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Noble gas control of diamond-like content and compressive stress in carbon films by arc-mixed mode high power impulse magnetron sputtering

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Abstract

Conventional DC magnetron sputter deposition from a carbon target with argon as the sputtering gas is limited by a low deposition rate, and the resultant coatings have low diamond-like sp^3 content. Here we study arc-mixed mode high power impulse magnetron sputtering (HiPIMS) of carbon using He, Ne, Ar, Xe and Kr gases and show an increase in deposition rate is achieved by using noble gases heavier than argon. On the other hand, a higher sp^3 fraction is achieved by using noble gases lighter than argon. The higher deposition rate of the heavier noble gases is attributed to the higher sputtering yield and an earlier arc onset owing to their lower ionization potential. The higher sp^3 fraction achieved by lighter noble gases is attributed to stress generation by knock-on collisions at the surface of the depositing film, in the absence of stress relief created by large thermal spike volumes. When neon was used as the sputtering gas, the inert gas content was higher than for any other noble gas. Our results lead to opportunities for grading the sp^3 content with depth simply by changing the gas composition, allowing fabrication of buried conductive channels in ta-C, Metal-Insulator-Metal (MIM) (low sp^3 /high sp^3 /low sp^3) structures and biosensor films (high sp^3 /low sp^3).

Key Words:

Noble gas; Magnetron sputtering; Amorphous carbon; Compressive Stress; sp^3 content; Arc-mixed HiPIMS

1. Introduction

Carbon films in their amorphous state may contain various amounts of diamond-like (sp^3) bonds, depending on the deposition conditions [1-4]. When the sp^3 content is dominant, the material is named tetrahedral amorphous carbon (ta-C) which shows the diamond-like properties of chemical inertness, high mechanical hardness, and wide bandgap suitable for particular optical applications[5]. Where high resistance to wear is required, especially in applications where fracture resistance is needed, the sp^3 content may be somewhat reduced to optimize the ratio of hardness (H) to the Young's modulus (E) [6] that correlates with fracture toughness. Other forms of amorphous carbon have special combinations of hardness and colour. For example, a form of ta-C known as a "rainbow ta-C coating" has become popular for applications in the decorative-tool market.

In order to synthesize amorphous carbon films with a broad range of functionalities, direct current magnetron sputtering (DCMS) is potentially useful as a coating technology. This technology, however, cannot be applied in commercial ta-C deposition because of the low deposition rate associated with the process and low sp^3 content of the resulting coatings compared to other technologies such as filtered cathodic arc [7]. Following the advent of high-power impulse magnetron sputtering (HiPIMS), amorphous carbon coatings with a wide range of sp^3 fractions [3, 4, 8-11], a smooth surface topography [3, 12] and improved coating-substrate adhesion with excellent wear resistance at high radii of curvature [4, 13] have been produced and commercial applications of diamond-like carbon (DLC) coatings have widened. However, increasing the deposition rate of carbon films with high sp^3 contents remains a key challenge in the field[14, 15].

The low sputtering rate of carbon is improved in a mixed-mode process, in which the discharge has a transition to a localized plasma resembling a cathodic arc plasma[10, 16]. Such mixed cathodic arc/sputtering mode has already been operated via a HiPIMS system to demonstrate the deposition of

tetrahedral amorphous carbon coatings [3, 4, 10]. In this mixed mode arc-HiPIMS, short-lived cathodic arcs form on the target, enhancing the presence of ionized carbon. The arc generation does not need a separate triggering operation but instead arises from the runaway increase in current. The characteristics of arcs generated in the mixed-mode are similar to those observed in cathodic arcs, including retrograde motion driven by the magnetic field and fractal-like branching of the arc spots generating carbon ions with an average energy of at least 20 eV [11, 17-19]. These arcs contribute to the enhanced ionization of deposited carbon atoms and subsequently pave the way for the high sp^3 fraction in the films by application of substrate bias, replicating the “energy window” effect wherein the sp^3 hybridization is maximum for a bias voltage of 100 V, approximately [2, 10, 20]. However, compressive stress is usually associated with films of high sp^3 content and can cause adhesion problems. A sputtering process that allows for deposition of carbon films with a range of sp^3 content in a controlled process with reduced compressive stress would, therefore, be useful for many applications [20-23]. Based on the correlation between the extent of compressive stress generation and the sp^3 fraction, we hypothesize that a change in the mass of the sputtering gas could optimize the formation of sp^3 bonding, while limiting compressive stress generation. However, a study of the relation between stress and sp^3 composition in a sputtering process while using noble gases other than argon has not yet been presented.

Here we study the use of a wider range of noble gases and noble gas mixtures as sputtering gases than has previously been used in mixed mode HiPIMS in an effort to overcome the sputtering rate limitation and tune the sp^3 content and internal stress. We use He, Ne, Ar, Kr, Xe and mixtures of He+Ne and He+ Ar as sputtering gases in HiPIMS deposition of carbon and show that the deposition rate and the sp^3 fraction, density, and the H/E ratio can be tuned by the choice of sputtering gas.

2. Experimental methods

Carbon coatings were deposited using the HiPIMS deposition technique in an AJA deposition system equipped with 4 magnetron assemblies (AJA International 1800 F). One magnetron assembly was used for the deposition of all samples. A schematic diagram of the sputtering system is presented in Figure 1. A compressed graphite sputtering target (Plan see Composite Materials GmbH) of 76 mm diameter was used. The magnetron assemblies were configured for operation in the unbalanced mode of the magnetic field, with the outer magnets having a magnetic field strength of 0.25 T, 15 - 25% stronger than the magnetic field of the central magnet. Sputtering gases were high purity noble gas or noble gas-mixtures

(99.999%) and were introduced into the deposition chamber using MKS mass flow controllers, with an adjustable flow rate to maintain a constant working pressure of 0.4 Pa during sputtering. The system was pumped down to a base pressure of at least 15×10^{-5} Pa before the coating process started. Individual noble gases and mixtures used were HE+NE mixture (50-50 at%), Ne, He+Ar (50-50 at%), AR, Kr, and Xe. The magnetron was operated using a SPIK3000A pulsed power controller (MELEC GmbH, Germany) which is capable of delivering a peak voltage and current of 1000 V and 1000 A, at a constant average power, respectively, supplied by a DC power supply. In this voltage-regulated power supply the discharge current was determined by the plasma impedance. The average output current was limited to 1000 A and the pulse length was set to 140 μ s. Under a constant voltage operation (785 V), the average power was also kept constant at 0.35 kW by automatically adjusting the frequency. Time varying current was measured using an oscilloscope.

The carbon films were deposited on 675 μ m thick n-type Antimony Doped Si(111) substrates (University Wafer, USA) with dimensions of 2×2 cm² and electrical resistance of 0.008 - 0.02 Ω -cm. The substrates were thoroughly cleaned in a mixed solution of ethanol 99.99% and deionized water using an ultrasonic cleaner for 15 minutes and, then dried using high purity N₂ gas. The silicon wafers were mounted on a substrate holder connected to a custom-made power supply to maintain a constant DC bias voltage of -85 V. The system was equipped with a fast arc suppression unit that could detect an unwanted arc, defined as one exceeding 150 A, and switch off the voltage pulse within 2 μ s. Deposition times were adjusted to achieve a thickness of $1 \mu\text{m} \pm 40$ nm for all samples.

Figure 1. Schematic illustration of the HiPIMS system used for the deposition of carbon coatings.

A KLA Tensor high vertical resolution (0.5 nm) stylus profilometer was used for coating thickness measurements. Rutherford Backscattering Spectrometry with 2 MeV helium ions (He^+) was used to evaluate the amount of argon content and the density of deposited carbon coatings. The obtained RBS spectra were fitted and evaluated using commonly available simulation software (RUMP). Nanoindentation measurements were carried out using a Hysteron Turbidimeter (model: TI 950) with a diamond Berkovich indenter to obtain hardness and elastic modulus of carbon coatings. The values reported here are the average of fifteen indentation measurements done using 10 Mn load. X-ray photoelectron spectroscopy (XPS) experiments were performed on carbon coatings and the sp^3 content in carbon coatings was evaluated by fitting the peaks in the C1s spectra. Charge compensation was achieved using a low energy-spread and high brightness electron source to increase the peak position accuracy in C1s spectra. Adequate charge compensation efficiency was achieved when the peaks were stable and located at the known binding energies for various argon beam spot sizes. After approximating the background contribution using Shirley method, C1s peak fitting was performed using Casa XPS software with a linear combination of 70% Gaussian and 30% Lorentzian fitting functions. The peak for the sp^2 component was positioned at 284.4 eV and allowed to vary by $\pm 0.1 \text{ eV}$ (with the peak width of $\text{FWHM} = 1.05 \pm 0.05 \text{ eV}$), while the sp^3 component was positioned at 285.2 eV and allowed to vary by $\pm 0.1 \text{ eV}$ (with the peak spread or $\text{FWHM} = 1.1 \pm 0.05 \text{ eV}$) [6, 24]. The three minor components C-O, C=O, O-C=O were fitted at binding energies of $286.5 \pm 0.5 \text{ eV}$, $288 \pm 0.5 \text{ eV}$ and $288.75 \pm 0.25 \text{ eV}$, respectively [25, 26]. All peak positions and widths were allowed to vary during the fitting procedure to achieve the best fit using CASA XPS.

Complementary estimates of sp^3 content were made by analyzing the D parameter from C_{KLL} spectra obtained by X-ray excited Auger electron spectroscopy (XAES) in a Thermo Scientific K-Alpha spectrometer equipped with an Al $\text{K}\alpha$ source (1486.7 eV). XAES is influenced by plasmon losses and allows the accurate determination of sp^3 content in the coatings independent of the C 1s curve fitting method. From the first derivative of XAES spectra with respect to binding energy, the energy separation “D” was obtained as the difference in binding energy position of the principal (highest) positive peak from the principal (lowest) negative peak. The corresponding sp^3 fractions were then calculated [6, 27]

Time-resolved intensity of emitted light ($\lambda=514.1$ nm) from carbon ions in the plasma using various rare gases and mixtures for sputtering were recorded using a spectrograph with a 1200 lines/mm grating (SpectraPro Acton Research corporation 2750). The spectrometer was triggered synchronously with HiPIMS voltage and used a charge-coupled device to record the instantaneous intensity of light emitted from ions of carbon at a definite wavelength (514.15 nm) during the discharge. The spectra were acquired at intervals of 5 μ s with an exposure time of 250 ns. The data was accumulated for 250 pulses to enhance the signal-to-noise ratio.

3. Results

Figure 2a shows the target current during each pulse as a function of time from the application of the pulse for a constant applied voltage of 850 V. The current initially increases rapidly with time and then enters a regime with a slower rate of increase. For the heavier sputtering gases, there is a tendency to show a shorter time before onset of the current and a higher current after the onset. Other authors have also observed the earlier onset of current for heavier gases. For example, Schmidt et al [28] showed an earlier onset for argon than for neon under the same deposition conditions. In our results, heavier gases also tend to form a distinct plateau before another strong increase in current begins. This second increase is identified as the onset of an arc in the mixed-mode process, first observed for argon HiPIMS sputtering of a carbon target and is associated with the formation of visible localized plasmas similar to cathodic arc spots on the target surface [16, 29]. The heavier noble gases tend to show an earlier onset of the mixed mode. The signature of the arc mixed-mode HiPIMS, which we define by the sudden second increase in current, is accompanied by a sharp increase in the emission intensity from carbon ions, shown in Figure 2. The exact alignment of the carbon ion emission onset with the current increase is marked in Figure 2 by vertical lines and confirms the presence of the hot, strongly ionizing cathode spot plasma associated with a cathodic arc occurs at the sudden increase in current [3].

Figure 2. (a) Target current as a function of time for sputtering of a carbon target in various noble gases and gas mixtures for a constant applied voltage of 800 V. The mixed mode is entered in the gas mixtures shown at the position of the vertical lines in the case of xenon and neon. At the time the arc mode is initiated, there is a simultaneous increase in the carbon ion emission intensity, an expected consequence of the creation of a hot cathode spot plasma. The heavier noble gases tend to show a higher current and an earlier onset of target current and of entering into the mixed mode. (b) The optical emission spectroscopy (OES) emission lines of Carbon II lines recorded at 514.15 nm obtained for HiPIMS discharges in various sputter gas mixtures.

It is useful to plot the net charge delivered to the target during the pulse by integrating the current drawn by the target during the pulse, as shown in Figure 3(a). The net charge delivered to the target only during

the arc regime is also provided in the same figure (Fig. 3(a)). The net charge per entire pulse and the net charge per pulse only during the arc are plotted as a function of the first ionization potential of the sputtering gas in Figure 3(b). The heavier gases with lower first ionization potentials are more readily ionized and form plasmas with higher plasma densities, leading to larger target currents. The deposition rate and the surface roughness both increase as a function of net charge transfer during the arc regime as shown in Figure 3(c). The deposition rate shows a linear increase per unit charge delivered, showing that per ion impact, assuming singly charged ions, the larger arcs in the discharge of heavier inert gases appear to have a greater effective carbon sputtering yield. The literature shows only a small dependence of the sputtering yield on noble gas type, where the maximum in sputtering yield occurs near neon and argon. [30] The variations in sputter yield are not sufficient to explain the large variations in deposition rate, since the frequency was decreased as the mass of the noble gas increased to keep the power and voltage constant. Power is expected to determine the deposition rate in a sputtering process [10, 31]. Therefore, we interpret our results not as an increase in the conventional sputtering yield, but as a change in the mode of removal of carbon atoms from conventional sputtering to the more effective ablation process created by the cathodic arc spots after the mixed mode is entered [4, 10]. The heavier gases have the highest deposition rates, which we explain by the mixed-mode being entered earlier during the pulse, as shown by the vertical lines in Figure 2. This explanation is also preferred over the formation of higher numbers of doubly charged ions, since the second ionization potential of the gases does not show a strong increase with atomic mass. The roughness measurements reveal that a lower peak-to-valley height (R_z) is achieved when coatings are deposited using lighter sputtering gases.

Figure 3: (a) The net charge delivered to the target during the pulse and during the time period when the arc regime exists for the various gas types. (b) The net charge delivered to the target for the various gas types as a function of the first ionization potential. (c) Deposition rate and the peak surface roughness as a function of the net charge delivered to the target during the arc regime of the pulse (the corresponding sputter gas or gas mixtures are provided for each datapoint in (a)). The influence of sputtering gas type on average peak-to-valley height is shown, indicating that the lighter gases produce lower surface roughness, as measured by stylus profilometry.

The sp^2 and sp^3 contents were obtained from the C1s photoelectron spectra by resolving the spectra into chemical groups of characteristic binding energy (BE). The C1s spectra were fitted with two significant components (sp^3 and sp^2 hybridization of carbon) and three minor components corresponding to three different chemical groups (C-O), (C=O), and (-C=O). The resolved components of the C1s spectra for films sputtered using He-Ne, Ar, and Xe are shown in Figure 4a.

Figure 4b shows the sp^3 fraction of the films as a function of the sputtering gas type. Irrespective of higher carbon ionization in the plasma (Fig. 1a), the heavier the sputtering gas, the less the sp^3 fraction. In a recent work, the importance of energy and momentum transfer in collisions between the target atoms and incident ions that generate stress has been discussed. [32] We calculated the fraction of the energy that is transferred from the incident ion in a primary head-on elastic collision for each of the inert gases, when colliding with a carbon atom. This fraction was calculated for each inert gas atom incident along the line of centers with a carbon atom, using conservation of energy and momentum in a fully elastic collision. The energy transfer is most efficient when the mass of the incident atom coincides most closely with that of the carbon atom. These results support the idea that a compressive pressure wave is generated by the incident ion and immediate knock-on atoms, which is responsible for the generation of compressive stress, which in turn correlates with the sp^3 fraction. The pressure wave would have larger amplitude when the primary energy transfer from the incident ion is more efficient, leading to more compressive stress and higher sp^3 fraction.

Figure 4: (a) Peak fitted C1s high resolution XPS spectra. (b) The sp^3 fraction, determined from peak fitting of C1s high resolution XPS spectra, for HiPIMS carbon films as a function of gas type in order of

increasing average atomic mass (left hand axis, circles). Also shown is the calculated fraction of the incident energy that is transferred to a carbon atom in a head-on collision (right hand axis, squares).

Complementary estimation of the sp^2 and sp^3 content was performed by calculating D parameters by analyzing the X-ray Auger electron spectroscopy (XAES) spectra under similar conditions as for the C1s spectra. The D parameter was calculated from the differences between maxima and minima of the binding energies obtained from the first derivative of CKLL spectra with respect to its intensity. Figure 5 exhibits the evaluated D parameters on the X-axis. As described by Mezz et al. [27], the D parameters are correlated with the sp^3 content obtained by C1s peak fitting (CF4)

Figure 5: The sp^3 fractions calculated from C1s fitting, labeled as C_{KLL} (hollow circles) are plotted along with the sp^3 fractions represented by the estimated D parameters (filled circles).

Figure 6 shows the density of carbon coatings as a function of the sputtering gas type measured using Rutherford Backscattering Spectrometry (RBS). The density correlates well with the sp^3 fraction, as observed in previous works on HiPIMS deposition of carbon[6, 33].

Figure 6: The density of the carbon film as a function of the gas type measured using Rutherford backscattering spectrometry.

Figure 7 shows the incorporation of inert gas atoms in the HiPIMS carbon films as a function of the various sputtering gas types. The content of inert gas reaches a maximum for neon, showing that neon has the highest probability of incorporation into the film. These results indicate that the content of inert gas in the film strongly depends on the size of inert gas atom and the deposition rate (Figure 3c). We have previously studied the mechanism of inert gas incorporation in HiPIMS carbon films in detail [6].

Figure 7. The incorporation of inert gas atoms in HiPIMS carbon films as a function of various sputtering gas types.

Figure 8 shows the manner in which the film's mechanical properties vary with the sputtering gas type. The hardness and young's modulus decrease together as the atomic number increases (Figure 8a), with an increase in the ratio H/E (Figure 8b). These data, together with the results shown in Figures 4 and 5, indicate that there is a strong correlation between the film sp^3 content, stress, and hardness.

Figure 8. The nanomechanical properties of HiPIMS carbon coatings obtained for sputter gas type. (a) The hardness and young's modulus both decrease with atomic number of inert gasses, (b) The compressive stress decreases, and the ratio of hardness (H) over modulus of elasticity (E) [H/E] increases with sputtering gas atomic number.

4. Discussion

We find that the sp^3 content is highest for the lightest noble gases, including neon alone and mixtures of helium and neon, so that light noble gas HiPIMS offers a capability similar to other popular deposition techniques such as pulsed laser deposition and cathodic arc evaporation. The presence of macroparticles in the films is a disadvantage of the other deposition methods [19, 34].

The sp^3 fraction of carbon films is strongly positively correlated with the biaxial stress level in the films (see Figures 4 and 8b), suggesting a causative link between the two properties. The need for compressive stress for sp^3 formation in the amorphous state was initially proposed by McKenzie et al

[20] and the maintenance of compressive stress to hold sp^3 hybridization is found to be important in the growth process. Since the substrate in our experiments was biased at $-100V$, there will be bombardment of the growing film by both noble gas and carbon ions that have been accelerated in the bias field. It is clear that the energy transfer to carbon atoms in the film from the lighter noble ions is most effective (Figure 4), so that more compressive stress is generated as the carbon atoms in the film are struck by the incident ion and driven deeper into the film. Although the plasma potential may differ for the various noble gases, this difference is not likely to be more than a few tens of volts [35, 36]. The most likely explanation for the difference in sp^3 fraction, therefore, lies in the collision dynamics at the growth surface. The heavier gas ions do not transfer energy and momentum as effectively to individual carbon atoms in the growing film and produce lower compressive stresses and lower sp^3 fractions, with a significant amount of their energy going into an extended volume of the film called a “thermal spike” [21], releasing stress by means of carbon atom displacement damage over a larger volume and without densification of the carbon film [37]. A detailed approach towards understanding the mechanism for ta-C formation has been studied by Miguel et al [32] using molecular dynamics simulations, where it was demonstrated that “peening” is likely the dominant mechanism for compressive stress generation and high sp^3 content. There is a narrow energy window where relatively shallow implantation occurs, generating compressive stress.

The current-time characteristics of the discharge vary in a systematic way with the noble gas atomic weight (Figure 2). The heavier gases show a higher current with an extended mixed-mode arc regime that has an earlier onset, indicated by a sudden increase in current and an increase in the population of carbon ions created in the cathode spot-like plasma of the arc mode. We ascribe the higher current and earlier onset of the arc regime to the lower ionization potential of the heavier noble gases, resulting in more ionization and a higher plasma density. On the other hand, the lighter gases show a smaller current, a later onset of the mixed-mode, and a shorter arc regime. The mixed-mode operates with a localized cathodic arc spot which releases ions from the carbon surface [16, 29]. These ions are useful in increasing the bombardment of the films by carbon atoms to generate compressive stress (Figure 8b), higher sp^3 content (Figures 4 and 5), and thus high-density films (Figure 6), but if the arc is allowed to develop, the more mature cathodic arc spot will generate more and larger macroparticles. The larger macroparticle content is represented in the form of high surface roughness measured on the films (Figure 2). The time dependence of the development of macroparticles has been observed to be less at earlier times in the cathodic arc formation process, although the ion generation is higher [19, 38-40].

Figure 7 shows a higher incorporation in the film for the lighter and smaller noble gas atoms, which are therefore retained in the film even when under bombardment. The heavier inert gas atoms are less soluble and more readily released by subsequent bombardment. In addition, a higher deposition rate also increases the incorporation of sputter gas atoms [6].

Figure 9 shows a schematic process representing the impact of the size of the sputter gas atom on the growing carbon film. The energy transfer to the carbon atoms in the film from the lighter noble ions is most effective, so compressive stress is generated as the individual carbon atoms in the film are struck by the incident ion and penetrate deeper into the film. The heavier gas ions do not transfer energy and momentum as effectively to individual carbon atoms in the growing film and produce lower stress and lower sp^3 fractions. This is explained by the fact a large amount of their energy is dissipated as heat over an extended volume of the film, releasing stress by local annealing and without densification of the carbon film.

The practical outcomes of our findings include the ability to grow highly tetrahedral films of high hardness with lower macroparticle content, which would be a distinct advantage over other methods, such as the continuous and pulsed cathodic arc methods. This, combined with the reduced surface roughness arising from the smaller macroparticles present in the film (Figure 3c), allows the production of smoother ta-C films [41]. The ability to grow carbon films with high content of sp^2 hybridized carbon atoms, and particularly in multilayer configurations through simple process control, is also an advantage when higher electrical conductivity is desired such as for (Metal-Insulator-Metal) MIM films [42] or biosensors [43, 44] or when the dry lubricant properties of a highly graphitic film are desired.

Figure 9. A schematic diagram contrasting the impact of light noble gas ions such as neon (small red circle, upper row) and a heavy noble gas ion such as xenon (big blue circle, lower row) onto a carbon film (black). For the light ion, the energy transfer to a single carbon atom is effective, so that stress is generated as knock-on carbon atoms are driven into the film and the incident ion is reflected. Heavier gas ions do not transfer energy as effectively in a collision with a carbon atom, creating a large volume of hot material (“thermal spike”) as they continue to travel into the film. Stress is relieved by the impact as the carbon atoms relocate in the hot “thermal spike” zone (yellow highlighted atoms) and the implanted ion is released in subsequent impacts.

5. Conclusions

Various noble gases and mixtures were used in arc-mixed mode HiPIMS sputtering of a carbon target to study the properties of amorphous carbon films deposited. Sputtering with pure and mixtures of He, Ne, Ar, Xe and Kr shows that higher atomic numbers of the sputtering gas led to higher deposition rates, and lower atomic numbers lead to higher sp^3 fraction, smoother films, and deposition rates higher than previously reported for films of the same sp^3 fraction. The delicate balance between three- and fourfold coordinated carbon atoms is influenced by the mass and size of the sputtering gas atoms. The higher sp^3 fraction and higher density achieved by lighter noble gases is attributed to a smaller but more effective momentum transfer that encourages compressive stress generation by knock-on collisions at the surface of the growing film, without producing stress relief. Impact by larger noble gas atoms does not transfer energy as effectively to carbon atoms in the surface and instead creates an extended thermal spike which relieves compressive stress and allows the formation of sp^2 hybridized carbon of lower density. Our

results lead to opportunities for grading the sp^3 content in a carbon film with depth, simply by changing the gas composition during deposition. The grading technique could be used to fabricate conductive contacts for electrical devices, dry lubrication over the protective hard carbon layers for micromechanical components and to produce functional coatings for biomolecule binding in biotechnology.

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Credit Author Statement

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

**Noble gas control of diamond-like content and compressive stress in carbon films
by arc-mixed mode high power impulse magnetron sputtering**

Highlights:

- *Arc-mixed mode HiPIMS deposition of carbon films with He, Ne, Ar, Xe, and Kr noble gases.*
- *The highest sp^3 fraction is achieved by He-Ne mixtures, attributed to effective momentum transfer.*
- *The density and compressive stress in the films decrease with increasing size of noble gas atoms.*
- *The results suggest creating buried conduction channels by changing the sputter gas composition.*