Mechanical Properties of Atomic Layer Deposited Tungsten

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Abstract:

Using passive test structures, the residual stress and through-thickness stress gradients for atomic layer deposition (ALD) tungsten on nickel were found to have a mean of 1555 pascals (Pa) and a standard deviation of 144 Pa and a mean of -77 Pa and a standard deviation of 572 Pa, respectively.

Introduction:

Because tungsten is a refractory metal, its use as a structural material in micro or nano-electromechanical devices allows the devices to operate at high temperatures. Atomic layer deposition tungsten (WALD) has the additional advantage of low deposition temperatures (120°C) in addition to the perfectly conformal coating of all surfaces—even those that have been undercut. In designing WALD devices, it is important to know the residual stress, which results from the mismatch between the thermal expansion coefficients of the deposited tungsten and the underlying material. Residual stress can cause cantilever structures to curl toward or away from the substrate, changing working distance and function of a device. In addition, residual stress can affect the resonant frequency, which is critical for sensor applications. Characterization of the residual stress should lead to better models and simulations of devices, allowing for the proper design of a functioning WALD device. Using passive test structures, the residual stress and through thickness stress of WALD deposited on nickel was measured.

Procedure:

First, a 10 nm thick layer of chromium, followed by 300 nm of nickel were deposited on a silicon substrate via thermal evaporation. Next, 32 nm of WALD was grown on the substrate at 120°C. Bridges and cantilevers were then patterned by optical lithography using spin-coated NR-9 negative resist. A hard-mask was developed by evaporation of a 35 nm thick layer of Ni followed by lift-off. The WALD structures were completed after reactive ion etching (RIE) for 45 seconds. The hard-mask and sacrificial layer were then removed via wet etching, releasing the WALD structures, and a critical point dryer used to avoid stiction caused by surface tension. Finally, a topographical map of the structures was obtained using a light interferometer, which could then be analyzed to find the displacements of the bridges and cantilevers.

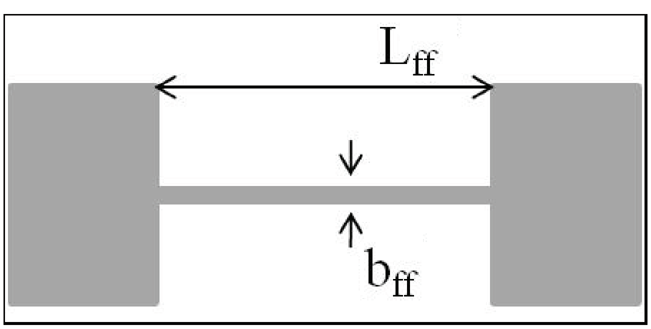

Figure 1: Schematic of bridge structure.

Results and Analysis:

The bridge structures allowed the compressive residual stress to be extracted, whereas the cantilevers allowed the through thickness stress to be measured. Residual stress can be calculated using Equation 1, where σ is the stress, L_{ff} is a geometrical constant from Figure 1, E is Young's modulus, v is Poisson's ratio, H is the maximum displacement of the beam, and h is the thickness [1].

$$\sigma = \frac{E\pi^2}{12(1-v)L_{ff}^2}(3H^2 + 4h^2)$$

Equation 1

The through thickness stress gradient is found using Equation 2, where Δσ is the through thickness stress gradient, E is Young's modulus, L_{cb} and h are geometrical constants from Figure 2, z is the deflection at the tip, K_0 is a constant in v and h, σ is the stress from Eq. 1, and K_1 is a constant in h [1].

$$\Delta\sigma = \frac{Ehz - K_0 \sigma L_{cb} h}{K_1 L_{cb} h + L_{cb}^2}$$

Equation 2

$$K_0 = (1.33 + 0.45v)(1.022 - 0.014h)$$

Equation 3

$$K_1 = 0.0086h^2 - 0.047h + 0.81$$

Equation 4

Young's modulus was taken to be the same as for bulk tungsten. The mean and standard deviation of the residual stress and stress gradient was found since the unevenness due to the growth process (mainly from the evaporation of nickel) far outweighed the uncertainty in measurement from the light interferometer.

Conclusion:

The residual stress of atomic layer deposition tungsten on nickel was found have a mean of 1555 Pa and a standard deviation of 144 Pa. The through thickness stress gradient was found to have a mean of -77 Pa and a standard deviation of 572 Pa. The residual stress is quite small especially when compared to the expected thermal stress for the same thickness of bulk tungsten on nickel, which should be about 331 MPA. The majority of the stress is believed to be thermal stress, but it would seem that the thermal expansion coefficient of WALD is much higher than bulk tungsten. This would not be that surprising as WALD is thought to be a nano-crystalline in structure. It is important to find the thermal expansion of WALD on nickel as the devices utilizing WALD will be operated at high temperatures and therefore could only be properly modeled by taking into account thermal expansion. Since the structure of WALD is different than bulk tungsten, it would be expected to have a different Poisson ratio and Young's modulus as well.

Future Work:

There is much more work to be done to truly understand WALD. Some of these include: finding Young's modulus, finding the thermal expansion coefficient (that way the stress due to thermal mismatch can be calculated), finding Poisson's ratio, and seeing how the growth parameters (temperature and time) of WALD affect its properties.

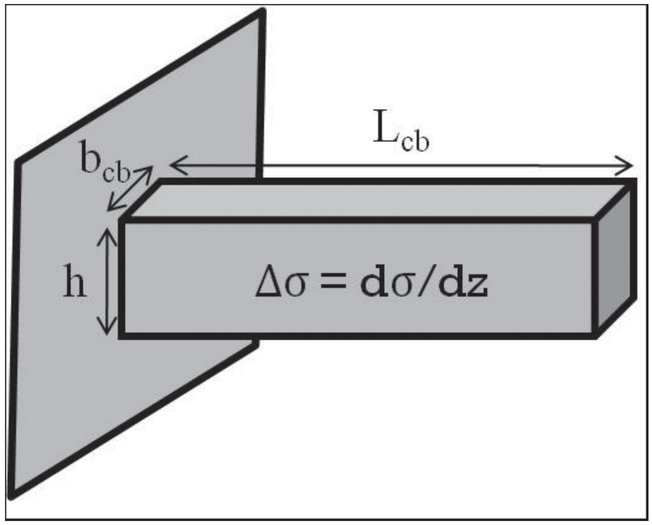

Figure 2: Schematic of cantilever structure.

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References:

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