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# Microstructure and nano-wear property of Si-doped diamond-like carbon films deposited by a hybrid sputtering system

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**Abstract**

Diamond like carbon (DLC) films have been extensively studied over the past decades due to their unique combination of properties. In particular, silicon-doped DLC (Si-DLC) films have attracted significant attention for their tribological applications. However, most of the efforts were focusing on friction and wear properties in conventional load range, while nano-scale tribological behavior remains being less investigated. In this study, Si-doped DLC films were deposited by a hybrid sputtering system combining high power impulse magnetron sputtering (HiPIMS) and radio frequency (RF) magnetron sputtering. The Si concentration in the films was controlled by altering the Si target power. The influence of the Si target power on the microstructure, mechanical and nano-wear properties of the Si-DLC films were investigated. The influence of the microstrure variation on mechanical and nano-wear property of the films were further studied. The results indicated that the hardness value was significantly influenced by the Raman $I_D/I_G$ ratio and the $I_D/I_G$ ratio also played an important role in the nano-wear behavior of the Si-DLC films.


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*Keywords:* Si-DLC; Microstructure; Hardness; Nanotribology; HiPIMS

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## 1. Introduction

Diamond-like carbon (DLC) film, an amorphous carbonaceous material mainly composed of $sp^2$ and $sp^3$ bonded carbon atoms, possesses unique properties such as high hardness, low friction coefficient, high wear resistance, and chemical inertness [1-5]. DLC films have attracted great attentions for use in various applications such as electronic, optical and wear protection due to their excellent properties [6,7]. However, without transition layer or element doping, DLC films can easily delaminate from most of the metal substrates due to high intrinsic stress and mismatch in chemical bonding between the DLC films and the substrates [8]. In addition, the thermal degradation caused by graphitization and hydrogen loss at elevated temperature limits the working temperature of the DLC films, and their tribological properties are strongly sensitive to the testing atmosphere [9]. Incorporation of other elements such as silicon is an effective way to improve the mechanical and tribological properties of the DLC films. Silicon-doped DLC (Si-DLC) films have a very low friction coefficient and possess the potential to improve wear performance in humid atmosphere and at elevated temperatures [10,11].

DLC films have been synthesized by several techniques including ion beam deposition, direct current (DC) or radio frequency (RF) magnetron sputtering, plasma enhanced chemical vapour deposition (PECVD), cathodic arc deposition, electron cyclotron resonance microwave plasma chemical vapour deposition (ECR-MPCVD) and pulsed laser deposition (PLD) [12-18]. However, sputtering is still widely used due to the advantages like low cost, simply control of the process and film homogeneity. High power impulse magnetron sputtering (HiPIMS) is a newly developed PVD technique which allows deposition of ultra-smooth and dense films. Plasma condition in HiPIMS is able to provide highly ionized target material and energetic bombardment, which is necessary for deposition of DLC films with high $sp^3$ content [19,20].

Furthermore, the friction and wear behavior of DLC films in conventional load range have been extensively studied and are fairly well understood. But in numerous engineering applications such as micro motors, micro pumps, micro tweezers, and micro mechanical assemblies, the applied load is substantially or even orders of magnitude lower than that employed in conventional laboratory tribological tests [21,22]. Therefore, the nano-scale tribology behavior with applied load in the range of nano to micro newton for these applications is needed to be well investigated.

In this study, Si-doped DLC films were deposited by a hybrid sputtering system combining HiPIMS and RF magnetron sputtering techniques. The Si concentration in the films was controlled by altering the Si target power. The influence of the Si target power on microstructure, mechanical and nano-wear property of the Si-DLC films were investigated and the mechanisms were also discussed.

## 2. Experimental details

### 2.1. Film deposition

A hybrid sputtering system with a HiPIMS source (HIPIMS+, Hauzer Techno Coating BV) applying on the graphite (99.9 %) target and a RF source (13.56 MHz, YSR-06AF, YOUNGSIN-RF. CO. Ltd) applying on the Si (99.9 %) target was utilized for deposition. The Si-doped DLC films were deposited on the ultrasonic cleaned single crystalline Si (100) wafers in a gas mixture of Ar and $C_2H_2$ (5 % volume ratio) for 2 h at working pressure of $5\times10^{-3}$ torr, and bias voltage of - 400 V. The Si concentration in the films was controlled by altering the Si target power from 0 W to 200 W, while the graphite target power was fixed at 600 W, with a HiPIMS pulsing width of 1500 μs, a repetition rate of 182 Hz, and peak current density of 0.2 $A/cm^2$. Fig. 1 (a) shows the schematic diagram of the deposition system.

Pre-experiments were performed to obtain the optimized deposition temperature for Si-DLC by HiPIMS technique. DLC films were deposited in Ar gas at working pressure of $5\times10^{-3}$ torr, bias voltage of - 100 V, and various deposition temperatures from room temperature to 400 °C, respectively. Fig. 2 shows the residual stress, hardness, and elastic modulus values of DLC films initially increased and then decreased as temperature rise from room temperature to 400 °C, and the DLC film with best mechanical properties was obtained at 200 °C. Therefore, substrate temperature of 200 °C was selected for Si-DLC deposition.