A STUDY OF SURFACE DIFFUSION OF METALS IN TUNGSTEN FOR NEMS APPLICATIONS

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ABSTRACT
Diffusion of 14 different ~20 nm thick metals into 100 nm thick tungsten films at 700 °C for up to 90 minutes was studied using atomic force microscopy and scanning electron microscopy. W-W yielded a restructured surface even at this relatively low (700°C) temperature (melting temperature of W is 3422 °C). Al, Cr and Pt films completely diffused and even reduced (20-50 nm) the original W surface height in certain cases. The Al-W alloy had low contact resistance but slightly higher surface roughness (5 nm rms compared to 2 nm rms). Cu and Mo completely diffused into W but they did not reduce W’s original thickness. Fe, Ta, Au, Ni, Ag, Co, Ti and NiCrFe increased the apparent Metal-W thickness. We conclude that Al, Cr, and Pt can be used as etch-less sacrificial layers with desirable electrical contact properties.

KEYWORDS
Surface solid diffusion, NEMS, hot contact alloys, etch-less sacrificial layer

INTRODUCTION
Nano-electro-mechanical systems (NEMS) have wide range of applications in mechanical processors for harsh environment [1-11], sensors, and related devices. Most NEMS devices require 10-100 nm structural regions separated by 1-10 nm air-gaps which are quite challenging to achieve uniformly across large areas. Sacrificial layers are routinely used to form these air-gaps but require etching steps that lead to stiction. Or given the very small gap openings, the etchants require very long time (2-6 hours) to etch away the sacrificial layers. This is quite undesirable in the presence of existing layers on the substrate when realizing complex logic circuits.

Additionally, NEMS switches require reliable “hot” contact materials that can withstand in excess of 10¹² switching cycles without changing contact resistance, stiction and micro-welding. Here we study the possibility of using a metal layer as an etch-less sacrificial layer that when it diffuses into the structural material of the MEMS/NEMS switch, it leaves behind the desired gap and its diffusion and alloying results in the suitable “hot” contact material.

Etch-less sacrificial layers do not require wet or dry etching and can be activated after packaging the chip provided that the activation temperature and duration do not cause problem for the packaging material or structures. Thus, it can be seen that etch-less sacrificial layer will be very suitable for preventing contamination of the air-gap with etchant residues, particulates, and can potentially eliminate stiction during release.

We chose tungsten as our structural material due to its high melting temperature (T_{\text{melt}}~ 3422 °C) and large Young’s modulus (411 GPa) [10, 11]. Its low resistivity (5.3 \mu\Omega\cdot cm) results in low contact resistance and its high melting point suppresses micro-welding in “hot” contact switches. Although W grows an oxide layer in the ambient environment, its oxide is conducting and does not increase its surface contact resistance appreciably.

In this paper we report solid diffusions of 12 different metals, one alloy (NiCrFe) and tungsten itself into tungsten at 700 °C for 60 and 90 minutes. Ultra-sharp AFM probes were used to study the film thickness, and surface roughness. Surface resistance was measured using W-probes and SEM was used to study the surfaces and cross-section of some of the samples.

FABRICATION AND EXPERIMENTAL PROCEDURE
The fabrication steps are as shown in Fig. 1. N-type Si wafers were cleaned in DI wafer and dried in nitrogen. Then, 100 nm of stoichiometric LPCVD silicon nitride was grown at 780 °C. Subsequently, 100 nm of tungsten was sputtered at 50W DC power and ~2.5 mTorr argon pressure.

![Fig. 1: Schematic of the fabrication steps used in forming etch-less sacrificial layer. The bottom schematic shows possible alloying between metal dots and W that results in thinner films in the alloyed regions.](image-url)
The W film had grain size less than 0.1 µm. Then, 20 nm thick films of 13 different metals including NiCrFe alloy and W film were deposited on 100 nm thick tungsten and patterned using lift-off technique. The deposited metals formed “dots” with diameters ranging from 0.5 mm to 5 mm on the structural tungsten layer.

High resolution Cypher AFM imaging technique was used to analyze the metal films. The initial thickness, surface resistance and roughness of the metal films were measured. Then, the wafers were cut into 4 pieces. One piece was kept as a control sample and one piece was annealed for 60 minutes and another piece was annealed for 90 minutes. The samples were placed in a CVD chamber that was pumped down for 1 hr to attain a pressure of 5 mTorr. The samples were then annealed at 700 ºC in hydrogen atmosphere (for different durations) with a temperature ramp up time of 15 minutes. The samples were then cooled in hydrogen atmosphere for 1 hr. The contact resistance of the alloyed film was analyzed using the Agilent 4156C parameter analyzer. If any of the samples yielded unexpected results, the fourth piece was used to check the reproducibility of the data.

RESULTS AND DISCUSSIONS

A comparison of the change in film thickness before and after 60 and 90 minutes of annealing at 700 ºC is shown in Fig. 2. Metals like Al, Pt and Cr resulted in reduction of the film thickness due to alloying with W. In some of these cases, the alloyed films had thickness less than the thickness of the 100 nm structural W film. Metals like Cu and Mo completely diffused into W but the thickness of the resulting alloy did not become less than the thickness of the initial structural W film. Metals like Ti, W, Co, Ag, Ni, Au, Ta, Fe and NiCrFe alloy increased the film thickness. SEM images of the Al-W film after 0, 60 and 90 minutes of annealing are shown in Fig. 3. The AFM images on the edge of Al/W dot is shown in Fig. 4. The trace line on the edge of the dot clearly shows the reduction of the film thickness due to alloying of Al with W.

![Fig. 2](image1.png)

**Fig. 2:** Plot of change in height of metal films for different annealing time at 700 ºC.

![Fig. 3](image2.png)

**Fig. 3 (a), (b), (c):** SEM images of Al on W after 0, 60 and 90 minutes of annealing respectively.
The change in roughness of the metal-W films due to annealing is shown in Fig. 5. Metals like Mo and Ti yielded negligible change in surface roughness of the film. Metals like Al, Cr, Cu, W, Pt and Ta showed small change of few nm in the surface roughness. However metals like Co, Ag, Ni and Fe showed relatively a large change in film roughness making them undesirable for NEMS application.

The change in two point resistance due to annealing is shown in Fig. 6. The two point resistance measurement was made by placing the probes of Agilent 4156C parameter analyzer on the edge of the metal dots opposite to each other. Most of the metals showed negligible change in resistance and remained conductive. This shows that the change in the film thickness was due to alloying and not due to oxidation. Fe and Ta showed a large change in film resistance making it not suitable for NEMS application. The alloying of Au with W, resulted in a film with intricate fractal structures that peeled off from W easily during the two point resistance measurements.

CONCLUSION
A novel method of generating gaps using etch-less sacrificial layers consisting of metal layers on tungsten is presented. When annealed at 700°C, these layers diffuse into W and leave behind a gap by reducing the initial metal-W thickness. In some cases we showed that it is
even possible to reduce the starting W film thickness due to the higher density of the resulting metal-W alloy. Based on the surface analysis of alloyed metal-tungsten films, we conclude that metals like Al, Pt and Cr result in film thickness reduction, acceptable final surface roughness and resistance. Also it can be concluded that the Fe and Ta alloying in W increases the surface resistance and alloying of Ag, Ni and Fe in W increases the surface roughness making these metals unsuitable for NEMS applications. We are developing a predicative model to design appropriate etch-less sacrificial films for a given air-gap and temperature constraints.

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REFERENCES