Work Function Tuning in Amorphous TaWSiC Metal Gates for Integrated Circuits

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Abstract:

Use of amorphous tantalum tungsten silicon carbide (TaWSiC) metal gates has the potential to reduce gate work function variation, but for application in integrated circuits, their work function should also be tunable. In this work, the ratio of W/Ta in TaWSiC gates was varied in order to tune the work function. While the results indicate a partial trend of increasing work function as the ratio of W/Ta is increased, data inconsistencies suggest that oxygen contamination during processing may have caused unreliable work function measurements.

Introduction:

As transistors continue to scale down in size to allow faster, denser, and more efficient integrated circuits, polycrystalline silicon, traditionally used as the transistor gate material, has been replaced by polycrystalline metal. For optimal circuit and device performance, the work function of this gate material should exhibit minimal variation and be tunable to specific values for different applications. However, the work function of polycrystalline metal has been shown to vary with grain orientation [1]. As gates are scaled down to sizes comparable to those of individual grains, the gate work function can vary significantly between devices, as illustrated in Figure 1 [2]. An amorphous metal, in contrast, avoids this work function variation because it lacks grains (Figure 1).

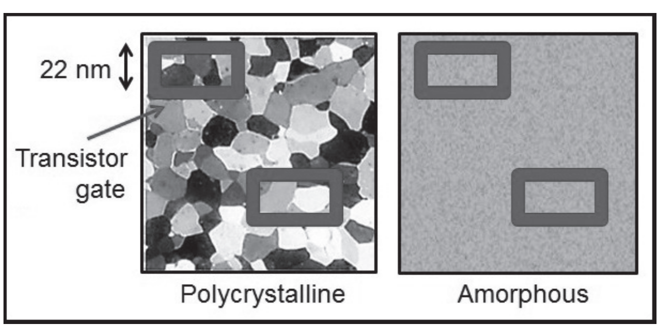

Figure 1: Illustration of gates on polycrystalline vs. amorphous metal. Different shades represent different grain orientations.

Tantalum tungsten silicon carbide (TaWSiC) is an amorphous alloy that is thermally stable, making it potentially compatible with integrated circuit processing [3]. However, additional work is needed to determine whether the work function of amorphous TaWSiC gates can be tuned to desired values for integrated circuit applications. The work function of an alloy depends on the work functions of the constituent metals. Thus, it is expected that varying the ratio of W/Ta in TaWSiC would allow tuning of its work function. A previous (unpublished) investigation by Ouyang suggested a trend of increasing work function with increasing tungsten percentage. Here, we report on a reinvestigation and extension of that previous study of work function tuning in TaWSiC.

Experimental Procedure:

Metal-oxide-semiconductor capacitors were fabricated to determine the work function of amorphous TaWSiC gates with various W/Ta ratios. Silicon oxide was thermally grown on n-doped silicon wafers and wet-etched to form a terrace of oxide with thicknesses ranging from 2 nm to 10 nm, followed by a 2 nm deposition of hafnium oxide using atomic layer deposition. TaWSiC gates 30 nm thick were deposited by co-sputtering with tantalum, tungsten and silicon carbide targets, and the ratio of W/Ta was varied by varying the power to the tungsten and tantalum targets. Capacitors 200 μm in diameter were patterned using photolithography and annealed in forming gas for 30 minutes at 300°C.

$$V_{FB} = \Phi_{ms} - \frac{Q}{\varepsilon} EOT$$

The effective work functions of the different gate compositions were extracted using the simplified equation in Figure 2, where V_{FB} is the flatband voltage, Φ_{ms} is the difference between the work functions of the metal gate and silicon, Q is the fixed charge in the oxide, ε is the permittivity of the oxide, and EOT is the effective oxide thickness. In order to model a linear relationship between V_{FB} and EOT, charges in the oxide were

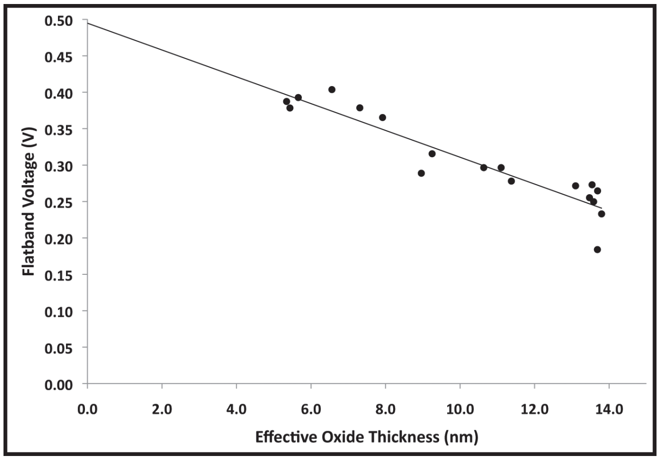

Figure 3: Example plot of V_{FB} vs. EOT; the y-intercept is Φ_{ms}.

Previous Work

	x	WF
0	0	4.58
20	0.25	4.68
40	0.5	4.82
60	0.75	4.9
80	1	4.57

Present Work

	x	WF
0	0	4.392
50	0.625	4.453
60	0.75	4.514
70	0.875	4.584
80	1	4.657

Figure 4: Work functions for various compositions of TaWSiC in this work compared with work function values found in the previous investigation by Ouyang.

assumed to be constant and evenly distributed. The flatband voltages for capacitors of various effective oxide thicknesses were determined from capacitance-voltage measurements.

A graph of V_{FB} vs. *EOT* was plotted for each composition, and a linear fit was used to extract Φ_{ms} from the y-intercept for each graph (Figure 3). The gate work function was then calculated from Φ_{ms} and the work function of the silicon wafer.

Results and Discussion:

Figure 4 displays the work functions for various compositions of TaWSiC in this work as well as a comparison with the previous investigation by Ouyang. We note that data was unable to be obtained for some of the compositions in this work due to time constraints.

Both data sets exhibited a partial trend of increasing work function as the ratio of W/Ta increased, but this trend was inconclusive due to inconsistencies in the data. Both data sets contained points that deviated from the trend. Additionally, the work function values of this work were shifted down from those found in the previous investigation for the same compositions. An examination of the calculations behind this data suggests that oxygen contamination in the metal gate may have contributed to these inconsistencies. Because Q and ε from the equation in Figure 2 were held to be constant, we expected the slopes of the V_{FB} vs. *EOT* graphs to be similar for all samples, but instead observed significant variation. Work by Grubbs has shown that oxygen contamination in tungsten gates shifts both the slope of the V_{FB} vs. *EOT* graph and the work function value, suggesting that oxygen contamination may explain similar shifts in this work [4].

Future Work:

Future work will focus on the development of simpler amorphous gate metals. Amorphous metal gates with fewer component elements would potentially be less susceptible to the inconsistent work function measurements discussed above and more compatible with other integrated circuit processing techniques, facilitating eventual implementation of amorphous metal gates to reduce work function variation in integrated circuits.

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