Interference signal induced by ultra-thin amorphous carbon films over flexible copper foils demonstrated by electromagnetic boundaries calculations

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Aim of the work and its relationship to the status of the field

This work aims to understand how light is reflected or adsorbed at amorphous ultra-thin carbon films (a-C) deposited onto reflective materials, here the copper is used as substrate and direct current magnetron sputtering for the deposition process. Once thin amorphous carbon films (< 100 nm) are deposited to dye or darken reflective surfaces, like copper, we demonstrate experimentally and theoretically the existence of interferences correlated with the a-C thickness. Experimental and theoretical analysis of diffusive reflectance were performed to understand the interference phenomena for a double layer Cu/ a-C. This study permits to optimized a-C thickness aiming to minimize the reflectance. This research proposes industrial scalable solutions that can be used for application such as electromagnetic interferences shielding, surface darkening, Love waves, solar cells, and strategy reducing the reflectance of copper metal additive manufacturing.

A summary of the applicant's specific contributions and how they demonstrate exceptional ability and future promise

The applicant proposed the theory of interferences of a-C over copper foils analyzing reflectance data. The theoretical model calculated the reflecting power *(r)* using optical constants obtained by ellipsometry of the deposited a-C to increase the reliability of the results. The applicant is concerned about using eco-friendly resources as amorphous carbon coating, low-cost materials, and simple processes. This work is relevant for the problem of reflective materials, in issues concerning black carbon, interferences, darkening using only two-layers. The external layer is designed to be effective, low-cost, scalable, fast (reduced deposition time since ultra-thin). Carbon appears to be one of the best candidates and it can be adapted to reach optimized optoelectronic properties.

Significant results of the work and how they relate to the specific research area

The experimental diffusive reflectance (DR) as a function of wavelenght is displayed in Figure 1, panels a)-b). In brief, DR measured between λ= 400 to 1000 nm at normal incidence decreases with the a-C film thicknesses up to 42 nm. For about 150 nm, the reflectance increases (not shown),[1] i.e. The film is more reflective than, for example, thinner films of 42 nm or 70 nm, all along the recorded spectrum. This behavior discloses that a well-chosen a-C thickness presents better light absorption than many others. It worth mentioning that thicker films are less effective in reducing DR.

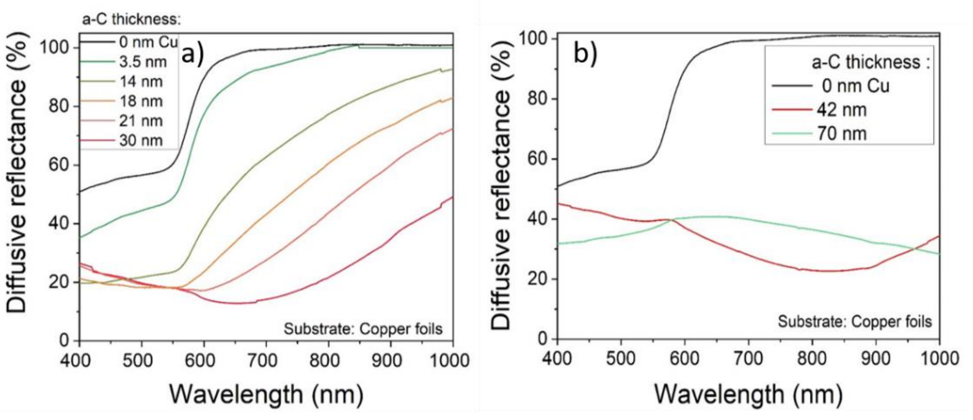

Figure 1 : Experimental results of diffusive reflectance at normal incidence beam from λ= 400 to 1000 nm of a-C films deposited over copper foils at different thicknesses a) up to 30 nm, b) 42 and 70 nm.

Based on this finding, the general aspect of DR was analyzed as a function of thickness, for different wavelengths, shown in Figure 2. Using data displayed in Figure 1, one can build the experimental part of Figure 2 a)-d) (symbols) at selected wavelengths (λ= 450, 650, 850, 1000 nm). The theoretical calculation (full line) was based on boundary conditions of electromagnetic (EM) waves. The tangential components of $\vec{E}$ and $\vec{B}$ are continuous across the boundary between one medium and the other (vacuum/carbon and carbon/copper) along a-C thickness .

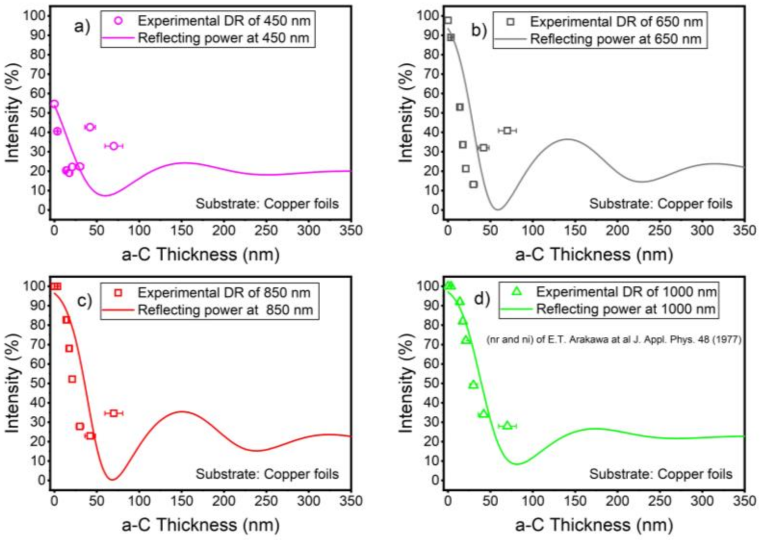

Figure 2 : Experimental (symbol) and theoretical (lines) diffusive reflectance and reflecting power (r) of a-C films deposited over copper foils versus thickness for a) 450 b) 650, c) 850 (nr, ni from [1]) and d) 1000 nm (nr, ni from Arawaka et al. J.Appl Phys. 48 (1977)).

The theoretical results disclosed nodes (maximum) and antinodes (*minimum DR point*) for a-C/ copper foils. The results of *(*r*)* confirm the behavior of experimental samples and the presence of a *minimum DR reflectance point*. For a-C thin films, the coating index is lower than the substrate index so the waves are reflected, from the substrate and from the a-C coating when they are out of phase interference takes place.

The reduction in reflection when thickness increases is seen until the *minimum DR reflectance point*. Experimental *minimum DR reflectance* was found for only 18 nm layer thick in blue range (at λ= 450 nm), increasing to 70 nm in the near IR (at λ= 1000 nm). Obviously, the increase of the thickness with the wavelength is related to the skin depth penetration of EM field into a-C films. The experimental and theoretical trends corroborate well, the antinode thicknesses increasing also with the wavelength.

In general, theoretical curves fit well experimental results up to the *minimum DR reflectance point*, corresponding to ultra-thin layers. The roughness (copper foils ($R_{ms} \approx 500$ nm)) can be an explanation for the DR shift of the antinode, heterogeneities in the thickness causing light scattering and hence increasing the reflectance, or reducing interference [2].

Conclusion

Interferences on amorphous carbon over copper reduces reflectance to a minimum point at certain a-C thicknesses much below 100 nm think, for all the spectra between λ= 400 and 1000 nm. The thickness of a-C can be precisely adjusted for a given wavelength.

[1] Â.E. Crespi, etal. Thin Solid Films. 712 (2020) 138319. https://doi.org/10.1016/j.tsf.2020.138319.

[2] Y. Ma, et al. J. Mater. Chem. C.8 (2020) 9945–9953. doi:10.1039/D0TC02087G.

Publications authored by the applicant that are relevant to this research

1. -Â.E. Crespi, C. Ballage, M.C. Hugon, J. Robert, D. Lundin, I. Vickridge, et al., Low resistivity amorphous carbon-based thin films employed as anti-reflective coatings on copper, Thin Solid Films. 712 (2020) 138319. doi.org/10.1016/j.tsf.2020.138319.
2. Oral presentation in XV MRS meeting Brazil, Low resistivity a-C:Fe thin films applied as anti-reflective coating on copper substrates. 2019. (Meeting)
3. **Bernhard Gross Award - XVIII Brazil MRS meeting** Best oral contribution of the Symposium U, Carbon based materials and devices - Low resistivity a-C:Fe thin films applied as anti-reflective coating on copper substrates -, 2019