

Carbon-13 Labeling for Improved Tracer Depth Profiling of Organic Materials Using Secondary Ion Mass Spectrometry

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^{13}C labeling is introduced as an alternative to deuterium labeling for analysis of organic materials using secondary ion mass spectrometry (SIMS). A model macromolecular system composed of polystyrene (PS) and poly(methyl methacrylate) (PMMA) was used to compare the effects of isotopic labeling using both deuterium substitution (dPS) and ^{13}C labeling (^{13}C -PS). Clear evidence is shown that deuterium labeling does introduce changes in the thermodynamic properties of the system, with the observation of segregation of dPS to an hPS:dPS/hPMMA interface. This type of behavior could significantly impact many types of investigations due to the potential for improper interpretation of experimental results as a consequence of labeling-induced artifacts. ^{13}C labeling is shown to provide a true tracer for analysis using SIMS. (J Am Soc Mass Spectrom 2006, 17, 1142–1145) © 2006 American Society for Mass Spectrometry

Secondary ion mass spectrometry (SIMS) has become a powerful analysis tool for depth profiling or chemical mapping of organic and biological systems [1–5]. One such application has been one-dimensional depth profiling of polymer films and multilayers, which has provided a significant driving force for growth in experimental and theoretical polymer physics over the past 20 years [6]. Deuterium substitution is by far the most common type of tracer labeling used for analysis of polymer films and multilayers [7], with the commercial availability of various labeled reagents and monomers. Unfortunately, it can introduce changes in the properties being measured. For instance, it has been established that deuterium substitution can affect polymer/polymer phase behavior, with reported changes in both bulk [8–10] and surface interactions [11, 12], and deuterium substitution has even been shown to alter polymer-solvent phase behavior [13]. More recently, it has been found that deuterium substitution can have a profound effect on the proper-

ties of a polymer/polymer heterogeneous interface, with the observation of diffusion-controlled segregation of deuterium labeled polystyrene (dPS) to an hPS:dPS/poly(methyl methacrylate) (hPMMA) interface [14]. This type of behavior could significantly impact several types of investigations, such as drug delivery mechanisms [15], with the potential for improper interpretation of experimental results due to labeling-induced artifacts. Alternative methods of tracer labeling are therefore required. Here, we demonstrate the development of one such method using ^{13}C labeling, with the expectation that this method will be generally applicable for analysis of various carbonaceous systems in fields ranging from polymer physics to biotechnology.

Experimental

Materials and Sample Preparation

For the investigation of dPS segregation to an hPS:dPS/hPMMA interface, the polymers were purchased from Polymer Source (Dorval, Canada), and are listed in Table 1 along with the glass transition temperatures (T_g) as determined using differential scanning calorimetry. hPMMA was cast from 1-chlorobenzene onto hydrogen-

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Table 1. Polymer properties

Polymer	M_w/kDa	M_w/M_n	$T_g/^\circ C$
dPS	82.8	1.15	97
hPS	73.0	1.04	96
^{13}C -PS	79.4	1.20	100
^{12}C -PS	73.7	1.19	100
hPMMA	155	1.05	127
^{12}C -PMMA	90.9	1.26	100

passivated Si (100) to a thickness of ca. 200 nm and annealed at 150 °C for 3 h. PS (90% hPS + 10% dPS vol/vol) was cast directly onto hPMMA from 1-chloropentane, a selective solvent for PS over PMMA, to a thickness of 210 nm and annealed for 94 h at 138 °C, which is a much longer time than required for equilibrium segregation of this system [14]. A 50 nm (approximate) hPS sacrificial layer was added to the sample before analysis to avoid pre-equilibrium sputtering at the hPS:dPS surface. For the novel ^{13}C depth profiling investigation, ^{13}C -PS, ^{12}C -PS, and ^{12}C -PMMA were synthesized using atom transfer radical polymerization (ATRP) with previously outlined conditions [16], and are listed in Table 1. A mixture of 33% α,β - ^{13}C labeled styrene (Isotec) and unlabeled styrene monomer were used in the synthesis of ^{13}C -PS resulting in 10.3% ^{13}C relative to the total carbon in the ^{13}C -PS, as determined using time-of-flight SIMS (PHI TRIFT I). ^{12}C -PS and ^{12}C -PMMA have 1.1% ^{13}C (natural abundance). For the first set of samples, ^{13}C -PS was cast onto Si (100) that had a 2 nm native oxide (SiO_x) layer to a thickness of 180 nm and annealed at 125 °C for 24 h. A second set of samples was prepared to evaluate the effects of isotopic labeling at the PS/PMMA interface. ^{12}C -PMMA was cast onto Si (100) that had a 2 nm SiO_x layer and was annealed at 125 °C for 30 min. Next, 5% ^{13}C -PS + 95% ^{12}C -PS (vol/vol, solvent free basis) was cast onto the PMMA from 1-chloropentane to a thickness of 175 nm and annealed at 125 °C for 24 h. A 125 nm layer of ^{12}C -PS was floated onto both of these sets of samples to establish the background (natural abundance) ^{13}C secondary ion yields.

Secondary Ion Mass Spectrometry

All depth profiles were performed using a CAMECA IMS-6f magnetic sector mass spectrometer (Courbevoie, France), which has the mass resolving capabilities to completely separate $^{12}C^1H$ (13.00,782 Da) from ^{13}C (13.00,335 Da) [4, 17]. A 20 nm Au coating was sputtered onto the samples before SIMS analysis to help minimize charging. Analysis conditions for O_2^+ primary ion bombardment included a 30 nA primary current rastered over a $180 \mu m \times 180 \mu m$ area, with 5.5 keV impact energy (10 kV primary with 4.5 kV sample bias) and a mass resolution ($m/\Delta m$) of 3000. The angle of incidence for the primary ions was 41° from normal. Positive secondary ions were detected from a 60 μm diameter optically gated area positioned in the center of the raster. For Cs^+ , analysis conditions included a 10 nA

primary current rastered over a $180 \mu m \times 180 \mu m$ area, with 6.0 keV impact energy (5 kV primary with –1 kV sample bias) and $m/\Delta m = 2910$. The angle of incidence for the primary ions was 27° from normal. Negative secondary ions were detected from a 60 μm diameter optically gated area positioned in the center of the raster.

Results and Discussion

Figure 1 shows an example of the effect of deuterium labeling at the heterogeneous hPS:dPS/hPMMA polymer/polymer interface. Because dPS has an energetic preference for hPMMA, there is an observed segregation of dPS to the hPS:dPS/hPMMA interface [14]. The hPS:dPS blend is well within the single-phase region of the hPS:dPS phase diagram [10], so the observed phenomenon is not due to bulk phase separation. This behavior has been described in detail elsewhere, with identification of diffusion-controlled behavior at very early times [14]. Figure 2 shows profiles of the ^{12}C -PS/ ^{13}C -PS bilayer using both 6.0 keV Cs^+ (Figure 2a and c) and 5.5 keV O_2^+ (Figure 2b and d) primary ion bombardment. In both profiles it is evident that the ^{13}C is indeed completely mass resolved, as the $^{12}C^1H$ profile clearly traces the ^{12}C profile and not the ^{13}C profile. Figure 2c and d show the profiles for the volume fraction of ^{13}C -PS (ϕ) as a function of effective depth (z), based on the PS sputtering rates, as determined by:

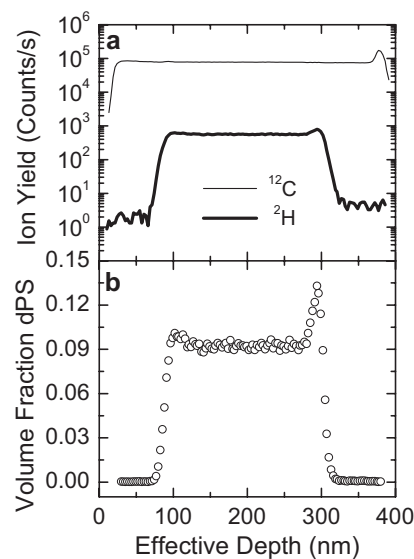


Figure 1. Segregation of dPS to the hPS:dPS/hPMMA interface and hPS:dPS surface after annealing for 94 h at 138 °C. Both the relative count rates (a) and dPS volume fraction (b) are presented. The segregation of dPS to the hPS:dPS/hPMMA interface clearly shows that dPS has an energetic preference for hPMMA. The hPS:dPS blend is well within the single phase region of the phase diagram. SIMS analysis was performed using 5.5 keV impact energy O_2^+ ion bombardment with detection of positive secondary ions. The effective depth was determined by assuming a constant PS sputtering rate throughout the analyzed film assembly.

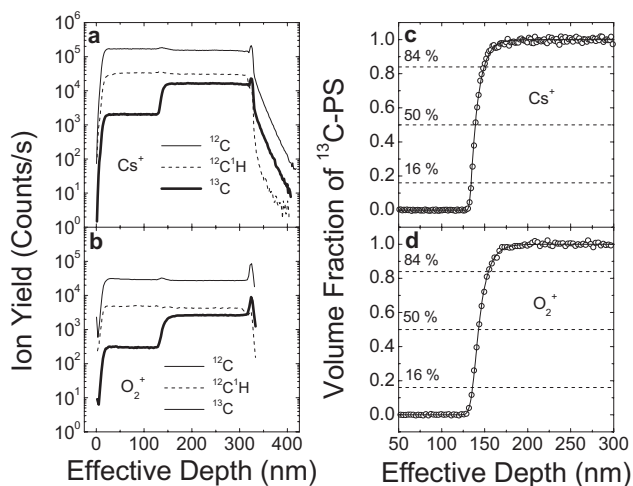


Figure 2. SIMS depth profiles showing ^{12}C (solid line), $^{12}\text{C}^{1}\text{H}$ (dashed line), and ^{13}C (bold line) secondary ion yields and (c, d) volume fraction of ^{13}C -PS in the ^{12}C -PS/ ^{13}C -PS bilayer. Both (a, c) 6.0 keV Cs^+ and (b, d) 5.5 keV O_2^+ primary ion bombardment, with detection of negative and positive secondary ions, respectively, were used for analysis of this sample. Shown in (c) and (d) are the midpoint (50%) and 16 and 84% intensity lines, which are used to semiquantitatively describe the asymmetry of the profiles (see Table 2). The solid lines in (c) and (d) are a fit using a step function convoluted with a Gaussian and an exponential function (see eqs 2–4). The effective depth was determined by assuming a constant PS sputtering rate throughout the film assembly.

$$\phi(z) = \frac{Y_{13}(z) - Y_{NA}}{Y_P - Y_{NA}}, \quad (1)$$

where $Y_{13}(z)$ is the ^{13}C ion yield, normalized to the total C ($^{12}\text{C} + ^{13}\text{C}$) ion yield, at depth z , Y_{NA} is the normalized ^{13}C ion yield of pure ^{12}C -PS (natural abundance), and Y_P is the normalized ^{13}C ion yield of pure ^{13}C -PS. Under the conditions implemented here for both O_2^+ and Cs^+ bombardment, excellent signal-to-noise (S/N) is observed in the profiles shown in Figure 2c and d, even though there is only 10.3% total ^{13}C , based on $^{13}\text{C}/(^{13}\text{C} + ^{12}\text{C})$, in the ^{13}C -PS. The profiles shown in Figure 2c and d for 6.0 keV Cs^+ and 5.5 keV O_2^+ were evaluated using an 84/16 analysis ($2\sigma_{84/16}$) and the standard deviation using 50/16 ($\sigma_{50/16}$) and 84/50 ($\sigma_{84/50}$) analyses, as shown in Table 2.

The profile lineshapes and nearly a factor of two difference between $\sigma_{50/16}$ and $\sigma_{84/50}$ observed through the ^{12}C -PS/ ^{13}C -PS interface clearly demonstrate that these profiles cannot be accurately represented by a symmetric Gaussian instrument resolution convoluted with a sharp intrinsic profile. The observed convolution-type arises primarily from ion-induced mixing of the ^{13}C and ^{12}C matrix and implantation of the ^{13}C further into the film (tailing) [18]. Analogous behavior has been observed for ^{30}Si implants in a ^{28}Si matrix [18]. Here we employ a simplified version of a convolution scheme that has been outlined previously [18, 19]. It combines a Gaussian with a standard deviation σ_{eff} that accounts for ion-induced mixing and sources of uncor-

related convolution, such as sample roughness, and an exponential for the observed tailing, which has a characteristic decay length λ_d . The Gaussian convolution function is

$$G(z) = \frac{1}{(2\pi)^{1/2} \sigma_{\text{eff}}} \exp \left[-\frac{1}{2} \left(\frac{z}{\sigma_{\text{eff}}} \right)^2 \right]; z \rightarrow (-\infty, \infty), \quad (2)$$

and the exponential decay is described by

$$F(z) = \frac{1}{\lambda_d} \exp \left(-\frac{z}{\lambda_d} \right); z \rightarrow (0, \infty). \quad (3)$$

$G(z)$ and $F(z)$ are numerically convoluted, using the Fourier transform method [20], with a Heaviside step function $\theta(z)$, where

$$\theta(z) = 0(-\infty, z_1) \text{ and } \theta(z) = 1(z_1, \infty), \quad (4)$$

to approximate the experimental profiles. These convoluted profiles are fit to the data with σ_{eff} and λ_d as regression parameters. Results for 6.0 keV Cs^+ and 5.5 keV O_2^+ primary ion bombardment are summarized in Table 2. The best fit lineshapes are also plotted as solid lines in the graphs shown in Figure 2c and d, clearly indicating that the combination of a Gaussian and exponential decay function yields excellent results. The effective location of the interface z_1 was determined by the fit.

Finally, the interface between PS and PMMA is probed using the ^{12}C -PS/ ^{13}C -PS/ ^{12}C -PMMA system with analysis using 6.0 keV Cs^+ primary ion bombardment. The nonmonotonic changes in the secondary ion yields for ^{12}C , $^{12}\text{C}^{1}\text{H}$, and ^{13}C at the PS/PMMA interface shown in Figure 3, which have been observed previously [4], are not due to sample charging, as determined from analysis of ^{12}C secondary ion energy spectra at several depths through the sample. After 24 h of annealing at 125 °C, there is no apparent segregation of ^{13}C -PS to the heterogeneous interface or free surface, as shown in Figure 3. Even though this is a lower temperature and annealing time than used with the hPS:dPS/hPMMA system (see Figure 1), it has been shown that a diffusion gradient and interfacial excess of 140 kDa dPS (5% vol/vol in 138 kDa hPS) were readily visible for an hPS:dPS/hPMMA system after 4 h at 128 °C [14]. The molecular weight dependency of diffusivity of entangled polymer chains in the melt ($D \propto M_w^{-2}$) is well known [21]. From this we can infer that discernible changes in the ^{13}C -PS profile would be

Table 2. Convolution results

	$(2\sigma)_{84/16}$ (nm)	$\sigma_{50/16}$ (nm)	$\sigma_{84/50}$ (nm)	σ_{eff} (nm)	λ_d (nm)
O_2^+	19	7	12	4.2	10
Cs^+	14	5	9	1.7	9

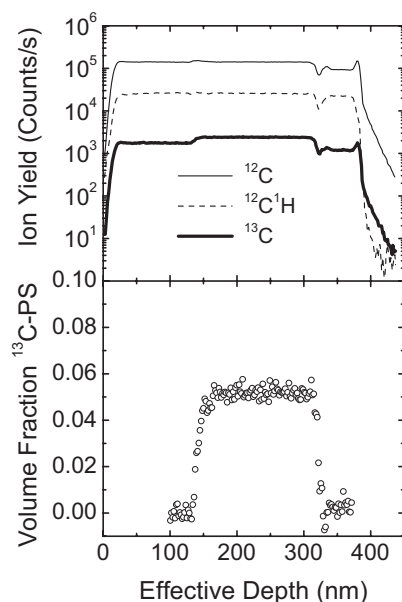


Figure 3. SIMS depth profile showing relative count rates and ^{13}C -PS volume fraction of an analogous system to that shown in Figure 2, except that ^{13}C -PS was used as the tracer instead of dPS. After 24 h at 125 °C, there is clearly no segregation of ^{13}C -PS to the ^{12}C -PS/ ^{13}C -PS/ ^{12}C -PMMA interface, thereby proving that ^{13}C labeling does indeed provide a true tracer for depth profiling of polymer films and multilayers. SIMS analysis was performed using 6.0 keV Cs^+ ion bombardment with detection of negative secondary ions. The effective depth was determined by assuming a constant PS sputtering rate throughout the analyzed film assembly.

observable at the ^{12}C -PS/ ^{13}C -PS/ ^{12}C -PMMA interface after ~ 1 h at 125 °C, if there were an energetic preference for ^{13}C -PS at the heterogeneous polymer/polymer interface. This is in stark contrast to the behavior witnessed at the hPS:dPS/hPMMA interface (see Figure 1), and is direct evidence that the use of ^{13}C labeling provides improved analysis conditions for tracer depth profiling using SIMS.

Conclusions

Significant changes in thermodynamic behavior due to deuterium labeling at an hPS:dPS/hPMMA interface have been shown [14], with the observation of segregation of dPS to the heterogeneous interface (see Figure 1). The molecular weight and annealing temperature of the hPS:dPS blend place this system well within the single phase region of the hPS:dPS phase diagram [10], which clearly demonstrates that the use of deuterium labeling may not provide a true tracer component for analysis using SIMS. This type of behavior could result in improper interpretation of experimental results due to labeling-induced artifacts. However, the use of ^{13}C labeling has been shown to be an exceptional alternative to deuterium labeling by providing a true tracer, with no observed segregation of ^{13}C -PS to a ^{12}C -PS/ ^{13}C -PS/ ^{12}C -PMMA interface (see Figure 3). Although we

don't anticipate the use of ^{13}C labeling to completely replace the use of deuterium labeling, it is expected that its use will indeed provide greatly improved analysis of various organic and biological systems.

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