Communication

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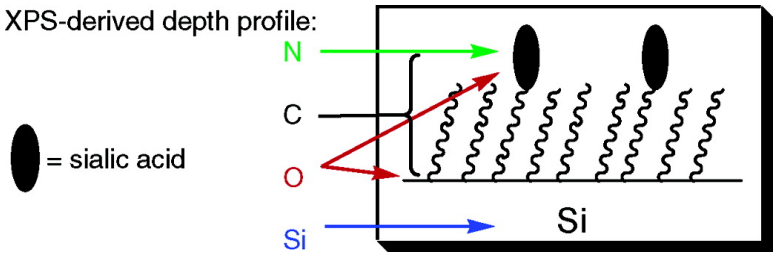

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Covalently Attached Saccharides on Silicon Surfaces

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The covalent attachment of organic moieties to silicon surfaces[1] allows for a significant extension of the use of silicon as substrate in optoelectronic elements. Especially the possibility to link bioactive molecules to these surfaces is highly attractive, given the possibilities of such surfaces in biosensing.[2] Standard methods to obtain covalently attached monolayers to well-defined Si surfaces include heating in neat alkene[3] or in refluxing mesitylene,[4] UV irradiation,[5] and Grignard reactions.[6] Although such reaction conditions yield stable[7] and densely packed monolayers,[8] they are frequently too harsh to allow the use of labile bioactive materials. One way out is to attach a precursor to the surface that can stand such harsh conditions, which is subsequently transformed into the bioactive monolayer.[9] Such an approach has been taken for DNA attachment studies.[8,10] Alternatively, mild reaction conditions that are compatible with such bioactive moieties can be used.[11] We have recently reported a new, extremely mild procedure for the functionalization of well-defined hydrogen-terminated silicon surfaces using visible light (447 nm).[12] This procedure yields water contact angles for alkyl monolayers derived from $C_{12}-C_{16}$ alkenes and alkynes that are at least as high as previously reported using thermal methods. We now report the first functionalization of hydrogen-terminated Si(100) surfaces with saccharides. Both a thermal and our mild photochemical method are used, depending on the thermal stability of the saccharide.

The attachment of saccharides to silicon surfaces opens up new routes to the detection of selective recognition of antibodies to oligosaccharide receptors. Arrays of oligosaccharides have been reported on glass or gold.[13] Although this allows for optical or spectroscopic detection, detection of such interactions via capacitance changes requires semiconducting substrates. Hydrogen-terminated Si(100) surfaces − obtained via etching of native oxide-covered Si wafers in 2.5% aqueous HF solution for 1−2 min − were functionalized with monosaccharides (Scheme 1) using either of two methods: refluxing in mesitylene for 2 h, or irradiation in mesitylene using a 447 nm pen lamp [Jelight; 3 mW/cm^2 at 0.5 cm from the substrate for 15 h].[14]

A mixture of an acetyl-protected β-glucose-functionalized alkene (compound **1**, Scheme 1) and 1-decene was used to modify a Si wafer thermally. Characterization of this surface using attenuated total reflectance IR (ATR-IR) measurements (Figure 1) displays the presence of carbonyl groups, which are present in this monolayer, and not in a reference monolayer obtained under identical conditions using only 1-decene. The position of the symmetric C−H stretch vibration at 2925 cm^{-1} shows that this and other sugar-containing monolayers are not well-ordered, which is partly due to the relatively bulky sugar moiety and partly intrinsic to the hydrogen-terminated Si(100) surface, as this is not molecularly flat as is hydrogen-terminated Si(111).[15]

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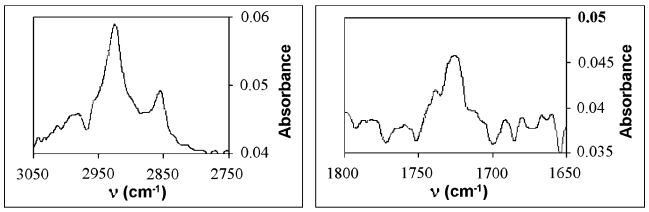
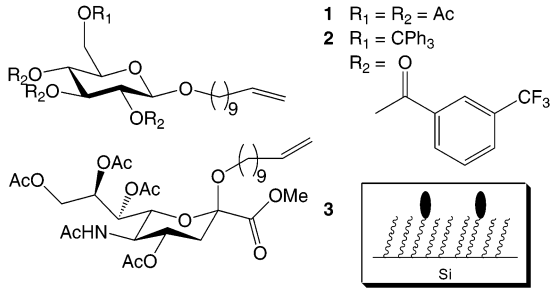


Figure 1. ATR-IR spectra of a covalently attached monolayer obtained by the thermal method, using a mixture of **1** (0.66%) and 1-decene (99.4%) in refluxing mesitylene.

Scheme 1. Structures of the 1-Alkenyl Monosaccharides **1**−**3** Used in the Preparation of Mixed Monolayers on the Si(100) Surface[16] (Inset Shows a Schematic Representation of a Functionalized Mixed Monolayer)



Compound **1** was modified in three steps into compound **2** of which the hydroxyl moieties at C2, C3, and C4 are protected with *meta*-(trifluoromethyl)benzoyl groups (Scheme 1). A mixture of compound **2** and 1-dodecene was used to thermally obtain a modified Si surface. Characterization of this surface using X-ray photoelectron spectroscopy (XPS; Theta Probe of Thermo Instruments; monochromatic Al Kα X-ray source with a 400 μm^2 spot at 100 W under UHV conditions; Figure 2, top) shows the attachment of the protected glucose moiety. The inset of Figure 2 is a magnification of the area specific for fluorine. Deconvolution of the peak clearly shows the presence of two types of fluorine. Even though the corresponding peaks are not baseline separated, this situation can be analyzed by angle-resolved XPS (ARXPS), which makes use of a two-dimensional microchannel detector (MCD) to simultaneously measure the intensity of the photoelectron emission as a function of emission angle (16 detection segments of 3.75° each). Large detection angles − with respect to the surface normal − yield surface-sensitive signals, while photoelectrons captured at small detection angles reflect more bulk-sensitive signals. Analysis of these signals provides a relative depth profile, which is basically a cross section of the monolayer (only 1.5 nm overall thickness!) per element. The MCD allows ARXPS experiments without tilting the sample and with a concomitantly constant analysis area for all detection angles. As a result, unparalleled resolution can be acquired with respect to the depth distribution of elements on the surface.[12]

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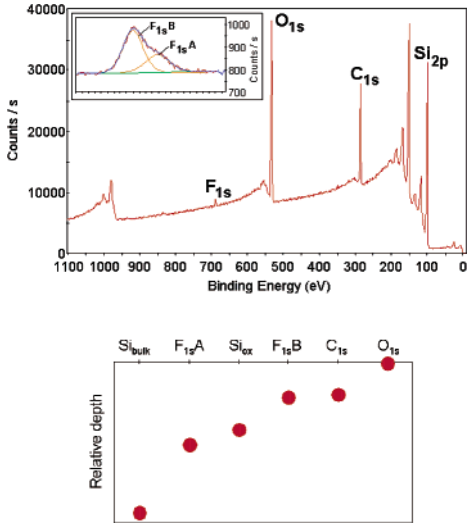

Figure 2. XPS spectrum (top) and relative depth profile (bottom) of a thermally attached mixed monolayer obtained from a mixture of compound **2** (12%) and 1-dodecene (88%) in mesitylene. The inset shows the presence of two different types of F atoms on the surface.

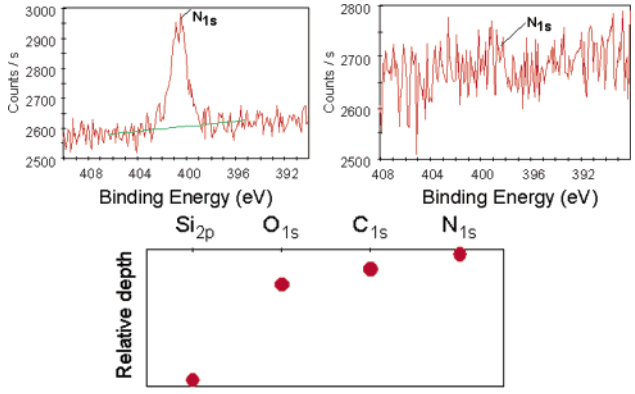

Figure 3. (top) XPS spectrum (N(1s) region) of a covalently attached monolayer containing **3** (top left), and a reference spectrum of a monolayer obtained from 1-hexadecene (top right) that shows the absence of this signal in unfunctionalized alkyl monolayers. (bottom) Relative depth profile of a mixed monolayer of **3** (25%) and 1-dodecene (75%) as obtained via parallel angle-resolved XPS measurements.

From the relative depth profile obtained by ARXPS (Figure 2, bottom) and the corresponding binding energies, it can be concluded that $F_{1s}A$ is bound to silicon via a Si−F bond that is likely introduced during the etching procedure, while $F_{1s}B$ is bound to carbon. The amount of silicon-bound fluorine is dependent on the etching procedure, and the data in Figure 2 thus also show the potential of ARXPS to analyze this even for fluorine-containing monolayers.

The value of the visible light attachment becomes evident for surface modification with sialic acid derivative **3**. Sialic acids are a crucial component in oligosaccharides that play a role in cell recognition processes.[17] Their chemistry frequently requires more subtle procedures for regio- and stereoselective introduction of glycosidic linkages.[17a,c,18] Sialic acid-containing saccharides display a diminished thermal stability, but are transparent for 447 nm light, which allows for the room-temperature attachment of **3** to hydrogen-terminated Si(100) surfaces. The high sensitivity of XPS allows for the detection of the single N atom in a monolayer obtained from a solution of 25% of **3** and 75% of 1-dodecene in mesitylene. The XPS data for the N(1s) region show a clear signal for the monolayer containing **3**, which is absent in a reference monolayer of 1-hexedecene (Figure 3, top).

To check whether the disorder in these sugar-containing monolayers results in burial of the headgroup in the monolayer, a relative depth profile was obtained using ARXPS (Figure 3, bottom). This displays nitrogen as − on average − the highest element in the monolayer. The alkyl chains of **3** and 1-dodecene yield a clear C_{1s} signal, which is on average located closer to the Si surface and in fact somewhat higher than the oxygen signal. This unresolved signal is composed of oxygen atoms that are part of the sugar and of surface bound oxygen. The latter is nearly absent in unfunctionalized alkyl monolayers,[1c] but is usually present in small amounts in functionalized monolayers.[19] As a result, oxygen is on average lower than carbon. At the bottom of the analyzed layer, silicon was detected. This profile supports the picture that the sialic acid moiety basically sticks out above the monolayer and is accessible for any bioactive material. In combination with the stability of such monolayers toward extended exposure to aqueous environments, this opens up the possibility for oligosaccharide-based biosensing.

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