost-effective systems with high performance. However, the technical realisation of this integration has been hindered mainly by high temperature (>600 °C) deposition required by polycrystalline silicon (poly-Si) [1], which is commonly used as structural material for MEMS. Recently, a-Si has been developed [2–4] as a promising alternative because it can be deposited at low temperatures (<250 °C). Most of the mechanical properties of a-Si are similar to those of poly-Si [4]. a-Si can also be easily integrated with low-cost Si-based IC and MEMS fabrication processes. Nevertheless, a-Si is usually dielectric and difficult to dope effectively. Thus it is unsuitable for many MEMS applications such as electrostatic and electrothermal devices. Metal layers had to be employed as conductive claddings for a-Si MEMS [5], which complicates the microfabrication process and introduces parasitic stress potentially causing deterioration of device performance.

In this work, co-sputtered a-Si/Ti nanocomposites have been deposited at low temperatures as a novel structural material, which is potentially suitable for above-IC MEMS. As a focus of this study, the electrical property of the a-Si matrix was tailored through the incorporation of Ti nanoparticulates. Ti was chosen because it can potentially suitable for above-IC MEMS. As a focus of this study, the electrical property of the a-Si matrix was tailored through the incorporation of Ti nanoparticulates. Ti was chosen because it can be effectively dry etched using the fluorinated and chlorinated chemistries [6], commonly used for Si surface micromachining. The electrical percolation conduction mechanism of the composite films was systematically investigated. It was found that the resistivity of a-Si/Ti exhibits a power law dependence on the Ti content with an exponent β equals to 2. Characterisation of surface morphology and dry etching of a-Si/Ti films was also carried out and discussed for their potential MEMS applications.

2. Experimental

Si chips (10 mm × 10 mm) covered with thermal oxide (SiO2) of 1 μm thickness were used as deposition substrates. A multi-substrate holder was employed to cover all edges of the substrates during deposition, preventing contacts between deposited layers and the Si substrates on the sides. Co-sputtering of high purity Si (99.999%) and Ti (99.95%) targets was carried out using DC and RF power supplies, respectively, in a Kurt J. Lester sputterer. By adjusting the power of the Ti target while keeping the power of the Si target constant, the percentage of Ti in the deposited films was controlled. Argon was used as sputtering gas and the chamber pressure was kept at 8 × 10⁻³ mbar.

Substrates were maintained at room temperature for all depositions. For each deposition, a-Si/Ti film on an Al substrate was also produced, which was subsequently used for material characterisation using the Energy Dispersive X-ray (EDX) analysis method. The motivation to use Al substrates was to eliminate possible Si spectra from the SiO2/Si substrates and thus ensure all Si EDX spectra can be attributed to the deposited layers. The relative Ti and Si weight percentages of the composite films were determined by subtracting the background Al and oxygen spectra. A selection of co-sputtered samples was subsequently annealed at temperatures (T a) from 200 to 500 °C for 2 h in ambient atmosphere to investigate the stability of the electrical properties of the composite films.

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properties and nanostructures of a-Si/Ti. The sheet resistance of the films was measured using a four-point probe method. The thickness of the deposited films ranges from 190 nm to 390 nm which was measured using a KLA Tencor stylus profiler. The electrical resistivity of the films was calculated using the measured values of sheet resistance and thickness. Nanostructure and surface morphology of the films were examined using an Atomic Force Microscope (AFM) (Asylum Research MFP-3D). Preliminary dry etching trials of the deposited composite films were conducted in a reactive ion etch (RIE) reactor using SF6 (20 sccm) and O2 (10 sccm) gas mixture.

3. Results and discussion

Typical RMS roughness is around 0.6–1.5 nm for deposited films with thickness of approximately 290 nm–390 nm and a typical AFM section profile is shown in Fig. 1. It is anticipated that the surface roughness could be further improved by lowering the sputtering pressure to meet the requirement of roughness <0.5 nm [7] for wafer bonding processes as an important microfabrication procedure for MEMS. As such a-Si(Ti) could also be employed for micro-opto-electro-mechanical systems (MOEMS) applications. The granular structures of the as-deposited and annealed samples are clearly shown in Fig. 2. The average grain size increases with annealing temperatures from approximately 20 nm at room temperature to approximately 40 nm at 500 °C. Nevertheless, compared with that of the as-deposited films, the annealing process did not cause an obvious increase of surface roughness.

As a primary aim of this work, the electrical resistivity of the a-Si/Ti films was systematically studied. Fig. 3 shows that the resistivity of the a-Si/Ti films can be tailored over a wide range as a function of the Ti percentage at different annealing temperatures. It was observed that the dependence of the resistivity on the Ti content in the composite films is in excellent agreement with the percolation theory [8] as the resistivity scales as

\[ \rho = a(T) X(T)^{\beta} \]

where \( a(T) \) is temperature dependent prefactor, \( X \) is the Ti percentage and \( \beta \) is the critical exponent. \( X(T) \) is the percolation threshold, i.e. the Ti percentage, at which a continuous transport network is formed by the metallic grains and thus metallic transition occurs [9]. \( X(T) \) depends on the system dimension and symmetry, while the critical exponent \( \beta \) depends on system dimension only. \( X(T) \) and \( a(T) \) were derived by fitting Eq.(1) to the experimental data using nonlinear regression as shown in Fig. 4. Since a critical exponent \( \beta =2 \) is typical in many granular films (such as co-sputtered Au-SiO2 [10]), in this study, \( \beta \) was initially set to 2 to obtain the best fit (Fig. 3), which was determined by the R-square test for the parameters \( a(T) \) and \( X(T) \). The R-square value for this fit was 99% for all values except for \( T_a=500 \) °C where the R-square value was 96%. To confirm this scaling behaviour, \( X(T) \) versus \( \rho(T)/a \) was plotted in Fig. 5, which shows a good data collapses into single curve of \( y=\alpha x^{-1/2} \). This data collapse justifies the value of \( \beta =2 \) and suggests that all the investigated a-Si/Ti films are three dimensional (3D), where the grain sizes are much smaller than the thickness of the films [11].

The a-Si/Ti films can be viewed as a random resistor network where grains are either conductive for Ti or non-conductive for Si. Indeed, the universality of \( \beta \) was confirmed by several numerical computations of random resistor network models where \( \beta =2 \) for 3D lattices [12,13]. A similar study of co-sputtered silicon–titanium deposited on poly-Si and SiO2 substrates was reported by Murarka and Fraser [14]. They found evidence of a titanium silicide (TiSi2) component after annealing of the films in temperature ranging from 600 °C to 1000 °C. No alloyed TiSi2 were found below 500 °C. More importantly, the presence of TiSi2 induced a decrease of the film resistivity, which is in contrast to our observations where the resistivity increased with annealing temperatures (Fig. 3) up to 500 °C. These observations alongside the percolation behaviour is a strong evidence that there are no silicide present in our composite films and that these films can be viewed as a 3D random network of Ti and Si grains. The constant value of \( \beta \) indicates that the grain size...
etching of a-Si/Ti was observed and the etch rate changes with the Ti percentage (e.g. range suf...electrical stability of the nanostructured a-Si/Ti composite...subject to dry etching was preliminary studied in this work by carrying out RIE on...dimensionality of the problem remains unchanged for annealing processes with...A \leq 300 ^\circ C. These two parameters are determined by the composite nanostructures and...is the minimum fraction of Ti, for which at least one group of grains expands from one side...to the coarsening of grains at $T_a > 300 ^\circ C$, which induces the formation of...paths. Furthermore, constant $X_c$ for $T_{a} \leq 300 ^\circ C$ (typically ~3% in Fig. 4) indicates the electrical stability of the nanostructured a-Si/Ti composite films for this temperature range sufficient for above-IC MEMS applications. Dry etching is a key patterning technique for the MEMS fabrication. The feasibility of...and process advantages suggests that a-Si/Ti has the potential to be a...potential low temperature MEMS processes. Furthermore, the a-Si/Ti films possess smooth surfaces and can be patterned using commonly available dry etching techniques. The combination of these material and process advantages suggests that a-Si/Ti has the potential to be a compelling structural material for future above-IC MEMS.

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References