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# Wear Behavior of Si-doped Diamond-like Carbon Coating under Electrical Contact

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**Abstract**

Electrostatic discharge (ESD) has become a critical reliability issue in advanced semiconductor manufacturing due to the increasing sensitivity of nanoscale devices. Conventional ESD spray coatings generally exhibit low hardness and poor wear durability under repeated sliding contact. Although hydrogenated diamond-like carbon (a-C:H) coatings provide superior tribological performance, the achievable $sp^3$ fraction is fundamentally limited by hydrogen incorporation during conventional chemical vapor deposition (CVD) processes. In this work, Si-doped diamond-like carbon (Si-DLC) coatings were developed using tetramethylsilane (TMS, $Si(CH_3)_4$) gas doping during PE-CVD. The effects of TMS gas flow ratio on the electrical, structural, mechanical, and tribological properties of Si-DLC coatings were systematically investigated under electrical contact conditions. Increasing TMS gas flow enhanced the formation of Si-C and Si-$H_x$ bonds, resulting in increased surface resistance from $10^5$ to $10^7$ $\Omega$ and an effective $sp^3$ fraction up to approximately 58%. However, excessive TMS incorporation reduced coating hardness due to the formation of amorphous SiC structures. Tribological evaluation under applied voltage demonstrated that coatings with increased $sp^3$ fraction exhibited more stable friction behavior, and improved wear durability during electrical sliding contact.

## 1 Introduction

Electrostatic discharge (ESD) is one of the major reliability issues in advanced semiconductor manufacturing systems because nanoscale electronic devices are highly vulnerable to electrical charging during handling and transportation processes. Wafer carriers and transport components are continuously exposed to frictional contact, resulting in static electricity accumulation and localized electrical discharge events. Therefore, electrostatic dissipative coatings are required to provide controlled charge dissipation while maintaining sufficient wear durability under repeated mechanical contact. Commercial ESD spray coatings generally provide electrical resistance within the electrostatic dissipative range; however, their low mechanical hardness (< 1 GPa) often causes severe wear damage, coating delamination, and eventual short-circuit behavior under repeated Hertzian contact conditions. Under continuous electrical sliding contact, the voltage drop caused by local coating failure accelerates coating degradation and partial substrate exposure.

Hydrogenated diamond-like carbon (a-C:H) coatings have attracted considerable attention as candidate ESD coatings because of their excellent wear resistance and tunable electrical properties. Increasing the $sp^3$ bonding fraction in DLC coatings can improve electrical insulation characteristics and tribological durability. However, the achievable $sp^3$ fraction in conventional CVD-grown DLC coatings is theoretically limited by hydrogen incorporation, and excessive hydrogen incorporation often results in polymer-like structures with degraded mechanical properties [1,2].

To overcome these limitations, Si-doped DLC (Si-DLC) coatings were developed using tetramethylsilane (TMS) gas during deposition. The incorporation of Si-C and Si-$H_x$ bonds is expected to increase the effective $sp^3$ fraction while simultaneously controlling electrical resistance and tribological behavior under electrical contact conditions. In this work, the effects of TMS gas flow ratio on the structural evolution, electrical properties, mechanical characteristics, and wear behavior of Si-DLC coatings were systematically investigated.

# 2 Experimental procedure

Si-DLC coatings were deposited using an anode linear ion source (ALIS)-assisted plasma coating system. SUS304 substrates were initially cleaned and Ar plasma etched prior to coating deposition. A Ti interlayer with a thickness of approximately 0.25 μm was deposited using unbalanced magnetron sputtering (UBMS) to improve coating adhesion. Subsequently, Si-DLC coatings with a thickness of approximately 1.5 μm were deposited using ionized acetylene ($C_2H_2$) and tetramethylsilane (TMS, $Si(CH_3)_4$) gases. The TMS gas flow ratio was systematically varied while maintaining a constant total gas flow rate. The coating conditions are summarized in Table 1.

| Sample | $C_2H_2$ (sccm) | TMS (sccm) | TMS fraction (%) |
|---|---|---|---|
| DLC #1 | 40 | 0 | 0 |
| Si-DLC #2 | 35 | 5 | 12.5 |
| Si-DLC #3 | 30 | 10 | 25 |
| Si-DLC #4 | 20 | 20 | 50 |
| Si-DLC #5 | 10 | 30 | 75 |
| Si-DLC #6 | 0 | 40 | 100 |

The working pressure during deposition was maintained between $1.5\times10^{-1}$ and $2.4\times10^{-1}$ Pa. The structural properties of the coatings were characterized using Raman spectroscopy, Mechanical properties including hardness and elastic modulus were measured using nanoindentation techniques. Surface electrical resistance was evaluated using a high-resistance measurement system. Tribological properties under electrical contact conditions were investigated using a ball-on-disk (BoD) tribometer equipped with a DC power supply. SUJ2 steel balls were used as counterpart materials. The applied normal load was 1 N, corresponding to a Hertzian contact pressure of approximately 580 MPa. Sliding tests were conducted at a linear speed of 15.7 mm/s under ambient conditions of 15–18 °C and 30% relative humidity. Both fixed-voltage and high-potential voltage tests were performed to evaluate electrical-contact wear behavior and ESD durability.

# 3 Results and Discussion

## 3.1 Electrical and mechanical properties

Figure 1 shows the deposition rate, hardness, elastic modulus, and electrical resistance of the Si-DLC coatings as a function of TMS gas flow fraction. As the TMS gas flow ratio increased, the electrical resistance gradually increased from approximately $5\times10^5$ Ω to $1\times10^7$ Ω. In contrast, hardness decreased from approximately 22 GPa to 13 GPa with increasing TMS concentration.

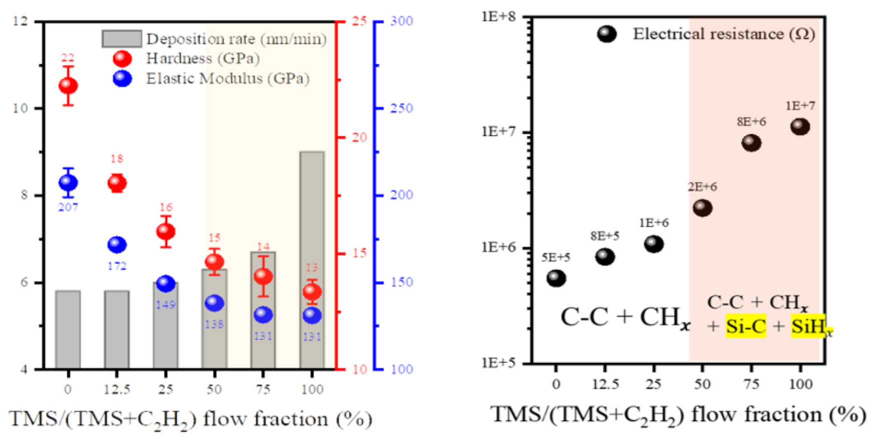


**Figure 1:** Deposition rate, hardness, elastic modulus, and electrical resistance of Si-DLC coatings as a function of TMS gas flow fraction.

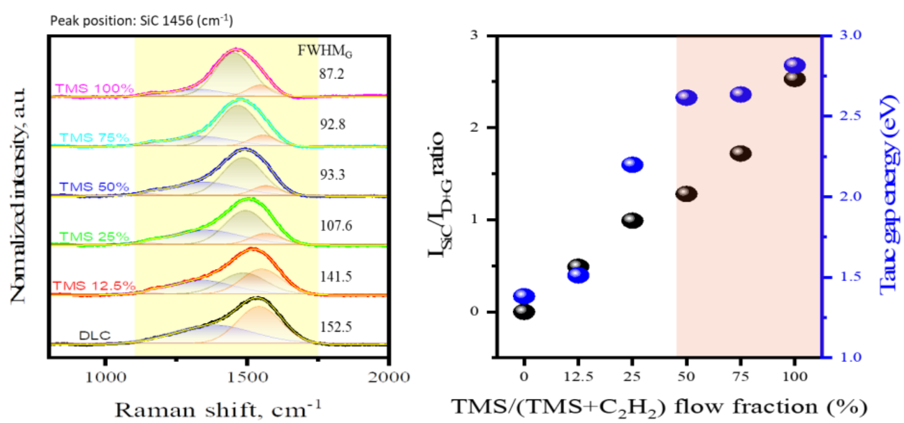


**Figure 2:** Raman spectra and $I_{SiC}/I_{D+G}$ ratio of Si-DLC coatings with increasing TMS gas flow fraction.

## 3.2 Structural evolution of Si-DLC coatings

The structural evolution of the Si-DLC coatings with increasing TMS gas flow fraction was investigated using Raman spectroscopy. The results indicate that TMS incorporation significantly modified the bonding configuration and chemical structure within the DLC matrix.
Figure 2 shows the Raman spectra of the coatings deposited under various TMS gas flow ratios. The conventional DLC coating without TMS exhibited typical broad D and G bands associated with amorphous carbon structures. As the TMS gas fraction increased, an additional shoulder peak centered near 1456 $cm^{-1}$, corresponding to Si-C bonding, became progressively more pronounced. The relative intensity ratio of the SiC-related peak to the combined D and G bands ($I_{SiC}/I_{D+G}$) continuously increased with increasing TMS fraction, confirming the progressive formation of Si-C bonding structures within the DLC matrix. In addition, the optical Tauc gap energy increased significantly with increasing TMS gas flow ratio, indicating suppression of conductive $sp^2$ carbon clustering and enhancement of insulating $sp^3$-type bonding structures.

## 3.3 Tribological behavior under electrical contact

The tribological behavior of the Si-DLC coatings under electrical sliding contact was evaluated using both high-potential voltage tests and fixed-voltage wear tests. The results demonstrated that the electrical and tribological properties of the coatings were strongly influenced by the $sp^3$ bonding fraction and the electrical resistance of the Si-DLC coatings.
Figure 3 shows the friction behavior and voltage response of the coatings during sliding contact under progressively increasing applied voltage conditions from 0 to 30 V. The conventional DLC coating and low-TMS Si-DLC coatings with relatively low $sp^3$ fractions exhibited unstable friction behavior accompanied by significant voltage fluctuations during sliding. In particular, abrupt increases in coefficient of friction (CoF) were frequently observed at elevated voltages, indicating local electrical breakdown and unstable discharge behavior at the contact interface.

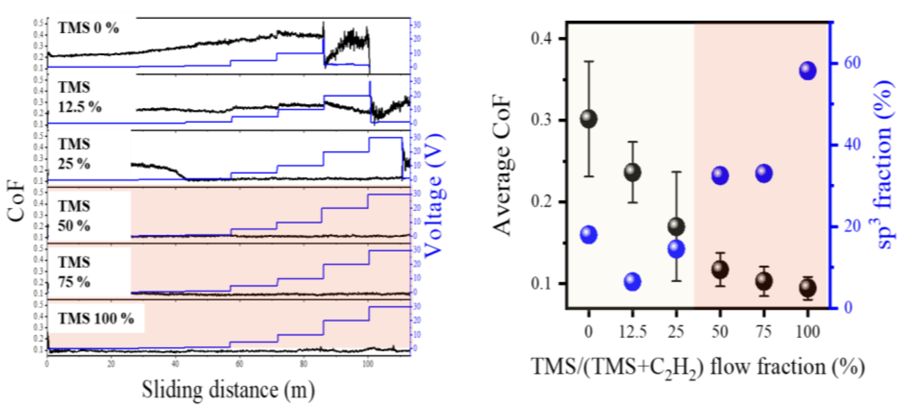


**Figure 3:** Friction behavior and voltage response of Si-DLC coatings during electrical sliding contact under increasing applied voltage conditions.

In contrast, coatings deposited with higher TMS gas fractions exhibited significantly more stable friction behavior during the entire sliding process, even under high-applied voltage conditions. The voltage response became increasingly stable as the TMS concentration increased, suggesting that enhanced Si-containing $sp^3$ bonding structures effectively suppressed localized discharge events and

stabilized the electrical contact behavior during sliding. The average coefficient of friction continuously decreased from approximately 0.30 for the undoped DLC coating to below 0.10 for the highly doped Si-DLC coatings as the effective $sp^3$ fraction increased. This reduction in friction coefficient indicates that the increase in Si-C and Si-$H_x$ bonding structures improved the tribological stability of the coating by reducing adhesive interaction and electrical damage at the sliding interface.
The improved tribological stability of the Si-DLC coatings can be attributed to the reduction of localized electrical discharge and frictional heating during sliding contact. In coatings with low surface resistance, accumulated electrical charges were rapidly discharged within a very short time scale, resulting in localized thermal spikes and severe interfacial damage. These rapid discharge events accelerated coating delamination and unstable wear behavior. By contrast, the Si-DLC coatings with increased electrical resistance promoted gradual or slow discharge behavior during sliding contact.

# 4 Conclusions

Si-DLC coatings were successfully developed using tetramethylsilane gas doping during plasma-enhanced DLC deposition for electrostatic dissipative applications. Surface electrical resistance increased from $10^5$ to $10^7$ Ω with increasing TMS gas flow ratio due to enhanced Si-containing bonding structures. Si-DLC coatings with increased $sp^3$ fraction exhibited improved friction stability, and wear durability under electrical contact conditions.

# References

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