Studying the Effect of Materials and Processing on the Electrical Properties of Bilayer Al / Amorphous CoTiN Metal Gates for Advanced Nanoelectronic Devices

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Abstract:

Amorphous metal gate stacks present several advantages over traditional polysilicon gate stacks, including lower electrical resistivity and the elimination of polysilicon depletion and boron penetration effects. Recent use of amorphous metal gates in complementary metal oxide semiconductor (CMOS) integrated circuits have been shown to enhance their electrical properties by reducing work function and threshold voltage variability [1]. Additionally, amorphous metal gates are expected to exhibit enhanced diffusion barrier properties, which would stabilize the work function by preventing metal interdiffusion. However, amorphous gate mechanics have yet to be fully investigated. Understanding the effect of structure, materials, and processing on the electrical properties of transistors as well as optimizing the gate stack remain a challenge. The goal of this project was to study such effects in a bilayer metal gate structure consisting of aluminum (Al) as an upper layer and either polycrystalline titanium nitride (TiN) or partially amorphous cobalt titanium nitride (CoTiN) as a bottom layer. This would be done by comparing the diffusion barrier properties of the CoTiN gates to those of the TiN gates by measuring capacitance-voltage characteristics with varying thickness and annealing temperature. The extracted work function could then be used to determine if the amorphous gates effectively resist Al diffusion and prevent threshold voltage fluctuation, properties essential to increasing operational speed and efficiency in industrial nanoelectronic devices.

Experimental Procedure:

Several bilayer metal gate stacks consisting of a 50 nm Al upper layer and a polycrystalline TiN or amorphous CoTiN layer underneath with varying thickness (1-50 nm) were fabricated. The metals were deposited via sputter deposition onto a step-etched HfO_2/SiO_2 dielectric (with 2 nm of atomic layer deposited hafnium dioxide, HfO_2, and 5-20 nm of thermally grown silicon dioxide, SiO_2) on a Si substrate.

Following deposition, the structures were etched and patterned into 200 μm diameter capacitors using standard lithography techniques. The wafers were coated with 1.6 μm of machine-spun Shipley 3612 positive photoresist, masked and patterned under high-intensity UV light, and then developed to strip away the weakened photoresist. The exposed Al was etched away using Al etchant, and the TiN or CoTiN metal underneath was dry etched with $CHClF_2$ (Freon 22) plasma. The remaining photoresist was then removed using a PRS3000 wet etch. Following the lithography procedure, hydrofluoric acid was used to remove the back oxide, thus improving the wafer back contact.

Inspection by optical microscope revealed that most samples sustained damage during etching and lithography procedures, possibly related to gas contamination or gas leakage in the system as observed from the plasma color differences during etching. Damages incurred by the capacitors included over-etched capacitor boundaries as well as thread-like projections from inner and outer rings, both of which could have degraded capacitor functionality.

Fortunately, one sample of Al on 6 nm of CoTiN remained unaffected by the etching and lithography problems. This sample was used to measure the change in work function as a function of annealing temperature. Figure 1 shows the undamaged and completed sample.

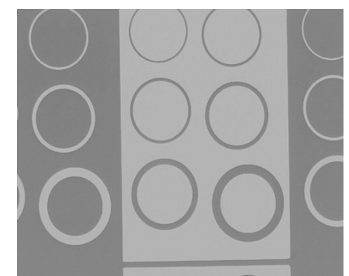

Figure 1: Salvageable Al / CoTiN (6 nm) capacitors as-deposited.

The capacitance-voltage (CV) characteristics of this sample were then measured using a bipolar bias sweep from 4V to -2.5V and back. These characteristics were used to determine several device parameters such as flatband voltage and equivalent oxide thickness, which can be used to calculate the work function as described in Reference 2.

CV characteristics for each oxide thickness of the sample were measured as-deposited and again after 300°C, 400°C, and 500°C anneals in forming gas for 20 min. Measurements were taken at 10 kHz, 100 kHz, and 1 MHz to confirm consistent device operation. Figure 2 represents CV measurements obtained from the sample after a 300°C anneal.

Flatband voltage is the voltage corresponding to the flatband capacitance; equivalent oxide thickness was derived from the maximum capacitance. Figure 3 represents a plot of flatband voltage as a function of equivalent oxide thickness.

By the equation used to calculate the metal work function, extrapolating a linear regression of flatband voltage versus equivalent oxide thickness gives the work function difference between the metal and the semiconductor. Adding the calculated work function of the semiconductor to this value yields the CoTiN work function for a particular anneal condition. Following this method, the CoTiN work function was extracted for each anneal condition and plotted with respect to annealing temperature in Figure 4.

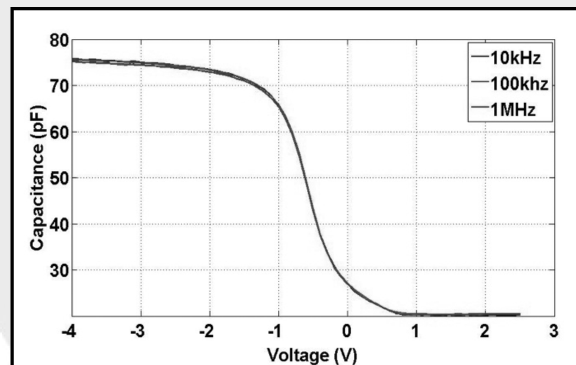

Figure 2: Capacitance-voltage characteristics of the Al / CoTiN (6 nm) sample.

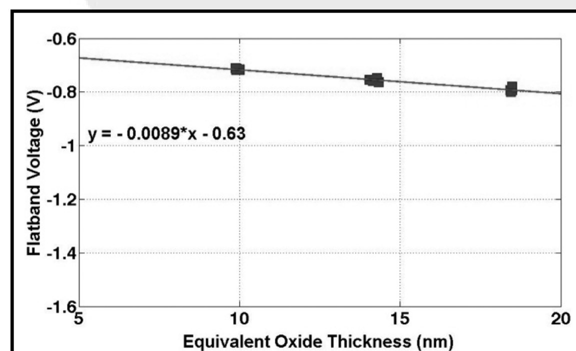

Figure 3: Plotting flatband voltage against equivalent oxide thickness is used to calculate the CoTiN work function.

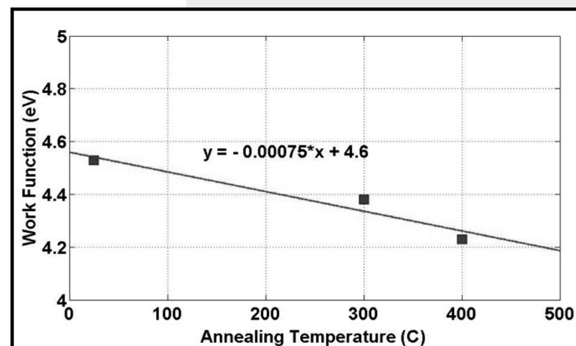

Figure 4: CoTiN work function plotted against annealing temperature shows a decrease with increasing temperature.

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Results and Conclusions:

The obtained results illustrate that the CoTiN metal work function nominally decreases with an increase in annealing temperature. Possible explanations include:

- Ineffective Al diffusion prevention,
- Annealing of interface defects,
- Structural changes in CoTiN during the annealing process, and,
- Interaction between dielectric and CoTiN interface.

The effectiveness of CoTiN as a diffusion barrier remains unclear. While results do indicate a change in work function of approximately 0.3 eV, this difference is relatively small compared to silicon's band gap and could be affected by any combination of the reasons cited. Further experimentation on the effects of thickness on the CoTiN work function as well as comparison to polycrystalline metals are needed to establish amorphous CoTiN barrier properties and its use as a gate material for industrial applications.

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References:

[1] T. Matsukawa, et al. "Suppression of threshold voltage variability of double-gate fin field-effect transistors using amorphous metal gate with uniform work function." Applied Physics Letters 102, 162104(2013); doi: 10.1063/1.4803040.

[2] J. Ouyang, et al. "Effect of Composition on Structural and Electrical Properties of Amorphous Ta-W-Si-C Metal Thin Films." Electrochemical Society Solid State Letters, 2 (10) P86-P88 (2013).