Quantifying Clustering in Disordered Carbon Thin Films

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Abstract

The quantification of disorder and the effects of clustering in the sp^2 phase of amorphous carbon thin films are discussed. The sp^2 phase is described in terms of disordered nanometer sized conductive sp^2 clusters embedded in a less conductive sp^3 matrix. Quantification of the clustering of the sp^2 phase is estimated from optical as well as from electron and nuclear magnetic resonance methods. Unlike in other disordered group IV thin film semiconductors, we show that care must be exercised in attributing a meaning to the Urbach energy extracted from absorption measurements in the disordered carbon system. The influence of structural disorder, associated with sp^2 clusters of similar size, and topological disorder due to undistorted clusters of different sizes is also discussed. Extensions of this description to other systems are also presented.

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I Introduction

Understanding the effects of disorder on the electronic properties of amorphous carbon (*a*-C) is important for the potential development of active devices. The presence of both sp^2 and sp^3 bonding results in a mixed phase material where many of the electronic, transport and optical properties are determined by the sp^2 phase with the mechanical and tribological properties being largely determined by the sp^3 phase [1, 2]. The ability to deposit *a*-C films over large areas with mirror smooth surfaces has resulted in the use of these films in biomedical coatings and in hard disks, however, only limited success on the development of electronic devices has emerged [3]. One notable and recent success has been the report of resonant tunnelling and fast switching from an all carbon quantum well structure with the barrier and well materials containing differing amounts of sp^2 and sp^3 carbon [4]. In general, the sp^2 phase in *a*-C and its hydrogenated form, *a*-C:H, tends to exist as nm-sized clusters in the form of graphitic rings or, to a lesser extent, olephinic chains. These clusters of sp^2 C atoms give rise to π and π^* bands and many of the optical properties are discussed in terms of transitions between the occupied π states to the unoccupied π^* states. The sp^3 phase is associated with the σ and σ^* states which lie further separated from each other.

In most disordered semiconductors, the optical energy gap between extended states is called the Tauc band gap. In the absence of disorder, the Tauc gap is given by the separation between the π - π^* bands and the larger the size of the sp^2 cluster the smaller the Tauc gap. An alternative band gap that is sometimes employed is to measure the energy at which the absorption coefficient is 10^4 cm^{-1} ; this is known as the E_{04} gap. Values associated with the E_{04} gap tend to be larger than the Tauc gap as the absorption associated with 10^4 cm^{-1} tends to occur between states beyond the π and π^* band edges. Transitions between extended-to-localised states in amorphous semiconductors are usually characterised by the Urbach energy, E_u . In this way the Urbach energy is often regarded as a measure of disorder within the film and estimates of the Urbach energy can be found by fitting an exponential function to the slope

of the absorption edge. A second measure of disorder, based upon bond angle distortion, is the full width half maximum of the Raman active G band, Γ_G . This Raman signal is found at around 1580 cm^{-1} and originates from the E_{2g} vibration between sp^2 C bonds and is therefore present in all sp^2 C containing materials [5]. It should be noted that special care must be exercised when using single wavelength Raman measurements and there is now a growing realisation that multi-wavelength measurements are important as a measure of disorder and clustering in a -C thin films. For example, if two films have the same G peak position under a single visible wavelength Raman measurement, the sample with the lower G peak shift under UV Raman excitation will have the higher degree of clustering [5]. A third measure of disorder is the dispersion of G peak position with excitation wavelength. Any dispersion of the G peak arises from the resonant excitation of sp^2 clusters of different sizes at different excitation wavelengths. As a consequence of this, films that consist of a fully delocalised sp^2 phase e.g. graphite, will not show any G peak dispersion. It is the aim of this paper to discuss the quantification of the disorder found in amorphous carbon materials. Specifically, we will examine what information can be obtained by optical methods as well as probing electron states near the Fermi level using magnetic resonance methods.

II Disorder in Amorphous Carbon – Optical Measurements

For mixed phase materials with different sizes of sp^2 clusters, dispersion of the G band will occur, as shown in Fig. 1 (a). Since the dispersion of the G peak reflects the presence of different sized clusters, it also acts as a measure of the Tauc band gap. The three series of data in Fig. 1(a) are for a high sp^2 containing narrow Tauc gap graphitic carbon film, with a dispersion of only $0.09 \text{ cm}^{-1}/\text{nm}$, a diamond-like carbon film with a dispersion of $0.23 \text{ cm}^{-1}/\text{nm}$ and a wide gap polymer-like film with a dispersion of $0.31 \text{ cm}^{-1}/\text{nm}$. This result shows that the as the Tauc gap increases the amount of G peak dispersion also increases. Indeed, Casiraghi *et al.* have shown that the dispersion of the G band also apparently increases linearly with Tauc

gap [5]. For a film with a Tauc gap of 1.5 eV, they estimated a dispersion is $0.22 \text{ cm}^{-1}/\text{nm}$, rising to $0.35 \text{ cm}^{-1}/\text{nm}$ for a film with a 3 eV Tauc gap. Such combined optical [6, 7, 8] and Raman studies [5, 9] are useful at probing qualitatively the disorder present, however have also produced some potentially unusual results. Shown in Fig. 1(b) is the variation of Urbach energy, E_u , with Tauc gap for several series of *a*-C and *a*-C:H films where it can be seen that the Urbach energy increases with Tauc gap. Specifically any description of disorder should explain why larger values of E_u are observed at the highest Tauc gaps (Fig. 1 (b)) where the cluster sizes are smallest and as a result there is only a limited number of different cluster conformations possible. In addition, it has also been observed that there is a maximum in the G band line width with Tauc gap and that the G band line width depends on the excitation wavelength with the narrower values of the linewidth observed at increasing excitation energy [10]. This observation of dispersion of the Raman line width implies that there is an inhomogeneous distribution in bond angle disorder. Furthermore, the reduction of the G width with increasing excitation energy implies that there is a narrower distribution of higher gap sp^2 states. This conclusion is clearly in contradiction with the suggestion above that there must be a larger distribution of sp^2 states required for the large Urbach energy.

Whilst the Urbach energy may be a useful measure of disorder in other amorphous group IV semiconductors such as *a*-Si and *a*-Ge, the larger number of bonding configurations in the mixed phase carbon system makes its use as a measure of disorder more questionable. Indeed, in a recent paper examining the optical properties of hydrogenated amorphous silicon carbon alloys, Nguyen-Tran and colleagues showed that E_u increased with methane flow (*i.e.* carbon content and wider Tauc gap) and also concluded that the Urbach energy may not be a good of disorder [11]. From the discussion above, it is apparent that the various optical measurements that have been undertaken are at worst producing inconsistent results or that they are measuring different types of disorder present. Fanchini and Tagliaferro proposed that disorder can be sub-divided into two types [12]:

- (i) a structural disorder associated with clusters of the same size but with different amounts of distortion and
- (ii) a topological disorder arising from undistorted clusters but of different sizes.

The former type of disorder would increase both the Urbach energy and the G band linewidth, whereas the latter would increase the Urbach energy but have no effect on the G linewidth.

III Disorder in Amorphous Carbon – Magnetic Resonance Measurements

It is therefore apparent that the extent of distortion in the sp^2 clusters plays an important role. As a consequence the difference between distorted and undistorted sp^2 clusters needs to be explored. The location of the sp^2 clusters in the energy gap depends on two factors; whether they consist of even or odd numbers of carbon atoms and whether they are distorted. Undistorted even numbered clusters will give rise to states near the Fermi level (E_F) only if they are sufficiently large. This differs from the case of odd numbered clusters which can give rise to gap states even if composed of a small number of atoms. In general, distorted clusters gives rise to states that are closer to E_F than undistorted clusters. Electron spin resonance (ESR) - also called electron paramagnetic resonance, is a technique that can be used to monitor singly occupied electron states near the Fermi level [13]. In the single electron approximation the density of states will be filled pairwise by electrons in order of the orbital energy and within this approximation no ESR signals should be visible. In order to explain the observations of the ESR signal observed in many different forms of *a*-C, correlation effects which prevent the spin pairing from occurring need to be considered. The correlation energy, U , is the difference between the Coulomb repulsion energy of two electrons in the same orbital and the energy gained by lattice relaxation at the defect site when the second electron is added to the orbital. Positive and negative U centers have different properties. If U is positive all the defect states will be single occupied and the sample will exhibit paramagnetism where states from $E_F - U$ to E_F are singly occupied; states below $E_F - U$ are doubly occupied and those above E_F are empty.

In this manner ESR can give a measure of the density of sp^2 states at the Fermi level, provided that a majority of these states have a net unpaired electron spin present. Note that measurements of ESR spin densities do not themselves measure the sp^2 content. For example, electron energy loss spectroscopy measurements made on PECVD grown films showed that the π bonds per carbon atom, taken to be the sp^2 content, varied from 63% to 72% for a change of negative self bias from 100 V to 265 V. This was accompanied by an increase in the spin density from $4.9 \times 10^{19} \text{ cm}^{-3}$ to $1.5 \times 10^{20} \text{ cm}^{-3}$. However, whilst increasing the negative self bias to 540 V the spin density hardly changed ($2\text{-}3 \times 10^{20} \text{ cm}^{-3}$), the sp^2 content increased to nearly 100 %. [13] Films grown with a high H content and low internal stresses tend to have much lower defect densities typically $\sim 10^{17} \text{ cm}^{-3}$ [14].

Films of $a\text{-C:H}$ were deposited on either the driven or earthed electrode of a Plasma Technology DP800 capacitively coupled radio-frequency 13.56 MHz plasma enhanced chemical vapor deposition system. Films were grown on Corning 7059 glass for optical measurements and high-resistivity substrates for ESR measurements. During deposition, feed gases of methane (30 sccm) with He (75 sccm) were used and the total deposition pressure was 200 mTorr. Film thicknesses were measured using ellipsometry. Figure 2 shows the variation of the spin density, N_s , and peak-to-peak linewidth, ΔB_{pp} , with negative self-bias for a series of films deposited from CH_4 as a hydrocarbon source gas. Two other sets reported in the literature are also presented [7, 8]. It is evident that the spin density rises from a low value of $\sim 10^{17} \text{ cm}^{-3}$ and saturates at 10^{20} cm^{-3} . The ESR linewidth initially increases, often as the spin density increases, but at higher biases the linewidth decreases before saturating. Since the spin densities under high bias conditions reported are typically $\sim 10^{20} \text{ cm}^{-3}$, corresponding to ~ 1 at. % of the material present, we may reasonably assume that the ESR signal can be considered as originating from a dilute paramagnetic material. It is therefore possible to apply the theory of Abragam to calculate the contribution to ΔB_{pp} from the dipole-dipole interaction between like spins [15]. Such a broadening mechanism will produce a Lorentzian ESR lineshape, consistent

with the observed lineshape. At lower biases, the lineshape is often Gaussian, characteristic of inhomogeneous broadening, and usually attributed to unresolved H hyperfine interactions. Assuming a spin concentration N_s , measured in cm^{-3} , the contribution to the dipolar interaction ΔB_{pp} , measured in mT, can be given as [13]

$$\Delta B_{pp} = 8.12 \times 10^{-21} N_s \quad (1)$$

Figure 3 shows the variation of ΔB_{pp} against N_s directly for the same three series of data reported in Fig. 2, as well the predicted linewidth (dashed line) based solely on dipolar broadening using Eq. (1). It is apparent that significant reductions in ΔB_{pp} are occurring at high N_s , when compared with the values predicted by Eq. (1), indicating an alternative mechanism to dipolar broadening is responsible for the linewidth. This additional interaction is due to the motional averaging of the electron wavefunction within the sp^2 cluster. As the sp^2 cluster increases in size the probability of the electron being associated with a particular atom decreases. This spread out or delocalization of the wavefunction as the cluster size increases is accompanied by a general reduction in the Tauc gap. Larger clusters will have greater amount of delocalization and the smaller Tauc gap.

It is further possible to relate the extent of the clustering by combining the ESR results above with the conclusions from nuclear magnetic resonance measurements (NMR). Jäger *et al.* used cross polarisation ^{13}C NMR to measure the effects on the proton relaxation times in different environments of films deposited from acetylene and benzene. It was reported [16] that two proton spin-lattice relaxations time constants of 14 and 120 ms were present and were attributed to the presence of two differently relaxing proton systems. The shorter relaxation time originated from CH groups in the sp^2 and sp^3 matrix. The longer relaxation time was believed to originate from the short CH_2 polymer units with a sp^3 configuration. These two environments are separated by regions of non-hydrogenated sp^2 C. It was also reported that the shorter T_1 component varied little with temperature suggesting that the protons are being relaxed via spin

diffusion to paramagnetic centers. Therefore it is the degree of electron aggregation or clustering around these paramagnetic centers that determines the proton relaxation.

On the basis of NMR measurements, Tamor *et al.* estimated the protonated and non-protonated C concentration with either sp^2 or sp^3 hybridisation [17]. At a self-bias of -500 V, the H content was estimated to be 36 at. % and the fraction of protonated sp^3 C atoms to be 0.16, non-protonated sp^3 C atoms to be 0.20, protonated sp^2 C atoms to be 0.25, and non-protonated sp^2 C atoms to be 0.37. For a film density of 1.7 g cm^{-3} , this result suggests there are $5.1 \times 10^{22} \text{ } sp^2 \text{ C atoms cm}^{-3}$ in the film. If the signal observed from ESR presented in Fig. 2(a) is associated with sp^2 C centers, then for a typical value of N_s of 10^{20} cm^{-3} , this corresponds to 1 spin per 510 sp^2 C atoms or 1 spin per 300 atoms of non-protonated sp^2 C atoms. If these spins were randomly distributed throughout the film co-operative effects, such as exchange, should not occur. Since exchange effects are observed to films grown at high bias, the combined use of NMR and ESR confirms and quantifies the clustering of the sp^2 phase that has taken place.

V Conclusions

In conclusion, the disorder and clustering within a wide variety of amorphous carbon thin films can be characterized in terms of states near the Fermi level. For polymer-like films with small clusters and a small distribution of cluster sizes the Urbach energy is not a good measure of disorder and topological disorder dominates. In DLC films, the increase in spin density (10^{20} cm^{-3}) coupled with the increase in the G band width implies more distorted clusters are present. At the higher spin density the ESR linewidth is no longer determined by the dipole interaction, with intracluster exchange interactions determining the linewidth. In this regime both topological and structural disorder is present and can affect the stress in the film.

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Figure captions

Figure 1 (a) Dispersion of the G peak band position for a polymer-like a-C:H film (■), a diamond-like carbon film (□) and a high sp^2 containing film (●) and (b) variation of the Urbach energy with Tauc gap for different a-C:H films.

Figure 2 Variation of (a) spin density and (b) peak-to-peak linewidth for three series of a-C:H films with negative self-bias.

Figure 3 Variation of peak-to-peak linewidth with spin density for the data presented in Figure 2. The dashed line represents the predicted dipolar contribution to the linewidth based on Eq. (1). Note that this is not a fit to data.

Carey and Silva, Figure 1

Carey and Silva, Figure 2