W-coating for MEMS

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ABSTRACT

The integration of miniaturized mechanical components has spawned a new technology known as microelectromechanical systems (MEMS). Surface micromachining, defined as the fabrication of micromechanical structures from deposited thin films, is one of the core technological processes underlying MEMS. Surface micromachined structures have a large ratio of surface area to volume which makes them particularly vulnerable to adhesion to the substrate or adjacent structures during release or in use- a problem is called stiction. Since microactuators can have surfaces in normal or sliding contact, friction and wear are critical issues for reliable operation of MEMS devices. Surface modifications are needed to reduce adhesion and friction in micromechanical structures. In this paper, we will present a process used to selectively coat MEMS devices with Tungsten using a CVD (Chemical Vapor Deposition) process. We will discuss the effect of wet and vapor phase cleans along with different process variables. Endurance of the W coating is important, especially in applications where wear due to repetitive contacts with the film may occur. Further, tungsten is hard and chemically inert. Tungsten CVD is used in the integrated-circuit industry, which makes this approach manufacturable.

Key Words: Hard Coating, Tungsten, MEMS

1. INTRODUCTION

Current MEMS devices are fabricated from polycrystalline silicon (Fig.1) which is used by the silicon microelectronics industry as a gate electrode and local interconnect.[1] The MEMS community has been able to adopt slightly modified IC Si deposition processes and make Si the cornerstone of nearly all surface micromachined devices. Parts fabricated from polysilicon, a material developed for its electronic and not mechanical properties have been demonstrated to be surprisingly robust.[2] However, wear has been identified as a significant failure mechanism, especially on load bearing surfaces. Furthermore, there continue to be problems associated with stiction[3] (the unintentional adhesion of surfaces), particularly following the removal of the sacrificial silicon dioxide layers at the end of processing. During the drying process, capillary forces pull together adjoining plates of polysilicon, making stiction a particular problem during this step in the process.[4,5,6] To overcome this difficulty a number of non-standard processes have been developed, including freeze sublimation and super-critical CO_2 drying.[7] All of these approaches increase processing complexity and are not supported by standard IC equipment sets. This is important since a key to the rapid growth of the MEMS technology has been the leveraging standard silicon processing technology.

Traditional approaches to the problem of wear are the introduction of a low friction polymeric coating, for example by PECVD (Teflon) or through wet chemical routes after the release process. In these approaches the deposited layer itself is not hard and wear is diminished by the reduction in the coefficient of friction. The long-term behavior of these very thin layers of polymeric materials is unclear, especially in vacuum environments. A fundamentally different approach to the wear problem is to substitute the polysilicon with intrinsically hard materials such as diamond or silicon carbide. However, this runs counter to the great enabling strength of surface micromachining, leveraging of IC processing technology and tool sets. An even bigger drawback to this approach involves process integration. Most devices with contacting layers consist of a minimum of three mechanical levels fabricated using a complicated combination of deposition, photolithographic, etch, and planarization processes. The introduction of completely new materials and processing technologies into these complex process flows would be very difficult. Therefore, development of better surface passivation and tribological coatings using standard IC processing tool set is of great importance for the successful widespread introduction of microelectromechanical systems (MEMS) sensors and actuators.

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In this paper we investigate the deposition of a thin, self-limiting, low temperature, selective deposition of tungsten onto the structural polysilicon at the end of the fabrication process. Tungsten has a number of attractive properties as a wear resistant coating. The W will act to create a wear resistant coating and to simultaneously release members, which may have become adhered to each other during the drying process. The selective deposition of tungsten through the silicon reduction of WF_6 was studied in detail in the late 1980's but never gained acceptance by the IC industry.[8,9] Endurance of the W coating is important, especially in applications where wear due to repetitive contacts with the film may occur. Unlike polymeric coatings, which only serve to reduce the coefficient of friction, W is hard. Also unlike the polymers, W is entirely compatible with the temperatures typically associated with packaging and is ultra high vacuum compatible. Tungsten CVD is used in the integrated-circuit industry, which makes this approach manufacturable.

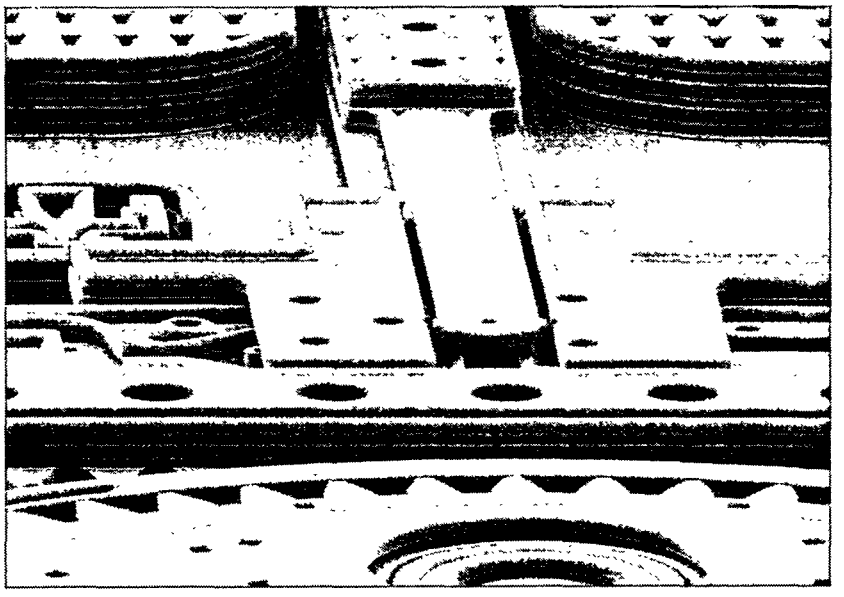

Figure 1. An example of a complex, five level MEMS structure fabricated using surface micromaching at Sandia National Laboratories. Stiction and wear are problems in processing such highly complex systems.

2. EXPERIMENTS

The displacement reaction used for W coating is as follows:

$$2WF_6 + 3Si \longrightarrow 2W + 3SiF_4 \uparrow \qquad (1)$$

When WF_6 encounters heated silicon, a reaction occurs in which SiF_4 gas is formed and W is deposited on the silicon surface. Once a continuous film of W is formed (after ~200Å) the WF_6 is shielded from the Si and the reaction slows or stops, because the WF_6 can no longer diffuse through the W (product) film to react with the underlying Si. This low temperature (~450°C) process is completely selective since the reaction occurs with Si alone, hence the W deposition can not occur on silicon dioxide or silicon nitride.

2.1 Surface preparation

The wet cleans prior to the deposition are extremely critical. The Pirhana clean (5:1 H_2SO_4:H_2O_2, 95°C, 5 minutes) removes any organic contaminants which if present prevent uniform W deposition. The selective reaction given in eq (1) reacts with silicon alone, hence any native oxide should be removed in regions where deposition is desired. This is accomplished by a clean in 100:1 HF just before loading the wafers. After these two cleans the wafers are loaded into the system, in this case Genus 8720, where the wafers are cleaned *insitu* at 450°C. The *insitu* clean is performed using NF_3. We believe that this process removes surface contamination. Eliminating the NF_3 surface preparation step leads to non-uniform

deposition and adhesion problems. The *insitu* NF_3 clean does not effect thick thermal oxides. Long (10 minutes) *insitu* cleans were performed on blanket oxide (~1000 Å) and the thickness change after the clean was within 1 Å.

2.2 Self Limiting Nature of Reaction

The self-limiting nature of the reaction was confirmed by measuring the thickness of W films deposited for different lengths of times. Tungsten was deposited at 450°C on 6" Si wafers with 2000 Å undoped polysilicon in Genus 8720. The wafers were wet cleaned, as described in the previous section, prior to the deposition. Following the wet cleans, an NF_3 *insitu* clean was performed prior to the tungsten deposition. The time was varied for the WF_6 exposure to check the self-limiting nature of reaction (1) from 2 minutes to 16 minutes. The thickness was measured using Rutherford Back Scattering (RBS) for the wafers with reaction time of 2, 4, 8, and 16 minutes. The RBS results are shown in Figure 2. Based on these RBS measurements the integrated value (W atoms/cm^2) under the curve for the different wafers is given in Table 1. The error in the data is ± 1.0E15. Assuming a nominal density of 19.3 gm/cc for tungsten and a beam size of 2.5 mm x 2.5 mm,

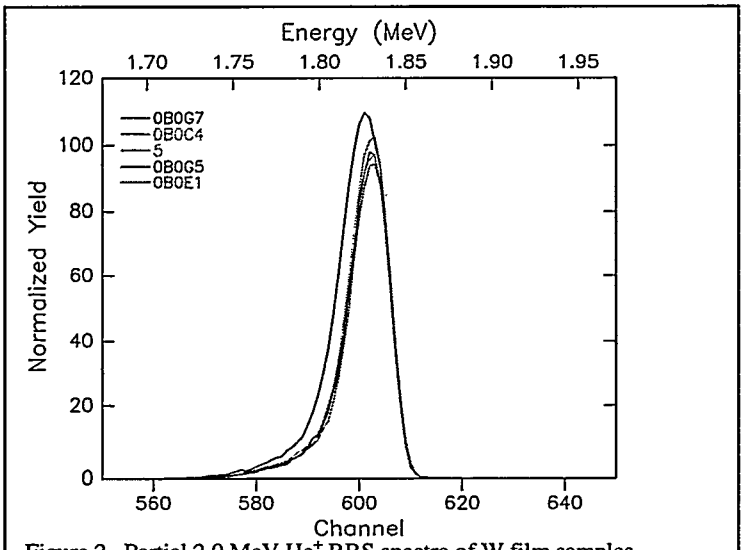

Figure 2. Partial 2.0 MeV He^+ RBS spectra of W film samples showing surface W peaks for wafers with varying deposition times.

the thickness of the film for the different deposition times varies from 68 Å to 93 Å as shown in Table 1. The fact that the film thickness is less than 100 Å over 16 minutes of deposition time indicates a self limiting reaction taking place. The gradual increase in thickness is possibly the result of the presence of small regions of surface contamination hindering the formation of a continuous film.

Table 1. Variation of tungsten film thickness over different deposition times.

W Deposition time (minutes)	W (atoms/cm^2)	W film thickness (Å)
16	5.88E15	93
.8	4.83E16	76
4	4.48E16	71
4	4.55E16	72
2	4.3E16	68

2.3 Tungsten Deposition Process:

The selective W deposited on polysilicon surfaces is extremely conformal as shown in a SEM micrograph in Figure 3. Polysilicon has been etched using HNO_3:HF to delineate the extremely thin W coating around the polysilicon structure,

which is a cantilever in this case. The W on the top surface is continuous even after the etch, demonstrating the absence of pin holes which would have been enhanced during the aggressive etch.

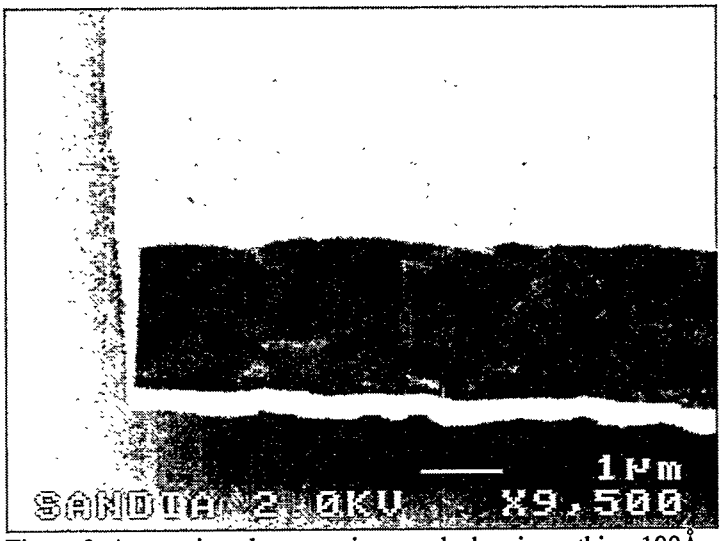

Figure 3. A scanning electron micrograph showing a thin ~100Å layer of silicon reduced W wrapped around all sides of a section of structural polysilicon. The silicon has been recessed using a HF/HNO_3 mixture in order to delineate the W.

During the displacement reduction reaction of Si by WF_6 shown in (1), the amount of Si thickness consumed is about twice the thickness of tungsten formed. This allows W coatings to deposit in very narrow gaps typically seen in MEMS devices. For every mole of tungsten formed 3/2 moles of polysilicon is consumed and

$$\#\ of\ moles = \frac{(area\ of\ film)(thickness\ of\ film)(density)}{mol\ wt.}. \qquad (2)$$

Using the material parameters for Si and W and assuming the area of Si film to be the same as the W film; the ratio of the film thickness results in $t_{Si} = 1.9 t_W$. This inherent difference in the deposited film thickness and the reacted film thickness results in W depositing in very narrow spaces making this process desirable for MEMS devices. Figure 4 shows undercutting in initially adhered Si members. The SEM image shows the backside of a cantilever beam where W has deposited. The structure was pulled using C-tape to SEM the backside. It appears that W penetrates between layers of Si which are initially adhered, thereby possibly overcoming the stiction problem.

3. DISCUSSION

Single level polysilicon cantilevers of varying width and lengths were fabricated to study the effect of W deposition. An extreme case of W deposition for 50 minutes leads to excessive penetration resulting in separated structures as shown in Figure 5. Tungsten penetrates along the single crystalline silicon – oxide interface consuming silicon and depositing W resulting in delaminated structures. The oxide is attached to the cantilevers making the beams curve up.

Figure 6 shows the underlying surface where separation between the single crystalline silicon and the cantilevers including the oxide on the backside has occurred.

Based on the above results the tungsten deposition time was limited to 5 minutes for active MEMS devices. Completely released (using standard procedures) MEMS devices, including some resonators, were deposited with tungsten after wet cleaning and the *insitu* clean. These resonators were electrically tested and compared with resonators fabricated without any tungsten deposition. Deposition process appears to depend on the release methods and surface contamination. It is extremely critical to have a surface free of any contamination for tungsten deposition. In some cases the springs are very

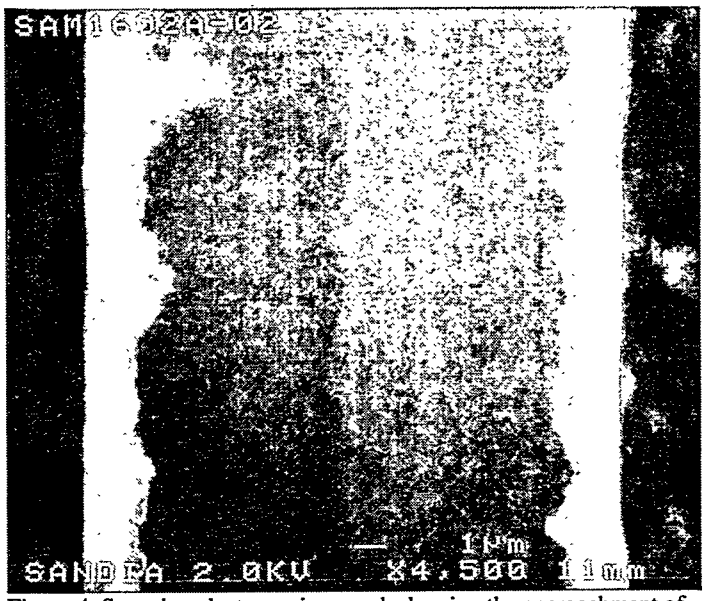

Figure 4. Scanning electron micrograph showing the encroachment of W under a beam of polysilicon that was initially stuck down to the silicon substrate. The W is clearly shown to deposit at the interface and could possibly be used to release adhered structures.

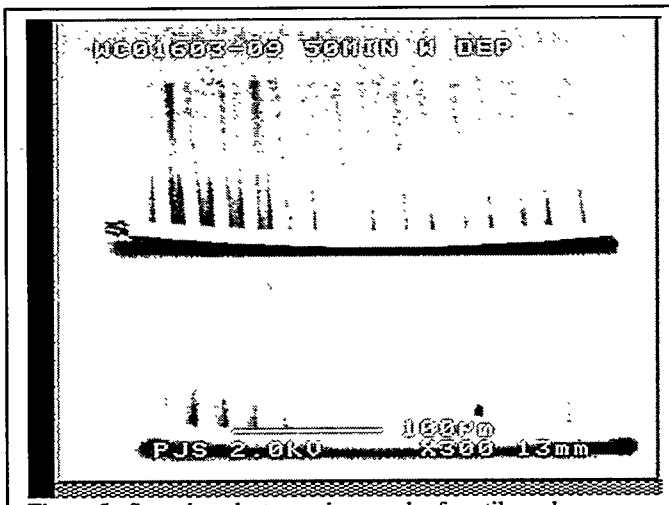

Figure 5. Scanning electron micrograph of cantilever beams after tungsten deposition for 50 minutes. W penetration is severe resulting in separation from anchors. The oxide is attached to the back of the beams.

long and it is not clear if the release methods work well for standard parts. The long resonator springs touch the substrates as shown in figure 7 (a) and (b). The testing indicated that the springs were touching the substrate and were not moving freely. In such cases the tungsten deposition process did not show much change in the spring strcuture.

On the other hand some of the resonators were released and free to move such as the one shown in Figure 8 (a) and (b). Electrical testing indicated improvement in the devices for the ones where the springs were not touching the surface but had a uniform coating of tungsten all around. Use of dimples as an aid in release will improve the removal of sacrificial oxide and improve in tungsten deposition, thus improving the stiction problem.

Tungsten deposition time places a major role in adhesion of the MEMS devices. Whether the structures of the base is polysilicon or nitride makes a difference, as W penetrates between silicon surfaces. This will have to be taken into

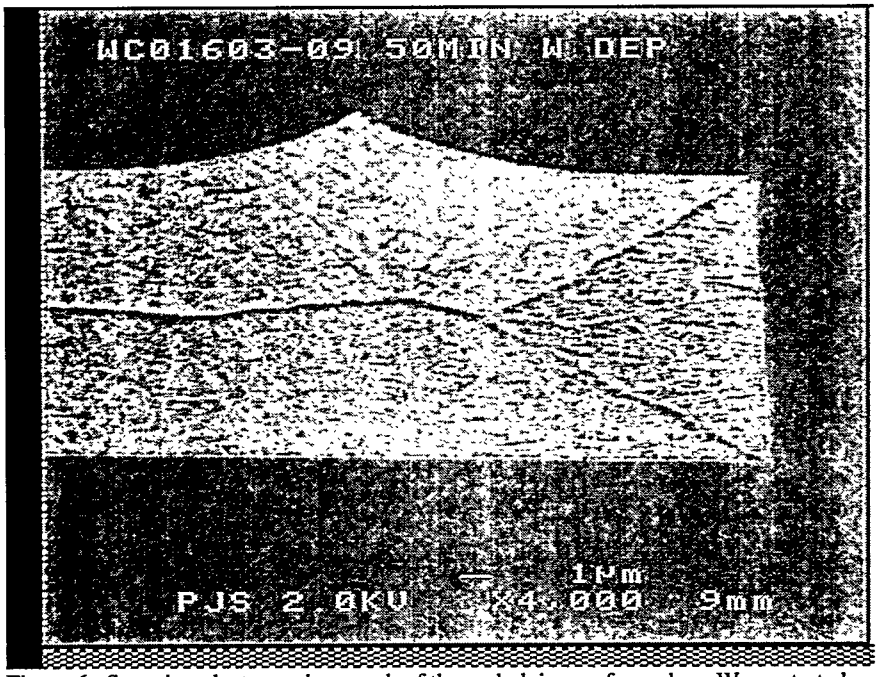

Figure 6. Scanning electron micrograph of the underlying surface where W penetrated causing separation of the cantilevers from the base.

consideration in device design. The cleanliness of the surface during the release and the wet cleans prior to tungsten deposition, both wet and insitu, play an extremely important role in forming uniform and conformal coating. Extremely long deposition times for tungsten effects the devices adversely, hence the optimum deposition time is 2 minutes to 4 minutes. The amount of tungsten used can be reduced by decreasing the tungsten flow without effecting the coating by maintaining constant WF_6 partial pressure.

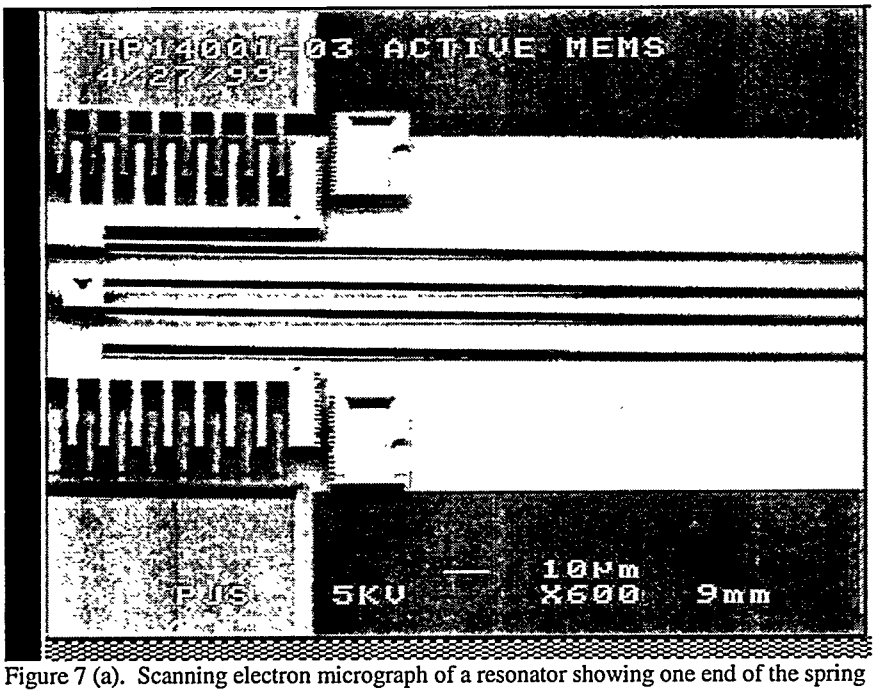

Figure 7 (a). Scanning electron micrograph of a resonator showing one end of the spring adhereing to the substrate.

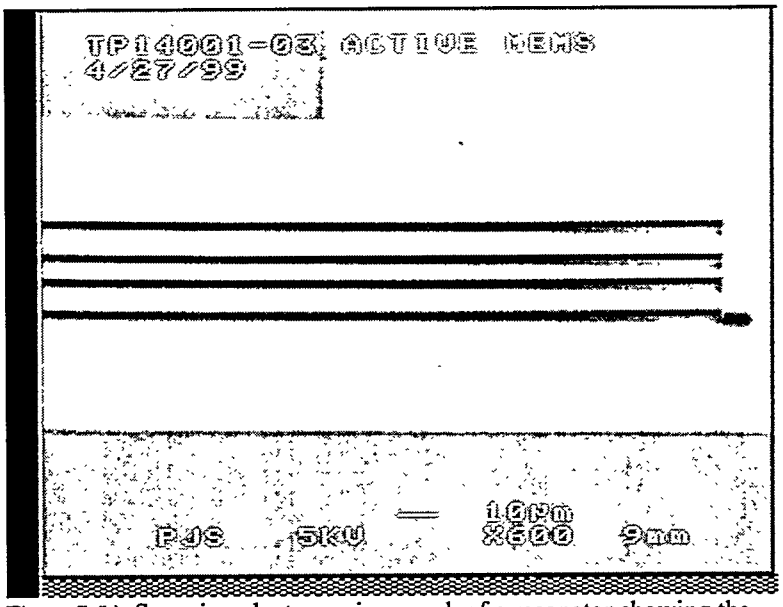

Figure 7 (b). Scanning electron micrograph of a resonator showing the other end of the spring adhereing to the substrate.

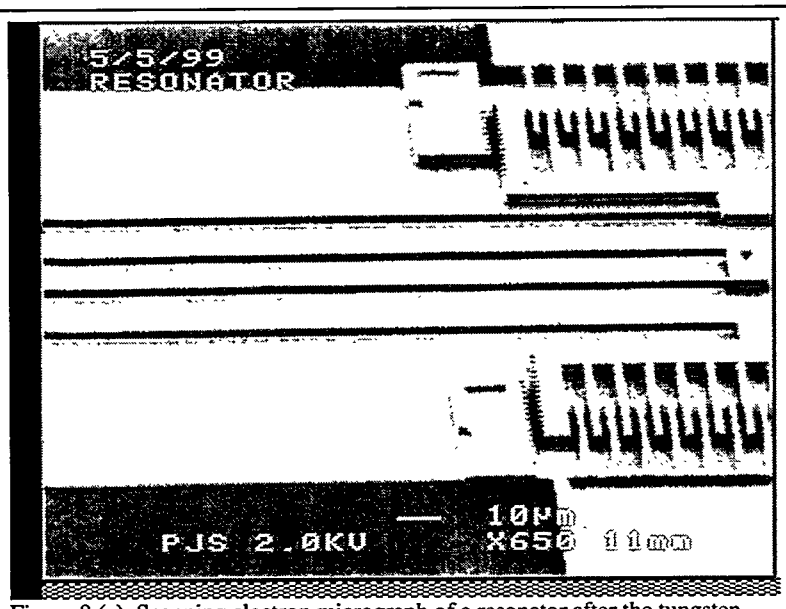

Figure 8 (a). Scanning electron micrograph of a resonator after the tungsten deposition showing one end of the spring completely released and free standing.

4. CONCLUSIONS

This work demonstrates that a thin tungsten layer can be deposited extremely conformal around polysilicon. The tungsten surface is free of any pin hole defects. The process uses standard IC processing tools making this approach manufacturable. Preliminary electrical test results on resonators deposited with tungsten showed some improvement over the as-released structures.

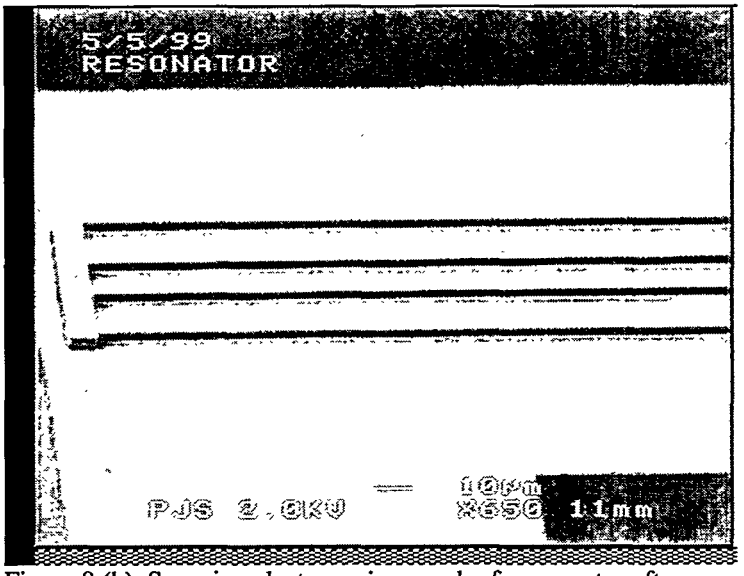

Figure 8 (b). Scanning electron micrograph of a resonator after tungsten deposition showing the other end of the spring completely released and free standing.

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