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Optimisation of diamond-like carbon films by unbalanced magnetron sputtering for infrared transmission enhancement

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Abstract

Diamond-like carbon (DLC) films have potential applications in infrared transmission enhancement. Reducing or eliminating mechanical stress and optical absorption of DLC is important in such applications because relatively thick films are necessary. In this work, DLC was deposited in an unbalanced magnetron sputtering (UBMS) system. Mechanical and optical properties of the DLC films were analysed. Thick DLC films were deposited which satisfied applications for the infrared windows at 3–5 and 8–10 μm. At optimised conditions, the stress in the DLC films decreased with increasing thickness, approaching 1 GPa. For single side DLC coated silicon substrate, about 69% transmittance was achieved at wavelengths near 5 μm, close to the theoretical value for non-absorbing DLC material. Other properties such as surface roughness, wetting angle, and stability were also studied, which showed that the DLC films produced in the UBMS system were excellent for infrared transmission enhancement applications in tough environments.

Keywords: Unbalanced magnetron sputtering (UBMS); Diamond-like carbon films (DLC); Infrared anti-reflection

1. Introduction

Infrared communication through the atmosphere or in space requires thin films with excellent mechanical, chemical, and thermal properties to enhance signal transmission. 3–5 and 8–12 μm wavelength ranges are two important windows for infrared communication. Infrared sensors or transducers for these windows use substrate materials such as Si and Ge. These materials have high refractive constants (3.5 for silicon and 4.0 for germanium). Without antireflection coatings the infrared transmission of the high refractive index substrates is about 50%, thus it is necessary to deposit antireflection layers. Unfortunately, conventional infrared antireflection thin films have some drawbacks, namely poor mechanical properties, low density, and moisture sensitivity. New infrared antireflection thin film materials are required for this application. Diamond-like carbon (DLC) thin film is unique in a number of properties for infrared transmission enhancement applications, including infrared transparency, high mechanical hardness, and chemical inertness. DLC thin films deposition methods and material properties have been widely studied. However, as far as we know, there is no detailed study reported for its properties related to infrared transmission enhancement applications using silicon or germanium substrates. It was reported [1] that DLC films using plasma enhanced chemical vapour deposition (PECVD) were deposited on ZnS substrates to enhance transmittance in the near infrared wavelength range (2.5 μm). ZnS is also an infrared transparent material, but has a low optical constant in the infrared range. It is known [2] that for a single layer of antireflection coating on a substrate with infinite thickness, the ideal optical index of the coating is equal to $n_s^{1/2}$, where n_s is the optical constant of the substrate. As the optical constant of DLC in the infrared range is about 2, substrates to match the antireflection coating of DLC should have optical indexes close to 4, such as silicon and germanium. In addition, silicon in the 3–5 μm infrared window and germanium in both 3–5 and 8–12 μm infrared windows has less absorption than that of ZnS which is important for high sensitivity applications.

With a single layer antireflection coating, the optical thickness (a product of physical thickness and optical constant) of the coating should be a quarter wavelength if the optical index of the layer is smaller than the optical index of the substrate [2]. For the infrared window 3–5 μm, DLC films

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should be about 500 nm thick, and for the infrared window 8–12 μm, the DLC films should be about 1250 nm thick. It is widely recognised that DLC films are often produced with high mechanical stresses. Cathodic arc deposition produces DLC films with compressive stress in the range 4–14 GPa [3]. PECVD DLC has relatively low stress in the range 0.2–4.7 GPa [4]. However, PECVD DLC often has low hardness and significant infrared absorption of hydrocarbon. Stress level in magnetron sputtering DLC films is usually between that of the cathodic arc and PECVD [5]. In other applications, an adhesion layer between substrate and DLC films may be deposited or formed by means such as high-energy ion bombardment. Unfortunately, such methods are not applicable for infrared transmission enhancement applications due to their introducing either significant absorption in the adhesion layer or complication in antireflection optimisation.

The origin of mechanical stress and the effect of the stress on DLC film properties have attracted attention in the research community. McKenzie et al. [6] showed that bombardment ion energy determined the stress level and the sp^3 content in carbon films using cathodic arc deposition. Ferrari et al. [7] found that stress did not correlate with the sp^3 content in carbon films deposited using a cathodic arc. Spanepen [8] used a PECVD method and showed that the stress was a function of a number of deposition parameters such as self-bias and acetylene flow rate. Yin et al. [9] combined PECVD with a cathodic arc by introducing hydrocarbon species into cathodic arc deposition. In this paper, we report on our work using the unbalanced magnetron sputtering (UBMS) method to produce DLC films on both silicon and germanium substrates. UBMS was proposed by Window and Savvides [10]. This method enables a higher rate of energetic ion bombardment on the substrate compared with conventional direct current magnetron sputtering. Extensive study has been done on the UBMS method [11,12] for other thin films. Our experimental results on infrared optical and mechanical stress properties are reported in this paper together with other related properties.

2. Experimental

Fig. 1 is a schematic diagram for the unbalanced magnetron sputtering system. In the unbalanced sputtering mode the excitation coils controlled the ratio of the unbalanced magnetic flux passing through the target. The target material was high purity (5N) graphite. Argon (5N purity) was used as the sputtering gas. The substrate holder could be electrically biased and a 2-dimensional scanning device was attached to the substrate holder to achieve uniformity on 200 mm diameter substrates.

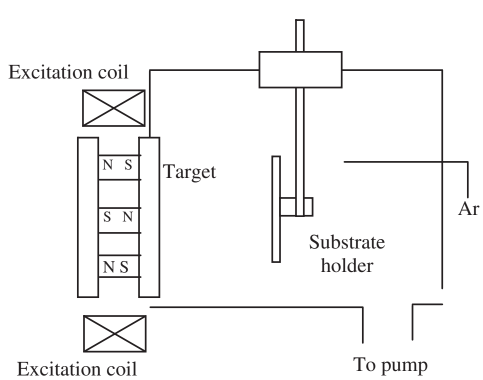

Fig. 1. Schematic diagram of the unbalanced magnetron sputtering system.

Table 1
Deposition parameters for different samples

Group	Ar (sccm)	Bias (− V)	Target current (A)	Coil current (A)
Art1	170	80	8	100
Art2	40	Floating	15	120
Art3	170	80	8	60
Art4	170	Floating	8	100

Film thickness was determined using a J.A. Woollam M-2000UI ellipsometer in the wavelength range from 400 to 1600 nm. Three incident angles, 65°, 70°, and 75° were used in the ellipsometry analysis. A Tecor P-10 thickness profiler was used for mechanical stress measurement and the stress value was determined by measuring the curvatures of the samples before and after deposition and applying the well-known Stoney equation [13]. In order to improve accuracy of the stress determination, an average was used for curvatures in the X and Y directions with 10 mm scanning lengths of the 12×12 mm double-sided polished silicon (100) substrates. A Shimadzu IR Spectrometer was used to analyse the infrared transmittance, with double-sided polished surfaces used to eliminate scattering effects. A Taimin HXD-1000 nano-indention analyser was used to measure hardness of the DLC films.

Optimisation of the plasma and deposition parameters of the UBMS system were previously reported [14,15]. A Faraday cup and Langmuir probe were used to determine the ion current density and the floating potential, respectively. Four groups of DLC samples were deposited as a function of film thickness. The deposition conditions of the four groups are shown in Table 1, noted as Art1, Art2, Art3, and Art4. Samples in Table 1 were on silicon substrates and the DLC films were deposited onto one side only. Substrate temperature was uncontrolled and was approximately between room temperature and 50 °C.

3. Results and discussion

The UBMS method has the advantage of producing a high flux of energetic ion bombardment on the substrate. The high flux of energetic ions was controlled with one of the most important parameters in UBMS: the excitation coil current. The floating potential and ion current near the substrate changed almost linearly with the excitation coil current. For sputtering conditions: argon flow 120 sccm, target current 13 A, and pressure 0.4 Pa; in the normal magnetron sputtering mode without excitation current, the floating potential was about −1 V, and ion current density was about 0.3 mA/cm^2. When the excitation current was increased to 180 A the floating potential was −18 V, and the ion current was increased to 3 mA/cm^2.

Mechanical stress of DLC thin films may depend on film thickness [5,16]. Fig. 2 shows the compressive stress as a